

PRODUCTION OF STRANGE PARTICLES BY 2.8-BeV/c  $\pi^-$  MESONS ON XENON NUCLEI

I. A. IVANOVSKAYA, E. V. KUZNETSOV, A. PROKESH, and I. V. CHUVILO

Institute of Theoretical and Experimental Physics; Joint Institute for Nuclear Research

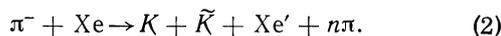
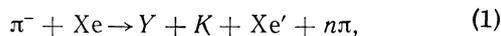
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The relative and absolute cross sections are measured for different channels of strange-particle production by 2.8-BeV/c  $\pi^-$  mesons on xenon nuclei. The angular and momentum distributions of strange particles in the laboratory system and in the pion-nucleon center-of-mass system are presented.

## 1. EXPERIMENT

USING a two-liter xenon bubble chamber,<sup>[1]</sup> we investigated the production of strange particles by 2.8-BeV/c  $\pi^-$  mesons in the reactions



Here Xe is the xenon nucleus, Xe' is the product nucleus, Y is a hyperon, and  $n = 0, 1, 2, \dots$ . We investigated mainly the production of  $\Lambda$  and  $K^0$  which decayed into charged components:



In the present article we discuss measurements of the cross sections for the different reaction channels (1) and (2), and also present the angular and momentum distributions of  $\Lambda$  hyperons and  $K^0$  mesons produced in these reactions. Here  $\Lambda$  production and  $K^0$  production will be understood to include both direct  $\Lambda$  and  $K^0$  production and their production via such short-lived intermediate particles as  $\Sigma^0$ ,  $Y_0^*$ ,  $K^*$  etc.

A detailed account of the experiment has been given in<sup>[2]</sup>; we shall mention here only the principal features of the technique. The  $20 \times 11 \times 10$ -cm chamber was photographed by a twin-lens stereo camera on 36-mm film. All photographs were scanned twice to detect strange-particle production. The coordinates of events in the film were measured with an UIM-21 measuring microscope; the space coordinates, angles, and ranges were calculated on electronic computers. The chamber was operated without a magnetic field. Particles were identified from the emission angles of decay products relative to the direction of the decaying particle and from the measured ionization and ranges of secondary particles. The momenta of

decaying particles were also determined from these measurements. Decay-product trajectories were, of course, required to be coplanar with the parent star. In some instances the available experimental data did not permit a clear determination as to whether a given event should be assigned to  $K^0$  decay or to  $\Lambda$  decay. These indeterminate events comprise about 10% of the total number of registered neutral-strange-particle decays. We have shown in<sup>[2]</sup> that the indeterminate events can be divided into approximately 90%  $\Lambda$  decays and only 10%  $K^0$  decays.

We investigated 398 instances of  $\Lambda$  production and 418  $K^0$ -meson productions, along with 82 indeterminate events. The total number of observed neutral-strange-particle decays was 898.

In order to check the reliability of our identification of strange particles we used our data to evaluate the  $\Lambda$  and  $K^0$  lifetimes.<sup>1)</sup> The lifetimes calculated by the method of maximum probability<sup>[3]</sup> were  $\tau_\Lambda = (2.53 \pm 0.28) \times 10^{-10}$  sec and  $\tau_{K^0} = (0.96 \pm 0.22) \times 10^{-10}$  sec, in good agreement with the values  $\tau_\Lambda = (2.505 \pm 0.086) \times 10^{-10}$  sec and  $\tau_{K^0} = (1.00 \pm 0.04) \times 10^{-10}$  sec in the literature.<sup>[4]</sup>

## 2. REGISTRATION EFFICIENCY

In order to calculate from our experimental data the cross sections for the strange-particle production reactions and to plot the angular and momentum distributions, the actual numbers of created particles had to be known; it was therefore most essential to determine corrections for registration efficiency. We took into account the following principal causes of losses: 1) the existence of neutral decay channels (correction factors 1.49 for  $\Lambda$  and

<sup>1)</sup>We investigated for this purpose the first 275  $\Lambda$  decays and the first 66  $K$  decays.

