Search for Structure in $\pi^- p \to \Lambda K^0$ at ΣK Threshold*

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We have measured the cross section, the angular distribution, and the Λ polarization for the reaction $\pi^- p \to \Lambda K^0$. A spark-chamber spectrometer was used to collect 8400 ΛK^0 events at fourteen beam momenta near ΣK threshold. Our data do not show the prominent cross-section enhancement suggested by some previous experiments. However, detailed structure in the cross section and the angular distribution agrees well with a simple model which includes a cusp effect at ΣK threshold.

The general properties of threshold, or cusp, phenomena have been understood[1-5] for some time. Although these effects are usually small and difficult to observe, some examples have been found in nuclear reactions[6,7] and $\pi\pi$ scattering at $K\bar{K}$ threshold.[8] Several experiments have sought a cusp in $\pi^- p \to \Lambda K^0$ at ΣK threshold (1033 MeV/c) without conclusive results.[9-12] A recent experiment[13] reported a narrow enhancement of the cross section just below ΣK threshold. We have searched for cusp phenomena in $\pi^- p \to \Lambda K^0$ by systematically measuring the cross section, angular distribution, and polarization as a function of π^- momentum near ΣK threshold.

Our experiment was performed at the Argonne National Laboratory (ANL) zero-gradient synchrotron. Λ's were produced by π^- interactions in liquid hydrogen at fourteen beam momenta between 930 and 1130 MeV/c. The beam momentum was calibrated by measuring the π^+-deuteron time-of-flight difference and the deuteron range at four momenta near ΣK threshold.[14] The momentum width was 10 MeV/c (full width at half-maximum) including the energy loss in the hydrogen target.

Directly produced Λ's and those from $\Sigma^0 \to \Lambda\gamma$ were detected by observing the decay $\Lambda \to p\pi^-$ in an optical spark-chamber magnetic spectrometer.[15] The trigger required (1) neutral production, (2) a slow "proton," and (3) one "pion" (see Fig. 1). A water Cherenkov counter on the proton side vetoed fast particles.

All 140 000 pictures were scanned and rescanned; 20% contained recognizable vees. These were measured at the ANL Applied Mathematics Division by a flying-spot digitizer, "Alice."[16] Track coordinates from Alice were fitted[17] to determine momenta, and the events were then kinematically analyzed. The combined scanning and measuring efficiency is estimated to be $\geq 93\%$.

To eliminate background, the reconstructed vees were subjected to cuts on invariant mass at the decay vertex, coplanarity, production and decay fiducial volumes, and missing mass at the production vertex. Event losses were taken into account by applying the same criteria to Monte Carlo events. The Monte Carlo simulation included the effects of a nonisotropic ΛK^0 produc-

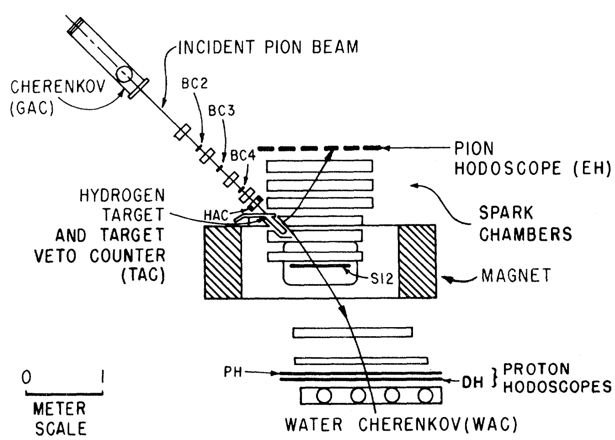

FIG. 1. Plan view of the spark-chamber spectrometer showing a typical $\Lambda \to p\pi^-$ decay. A counter with a 1-in.-diam hole, HAC, was used to define the beam. The liquid-H_2 vessel was surrounded by a veto counter. PH and DH are seven-element hodoscopes. The event trigger = (neutral production) × (proton) × (pion), where (neutral production) = $\overline{\mathrm{GAC}}\cdot\mathrm{BC2}\cdot\mathrm{BC3}\cdot\mathrm{BC4}\cdot\overline{\mathrm{HAC}}\cdot\overline{\mathrm{TAC}}$, (proton) = $\mathrm{S12}\cdot\mathrm{PH}\cdot\mathrm{DH}\cdot\overline{\mathrm{WAC}}$, and (pion) = EH (only one of six).

tion distribution, the full detection geometry, measuring errors, multiple scattering, energy loss, and pion decays in flight. The cut on missing mass at the production vertex separated ΛK^0 and $\Sigma^0 K^0$ events. Less than 2 % of our ΛK^0 sample comes from misidentification of $\Sigma^0 K^0$ events. We note that the beam momentum calibration[14] is verified to a few MeV/c by our reconstructed K^0 mass *and* by the observed onset of $\Sigma^0 K^0$ production at the expected beam momentum.

