PRODUCTION OF Ξ^- HYPERONS BY 7- AND 8-Bev/c π^- *MESONS*

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The production and decay of Ξ^- hyperons produced in the interaction between π^- mesons in propane at momenta of 6.8 ± 0.6 and ~ 8 Bev/c were studied. A total of 11 Ξ^- hyperons were observed. Their decay energy Q (1), lifetime τ_0 (2), and production cross section (3) are given.

THE first cascade hyperons were obtained in cosmic-ray experiments. A brief review of the data on 16 Ξ^- hyperons produced by cosmic rays was given by Franzinetti and Morpurgo.[1] Later on, Ξ^- hyperons were produced in accelerators by 5.5-Bev/c π^- mesons (2 cases)[2] and by 1.15-Bev/c K^- mesons (16 cases).[3]

We used for our experiment a 24-liter propane bubble chamber placed in a constant magnetic field of 13 700 oe. The chamber was exposed to beams of π^- mesons of ~ 7 and ~ 8 Bev/c. The experimental arrangement has been described previously.[4] We scanned 27 000 photographs with 6.8 ± 0.6 Bev/c π^- mesons and 75 000 photographs with ~ 8-Bev/c π^- mesons. The photographs were scanned twice on stereo-viewers and reprojectors; part of them were scanned three times. In the scanning, we selected all events which could be ascribed by inspection to decays of cascade particles via the scheme $A \rightarrow V^0 + B$, $V^0 \rightarrow C + D$ (see, for example, Figs. 1 and 2) and also all secondary one-prong stars from whose vertex a V^0 particle is emitted. In this way we selected 90 cases.

The measurements were made on UIM-21 microscopes by measuring the coordinates of corresponding points on two stereo-photographs. The results of the measurements were fed to a Ural electronic computer, which gave the coordinates of the points, and the values of the momenta and angles. In the determination of the error in the particle momenta, we took into account the inaccuracy of the coordinate measurements on the microscope, the change in the track curvature due to multiple scattering in propane, and the nonuniformity of the magnetic field over the chamber volume.

The following criteria were used to identify the Ξ^- hyperons: 1) the character of the V^0 decay should be in agreement with the kinematics of the decay of Λ^0 particles into a proton and π^- meson; 2) the vertex formed by tracks A and B should lie in the decay plane of the Λ^0-particle decay, where the transverse momenta of the secondary π^- meson and proton should be balanced with respect to the direction of flight of the Λ^0 particle; 3) the point of decay of the Λ^0 particle should lie in the plane determined by the tracks of particles A and B; 4) the transverse momenta of the Λ^0 and B particles at the vertex formed by tracks A and B should be balanced; 5) the decay scheme of the Ξ^- decay, i.e., $\Xi^- \rightarrow \Lambda^0 + \pi^- + 65$ Mev, should be satisfied. Moreover, when possible, we checked the ionization of the decay products.

After analysis, we discarded 47 cases in which the V^0 decay was not associated with a vertex formed by A and B. Fourteen cases satisfied criterion 2, but the V^0 particles were identified as K_1^0. Of 29 cases satisfying criteria 1 and 2, only 15 satisfied criterion 3 (coplanar cases), but four of them did not satisfy criteria 4 and 5. Among the remaining 11 cases satisfying all five criteria, one was obtained in the 6.8 Bev/c π^--meson beam and 10 in the π^--meson beam at ~ 8 Bev/c. There were three cases (of the eleven) in which the V^0 particles were in agreement, within the limits of experimental error, with a K_1^0 or Λ^0 decay, where the ionization measurements did not make possible a choice between the Λ^0 and K^0 decays, owing to the large momenta of the positive decay products. However, since all three cases were in good agreement with the kinematics of a Ξ^- decay, we also attributed these cases to hyperons.

