particle effects are large. We also observe a positive neighboring correlation when one of the pions is close to the end region, $-2 < y_+ < -1$. This demonstrates clustering of unlike charges at the end regions for low multiplicities.

We have presented inclusive and semi-inclusive correlation distributions for pions produced in 100 GeV/c π^+p and pp interactions. Corresponding distributions from different incident particles (π^+ or p) were shown to be very similar. The inclusive correlation distributions are peaked at $\Delta y = 0$, dropping off by 0.5 from their maximum values when $\Delta y = y_d = 2$. At fixed pion multiplicity, however, there is little or no correlation among like-charged pions, and any clustering of $\pi^+\pi^-$ pairs is associated with leading-particle effects. Therefore, at our energy; the inclusive correlation must arise from the relationship between the multiplicity distribution and the single-particle spectra at each multiplicity, rather than from a tendency for pions to be formed in clusters.

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[1]W. Ko, Phys. Rev. Lett. 28, 935 (1972); R. L. Lander, in *Proceedings of the Seventh Rencontre de Moriond, 1972,* edited by J. Tran Thanh Van (Centre National de la Recherche Scientifique, Paris, 1972).

[2]W. D. Shephard, J. T. Powers, N. N. Biswas, N. M. Cason, V. P. Kenney, and D. W. Thomas, Phys. Rev. Lett. 28, 703 (1972).

[3]E. L. Berger, B. Y. Oh, and G. A. Smith, Phys. Rev. Lett. 29, 675 (1972).

[4]S. Stone, T. Ferbel, P. Slattery, and B. Werner, Phys. Rev. D 5, 1621 (1972).

[5]J. Hanlon, R. S. Panvini, and W. H. Sims, Nucl. Phys. B52, 96 (1973).

[6]R. Singer, Y. Cho, T. Fields, L. G. Hyman, P. A. Schreiner, L. Voyvodic, R. Walker, J. Whitmore, R. Engelmann, T. Kafka, C. Moore, and M. Pratap, Phys. Lett. 49B, 481 (1974).

[7]J. Erwin, J. H. Klems, W. Ko, R. L. Lander, D. E. Pellett, P. M. Yager, and M. Alston-Garnjost, Phys. Rev. Lett. 32, 254 (1974).

[8]J. Erwin, W. Ko, R. L. Lander, D. E. Pellett, P. M. Yager, and M. Alston-Garnjost, University of California at Davis Report No. UCD-PPL-6-15-74 (to be published).

[9]R. F. Amann and P. M. Shah, Phys. Lett. 42B, 353 (1972).

Strange-Particle Production in Neutrino Interactions*

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Seven examples of strange-particle production by neutrinos are observed in the 12-ft bubble chamber. One event represents the first observation of associated production by the weak neutral current.

In this Letter we present data on strange-particle production in neutrino-nucleon interactions. We observe the first associated-production event induced by the weak neutral current, four events of associated production by the charged current, and two strangeness-changing ($\Delta S = \Delta Q = 1$) charged-current events. Although the data sample is small, it nevertheless provides the first glimpse of the threshold behavior of neutrino-induced strange-particle-production cross sections.

The data were obtained from three exposures of the 12-ft bubble chamber to the neutrino beam at the Argonne National Laboratory (ANL) zero-gradient synchrotron. The neutrino flux distribution,[1] which is known to an accuracy of ±15% below 2 GeV and to ±25% above 2 GeV, is shown in Fig. 1. Since it is a low-energy beam, strange-particle production is expected to occur only in the simplest channels. From 365 000 pictures in hydrogen and 580 000 in deuterium, the following reactions were observed in an 11.1-m^3 fiducial volume:

$$\nu_\mu d \to \nu_\mu \Lambda K_s^0(p_s)\ \{\Lambda \to p\pi^-,\ K_s^0 \to \pi^+\pi^-\}\ \text{(1 event)}, \quad (1)$$

$$\nu_\mu d \to \mu^- \Lambda K^+(p_s)\ \{\Lambda \to p\pi^-\}\ \text{(2 events)}, \quad (2)$$

$$\nu_\mu d \to \mu^-\pi^+\Lambda K_L^0(p_s)\ \{\Lambda \to p\pi^-,\ K_L^0 \to \pi^+\mu^-\bar{\nu}\}\ \text{(1 event)}, \quad (3)$$

