Polarization of the Σ^0 Particles Produced in the Reaction $\pi^- + p \rightarrow K^0 + \Sigma^0$ at 1.5 and 1.8 BeV/c†

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The polarization of the Σ^0 particles produced in the reaction $\pi^- + p \rightarrow K^0 + \Sigma^0$ has been measured at 1.5 and 1.8 BeV/c, using a spark-chamber magnet system. The product $\alpha_\Lambda \langle \sigma_{\Sigma^0} \rangle$ was found to be -0.47 ± 0.33, $+0.51 \pm 0.27$, and $+0.82 \pm 0.44$, respectively, in Σ^0 c.m. angular intervals centered at $\cos\theta^* = 0.8$, -014, and 0.0 at 1.8 BeV/c; and -0.55 ± 0.23, -0.31 ± 0.38, and -0.82 ± 0.46 at the same production angles at 1.5 BeV/c. The Σ^0 production angular distributions in the backward hemisphere at both momenta are also given. Both polarization and angular distribution are found to vary rapidly with energy.

I. INTRODUCTION

THE polarization of the Σ^0 particles produced in the reaction $\pi^- + p \rightarrow K^0 + \Sigma^0$ has been measured previously at several beam momenta.[1–3] Anderson *et al.*[1] measured the polarization at 1.17 BeV/c and Binford *et al.*[2] measured it in the momentum range -1.1 to 1.325 BeV/c. The polarization reported by these authors is consistent with zero within their large statistical errors. Yoder *et al.*[3] measured the polarization at 1.51 BeV/c from a sample of 134 Σ^0's and obtained $\langle \sigma_{\Sigma^0} \rangle = -0.39 \pm 0.67$, which is also consistent with zero within the uncertainty.

In this paper, we report on our measurement of the Σ^0 polarization and production angular distributions at 1.5 and 1.8 BeV/c. The measurement was obtained from pictures taken by an Argonne group at the CERN proton synchrotron in a magnetic spark chamber system with a $1.4 \times 1.5 \times 8.0$-cm CH_2 target.[4,5]

II. EXPERIMENTAL PROCEDURE

The experimental setup used in this experiment has been discussed in detail elsewhere.[4,5] A diagram of the arrangement of spark chambers is shown in Fig. 1. The runs at 1.5 and 1.8 BeV/c were taken initially for the purpose of studying neutral meson decays into gamma rays.[6] Consequently, more lead was used than in the runs at lower energies, with a resulting decrease in momentum accuracy.

Roughly 50 000 pictures were taken at each momentum. Of these, about 2500 (at each momentum) showed two or more neutral V's. Of this set, pictures were rejected at the scanning table if there were no beam tracks that could be uniquely interpreted as source of production. The scanners were instructed to classify these V's as K^0, Λ^0, or γ-conversion pair through track ionization and the opening angle of the V.

The accepted events were measured on an image-plane digitizer and then were processed through a series of data analysis programs, GEOM–GRIND–RESONA.[4] GEOM performs the space reconstruction of the measured tracks and through a helix (or straight line) fit to the tracks, finds their momentum vector (or direction cosines) and the decay vertex. GEOM is coupled via magnetic tapes to GRIND. GRIND tests the V's for the hypotheses $K^0 \rightarrow \pi^+ + \pi^-$ and $\Lambda^0 \rightarrow p + \pi^-$. If both V's can be fitted with a χ^2 probability greater than 1%, then it further tests the event for the following multivertex hypotheses:

$$\pi^- + p \rightarrow K^0 + \Lambda^0 \quad (1)$$
$$\rightarrow K^0 + \Sigma^0 \quad (2)$$
$$\rightarrow K^0 + \bar{K}^0 + n \quad (3)$$
$$\rightarrow K^0 + \Lambda^0 + \pi^0, \quad (4)$$

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[1] J. A. Anderson, University of California Radiation Laboratory Report UCRL-10338, 1963 (unpublished); J. A. Anderson, F. S. Crawford, and J. C. Doyle, Bull. Am. Phys. Soc. **10**, 467 (1965).

[2] T. O. Binford, V. G. Lind, and D. Stern, Bull. Am. Phys. Soc. **10**, 115 (1965).

