PRODUCTION OF $\Lambda(\Sigma^0)$ HYPERONS AND K^0 MESONS IN INTERACTIONS BETWEEN 7 GeV π^- MESONS AND CARBON

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The production of $\Lambda(\Sigma^0)$ hyperons (henceforth denoted Λ hyperons for short) and K^0 mesons by negative pions on carbon was investigated. The angular and momentum distributions of these particles and the cross sections for their production are determined, and the cross sections of the different channels of the reactions are estimated. The fraction of strange particles produced in the secondary processes is estimated for the first time. The momentum spectrum of the Λ hyperons (in the pion-nucleon c.m.s.) is compared with the spectrum for π^-p interactions. The experimental data are compared with the results of cascade-model calculations made by the Monte Carlo method.

INTRODUCTION

KNOWLEDGE of the conditions for the generation of strange particles in complex nuclei is in many cases of considerable interest. Thus, for example, comparison of the characteristics of the production of strange particles on nucleons and on complex nuclei can help explain the peculiarities of the production processes on bound nucleons, determine the fraction of the secondary interactions of strange particles inside the parent nucleus, estimate the possibility of obtaining beams of strange particles in interactions between fast particles and a complex nucleus, etc. For chambers filled with liquids consisting of atoms of several elements, knowledge of the conditions of generation of complex nuclei makes it possible to estimate the influence of the admixture of such interactions on the investigated class of phenomena. For example, when working with propane the question always arises of the possibility of distinguishing between the hydrogen and carbon events. In particular, it was already noted[1,2] that the hard part of the momentum spectrum of Λ hyperons has a maximum in the c.m.s. for πp interactions. The investigation of the generation of Λ hyperons on carbon makes it possible to verify the influence of the admixture of carbon events on this part of the spectrum and to exclude the possible errors.

The interaction between negative pions and complex nuclei with production of charged particles was investigated in several papers [3-7], three[6,4,3] devoted to a study of the interaction with carbon at π^--meson momenta 1.3, 1.5, and 1.9 GeV/c respectively, and one[7] dealing with freon at 2.8 GeV/c. It was deemed interesting to explain the variation of the Λ-hyperon and K^0-meson production on nuclei at large momenta.

We shall study the process of interaction between carbon and π^- mesons with momentum 7 GeV/c. The production of strange particles by negative pions on protons at this momentum was investigated by us earlier[8]. A simultaneous examination of the data on the production of strange particles in π^-p and π^-C interactions at a π^--meson momentum of 7 GeV/c makes it possible to estimate the fraction of the secondary interactions.

DATA REDUCTION PROCEDURE

The work was performed with the aid of a 24-liter propane bubble chamber in a 13,700-Oe permanent magnetic field. The experimental setup is analogous to that described in [9]. We report here the results obtained by processing 12,000 photographs scanned with a stereo magnifier. The efficiency of the double scanning was found to be 96%. The events were measured with UIM-21 microscopes. The spatial coordinates, momenta, angles, complanarity, etc. were determined with the aid of the electronic computer of the Computation Center of the Joint Institute of Nuclear Research. The kinematics of the events were analyzed by a graphic method proposed by Bubelev[10].

Events with generation of V^0 particles in π^-C interactions were separated from the total number of observed events by excluding the events due to the π^-p interactions. The criteria for identifying π^-p interactions are described in [8].

EXPERIMENTAL DATA

Identification of all the selected V^0 events in the fiducial volume of the chamber left 550 stars containing 607 "forks." The distribution by type of event is listed in the table.

V^0 events from π^-C interactions

Type of particle	Number of particles	Type of particle	Number of particles
Λ	198	$\Lambda+\Lambda$	1
K^0	248	$K^0+K^0+\Lambda$	1
Λ or K^0	45	$K^0+(\Lambda$ or $K^0)$	5
$\Lambda+K^0$	39	$\Lambda+(\Lambda$ or $K^0)$	1
$K^0+\overline{K^0}$	9	$\overline{\Lambda}$ or K^0	3

It was shown earlier[11] that at our energies more than 90% of all the particles which in accordance with the kinematics cannot be separated into Λ hyperons and K^0 mesons are Λ hyperons. All the events designated in the table as Λ or K^0 were therefore assumed to be Λ hyperons. Since the total number of indistinguishable particles amounts to less than 10% of all the V^0 particles, the fraction of K^0 mesons in the total number of Λ hyperons does not exceed 2% and was disregarded in the subsequent construction of the angular and momentum distributions.

