Associated Production of ΛK at the ΣK Threshold*

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The reaction $\pi^- + p \to \Lambda + K$ has been studied in the liquid-hydrogen bubble chamber at the threshold energy for the reaction $\pi^- + p \to \Sigma + K$. The differential cross section for Λ production has been found to be $d\sigma/d\Omega = 50 - 10\cos\theta - 25\cos^2\theta - 51\cos^3\theta + 56\cos^4\theta$ μb/sr with a total cross section of 0.67 ± 0.04 mb. The Λ's produced are nearly completely polarized normal to the production plane, and their decay is characterized by $|\alpha\bar{P}| = 0.60 \pm 0.05$. Two leptonic Λ decays have been identified giving a rate for the leptonic decay consistent with one in a thousand. An unsuccessful attempt has been made to detect cusp-like effects. This attempt has failed because of the presence of high angular momentum states in the ΛK production process.

I. INTRODUCTION

We report here on the results of an experiment to measure the total and differential cross sections for the reaction $\pi^- + p \to \Lambda^\circ + K^\circ$ at a pion momentum of 1020 MeV/c. The incident beam momentum was chosen to be at the threshold for the competing reactions $\pi^- + p \to \Sigma^{-,\circ} + K^{+\circ}$, with the hope of observing cusp-like behavior in the measured cross sections. No such behavior was observable because of the large contribution made by angular momentum states higher than s and p waves. The results of the experiment are as follows:

(a) The total cross section for $\pi^- + p \to \Lambda^\circ + K^\circ$ is 0.67 ± 0.05 mb for 1.02 BeV/c π^-.
(b) The angular distribution of the Λ's is given by $d\sigma/d\Omega = 50 - 10\cos\theta - 25\cos^2\theta - 51\cos^3\theta + 56\cos^4\theta$ μb/sr.
(c) The Λ's produced are polarized normal to the production plane, the polarization being as complete as possible.
(d) The leptonic decay rate of the Λ is one in a thousand (within a factor of 2).

II. THE EXPERIMENT

The experiment consisted of two runs. During the first run about 100 000 pictures were taken in the Columbia 12-in. liquid-hydrogen bubble chamber. During the second run 120 000 pictures using the Brookhaven 20-in. liquid-hydrogen bubble chamber were made. In the following description of experimental procedures we shall refer to both runs most of the time, but occasionally differences between run 1 and run 2 will be pointed out.

The arrangement of the 1.02-BeV/c π^- beam is shown in Fig. 1, where T indicates a copper target bombarded by a 2-BeV proton beam from the cosmotron, S is a bending magnet for charge separation, and B^1 and B^2 are bending magnets for momentum definition. These two magnets have been shimmed to obtain a uniform magnetic path for all particles in the beam. q is a single quadrupole magnet for horizontal focusing; inside it is situated a beam defining 6-in.-diam lead aperture.

For run 2, which was made using the 20-in. BNL bubble chamber, it was necessary to place a "pitching magnet" in front of the bubble chamber to deviate the π beam in the vertical direction and compensate for the fringing field of the bubble chamber.

The energy resolution of the π^- beam for the first run was determined by scanning for, and measuring the $\pi^- + p \to \Sigma^- + K^+$ events. The laboratory production angle of the Σ^- is a very sensitive function of the π^- momentum. Measurements of 22 such events indicated that the beam momentum spread was about ± 1 MeV at each position in the chamber, and was consistent with the momentum dispersion calculated from the geometry of the beam, which gave 1-MeV/c change per centimeter of lateral displacement.

For each event of the second run the momentum of the π^- track was determined by the fitting program, rather than being taken as known from the parameters of the beam.

III. ANALYSIS OF PICTURES

The events found in the film were analyzed in a fairly standard way. All film was scanned twice, beam tracks were counted on every fiftieth frame, and the events which were found were measured on a digitized microscope. At this stage, no fiducial volume was selected and all measurable events were measured. The spatial reconstruction of the tracks was carried out using a pro-

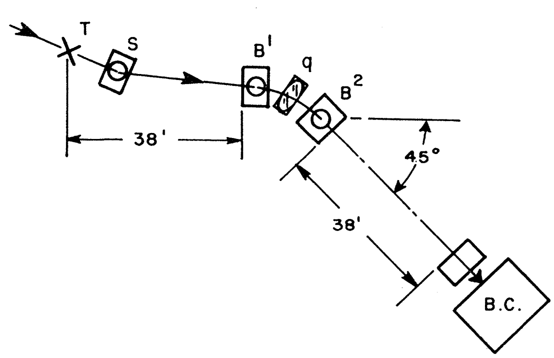

FIG. 1. Beam layout.

