Production of Strange Particles by 1.5-Bev π^- Mesons in C, Fe, and Pb†

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The production of Y^0 (Λ^0,Σ^0), θ^0, Σ^- particles by 1.5-Bev π^- mesons has been observed in a multiplate cloud chamber with one-half inch plates of C, Fe, and Pb. The fraction of the inelastic nuclear interactions which result in strange particle production remains approximately constant from C to Pb, with the following yields: Y^0, 1.7±0.4%; θ^0, 1.4±0.5%; Σ^-, 0.2±0.1%. The production angular and momentum distributions are given, along with the distributions obtained from Monte Carlo calculations which do not include secondary interactions of the strange particles.

The yields of hyperons and θ^0's are close to those expected on the basis of the known cross sections in elementary $\pi-p$ collisions. However, the Σ^-/Y^0 ratio is observed to be much less than expected, indicating at least geometric cross section for $\Sigma^-+p\rightarrow Y^0+n$.

The following lifetimes were obtained: Λ^0, $(2.72_{-0.27}^{+0.29})\times10^{-10}$ sec; θ_1^0, $(1.09_{-0.15}^{+0.18})\times10^{-10}$ sec. No statistically significant Λ^0 decay asymmetries (up-down, forward-backward, decay proton scattering) were found. Four likely and two possible examples of θ_2^0 interactions were observed, in good agreement with the number expected if the interaction cross section were geometric.

EARLY results on the production of strange particles in Cosmotron beams indicated that the cross section in pion beams were considerably higher than those in proton or neutron beams.[1] On the basis of these results, it was suggested that the dependence of the production cross sections on the atomic weight, A, of the target nuclei would be markedly different in pion and proton beams.[2] This work was undertaken to study the A-dependence of strange-particle production by pions and protons, using a multiplate cloud chamber. The results of production by protons, as well as a detailed comparison between the yields from pions and protons, appear in the following paper,[3] hereafter referred to as II. In this paper, the production cross sections and distributions of strange particles produced by π^- in C, Fe, and Pb are discussed. Since most of the strange particles observed in this work were produced in the pion beam, the results obtained concerning their decay lifetimes and asymmetries, and their nuclear interactions, will also be presented in this part.

Just prior to this work, the Columbia cloud-chamber group studied the production of strange particles by 1.9-Bev π^- in C and Pb.[4] The Y^0/θ^0 ratio was found to be appreciably larger in Pb than in C, which was interpreted as evidence of an appreciable number of Σ^-'s converting to Y^0's within the nucleus of production in Σ^--proton interactions. Another result which has subsequently become of greater interest in connection with parity nonconservation was the observation of an apparently significant forward-backward asymmetry in Λ^0 decay.

At the same time that photographs were being taken with the Princeton cloud chamber, the MIT cloud-chamber group was observing the production of strange particles in Fe by 1.2–1.8 Bev π^-. In addition to reporting preliminary production cross sections,[5] Λ^0 and θ^0 lifetimes,[6] evidence for the $2\pi^0$ decay mode of the θ_1^0,[7] and evidence for θ_2^0 interactions,[8] they have found in Λ^0 decay a significant up-down asymmetry for Λ^0's with momenta between 0.7 and 1.0 Bev/c, and an asymmetry in the scattering of the decay protons.[9]

In the following sections our observations of pion-produced strange particles from complex nuclei will be

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[1] W. B. Fowler, R. P. Shutt, A. M. Thorndike, and W. L. Whittemore, Phys. Rev. **91**, 1287 (1953); **93**, 861 (1954); **98**, 121 (1955); M. M. Block, E. M. Harth, W. B. Fowler, R. P. Shutt, A. M. Thorndike, and W. L. Whittemore, Phys. Rev. **99**, 261 (1955); R. M. Walker, R. S. Preston, E. C. Fowler, and H. L. Kraybill, Phys. Rev. **97**, 1086 (1955); E. R. Mosburg, E. C. Fowler, and H. L. Kraybill, Phys. Rev. **108**, 865 (1957).

[2] G. T. Reynolds, *Proceedings of the Fourth Annual Rochester Conference on High-Energy Physics* (University of Rochester Press, Rochester, 1954); R. Jastrow, Phys. Rev. **97**, 181 (1955).

[3] T. Bowen, J. Hardy, G. T. Reynolds, G. Tagliaferri, and A. E. Werbrouck, following paper [Phys. Rev. **119**, 2041 (1960)]. (Hereafter referred to as II.)

[4] H. Blumenfeld, W. Chinowsky, and L. M. Lederman, Nuovo cimento **8**, 296 (1958).

[5] E. Boldt, H. S. Bridge, D. O. Caldwell, and Y. Pal, International Conference on Mesons and Recently Discovered Particles, Padua-Venice, 1957, I–74.

[6] E. Boldt, D. O. Caldwell, and Y. Pal, Phys. Rev. Letters **1**, 148 (1958).

[7] E. Boldt, H. S. Bridge, D. O. Caldwell, and Y. Pal, Phys. Rev. **112**, 1746 (1958).

[8] E. Boldt, D. O. Caldwell, and Y. Pal, Phys. Rev. Letters **1**, 150 (1958).

[9] E. Boldt, H. S. Bridge, D. O. Caldwell, and Y. Pal, Phys. Rev. Letters **1**, 256 (1958); E. Boldt, thesis, Massachusetts Institute of Technology, 1958 (unpublished).

interpreted in the light of the information now available from elementary π-p collisions.[10]

A. EXPERIMENTAL ARRANGEMENT

The π^- beam had an energy well above the threshold for strange-particle production, and the center-of-mass kinetic energy of a pion-nucleon collision was comparable to that of 3-Bev proton-nucleon collisions. The beam arrangement is shown in Fig. 1. The pion beam originated in an Al target inside the Cosmotron vacuum chamber, was collimated by a channel in the Cosmotron shield wall and deflected 10° by a 36-inch analyzing magnet. The pion energy spectrum at the chamber is shown by the smooth curve in Fig. 2, calculated for the known geometry and magnetic fields of the Cosmotron and bending magnets. Since a considerable range of particle momenta could pass through the beam-defining system, it was necessary to also have some knowledge of the pion momentum spectrum at the target. This was calculated from the isobar model of pion production in proton-nucleon collisions,[11] which agrees well with measurements available at lower momenta. From this spectrum, the median pion energy is 1.5 Bev, and the beam width is of the order of ± 0.2 Bev. As a rough check, the histogram in Fig. 2 shows the distribution from associated hyperon-K meson productions of the total visible energy. Since some energy disappears from view via low-energy charged secondaries and neutral secondaries, the agreement seems satisfactory. At the cloud chamber, the muon contamination was computed to be 20%. This was independently checked by the distribution among the plates of nuclear interactions.[12]

The multiplate cloud chamber was conventional in design and operation, filled with argon and water-alcohol vapor.[13] The fiducial volume of the chamber, in which all interaction and decay points used in the analysis were located, was 24 cm deep, 63 cm wide, and an average of 71 cm in the beam direction. Tracks were clearly visible for at least 2.5 cm outside all sides of this fiducial volume. All plates were 0.5-inch thick, with 0.020-inch Al reflectors on each surface. The various arrangements of C, Fe, and Pb plates used are listed chronologically in Table I. The 11-plate assembly was found by experience to represent the closest plate spacing which is satisfactory in this type of work. There was no magnetic field.

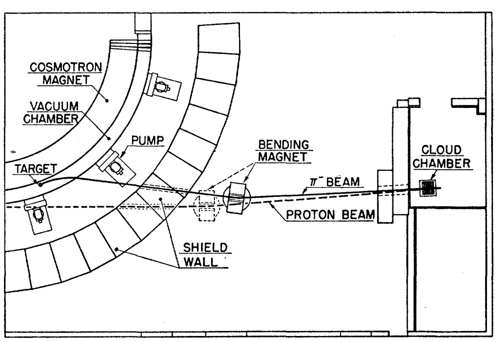

FIG. 1. Plan view of the arrangement in the 1.5-Bev π^- meson beam. The dotted lines show the arrangement in the 2.8-Bev proton beam.