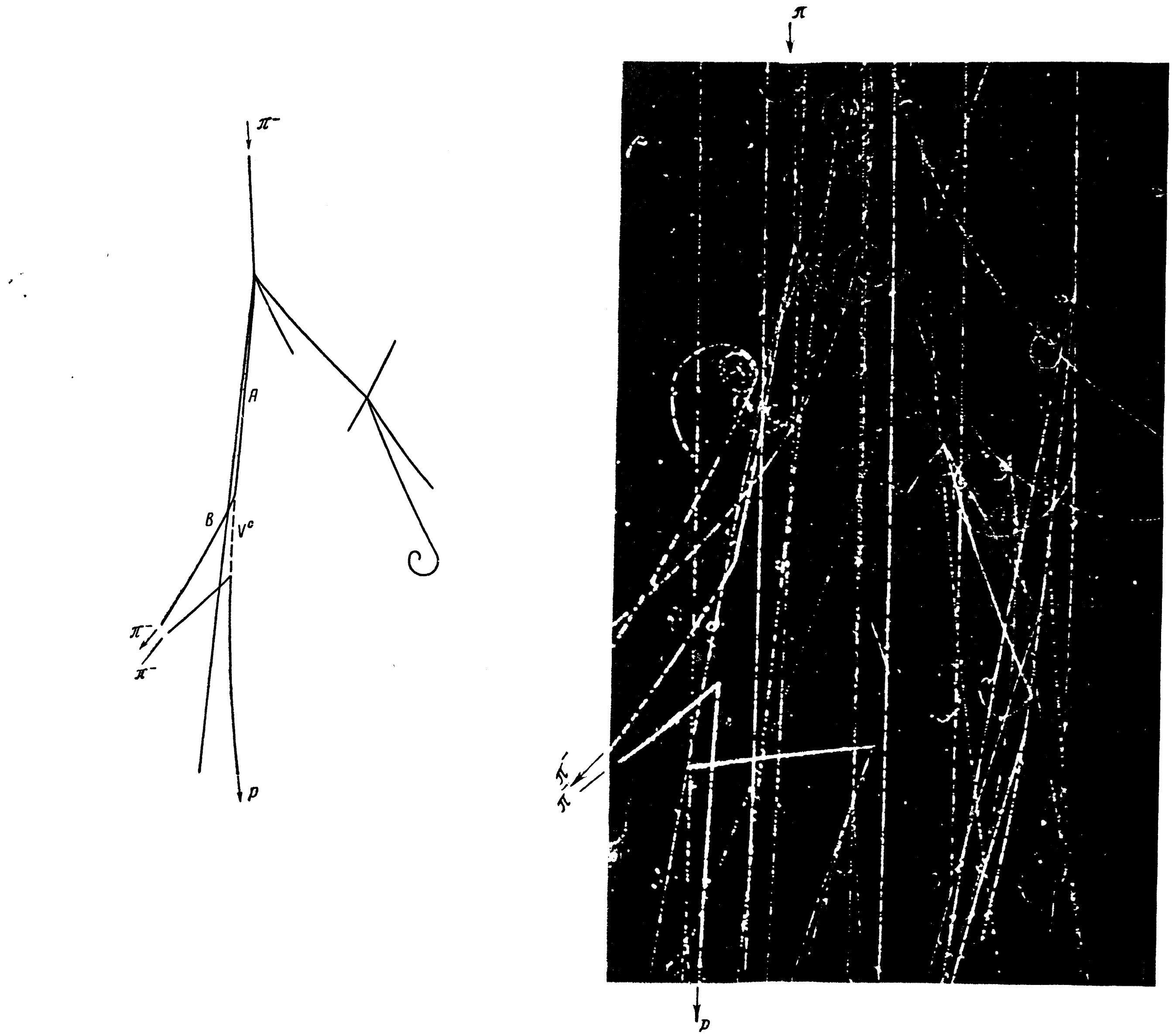

FIG. 1. Event No. 171-218. Decay of a Ξ^- hyperon.

Table I lists the angular and momentum characteristics of the Ξ^- hyperons identified by us. All the data were obtained by averaging the results from two to four independent measurements on the microscope. Also shown in the table are energy of decay Q and the lifetime up to the decay of the Ξ^- hyperons in their rest system.

