PHYSICAL REVIEW D VOLUME 5, NUMBER 11 1 JUNE 1972

Negative-Kaon–Hydrogen Charge-Exchange Scattering at 1.8 GeV/c*†

Norman D. Sossong‡ and Robert Ellsworth§
Department of Physics, University of Washington, Seattle, Washington 98105

and

James R. Carlson,‖ Howard F. Davis, and Delbert E. Jauch**
Department of Physics, Oregon State University, Corvallis, Oregon 97331
(Received 10 May 1971)

An experiment measuring the differential cross section for K^-p charge-exchange scattering was done at 1.8 GeV/c. The results of the neutral-trigger spark-chamber detection scheme gave 2610 events with neutral mass range 900–1700 MeV. The results were fitted to Legendre polynomials to order 7 for $d\sigma/d\Omega$. The results are significant to order 6 for $d\sigma/d\Omega(K^-p \to \bar{K}^0 n) = \sum_n a_n P_n(\cos\theta^*)$; $a_0 = 52 \pm 6$, $a_1 = 112 \pm 14$, $a_2 = 122 \pm 23$, $a_3 = 106 \pm 22$, $a_4 = 84 \pm 26$, $a_5 = 59 \pm 18$, $a_6 = 26 \pm 19$. Earlier data show a dip in the forward $d\sigma/d\Omega$; no such dip is evident from the data of this experiment. The results of this experiment in the forward direction are not inconsistent with an absorption-model modified ρ-exchange mechanism for the charge-exchange process.

I. INTRODUCTION

During the past decade K^-p charge-exchange experiments have been performed over a wide range of incident beam momenta.[1-24] The $d\sigma/d\Omega(K^-p \to \bar{K}^0 n)$ seems to follow a regular pattern of change as the incident momenta increase. At 1.8 GeV/c (Ref. 13) and at 2.45 GeV/c (Ref. 16) it was noticed that there was measured a $d\sigma/d\Omega$ with a distinct dip in the forward direction, i.e., for minimum $-t$. This differed from the regular pattern at neighboring momenta. This dip was also not consistent with a simple vector-meson-exchange model. The data on $d\sigma/d\Omega(K^-p \to \bar{K}^0 n)$ from the measurements of this experiment do not have this somewhat anomalous forward dip. This experiment's data at 1.8 GeV/c in fact give credence to ρ exchange in $K^-p \to \bar{K}^0 n$ at this intermediate momentum.

The data were collected in a counter-spark-chamber experiment run at the Bevatron. The details of the 1.8-GeV/c K^- enriched negative-meson beam are described elsewhere.[25] The useful negative-kaon beam was focused to pass through a series of beam-defining counters (Fig. 1). It then passed through an ethylene differential Čerenkov counter which selected K^-/π^- electronically to $\gtrsim 10^2/1$. The physical K^-/π^- ratio at the liquid-hydrogen target was ~1/10. The beam spread was ±5%.

II. EXPERIMENT

The negative-kaon–proton interactions occurred in the liquid-hydrogen target, LH_2. The LH_2 consisted of a cylindrical flask ~15 cm long and ~5 cm in diameter (Fig. 2). The LH_2 was ~1 g/cm^2 of liquid hydrogen in the kaon beam path. Scintillation counter detectors formed a cylinder, closed on one end, around the LH_2 flask. Except for those in the most backward hemisphere this cup-shaped detector subtended almost all the solid angle for particles originating in the LH_2. This detector was used to detect and electronically veto-out charged particles which: (1) entered the liquid hydrogen but passed straight through without interacting; (2) scattered out elastically; (3) originated from inelastic interactions with particles at the production vertex. The inefficiency of the "bottom of the cup," a disk-shaped element in the kaon beam, T_3, was measured to be ≤0.06%. The "sides of the cup," a cylindrically shaped element coaxial to the kaon beam, T_2, had a measured inefficiency of ≤4%.

The negative-kaon beam was defined by the ethylene differential Čerenkov detector and a series of four scintillation detectors placed upstream to the LH_2 flask, (Fig. 2). The placement of the thin scintillation detector just upstream of the LH_2 was critical to the realization of high veto efficiency of the noninteracting kaons. The function of the other beam-defining detectors is evident from their physical placement and their use in the electronic logic (Table I).

The neutral-particle production was partially separated from charged-particle production by using the cup-shaped detectors surrounding the LH_2 in the veto-logic mode.

The detection of $K^-p \to \bar{K}^0 n$ through the $\bar{K}^0 \to \pi^\pm$ channel was effected by using the vertical double-plane picket-shaped hodoscope configuration of scintillation detectors (Fig. 3). The electronic

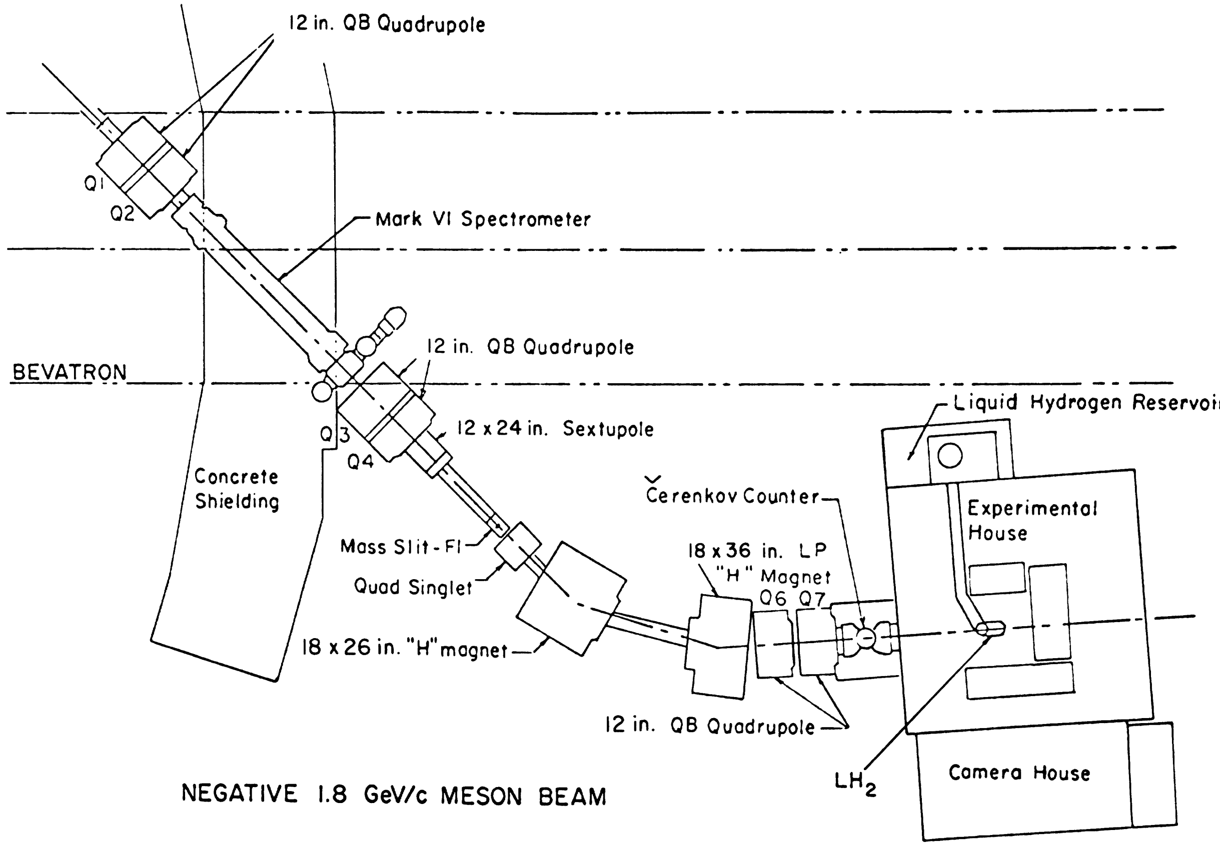

FIG. 1. Details of the 1.8-GeV/c K^- enriched negative-kaon beam.