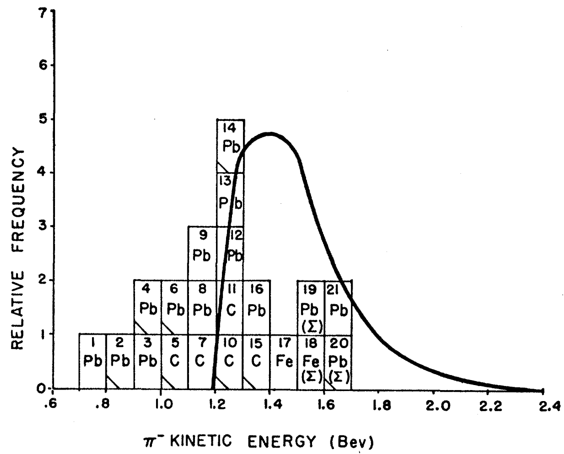

FIG. 2. Calculated energy spectrum of π^- mesons entering the cloud chamber (smooth curve). The histogram shows the distribution of visible energies of 18 associated $Y^0-\theta^0$ events and 3 $\Sigma^- - \theta^0$ events. The production nucleus is indicated in the rectangle for each event. Rectangles with a diagonal bar indicate events with additional charged secondaries.

Expansion took place before arrival of the beam, resulting in sharp, post-expansion tracks. Each expansion was photographed on 70-mm film by two cameras 386 cm from the center of the chamber and separated by 74 cm. Approximately 7000 acceptable two-view photographs were obtained in the pion beam, with an average of 16 tracks, each.

B. METHOD OF ANALYSIS

In a multiplate cloud chamber at Cosmotron energies, only the following decays are observed with high efficiency:

$$\Lambda^0 \rightarrow p + \pi^-, \quad (1)$$

$$\theta_1{}^0 \rightarrow \pi^+ + \pi^-, \quad (2)$$

$$\Sigma_\pi{}^\pm \rightarrow \pi^\pm + n. \quad (3)$$

The Λ^0 decays result both from Λ^0's and Σ^0's emerging from the production nuclei. Since the proton decay mode of a Σ^+ is generally indistinguishable from a π-μ decay, we count only events with a pion decay mode [Eq. (3)]. Few $K^\pm$'s and $\theta_2{}^0$'s decay or stop in the cham-

[10] *Proceedings of 1958 Annual International Conference on High-Energy Physics at CERN*, edited by B. Ferretti (CERN Scientific Information Service, Geneva, 1958), p. 147.

[11] S. J. Lindenbaum and R. M. Sternheimer, Phys. Rev. **105**, 1874 (1957).

[12] T. Bowen, G. Tagliaferri, M. Di Corato, and W. H. Moore, Nuovo cimento **9**, 908 (1958).

[13] For further details, see J. Hardy, Technical Report No. 19, 1958 (unpublished), and A. E. Werbrouck, Technical Report No. 22, Elementary Particles Laboratory, Princeton University, 1959 (unpublished).

TABLE I. Cloud-chamber plate assemblies.

No. of plates	Material[a]	Effective thickness (g/cm²)	Average fiducial gap (cm) Original	Modified[b]
15	15 Fe	95	2.1	0 (Lifetimes) 2.1 (Cross sections)
7	7 Pb	82	6.7	4.8
8	3 C-Pb-C-Pb-C-Pb	C:11 Pb:36	6.7	4.8
11	4 C-Pb-C-Pb-C-Pb-C-Pb	C:15 Pb:44	3.8	1.9

[a] Order of plates in beam direction.
[b] All results are based upon the events found in the modified fiducial volumes.

ber. All of the above decays appear as V-type events in the gas of the cloud chamber.

Scanners looked for all V-type events and counted beam tracks in each picture. Track counts were accurate to 5%. Over-all scanning efficiency, found by comparison of scan and rescan records, was 0.75 on the first scan and 0.90 on the rescan. No significant differences in scanning efficiency were found for the various plate assemblies, except in the case of Fe, where it was lower. The efficiency was essentially the same for Λ^0 and θ_1^0, but lower for $\Sigma_\pi^\pm$. The latter effect was attributed largely to the difficulty of finding small angle $V^\pm$ decays, which are events in which the decay pion is emitted forward in the c.m. system. In 26 events the decay pion was emitted backwards in the c.m. system, but in only 12 events was the pion emitted forward. Since equal numbers are expected forward and backward,[14] the reduction in scanning efficiency is estimated to be 0.73±0.08. Pictures of poor quality or with 40 or more beam tracks were not used for cross-section determinations. In the pictures taken with the Fe plates in the pion beam, only pictures with 30 or less beam tracks were accepted.

Geometrical analysis was done analytically on the Remington Rand 409-2R punched card digital computer at Brookhaven.[13] To obtain the best values of angles and their errors, which are used in identifying neutral strange particles, a least squares and error analysis was applied to each event by the computer. In the least squares analysis, an origin point and three measured points in the decay plane were fitted to a best-fit plane. Because of the small stereo angle, the component of the measurement error along the lens axis (z-direction) was the most serious one. The error analysis was carried out by introducing a known error into each z-coordinate measurement, one at a time, and then recomputing the final angles. Occasionally, several origins appeared possible for one V^0. The proper one could be selected by consideration of the residual sum of squares in the least squares analysis and by the closeness of the fit to an interpretation as a Λ^0 or θ_1^0.

[14] L. W. Alvarez, H. Bradner, P. Falk-Vairant, J. D. Gow, A. H. Rosenfeld, F. T. Solmitz, and R. D. Tripp, Nuovo cimento **5**, 1026 (1957); F. Eisler *et al.*, International Conference on Mesons and Recently Discovered Particles, Padua-Venice, 1957, I–3.

Identification of the unstable particles seen to decay depended upon measurements of angles, ranges, ionizations, and path lengths. Usually, the most reliable information was the laboratory decay angles. In many cases, very little information was gained from ranges because of particles leaving the chamber or stopping in the first plate entered. Ionization estimates were made by visually comparing tracks with nearby minimum-ionizing tracks.

Identification of the V^0's was accomplished by plotting the laboratory V^0 opening angle versus one of the interior angles with the line of flight. The loci of constant laboratory momentum for the decay secondaries appropriate to Λ^0 or θ_1^0 decay[15] marked permanently on the respective graphs allowed momentum estimates from range and ionization to be plotted. For most events, the available information will define an allowed region on only one plot, resulting in a definite identification as Λ^0 or θ_1^0. When the momentum of a Λ^0 or θ_1^0 is greater than about 1.0 Bev/c, a fit is often possible on both plots. If the fit of one interpretation is significantly poorer than the other, the identity of the associated strange particle is known, or $|\cos\theta^*|>0.9$ (θ^* is the c.m. angle between the V^0 line of flight and a decay pion), the event is given a probable identity, and remaining completely ambiguous cases are called V^0's. In calculating cross sections, one half the weight of V^0 events has been assigned to Λ^0 and θ_1^0 categories, each, and the error estimates have been increased by the same amount.

A charged V has considered a candidate for further analysis if the transverse momentum of the decay secondary (considered as a muon) was greater than is possible in π-μ decay. For these, the available information was plotted on a kinematics graph in which the laboratory decay pion momentum is shown as a function of laboratory decay angle, with the $\Sigma_\pi^\pm$ primary momentum as a parameter. Most of the events which were thus found to be consistent with $\Sigma_\pi^\pm$ decay [Eq. (3)] would also be consistent with the kinematics of $K_{\pi2}$ or $K_{\mu2}$ decay. The estimate of time of flight before decay served to separate statistically between $\Sigma^\pm$ and

[15] L. B. Leipuner, Brookhaven National Laboratory Report BNL-513, 1958 (unpublished).

$K^\pm$ decays, and all events which lived less than 5×10^{-10} second in their c.m. system were identified as probable $\Sigma_\pi{}^\pm$'s.