The mean value of Q for the 11 cases of Ξ^--hyperon decay is

$$Q = 61{,}9 \pm 2{,}2 \text{ Mev} \tag{1}$$

from which we obtain the mass of the particle: $M_{\Xi^-} = 1317.0 \pm 2.2$ Mev. The lifetime of the Ξ^- hyperon was calculated by the maximum likelihood method and turned out to be

$$\tau_0 = \left(3.5 \begin{smallmatrix} +3.4 \\ -1.2 \end{smallmatrix}\right) \cdot 10^{-10} \text{ sec.} \tag{2}$$

After the identification of the Ξ^- hyperons, we analyzed the primary stars in which they were produced. Except for two cases (Nos. 6-230 and 370-252), all Ξ^- hyperons were produced inside the chamber. The tracks from the primary stars were measured twice and the momentum and energy balance was calculated for each star. The results are given in Table II. Six Ξ^- hyperons were produced in stars with an even number of prongs and resultant charge of zero. However, only five of them could be interpreted as π^-p interactions. (In event No. 171-218, the change in momentum in the collision was larger than the change in energy.)

Table I. Data on identified Ξ^- hyperons

p_{π^-}, Bev/c	Event No.	p_{Ξ^-}, Mev/c*	p_Λ, Mev/c	p_{π^-}, Mev/c	$\Theta_{\Xi-\Lambda}$	$\Theta_{\Xi-\pi^-}$	$\Delta p_\perp$, Mev/c**	Angle of noncoplanarity η***	Q_{Ξ^-}, Mev	τ_0, 10^{-10} sec
~7	182—42	3517 ± 420	3166 ± 415	374 ± 67	2°54′ ± 30′	18°30′ ± 30′	41 ± 42	9′	63.4 ± 14.4	1,13 ± 0,11
~8	91—145	1894 ± 150	1507 ± 150	406 ± 48	4°7′ ± 40′	15°25′ ± 40′	1 ± 25	14′	55,7 ± 13,7	2,53 ± 0,11
~8	196—160	1247 ± 185	963 ± 180	317 ± 44	6°45′ ± 30′	23°11′ ± 30′	12 ± 28	18′	69,1 ± 18,5	3,37 ± 0.27
~8	19—179	2811 ± 490	2407 ± 490	445 ± 64	4°9′ ± 30′	18°43′ ± 30′	31 ± 46	20′	73.2 ± 16.5	0.93 ± 0.11
~8	171—218	1398 ± 235	1181 ± 230	263 ± 29	6°22′ ± 1°20′	31°36′ ± 30′	8 ± 38	47′	64.4 ± 11.0	3.29 ± 0.37
~8	6—230	2008 ± 190	1583 ± 185	438 ± 39	2°58′ ± 1°	13°2′ ± 50′	17 ± 29	1°4′	52.5 ± 11.5	1.9
~8	370—252	878 ± 155	753 ± 151	197 ± 39	10°1′ ± 40′	46°20′ ± 30′	11 ± 39	2′	67.5 ± 20.3	6,4
~8	114—290	751 ± 93	625 ± 94	196 ± 19	13°1′ ± 27′	43°27′ ± 27′	6 ± 30	3° ****	63.4 ± 9.5	2,79 ± 0,41
~8	355—298	1812 ± 227	1593 ± 223	253 ± 44	4°58′ ± 1°30′	27°25′ ± 30′	21 ± 51	58′	53.2 ± 17.3	0.61 ± 0.09
~8	150—307	2440 ± 307	2098 ± 305	372 ± 45	5°1′ ± 1°	19°42′ ± 40′	58 ± 48	1°26′	56,2 ± 15,3	0.46 ± 0,07
~8	186—336	982 ± 115	702 ± 116	315 ± 51	8°35′ ± 30′	24°4′ ± 30′	23 ± 27	24′	86 ± 26	0.77 ± 0.14
Mean value		1794							61.9 ± 2.2	2.20

*Owing to the fact that some tracks were short, not all momenta could be obtained directly from the measurements. The values listed were calculated from the formula $p_{\Xi^-} = p_\Lambda \cos \Theta_{\Xi\Lambda} + p_\pi \cos \Theta_{\Xi\pi}$.

**$\Delta p_\perp = |p_\Lambda \sin \Theta_{\Xi\Lambda} - p_\pi \sin \Theta_{\Xi\pi}|$.

***η is the angle between the primary particle of the one-prong star and the plane determined by the Λ^0 particle and the secondary particle from the star; the error in the determination of the angle η is $\sim 1°30'$.