Reaction products	No. of observed events	Actual no. of events	Relative cross section, mb	Absolute cross section, mb
All $\Lambda K$		1380±64	1±0.046	42±4
Including $\left\{ \begin{array}{l} \Lambda K^0 \\ \Lambda K^+ \end{array} \right.$	56	735±98	0.53±0.07	22±3, 4
All $K\bar{K}$		645±117	0.47±0.09	20±5
		1142±200	0.83±0.15	35±9
Including $\left\{ \begin{array}{l} K^0 \bar{K}^0 \\ K^+ K^- \\ \bar{K}^0 K^+, K^0 K^- \end{array} \right.$	15	283±74	0.21±0.06	9±3
		283±74	0.21±0.06	9±3
		576±171	0.42±0.13	18±7
$\Sigma^\pm K^0$	3	13±8		
$\Lambda^0$	470	1380±64		
$K^0$	428	1890±92		

1.33 for  $K^0$ );<sup>[5]</sup> 2) the presence of a long-lived  $K_2^0$  component (2); 3) decays outside of the chamber and decays too close to the parent stars (averaging factors 1.41 for  $\Lambda$  and 1.46 for  $K^0$ ); 4) events with extreme emission angles of decay  $\pi^-$ -mesons relative to the trajectory of the decaying particle (factors 1.32 for  $\Lambda$  and 1.04 for  $K^0$ ); 5) particle emission at angles close to  $0^\circ$  and  $180^\circ$  relative to the camera axis (factors 1.02 for  $\Lambda$  and 1.04 for  $K^0$ ); 6) events overlooked in two scannings (factors 1.05 for both  $\Lambda$  and  $K^0$ ).

The corrections 3)–6) were determined from our experimental data. Corrections for decays outside of the chamber and decays occurring too close to the parent stars were determined individually for each decay event from the potential range of the particle. This appears to be the most accurate procedure since it automatically takes into account (through the potential range of each decaying particle) the star distribution in the chamber, the shape of the chamber, and the angular distributions and energy spectra of  $\Lambda$  and  $K^0$ . The total correction factors (with averaging for correction 3) are  $A_\Lambda = 2.98$  and  $A_{K^0} = 4.4$ .

### 3. CROSS SECTIONS FOR STRANGE-PARTICLE PRODUCTION

The second column of the accompanying table gives the numbers of observed  $\Lambda K^0$  and  $K^0 \bar{K}^0$  pairs and the total numbers of observed  $\Lambda$  and  $K^0$  (including cases when only one of the strange particles is actually seen). Since  $\sim 90\%$  of all indeterminate events pertain to  $\Lambda$  particles, all these events were divided in the ratio  $\sim 9:1$  between  $\Lambda$  and  $K^0$ . The table does not include data on charged K-meson production because of the great uncertainty regarding registration efficiency for these particles. It must also be noted that the number of events  $n(\Sigma^\pm K^0)$  given in the table is not very reliable, because for short ranges it is very easy to confuse  $K^\pm$  decay with  $\Sigma^\pm$  decay. The given value of  $n(\Sigma^\pm K^0)$  is only tentative.

The third column of the table gives the actual numbers of events derived through multiplying the data in the first column by the correction factors given in the preceding section. In the calculations it was assumed that the registration probabilities of the two strange particles are independent. Therefore the numbers of events in which  $\Lambda$  and  $K^0$ , or  $K^0$  and  $\bar{K}^0$ , were observed simultaneously were multiplied by  $A_\Lambda A_K$  or  $A_K^2$ , respectively. (Only the statistical errors are indicated.)

In calculating the number of  $K^0 \bar{K}^0$  pairs the total correction factor 4 was assumed for the long-lived  $K_2^0$  component. It was shown in <sup>[6]</sup> that this is not entirely correct; however, in view of the fact that the incident  $\pi^-$  energy was almost 2 BeV above the  $K\bar{K}$  pair-production threshold, and considering that many  $K\bar{K}$  pairs are evidently produced through  $\pi^- + N \rightarrow K + Y^* (\rightarrow N + \bar{K})$  intermediate reactions,<sup>[7]</sup> this approximation can be regarded as sufficiently accurate.

In calculating the numbers of  $\Lambda K$ ,  $\Lambda K^+$ , and  $K^+ K^-$  pairs we used the two obvious relations:  $N(\Lambda K) = N(\Lambda)$  and  $N(\Lambda K^+) = N(\Lambda K) - N(\Lambda K^0)$  and the hypothesis  $N(K^+ K^-) = N(K^0 \bar{K}^0)$ . The number of  $K\bar{K}$  pairs produced in the two other channels can be calculated from the relation<sup>2)</sup>

$$N(\bar{K}^0 K^+) + N(K^0 K^-) = N(K^0) - N(\Lambda K^0) - 2N(K^0 \bar{K}^0) - N(\Sigma^\pm K^0).$$

The value of  $N(\bar{K}^0, K^+) + N(K^0, K^-)$  given in the table was calculated assuming 100% registration efficiency for  $\Sigma^\pm$  particles. The error incurred through this assumption is considerably smaller than our statistical errors, since  $N(\Sigma^\pm K^0)$  is very small.