After the identity, momentum, origin, and direction of each observed Λ^0, $\theta_1{}^0$ or $\Sigma_\pi{}^\pm$ had been determined, the probability, ϕ_d, of decaying in the observable region of the cloud chamber with the appropriate plate assembly was evaluated.[16] The over-all observation probability, ϕ, was taken to be the product of three factors:

$$\phi=\phi_c\phi_d\phi_s, \tag{4}$$

where ϕ_c is the probability of decay into a charged pion decay mode,[17] and ϕ_s is the scanning efficiency. Each event is then assigned a weight, W, which is

$$W=1/\phi=1/\phi_c\phi_d\phi_s. \tag{5}$$

These weights are then summed to compute cross sections or plot histograms. The weight, W_N, of N events would be

$$W_N=\sum_1{}^N W_i\pm(\sum_1{}^N W_i{}^2)^{\frac{1}{2}}. \tag{6}$$

For $\Sigma_\pi{}^\pm$ events, there may be ambiguity in assigning a weight because, having no magnetic field, the charge is unknown. In the case of production by a π^-, the event is assumed to be a Σ^-, since a Σ^+ could only be produced by a cascade of two interactions, and only one-half of any such Σ^+'s would be $\Sigma_\pi{}^+$'s. When the $\Sigma_\pi{}^\pm$ was produced by a proton (see II), the weight was computed separately assuming it to be a Σ^- or a Σ^+ and averaged, increasing the quoted error appropriately to account for the additional uncertainty.

It is evident from Eq. (6) that, if, in a small sample of events, a few have very high weights, the statistical uncertainty in the result for W_N is very large. In this experiment, strange particles emitted with low momenta or angles close to 90° would rarely escape from the plate of production. If a few happened to be observed, they would be assigned high weights and error estimates from Eq. (6) would be greatly increased. The results can be made statistically more certain by considering a group of events satisfying an additional condition, such that high weights cannot be present. The probability of escape from the plate will depend upon the decay length, λ, in the beam direction, which is given by:

$$\lambda=\tau P\cos\theta/M, \tag{7}$$

where τ is the mean life, P the laboratory momentum, θ the laboratory production angle, and M the mass of the particle. For the one-half inch plate thickness of this experiment, all events with $|\lambda|\geq1$ cm have weights within a range of a factor of two. In many cases, the results based upon this group will be presented in addition to those based upon all the events. For $|\lambda|<1$ cm, the probability of observation rapidly decreases, resulting in very high weights for the occasional events in this interval.

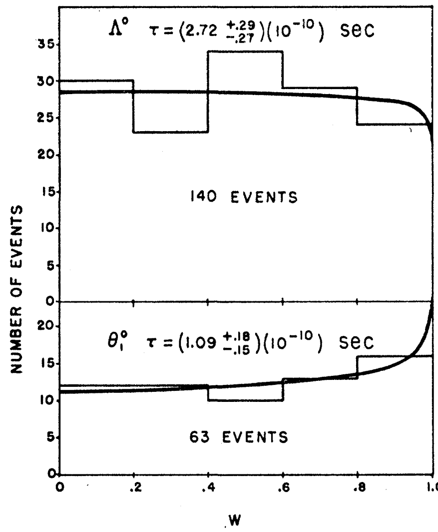

FIG. 3. The histograms show the observed distribution of w (defined in the text) for 140 Λ^0 decays (top) and 63 $\theta_1{}^0$ decays (bottom). The smooth curves were calculated for the lifetimes given, and represent the best fits to the data. The distributions of w would be uniform if the true lifetimes were those in reference 16.

C. Λ^0 AND $\theta_1{}^0$ LIFETIMES

The procedure for obtaining Λ^0 and $\theta_1{}^0$ mean lifetimes from the events of this experiment is an indirect one, and assumes that the lifetimes are already approximately known. For each event, on the basis of this assumed lifetime, the probability, ϕ_d, that such a V^0 decay within the observable region of the chamber is calculated. In addition, the probability, ϕ_v, that it decay in the observable region before its actual decay point is calculated. The ratio:

$$w\equiv\phi_v/\phi_d \tag{8}$$

is the probability that the V^0 decay in the observable region before its actual decay point, given that it is observed. Provided that we have assumed the correct value for the mean life, τ, and we have found the events in an unbiased manner, there should be equal numbers of events in equal intervals of w. If the actual lifetime differs from the assumed lifetime, the distribution of w will no longer be uniform, and it is possible to calculate the expected shape.

To apply the above procedures, the V^0 entrance boundary planes of the observable volume were chosen to be 0.60 cm from the surface of each plate, and the exit boundary of each observable region was placed 2.50 cm from the plate surface because of decreased scanning efficiency for decay near a plate. This eliminated all the events produced in the Fe assembly from the lifetime determination. The effects of uncertainty

[16] The following decay lifetimes were assumed (in units of 10^{-10} second): Λ^0, 2.77; $\theta_1{}^0$, 0.95; Σ^-, 1.7; Σ^+, 0.75.

[17] F. S. Crawford, M. Cresti, R. L. Douglass, M. L. Good, G. R. Kalbfleisch, M. L. Stevenson, and H. Ticho, Phys. Rev. Letters, 2, 266 (1959).

TABLE II. Up-down decay asymmetry of Λ^0's with $0.7 \leq P \leq 1.0$ Bev/c.

Production nucleus	Up	Down	Total	$\alpha \bar{P}_\perp$
C	6	7	13	$+0.02\pm0.48$
Fe	3	3	6	$+0.03\pm0.71$
Pb	15	9	24	$+0.27\pm0.35$
Fe(MiT)[a]	32	21	53	$+0.42\pm0.24$

[a] See reference 9.

in the momenta of Λ^0's and θ_1^0's were found to contribute negligibly compared to purely statistical uncertainties.

The distributions of w for 140 Λ^0 events and 63 θ_1^0 events are shown in Fig. 3. The smooth curves show the theoretical distributions which give best fits to the observed distributions. We find for the Λ^0 mean life, $(2.72_{-0.27}^{+0.29})\times10^{-10}$ sec, and for the θ_1^0, $(1.09_{-0.15}^{+0.18})\times10^{-10}$ sec. These values are in good agreement with those originally assumed,[16] and with the best values currently reported.[18]

D. Λ^0-DECAY ASYMMETRIES

An "up-down" asymmetry in Λ^0 decay has been observed with Λ^0's produced in elementary π^--p collisions.[19] In an earlier publication,[20] we reported no significant up-down asymmetries in the Λ^0's observed from C, Fe, and Pb. Since then, the behavior of the Λ^0 polarization in π^--p collisions has been studied in greater detail[10] as a function of the c.m. production angle. The MIT cloud chamber results in Fe also showed no significant polarization when including all Λ^0's.[9] However, when only those Λ^0's with laboratory momenta between 0.7 and 1.0 Bev/c were examined, a significant asymmetry was found in the expected direction.

The observed up-down asymmetry of our Λ^0's in the 0.7–1.0 Bev/c momentum range are given in Table II, in terms of the pseudoscalar:

$$\cos\theta = \frac{\mathbf{P}_\pi^* \cdot (\mathbf{P}_i \times \mathbf{P}_\Lambda)}{|\mathbf{P}_\pi^*|\,|\mathbf{P}_i \times \mathbf{P}_\Lambda|} \tag{9}$$

where $\mathbf{P}_i$, $\mathbf{P}_\Lambda$, and $\mathbf{P}_\pi^*$ are the momenta of the incident pion in the laboratory, the Λ^0 in the laboratory, and the decay pion in the Λ^0 c.m. system, respectively. In Table II, the number of events "up" ($\cos\theta$ positive) and "down" are given. The listed values of $\alpha\bar{P}_\perp$, where α is the decay asymmetry parameter[21] and $\bar{P}_\perp$, the Λ^0 polarization along the axis $\mathbf{P}_\Lambda \times \mathbf{P}_i$, which would give the observed asymmetry are found from the equation:

$$\alpha\bar{P}_\perp = \frac{3}{N}\sum_i^N \cos\theta_i \pm \left(\frac{3}{N}\right)^{\frac{1}{2}}. \tag{10}$$

The number of events from C and Fe are too few to allow conclusions to be drawn. The asymmetry observed from Pb is in the expected direction, and is consistent with the MIT result, but the possibility of a significantly smaller polarization of the Λ^0's from Pb than from Fe cannot be excluded. The fact that the remainder of the Λ^0's (nearly all at lower momenta) show no polarization, seems to support the view that Λ^0's are depolarized by the subsequent collisions within the production nucleus.