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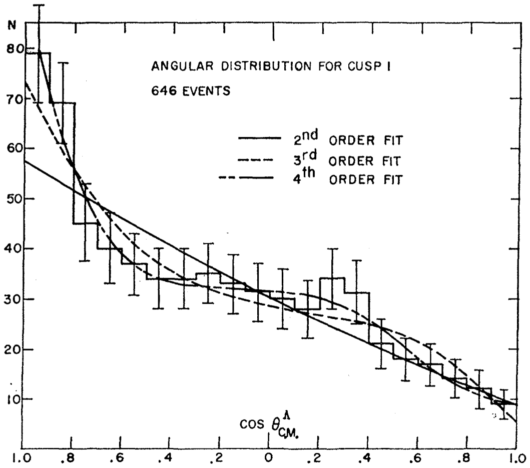

FIG. 2. Angular distribution for first run.

gram written by Professor R. Plano for the IBM 650 computer.

At the time of the first run we did not have a kinematic fitting program, and therefore, the events were analyzed on a Wulff chart. By the time of the second run we had a complete data analysis system available, and the events were run through a kinematic fitting program for analysis.

IV. RESULTS

The results of the first run, for which 646 events were analyzed, indicated that the angular distribution of the Λ's cannot be fitted by a quadratic function of the cosine of the production angle (see Fig. 2) and that, therefore, angular momentum states higher than *s* and *p* waves contribute to the production. In order to clear up this point the second set of pictures was taken.

As mentioned before, the events of the second run were machine analyzed, and therefore acceptability criteria could be applied objectively. These included limits on the π^- momentum (1020 ± 35 MeV/c), χ^2 criteria in production and decay, minimum length of 0.4 cm for neutral single *V* events, and finally, fiducial region restrictions on the production vertex.

A. Angular Distribution

The observed angular distribution for the second run is presented in Fig. 3. Here, as in Fig. 2, we observe that the angular distribution cannot be fitted by a quadratic function of $\cos\theta^{\Lambda}{}_{\text{c.m.}}$.

The histograms of Figs. 4 and 5 are the angular distributions of the events for the second run and for all events combined, after the various geometrical corrections have been applied. The curves are the least-square fits to the angular distributions by polynomials.

Applying goodness of fit tests to the fitted polynomials, it is seen that in no case is a quadratic fit adequate. The highest probability for a fit is obtained by a quartic function of $\cos\theta^{\Lambda}{}_{\text{c.m.}}$. This fit gives

$$d\sigma/d\Omega=(9.5\pm0.5)-(2.0\pm1.0)\cos\theta-(4.7\pm3.0)\cos^2\theta-(9.6\pm2.0)\cos^3\theta+(10.5\pm4.0)\cos^4\theta.$$

Normalizing the angular distribution to the total cross section of 0.67 mb (see next section), we obtain

$$d\sigma/d\Omega=50-10\cos\theta-25\cos^2\theta-51\cos^3\theta+56\cos^4\theta\ \mu\text{b/sr}.$$

B. Cross Section

To calculate the cross section for the observed reaction we have to know three quantities: The number of events produced within a certain fiducial region of the chamber; the total length of π^- tracks responsible for the production of these events; and the density of hydrogen in the chamber. Of these three quantities, two are obtained after appropriate corrections from the observational results of this experiment, while the third one, the density of hydrogen, is taken as known (0.064 g cm^{-3}) from other bubble chamber experiments.

(1) *Beam count.* The number of beam tracks was estimated in two different ways. In the first beam count tracks within 1° of the "mean beam direction" were counted on every fiftieth picture. In the recount all tracks were counted (on every fiftieth picture) and then the "nonbeam" tracks were counted separately. These counts gave an average of 33.41 ± 0.21 beam tracks per picture, with a net number of pictures $124{,}250\pm250$, giving a total of $(3.82\pm0.02)\times10^6$ tracks for the second run.

(2) *Corrections to beam count.* Some 2000 beam tracks were measured to find the spatial distribution of the beam in the chamber. It was found that $(11.4\pm1.5)\%$ and $(12.2\pm1.0)\%$ of the measured 2000 tracks fell outside the chosen *z* and *y* fiducial limits.

The beam entering the chamber should consist of only π^- particles. In principle, there can be a background consisting of e^-, μ^-, and K^-. From theoretical considerations, it is apparent that the K^- contamination will be entirely negligible, the e^- contamination will be small, but the μ^- contamination will be important, and should be determined experimentally.