[3] L. L. Yoder, C. T. Coffin, D. I. Meyer, and K. M. Terwilliger, Phys. Rev. **132**, 1778 (1963).

[4] Young S. Kim, G. R. Burleson, P. I. P. Kalmus, A. Roberts, and T. A. Romanowski, Phys. Rev. **140**, B1655 (1965).

[5] A. Roberts, *Proceedings of the International Symposium on Nuclear Electronics* (O. C. D. E., Paris, 1963), p. 21; G. R. Burleson, J. A. DeShong, T. F. Hoang, P. I. P. Kalmus, R. L. Kuskowski, L. Q. Niemela, A. Roberts, T. A. Romanowski, S. D. Warshaw, and G. E. Yurka, Nucl. Instr. Methods **20**, 448 (1963); **20**, 80 (1963); **20**, 185 (1963).

[6] G. R. Burleson, T. F. Hoang, P. I. P. Kalmus, L. Q. Niemela A. Roberts, T. A. Romanowski, and S. D. Warshaw, Bull. Am. Phys. Soc. **9**, (1964).

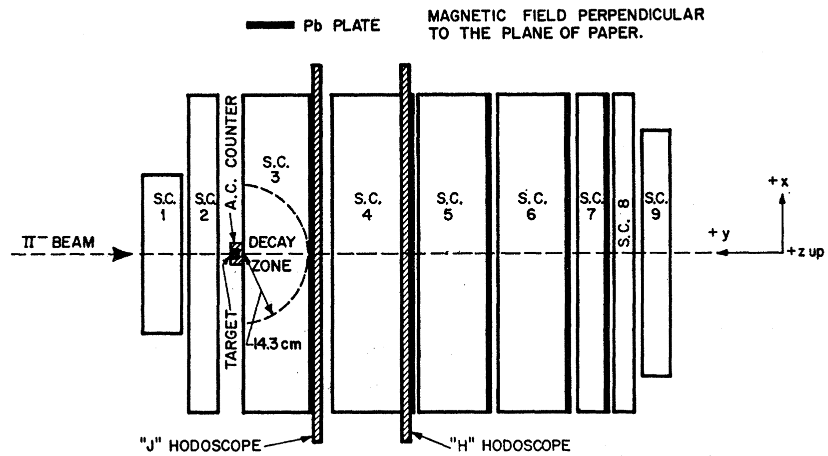

FIG. 1. Schematic diagram showing the spark-chamber arrangement. The whole assembly was in a magnetic field of 13 kG. The J and H hodoscopes each included 8 scintillation counters. A typical trigger requirement, in addition to an incoming meson and no outgoing charged particles, was any 3 J counters and any 2 H counters triggered in coincidence.

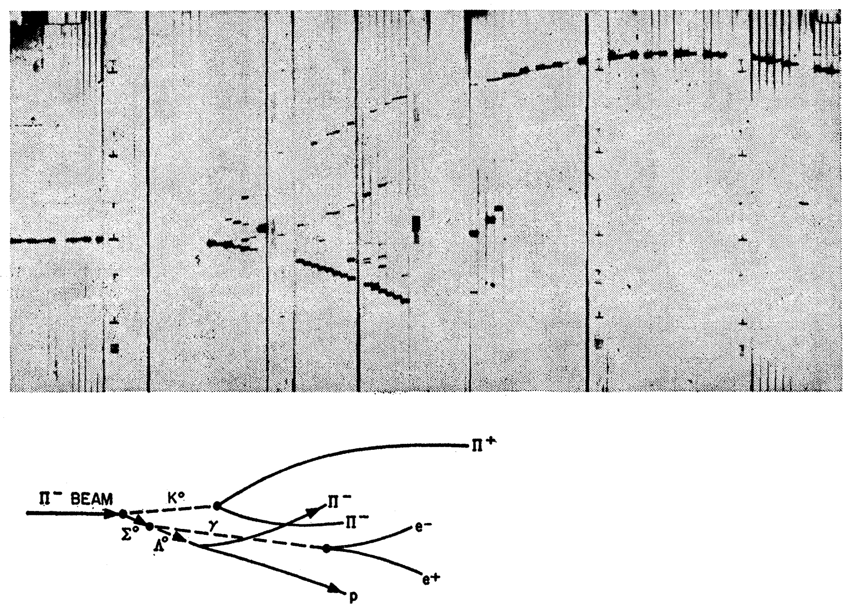

FIG. 2. A $K^0\Sigma^0$ associated production in which Σ^0 decays into $\Lambda^0+\gamma$ which, respectively, decay into π^- and p and converts into an e^+e^- pair. The K^0 decays into π^+ and π^-. Only 10% of the γ's from Σ^0 decays are converted in our chambers.

