объединенный
институт
ядерных
исследований
дубна

E1-89-222

PRODUCTION OF Λ-HYPERONS AND K^0_S-MESONS IN ANNIHILATION OF ANTIPROTONS IN ^{4}He NUCLEI AT 600 MeV/c

Submitted to "Ядерная физика"

1989

INTRODUCTION

Recent experiments [1–3], in which the production of strange particles in annihilation of antiprotons on nuclei was studied, have yielded unexpected results. Thus, the measurement of production cross sections of Λ, $\bar{\Lambda}$ и K^0_S-mesons in annihilation of antiprotons in Ta at 4 GeV/c, presented in [1], revealed an exceptionally high yield of Λ-hyperons, twice as high as that of K^0_S-mesons. (The production cross section of K^0_S-mesons in annihilation in the deuterium is known to be five times larger than that of Λ [2].)

Still more surprizing results were obtained in our PS 179 experiment at CERN [3], in which the production of neutral strange particles was investigated in annihilation of antiprotons in Ne at 600 MeV/c (corresponding kinetic energy is 180 MeV). At this energy the production of a Λ on a single nucleon is impossible, since the threshold of the reaction $\bar{p}p \to \Lambda\bar{\Lambda}$ 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, in this case the Λ cross section is also high and the ratio $R=\sigma(\Lambda)/\sigma(K^0_S)$ is $R = 2.3 \pm 0.7$.
In the present work we have extended the investigation of the production of neutral strange particles in antiproton annihilation to another target, the ^{4}He nucleus, at 600 MeV/c.

2.TREATMENT OF EVENTS

We have studied the following reactions:

$$\bar{p} + {}^4He \to \Lambda + X \qquad (1)$$
$$\bar{p} + {}^4He \to K^0_S + X \qquad (2)$$

The data were obtained using a streamer chamber [4] exposed to the LEAR antiproton beam at 607.7 MeV/c at CERN. The LEAR antiproton beam is characterized by a high intensity (10^5- 10^6 $\bar{p}$/sec), a high momentum resolution ($\Delta p/p \approx 10^{-3}$) and the absence of any pion and kaon contamination whatsoever. The beam was about 1 cm in diameter. The self-shunted [5] chamber (90×70×18 cm^3) was filled with helium at atmospheric pressure. The chamber was placed in a magnetic field 0.8T. The processing of the data obtained is considered in detail in ref.[6].

About $9\cdot10^4$ pictures were scanned to searching for candidates for neutral strange particle decay (V^0). Approximately $3\cdot10^4$ photographs were examined twice for determination of the scanning efficiency. Selected events were measured and processed using the HYDRA program for geometrical reconstruction and kinematic analysis. The final statistics consist of 110 V^0 particles which were produced in 106 interactions. From these events 60 have been identified as K_S^0 decay, and 50 as Λ decay. In Fig.1 the effective mass distributions for the V^0 particles are shown. The mean values of the effective masses

$$M_\Lambda = (1120 \pm 7)\ \mathrm{MeV/c^2} \text{ and } M_K = (489 \pm 15)\ \mathrm{MeV/c^2}$$

are in good agreement with the tabulated values.

For the further analysis events were selected which satisfied the following criteria:

1) the antiproton interaction vertex was required to be further than 15 cm from the entrance and exit (along the beam) walls of the chamber;

2) the V^0 decay vertex was required to be within the effective fiducial volume, i.e. not closer than 15 cm to the walls of the chamber along the beam, not closer than 10 cm to the lateral walls and not closer than 4 cm to the upper and lower glass planes of the chamber;

3) the V^0 decay vertex was required to be separated from the annihilation vertex by not less than 1 cm.

The first two criteria provided good conditions for registration of the vertices and for track measurements. Application of the last criterion was caused by substantial losses of the V^0, decaying in the vicinity of the interaction vertex (see Fig.2). The above criteria were satisfied by 54 K_S^0 and 43 Λ.

The losses of V^0-particles decaying outside the effective fiducial volume or in the vicinity of the interaction vertex were taken into account by introducing weights. For each event the weight W (representing the reciprocal value of the event registration probability) was calculated by simulation. The average weights turn out to be $\langle W\rangle=1.8$ for the Λ and $\langle W\rangle=1.6$ for the K_S^0.