We have calculated the cross section for $\pi^- p \rightarrow$ neutrals (all neutral final states) from our neutrals counting rate and the incident π^- flux. The flux was corrected for random anticoincidences, π^- interaction losses, beam divergence effects, and a 3% muon contamination.[18] Our neutrals cross section varies smoothly with momentum and agrees well (± 3%) with values from other experiments.[19] We take this to indicate the reliability of our flux calculation and proceed to evaluate the ΛK^0 cross section, $\sigma(\Lambda K^0)$, using the Monte Carlo detection efficiency. The values are given in Fig. 2(a) and in Table I.

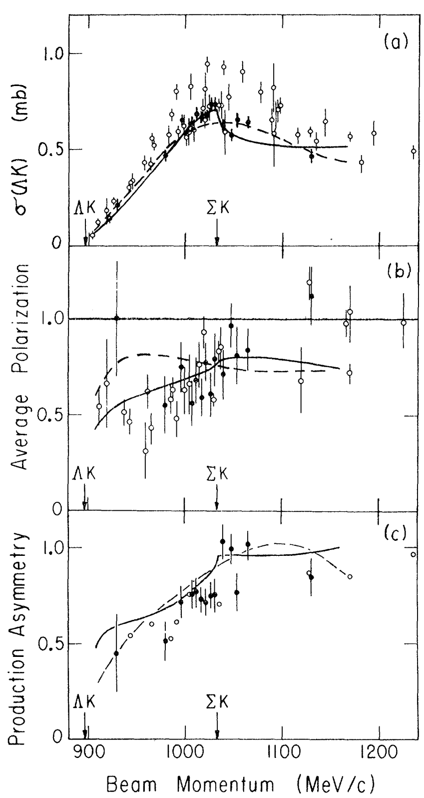

FIG. 2. (a) $\pi^- p \rightarrow \Lambda K^0$ cross section $\sigma(\Lambda K)$; (b) average Λ polarization $\langle P \rangle$; (c) Λ production asymmetry $A_{\Lambda K}$. Open circles, values obtained from Refs. 19, 20, and 21; closed circles, our data; solid and dashed curves, cusp and no-cusp fits, respectively, described in the text.

The 8400 ΛK^0 events were fully reconstructed in the production center of mass, thus allowing us to correct the angular distribution for biases. The average Λ polarization[22] and the Λ backward-forward production asymmetry, $A_{\Lambda K} = 2(B-F)/(B+F)$, are shown in Figs. 2(b) and 2(c). As expected from the intrinsic up-down symmetry of our apparatus, Monte Carlo corrections to the Λ polarization are negligible; corrections to $A_{\Lambda K}$ never exceed our stated (statistical) error and vary only slightly with beam momentum.

Detailed structure is seen in our $\sigma(\Lambda K^0)$ and $A_{\Lambda K}$ data near the ΣK threshold. It is too narrow to be associated with known πN resonances whose widths are typically 100 MeV. We associate the structure with the isospin-$\frac{1}{2}$ ΣK cross section which is rapidly increasing, reaching 60% of its maximum value within 15 MeV/c of threshold. The necessary criteria for this to produce a cusp in the ΛK^0 S-wave amplitude are met as follows: (a) The $I=\frac{1}{2}$ ΣK system is in an S state near threshold[10]; (b) the $\Sigma\Lambda$ relative parity is even[23]; (c) the ΛK^0 system is pure $I=\frac{1}{2}$, and near ΣK threshold is about 50% S wave.[24-26] Sizable cusp effects may be expected since $\sigma(\Sigma K, I=\frac{1}{2}) \approx \sigma(\Lambda K^0)$ not far above ΣK threshold.[20]

Previous analyses[24-26] of $\pi^- p \rightarrow \Lambda K^0$ have found S_{11} and P_{11} resonances to be dominant. In order to make a simple model, we posit that the $S_{11}(1700)$ πN resonance also decays to $|\Sigma K, I=\frac{1}{2}\rangle$ and treat the threshold effect in a manner similar to Flatté *et al.*[8] and to Votava and Thompson.[6] The ΛK^0 S-wave amplitude (with no background)

TABLE I. Summary of cross section, production asymmetry, and average polarization data. The errors quoted are statistical. The overall normalization of $\sigma(\Lambda K)$ is uncertain by ± 10%.

Momentum (MeV/c)	$\sigma(\Lambda K^0)$ μb	$A_{\Lambda K}$	<P>
930	220±23	.45±.22	1.00±.30
980	459±25	.51±.11	.55±.15
997	647±31	.72±.10	.75±.13
1007	617±28	.76±.09	.56±.12
1012	678±31	.77±.09	.68±.12
1017	673±26	.73±.08	.59±.10
1022	666±26	.72±.08	.78±.10
1027	730±28	.75±.08	.61±.10
1031	737±34	.76±.09	.80±.12
1039	616±31	1.03±.10	.71±.13
1048	570±25	.99±.09	.97±.12
1054	652±37	.77±.11	.81±.15
1065	642±26	1.01±.08	.84±.11
1130	454±26	.84±.11	1.12±.15

is written as

$$S_{\Lambda K} = (\Gamma_{\pi p}\Gamma_{\Lambda K})^{1/2}/[2(E_R - E) - i\Gamma_T], \qquad (1)$$