In plotting the momentum and angular distributions and in determining the cross sections for the production of Λ hyperons and K^0 mesons on the hydrogen nucleus, we took account of the probability of their decay into charged particles within the fiducial volume of the chamber.

Figure 1 shows the l.s. momentum and angular distributions of the Λ hyperons produced in π^-C interactions, while Fig. 2 shows the same distributions for K^0 mesons. Figure 3 gives the momentum distribution of the Λ hyperons in an arbitrary 1) pion-nucleon center of mass system. For comparison we show throughout the corresponding distributions for the production of strange particles by the protons.

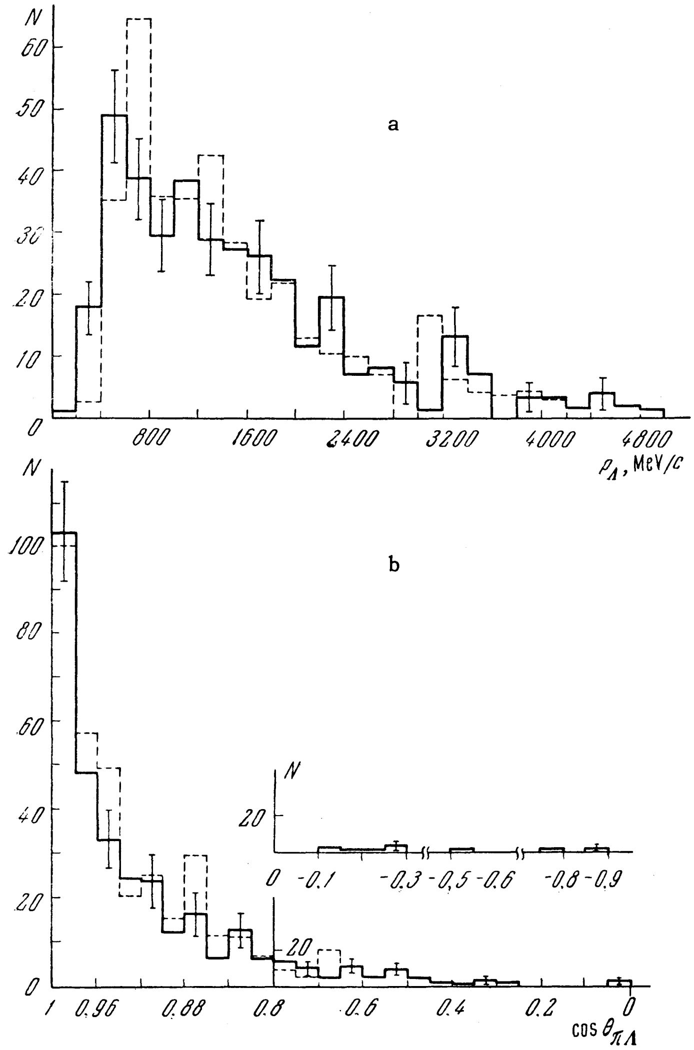

FIG. 1. Momentum (a) and angular (b) distribution of Λ hyperons from π^-C interactions at a π^- meson momentum 7 GeV/c (in the laboratory system). The dashed lines show the analogous distributions for π^-p interactions[8].

CROSS SECTIONS FOR THE PRODUCTION OF Λ AND K^0 PARTICLES

The neutral strange particles which we have registered are produced as a result of the following reactions in the carbon nucleus 2):

$$\pi+N\to\begin{cases}\Lambda\,(\Sigma^0)+K^0+s\pi\\ K^0+\overline{K}\,(K^-)+N+s\pi, & s=0,1,2,\ldots\\ \overline{K}^0+K^++N+s\pi\\ \Sigma^\pm+K^0+s\pi.\end{cases}$$

These reactions take place in both the primary and secondary interaction acts. In addition, strange particles are produced also as a result of secondary reactions of the type (s = 0, 1, 2, ...)