The cross section was calculated by the formula

$$\sigma = \frac{\sigma_0 \cdot \sum_i W_i}{\varepsilon \cdot Br} \qquad (3)$$

where ε is the total efficiency of scanning, measurement and geometrical reconstruction (ε=93%);

Br is the probability for a V^0 to decay into charged particles (68.6% for K^0 and 64.2% for Λ);

$\sigma_0 = (N_{in} \cdot \rho \cdot L)^{-1}$ ($N_{in} \simeq 23 \cdot 10^6$ is the total number of antiprotons that passed through the target, ρ is the number of ^{4}He nuclei per unit volume, L = 60.7 cm is the effective length of the target);

W_i is the weight assigned to the i-th event.

Table 1

Λ- and K_S^0 production cross sections in annihilation of antiprotons on different nuclei (see [1-3]). The cross sections, published in [2], were corrected for V^0 neutral mode decays. Results of theoretical calculations [7] are included in the table.

	$\sigma(\Lambda)$, mb	$\sigma(K_S^0)$, mb	$R=\sigma(\Lambda)/\sigma(K_S^0)$
^{2}H (600 MeV/c)			
[2]	0.65±0.14	3.74±0.56	0.17±0.05
Theory [7]	0.43	2.77	0.16
^{4}He (600 MeV/c)			
This Experiment	3.67±0.56	3.90±0.53	0.94±0.19
Theory [7]	2.35	3.96	0.59
^{20}Ne (600 MeV/c)			
[3]	12.3±2.8	5.4±1.1	2.3±0.7
Theory [7]	10.8	10.1	1.1
Ta (4 GeV/c)			
[1]	193±12	82±6	2.4±0.3

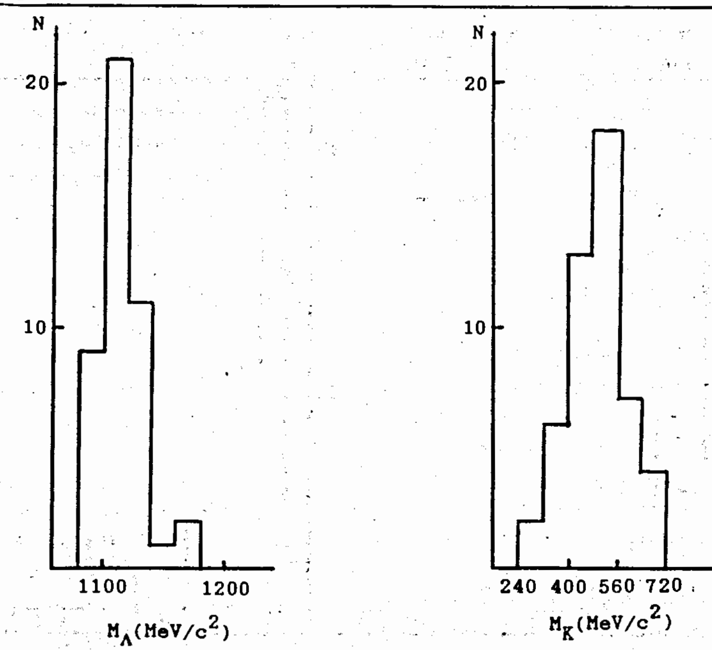

Fig.1.Effective mass distributions for V^0, identified as Λ and K^0.

Table 2

Mean values of momentum (MeV/c) and rapidity (in laboratory system) of secondary particles in $\bar{p}^4$He annihilation from the experiment and simulation. The simulated Λ parameters are given for two versions: (I) – the energy dependence $\sigma(\bar{K}N \to \Lambda\pi)$ is taken into account; (II)- this energy dependence is neglected.