logic determined that two or more of the 5-cm-wide narrow pickets were triggered within a 30-nsec gate generated by a kaon beam particle associated with no charged particles passing through the cup-shaped detector around the LH_2. This detector-electronic logic system was partially effective in selecting single-prong events associated with $\bar{K}^0 \to \pi^\pm$. Film scanning and measuring of the spark-chamber pictures of these events was used to select the true events as well as to supply the measurements from which the $K^- p \to \bar{K}^0 n$ angular distribution was determined.

Incident kaon beam particles and the $\bar{K}^0 \to \pi^\pm$ charged particles from $K^- p \to \bar{K}^0 n$ were detected in an array of six spark chambers.[26] Two were located upstream of LH_2. Four were located between the LH_2 and the hodoscope detectors (Fig. 1). The chambers were designed to subtend $\gtrsim 2\pi$ sr of the solid angle for particles originating near the LH_2. Fiducial markers, event numbers, and some electronic logic information on coded lights were recorded with this particle spark-track data on 70-mm film for later scanning and measuring. The cameras were located above and to the side of the particle detectors. The individual tracks were recorded by approximately 90° stereo views by using

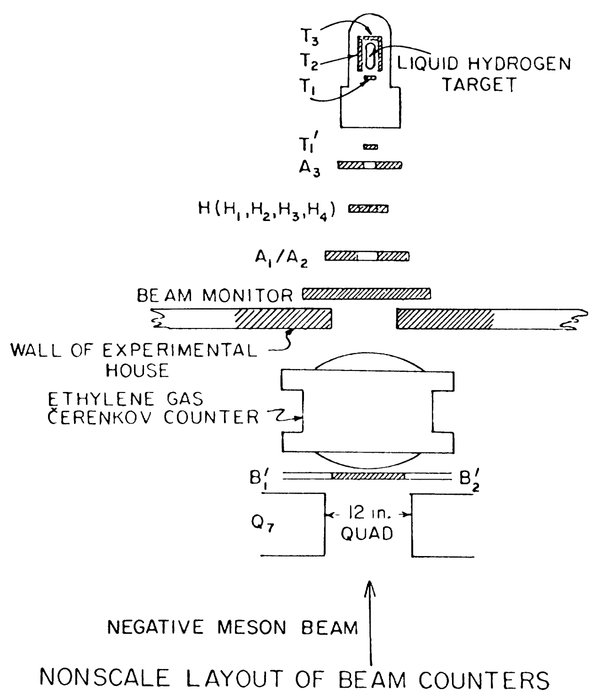

FIG. 2. Layout of ethylene differential-Čerenkov counter, K^- beam counters, and LH_2.

TABLE I. Basic electronic logic definition of negative-kaon–hydrogen charge-exchange reaction. See Figs. 1, 2, and 3.

Negative meson (π^- or K^-)	$\underline{MESON}=B'$. NOT. $A_{1,2}$. AND. H. NOT. A_3
Negative kaon (C = Čerenkov)	$\underline{K^-}=C$. AND. MESON
Negative-kaon-induced (neutral) interaction in LH_2	$\underline{K_R^-}=K^-$. AND. T_1. NOT. T_3 OR $=K^-$. AND. T_1. NOT. (T_2. OR. T_3)
Use of FAN-INs, LINEAR GATES, and DISCRIMINATORS gave an output pulse for two coincident picket counter pulses	$\underline{\bar{K}^0}$
$K^-p\to\bar{K}^0n$ charge-exchange triggering condition	$\underline{EVENT}=\bar{K}^0$. AND. K_R^-

one or more side mirrors to realize this stereo viewing.

III. DATA

The data were taken in two different modes. Most of the data were taken with both $\overline{T}_2$ and $\overline{T}_3$ used to electronically veto charged particles. A small part of the data was taken using only $\overline{T}_3$ to electronically veto charged particles.

The data from the two modes were analyzed separately to accommodate the different detector acceptance for these two modes called "$\overline{T}_2$ or $\overline{T}_3$" and "$\overline{T}_3$ only." Approximately 2.8×10^4 pictures were taken in the "$\overline{T}_2$ or $\overline{T}_3$" mode and the remaining were taken in the "$\overline{T}_3$ only" mode. In the "$\overline{T}_2$ or $\overline{T}_3$" mode there were 1320 K^-'s/master trigger. In the "$\overline{T}_3$ only" mode there were 235 K^-'s/master trigger. The total number of K^-'s incident upon the target was estimated to be 21×10^6 for the "$\overline{T}_2$ or $\overline{T}_3$" mode and 2.9×10^6 for the "$\overline{T}_3$ only" mode.

The $K^-p\to\bar{K}^0n$ event scanning selected events with one incident beam track and two outgoing divergent tracks. Events were accepted for measurement if they also included a "straightthrough"