where the target proton is assumed to be at rest. Table I gives the number of events accepted for each of the production reactions listed above. The number of events in reaction (3) is too small to yield any significant data. The number of events in reaction (1) is small compared to that obtained by Schwartz[7] and they furnish no new information. The results obtained on reaction (4) are being reported elsewhere and this paper deals only with reaction (2).

TABLE I. Number of observed events.

Beam P (BeV/c)	$K^0\Lambda^0$	$K^0\Sigma^0$	$K^0\Lambda^0\pi^0$	$K^0\bar{K}^0n$
1.5	241	253	154	...
1.8	176	234	259	20
Total	417	487	413	20

[7] J. A. Schwartz, University of California Radiation Laboratory Report No. UCRL-11360, 1964 (unpublished).

In the multivertex fits, the beam momentum was assigned to the incident π^- track, but its direction cosines were those which were measured in each event. An event was required to pass one of the above mass assignments with a χ^2 probability greater than 1% in order to be accepted as a "good" event. A "good" event was further rejected if it failed to meet any of the following conditions:

(1) The decay points must lie inside the fiducial volume defined by a semicylinder whose flat side surface was defined by the anticoincidence (A.C.) counter (see Fig. 1), whose height was twice that of the target, and whose radius was 14.3 cm.

(2) The production point computed from the fitted K^0 and Λ^0 movements must lie inside the target.

(3) An event must not satisfy more than one multi-vertex hypothesis with a χ^2 probability ratio less than 3.

As a check of the GRIND Σ^0 routine, events classified as Σ^0's by GRIND from data only on K^0 and Λ^0 decays were rescanned for the Σ^0 decay γ conversion pair. In about 10% of the Σ^0's, a γ conversion pair whose direction was in fair agreement with that predicted by GRIND was found. The observed pair-conversion efficiency is in agreement with an estimate made from a Monte Carlo computation. A photograph of a $K^0\Sigma^0$ production event in which the γ-conversion pair is observed is shown in Fig. 2. Table II lists the number of Σ^0's accepted at various Σ^0 production angles in the $\pi^- p$ c.m. system.

III. EXPERIMENTAL ERRORS AND BIASES

Figure 3 shows the square of K^0 invariant mass computed from the measured pion momenta for a sample of the 1.8 BeV/c data. A similar resolution was also obtained at 1.5 BeV/c. Much of the error is attributable to scattering from the lead plates in the system (see Fig. 1.).

The various systematic biases inherent in our detection system have been described in detail elsewhere[4,5] and we present here only briefly some pertinent data on the performance of the spark-chamber–magnet system in the arrangement used.

The requirement that both K^0 and Λ^0 be observed in the fiducial volume of our system introduces certain kinematic cutoffs in the Σ^0 production angular distribution (see Table II). The type of bias most important in polarization measurements is a false up-down asymmetry in the detection system with respect to any arbitrary production plane and to verify the absence of any significant intrinsic asymmetry in our system, the up-down asymmetry of the π^- from K^0 decay with respect to the K^0 production plane was measured, and no significant asymmetry was detected (see Fig. 4).