1) The arbitrariness lies in the assumption that the nucleon is at rest in the nucleus and the event is regarded as a πN interaction.

2) Reactions with production of Ξ^0 and Ξ^- hyperons are disregarded, since the cross section for the production of cascade hyperons at 7.0 GeV is small[12].

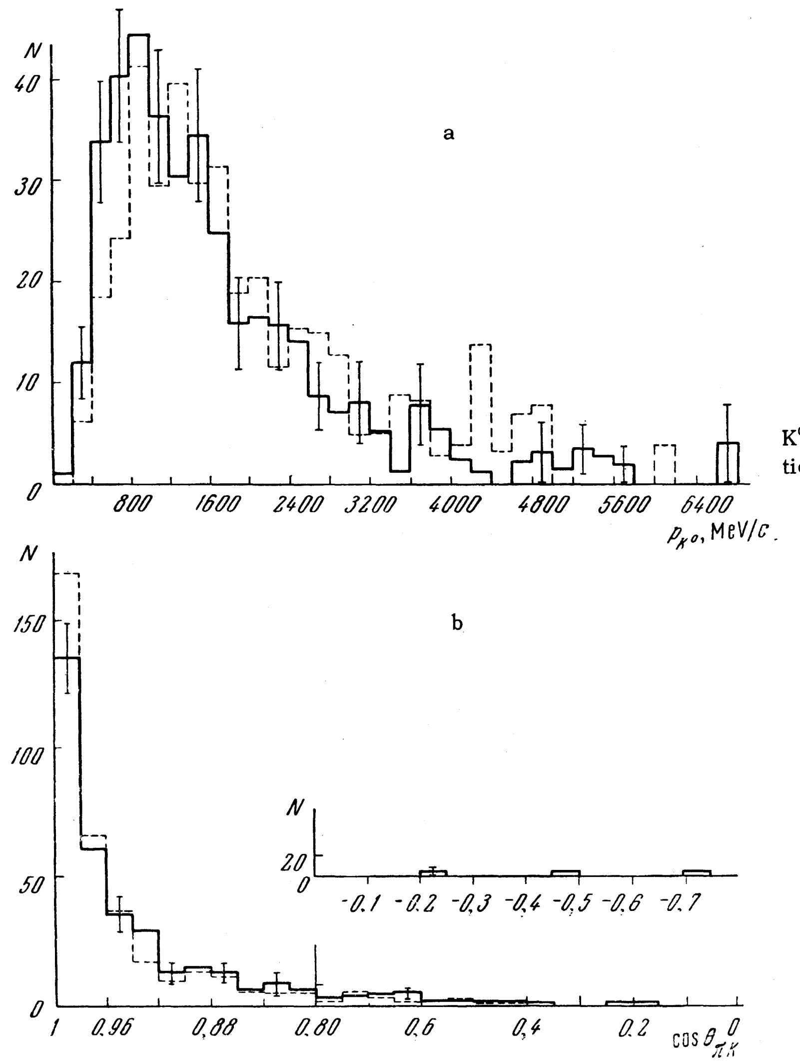

FIG. 2. Momentum (a) and angular (b) distribution of K^0 mesons (in the laboratory system). Dashed – distribution for π^- p interactions.

$$N + N \to \begin{cases} \Lambda + K^0\,(K^+) + N + s\pi \\ K^0 + \overline{K}{}^0\,(K^-) + N + N + s\pi, \\ \overline{K}{}^0 + K^+ + N + N + s\pi \end{cases}$$

$$K^- + N \to \begin{cases} \Lambda + s\pi, \\ \overline{K}{}^0 + N + s\pi, \end{cases}$$

$$\overline{K}{}^0 + N \to \begin{cases} \Lambda + s\pi \\ \overline{K}{}^0 + N + s\pi, \end{cases}$$