The possibility of parity nonconservation in strong interactions involving strange particles has been investigated by several authors.[22,23] Experimentally, any component of polarization parallel to the direction of motion would be indicative of parity nonconservation. Tendencies for protons to be emitted backward in the Λ^0 rest system have been observed by others.[24]

The forward-backward asymmetry is treated in a manner exactly analogous to the up-down asymmetry of the preceding paragraphs. Any component of polarization, $\bar{P}_{\parallel}$, along the direction of motion of the Λ^0 would be revealed by the distribution of $\cos\theta^*$, where θ^* is the angle between the decay pion and the Λ^0 line of flight in the Λ^0 c.m. system. Table III lists the results.

The original method of analysis, utilizing ionization, ranges, and angles, was modified to reduce the dependence on ionization estimates by finding $\cos\theta^*$ on the basis of angles and ranges only. While the modified method affected negligibly the Λ^0 momentum distribution, it should have significantly reduced the possible systematic error in $\cos\theta^*$. To further reduce biases, the modified analysis was applied only to those events observed in plate assemblies with plate separations >7.8

TABLE III. Forward-backward decay asymmetry of Λ^0's.

Group	Production nucleus	Forward	Backward	Total	$\alpha\bar{P}_{\parallel}$
All momenta	C	8	6	14	-0.14 ± 0.46
	Pb	33	40	73	$+0.06\pm0.20$
	All	41	46	87	$+0.03\pm0.19$
$P \leq 0.5$ Bev/c	C	1	2	3	
	Pb	22	22	44	$+0.16\pm0.26$
	All	23	24	47	$+0.13\pm0.25$

[18] *Proceedings of 1958 Annual Conference on High-Energy Physics at CERN*, edited by B. Ferretti (CERN Scientific Information Service, Geneva, 1958), p. 270.

[19] F. S. Crawford, M. Cresti, M. L. Good, K. Gottstein, E. M. Lyman, F. T. Solmitz, M. L. Stevenson, and H. Ticho, Phys. Rev. **108**, 1102 (1957); F. Eisler *et al.*, Phys. Rev. **108**, 1353 (1957).

[20] T. Bowen, J. Hardy, G. T. Reynolds, G. Tagliaferri, A. E. Werbrouck, and W. H. Moore, Phys. Rev. Letters **1**, 11 (1958).

[21] T. D. Lee and C. N. Yang, Phys. Rev. **108**, 1645 (1957).

[22] G. Geinberg, Phys. Rev. **108**, 878 (1957); V. G. Soloviev, Nuclear Phys. **6**, 618 (1958); S. D. Drell, S. C. Frautschi, and A. M. Lockett, Technical Report No. 30, Physics Department, Stanford University, June, 1958 (unpublished); A. Pais, Phys. Rev. Letters **1**, 418 (1958).

[23] F. S. Crawford, M. Cresti, M. L. Good, F. T. Solmitz, and M. L. Stevenson, Phys. Rev. Letters **1**, 209 (1958); **2**, 11 (1959).

[24] Reference 4 and the references cited therein; D. F. Hotz, University of California Radiation Laboratory Report UCRL-8715, 1959 (unpublished).

TABLE IV. Numbers of strange particles observed from 1.5-Bev π^- interactions.

Material		C			Fe[a]			Pb		
Number of nuclear interactions[b]		9060			5580			25 500		
Particle		Λ^0	θ_1^0	Σ^-	Λ^0	θ_1^0	Σ^-	Λ^0	θ_1^0	Σ^-
Weighted numbers of	Definite	141 (32)	50 (14)		59 (14)	39 (10)		334 (92)	153 (33)	
strange particles (actual	Probable	12 (3)	7 (2)	16 (6)	5 (1)		23 (5)	36 (9)	15 (5)	34 (13)
numbers in parentheses)	Ambiguous	11 (3)						23 (6)		
Strange particles per 1000	All events	17.5±3.5	6.9±2.2	1.8±0.7	11.4±3.0	6.9±2.2	4.2±1.9	15.9±2.1	7.0±1.7	1.3±0.4
Nuclear interactions	Events with $\lvert\lambda\rvert \geq 1$ cm	17.0±3.5	6.9±2.2	1.8±0.7	11.4±3.0	6.9±2.2	4.2±1.9	15.0±2.0	5.4±1.4	1.3±0.4

[a] Due to the closer place spacing, results for strange particles from Fe are lower limits only.
[b] Calculated from track counts, fraction of π's in the beam, and total cross sections.

cm. The Λ^0's with momenta less than 500 Mev/c were considered separately because parity nonconservation was suspected[22,25] in the reaction

$$\Sigma + N \rightarrow \Lambda^0 + N, \tag{11}$$

which would yield low-momentum Λ^0's. As indicated in Sec. F, we believe that many of the Λ^0's emitted from complex nuclei result from reaction (11). The Λ^0's produced by 1.5-Bev π^- in this experiment were consistent with no polarization along the direction of Λ^0 motion in the laboratory.

Efforts to determine the helicity of the proton emitted in Λ^0 decay from proton polarization[9] led to the consideration of 117 decay protons that penetrated one or more plates. After applying selection criteria which eliminated most questionable scatters, 21 scatters remained for further analysis.[26] However, a statistical analysis of the information available from these scatters revealed that we should only have a 54% chance of deducing the correct sign of the proton helicity in Λ^0 decay.

E. STRANGE PARTICLE PRODUCTION

The observed yields of strange particles which could be detected with high efficiency are listed in Table IV for C, Fe, and Pb. The number of nuclear interactions of pions in each material was calculated from the track counts, fraction of pions in the beam, thickness and position of the plates, and total absorption and attenuation cross sections found from a portion of the photographs.[12] The weighted number of events in each identity category, as described in Sec. B, is given, with the actually observed number of events in parentheses. For Λ^0 and θ_1^0, it is seen that the number of events with a probable identity is only about 9% of the total, and the number which are ambiguous is about 4%. Hence, the results are not sensitive to uncertainties in identification.

The fractions of nuclear interactions leading to strange particle production are given in Table IV in terms of Λ^0's, θ_1^0's, and Σ^-'s per 1000 nuclear interactions. These yields remain almost constant from C to Pb as expected for a neutron to proton ratio ≈ 1, and if the particles observed are determined by the first inelastic collision in the nucleus. The yields are also given for those events for which the mean longitudinal decay length satisfies the condition: $|\lambda| \geq 1$ cm, which does not greatly affect the yield (see II, Sec. C for further discussion). The yields from Fe are regarded as lower limits because the plates of the Fe assembly were closely spaced, causing excessive scanning inefficiencies. In the case of the C and Pb plates, it was possible to choose the boundaries of the fiducial volume at greater distances from the plates. In addition, the comparison

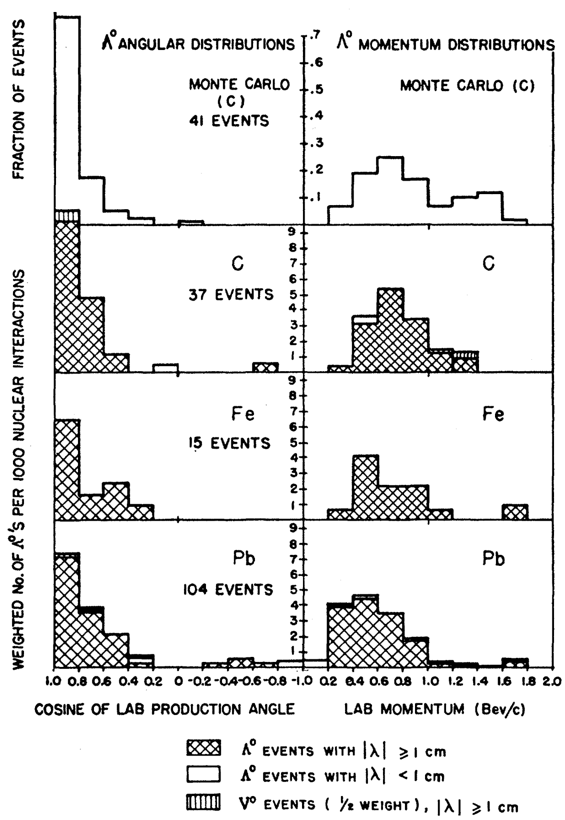

FIG. 4. Λ^0 distributions observed from 1.5-Bev π^- interactions. At the top, the calculated production distributions, neglecting subsequent interactions of hyperons, are shown for C. The observed distributions appear below for production in C, Fe, and Pb.