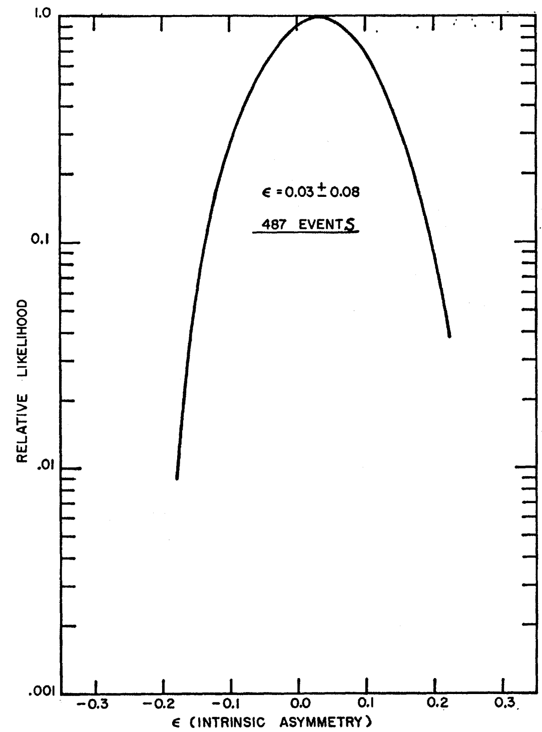

FIG. 4. The maximum likelihood function for the up-down asymmetry of π^- from the decay of K^0's produced in the reaction $\pi^-+p \to K^0+\Sigma^0$ with respect to the production plane. In the absence of any intrinsic detection asymmetry, this should peak at zero.

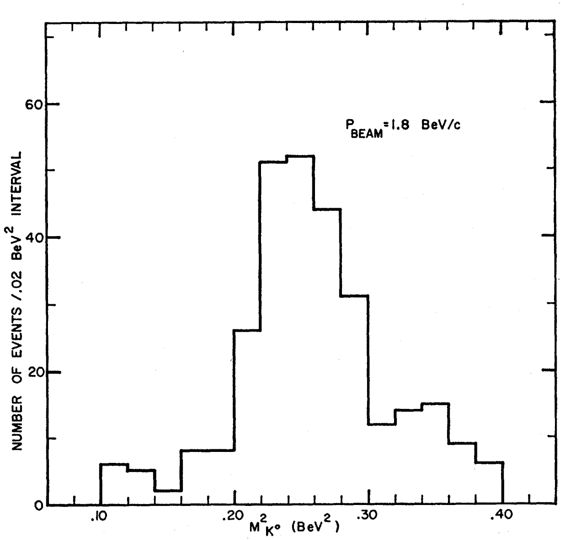

FIG. 3. Distribution of K^0 invariant mass squared computed from measured π momenta. The distribution indicates that our K^0 mass resolution is about 6% and that there is no significant systematic error in our momentum determination.

The fraction of Σ^0's made from protons in the carbon content of our CH_2 target was estimated to be about 25%. This figure is based on our comparative study of $K^0\Sigma^0$ pairs produced in CH_2 and in carbon at 1.17 BeV/c. The background Σ^0's are mostly made from

TABLE II. Number of accepted Σ^0's at various c.m. production angles.

$\cos\theta_{\Sigma^0}$	1.8 BeV/c Observed	Weight[a]	1.5 BeV/c Observed	Weight[a]
−0.9	75	2.5	86	2.4
−0.7	26	2.5	45	2.46
−0.5	48	2.0	35	2.42
−0.3	44	2.2	29	2.2
−0.1	25	2.2	20	2.6
0.1	12	2.3	13	2.8
0.3	4	2.8	8	2.96
0.5	...	...	12	4.0
0.7	...	...	5	15.6
Total	234		253	

[a] The weight is taken to be the inverse of the $K^0\Lambda^0$ pair-detection efficiency computed from our fiducial-volume requirement. The Λ^0 mean lifetime was taken to be 2.5×10^{-10} sec and the K_1^0 mean lifetime 0.9×10^{-10} sec.