$$K^0\,(K^+) + N \to K^0 + N + s\pi,$$

$$\Lambda + N \to \begin{cases} \Lambda\,(\Sigma^{0,\pm}) + N + s\pi, \\ \overline{K}{}^0 + N + N' + s\pi \end{cases}$$

$$\Sigma^0\,(\Sigma^\pm) + N \to \begin{cases} \Lambda + N + s\pi \\ \overline{K}{}^0 + N + N + s\pi, \end{cases}$$

$$\Sigma^0 \to \Lambda + \gamma.$$

The cross sections for the production of the Λ and K^0 particles were calculated in analogy with [8]. In determining the total number of events we introduced the following corrections: 1) for the scanning efficiency, 2) for the departure of the V^0 particles from the fiducial volume of the chamber, 3) efficiency of registration of particles emitted at different azimuth angles, 4) admixture of muons in the beam, 5) neutral type of decay, and in the case of K^0 mesons additional account was taken of the long-lived K^0 particles. In addition, it was recognized that some fraction of the events from the carbon cannot be distinguished from π^-p interactions[8]. Allowing for all these factors, the total correction factor was found to be 2.69 for the hyperons and 4.29 for the K^0 mesons.

We obtain the following distribution of events over the reaction channels (the errors are statistical):

	Y^0K^0	Y^0K^+	$K^0\overline{K}{}^0$	$K^0K^- + K^+\overline{K}{}^0$	$\Sigma^\pm K^0$	Y^0Y^0KK
Number of events:	427±69	223±81	147±52	323±127	80±31[3]	4[4]
Cross section, mb:	4.8±0,8	2.5±0,9	1,7±0,6	3,6±1.4	0,9±0,4	0.04

[3] The number of events in the $\Sigma^\pm K^0$ channel was calculated from the known cross section for the production of charged hyperons in π^- p interactions[13].

[4] The azimuthal correction was disregarded in the determination of this number.

It was calculated that each interaction with carbon has a cross section 0.0113 mb. Starting with this value, we obtain for the cross sections for the production of the neutral hyperon paired with a $K^{0,+}$ meson and for the production of a neutral K meson with an anti K^0 meson

$$\sigma(Y^0K^{0,+}) = 7.3 \pm 1.2 \text{ mb},$$
$$\sigma(K^0\overline{K}) = 5.3 \pm 1.5 \text{ mb}.$$

The ratio of these cross sections is $\sigma(K_0\overline{K})/\sigma(Y^0K^{0,+}) = 0.73 \pm 0.24$. The value obtained for this ratio with the aid of a freon chamber[7] at 2.8 GeV/c π^--meson momentum is 0.65 ± 0.15, and according to the data obtained with the xenon chamber[6] at the same momentum it amounts to 0.54 ± 0.18. What is striking is that this ratio tends to decrease with increasing Z_{eff} of the substance, although the errors are very large in all the experiments.

The total cross section $\sigma(Y^0K) + \sigma(K^0\overline{K})$ amounts to (5.0 ± 1.7)% of the total π^--meson carbon interaction cross section at 7 GeV/c. The total cross section was assumed to be 250 ± 20 mb[14].

The cross section for the production of double pairs of the type Y^0Y^0KK has been estimated with the aid of one well identified event in which a $\Lambda\Lambda$ pair was produced, and was found to be ~ 0.04 mb. [5)]

DISCUSSION OF RESULTS

A. Momentum and angular distributions. As can be seen from Fig. 1a, the momentum distribution of Λ hyperons produced in π^-C interactions differs little from the analogous distribution for π^-p interactions (in the laboratory system). This distribution contains only an indication of the smearing out of the spectrum both towards larger and towards smaller momenta. The presence of such a smearing is natural in view of the presence of secondary interactions and the Fermi motion of the nucleons in the carbon nucleus.

The angular distribution of Λ hyperons produced in π^-C interactions (Fig. 1b) does not differ in practice from the angular distribution of the Λ hyperons produced in π^-p interactions. The number of events outside the production angles that is admitted by the kinematics of the π^-p interactions is less than 5%.