[25] M. Schwartz (private communication).
[26] For further details see T. Bowen, C. R. Sun and A. E. Werbrouck, Technical Report No. 21, Elementary Particles Laboratory, Princeton University, 1958 (unpublished).

TABLE V. Strange particle production cross sections by 1.5-Bev π^-. (All figures are mb.)

Material	C			Fe[a]			Pb		
Nuclear absorption cross section[b]	240±14			705±37			1600±95		
Particle	Y^0	θ^0	Σ^-	Y^0	θ^0	Σ^-	Y^0	θ^0	Σ^-
All events	4.2±0.8	3.3±1.1	0.43±0.19	8.1±2.1	9.8±3.2	3.0±1.4	23.6± 3.1	22.5± 5.4	2.1±0.6
Events with $\|\lambda\|\geq 1$ cm	4.1±0.8	3.3±1.1	0.43±0.19	8.1±2.1	9.8±3.2	3.0±1.4	22.2± 3.0	17.4± 4.4	2.1±0.6
Other experiments									
Columbia[c]	3.2±1.3	4.8±2.1	0.45±0.24				48.8±19.5	23.4±10.5	3.5±1.8
M.I.T.[d]				20.5±2.9	20.9±4.1	2.1±0.7			

[a] Due to the closer place spacing, our results for strange particles from Fe are lower limits only.
[b] See reference 12.
[c] 1.9-Bev π^- beam in a cloud chamber with 0.5-inch C and 0.25-inch Pb plates, reference 4. The figures in this table are our estimates from the published information. The errors include a ±40% uncertainty in estimating the conversion factor for absolute cross sections.
[d] 1.2–1.8 Bev π^- beam in a cloud chamber with 0.5-inch Fe plates, reference 5.

between C and Pb is made more dependable because most of the events were found using plate assemblies in which the C and Pb were intermixed.

In Table V total production cross sections are compared with the total pion nuclear absorption cross sections.[12] Since we cannot distinguish directly produced Λ^0's from those resulting from the production and decay of Σ^0's, we shall use the symbol Y^0 for both. Fortunately, the laboratory momentum of the decay Λ^0 is only slightly different from that of the original Σ^0.

For comparison, the Columbia[4] and MIT[5] results at

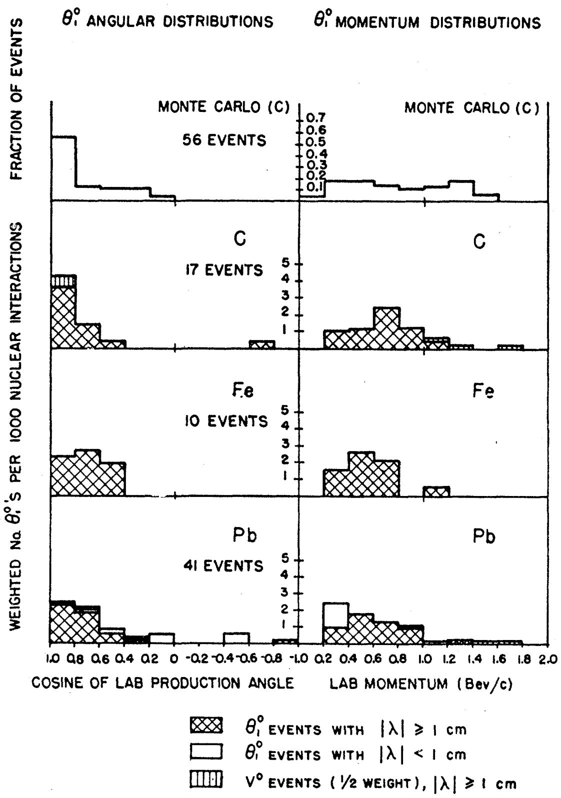

FIG. 5. θ_1^0 distributions observed from 1.5-Bev π^- interactions. At the top, the calculated production distributions, neglecting subsequent interactions of K mesons, are shown for C. The observed distributions appear below for production in C, Fe, and Pb.

slightly higher pion energies are given. There is an estimated ±40% absolute calibration error for the Columbia data, so the errors of each entry cannot be regarded as completely independent. The Y^0/θ^0 production ratio differs considerably from Y^0/θ^0 found by the Columbia group, perhaps because of production of strange particles by secondary π^0 and $\pi^\pm$ mesons at 1.9 Bev.

The angular and momentum distribution of Λ^0's observed from C, Fe, and Pb are shown in Fig. 4. There is a trend from C to Pb toward a wider angular distribution and a momentum distribution peaked at a lower momentum. Monte Carlo calculations were carried out, following 100 collisions through each element, using diffusion chamber data on elastic[27] and inelastic[28] π^--p collisions, bubble chamber strange particle production cross sections and angular distributions,[10] and Fermi motion. An electronic computer program has since been completed[29] which carries out a similar procedure. Since subsequent interactions of the strange particles are not taken into account, a comparison of the results with the observed distributions provides a means of investigating their secondary interactions. At the top of Fig. 4, the Monte Carlo results for 100 collisions in C are plotted. The corresponding distributions for Fe and Pb show only a slight widening of the angular distribution and a small enhancement of the lower peak in the momentum distribution; hence, only the distributions for C are shown. Progressive changes in the distributions probably result from the effects of subsequent interactions of hyperons before escaping from the nucleus, these effects being most strongly felt in the large Pb nucleus where the hyperons must traverse more nuclear matter before escaping.

The θ_1^0 angular and momentum distributions are shown in Fig. 5 for C, Fe, and Pb, along with the dis-

[27] M. Chretien, J. Leitner, N. P. Samios, M. Schwartz, and J. Steinberger, Phys. Rev. **108**, 383 (1957); R. C. Whitten and M. M. Block Phys. Rev. **111**, 1676 (1958).
[28] L. M. Eisberg, W. B. Fowler, R. M. Lea, W. D. Shephard, R. P. Shutt, A. M. Thorndike, and W. L. Whittemore, Phys. Rev. **97**, 797 (1955); G. D. Gordon, R. H. Milburn, J. C. Street, and L. A. Young, Phys. Rev. **108**, 1315 (1957).
[29] L. Sartori, A. E. Werbrouck, J. K. Wooten, and R. L. Bivens, Bull. Am. Phys. Soc. **4**, 289 (1959).

TABLE VI. Calculated and observed yields of strange particles. All figures are numbers of strange particles per 1000 nuclear interactions.

	C			Fe			Pb		
	Calculated			Calculated			Calculated		
Particle	One-dimensional	Monte Carlo	Observed	One-dimensional	Monte Carlo	Observed	One-dimensional	Monte Carlo	Observed
Σ^-	5.8	6.5	1.8±0.7	6.3	7.6	4.2±1.9	6.7	8.1	1.3±0.4
Y^0	7.3	8.7	17.5±3.5	7.5	9.7	11.4±3.0	6.8	9.8	15.9±2.1
$Y^0+\Sigma^-$	13.1	15.2	19.3±3.5	13.8	17.3	15.6±3.5	13.5	17.9	17.2±2.1
θ^0	10.1	11.8	13.8±4.4	10.6	13.6	13.8±4.4	10.6	13.6	14.0±3.4

tribution obtained from the Monte Carlo calculation for C, which remains almost unchanged for Fe and Pb. It is seen that the angular distributions widen and the momentum distributions shift downward as the size of the production nucleus is increased.