****The large error is due to difficulties of measurement.

Table II. Data on primary stars in which Ξ^- hyperons are produced

p_{π^-}, BeV/c	Event No.	Type of star	Other identified strange particles	$\sqrt{(\Delta E)^2+(\Delta p)^2}$, Mev *	Possible reaction of type**
~7	182—42	2-prong (1+, 1–)		1826 ± 210	(1)
~8	91—145	10-prong (7+, 2– and 1?)	K^+, stops and decays	394^{+150}_{-270}	(2)
~8	196—160	2-prong (1+, 1–)		1880 ± 180	(1)
~8	19—179	6-prong (3+, 3–)	K^+, stops and decays	185^{+100}_{-140}	(3)
~8	171—218	4-prong (2+, 2–)		$\Delta p > \Delta E$	(4)
~8	114—290	5-prong (4+, 1–)	K^0, decays	$\Delta p > \Delta E$	(5)
~8	355—298	3-prong (1+, 2–)		~1100	(6)
~8	150—307	2-prong (1+, 1–)		~2100	(7)
~8	186—336	2-prong (1+, 1–)		~1520	(1)

*The value of ΔE was calculated under the assumption of an interaction between a π^- meson and a free nucleon.

** $\pi^- + p \to \Xi^- + \pi^+ + (K^0 + K^0 + \ldots)$ (1)

$\pi^- + C \to \Xi^- + K^+ + K^+ + \pi^+ + 4p + \pi^- + \ldots$ (2)

$\pi^- + p \to \Xi^- + K^+ + K^+ + \pi^+ + \pi^- + \pi^- + \pi^0$ (3)

$\pi^- + C \to \Xi^-$ + other particles (4)

$$\pi^- + C \left\} \begin{array}{l} \to \Xi^- + K^0 + \pi^+ + \pi^+ + 2p + (K^0 + \ldots) \\ \to \Xi^- + K^0 + K^+ + \pi^+ + 2p \ldots \end{array} \right. \quad (5)$$

$$\pi^- + n \left\} \begin{array}{l} \to \Xi^- + \pi^- + \pi^+ + (K^0 + K^0) \\ \to \Xi^- + \pi^- + K^+ + (K^0 + \ldots) \end{array} \right. \quad (6)$$

$$\pi^- + p \left\} \begin{array}{l} \to \Xi^- + \pi^+ + (K^0 + K^0 + \ldots) \\ \to \Xi^- + K^+ + (K^0 + \ldots) \end{array} \right. \quad (7)$$

Assumed particles are shown in parentheses.