The momentum distribution for the production of K^0 mesons has in the laboratory frame (Fig. 2a) a maximum which is noticeably shifted towards the smaller momenta compared with the distribution of the K^0 mesons from the π^-p interactions. The average momentum of the K^0 mesons is equal here to 1.71 GeV/c, whereas for the interactions with the protons it was equal to 1.97 GeV/c.

The angular distribution of the K^0 particles differs from their angular distribution for production on a free nucleon only in the interval cos θ = 1.0—0.98, where the number of K^0 mesons from πC interactions is 20% lower.

From a comparison of the data for the momentum distributions of the Λ hyperons in the pion-nucleon c.m.s. (Fig. 3) for interactions with carbon and hydrogen we see that the presence of a second maximum for carbon events (a fact noted in [2]) is less strongly pronounced. Under these conditions the admixture of carbon events in [2] could have only smoothed out the curve in the momentum region above 1300 MeV/c, i.e., it could have reduced the fraction of Λ hyperons produced in interactions with small momentum transfer. Thus, the presence of a second maximum in the momentum spectrum of the Λ hyperons is not due to an admixture of carbon events.

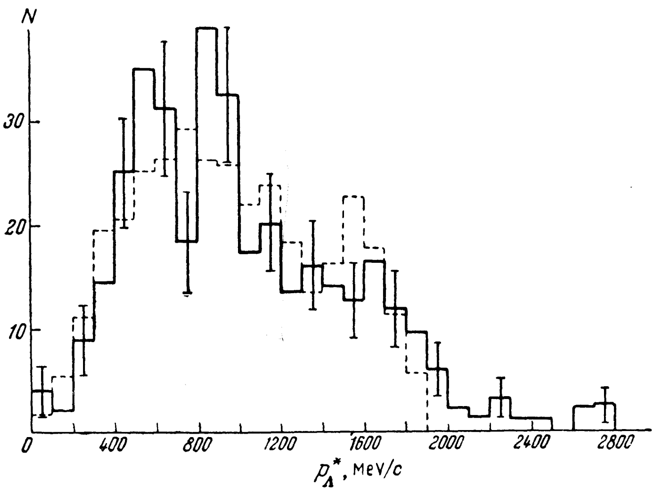

FIG. 3. Momentum spectra of Λ hyperons in pion-nucleon center of mass system for π^-C interactions (continuous curve) and π^- p interactions (dashed).

B. Cross sections of the processes. It is of interest to compare the ratio of the cross sections for the production of Λ hyperons to the total inelastic cross section (σ_{in}) at our energy with the ratio at lower energies. The total cross section of inelastic interaction of pions with carbon at

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[5)]The event of the type $\Lambda + (\Lambda \text{ or } K^0)$ listed in the table was disregarded in the estimate of this cross section, since Λ and K^0 are indistinguishable in this reaction not kinematically but as a result of the large measurement errors.

7.0 GeV/c was chosen to be 197 ± 7 mb [14]. The data are as follows:

π^--meson momentum, GeV/c:	1.5 [4]	2.8 [7]	7.0
Λ yield, per cent:	1.7±0.4	2.5±0.5	3.7±0.3
K^0 yield, per cent:	1.4±0.5	7±1	6.4±0.5

We see that, compared with π^-C interaction at 1.5 GeV/c, the yield of neutral hyperons at our energy is double, while that of neutral K mesons is approximately five times as large.

An analogous energy dependence of the cross section for the production of Λ can be traced also for pion-nucleon interactions. In this case at 1.59 GeV/c pion momentum [15] we have $\sigma(\Lambda K^0)/\sigma_{in}$ = (1.7 ± 0.4)%, which coincides exactly with the ratio obtained for the interactions with carbon. At 7 GeV/c, this ratio, in accordance with the data of our earlier investigations [8,9], is (3.5 ± 1.2)% for hydrogen reactions and (3.7 ± 0.3)% for carbon events. Unfortunately, the errors are too large to draw any definite conclusions. However, an analysis of a large number of experimental data, made by Barashenkov and Patera [16] indicates that the actual error in the determination of the cross section of production of Λ hyperons on nucleons is apparently several times smaller than the value given in [8]. This gives grounds for stating with great assurance that the ratios $\sigma(\Lambda K^0)/\sigma_{in}$ are the same for hydrogen and carbon events at 7 GeV/c.