The angular and momentum distributions of the observed Σ^-'s are shown in Fig. 6. The momentum determinations for the Σ^-'s were very crude, since they depend mainly upon ionization estimates. The discussion of the next section will show that very few of the Σ^-'s presumably produced in elementary pion-nucleon collisions are actually observed. However, the distributions in Fig. 6 seem to indicate that the few which are observed have escaped without appreciable change in direction or momentum loss, even when produced in Pb.

F. STRANGE PARTICLE INTERACTIONS

Σ^- Interactions

The most striking difference between observation and expectation in this experiment was in the Σ^-/Y^0 ratios. The first comparison is with a one-dimensional model, which is useful because analytic solutions can easily be obtained, even when a succession of two or three reactions is involved. Pion-nucleon elastic and charge exchange scattering is neglected; the π-nucleon inelastic cross section is 23 mb; the nuclear density is uniform with nuclear radius, R, given by:

$$R=1.06A^{\frac{1}{3}}+1.11 \text{ fermi}; \qquad (12)$$

all strange particles emerge; and only in the first inelastic π-nucleon interaction are strange particles produced. The constants of Eq. (12) were chosen to fit the total cross sections determined from our data[12] and with the total π-nucleon cross section equal to 33 mb.[30] The one dimensional model seems reasonable geometrically because most of the hyperons are emitted at small forward angles. The following [Eqs. (13)–(16)] production processes and trial cross sections are assumed:

$$\pi^-+p\to\Lambda^0+\theta^0: \quad 0.24 \text{ mb}, \qquad (13)$$

$$\Sigma^0+\theta^0: \quad 0.18 \text{ mb}, \qquad (14)$$

$$\Sigma^-+K^+: \quad 0.18 \text{ mb}, \qquad (15)$$

$$\pi^-+n\to\Sigma^-+\theta^0: \quad 0.15 \text{ mb}. \qquad (16)$$

[30] R. Cool, O. Piccioni, and D. Clark, Phys. Rev. **103**, 1082 (1956).

The cross section assumed for reaction 16 is taken as that observed by the Michigan group.[31]

The second comparison is with a Monte Carlo calculation[29] assuming constant nuclear density and a Fermi gas, which follows all pion-nucleon interactions in three dimensions until all the pions have been degraded below the strange particle production threshold utilizing empirical cross sections. Likewise, this calculation does not follow the strange particles after production.

Table VI presents the comparisons between the observations, the one-dimensional model and the Monte Carlo calculations.

The one-dimensional model results are slightly low, perhaps because of choosing trial cross sections subsequently seen to be low and neglecting strange-particle

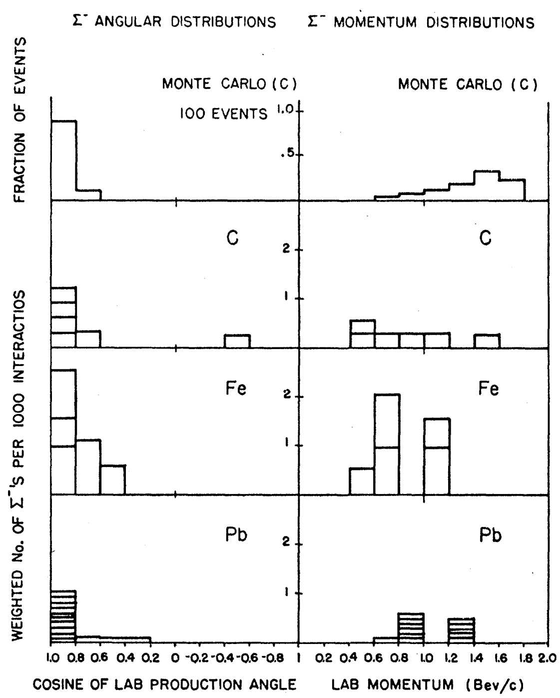

FIG. 6. Σ^- distributions observed from 1.5-Bev π^- interactions. At the top, the calculated production distributions, neglecting subsequent interactions of hyperons, are shown for C. The observed distributions appear below for production in C, Fe, and Pb. Each rectangle represents one event.

[31] J. L. Brown, D. A. Glaser, D. I. Meyer, M. L. Perl, J. Vander Velde, and J. W. Cronin, Phys. Rev. **107**, 906 (1957).

TABLE VII. Calculated and observed Σ^-/Y^0 ratios.

Source	C	Fe	Pb
Calculated			
One-dimensional	0.79	0.84	0.98
Monte Carlo	0.76	0.79	0.82
Observed			
Princeton	0.10±0.04	0.27±0.14	0.08±0.03
Columbia[a]	0.14±0.06		0.08±0.03
M.I.T.[b]		0.10±0.04	

[a] See reference 4.
[b] See reference 5.

production by pions emitted from π-nucleon inelastic collisions. The Monte Carlo calculation indicates that both of these effects are comparable. Using observed production of θ^0 and $Y^0+\Sigma^-$ to carry out a least squares determination of the parameter which must multiply the Monte Carlo results to fit the experimental data, we find 1.15±0.1. The sum of the trial π^-+p cross sections is 0.60 mb. Multiplying by the scale factor yields 0.69±0.06 mb as our best estimate of the total π^--p strange-particle production cross section. This is to be compared with the results of the Columbia group[32] at 1.3 Bev (0.79±0.09 mb); Fowler *et al.*[33] at 1.37 Bev (≈0.9 mb); and Slaughter *et al.*[34] at 1.9 Bev (≈1 mb). Effects of possible $\theta^0 \rightarrow K^+$ charge exchange and some hyperon captures do not give effects outside the errors. Therefore, the total yields of hyperons and θ^0's from complex nuclei appear to agree well with what is expected from our knowledge of elementary π^--p and π^+-p interactions.

In spite of this agreement, it is evident from Table VI that fewer Σ^-'s and more Y^0's than expected are observed. This effect is summarized in Table VII, where the Σ^-/Y^0 ratios calculated by the two models, and observed by us and others, are listed. The observed Σ^-/Y^0 ratios are lower by a factor of 5 to 10 than expected if production proceeds as in elementary pion-free nucleon collisions, and if charge exchange interactions of the hyperons are neglected.

The low Σ^-/Y^0 ratio might be attributed to the presence of other nucleons which significantly affect the mechanism for production of strange particles, or to the presence of charge-exchange interactions of hyperons. Evidence for the former explanation is the almost constant Σ^-/Y^0 ratio independent of nuclear size. However, it would be very surprising if the presence of other nucleons would drastically alter the Σ^-/Y^0 production ratio, yet not affect the absolute yields of hyperons or θ^0's. An explanation in terms of hyperon charge exchanges seems more plausible.

If we assume that the observed Σ^-/Y^0 ratio has been altered from the expected ratio only by charge exchange of Σ^- to Y^0,

$$\Sigma^-+p \rightarrow Y^0+n, \qquad (17)$$

and we neglect Y^0 to Σ^- charge exchanges, then we can

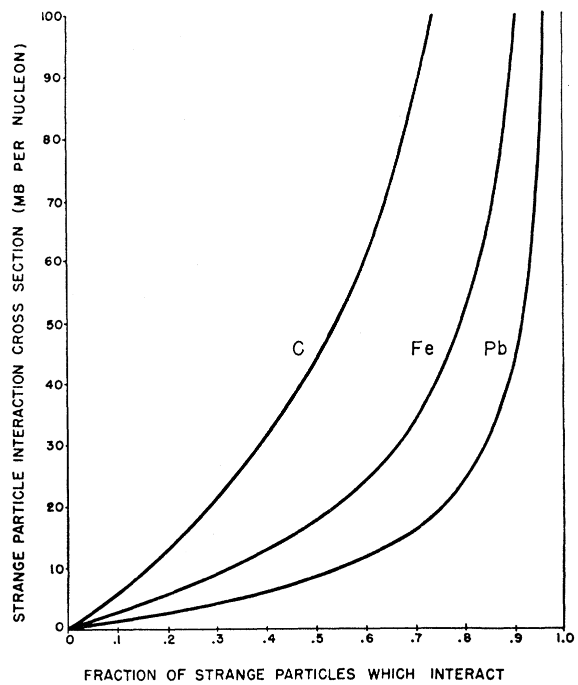

FIG. 7. Strange particle interaction cross section per nucleon as a function of the fraction which interacts before escaping from C, Fe, and Pb production nuclei.