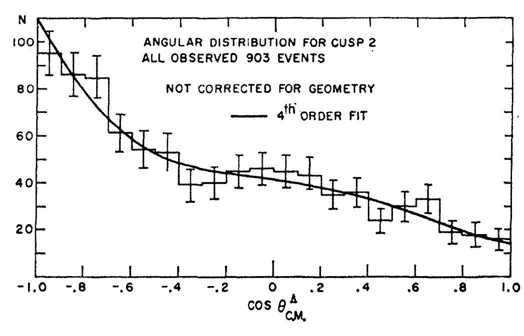

FIG. 3. Observed angular distribution for second run.

To determine the μ^- (and e^-) contamination we scanned for, and measured, all high-energy δ rays produced by the beam tracks. Since the cross sections for the production δ rays of high energies is different for π's, μ's, and e's (see, for example, Rossi[1]), it is possible to determine from the variation of the δ-ray production cross section with energy the fraction of μ's and e's constituting the beam. This was done by measuring all δ rays with energies above 50 MeV, and on a sample of film (5000 pictures) all δ rays with energies above 30 MeV. The result of this analysis is that the μ contamination is $(10.0 \pm 1.7)\%$, and the electron contamination is $\sim 0.3\%$.

Applying these corrections we obtain the corrected beam count of $2.68\times 10^6 (\pm 2.5\%)$ π^- beam tracks in the right fiducial region.

(3) *Event count and corrections.* For the calculation of the total cross section only events with production vertices in the restricted fiducial region (of 20-cm length along the beam track) were chosen. We found 903 such events. To obtain the actual number of associated productions, it is necessary to apply various corrections. These are: scanning efficiency, geometrical corrections, and corrections for the neutral (and hence not visible) decay modes of the Λ's and K's.

The results of the scanning efficiency calculations indicated that the probable number of events missed on both scannings is 2. This correction is not significant, but the result of corrections for geometry (particles which escape from the chamber before decay) and neutral decay modes is that the 903 observed events correspond to 1377 ± 65 actual associated production events in the fiducial region.

(4) *Result.* The total cross section obtained from the above data is $\sigma = 0.67\pm 0.04$ mb where the 6% error includes a 5% error in the number of events, and a 2.5% error in the number of tracks.

C. Polarization of the Λ

To detect any Λ polarization, the up-down, right-left, and fore-aft asymmetries are studied in the Λ decay.

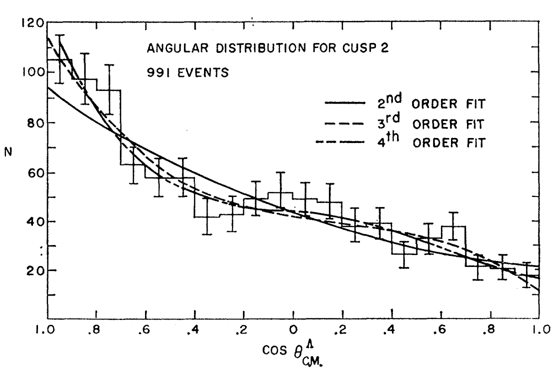

FIG. 4. Angular distribution for second run.

[1] B. Rossi, *High Energy Particles* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1952), p. 14.

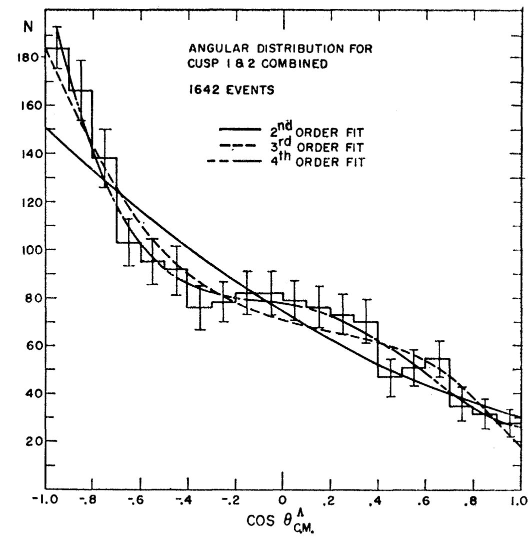

FIG. 5. Angular distribution of all events.