The fourth column of the table gives the relative cross sections for the different channels of strange-particle production, with  $\Lambda K$  pair production taken as unity. It is seen that reactions differing only in

<sup>2)</sup>We did not observe a single instance of  $\Xi$ -hyperon decay; we can therefore neglect the production of  $\Xi K K$  triplets.

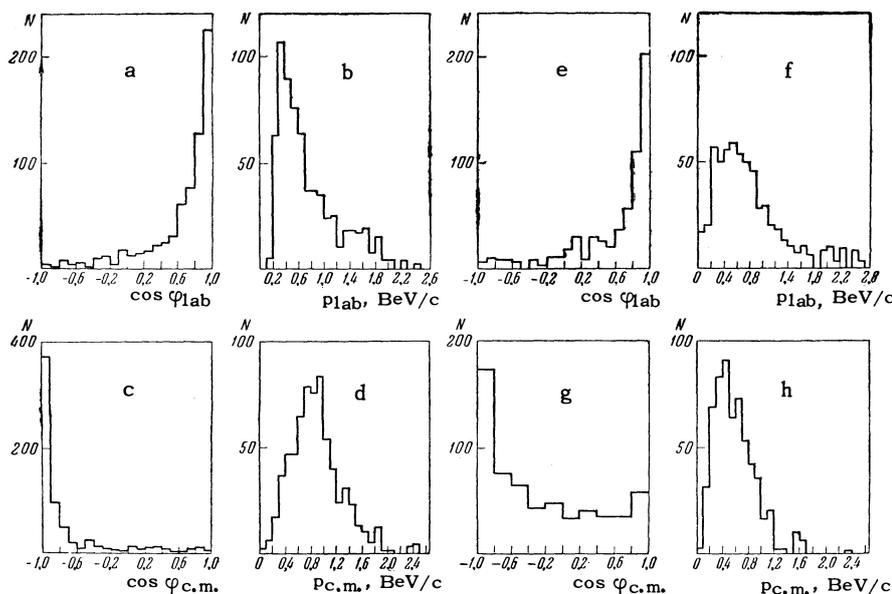


FIG. 1. Angular and momentum distributions of all  $\Lambda$  hyperons (a-d) and  $K^0$  mesons (e-h) in the laboratory system ( $\varphi_{lab}$  and  $p_{lab}$ ) and c.m. system ( $\varphi_{c.m.}$  and  $p_{c.m.}$ ).

the charges of the strange particles are equally intense, within statistical errors.

For  $\sigma(K^0\bar{K}^0)/\sigma(\Lambda K^0)$  our preliminary result in [8] and the value given in [9] are  $0.54 \pm 0.18$  and  $0.65 \pm 0.15$ , respectively; these values agree, within the statistical errors, with our present work.

A statistical-theory calculation based on a refined Fermi model allowing for  $\pi N$  isobars of mass 1230 MeV at  $P_{\pi^-} = 3$  BeV/c, converted to the nucleon mixture in the xenon nucleus, gives the ratio  $\eta = \sigma(K\bar{K})/\sigma(\Lambda K) = 0.99$ , [10] which is very close to the experimental value. This agreement appears to be accidental, since the calculation neglected the numerous pion-nucleon, hyperon, K-meson, and pion resonances that are known at the present time. The calculation also includes a very high value of the  $\Sigma$  yield:  $\sigma(\Sigma K)/\sigma(\Lambda K) = 1.67$ , whereas experimentally this ratio does not exceed 10–15% according to the highest estimates.