TABLE VIII. $\Sigma^-+p \rightarrow Y^0+n$ charge exchanges.

	C	Fe	Pb
Fraction of Σ^-'s which charge-exchanges before escaping from the nucleus[a]	0.79±0.08	$0.52_{-0.18}^{+0.22}$	0.84±0.06
Total cross section in mb for Σ^- charge exchange[b]	176	39_{-17}^{+45}	73_{-18}^{+33}

[a] Lower limits calculated from Σ^-/Y^0 ratios expected (Monte Carlo) and observed (Princeton), neglecting the reverse of Eq. (18).
[b] Lower limits, neglecting the reverse of Eq. (18), found from Fig. 7.

obtain the lower limits on the fraction of Σ^-'s which must undergo charge exchange [Eq. (17)] before escaping from the nucleus, listed in Table VIII. The fraction which undergoes charge exchange can be interpreted in terms of a cross section for reaction 17 if we assume that the protons and neutrons are randomly distributed within the production nucleus. The relation between the fraction interacting and the interaction cross section per nucleon computed from the uniform one-dimensional model is shown in Fig. 7 for C, Fe, and Pb. To illustrate its use, Table VIII lists the fraction of Σ^-'s which charge exchange in Pb, for example, as 0.84. Referring to Fig. 7, this indicates an interaction cross section of 29 mb per nucleon. However, reaction 18

[32] F. Eisler *et al.*, Nuovo cimento **10**, 468 (1958).
[33] W. B. Fowler, R. P. Shutt, A. M. Thorndike, and W. L. Whittemore, Phys. Rev. **98**, 121 (1955).
[34] G. G. Slaughter, E. M. Harth, and M. M. Block, Phys. Rev. **109**, 2111 (1958).

requires a proton, so the cross section per nucleon must be multiplied by A/Z, which gives 73 mb.

From Table VIII, if the low Σ^-/Y^0 ratio is to be explained by the charge exchange of Σ^-'s [Eq. (17)], then the cross section must be of the order of geometric, although no one value gives a simultaneous good fit to the observations from C, Fe, and Pb. It might be conjectured that the large fraction which charge exchange in C is due to correlation between the position of nucleons within the C nucleus, so that at the point of production of a Σ^- by a π-nucleon collision there is also an appreciable amplitude of a proton wave function present.

θ^0 Interactions

Figure 7 can also be employed to interpret the secondary interactions of other strange particles within the production nucleus. For example, the histograms of Fig. 5 give the evidence that many θ^0's scatter before leaving the production nucleus. The total θ^0-p and θ^0-n cross sections can be estimated from the measured charge symmetric K^+-n and K^+-p cross sections[35] to be about 17 mb in our energy region. Referring to Fig. 7, we find that the fraction of θ^0's which would be expected to interact before escaping is 0.26 in C, 0.50 in Fe, and 0.72 in Pb. The observed distributions which appear in Fig. 5 seem in accord with these predictions.

$\bar{\theta}^0$ Interactions

After the prompt decay of the $\theta_1{}^0$'s in this experiment there remained an equal number of $\theta_2{}^0$'s of effectively infinite lifetime, some of which interacted in traversing the cloud-chamber plates. Of particular interest were the interactions of the $\bar{\theta}^0$ component of $\theta_2{}^0$'s producing easily recognized Λ^0 and $\Sigma^\pm$ decays.

V events, for which no beam origin could be discovered, were examined closely for origins produced by neutral particles. Definite neutral origins were found in four cases. In three cases a Λ^0 was observed, and in the other, a $\Sigma_\pi{}^\pm$. Two other probable $\theta_2{}^0$ interactions in which the origin of the strange particle was less certain were also found, one a Λ^0, and the other a $\Sigma_\pi{}^\pm$. In each case, there were one or more possible origins for the $\theta_2{}^0$, but only in one of the probable events was an associated hyperon seen (from six events, we would expect to see, on the average, two hyperons).

In order to compute the number of $\theta_2{}^0$ interactions expected, the total amount of material traversed by all observed $\theta_1{}^0$'s, had they not decayed, was computed. The range in the production plate was not included. If the $\bar{\theta}^0$ absorption cross section is taken as geometric,[36] then there should have been 15 $\bar{\theta}^0$ inelastic interactions in the cloud chamber. If most of these interactions lead to Y^0 or $\Sigma_\pi{}^\pm$ production, then we would expect to see 6.3 $\bar{\theta}^0$ interactions, which is in agreement with the actual observation of four good events and two possible events.

There were two events with coplanar beam origins which were identified as $\theta_1{}^0$'s, but with extremely long lifetimes of 23.5×10^{-10} and 11.9×10^{-10} sec, respectively. These are possible examples of $\theta_2{}^0$'s regenerating into $\theta_1{}^0$'s with practically no scatter.

TABLE IX. Associated strange particle events.

Hyperon identity	K-meson identity	Number of events
Λ^0 (definite)	$\theta_1{}^0$ (definite)	12
Λ^0 (probable)	$\theta_1{}^0$ (definite)	2
Λ^0 (definite)	$\theta_1{}^0$ (probable)	2
V^0 (ambiguous)	$\theta_1{}^0$ (definite)	2
	Total	18
Σ^- (probable)	$\theta_1{}^0$ (definite)	3
Λ^0 (definite)	K^+ (definite)	2

G. ASSOCIATED PRODUCTION

In all the events in the pion beam in which two strange particles originated in the same interaction, the two could either be definitely identified as a hyperon and K meson produced in association, or were consistent with such an interpretation. A tabulation of the various combinations and identification ratings observed is given in Table IX. Since the detection efficiency for Λ^0+K^+ is hard to estimate, these events are not considered further. The two events in which the identity of the V^0 is ambiguous could be examples of $\theta^0+\bar{\theta}^0$ production. However, this seems unlikely, since no certain case was observed, and to balance energy this interpretation would require pions of 2.1- and 2.3-Bev kinetic energy, respectively, which would be unlikely

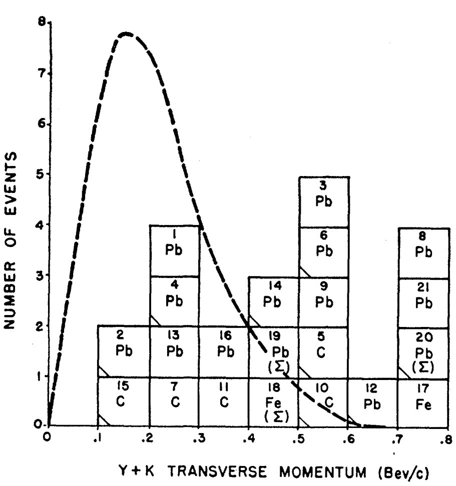

FIG. 8. The histogram shows the transverse momentum distribution of 18 $Y^0-\theta^0$ events and 3 $\Sigma^--\theta^0$ events. The production nucleus is indicated in the rectangle for each event. Rectangles with a diagonal bar indicate events with additional charged secondaries. The curve shows the distribution which would be due to a Gaussian distribution of Fermi momentum.

35 H. C. Burrowes, D. O. Caldwell, D. H. Frisch, D. A. Hill, D. M. Ritson, and R. A. Schluter, Phys. Rev. Letters **2**, 117 (1959).