		⟨P⟩	$\langle P_T \rangle$	$\langle P_L \rangle$	⟨Y⟩
Experiment:					
$\bar{p}^4He \to \Lambda X$	Λ	433±33	354±30	86±38	0.07±0.03
	π^-	366±37	253±31	148±44	0.37±0.13
$\bar{p}^4He \to K^0_S X$	K^0_S	555±35	393±30	254±44	0.35±0.06
	π^-	395±34	264±24	165±43	0.43±0.11
Simulation:					
(I)	Λ	399	307	78	0.06
$\bar{p}N \to \bar{K}K^0_S \pi^-\pi$ (II)	Λ	464	352	138	0.11
$\bar{K}N \to \Lambda\pi$	K^0_S	441	315	202	0.31
	π^-	321	237	107	0.31
$\bar{p}N \to \pi\pi\pi\pi$	Λ	653	381	489	0.40
$\pi N \to \Lambda K$	π	488	366	153	0.31

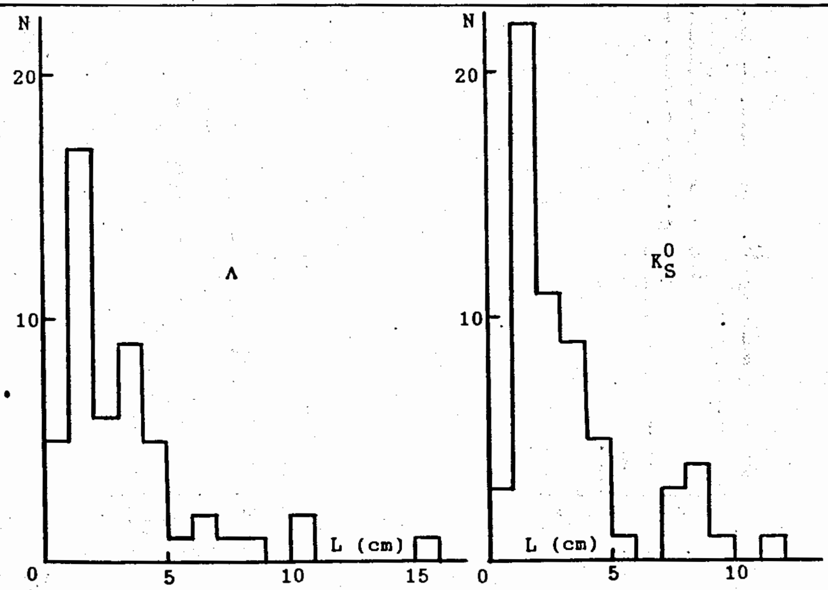

Fig.2.Decay length, L, distributions for Λ and K^0_S.

3.DISCUSSION OF RESULTS

The production cross sections for the Λ and K^0_S in antiproton annihilation on helium nuclei as well as their ratio R are presented in Table 1. The results of other experiments are also shown. Note that the process $\bar{p}\,^4He \to \Sigma^0 X$, $\Sigma^0 \to \Lambda\gamma$ contributes to the cross section of Λ production σ(Λ).

From Table 1 one can see that the Λ production cross section is quite significant, $\sigma(\Lambda) \approx \sigma(K^0_S)$, even for such a light nucleus as ^{4}He. Note that the situation is different in annihilation on deuterium where σ(Λ) is five times less than $\sigma(K^0_S)$. Since at 600 MeV/c the production of a Λ on a single nucleon is forbidden (the threshold of the reaction $\bar{p}p \to \Lambda\bar{\Lambda}$ is p_{th}=1435 MeV/c), this abundant Λ production on nuclei can be explained only assuming a high probability for the processes in which several nucleons take part.

The distributions of the momentum P, of its longitudinal and transverse components (P_L and P_T) and of the rapidity Y for Λ and K^0_S are presented in Fig.3-4. One can see that the momentum distribution for Λ is enriched with events with low momenta. The distribution of P is satisfactory described by a parametrization like:

$$dN/dP \propto P^2 \exp(-T/A) \qquad (4)$$

where T is the kinetic energy of a particle, and the value of parameter A is equal to A = (70±14) MeV for Λ and A = (88±16) MeV for K^0_S. In Fig.3-4 (see dashed line) transverse momentum spectra are shown, which were calculated with the help of parametrization obtained in [2] for description of P_T-distributions for Λ and K^0_S produced in $\bar{p}$d annihilation within a momentum range from 0.3 to 1 GeV/c:

$$dN/dp_T = N_0\,(2p_T/a)\,\exp\,(-p_T^2/a) \qquad (5)$$

Here N_0 is the number of events, a = 0.18 ± 0.01 $(GeV/c)^2$ for the Λ spectrum and a = 0.143± 0.003 $(GeV/c)^2$ for the K^0_S one. One can see that the P_T-distributions are well described by parametrization (5) in the case of $\bar{p}^4$He-annihilation, as well.