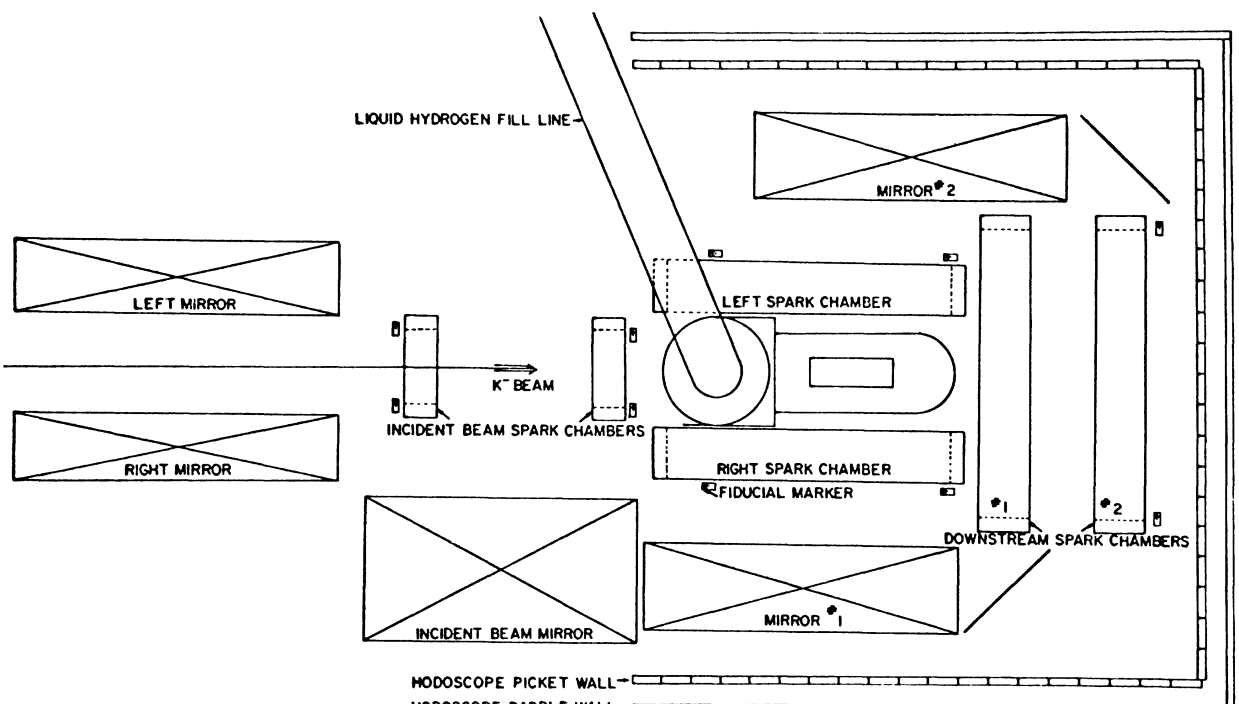

FIG. 3. Layout of K^- beam and $\bar{K}^0\to2\pi$ spark chambers, $\bar{K}^0\to2\pi$ hodoscopes, and LH_2.

parallel to the kaon beam or a "stray track" no LH_2 originated. These "extra" tracks were ignored in the event-track measurements. In "marginal" cases the event was included rather than excluded. Non-$K^-p\to\bar{K}^0n$ events were discarded from measurements based upon geometrical or kinematical criteria.

The $K^-p\to\bar{K}^0n$ event measuring was done on the LRL SCAMP.[27] This is a film-plane digitized machine with a fixed format magnetic tape output. The least count of SCAMP is 1 μ. This corresponds to ~0.06 mm in laboratory space. The optical lab/film demagnification was ~60 : 1. A measurement accuracy of about 5 μ could be realized. A typical measurement accuracy was 10 μ.

The film event editing, track spatial reconstruction, and event kinematical fitting was done in three stages using programs EDITOR, GEOMET, and KINEMM. The events from the SCAMP measuring machines were checked. Events that contained "obvious" errors were eliminated.[28]

These edited measured events were digitized in SCAMP measuring machine's coordinates. Parameters obtained from surveyed values of the fiducials were used to calculate the event-track coordinates in the laboratory coordinate system.

IV. ANALYSIS

Further geometrical reconstruction and some kinematical fitting were done by KINEMM. Vertices of "V's" from $\bar{K}^0\to\pi^++\pi^-$ candidates were determined. Events with acceptable separation distance between the π^+,π^- track pair, which were associated with a neutral link from the point of negative-kaon-beam interaction in LH_2 target, were preserved for kinematical analysis. The kinematics of $K^-p\to\bar{K}^0n$ reconstruction are summarized in Fig. 4. The kinematical analysis of event reconstruction was based on the following pattern: (1) a single clear beam track was identified; (2) a pair of nonbeam tracks were identified; (3) the vertex of the secondary pair of nonbeam tracks was measured through a criterion for minimum distrace of closest approach for the extrapolated nonbeam tracks; (4) the intersection of the V plane with the beam track had to lie within the hydrogen target, and the beam-track V combination had to be structurally consistent with a possible $\bar{K}^0n$ event; (5) now assuming the tracks are consistent with a $K^-p\to\bar{K}^0n$ event the momentum of the $\bar{K}^0$ and the MM of $K^-p\to\bar{K}^0$MM are calculated. This is the MM distribution of Fig. 4.

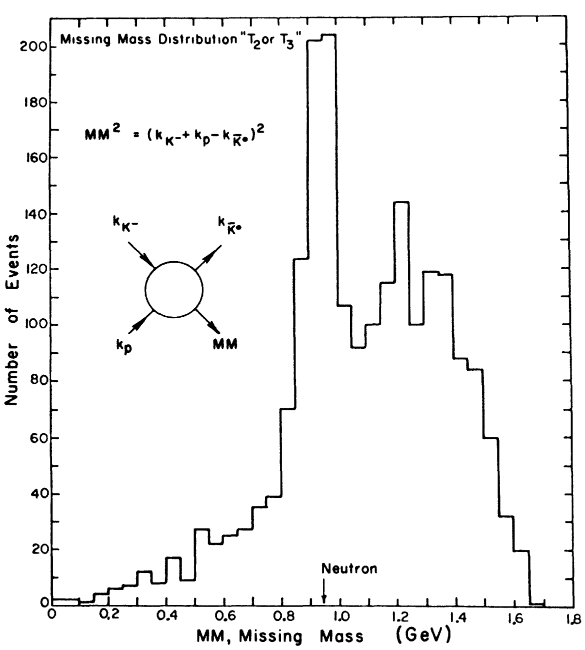

FIG. 4. Missing-mass distribution before cuts for "$\bar{T}_2$ or $\bar{T}_3$" trigger mode. (Insert: kinematics of $K^-p\to\bar{K}^0n$ reconstruction.)

About 7203 events were measured. Of these, 4534 were successfully geometrically reconstructed. About one fourth of the events had the reconstructed point of the negative-kaon-beam interaction point outside the LH_2. This left 3331 acceptable events. Of these 3331 "target originated" events, 2023 of the "$\bar{T}_2$ or $\bar{T}_3$" mode events and 587 of "$\bar{T}_3$ only" mode events gave positive values for the missing mass assuming $K^-+p\to\bar{K}^0+$MM. The ensembles of these missing masses, MM, are shown in Figs. 4 and 5.