36 W. K. H. Panofsky, V. L. Fitch, R. M. Motley, and W. G. Chestnut, Phys. Rev. **109**, 1353 (1958).

according to the beam spectrum of Fig. 2. Therefore, we estimate that $\theta^0-\bar{\theta}^0$ production at 1.5-Bev pion kinetic energy is less than 10% of $Y^0-\theta^0$ production.

The numbers of associated events observed agree with expectations based upon the elementary cross sections of Eqs. (13)–(16), if the observation efficiencies (Sec. B) and $\Sigma^- \rightarrow Y^0$ conversions (Sec. F) are taken into account. A histogram showing the visible energy for each associated production is plotted in Fig. 2. As might be expected, in Pb collisions neutral particles more frequently carry away several hundred Mev of the available energy. Also, it appears that in those cases where a Σ^- escapes from the production nucleus, very little energy is lost to invisible secondaries, in agreement with our conclusions from the production angular and momentum distributions of Σ^-'s (Sec. E) that those which escape do so without appreciable scattering or momentum loss.

The transverse momentum of each hyperon-θ_1^0 pair is plotted in Fig. 8. If the pion interacted with only one nucleon to produce the strange particles, and these escaped without further interactions, then the transverse momentum unbalance would be due to the Fermi momentum of the struck nucleon. The curve shows the expected shape of the transverse component of the Fermi momentum of a nucleon, assuming a Gaussian distribution.[37] It is apparent that at least half of the associated production events involve more complicated processes. The corresponding rectangles of the energy balance and momentum balance histograms have been assigned numbers. Little or no correlation appears between events with low visible energy and high momentum unbalance, indicating that neither type of unbalance by itself is sufficient to distinguish which events involve secondary interactions.

The events with an additional charged secondary able to escape from the plate of production are indicated in Figs. 2 and 8. In most cases it is impossible to distinguish whether the secondary is a proton or pion, but, if they are protons, they range from 40 to 300 Mev in energy. Throughout our analysis we have neglected any elementary pion-nucleon reactions which lead to an associated pair and a pion in the final state. The experimental justification for this is that of nine Y^0 or θ^0 production events at 1.4 Bev,[33] and 2 events at 1.9 Bev[34] observed in a hydrogen diffusion chamber, all except one event at 1.9 Bev could be interpreted as $\Lambda^0-\theta^0$ or $\Sigma^0-\theta^0$ productions, with no additional meson. The presence of additional secondaries does not seem strongly correlated with either energy or momentum unbalance. If we count the events which appear to be "simple" events involving only a single pion-nucleon interaction, we have from C two or possibly three $Y^0-\theta^0$ of the five observed, from Pb, two $Y^0-\theta^0$ events of the 12 observed, and two $\Sigma^- - \theta^0$ of the three observed. These observations accord with what might be predicted, with the help of Fig. 7, if the θ^0-nucleon total cross section is ≈ 17 mb, and the Σ^--proton charge exchange cross section is ≈ 60 mb. The predictions are not sensitive to any assumed values of the Σ^--nucleon and Y^0-nucleon scattering cross sections because of the already large effects due to charge exchange reactions.

H. CONCLUSIONS

The mean lifetimes found in this work for Λ^0 and θ_1^0 decays are in good agreement with the results of others. Since the procedure for correcting for events missed and the procedure for determining these lifetimes were closely interrelated, the agreement increases our confidence that no large biases were introduced because of the necessity of these corrections. No statistically significant forward-backward Λ^0 decay asymmetries were observed. Although, in the case of Pb, the number of events is sufficient to conclude that the up-down asymmetry is significantly less than in elementary collisions, the data suggests that there might be a large up-down asymmetry for Λ^0's with laboratory momenta from 0.7 to 1.0 Bev/c, in agreement with the results of the MIT group for Fe.

The fraction of inelastic pion-nucleus collisions which lead to strange particle production was found to remain approximately constant in C, Fe, and Pb for each type of strange particle investigated (Y^0,Σ^-,θ^0). This is expected if most strange particles are produced in the first inelastic pion-nucleon collision within the nucleus, and if most of the strange particles produced succeed in escaping from the nucleus. The numbers of hyperons $(Y^0+\Sigma^-)$ and θ^0's produced are in good agreement with the predictions from the known elementary pion-nucleon production cross sections. This would seem to indicate that the production process is not greatly affected by neighboring nucleons, and that the net loss of θ^0's due to charge exchange into K^+'s is not great.

The effects of strange particles interacting before escaping from the production nucleus can be clearly seen by comparing the angular and momentum distributions for strange particles from C, Fe, and Pb with the results of Monte Carlo calculations which use the known elementary pion-nucleon cross sections, but neglect subsequent interactions of the strange particles. In the case of θ^0 production, the observed changes in the distributions are in good qualitative agreement with ≈ 17 mb total K-nucleon scattering cross section.

Although the total number of hyperons observed agrees well with expectations, the observed Σ^-/Y^0 ratio is much lower. This indicates that most Σ^-'s charge exchange into neutral hyperons. In order to account for the observed Σ^-/Y^0 ratio, the Σ^--proton charge-exchange cross section must be at least geometric.

Evidence for interactions of the $\bar{\theta}^0$ component of θ_2^0's was found in four likely and two possible cases where hyperons were produced by a neutral primary. This number is in good agreement with the number expected

[37] J. M. Wilcox and B. J. Moyer, Phys. Rev. 99, 875 (1955).

if the total cross section were geometric. In addition, two possible θ_1^0 regenerations were found.

All 23 events in which two strange particles originated in the same pion interaction were certain or probable hyperon-K meson associated productions. Only a few of these events are "simple" events; that is, are consistent with production by a single pion-nucleon collision. The fractions of the events which are simple agree well with those expected based upon our estimates of the θ^0-nucleon scattering and Σ^--proton charge exchange cross sections.

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Production of Strange Particles by 2.8-Bev Protons in C, Fe, and Pb†

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Observations of Λ^0, θ_1^0, and $\Sigma_\pi^\pm$ particles from 2.8-Bev proton interactions have been made in a multiplate cloud chamber with one-half inch plates of C, Fe, and Pb. The $Y^0(\Lambda^0, \Sigma^0)$ and θ^0 cross sections, when compared with those observed for production by 1.5-Bev π^- mesons with the identical arrangement, are lower by at least a factor of four for C and a factor of two for Pb. Production of $\Sigma_\pi^\pm$'s by protons and pions seem to be of comparable magnitude in either C or Pb. Since protons are less effective than pions of similar kinetic energy (in the center-of-mass system) in producing strange particles, it is estimated in the case of incident protons that indirect production of strange particles by intermediate pions accounts for $(40_{-13}^{+28})\%$ of the observed particles in C and $(64_{-14}^{+21})\%$ in Pb. The different A dependence of the proton and pion cross sections for producing observable strange particles (Λ^0, θ_1^0, $\Sigma_\pi^\pm \rightarrow \pi^\pm + n$) may be fitted by a total proton-nucleon direct production cross section of 0.09 ± 0.06 mb.

The proton-produced strange particle events were used to compute what would be expected when decay γ rays emitted at 90° to the beam direction are observed in the geometry used by Berley and Collins. The predicted decay curve is in excellent agreement with their observations, and the absolute and relative yields agree within the estimated experimental uncertainties.

IN the earliest observations of Λ^0's, θ^0's, and $\Sigma^\pm$'s produced in Cosmotron beams, there was evidence that although the production cross section was ≈ 1 mb for 1.4-Bev π^--p collisions,[1] it was appreciably lower in 2.7-Bev p-p[2] and p-nucleus[3] collisions and in 1–2 Bev neutron-nucleus collisions.[4] The numbers of strange particles observed from protons and neutrons[3,4] on Pb were such as to be entirely attributable to indirect production by intermediate real pions in a two-stage process:

$$N+N \rightarrow N+N+n\pi, \quad (1)$$

$$\pi+N \rightarrow Y+K. \quad (2)$$

A direct strange particle production would be simply

$$N+N \rightarrow N+Y+K. \quad (3)$$

It was pointed out[5,6] that the indirect production

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