The rapidity distributions (in the laboratory system) of Λ and K^0_S (see Fig.3-4) are approximately symmetric and their mean values are:

$$\langle Y\rangle_\Lambda = 0.07 \pm 0.03 \text{ and } \langle Y\rangle_K = 0.35 \pm 0.06.$$

A similar difference between the Λ and K^0_S rapidity spectra was observed in the experiments [1,3]. It is the evidence that the Λ and K^0_S production mechanisms are different. In [1], for example, it was supposed that the strange particles are produced in the evaporation of multinucleon sources which can be created in the antiproton-nuclei annihilation. In the rest frame of the source the peak of the rapidity distribution must be at $\langle Y_{c.m.}\rangle$=0. The center-of-mass system where the

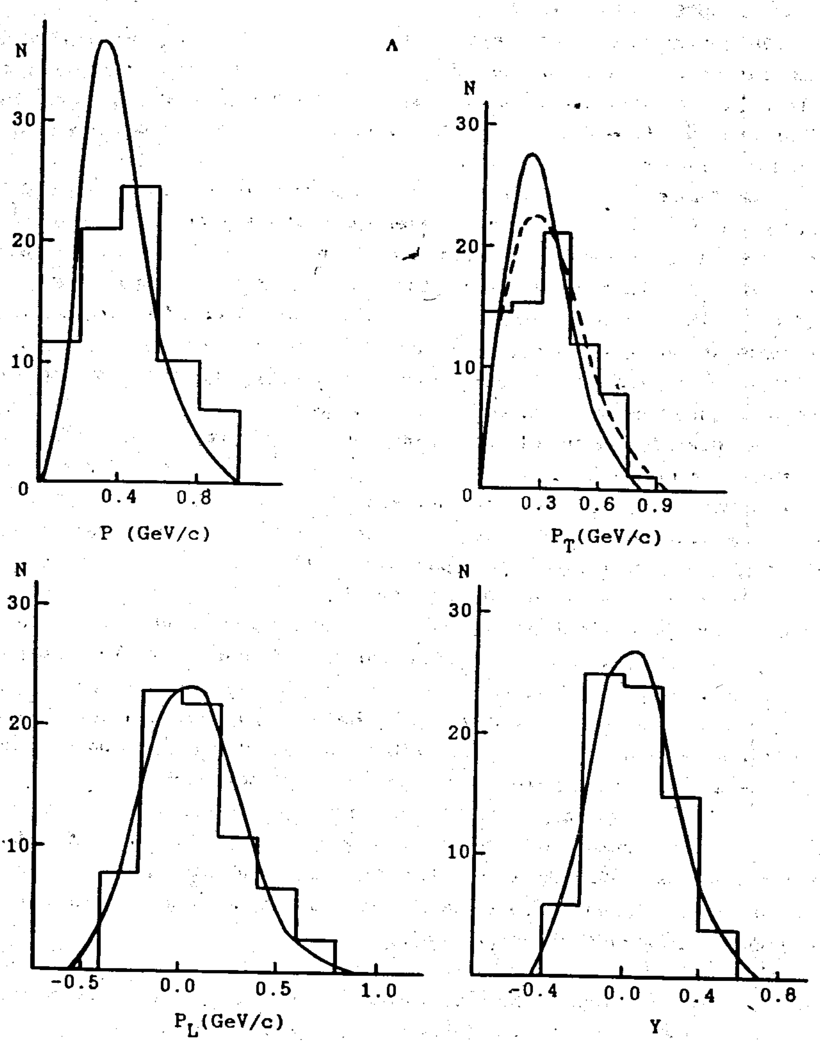

Fig.3. Momentum P, its transverse P_T and longitudinal P_L components and rapidity Y (in laboratory system) distributions for Λ (weighted events). Dashed line: parametrization of P_T spectrum from [2]. Solid lines: results of simulation.

