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PRODUCTION OF NEUTRAL STRANGE PARTICLES IN ANTIPROTON - ^{3}He ANNIHILATION AT REST

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An unexpectedly high Λ-hyperon production yield has been observed recently /1-3/ 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 $\bar{p}p \to \Lambda\bar{\Lambda}$ reaction, multiplied by $A^{2/3}$.

Still more surprizing results were obtained in our PS 179 experiment at CERN /2,3/, in which the production of neutral strange particles was investigated in the annihilation of antiprotons in ^{20}Ne and ^{4}He at 600 MeV/c (the corresponding kinetic energy is 180 MeV). At this energy the production of a Λ on a single nucleon is forbidden, since the $\bar{p}p \to \Lambda\bar{\Lambda}$ reaction threshold is p_{th}=1435 MeV/c (associative Λ-production, such as $\bar{p}N \to \Lambda K$, is also forbidden owing to conservation of the baryon number). Nevertheless, the Λ cross section turns out to be high, comparable or even greater than the cross section for the allowed of K_S^0 production channel (the ratio $R=\sigma(\Lambda)/\sigma(K_S^0)$ is $R=2.3\pm0.7$ and 0.94 ± 0.19 for annihilation in ^{20}Ne and ^{4}He, respectively).

In this article we continue the investigation of subthreshold Λ production in the case of antiproton annihilation in ^{3}He at rest. We have studied the following reactions involving annihilation of stopping antiprotons :

$$\bar{p} + {}^{3}He \to \Lambda + X \qquad (1)$$
$$\bar{p} + {}^{3}He \to K_S^0 + X. \qquad (2)$$

Data were obtained using a streamer chamber exposed to the LEAR antiproton beam of 105 MeV/c at CERN. The experimental apparatus has been described in detail previously /4/, so here we shall only recall the main features.

The ($90 \times 70 \times 18$ cm^3) self-shunted /5/ streamer chamber was filled with helium at atmospheric pressure. For achieving well-localized bright tracks in the chamber, an admixture of C_4H_{10} (0.14%) was included. The chamber was placed in a magnetic field of 0.4 T. The trigger was provided by a hodoscope of thin scintillation counters placed along the beam in front of the chamber. Due to energy losses occurring in the end-wall of the vacuum line of LEAR, in the trigger counters and in the entrance window of the chamber, the kinetic energy of antiprotons entering the chamber was reduced to 2.5 MeV. As a result, the antiproton stopping points were in the central region of the chamber.

About $1.5 \cdot 10^4$ pictures were scanned in search of candidates for neutral strange particle decays (V^0) into charged particles. Selected events were measured and processed using the HYDRA program for geometry reconstruction and kinematical analysis. Processing of the obtained data is considered in detail in refs./2,3,6/. The final statistics consisted of 78 K^0_S and 25 Λ. The total number of antiproton interactions was 14319. We estimated /7/ the events due to annihilation on the admixture in the ^{3}He gas which could be confused with annihilation on ^{3}He to make up for about 2.4% of the total number of events. Our detection efficiency is about 100% for V^0 vertices separated from the annihilation vertex by not less than 1 cm, while there is a substantial loss of the V^0 decaying in the vicinity of the interaction vertex. The losses of these V^0 as well as of those decaying outside the fiducial volume were taken into account by introducing weights. The weight W (representing the inverse registration probability for a given event) was calculated by simulation. The average weights turned out to be $\langle W \rangle = 1.85 \pm 0.16$ for the Λ and $\langle W \rangle = 1.62 \pm 0.13$ for the K^0_S.

To obtain the absolute V^0 yields corrections were made taking into account neutral decay modes, the scanning efficiency and the efficiency of measurement and reconstruction. Note that the process $\bar{p}\,^3He \to \Sigma^0 X \to \Lambda \gamma X$ also contributes to the measured yield of Λ. The corrected absolute yields of Λ and K^0_S turned out to be:

$$Y_\Lambda = (0.55 \pm 0.11) \cdot 10^{-2} \quad (3)$$

$$Y_K = (1.59 \pm 0.20) \cdot 10^{-2}. \quad (4)$$

We have estimated the ambiguity in the determination of (3)-(4) to be about 13 % (it comes mainly from the events rejected by the geometry reconstruction program).