The neutron peak, MM $\simeq$ 940 MeV, is clear. The spread in the neutron peak arose from several sources including (1) track measuring errors, (2) the physical jitter of the sparks in the spark chamber which caused the particle tracks to be imperfect lines, and (3) uncertainty introduced by assumming the momentum of the incident kaon to be 1.8 GeV/c when, in fact, there was a spread in the beam momentum of full width at half maximum, FWHM, of approximately 45 MeV/c. The spread

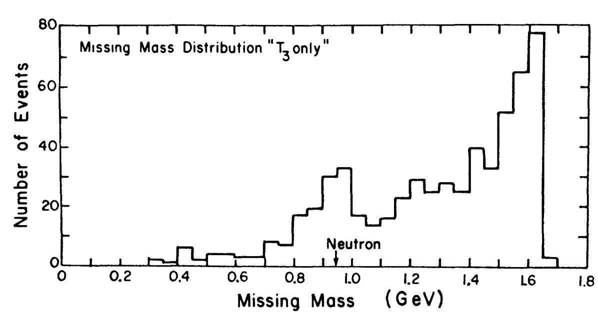

FIG. 5. Missing-mass distribution before cuts for "$\bar{T}_3$ only" trigger mode.

in the neutron peak originating from all these sources was calculated by the Monte Carlo technique (Fig. 6). The cuts for the neutron peak, to select $K^-p\to\overline{K}^0n$ events, were taken at 840 MeV and 1040 MeV. To select $K^-p\to\overline{K}^0n$ events, it was necessary to take into consideration background reactions which could simulate the trigger mode and topology of the $K^-p\to\overline{K}^0n$ reaction. Background reactions include the following final-state two-body reactions:

$$\overline{K}^0+\Xi^0\,, \tag{1}$$

$$\overline{K}^{0*}+n\,, \tag{2}$$

$$\Lambda+\pi^0\,, \tag{3}$$

and

$$\Sigma^0+\pi^0\,; \tag{4}$$

and the multiparticle final states

$$\overline{K}^0+n+(N)\pi^0\,, \tag{5}$$

$$\overline{K}^{0*}+n+(N)\pi^0\,, \tag{6}$$

$$\Lambda+\pi^0+(N)\pi^0\,, \tag{7}$$

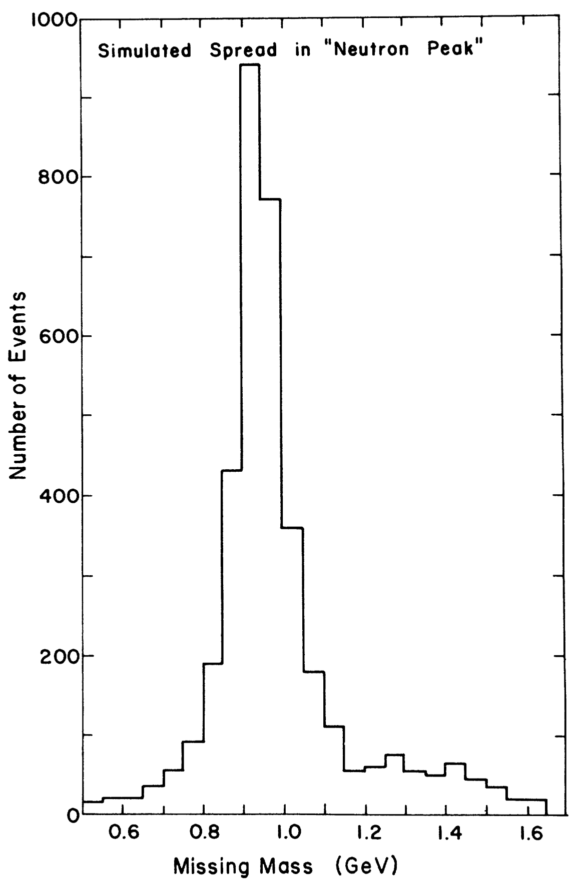

FIG. 6. Monte Carlo-simulated spread in $\overline{K}^0n$ "neutron peak" due to spread in beam momentum, track measuring errors, and intrinsic spark jitter.

and

$$\Sigma^0+\pi^0+(N)\pi^0\,. \tag{8}$$

Reaction (1) has a small cross section (~75 μb at 1.8 GeV/c).[29] It may give four charged particles, thus further lowering the probability of seeing it in the $\overline{K}^0n$ simulation. Reaction (5) would not need to be considered further; it cannot simulate $\overline{K}^0n$ with the n mass inside the experimental resolution for the n mass. The MM resolution varies slowly with $\cos\theta^*$. Reaction (5), $K^-p\to K^0n(N\pi^0)$, does not contribute to $K^-p\to\overline{K}^0n$ over any of the range of the neutron peak. It lies entirely outside of the neutron peak both at the forward and intermediate angles of $\overline{K}^0$ production.

The missing mass for events arising from reaction (2) is higher than the neutron peak and thus it does not simulate $\overline{K}^0n$. Similarly, reaction (6) does not contribute to the $\overline{K}^0n$ "neutron peak."

Reactions (3), (4), (7), and (8) all contributed to the $\overline{K}^0n$- "neutron peak" simulation. Data on these reactions near 1.8 GeV/c are sparse. Based upon experiments done at 1.2 GeV/c (Ref. 9) and at 2.24 GeV/c (Ref. 15), an approximation to the partial cross sections was obtained. A linear interpola-

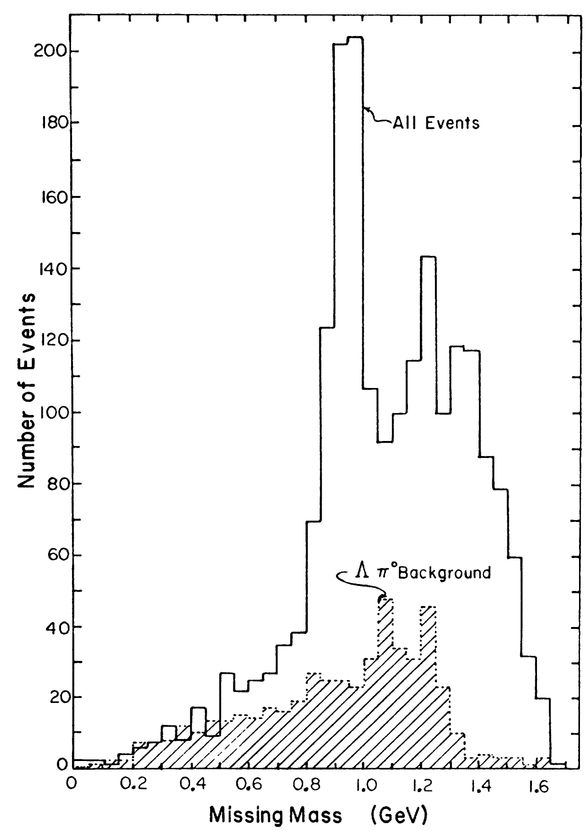

FIG. 7. The nonbackground corrected missing-mass distribution for all events for both trigger modes, and the Λ-π zero background that was subtracted.