In order to determine the absolute cross sections we counted the total number of interactions in 10,000 photographs and the total number of  $\Lambda$  and  $K^0$  productions. The relative yields of  $\Lambda$  and  $K^0$  corrected for registration efficiency were  $(3.5 \pm 0.3)\%$  and  $(4.9 \pm 0.5)\%$  per single interaction. The yield of  $\Lambda K$  pairs equalled the  $\Lambda$  yield  $(3.5 \pm 0.3)\%$ ; the  $K\bar{K}$ -pair yield was  $(2.9 \pm 0.3)\%$ . In [9], where strange-particle production on light nuclei was investigated, different values of the  $\Lambda$  and  $K^0$  yields were obtained:  $(2.5 \pm 0.5)\%$  and  $(7 \pm 1)\%$ . The pion beam bombarding the chamber contained considerable muon contamination; therefore as a reference value for calculating the absolute cross sections we used the cross section for inelastic processes on xenon,  $\sigma_{inel} = 1200$  mb,

calculated on the optical model for a nucleus having nonuniform nucleon density. [11,12] <sup>3)</sup> This result and the relative  $\Lambda$  yield were used to calculate the cross section  $42 \pm 4$  mb for  $\Lambda K$  pair production on xenon. This result and the foregoing calculated relative cross sections were used to determine the absolute cross sections for the other strange-particle production channels (the fifth column of the table).

#### 4. MOMENTUM AND ANGULAR DISTRIBUTIONS OF $\Lambda$ HYPERONS AND $K^0$ MESONS

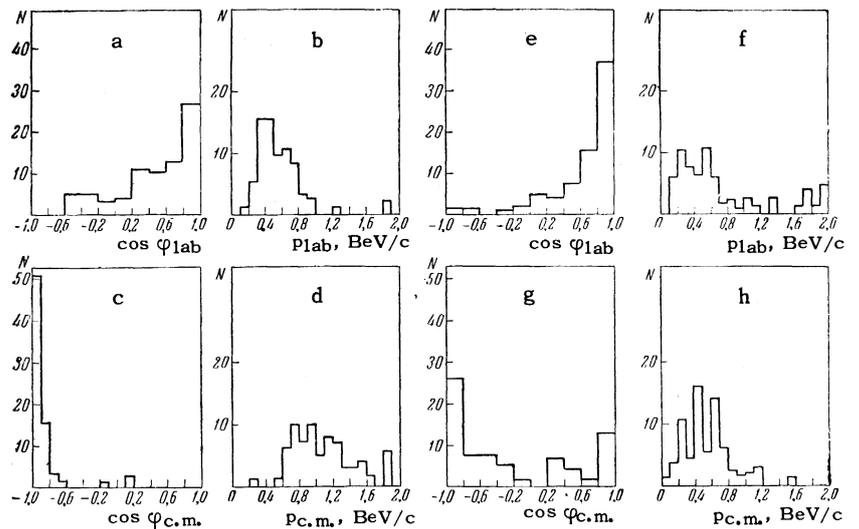
Figures 1–3 show the  $\Lambda$  and  $K^0$  angular and momentum distributions. In plotting the histograms an individual correction for decays outside of the photographed volume was introduced for each event. All angular distributions in the laboratory system are peaked strongly forward. Distributions in the c.m. system were calculated assuming that the incident  $\pi^-$  meson collided with a quasi-free nucleon at rest.

Figure 1 shows the momentum and angular distributions of all  $\Lambda$  hyperons and  $K^0$  mesons observed either singly or in pairs. The  $\Lambda$  angular distribution (c.m.s.) shows its characteristic strong backward peaking, which has also been noted by many other investigators (in [13], for example). The figure also reveals a small  $\Lambda$  group having an isotropic angular distribution in the pion-nucleon c.m. system.

The maximum angle of  $\Lambda$  emission is  $47^\circ$ ; the

<sup>3)</sup>The same value is obtained when experimental data for nuclear emulsions are converted to the xenon nucleus.

FIG. 2. Angular and momentum distributions of  $\Lambda$  hyperons and  $K^0$  mesons from  $\Lambda K^0$  pairs. a, b— $\Lambda$  in lab. system; c, d— $\Lambda$  in c.m. system; e, f— $K^0$  in lab. system; g, h— $K^0$  in c.m. system.



minimum laboratory momentum is 250 MeV/c. Particles appearing outside of these limits are associated with scattering in the parent nucleus, with  $\Lambda$  production in secondary events, and with the influence of nucleonic Fermi motion in the nucleus; these particles comprise about 30%. For  $\Lambda$  momentum under 300–350 MeV/c,  $\Lambda$  decays lose their characteristic V shape and can be overlooked when scanning; considerable systematic distortion of the soft spectrum is therefore possible. The c.m. momentum spectrum of  $\Lambda$  hyperons therefore extends beyond the resolved region.

The c.m. angular distribution of  $K^0$  mesons differs considerably from that of  $\Lambda$  hyperons; the former is approximately isotropic with some backward peaking.