These asymmetries are seen in the distribution of the x, y, and z direction cosines of the decay proton in the center of mass of the Λ in the following coordinate system: $\hat{\pi}$ and $\hat{\Lambda}$ are unit vectors along the incoming π^- and the Λ, respectively; the z axis is chosen along the $\hat{\Lambda}$, the x axis is along $\hat{\pi}\times\hat{\Lambda}$, and the y axis is in the plane of $\hat{\pi}$ and $\hat{\Lambda}$ in such a way that x, y, z form a conventional right-handed system.

Parity nonconservation in the associated production would cause Λ polarization in the plane of production which could be detected by the presence of fore-aft or right-left asymmetry. If parity is conserved in the production then any Λ polarization must be normal to the plane of production, and parity nonconservation in decay of the Λ° would result in an up-down asymmetry.

If we write α for the decay asymmetry of the Λ, and $P(\theta)$ for the polarization of the Λ as a function of the cm production angle of the Λ, we get for the angular distribution of the proton

$$f(\varphi_{ud})\tfrac{1}{2}[1+\alpha P(\theta)\cos\varphi_{ud}],$$

where φ_{ud} is the angle between the Λ decay proton and the x axis, as defined above.

To determine $|\alpha\bar{P}|$, we average over all production angles; denote the number of events with $\cos\varphi_{ud} \gtrless 0$ by U and D, respectively, then

$$|\alpha\bar{P}| = 2(U-D)/(U+D).$$

In the second run we observed 1265 useful Λ's, with $U=829$, $D=436$ giving

$$|\alpha\bar{P}| = 0.62\pm 0.05.$$

A slightly better expression for $|\alpha\bar{P}|$ is

$$|\alpha\bar{P}| = \frac{3}{N}\sum_{i=i}^{N}\cos\phi_{ud},$$

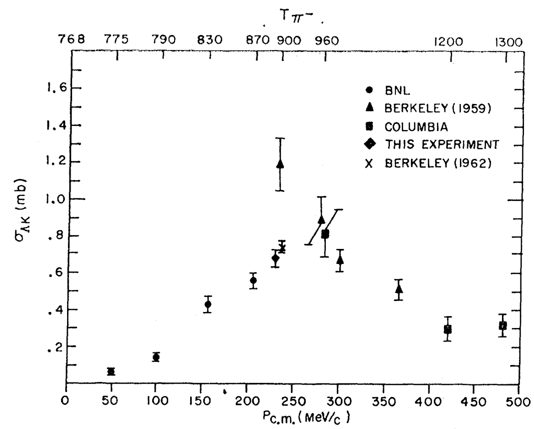

FIG. 6. $\pi^-+p\rightarrow\Lambda+K$ total cross section as a function of π^- energy.

with $\Delta(|\alpha\bar{P}|)\simeq(3/N)^{1/2}$. This gives for the same sample of 1265 Λ's $\alpha\bar{P}=0.58\pm0.03$. This result is to be compared with the value of α obtained by Cronin[2] $\alpha=+0.62\pm0.07$. The comparison indicates that the Λ's are nearly completely polarized normal to the production plane.

The values for the fore-aft and right-left asymmetries are $\alpha_{RL}=-0.04\pm0.07$ and $\alpha_{FA}=+0.10\pm0.07$, indicating that the Λ polarization in the plane of production is consistent with zero, and thus providing absolutely no evidence for parity nonconservation in the strong production process.

[2] J. W. Cronin and O. E. Overseth, Phys. Rev. **129**, 1795 (1963).

D. Leptonic Decays

Among the events which were rejected as normal Λ or K decays, there were found nine K_2 decays and two leptonic Λ decays. The sample of K_2 decays is insufficient for any calculations. One of the Λ decays is a μ decay, and has been reported previously.[3] The second leptonic Λ decay which was found is ambiguous; it fits $\Lambda\rightarrow p+e^-+\nu$ or $\Lambda\rightarrow p+\mu^-+\nu$ equally well.

V. CONCLUSIONS

The total cross section obtained in this experiment has been plotted for comparison with values obtained at various other energies (see Fig. 6).[4]

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[3] F. Eisler, J. M. Gaillard, J. Keren, M. Schwartz, and S. Wolf, Phys. Rev. Letters **7**, 136 (1961).

[4] L. Bertanza, P. L. Connoly, B. B. Culwick, F. R. Eisler, T. Morris, R. Palmer, A. Prodell, and N. P. Samios, Phys. Rev. Letters **8**, 332 (1962); J. A. Anderson, F. S. Crawford, B. B. Crawford, R. L. Golden, L. J. Lloyd, G. W. Neisner, and L. R. Rice, *1962 International Conference on High-Energy Physics at CERN* (CERN, Geneva, 1962), p. 271.