If we assume that the values of this ratio for carbon and hydrogen at 7 GeV/c are equal, then we can estimate the cross section for inelastic interaction of neutral hyperons with the nucleons of the parent carbon nucleus. In fact, these hyperons are produced in the nucleus by both primary and secondary reactions. The hyperon production due to secondary acts should cause an excess growth with energy of the ratio $\sigma(\Lambda K^0)/\sigma_{in}$ for carbon over the growth of the same ratio for hydrogen, where there are no secondary sources. If there is no such excess, this means that the fraction of the Λ hyperons produced in the primary events and vanishing as a result of inelastic secondary interactions is equal to the fraction of Λ hyperons produced in the secondary events.

Using the estimate given below for the fraction of Λ hyperons produced by secondary interactions in the carbon nucleus, we can proceed to estimate the cross section of inelastic interaction of the Λ hyperons. This question is of definite interest. Although we do not make such an estimate here, nevertheless we consider it useful to point to this fundamental possibility. This method can be used when more accurate experimental data become available. When the experimental data have good accuracy, it is possible to determine the cross section for the inelastic interaction by this method using not only the equality of the ratios $\sigma(\Lambda K^0)/\sigma_{in}$, but also the difference in the rate of their increase with energy.

C. Estimate of the fraction of Λ hyperons produced in secondary processes. We have already determined the cross section for the production of Λ hyperons by a carbon nucleus. It is clear that this cross section contains an addition due to Λ hyperons produced in the secondary processes in the nucleus, of the type

$$\pi + N \to \Lambda + K\Lambda + s\pi,$$

$$\overline{K} + N \to \Lambda + s\pi,$$

$$\Sigma^{\pm} + N \to \Lambda + N + s\pi.$$

Let us attempt to estimate the value of this addition.

The contribution of the first reaction can be determined on the basis of one case of production of two Λ hyperons in a single star. We shall assume that one Λ hyperon from the $\Lambda\Lambda$ pair was produced in the primary interaction of the π^- meson with one of the nucleons of the nucleus, while the second was produced as a result of interaction of one of the secondary pions.[6)] The cross section of this process can be obtained from the relation

$$\sigma(\Lambda)_{\pi\,\mathrm{sec}} = B\sigma(\Lambda\Lambda),$$

where $\sigma(\Lambda\Lambda)$ is the cross section for the production of a $\Lambda\Lambda$ pair, while the coefficient B takes into account the ratio of the fluxes of the secondary pions, which can be produced both with strange particles and without them, i.e.,

$$B = (\sigma_{in} n_\pi + \sigma_{el} \cdot 1)/\sigma(\Lambda K^0)\, n_{\Lambda\pi}.$$

Here n_π and $n_{\Lambda\pi}$ are the multiplicities of the pions produced without and with strange particles, while σ_{in} and σ_{el}—inelastic and elastic cross sections. Assuming that at our energy n_π = 3.8 [17], $n_{\Lambda\pi}$ = 3.5 [18], σ_{in} is equal to the difference between σ_{tot} = 31 mb [19,9] and σ_{el} = 5.5 mb [9], and $\sigma(\Lambda K)$ = 0.8 mb [8], we obtain

$$\sigma(\Lambda)_{\pi\,\mathrm{sec}} \approx 1.5 \text{ mb}.$$

When estimating the contribution of the second reaction we took account of the fact that the K mesons are produced with a cross section of 1.6

6)The probability of occurrence of Λ hyperons from tertiary and following interactions of $\overline{K}$ mesons and $\Sigma^{\pm}$ hyperons, which can be produced in the second event, are neglected here.

mb[7] and go over into Λ hyperons with a cross section 5.2 mb[20].