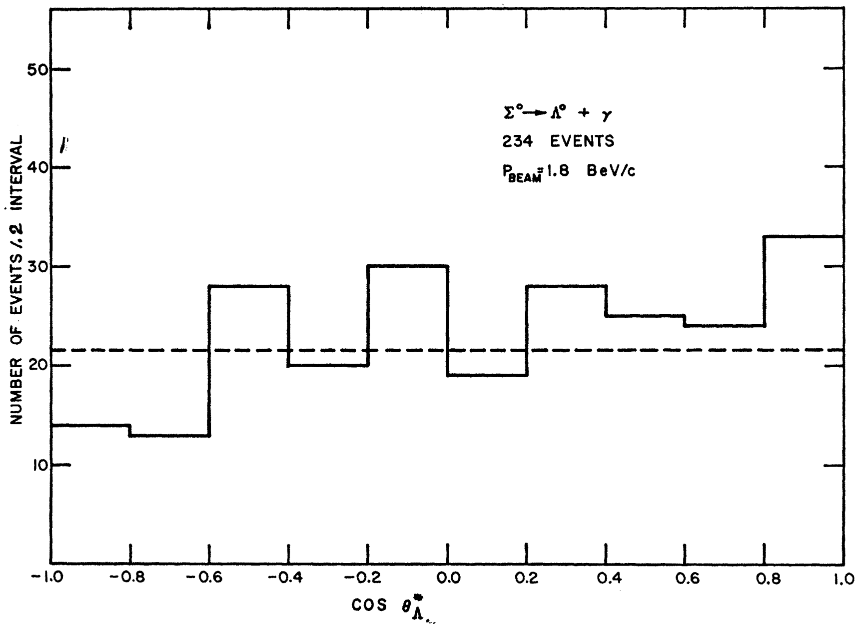

FIG. 5. Angular distribution of Λ^0 from Σ^0 decay in the Σ^0 rest frame. The slight anisotropy is apparently due to the $K^0\Lambda^0$ contamination.

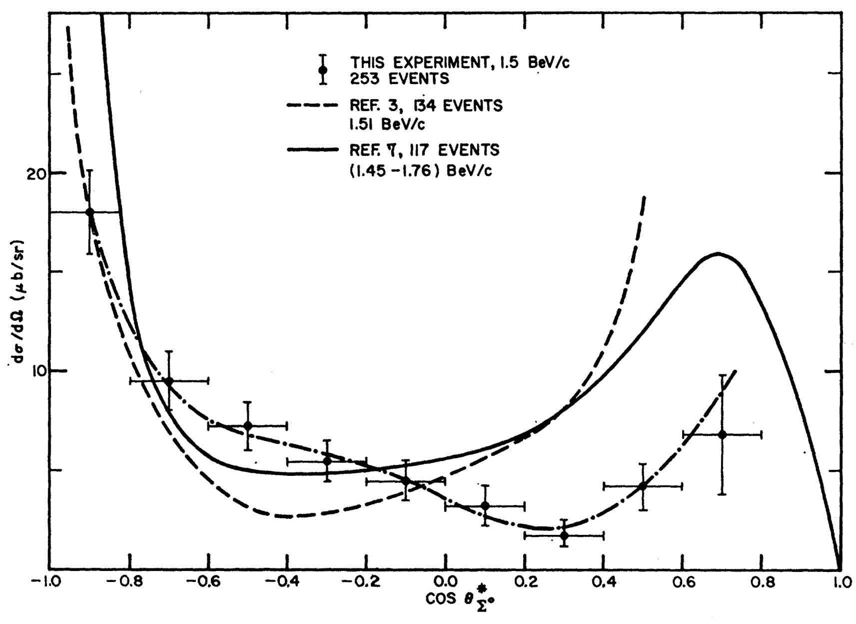

FIG. 6. Center of momentum production angular distribution of Σ^0 at 1.5 BeV/c. The smooth curve through our data points is a least-square fit to a series of the form

$$\sum_{n=0}^{5} A_n \cos^n\theta_{\Sigma^0}.$$

The solid curve is the best fit to the data given in Ref. 6 based on 117 events in the momentum interval 1.45–1.76 BeV/c. The broken curve is the best fit to the data given in Ref. 3 based on 134 events at 1.51 BeV/c. Our data seem to show a small hump in the backward hemisphere.

carbon protons, in which the average Fermi momentum is low. We have found that the Λ's produced from protons in carbon at 1.17 BeV/c[4] have a polarization and angular distribution very similar to those made from free protons. In the absence of data with a carbon target, we may assume, by analogy, similar behavior for Σ^0's produced at 1.5 and 1.8 BeV/c. Hence no attempt has been made to subtract these from our Σ^0 sample.

Because of the limited resolution, a number of the events accepted as Σ^0's are probably $K^0\Lambda^0$'s. The extent of this background may be estimated from the number (about 15% of the total Σ^0's accepted) of Λ^0-Σ^0 ambiguous events in which the latter hypothesis has a higher confidence level. The ambiguity is a consequence of the kinematics of these two production reactions,[1] and also of the Fermi momentum of the protons in the carbon nucleus (roughly 10% of these ambiguous events showed γ conversion pairs and thus many of these are true $K^0\Sigma^0$ events). The Σ^0 polarization was examined with the ambiguous events excluded from the sample; no appreciable change in the polarization was observed. In most events in which Λ's simulate Σ^0's, they are emitted forward with respect to the Σ^0 line of flight (see Fig. 5) and hence have little analyzing power [see Eq. (5)] for the Σ^0 polarization.