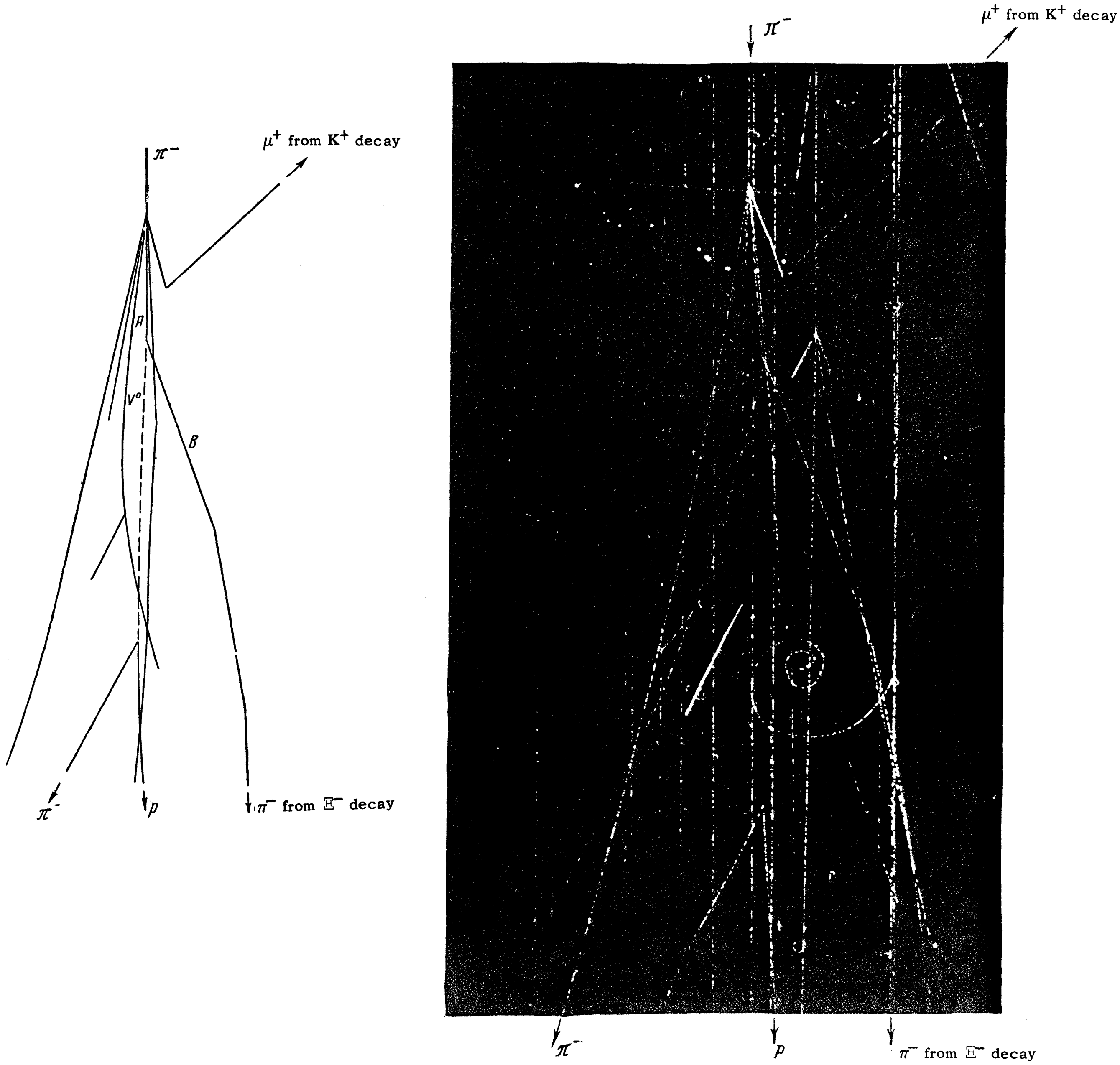

FIG. 2. Event No. 19–179. Decay of a Ξ^- hyperon.

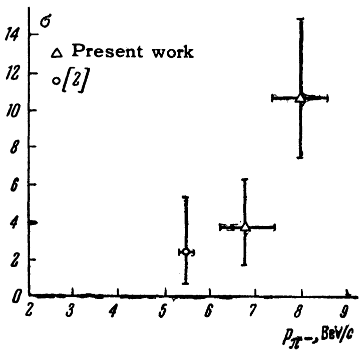

FIG. 3. Dependence of Ξ^--hyperon production cross section on energy of incident π^- mesons.

Assuming a strangeness of $S = -2$ for the Ξ^- particle, we should expect that two K mesons (K^0, K^+) with $S = +1$ are produced along with the cascade hyperon. Only in three cases could K mesons be identified from the kinematics of the decay. In event No. 91-145, four stopping protons were identified; a π^+ meson was well-identified from its momentum and ionization and a K^+ meson, from the kinematics of the decay. The seventh particle, which was positive, could not be a π^+ meson because of its momentum and ionization; this means that it was either a K^+ meson or a proton. In event

Table III.