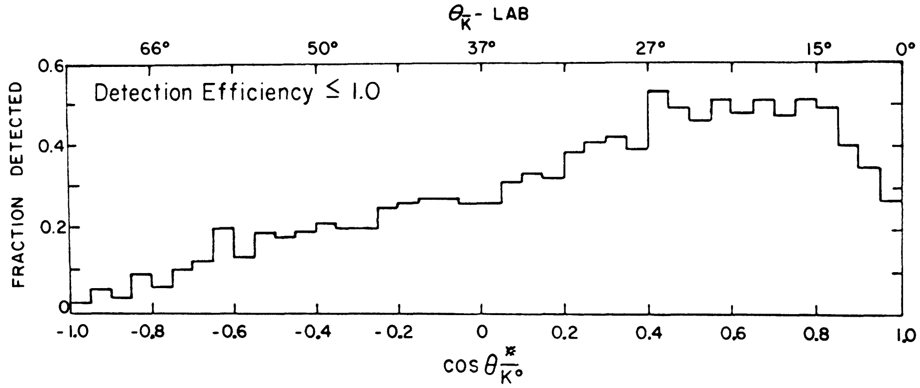

FIG. 8. Monte Carlo-generated detection efficiency for $K^-p \to \bar{K}^0 n$ for the experimental set up shown in Fig. 3.

tion gave $\sigma(\Lambda^0 + \text{neutrals}) + \sigma(\Sigma^0 + \text{neutrals}) \leq 1.2$ mb. An extrapolation of the data at 1.2 GeV/c indicated that $\sigma(\Sigma^0 + \pi^0) \simeq 0.4$ mb at 1.8 GeV/c. Data on (3) at 1.7 GeV/c (Ref. 11) indicated it was ~0.9 mb at 1.8 GeV/c. A Monte Carlo study of the background reaction, if the four partial cross sections were the same, showed that (3) gave the largest fractional simulation to the neutron peak. Using the production angular distribution from data at 1.7 GeV/c (Ref. 23), (3) was simulated as it would have been detected. The background summarized in Fig. 7 and at the lower end of the missing-mass spectrum was primarily from reaction (3). A subtraction was made for this background. A corresponding subtraction was then made in the angular distributions. Only reactions (3), (4), (7), and (8) can produce a background that would lie within the neutron peak of $K^-p \to K^0 n$. None of these reactions

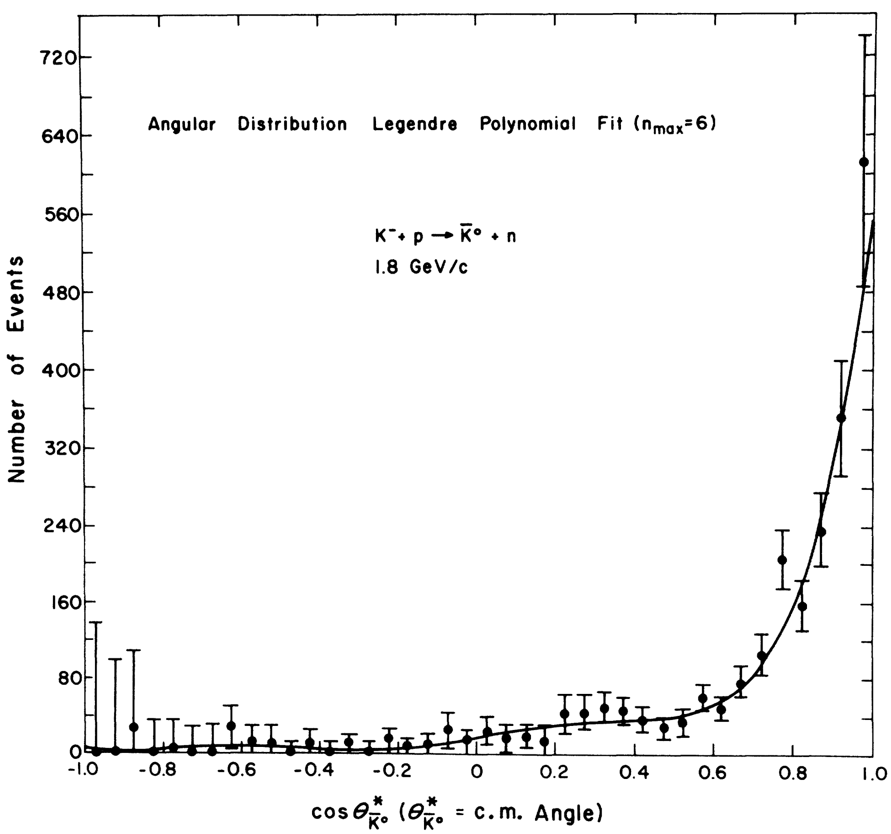

FIG. 9. The final corrected $K^-p \to \bar{K}^0 n$ differential cross section at 1.8 GeV/c (experimental points with error bars) fitted to Legendre polynomials through $P_6(\cos\theta^*)$.

TABLE II. Coefficients and errors for Legendre polynomial fit.

$l_{\max}$	P_5 $a_i \pm \Delta a_i$	P_6 $a_i \pm \Delta a_i$	P_7 $a_i \pm \Delta a_i$
a_0	48.5 ± 5.1	52.3 ± 5.9	52.7 ± 5.9
a_1	114 ± 14	112 ± 14	113 ± 17
a_2	102 ± 17	122 ± 23	122 ± 23
a_3	112 ± 22	106 ± 22	108 ± 29
a_4	55.4 ± 15	84.1 ± 26	83.8 ± 27
a_5	62.4 ± 18	58.5 ± 18	60.5 ± 29
a_6		25.9 ± 19	25.7 ± 19
a_7			1.75 ± 20
χ^2	18.7	16.4	16.9
Degrees of freedom	34	33	32
Confidence level	98.1%	98.8%	98.3%

produces a peak. Rather their contribution is quantitatively small and not artificially enhanced in the important neutron-peak area. Although the cross sections for these reactions are not known well at 1.8 GeV/c they are known well enough to accurately correct their contribution to the neutron peak of $K^0 p \to \bar{K}^0 n$.

A Monte Carlo calculation of the instrument detection efficiency, $\eta(\bar{K}^0 n)$, for $K^- p \to \bar{K}^0 n$ (fraction of events detected per interval of $\cos\theta^* = 0.05$) is shown in Fig. 8. This efficiency was then folded into the background-corrected data. The characteristic biases for the two trigger modes, "$\bar{T}_2$ or $\bar{T}_3$" and "$\bar{T}_3$ only," were determined. The final result is in Fig. 9.

V. RESULTS AND CONCLUSIONS

The $d\sigma/d\Omega(K^- p \to \bar{K}^0 n)$ data were fitted to the Legendre-polynomial series

$$f(\cos\theta^*) = \sum_n a_n P_n(\cos\theta^*).$$

These results are in Table II. An examination of the $f(\cos\theta^*)$ with the a_n coefficients, Table II, indicates that terms through order 5 are essential. Terms through order 6 are significant. The $K^- p \to \bar{K}^0 n$ data are thus adequately fitted with Legendre polynomials if one includes terms up to and including $P_6(\cos\theta^*)$. See Fig. 9. This curve is based on the data in this experiment and thus is on a relative scale.

It should be noted that there was a low detection efficiency for neutral K's for $\theta_K > 75°$ (Fig. 8). The absence of backward $\bar{K}^0$'s in this experiment is thus not regarded as significant.