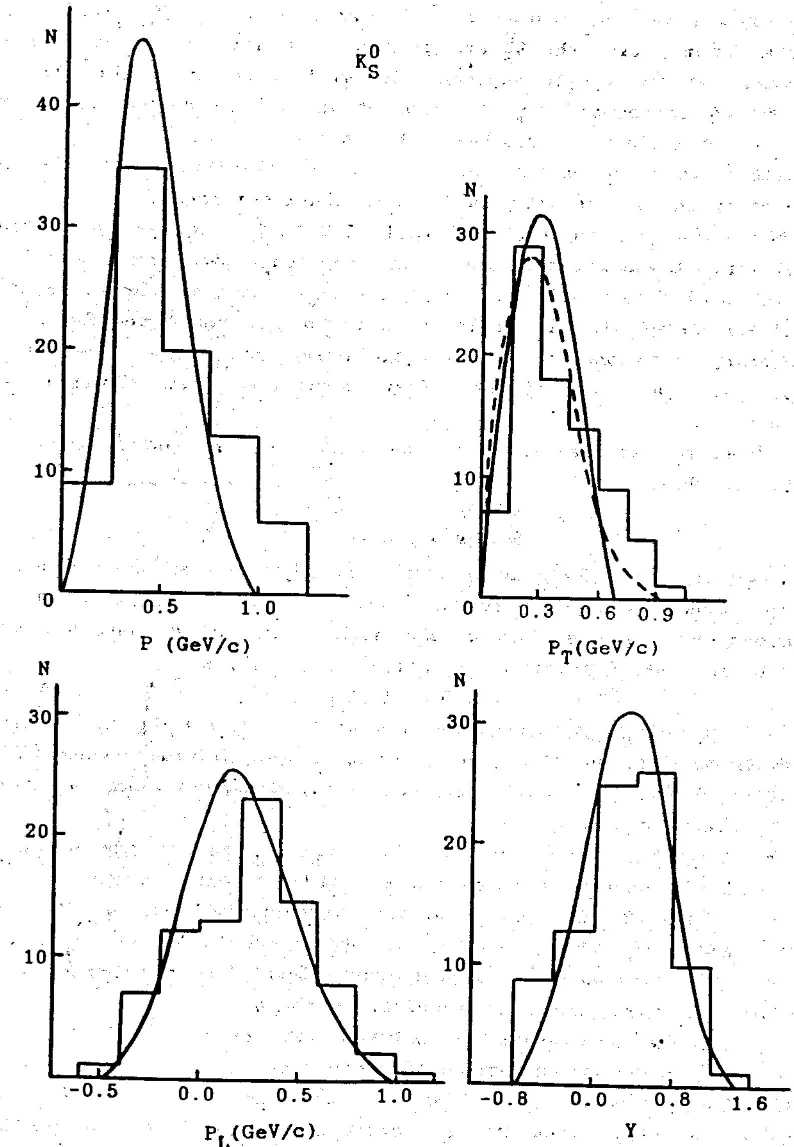

Fig.4. Momentum P, its transverse P_T and longitudinal P_L components and rapidity Y (in laboratory system) distributions for K^0_S (weighted events). Dashed line: parametrization of P_T spectrum from [2]. Solid lines: results of simulation.

K_S^0 rapidity peak $\langle Y \rangle_K = 0.35 \pm 0.06$ corresponds to $\langle Y_{c.m.} \rangle = 0$ is the $\bar{p}$-1N c.m. frame, i.e. the K_S^0 are produced in annihilation of primary antiprotons on the single nucleon. The similar rapidity distribution shift for Λ correspond to its production in the system $\bar{p}$-(8±4)N. Obviously, it is hard to imagine such a situation for ^{4}He. There is a more natural explanation for the low value of rapidity for Λ - by the Λ production in the rescattering of annihilation mesons .