$$\nu_\mu p \to \mu^- p K^+ K_s^0 \pi^0\ \{K^+ \to \mu^+ \nu,\ K_s^0 \to \pi^+\pi^-\}\ \text{(1 event)}, \quad (4)$$

$$\nu_\mu d \to \mu^- p K_s^0(p_s)\ \{K_s^0 \to \pi^+\pi^-\}\ \text{(1 event)}, \quad (5)$$

$$\nu_\mu p \to \mu^- p K^+. \quad (6)$$

More than 80% of the film was double-scanned; the scanning efficiency for events of the above reactions is greater than 90%. The candidates for Reactions (1)–(6) were measured in three views and processed through the standard ANL versions of the TVGP-SQUAW geometrical-reconstruction and kinematic-fitting programs. The K_s^0 and Λ momenta were determined from three-constraint kinematic fits to the decay vertex; the K_L^0 decay is a zero-constraint fit. At the primary neutrino-interaction vertex, the neutrino beam direction is known to be 1°, so that Reactions (2), (3), (5), and (6) can be analyzed by three-constraint fits[2] and Reactions (1) and (4) by zero-constraint calculations.

The candidate for Reaction (1), as shown in Fig. 2, consists of two vees, neither of which points back to the vertex of the other. From one-constraint fits to these K_s^0 and Λ decays, the directions of the strange particles are determined. From repeated measurements of the event, the distance of closest approach of the two neutral trajectories is 0.10±0.10 cm. The flight paths of the K_s^0 and Λ are 8.0 and 5.5 cm; these distances correspond to 1.8 and 1.0 lifetimes, respectively. At the "interaction vertex" no proton spectator is visible; for comparison, we note that in our $\nu d \to \mu^- p(p_s)$ events in the same film, only 30% of the spectators are visible.[3] In order to test quantitatively the hypothesis that the K^0 and Λ originated from a common vertex, a three-vertex kinematic fit was performed. The unknowns were the x, y, and z coordinates of the primary vertex, and the K^0 and Λ energies. The χ^2 probability for the three-constraint fit is an acceptable 30%. Finally, we note that the presence of one or more π^0's in the final state cannot be excluded, but because the neutrino flux distribution falls steeply with increasing energy, one would expect such final states to be suppressed; the event could also be a $\nu K^0\Sigma^0$ final state.

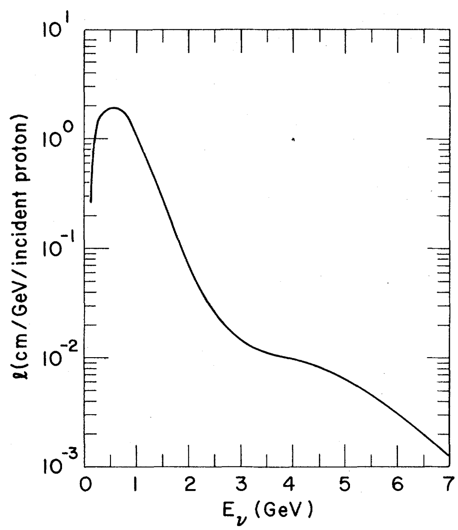

FIG. 1. Neutrino energy spectrum in units of path length per GeV neutrino energy per incident proton.

While any background or ambiguities to Reactions (2)–(6) are certainly negligible (except for the Λ/Σ^0 ambiguity), one must seriously consider the possibility that the zero-constraint fit with Reaction (1) is really due to a neutron-induced process such as

$$nd \to n\Lambda K^0(p_s),$$
$$nd \to n\Sigma^0 K^0(p_s), \quad (7)$$
$$nd \to n\Lambda K^0\pi^0(p_s).$$