Figure 2 shows the  $\Lambda^0$  and  $K^0$  momentum and angular distributions for all events in which both particles decay within the working volume of the chamber. It is an interesting characteristic of these distributions that in a considerable number of events both strange particles are emitted in the backward hemisphere making a small angle relative to each other. This served as a starting point for [14], in which work it was concluded that a particle having the mass 1650 MeV exists and is subject to the decay



Figure 3 gives the corresponding distributions for  $K^0$  mesons from  $K^0 \bar{K}^0$  pairs. Since we cannot distinguish  $K^0$  from  $\bar{K}^0$ , both mesons are included in the distributions on an equal basis. The number of events is very small; therefore the distributions can only serve as a very general description. The c.m. angular distribution of  $K^0$  mesons is approximately isotropic; the c.m. angles between the  $K^0$  mesons vary from  $0^\circ$  to  $180^\circ$ .

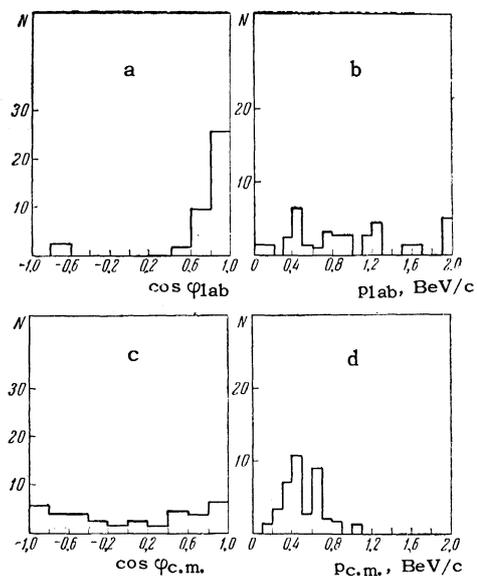


FIG. 3. Angular and momentum distributions of  $K^0$  mesons from  $K^0 \bar{K}^0$  pairs in the lab. system (a, b) and in the c.m. system (c, d).

It is interesting to compare the c.m. angular distributions for  $\Lambda$  hyperons and  $K^0$  mesons produced on xenon nuclei and on light nuclei in a freon chamber; [9] the distributions pertaining to xenon nuclei exhibit more pronounced backward peaking. This effect is considerably sharper for  $K^0$  mesons paired with  $\Lambda$  hyperons than for those from  $K^0 \bar{K}^0$  pairs. This result can easily be accounted for by the formation of the aforementioned resonance state of a KN system, which is scattered as a unit with a considerable cross section on the xenon nucleus; this results in a quite large number of  $K^0$  mesons emitted at large c.m. angles relative to the incident beam. The effect is absent from  $K^0 \bar{K}^0$  pair production, since the  $K^0$  scattering cross section is considerably smaller.

## CONCLUSIONS

1. Reactions differing only with regard to the charge of strange particles occur with identical intensity.

2. The experimental ratio  $\sigma(K\tilde{K})/\sigma(\Lambda K)$  is in good agreement with statistical theory calculations based on a refined Fermi model allowing for isobars of 1230-MeV mass.<sup>[10]</sup> The experimental ratios  $\sigma(K\tilde{K})/\sigma_{\text{inel}}$  and  $\sigma(\Lambda K)/\sigma_{\text{inel}}$  are 1.5 times smaller than the calculated ratios. The  $\Sigma^\pm$  yield is many times smaller than the calculated yield.

3. In the pion-nucleon c.m. system the great bulk of  $\Lambda$  hyperons are emitted backward within a 154–180° cone. A small (~10%) group exhibits an isotropic angular distribution.

4. A comparison of Figs. 1 and 2 indicates that the angular distributions also depend only slightly on the strange-particle charge.

5. About 30% of the  $\Lambda$  hyperons are scattered in the parent nucleus. A comparison of data on  $K^0\tilde{K}^0$  pairs produced in freon<sup>[14]</sup> and xenon indicates that  $K^0$  mesons are scattered considerably less frequently (~14% of the events) in the nucleus.  $K^0$  mesons from  $\Lambda K^0$  pairs are scattered considerably more strongly (with ~30% probability); this can be accounted for by the formation of a strongly scattered intermediate  $Z^0$  particle decaying into  $\Lambda$  and  $K^0$  outside the nucleus.

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<sup>14</sup>Kuznetsov, Kuznetsov, Shalamov, and Grashin, JETP 42, 1675 (1962), Soviet Phys. JETP 15, 1163 (1962); Phys. Rev. Letters 1, 314 (1962).