p_{π}, Bev/c	Event No.	$p^*_{\Xi^-}$ (in π–N c.m.s.), Mev/c	$(p_\perp)_{\Xi^-}$, Mev/c	$\theta^*_{\Xi^-}$ (in π–N c.m.s.), deg	θ^*_{Λ} (in Λ^0 system), deg	θ^*_{p} (in Λ^0 system), deg	$\omega^0_{\Xi\Lambda}$, angle between decay planes of Ξ^- and Λ^0, deg	Direction of flight of proton relative to the Ξ^--decay plane
~7	182—42	558±62	375 ± 48	42 ± 11	71 ± 5	92 ± 5	146 ± 5	down
~8	91—145	414±47	145 ± 26	159 ± 4	122 ± 5	42 ± 5	131 ± 4	up
~8	196—160	1001±99	290 ± 30	162 ± 3	123 ± 5	67 ± 6	52 ± 3	down
~8	19—179	294±41	293 ± 41	94 ± 11	88 ± 10	73 ± 5	161 ± 5	down
~8	171—218	977±107	410 ± 47	155 ± 4	94 ± 5	50 ± 7	87 ± 4	down
~8	6—230				132 ± 8	75 ± 5	100 ± 6	up
~8	370—252				91 ± 10	130 ± 5	23 ± 5	up
~8	114—290	1538±110	273 ± 36	170 ± 3	102 ± 5	105 ± 5	168 ± 6	up
~8	355—298	1070±102	729 ± 92	137 ± 6	73 ± 5	35 ± 10	82 ± 4	down
~8	150—307	140^{+145}_{-64}	71 ± 31	149^{+22}_{-86}	75 ± 15	70 ± 15	88 ± 8	down
~8	186—336	1248±110	273 ± 36	167 ± 4	126 ± 4	102 ± 5	66 ± 4	down
Mean value		804	318 ± 35					

Table IV. "Background" cases (the V^0 particles were identified as Λ particles)

Event No.	Sign of charge	Angle of noncoplanarity η	$\Delta p_\perp$, Mev/c	One of the possible interactions*	Event No.	Sign of charge	Angle of noncoplanarity η	$\Delta p_\perp$, Mev/c	One of the possible interactions*
344—314	+	1′	225	(1)	273—125	+	10°10′	827	(5)
250—35	+	16′	200	(1)	140—45	+	22°42′	244	(3) ***
267—233	+	1°19′	48	(1)	99—68	—	3°36′	86	(2)
150—286	—	22′	126	(2)	179—221	—	4°27′	125	(6) **
502—12	+	2°39′	56	(1)	144—219	—	7°4′	106	(7)
185—91	+	4°56′	58	(3)	152—188	—	16°40′	59	(6) **
52—246	+	4°57′	16	(1)	64—69	—	17°30′	70	(6) **
189—275	+	5°54′	17	(1)	61—174	—	30°		(8)
33—221	+	8°53′	497	(4)	288—193	—	40°	50	(6) **

* $\pi^+ + n \rightarrow \Lambda + K^+$ (1)
$K^- + n \rightarrow \Lambda + \pi^-$ (2)
$\pi^+ + n \rightarrow \Lambda + (K^{\theta}) + \pi^+$ (3)
$\pi^+ + C \rightarrow \Lambda + p + (K^0) + \ldots$ (4)
$\pi^+ + n \rightarrow \Lambda + (+?) + \ldots$ (5)
$\pi^- + n \rightarrow \Lambda + \pi^- + \ldots$ (6)
$K^- + n \rightarrow \Lambda + \pi^- + \ldots$ (7)
$\pi^- + n \rightarrow \Lambda + \pi^- + K^0 + \ldots$ (8)

**Possible K^- + n interaction.

***In this case another reaction with the production of a Λ particle is possible; we have indicated the more probable one.

No. 19-179, under the assumption of a π^-p interaction, the neutral particle could be only a π^0 meson, and then the positive particle, which could not be identified from its momentum and ionization, should be a K^+ meson. Hence there was not a single case of associated production of a Ξ^- hyperon with two well-identified K^+, K^0 mesons, but neither were there any cases which would contradict such a scheme of associated production.

Table III lists the momentum p*, the transverse momentum $p_\perp$, and the angle of flight θ^* of the Ξ^- hyperons in the c.m.s. of the π^- meson and nucleon under the assumption that the Ξ^- particle is produced in a collision of primary π^- mesons with free nucleons.