The magnitude and general directional properties

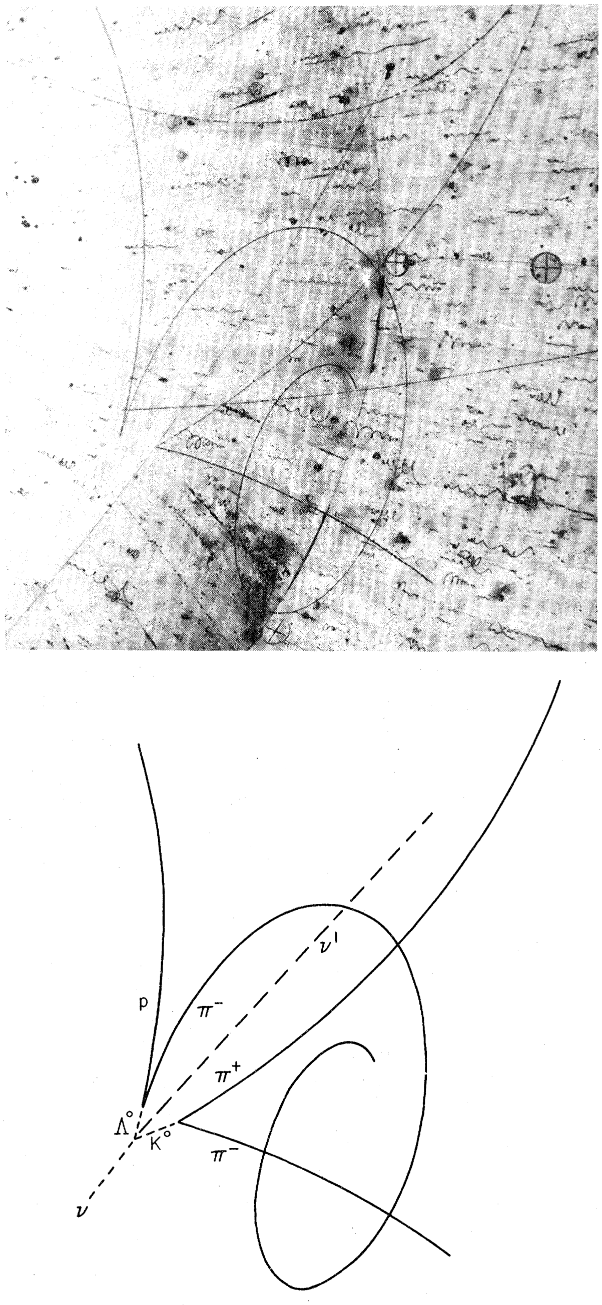

FIG. 2. (a) Photograph of the $\nu n \to \nu\Lambda K^0$ event. Note the presence of a cosmic ray leaving the chamber bottom and a wire which is stretched across the chamber. In real space, the cosmic track is $\frac{1}{2}$ m away from the $\nu\Lambda K^0$ event. (b) The charged particles are represented by solid lines and the neutral particles by dashed lines.

of the neutron background are measured by using one-constraint fits with the reaction $nd \to pp\pi^-(n_s)$. These events were found as part of the regular three-prong scan of the film; their properties have been presented elsewhere.[4] Using the twelve $pp\pi^-(n_s)$ events and the measured cross sections[5] for the charge-symmetric reactions to (7), such as $pp \to p\Lambda K^+$, we determined the neutron-induced background to be only 0.021 ± 0.016 events. Other possible backgrounds due to associated production by photons and $K_L{}^0$'s, antineutrino-induced strangeness-changing reactions, and charged hadrons that enter the chamber and scatter have been determined to be much less than the neutron-induced background and hence negligible. There is no background from charged-current neutrino interactions since the absence of a muon at the production origin is clearly evident. The probability that this event is due to background processes is thus 2%. This event by itself establishes the existence of neutral currents and demonstrates for the first time that weak neutral currents can mediate associated production.[6]

One of the events which are fitted by Reaction (2) is also fitted by $\nu d \to \mu^-\Lambda\pi^+(p_s)$. Because the π^+ has momentum 862 ± 11 MeV/c and leaves the chamber without any secondary interaction, we are not able to resolve directly the π^+/K^+ mass ambiguity. But since the kinematic χ^2 probability for hypothesis (2) is 6 times larger than that for $\mu^-\Lambda\pi^+(p_s)$ and since the reaction $\nu d \to \mu^-\Lambda\pi^+(p_s)$ would violate the $\Delta S = \Delta Q$ rule, we accept only the $\mu^-\Lambda K^+(p_s)$ hypothesis. The K^+ track in the $\mu^- pK^+$ event is 1.2 m long and has a measured momentum of 379 ± 9 MeV/c; the pion and proton mass assignments can be excluded by comparing the measured track shape with shapes calculated on the basis of energy loss (dE/dx) in the liquid. The bubble density of the tracks in all the events is consistent with that predicted by the mass assignments in the kinematic fits.