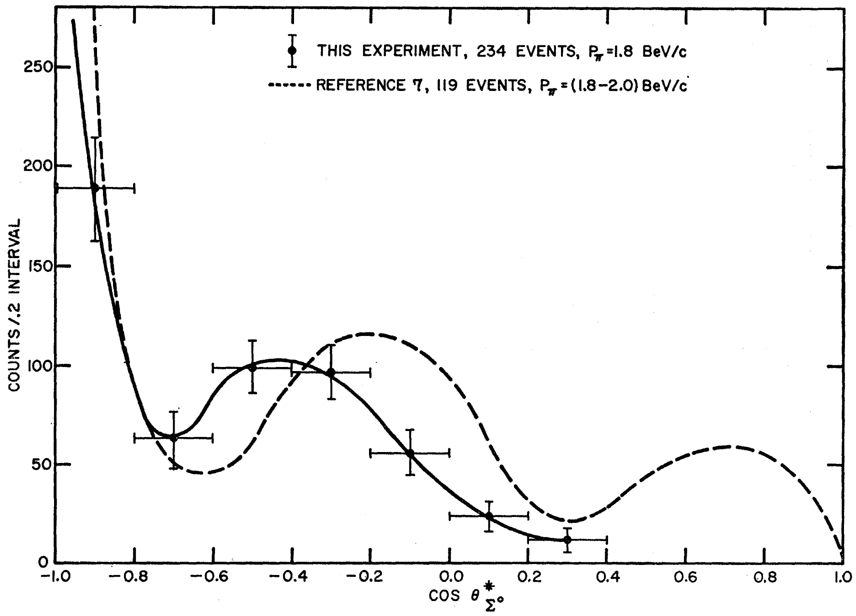

FIG. 7. Center-of-momentum production angular distribution of Σ^0 at 1.8 BeV/c. The smooth curve through our data points is a least-square fit to a power series of the form

$$\sum_{n=0}^{5} A_n \cos^n\theta_{\Sigma^0}.$$

The broken curve is the best fit to the data given in Ref. 6 based on 119 events in the momentum interval 1.8–2.0 BeV/c. The latter curve has been arbitrarily normalized to our data.

IV. RESULTS AND DISCUSSIONS

A. Angular Distributions

The angular distributions for the two beam momenta are given in Figs. 6 and 7. The points given in the figures have been corrected for the fiducial volume bias (see Table II), due mainly to the A.C. counter surrounding the target. The correction factor varies slowly, and is due to effects that can be calculated with reliability.[4,8]

The smooth curves through our data represent the least-squares fits to a power series in $\cos\theta_{\Sigma^0}$. In the figures are also shown the existing experimental data on the angular distributions at (or near) our beam momenta.[1,3,6] In Fig. 6, the solid curve represents Schwartz's data[6] based on 117 events in the momentum interval 1.45–1.76 BeV/c and the broken curve represents data given by Yoder *et al.*[3] based on 134 events at 1.51 BeV/c. The figure gives these two curves in μb/sn (that is, their numerical values are the same as given by their authors). Since we do not observe the whole range of the production angle and since the total cross section for the Σ^0 production is not well known at these momenta, the absolute differential cross section is unknown. Our data have been normalized so that the first coincides with the first point of Yoder *et al.* In view of the large statistical uncertainties in these three experiments, and of the large momentum interval of Schwartz's data, the general shape of these three curves can be said to be in agreement. In Fig. 7, the broken curve represents Schwartz's data based on 119 events in the momentum interval 1.8–2.0 BeV/c; it has been normalized to our data. The general shape of the two distributions are very similar.