At two intermediate momenta, 1.8 GeV/c (Ref. 13) and 2.45 GeV/c (Ref. 16), $d\sigma/d\Omega(K^- p \to \bar{K}^0 n)$ has a significant dip in the number of events in the

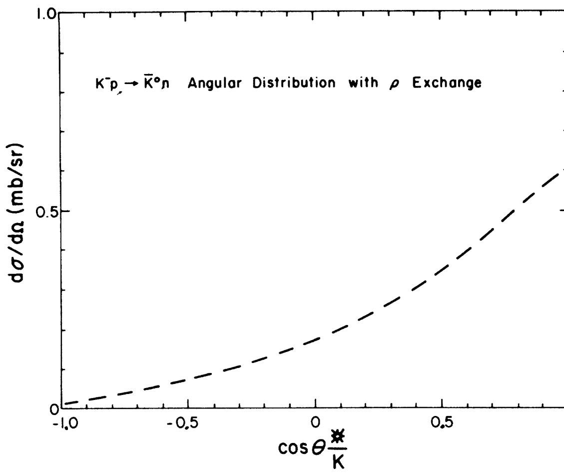

FIG. 10. $K^- p \to \bar{K}^0 n$ angular distribution for simple ρ exchange. See Ref. 11.

small-t data bin ($0.95 < \cos\theta^*_{\bar{K}^0} < 1.00$). This was used to preclude an interpretation of the cross section in terms of a ρ-exchange mode.[30,31] This experiment's results for $d\sigma/d\Omega(K^- p \to \bar{K}^0 n)$, for small momentum transfer squared $-t$, show a decrease with increase in momentum transfer (Fig. 9). While a forward dip would preclude the use of the simple ρ-exchange model to describe the angular distribution, even without the forward dip this model is inadequate to accurately interpret the results of this experiment. The differential cross section for $K^- p \to \bar{K}^0 n$ at 1.7 GeV/c was calculated using the simple ρ-exchange model[11] (Fig. 10). A comparison of its general shape with the data of this experiment or with any of the other experiments at nearby momenta shows that the model is inadequate to account for the experimentally obtained results (Fig. 11).

It is possible, however, that a modified form of the single-particle-exchange idea may be useful to explain the significant forward peak seen in this experiment as well as in most of the other experiments above 1.7 GeV/c. Some of the modifications that have been suggested include the use of form factors at the vertices,[32] absorption in the initial and final states,[33] direct-channel resonances,[34] and the exchange of Reggeized particles.[35–38] Other models invoked for $K^- p \to \bar{K}^0 n$ in the intermediate and high-energy regions are diffraction[14,39] and dispersion relations.[40]

An attempt was made to fit the data of this experiment to a Regge pole using the ρ and A_2.[41–43] The fit was not satisfactory. The intrinsic aspects of this model may not be valid at this intermediate energy. Arnold[44] develops the simple single-particle-exchange model for $K^- p \to \bar{K}^0 n$ in dispersion theory.[45,46] Arnold formulated the $K^- p \to \bar{K}^0 n$ scat-

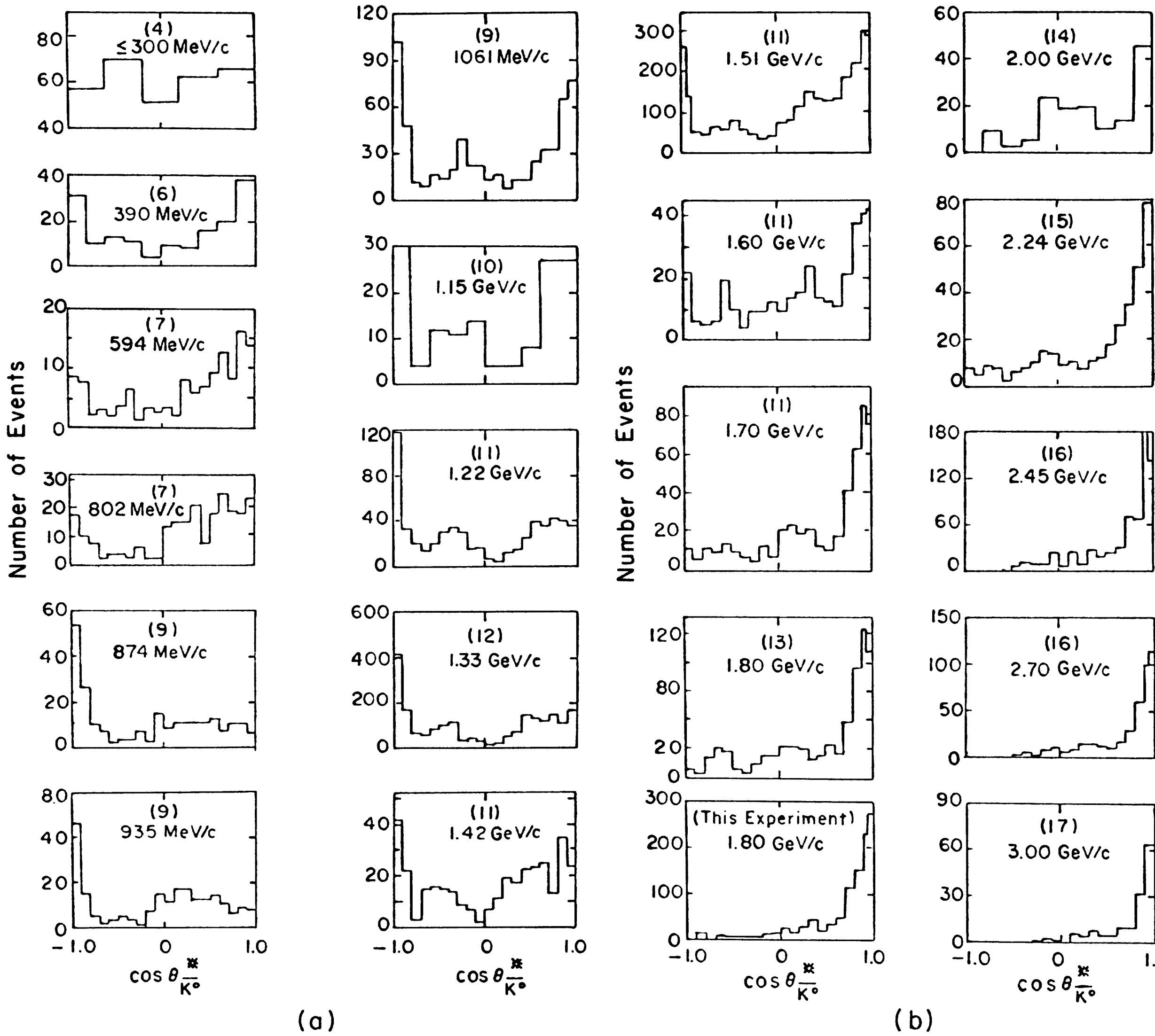

FIG. 11. $K^- p \to \bar{K}^0 n$ angular distribution for (a) threshold $\leq K^-$ beam momentum ≤ 1.42 GeV/c, (b) $1.51 \leq K^-$ beam momentum ≤ 3.00 GeV/c.

tering to satisfy unitarity in the high-energy limit. For small momentum transfer the fit is fair. However, it fits the data of this experiment better than that of Dauber[13] in the comparison by Arnold.[44]

ACKNOWLEDGMENTS

We would like to thank Dr. Lofgren and the staff of the Bevatron at the Lawrence Radiation Laboratory for help during all stages of this experiment. We want to thank Weldon Purcell and other machinists in the physics shop at the University of Washington for building much of the equipment. We thank J. Jaske and E. Dunn for assistance during many phases of the experiment. One of us (N.S.) wishes to acknowledge discussions with Dr. N. Bali.