We measure the neutral-current to charged-current cross-section ratio to be

$$\sigma(\nu\Lambda K^0)/\sigma(\mu^-\Lambda K^+) = 1.5 \pm 1.5,$$

which suggests that perhaps associated production in neutral currents is stronger than in charged currents, since the neutral- to charged-current overall rate is 1 to 5.[7]

Furthermore, the cross-section ratios of charged-current ΛK and $\Delta S = 1$ production to charged-current pion production are

$$\frac{\sigma(\nu n \to \mu^-\Lambda K^+)}{\sigma(\nu N \to \mu^- N(m\pi))} = 0.04 \pm 0.03$$

and

$$\frac{\sigma(\nu N \to \mu^- pK)}{\sigma(\nu N \to \mu^- N(m\pi))} = 0.03 \pm 0.03,$$

TABLE I. Properties of the strange-particle events.

Reaction	E_ν (GeV)	$-q^2$ $[(\mathrm{GeV}/c)^2]$	$\frac{E_\nu - E_l}{E_\nu}$	Hadronic mass (GeV)	Approximate Λ, K detection probability
$\nu_\mu n \to \nu_\mu \Lambda K^0$	2.05 ± 0.45	0.19	0.68	1.819	2/9
$\nu_\mu n \to \mu^- \Lambda K^+$	1.73 ± 0.02	0.10	0.72	1.824	2/3
	2.29 ± 0.02	0.42	0.62	1.753	2/3
$\nu p \to \mu^- p K^+ \bar{K}^0 \pi^0$	5.52 ± 0.40	2.72	0.91	2.748	1/3
$\nu_\mu n \to \mu^- \pi^+ \Lambda K^0$	5.81 ± 0.10	0.59	0.54	2.493	a
$\nu_\mu n \to \mu^- p K^0$	1.59 ± 0.02	0.09	0.45	1.442	1/3
$\nu_\mu p \to \mu^- p K^+$	6.13 ± 0.13	0.20	0.12	1.445	1

[a]The K_L^0 particle in this event travels 1.2 m before decaying. Calculating the relative probability of a $K_L^0 d$ scatter to a K_L^0 decay, we suspect that the K_L^0 has scattered before its decay. This would also explain the absence of $\mu^- \pi^+ \Lambda K_s^0$ events in our experiment.

where $m \geq 1$. In calculating these ratios, we have only considered the neutrino energy interval 1.5 to 3.0 GeV, where our flux is of reasonable magnitude; in this interval, the average neutrino energy is 2.0 GeV. The observation of $\Delta S = 1$ processes implies the presence of a nonzero antiquark component in the nucleon.[8]

The fitted neutrino energy, the four-momentum transfer q^2 between the leptons, the energy transfer between the leptons, the invariant hadronic mass, and the strange-particle detection efficiency are given for each event in Table I. The q^2 values are small (except for the $K\bar{K}$ event) as one would expect from the usual hadronic form factors. The values of the three ΛK invariant masses are consistent with distributions seen in hadron-hadron scattering experiments. In contrast, the pK masses from Reactions (5) and (6) are both only ~10 MeV above threshold; this possible threshold peaking is not understood.

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[1]J. Campbell *et al.*, Phys. Rev. Lett. 30, 335 (1973).

[2]This assumes that the spectator nucleon is visible and can be measured. For unseen spectators, the nucleon is given 0 ± 50 MeV/c for the x, y, and z momentum components.

[3]W. A. Mann *et al.*, Phys. Rev. Lett. 31, 844 (1973).
[4]S. J. Barish *et al.*, Phys. Rev. Lett. 33, 448 (1974); S. J. Barish, Argonne National Laboratory Report No. ANL/HEP 7418 (unpublished).
[5]E. Bracci *et al.*, CERN Report No. CERN/HERA 73-1, 1973 (unpublished).