As seen from Table III, the mean transverse momentum $\overline{p}_\perp$ is equal to 318 ± 35 Mev/c. It is interesting to note that this value of $\overline{p}_\perp$ for the Ξ^- hyperons is close to the value of the transverse momentum for protons and Λ^0 hyperons.[5] Moreover, the Ξ^- hyperons are emitted mainly backwards, similarly to protons and Λ^0 and $\Sigma^\pm$ hyperons in π^-p interactions involving 6.8-Bev/c mesons.[6*]

Table III also lists the following angular characteristics: the angle of flight of the Λ^0 particle in the Ξ^- rest system θ^*_Λ, the angle of flight of

*It should be noted that both Ξ^- hyperons observed in reference 2 are emitted backwards in the c.m.s.

the proton from the Λ^0-particle decay in the Λ^0 rest system θ_p^*, and the angle $\omega_{\Xi\Lambda}$ between the Ξ^-- and Λ^0-particle decay planes. No asymmetry in the θ_Λ^* and $\omega_{\Xi\Lambda}$ distributions was observed.

In the forward-back (θ_p^*) and up-down distributions of the proton decay products from the Λ^0-particle decay, some asymmetry was observed (seven cases forward, three cases backwards, one at an angle of 90°; eight cases down, three cases up). We note that the protons from the Λ^0 decays are directed forward in the Λ^0 rest system.[2] An asymmetry in the angular distributions characterizes the polarization of the Λ^0 particles from the Ξ^--particle decay. Longitudinal polarization of the Λ^0 hyperons from the decay of Ξ^- particles, if it exists, would be evidence of the parity nonconservation in the decay of Ξ^- hyperons.

In order to determine the production cross section for Ξ^- hyperons, we counted the number of π^- mesons in the primary beam and determined the effective length of the chamber for the recording of Ξ^- hyperons; this was equal to 30 ± 5 cm. We then took into account corrections for the following: 1) the μ^--meson contamination (5 ± 2)%; 2) the loss of part of the primary π^- mesons due to interactions in the chamber;* 3) the efficiency of finding Ξ^- hyperons in scanning the photographs (80 — 90%); 4) the geometric conditions for recording the particles (2.0 ± 0.3); and 5) the decay of secondary Λ^0 hyperons into neutral particles. We thus found the mean free path of π^- mesons for the production of Ξ^- hyperons in propane to be $l = (2.02^{+2.86}_{-0.84}) \times 10^6$ cm for 6.8-Bev π^- mesons and $l = (0.68^{+0.29}_{-0.20}) \times 10^6$ cm for π^- mesons at ~ 8 Bev/c. If it is assumed that the production cross section for hyperons on nuclei is proportional to $A^{2/3}$, then for the Ξ^--hyperon production cross section (per nucleon) in propane, we have

$$\sigma = 3.6\,^{+2.5}_{-2.1}\,\mu\text{b at } 6.8 \text{ Bev/c}$$
$$\sigma = 10.6\,^{+4.4}_{-3.2}\,\mu\text{b at } \sim 8 \text{ Bev/c}. \qquad (3)$$

In the work of Fowler et al.[2] the cross section for the production of Ξ^- hyperons (per nucleon) by 5.5-Bev/c π^- mesons was found to be $\sigma = 2.3^{+3.1}_{-1.6}\,\mu$b. Figure 3 shows the variation of the Ξ^- hyperon production cross section as a function of the incident π^- meson energy.† Finally, Table IV lists the "background" cases, among which are four coplanar and 14 noncoplanar cases. The coplanar cases can be explained well by the reactions indicated in Table IV. Since the reaction $\pi^- + n \to \Lambda^0 + K^-$ is forbidden by the law of conservation of strangeness and since there are less K mesons than π^+ mesons, the greater part of the coplanar cases are due to π^+ mesons. The noncoplanar cases can be caused by both π^+ and π^- or K^- mesons. In our case, there were seven interactions caused by π^+ mesons and seven caused by negative particles. Interactions Nos. 150-286, 99-68, and 144-219 could be due only to K^- mesons, since the energy of the π^- meson in these cases was below the threshold for the production of a Λ^0 particle.

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*The interaction mean free path of 6–8 Bev/c π^- mesons in propane is equal to 219 ± 5 cm.

†We recall that the threshold for the production of hyperons by π^- mesons via the reaction $\pi^- + N \to \Xi^- + K + K$ with allowance for the motion of the nucleons in the nucleus is equal to $2.19^{+0.16}_{-0.43}$ Bev.[7]

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