From the distributions presented in Figs. 5 and 6 and also from data given by Anderson *et al.*[1] at 1.17 BeV/c and Schwartz[7] at 2.2 BeV/c, one may conclude that the shape of the Σ^0 production differential cross section varies very rapidly with beam momentum. At 1.17 BeV/c,[1] the cross section is very nearly symmetric in the forward and backward hemisphere; near 1.5 BeV/c, a sizable hump appears in the backward hemisphere, which increases in magnitude and moves slowly forward with beam momentum. The pronounced backward peak appears to remain the same in intensity, but the forward peak decreases fairly rapidly with beam momentum.

B. Σ^0 Polarization at 1.5 and 1.8 BeV/c

The Σ^0 polarization was estimated using the maximum-likelihood function[8]

$$L=\Pi_i[1-\alpha_\Lambda\langle\sigma\rangle_{\Sigma^0}(\boldsymbol{\eta}\cdot\mathbf{P}_\Lambda)(\mathbf{P}_\Lambda\cdot\mathbf{P}_\pi)], \tag{5}$$

where $\mathbf{P}_\pi$ = unit vector along the π^- momentum in the Λ^0 rest frame, $\mathbf{P}_\Lambda$ = unit vector along the Λ^0 momentum in the π^-p c.m. frame, and $\boldsymbol{\eta}$ is the unit vector normal to the Σ^0 production plane, i.e., $\mathbf{P}_{K^0}\times\mathbf{P}_{\Sigma^0}|\mathbf{P}_{K^0}\times\mathbf{P}_{\Sigma^0}|$. In Eq. (5) α_Λ is the usual Λ^0 decay asymmetry parameter and the appropriate momenta were translated through the "direct" Lorentz transformation[9,10] from the labora-

[8] For example, the $K_1{}^0$ and Λ^0 mean lifetimes computed from the Bartlett's S function for a sample of 737 $K^0\Lambda^0$ pairs are $(1.05_{-0.06}^{+0.07})\times10^{-10}$ sec and $(2.80_{-0.14}^{+0.16})\times10^{-10}$ sec, respectively. The Bartlett's S function corrects for the fiducial volume biases.

[9] See, for example, R. Gatto, Phys. Rev. **109**, 610 (1957); H. P. Stapp, *ibid.* **103**, 425 (1956).

[10] W. Koch, in *Proceedings of the 1964 Easter School of Physicists* (CERN, Geneva, 1964), Vol. 2, p. 75.

tory system to the $\pi^- p$ c.m. system, from there to the Σ^0 rest frame, and finally to the Λ^0 rest frame.

Figure 8 shows our measurements of the Σ^0 polarization at π^- beam momenta of 1.5 and 1.8 BeV/c. The Σ^0 polarization at 1.17 BeV/c given in Ref. 1 is also shown for comparison.

The polarization at 1.8 BeV/c seems to have the same general shape as the polarization at 1.17 BeV/c.[1] However, the polarization at 1.5 BeV/c remains positive[11] in the backward hemisphere and seems to have a strikingly different distribution from that of the polarization at 1.17 and 1.8 BeV/c.

The mean $\alpha_\Lambda\langle\sigma_{\Sigma^0}\rangle$ for all Σ^0's detected is -0.41 ± 0.18 at 1.5 BeV/c and $+0.13\pm0.19$ at 1.8 BeV/c. Other experiments give 0.08 ± 0.16 at 1.17 BeV/c,[1,12] and 0.24 ± 0.42 BeV/c.[3] The value at 1.51 BeV/c was obtained in an angular interval very similar to that of our data. The discrepancy is 1.5 times the combined standard deviation, and in view of the possibility of large systematic errors quoted,[3] it should not be taken seriously.

C. Possible Influence of N^* (1924)

The striking change of polarization between 1.5 and 1.8 BeV/c and the corresponding notable variation in the angular distribution are both indicative of rapidly varying phase shifts in this interval. One plausible reason for such behavior would be the existence of a resonance in the interaction between the final products, the K^0 and Σ^0,[13] such as the N^* resonance at 1924 MeV. The quantum numbers of this resonance are $I=\frac{3}{2}$, $J=\frac{7}{2}^+$.[14,15] In the π^--proton system the threshold for producing this resonance is at 1.55 BeV/c. The resonance has been observed to decay into $K+\Sigma$; in fact, it is the only N^* resonance presently known to do so.[13] All the observed features of the data are consistent with such a possibility; but the data needed for quantitative confirmation of this hypothesis are not now at hand.