*Work supported in part by the National Science Foundation.

†Work supported in part by the Oregon State University Research Council and the Oregon State University Computer Center.

‡Now at Walla Walla College, College Place, Wash. 99324.

§Now at University of Maryland, College Park, Md.

20742.
‖ Now at Naval Weapons Laboratory, Dahlgren, Va. 22248.
**Deceased.

[1]P. Eberhard, A. H. Rosenfeld, F. T. Solmitz, R. D. Tripp, and M. B. Watson, Phys. Rev. Letters 2, 312 (1959) (threshold to 410 MeV/c).

[2]W. E. Humphrey and R. R. Ross, Phys. Rev. 127, 1305 (1962); R. R. Ross, Ph.D. thesis, Lawrence Radiation Laboratory Report No. UCRL-9749, 1961 (unpublished) (threshold to 275 MeV/c).

[3]G. S. Abrams and B. Sechi-Zorn, University of Maryland Technical Report No. 441, 1965 (unpublished) (threshold to 250 MeV/c).

[4]W. Kittel, G. Otter, and I. Wacek, Phys. Letters 21, 349 (1966) (threshold to 300 MeV/c).

[5]P. Nordin, Jr., Ph.D. thesis, Lawrence Radiation Laboratory Report No. UCRL-9489, 1960 (unpublished) (300 and 400 MeV/c).

[6]M. B. Watson, M. Ferro-Luzzi, and R. D. Tripp, Phys. Rev. 131, 2248 (1963); M. B. Watson, Ph.D. thesis, Lawrence Radiation Laboratory Report No. UCRL-10175, 1962 (unpublished) (250 to 513 MeV/c).

[7]L. Bertanza, A. Bigi, R. Carrara, R. Casali, R. Pazzi, D. Berley, E. L. Hart, D. C. Rahm, W. J. Willis, S. S. Yamamoto, and N. S. Wong, Phys. Rev. 177, 2036 (1969) (594 to 820 MeV/c).

[8]P. L. Bastien and J. P. Berge, Phys. Rev. Letters 10, 188 (1963); P. L. Bastien, Ph.D. thesis, Lawrence Radiation Laboratory Report No. UCRL-10779, 1963 (unpublished) (620, 760, and 850 MeV/c).

[9]R. Armenteros, M. Ferro-Luzzi, D. W. G. S. Leith, R. Levi-Setti, A. Minten, R. D. Tripp, H. Filthuth, V. Hepp, E. Kluge, H. Schneider, R. Barloutaud, P. Granet, J. Meyer, and J. P. Porte, Nucl. Phys. B8, 233 (1968) (777 to 1226 MeV/c).

[10]W. Graziano and S. G. Wojcicki, Phys. Rev. 128, 1868 (1962) (1.15 GeV/c).

[11]C. G. Wohl, F. T. Solmitz, and M. L. Stevenson, Phys. Rev. Letters 17, 107 (1966); C. G. Wohl, Ph.D. thesis, Lawrence Radiation Laboratory Report No. UCRL-16288, 1965 (unpublished) (1.22, 1.42, 1.51, 1.60, and 1.70 GeV/c).

[12]W. P. Trower, J. R. Ficenec, R. L. Hulsizer, J. Lathrop, J. N. Snyder, and W. P. Swanson, University of Illinois Report No. C00-1195-95, 1967 (unpublished) (1.33 GeV/c).

[13]P. M. Dauber, Phys. Rev. 134, B1370 (1964) (1.80 GeV/c).

[14]D. Barge, W. Chu, L. Leipuner, R. Crittenden, H. J. Martin, F. Ayer, L. Marshall, A. C. Li, W. Kernan, and M. L. Stevenson, Phys. Rev. Letters 13, 69 (1964) (2.00 GeV/c).

[15]G. W. London, R. R. Rau, N. P. Samios, S. S. Yamamoto, M. Goldberg, S. Lichtman, M. Prime, and J. Leitner, Phys. Rev. 143, 1034 (1966) (2.24 GeV/c).

[16]F. T. Shively, A. Barbaro-Galtieri, and R. D. Tripp, Bull. Am. Phys. Soc. 10, 529 (1965); A. Barbaro-Galtieri and R. D. Tripp, in *Proceedings of the Twelfth International Conference on High Energy Physics, Dubna, 1964* (Atomizdat, Moscow, 1966), Vol. I, p. 699; Lawrence Radiation Laboratory Report No. UCRL-11429, 1964 (unpublished) (2.45, 2.63, and 2.70 GeV/c).

[17]J. Badier, M. Demoulin, J. Goldberg, B. P. Gregory, P. Krejbich, C. Pelletier, M. Ville, R. Barloutaud, A. Leveque, C. Louedec, J. Meyer, P. Schlein, A. Verglas, E. S. Gelsema, J. Hoogland, J. C. Kluyver, and A. G. Tenner, in *Proceedings of the Twelfth International Conference on High Energy Physics, Dubna, 1964* (Ref. 16), Vol. I, p. 650 (3 GeV/c).

[18]A. D. Brody and L. Lyons, Nuovo Cimento 45A, 1027 (1966) (3.5 GeV/c).

[19]P. Astbury, G. Brautti, G. Finocchiaro, A. Michelini, K. Terwilliger, D. Websdale, C. H. West, P. Zanella, W. Beusch, W. Fischer, B. Gobbi, M. Pepin, and E. Polgar, Phys. Letters 23, 396 (1966) (5, 7, and 12 GeV/c).

[20]D. C. Colley, W. P. Dodd, F. MacDonald, B. Musgrave, S. K. Tuli, W. Blair, R. Erskine, J. Gordon, I. Hughes, R. Turnbull, P. Chaudhuri, A. Eskreys, S. J. Goldsack, K. Paler, K. Sisterson, W. Blum, G. Dehm, N. Schmitz, W. Schrankel, J. Allison, W. W. M. Allison, A. D. Brody, D. H. Locke, L. Lyons, P. Finney, C. Fischer, L. K. Rangan, and A. Segar, Nuovo Cimento 53A, 552 (1968) (6 GeV/c).

[21]A. Buffington, D. H. Frisch, and E. E. Ward, Phys. Rev. 176, 1628 (1968); A. Buffington, Ph.D. thesis, Massachusetts Institute of Technology, 1966 (unpublished) (7.7 GeV/c).

[22]P. Astbury, G. Finocchiaro, A. Michelini, C. Verkerk, D. Websdale, C. H. West, W. Beusch, B. Gobbi, M. Pepin, M. A. Pouchon, and E. Polgar, in *Proceedings of the Twelfth International Conference on High Energy Physics, Dubna, 1964* (Ref. 16), Vol. I, p. 702; Phys. Letters 16, 328 (1965) (9.50 GeV/c).

[23]M. L. Stevenson, in *Lectures in Theoretical Physics* (Colorado Univ. Press, Boulder, 1965), Vol. VII B, pp. 285–334. This gives a review of Kp interactions from 0.3 to 5.0 GeV/c.