The ratio $R = Y_\Lambda / Y_K$ is:

$$R = 0.35 \pm 0.08. \quad (5)$$

We have 8 double V^0 that were identified as 3 ΛK^0_S and 5 $K^0_S K^0_S$. The corresponding yields are:

$$Y(\Lambda K^0_S) = (0.15 \pm 0.08)\cdot 10^{-2} \quad (6)$$

$$Y(K^0_S K^0_S) = (0.20 \pm 0.09)\cdot 10^{-2}. \quad (7)$$

We also obtained the multiplicity distributions (see Table 1) for events associated with Λ and K^0_S. It is noteworthy that these distributions are rather similar.

Table 1. Charged-prong multiplicity distribution for events associated with V^0. The probability for such events with M charged particles is given in percents.

type of V^0	Number of prongs - M: 1	3	5	7
K^0_S	18.0 ± 4.3	66.7 ± 5.3	14.1 ± 3.9	1.28 ± 1.27
Λ	28.0 ± 9.0	56.0 ± 9.9	16.0 ± 7.3	-

The mean numbers of negative charged mesons (π^- and K^-) produced in the primary annihilations associated with V^0 are:

$$\langle n \rangle_- = 0.99 \pm 0.07 \quad \text{for } K^0 \quad (8)$$

$$\langle n \rangle_- = 0.88 \pm 0.13 \quad \text{for } \Lambda. \quad (9)$$

These values are significantly lower than the corresponding overall average multiplicity of negative charged mesons produced in $\bar{p}^3He$ annihilation /7/: $\langle n \rangle_- = 1.61 \pm 0.03$.

The most simple case for identification of a particular reaction channel is represented by one-prong events associated with K_S^0. These events are mainly due to annihilation on a proton in ^{3}He into neutral π-mesons and a $\bar{K}^0K^0$ pair:

$$\bar{p} + {}^3\mathrm{He} \Rightarrow \bar{K}^0K^0 + m\pi^0 + p + n. \qquad (10)$$

The rate of (10) depends on the probability W_p for the antiproton to annihilate on a proton in ^{3}He and on the yield $Y(\bar{p}p \Rightarrow K_S^0X^0)$ of K_S^0 in the channel $\bar{p}p \Rightarrow \bar{K}^0K^0 + m\pi^0$:

$$W(1,K_S^0) = W_p \cdot Y(\bar{p}p \Rightarrow K_S^0X^0). \qquad (11)$$

We have found 14 one-prong events with K_S^0, corresponding to $W(1,K_S^0)=(0.286\pm0.073)\%$. Previously, we obtained for $\bar{p}^3$He annihilation at rest /8/ $W_p= 0.81\pm0.02$. Substituting W_p into (11) and taking into account the value of $W(1,K_S^0)$ from our measurements we obtain:

$$Y(\bar{p}p \Rightarrow K_S^0X^0) = (0.35 \pm 0.09)\cdot 10^{-2}. \qquad (12)$$

Of course, the charge exchange and absorption of pions or kaons may also yield one-prong events with K_S^0. We have estimated the contribution of these final state interactions to lead to a 10% uncertainty in (12).

One must compare the value in (12) with those obtained from measurements of $\bar{p}p \Rightarrow K_S^0X^0$ annihilation in bubble chambers /9/ where $Y(\bar{p}p \Rightarrow K_S^0X^0)=(0.256\pm0.015)\cdot 10^{-2}$. This value is slighlty smaller than (12) but both results are compatible within the errors. One may consider (12) as the first measurement of the $\bar{p}p \Rightarrow K_S^0X^0$ annihilation channel in a gas. It is important that antiproton annihilation at rest in a ^{3}He gas occurs mainly from P- and D-levels (with probabilities equal to 49% and 43%, respectively, /10/), while the bubble chamber result concerns $\bar{p}$ annihilation in liquid hydrogen which takes place, in the main, from S-states (see, e.g. /11/).