This mechanism was analyzed in [7-9]. In [7] it was shown that rescattering of annihilation mesons can reproduce the Λ cross sections for light nuclei (see Table 1). To check if it is possible to explain the difference between the rapidity distributions for Λ and for K_S^0 by rescattering of mesons, we made the following estimations. Spectra of momenta and rapidity of secondary particles were obtained by simulation.

Λ-hyperons are assumed to be produced in rescattering of annihilation kaons:

$$\bar{p} + N \rightarrow \bar{K} + K + \pi + \pi \qquad (6)$$

$$\bar{K} + N \rightarrow \Lambda + \pi \qquad (7)$$

The characteristics of the secondary π- and K-mesons are determined by the phase space volume of reaction (6). The characteristics of the Λ-hyperons were obtained taking into account the energy dependence of the cross section of reaction (7) (taken from [2]):

$$\sigma(\bar{K}N \rightarrow \Lambda\pi) = 8.5 \cdot (0.6/P_K)^{1.41} \text{ mb} \qquad (8)$$

for the kaon momenta P_K from the interval $0.1 < P_K < 0.6$ (GeV/c). Outside this range the values of σ corresponding to the extreme values of P_K are taken. Fermi-motion of the nucleons participating in reactions (6-7) is also taken into account.

The simulated distributions of P, P_T, P_L and Y are shown in Figs.3-4. Their mean values are compared with the experimental ones in Table 2. Table 2 also contains the experimental values for the negative particles (the majority of which should be π^-) produced together with the neutral strange particles. For simulation of Λ production two versions of the results are shown:

(I) - energy dependence (8) is taken into account;

(II)- this energy dependence is neglected.

The associative production of Λ and K_S^0 by secondary pions (such as $\pi N \rightarrow K\Lambda$) is illustrated by inclusion in Table 2 of the results obtained from simulation of reaction (6-7) with π-mesons substituted for the kaons.

From the results presented in Table 2 and Fig.3-4, it can be seen that:

1) satisfactory description of the distributions for Λ can be obtained if one assumes that they were produced in rescattering of K-mesons;

2) rescattering of pions cannot evidently be the main source of Λ, since it would lead to the production of "fast" Λ-hyperons;

3) characteristics of K_S^0- and π-mesons are well described by the assumption of their production in the elementary act of antiproton annihilation on a single nucleon of the nucleus.

Noteworthy is that the experimentally observed low rapidity for Λ-hyperons is obtained when rescattering of $\bar{K}$-mesons is taken into account. Thus, there is no need to introduce the concept of some multinucleon clusters which would serve as sources for the Λ production.

In fact, as demonstrated in ref.[7], to explain the Λ production cross section, one must take into account not only the K- and π-meson rescattering, but also the contribution from η- and ω-mesons, which may produce Λ in associative production reactions, such as $\eta N \rightarrow K\Lambda$. However, consideration of η- and ω-meson rescattering in our scheme does not change the results. Our simulation depends only on the masses of the particles, and the η and K masses are very similar. Account of ω-mesons must also lead to low Λ rapidities.

An alternative to the rescattering model is the model [10,11] of the evaporation of fireballs of baryon number B=1. It predicts that if such a fireball is formed in antiproton-nucleus annihilation, then among the products of its evaporation there should be a noticeable fraction of Λ-hyperons, which could amount to ≈ 10% [10] (the Λ from the Σ^0 decays are also included). In this model, however, the formation probability of such fireballs remains uncertain. If all the Λ observed in our experiment are assumed to be produced only as a result of the evaporation of such fireballs, then the upper limit can be imposed on the probability W_f for the fireballs to be produced in $\bar{p}^4$He annihilation at 600 MeV/c:

$$W_f = W_\Lambda \,/\, Br(\text{fireball} \rightarrow \Lambda X) < 0.16 \pm 0.02 \qquad (9)$$

where $W_\Lambda = 0.016 \pm 0.002$ is the yield of Λ (see Table 1 and [12]).