[6]In addition to this two-vee event, we also observe six single-vee events which give a good one-constraint fit with $\Lambda \to p\pi^-$ in which the negative track is identified as a π^-. Two of these Λ's are produced more than 90° from the ν beam direction and, therefore, cannot be due to Reaction (1); we believe that they are produced by the processes $K_L^0 n \to \Lambda\pi^0$ or $\Sigma^0\pi^0$ since we have observed two events of the reaction $K_L^0 p \to \Lambda\pi^+$. If the K^0's have no preferred direction, one would the expect 2 ± 2 single-Λ events to be due to Reaction (1). We have also searched for the process $\nu_\mu p \to \nu_\mu \Lambda K^+$ but have found no unique candidates.

[7]F. Hasert *et al.*, Phys. Lett. 46B, 138 (1973); B. Aubert *et al.*, Phys. Rev. Lett. 32, 1454 (1974).
[8]D. Perkins, in ***Proceedings of the Sixteenth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, 1972,*** edited by J. D. Jackson and A. Roberts (National Accelerator Laboratory, Batavia, Ill., 1973), Vol. 4, p. 189.

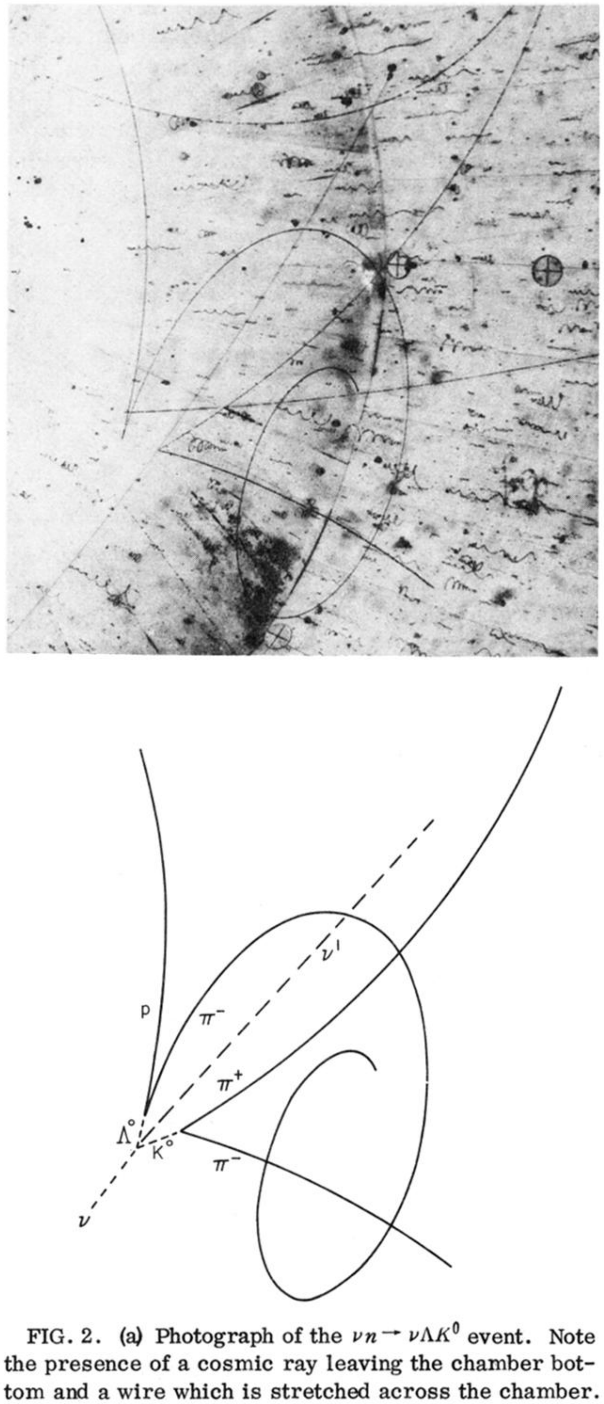

FIG. 2. (a) Photograph of the $\nu n \rightarrow \nu \Lambda K^0$ event. Note the presence of a cosmic ray leaving the chamber bottom and a wire which is stretched across the chamber. In real space, the cosmic track is $\frac{1}{2}$ m away from the $\nu \Lambda K^0$ event. (b) The charged particles are represented by solid lines and the neutral particles by dashed lines.