We try to analyse the characteristics of Λ production in $\bar{p}A$ annihilation at rest under the assumption that a Λ is produced in $\bar{K}$ rescattering on one of the residual nucleons:

$$\begin{aligned} &\bar{p}\ N \Rightarrow K\bar{K} + m\pi \\ &\qquad\quad \bar{K} + N \Rightarrow \Lambda + X. \end{aligned} \tag{13}$$

This mechanism was investigated in detail for antiproton annihilation on heavy nuclei in the framework of different cascade models /12-16/. A number of channels were shown to exist for Λ production, for instance, via Σ^0 formation - $\bar{K}N \Rightarrow \Sigma^0 X \Rightarrow \Lambda\gamma X$, or $\Sigma^{\pm}$ charge exchange - $\bar{K}N \Rightarrow \Sigma^{\pm}X$, $\Sigma^{\pm}N \Rightarrow \Lambda X$, or two-nucleon kaon absorption - $\bar{K}NN \Rightarrow \Lambda N$, or in $\eta(\omega)$-meson rescattering. However, in the case of $\bar{p}$ annihilation on the lightest nuclei not all rescattering processes are important or possible and one can hope to treat Λ production in a simple phenomenological way. We restricted our consideration to Λ production in kaon rescattering (13). We shall assume the probability of Λ production to depend only on the number of nucleons in the residual nucleus, according to the binominal law. So, for $\bar{p}^3He$ and $\bar{p}^4He$ annihilation the probabilities P_2 and P_3 of Λ production on 2 or 3 nucleons depend on the Λ production probability on a single nucleon P_1 as follows:

$$P_2 = 2 \cdot P_1 \cdot (1 - P_1) \tag{14}$$
$$P_3 = 3 \cdot P_1 \cdot (1 - P_1)^2 . \tag{15}$$

For estimation of P_1 we take the Λ yield in $\bar{p}d$ annihilation, $Y(\Lambda)_{\bar{p}d} = (0.36 \pm 0.06) \cdot 10^{-2}$ /17/, and the $K\bar{K}$ yield, which we derive from the $\bar{p}p$ and $\bar{p}n$ data (see discussion below):

$$Y_{\bar{p}d}(K\bar{K}m\pi) = W_p Y_{\bar{p}p}(K\bar{K}m\pi) + W_n Y_{\bar{p}n}(K\bar{K}m\pi) = (4.86 \pm 0.17) \cdot 10^{-2}, \tag{16}$$

where $W_p(W_n)$ is the probability of annihilation on the proton (neutron) in the deuteron. Then:

$$P_1 = Y(\Lambda)_{\bar{p}d} \ / \ Y_{\bar{p}d}(K\bar{K}m\pi) = 0.074 \pm 0.013. \tag{17}$$

Applying P_1 from (17), i.e. starting from the $\bar{p}d$ data, it is possible to calculate the probabilities (14-15) and to estimate the overall Λ yields in $\bar{p}^3He$ and $\bar{p}^4He$ annihilation:

$$Y_{^3He}(\Lambda) = P_2 \cdot Y_{\bar{p}^3He}(K\bar{K}m\pi) = (0.67 \pm 0.11) \cdot 10^{-2} \qquad (18)$$

$$Y_{^4He}(\Lambda) = P_3 \cdot Y_{\bar{p}^4He}(K\bar{K}m\pi) = (0.93 \pm 0.14) \cdot 10^{-2}. \qquad (19)$$

The kaon yields $Y_{\bar{p}A}(K\bar{K}m\pi)$ in $\bar{p}A$ annihilation were calculated in the same manner as in the case of $\bar{p}d$ (see, eq. (16)). The calculated yields of Λ (18-19) are in good agreement with the experimental values:

$Y_{^3He}(\Lambda)=(0.55\pm0.11)\cdot10^{-2}$ (this work) and
$Y_{^4He}(\Lambda)=(1.12\pm0.12)\cdot10^{-2}$ from ref./18/.