[24]See *Proceedings of the International Conference on High Energy Physics, Berkeley, 1966* (Univ. of California Press, Berkeley, 1966), pp. 183–211. This is a general summary and bibliography.

[25]G. McD. Bingham, V. Cook, J. W. Humphrey, O. R. Sander, R. W. Williams, G. E. Masek, T. Maung, and H. Ruderman, Phys. Rev. D 1, 3010 (1970).

[26]The spark chambers' plates were 1-mil aluminum foil plates separated by $\frac{1}{4}$-in. transparent Plexiglas frames. The two upstream chambers had six active gaps each. The four other chambers had 12 active gaps each. The chambers were pulsed with 7 kV and used a neon-helium mixture.

[27]F. N. Terwilliger, Lawrence Radiation Laboratory Report No. Bev-989, 1968 (unpublished), and Lawrence Radiation Laboratory Report No. Bev-991, 1968 (unpublished).

[28]N. D. Sossong, Ph.D. thesis, University of Washington, 1969 (unpublished).

[29]P. M. Dauber, J. P. Berge, J. R. Hubbard, D. W. Merrill, and R. A. Muller, Phys. Rev. 179, 1262 (1969).

[30]S. D. Drell, Phys. Rev. Letters 5, 342 (1960); Rev. Mod. Phys. 33, 458 (1961).

[31]F. Salzman and G. Salzman, Phys. Rev. 120, 599 (1960).

[32]E. Ferrari and F. Selleri, Suppl. Nuovo Cimento 24, 453 (1962). Appendix IV contains many references.

[33]J. D. Jackson, Rev. Mod. Phys. 37, 484 (1965). This article reviews the problems of peripheral models.

[34]S. Minami, Phys. Letters 24B, 188 (1967).

[35]V. Singh, Phys. Rev. 129, 1889 (1963).

[36]R. J. N. Phillips and W. Rarita, Phys. Rev. 139, B1336 (1965).
[37]P. Salin, Nucl. Phys. B3, 323 (1967).
[38]V. Barger, Rev. Mod. Phys. 40, 129 (1968). This article contains a review of Regge poles and SU(3) as applied to high-energy scattering.
[39]A. O. Barut and H. Kleinert, Phys. Rev. Letters 16, 950 (1966).
[40]M. Lusignoli, M. Restignoli, G. A. Snow, and G. Violini, Nuovo Cimento 49A, 705 (1967).
[41]A. Derem and G. Smadja, Nucl. Phys. B3, 628 (1967).
[42]A. Derem, Nucl. Phys. B3, 106 (1967).
[43]R. K. Loban, Nuovo Cimento 57, 712 (1968).
[44]R. C. Arnold, Phys. Rev. 136, B1388 (1964).
[45]R. Blankenbecler and M. L. Goldberger, Phys. Rev. 126, 766 (1962).
[46]M. Baker and R. Blankenbecler, Phys. Rev. 128, 415 (1962).

PHYSICAL REVIEW D VOLUME 5, NUMBER 11 1 JUNE 1972

Search for Direct Processes in $K^{\pm} \to \pi^{\pm} \pi^0 \gamma$ Decays*

R. T. Edwards,† E. W. Beier,‡ W. K. Bertram,§ D. P. Herzo,|| L. J. Koester, and A. Wattenberg
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

(Received 24 January 1972)

We have found 33 events of the type $K^+ \to \pi^+\pi^0\gamma$ and 31 of the type $K^- \to \pi^-\pi^0\gamma$ in an experiment using spark chambers. The angles of the observed decay products were used to determine the angle between the charged pion and the γ ray in the K rest frame. The distribution of this angle showed no indication of a direct radiative process but instead was consistent with internal bremsstrahlung. In order to be quantitative concerning the amount of direct interaction, we selected 24 events with the charged-pion kinetic energy T_π restricted to $58 \le T_\pi \le 90$ MeV and carried out maximum-likelihood fits for various assumptions regarding the radiative amplitudes, final-state interaction, and amount of CP violation. Assuming no magnetic dipole, the largest value found by the maximum-likelihood fit for the direct (electric dipole) amplitude is $A_E = -0.12^{+0.21}_{-0.25}$ relative to the internal-bremsstrahlung amplitude. If the direct process occurs, and if CP is appreciably violated in the $K^\pm \to \pi^\pm\pi^0\gamma$ decay, there would be a difference between the rates for $K^+ \to \pi^+\pi^0\gamma$ and $K^- \to \pi^-\pi^0\gamma$. Our result is $\Gamma(K^- \to \pi^-\pi^0\gamma)/\Gamma(K^+ \to \pi^+\pi^0\gamma) - 1 = 0 \pm 0.24$. Thus a large asymmetry suggested by some theories is ruled out by this observation.

I. INTRODUCTION

The decay $K^\pm \to \pi^\pm\pi^0\gamma$ can occur through either the internal-bremsstrahlung (IB) mechanism or a so-called direct process. In the IB process, one of the charged particles which appears in the laboratory ($K^\pm$ or $\pi^\pm$) emits the photon, and the weak interaction $K^\pm \to \pi^\pm\pi^0$ therefore proceeds with that particle off the mass shell. In the direct process, it is impossible to separate the radiative vertex from the weak decay interaction. The two types of processes are represented in simplified form by the diagrams of Fig. 1.

The decay $K^\pm \to \pi^\pm\pi^0$ violates the $\Delta I = \frac{1}{2}$ rule because the pions must be in an $I = 2$ final state. It is suppressed relative to the decay $K^0 \to \pi\pi$ by a factor of about 600; therefore the direct decay, $K^\pm \to \pi^\pm\pi^0\gamma^0$, can compete more favorably with the IB rate, which is on the order of 1% of the $K^+ \to \pi^+\pi^0$ rate. If a direct amplitude is observable, then it is possible to test CP invariance in the electromagnetic and/or weak interaction by comparing the partial decay rates and Dalitz-plot densities for the reactions $K^+ \to \pi^+\pi^0\gamma$ and $K^- \to \pi^-\pi^0\gamma$.[1] According to some estimates,[2] the ratio $\Gamma(K^- \to \pi^-\pi^0\gamma)/\Gamma(K^+ \to \pi^+\pi^0\gamma)$ of these partial rates might be as large as 3.

Three experiments have been reported[3-5] on the decay $K^+ \to \pi^+\pi^0\gamma$ to date. None of these experiments shows evidence of an appreciable amplitude for the direct process.

In this paper we report the observation of 33 events of the type $K^+ \to \pi^+\pi^0\gamma$ and 31 of the type $K^- \to \pi^-\pi^0\gamma$. Section II presents a description of the experimental procedure including the event reconstruction, and Sec. III contains a description of the analysis procedure. In Sec. IV we present the conclusions.

II. EXPERIMENTAL PROCEDURE

A. Apparatus and Technique

The $K^\pm \to \pi^\pm\pi^0\gamma$ events were obtained during a measurement of the relative partial decay rates for $K^\pm \to \pi^\pm\pi^0\pi^0$.[6] The apparatus is described in detail in Ref. 6, so we present only a summary of