To choose between the model with rescattering and the fireball model it is nesessary to obtain additional experimental information about cross-sections of exclusive channels with strange particle production. We registered 4 events with two V^0, 3 of them being identified as $K_S^0 \bar{K}_S^0$ and 1 as ΛK_S^0. This corresponds to the following estimation of cross-sections: $\sigma(\bar{p}^4He \to K_S^0 \bar{K}_S^0 X) = (0.55 \pm 0.32)$mb and $\sigma(\bar{p}^4He \to \Lambda K_S^0 X) = (0.17 \pm 0.17)$mb. It is clear that this statistics is too low for reliable determination of cross-sections of these channels.

4. CONCLUSIONS

In this work Λ-hyperon and K_S^0-meson production cross sections in antiproton annihilation in ^{4}He at 600 MeV/c have been measured. An anomalously high yield of Λ is observed which is comparable to that of K_S^0:

$$R = \sigma(\Lambda)/\sigma(K) = 0.94 \pm 0.19.$$

It was shown that the difference in the Λ and K_S^0 rapidity distributions may be explained by different mechanisms of production of these particles:
K_S^0-mesons are produced mainly in $\bar{p}$ annihilation on single nucleons from the nucleus, and Λ-hyperons in the secondary processes of rescattering of the annihilation mesons.

In this connection the large Λ production at low energies observed in $\bar{p}^4$He and $\bar{p}$Ne annihilation [3] can be considered as clear indication of the high probability of rescattering of annihilation mesons in the antiproton-nucleus interactions.

This interesting feature of antiproton-nucleus annihilation makes it possible to investigate a broad spectrum of nontrivial phenomena. For example, the enhanced yield of Λ-hyperons must lead to an enhanced probability of hypernuclei production, which, as shown in experiments [13], achieve values up to 10^{-4} per annihilation. In the antiproton-nucleus annihilation at higher energies different charmonium states may be produced. Their subsequent rescattering in the nucleus must lead to Λ_c^+ charmed baryon production which, in turn, may lead to the creation of supernuclei [14] (nuclei containing charmed baryon). One may also use rescattering of annihilation mesons to search for the H-dibaryon [15], to study the absorption of η- and ω-mesons [16], to obtain various nuclides [17].

The LEAR and South Hall CERN Area teams are gratefully acknowledged for their continuous support during data taking. The authors also thank Prof. L.A.Kondratyuk and Dr. D.E.Kharzeev for useful discussions. The authors are especially grateful to V.V.Bogdanova, G.A.Kulkova, M.N.Shelaeva and L.A.Vasilenko for their essential help in scanning and measuring the experimental material.

REFERENCES

1. Miyano K. et al. - Phys. Rev., 1988, v.C38, p.2788.
2. Parkin S.J.H et al. - Nucl. Phys., 1986, v.B277, p.634.
3. Balestra F. et al. - Phys. Lett., 1987, v.B194, p.192.
4. Balestra F. et al. - Nucl. Instr. Meth., 1985, v.A234, p.30.
5. Falomkin I.V. et al. - Nucl. Instr. Meth., 1967, v.53, p.266.
6. Balestra F. et al. - Nucl. Instr. Meth., 1987, v.A257, p.114.
7. Kharzeev D.E., Sapozhnikov M.G. - JINR E4-88-930, Dubna, 1988.
8. Che Ming Ko, Ruixi Yuan - Phys. Lett., 1987, v.B192, p.31.
9. Dover C.B., Coch P. - BNL Preprint, Brookhaven, 1988.
10. Cugnon J., Vandermeulen J. - Phys. Rev., 1987, v.C36, p.2726.
11. Rafelski J. - Phys. Lett., 1988, v.B207, p.371.
12. Balestra F. et al. - Nuovo Cim., 1988, v.A100, p.323.
13. Bocquet J.P. et al. - Phys. Lett., 1986, v.B182, p.146, 1987, v.B192, p.312.
14. Tyapkin A.A. - Sov. J. Nucl. Phys., 1975, v.22, p.181.
15. Guaraldo C. - In: Hadronic Physics at intermediate energy, Elsevier Science Publishers B.V., Amsterdam, 1987, Vol.II, p.139.
16. Iljinov A.S. et al. - Nucl. Phys., 1982, v.A382, p.378.
17. Moser E.F. - Phys. Lett., 1986, v.B179, p.25.