The calculation of the contribution of the third reaction is more complicated, since the cross section of the transition of a $\Sigma^{\pm}$ hyperon into a Λ hyperon is not known. If, in analogy with the inelastic pp interaction (for the same energy), we assume it to be 20 mb, and take the cross section for the production of the Σ^- hyperons to be 0.1 mb[13], then the total contribution of the two last reactions will amount to approximately 1 mb.[8]

Thus, the cross section for the production of Λ hyperons via all the secondary processes is ~ 2.5 mb, and the cross section which we have calculated earlier for their production via the primary and secondary processes together amounts to 7.3 mb, i.e., approximately 35% of all the Λ hyperons are produced in the secondary processes. In spite of this high percentage of the neutral hyperons produced in the secondary acts, the small value of the cross section for the production of double pairs of the type YYKK indicates that the overwhelming majority of the pairs which we registered were produced in a single interaction event, either the primary or the secondary[9].

CALCULATION BY THE MONTE CARLO METHOD[10]

For comparison with the experimental data on the production of Λ hyperons and K^0 mesons on carbon, we calculated the cascade produced by a negative pion with momentum 7 GeV/c. In this calculation, each particle was completely determined by specifying its coordinates inside the nucleus, the flight angles, the mass, and the momentum. The interaction between the particle and the nucleons of the nucleus was specified by the possible reaction channels, compatible with the conservation laws for energy, baryon number, and strangeness. The probabilities of each of the possible channels for all the particles participating in the cascade together with the angular distributions in the elastic channels, momentum spectra, and angular distributions in the inelastic channels were all specified in the calculation as initial characteristics of the interactions. The nuclear model used was the model of a Fermi gas filling with uniform density a sphere of radius $R = r_0A^{1/3}$, where $r_0 = 1.37 \times 10^{-13}$ cm and A = 12 (carbon).

The entire pion energy interval under consideration was subdivided into two regions, one containing all the secondary pions and the other the primary pions with energy 7 GeV[11]. In each region the probabilities of the channels, and also the energy and angular characteristics of the particles in the elastic and inelastic πN interactions, were assumed to be constant and independent of the energy. For the secondary particles—pions, nucleons, K mesons and hyperons produced as a result of the primary πN interaction or the subsequent collisions of the secondary particles with the nucleons inside the nucleus—the characteristics of the interaction with the nucleons were assumed to be constant over the entire energy interval that is allowed for each of these particles. The details of the calculation are given in [21].

Figure 4 shows the angular distributions and Fig. 5 the momentum distributions of the Λ hyperons and K^0 mesons[12] obtained by calculation, as well as the experimental distributions[13]. As can be seen from the figures, the distributions coincide. According to the Kolmogorov-Smirnov test, the percentage of coincidences is equal to 93 for the momentum distribution and 98 for the angular distribution of the Λ hyperons and respectively 19 and 100% for the K^0 mesons.

For the $Y^0K^{0,+}$ and $K^0\overline{K}$ pairs we calculated the values of the cross sections. They were found to be equal to those obtained experimentally, namely

$$\sigma\,(Y^0K^{0,+}) = 7.4 \pm 0.5 \text{ mb}, \quad \sigma(K^0\overline{K}) = 6.0 \pm 0.4 \text{ mb}.$$

Here $\sigma(K^0K) = \sigma(K^0K^0) + \sigma(K^0K^-) + \sigma(K^0K^+)$.

The average experimental values of the momenta in the interval from zero to 3 GeV/c coincide with the calculated values and are equal to 1.23 ± 0.04 and 1.24 ± 0.08 GeV/c respectively for the Λ hyperons and 1.32 ± 0.04 and 1.42 ± 0.6 GeV/c for the K^0 mesons.

[7]We added the cross section for the production of the K^+K^- pairs to the value of the cross section for the production of $K^0\overline{K}$ pairs, given in[8].

[8]No account is taken here of the transition of the secondarily produced Λ hyperons into other particles.

[9]This circumstance indicates that it is possible in principle to investigate resonances in pairs of strange particles (ΛK, KK, etc.) on light nuclei. It must be borne in mind here that the number of background combinations due to elastic scattering of one of the particles and charge exchange may be appreciable.

[10]The calculations were performed by the Computation Center of the Joint Institute for Nuclear Research.

[11]We investigated also the case when the energy was divided into two regions: from zero to 3 GeV and above 3 GeV. In this case the agreement between calculation and experiment becomes worse.