[11] α_Λ is negative; see, for example, J. W. Cronin and O. E. Overseth, Phys. Rev. **129**, 1795 (1963).

[12] Our preliminary measurement of $\alpha_\Lambda\langle\sigma_{\Sigma^0}\rangle$ at 1.17 BeV/c based on 69 events gives 0.02 ± 0.47.

[13] W. G. Holladay, Phys. Rev. **139**, B1348 (1965).

[14] A. H. Rosenfeld, A. Barbara-Galtieri, W. H. Barkas, P. L. Bastien, J. Kirz, and M. Roos, University of California Radiation Laboratory Report No. UCRL-8030, Part 1, 1965 (unpublished).

[15] P. J. Duke, D. P. Jones, M. A. R. Kemp, P. G. Murphy, J. D. Prentice, J. J. Thresher, A. H. Atkinson, C. R. Cox, and K. S. Hand, Phys. Rev. Letters **15**, 468 (1965).

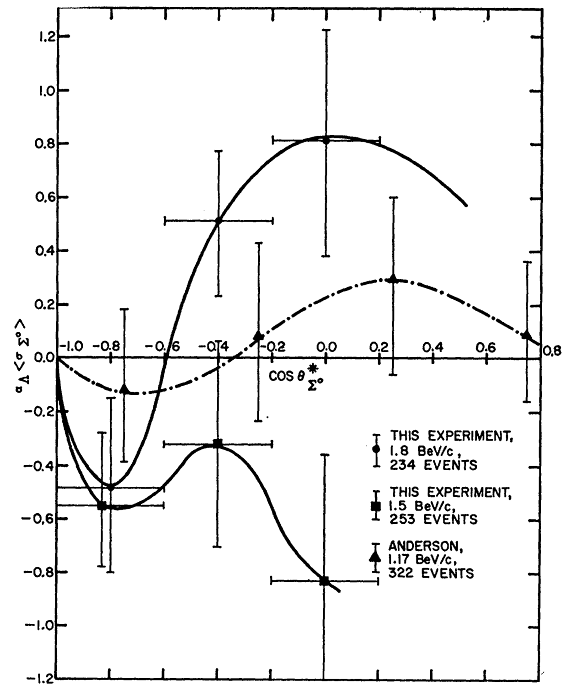

FIG. 8. Angular dependence of $\alpha_\Lambda\langle\sigma_{\Sigma^0}\rangle$ at 1.5 and 1.8 BeV/c. The data given in Ref. 1 at 1.17 BeV/c are also shown for comparison. The smooth lines were drawn through points to guide eyes only.

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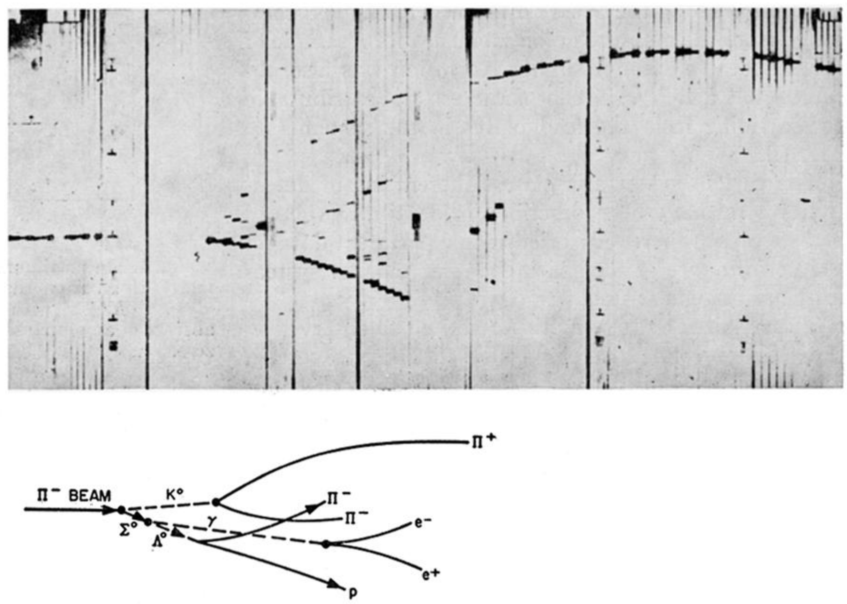

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