and similarly for ΣK. Here Γ_β is the partial decay width to the channel β, and $\Gamma_T = \Gamma_{\pi p} + \Gamma_{\Lambda K} + \Gamma_{\Sigma K} + \Gamma_x$, where x refers to all other channels. The partial width $\Gamma_{\Sigma K}$ is bq above threshold and $ib|q|e^{-|\xi q|}$ below threshold, where we have introduced the damping parameter ξ below threshold.[27] We fix the proportionality constant b by requiring the $I=\frac{1}{2}$ ΣK cross section to be 550 μb at 1080 MeV/c. Otherwise, our parametrization is that of Ref. 25 with each Breit-Wigner resonance multiplied by an adjustable phase.[26]

We have performed a series of χ^2 fits to our $\sigma(\theta)$ and $\sigma(\theta)P(\theta)$ data (thirty values at each of fourteen momenta for a total of 420 points). Typically, ten parameters were varied. We guided the χ^2 minimization program[28] to find *a priori* reasonable solutions; that is, we required S_{11} and P_{11} to be dominant.

The solid curves in Fig. 2 represent our best fit including the cusp at ΣK threshold. This solution has $\chi^2 = 442$ and a 12% confidence level. A measure of the significance of the threshold effect may be obtained by setting $\Gamma_{\Sigma K} = 0$ and reminimizing χ^2. The resulting χ^2 is 482, and the associated probability is 0.6%. This solution is shown by the dashed curves in Fig. 2. It is important to note that including the cusp improves the fit substantially without introducing additional freedom into the model ($\Gamma_{\Sigma K}$ is fixed by the ΣK cross section) exactly because it produces a simultaneous drop in $\sigma(\Lambda K)$ and rise in $A_{\Lambda K}$ at ΣK threshold.

We conclude that there is no large enhancement in $\sigma(\Lambda K^0)$ at ΣK threshold, but that the observed structure suggests a cusp effect corresponding to the currently accepted associated production amplitudes.

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Direct Production of Electron Pairs by Energetic Protons

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In a study of nuclear collisions produced by 200-GeV protons in emulsion, we have found eight events attributable to the direct production of electron pairs by protons. A crude measure of the cross section, 6.7 ± 2.4 mb, is obtained. This result is viewed in relation to foregoing work on direct pair production by energetic leptons.

In the literature describing direct pair production by fast electrons, a number of experimental and theoretical difficulties appear. Cross-section measurements[1] are subject to large corrections due to competing electromagnetic effects. Calculation of the cross section has been carried out with increasing accuracy,[2,3] the result of Murota, Ueda, and Tanaka[4] being considered the most valid.[5] The theory has been extended to the production of muon pairs.[6,7] Experimental results have been in reasonable agreement with theory, including the $\ln^3 U$ dependence, for primary energies U up to ~100 GeV.[1,8-11] Typically, electron tridents exhibit a created pair, which carries away 5–50% of the primary energy,[8] and a small opening angle similar to ordinary photon conversion pairs of the same energy.

We report here observations of 200-GeV proton-nucleus collisions in emulsion for which the sole visible product is a directly created pair of small (~0.05%) fractional energy transfer and large opening angle. These pairs originate on, and are closely aligned with, the beam proton tracks, under conditions where the competing electromagnetic effects are satisfactorily low.

Ilford K5 emulsions 600 μm thick were exposed to $3\times10^4/\text{cm}^2$ 200-GeV protons[12] with the beam direction parallel to the emulsion plane. The fine grain size of K5 emulsion is valuable for resolving lightly ionized tracks of small separation. Starting at the input edge of the stack, beam tracks were followed in doublets. A criterion of parallelism was applied to each doublet since multiple Coulomb scattering causes no perceptible change in the separation signature of two 200-GeV proton tracks over a path length of 1 cm. Tracks which failed to satisfy the parallelism criterion were identified as contamination, and the level of this was evaluated at $(7\pm2)\%$, of which we estimate no more than $\frac{1}{4}$ was leptonic.

As in similar experiments,[13,14] data on nuclear collisions of beam particles were collected by following beam tracks at scan speeds between 10 and 20 cm/h, but preserving the parallelism requirement for track doublets in order to exclude contamination. The separation signature of a doublet served as a useful mutual reference in the presence of background tracks. Beam doublets were followed for distances up to a maximum 5 cm from the input edge because at greater distances into the stack the background, including electromagnetic cascades with tridents,[1] was found to retard the scan.

In a total beam path of 132 m, 390 nuclear collisions of beam particles were found and, of these, 85 showed no visible nuclear evaporation although the tracks of β particles were often visible. For such "white" stars, all emergent tracks had ionization at or less than the plateau level, corresponding to velocities $>0.85c$. Ten of these white stars showed just three emergent tracks, and eight of these ten were remarkable in the following respects: (a) There was no detectable deflection (>0.1 mrad) of the middle secondary relative to the primary; (b) the outlying secondary (pair) tracks emerged on opposite