[12]The comparison was made in the laboratory system in view of the appreciable role of the secondary processes.

[13]According to the calculation conditions, the momentum spectrum was taken from zero to 3 GeV/c.

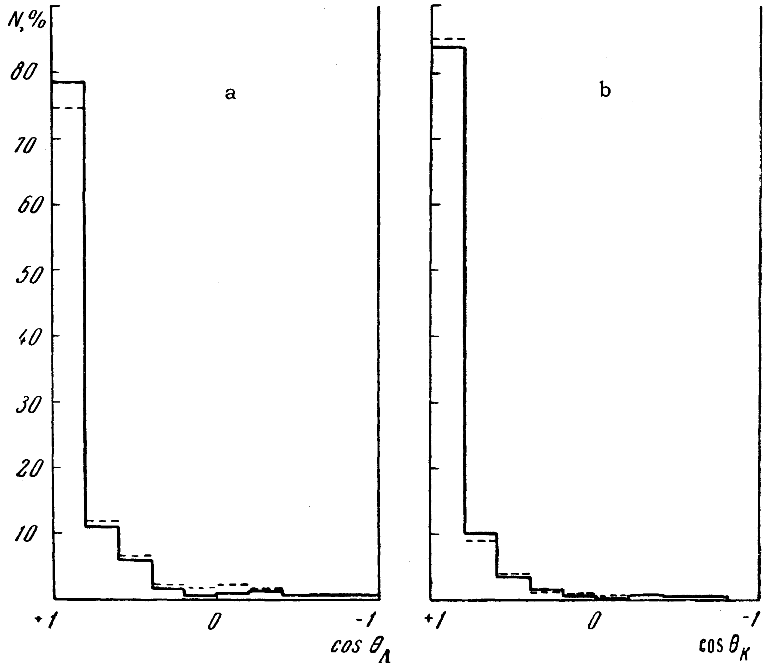

FIG. 4. Angular distribution of Λ hyperons (a) and K^0 mesons (b) from π^-C interactions at 7 GeV/c, obtained by experiment (continuous curve) and by Monte-Carlo calculations (dashed).

It follows from the calculations that the fraction of the Λ hyperons produced only in the secondary processes is approximately 50%. This value agrees also with that obtained by experiment. The fraction of the K mesons produced in the secondary processes is by calculation equal to $\sim 25\%$.

CONCLUSIONS

Thus, the good agreement between the calculated spectra of the Λ hyperons and K^0 mesons with the experimental values makes it possible to assume that the cascade interaction model used in the calculations is true for the investigated classes of phenomena.

The previously observed hard part of the pion-nucleon c.m.s. momentum spectrum of the Λ hyperons in π^-p interactions is not due to an admixture of carbon events.

The role of the secondary processes which lead to the production of strange particles is quite appreciable even on the carbon nucleus.

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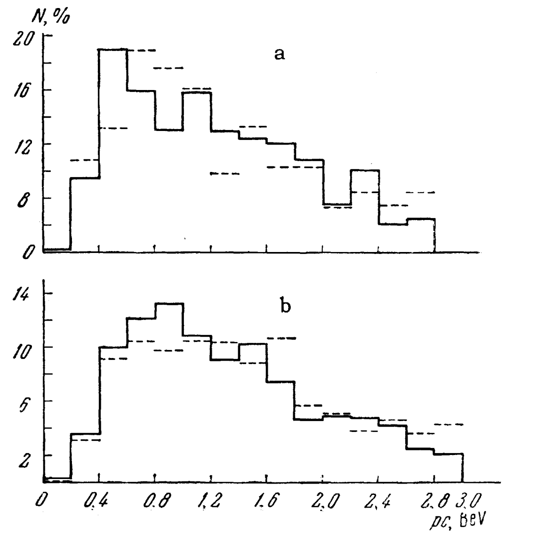

FIG. 5. Experimental (continuous curve) and Monte-Carlo (dashed) momentum distributions of Λ hyperons (a) and K^0 mesons (b) from π^- C interactions at a negative pion momentum 7 GeV/c.

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