This merely reflects the fact that in antiproton annihilation on the lightest nuclei the Λ yield is roughly proportional to the number of nucleons remaining after annihilation.

Additional support of the rescattering scheme (13) is provided by calculation of the partial yields $Y(M,\Lambda)$ and $Y(M,K^0_S)$ of events with M charged particles associated with Λ and K^0_S. We try to calculate these values starting from the yields of kaons in $\bar{p}p$ and $\bar{p}n$ annihilation. In Table 2 we present the partial rates of $\bar{p}N \Rightarrow K\bar{K}m\pi$ annihilation at rest calculated from the data of ref./9/. Unfortunately, the main bulk of kaon channels measured up to now includes only reactions with K^0_S in the final state. The partial rates of $\bar{p}N \Rightarrow K^+K^-m\pi$ are not known, and we have assumed them to be the same as for the $\bar{p}N \Rightarrow K^0\bar{K}^0m\pi$ channel. It is interesting to note that the total kaon yield $Y(K\bar{K}m\pi)$ in $\bar{p}p$ annihilation obtained in this way is $Y_{\bar{p}p}(K\bar{K}m\pi)=(4.74\pm0.22)\cdot10^{-2}$. It is smaller than the frequently quoted value $Y_{\bar{p}p}(K\bar{K}m\pi)=(6.82\pm0.25)\cdot10^{-2}$, which was obtained in an old experiment /19/ the $K^+K^-m\pi$ channels being not measured but estimated. However, we have checked that the multiplicity distributions $Y(M,\Lambda)$ and $Y(M,K^0_S)$ for $\bar{p}^3He$ annihilation calculated using both these values coincide within the errors. The total kaon yield $Y(K\bar{K}m\pi)$ in $\bar{p}n$ annihilation is $Y_{\bar{p}n}(K\bar{K}m\pi)=(5.01\pm0.27)\cdot10^{-2}$.

Table 2. Partial rates of $\bar{p}N \Rightarrow K\bar{K}m\pi$ annihilation at rest. Branching ratios (in percents of the total $\bar{p}N$ annihilation probability) are classified according to the type of $K\bar{K}$ pair and the number $N(\pi^+\pi^-)$ of $\pi^+\pi^-$ pairs produced. The yields of channels with fixed $N(\pi^+\pi^-)$ were obtained from the data of ref./9/ by summing up all channels with neutral π-mesons.

	$\bar{p}p \Rightarrow K\bar{K}m\pi$	
Number of $\pi^+\pi^-$ pairs	$K^0\bar{K}^0$ or K^+K^-	$\bar{K}^0K^+\pi^-$ or $K^0K^-\pi^+$
0	0.563 ± 0.035	0.682 ± 0.061
1	1.056 ± 0.085	0.071 ± 0.007

	$\bar{p}n \Rightarrow K\bar{K}m\pi$		
Number of $\pi^+\pi^-$ pairs	$K^0\bar{K}^0\pi^-$ or $K^+K^-\pi^-$	$\bar{K}^0K^+\pi^-\pi^-$	K^0K^-
0	1.530 ± 0.124	0.264 ± 0.027	0.507 ± 0.047
1	0.075 ± 0.026	-	1.027 ± 0.073

To describe K^0_S multiplicity distributions we assume kaons to be produced directly in $\bar{p}p$ and $\bar{p}n$ annihilation and part of them to be lost in the rescattering process $\bar{K}N \Rightarrow \Lambda X$. The multiplicity distribution of events associated with Λ was calculated assuming the rescattering mechanism (13). The probabilities for a kaon to rescatter into Λ on a proton or a neutron were taken to be equal. To obtain the partial yields $Y(M,\Lambda)$ and $Y(M,K^0_S)$ we summed up the branching ratios of all channels providing a given charged particle multiplicity M in the final state taking into account that this multiplicity may undergo changes in the rescattering process:

$$Y(M,\Lambda) = [W_p\cdot\sum_i Y_p^i(K\bar{K}+m\pi) + W_n\cdot\sum_i Y_n^i(K\bar{K}+m\pi)]\cdot P_2 \qquad (20)$$

$$Y(M,K_S^0) = W_p\cdot\sum_i Y_p^i(K\bar{K}+m\pi)\cdot F_p^i + W_n\cdot\sum_i Y_n^i(K\bar{K}+m\pi)\cdot F_n^i, \qquad (21)$$

where Y_p^i (Y_n^i) are branching ratios of channels $\bar{p}p\Rightarrow K\bar{K}m\pi$ ($\bar{p}n\Rightarrow K\bar{K}m\pi$), $F_{p,n}^i$ is a correction factor which takes into account the loss of kaons due to rescattering. The results of calculations are given in Table 3.

Table 3. Comparison of calculated and measured charged-prong multiplicity distributions for events associated with Λ and K_S^0. The yields of events with M charged particles are given in percents of the total $\bar{p}^3$He annihilation probability

type of V^0		Number of prongs - M 1	3	5
K_S^0	Calc.	0.35 ± 0.02	1.37 ± 0.08	0.22 ± 0.01
	Exp.	0.29 ± 0.07	1.06 ± 0.13	0.22 ± 0.07
Λ	Calc.	0.14 ± 0.02	0.43 ± 0.07	0.08 ± 0.01
	Exp.	0.16 ± 0.06	0.31 ± 0.08	0.09 ± 0.04

From the values given in Table 3 one can see that the simple rescattering scheme allows to explain both kaon and Λ multiplicity distributions. It is noteworthy that the only input to (20-21) are the kaon branching ratios and the Λ production probability in $\bar{p}N$ annihilation (14).

The rescattering scheme (13) is also capable of reproducing the yield of double V^0 events such as ΛK_S^0. In this scheme K_S^0 originate only from kaons but not from antikaons. Antikaon rescattering $\bar{K}N\Rightarrow\Lambda X$ produces Λ:

$$Y(\Lambda K_S{}^0) = [W_p\cdot Y_p(K^0\bar{K}+m\pi) + W_n\cdot Y_n(K^0\bar{K}+m\pi)]\cdot P_2/2\,. \qquad (22)$$

Substituting into (22) the value of P_2 from (14) and the branching ratios Y_p, Y_n of channels $\bar{p}N \to K^0\bar{K}m\pi$ from Table 2 one can obtain:

$$Y(\Lambda K_S^0) = (0.17 \pm 0.03)\cdot 10^{-2},$$

which is in a good agreement with the experimental value (6).

To conclude, the yield of K_S^0 from $\bar{p}p$ annihilation into $\bar{K}^0K^0m\pi^0$ has been determined for annihilation in ^3He gas:

$$Y(\bar{p}p \to K_S^0\, X^0) = (0.35 \pm 0.09)\cdot 10^{-2}.$$

We have measured the Λ and K_S^0 yields from antiproton annihilation in ^3He at rest:

$$Y_\Lambda = (0.55 \pm 0.11)\cdot 10^{-2} \text{ and } Y_K = (1.59 \pm 0.20)\cdot 10^{-2}.$$

It turns out that even stopping antiprotons produce Λ with a noticeable probability. The most natural explanation of this fact seems to be rescattering of the annihilation kaons. This mechanism is capable of reproducing the absolute Λ yields as well as the multiplicity distributions of events with neutral strange particles and the yield of double V^0 in the ΛK_S^0 channel. Our results that reveal an essential Λ production even in the annihilation of stopping antiprotons provide an explanation for the significant yield (up to 10^{-3} per annihilation) of heavy hypernuclei observed recently in the PS 177 experiment at LEAR /20,21/. From comparison of the absolute Λ yield /18/ and the rate of hypernucleus formation one can estimate that approximately 10% of all the Λ produced in $\bar{p}A$ annihilation at rest are bound into hypernuclei.

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