octuplet states. The modified (mass)^2 formula is

$$(\eta-\pi)(\delta-\pi)=\tfrac{4}{3}(K-\pi)(\eta+\delta-2K)+8/9(1-\alpha^2)(K-\pi)^2$$

or

$$\delta-\pi=\frac{K-\pi}{K-\frac{1}{4}(3\eta+\pi)}\times[2K-\eta-\pi-\tfrac{2}{3}(1-\alpha^2)(K-\pi)]\geq\tfrac{4}{3}(K-\pi).$$

The lower limit, $\delta^{1/2}\geq 567$ MeV, is reached for $\alpha=0$. The maximum value $\delta^{1/2}\leq 1560$ MeV occurs for $|\alpha|=1$. The actual magnitude of α will be determined by considerations of dynamical stability. Thus, increasing α raises δ, which then tends to decrease α, the overlap factor. The δ mass should be some reasonable average of the two unattainable extremes: 567 MeV$<\delta^{1/2}<$1560 MeV.

A new meson that decays into $\pi^++\pi^-+\eta$ has been announced [G. R. Kalbfleisch, L. W. Alvarez, A. Barbaro-Galtieri, O. I. Dahl, P. Eberhard, *et al.*, Phys. Rev. Letters **12**, 527 (1964); M. Goldberg, M. Gundzik, S. Lichtman, J. Leitner, M. Primer *et al.*, *ibid.* **12**, 546 (1964)]. Its properties are consistent with the quantum numbers $T=Y=0$, $J^P=0^-$, and $G=+1$, which are those of the δ meson. The mass observed for the particle is 959$\pm$2 MeV. The value of the overlap parameter required to represent this mass is $|\alpha|=0.53$. If we accept the identification of the new meson with δ, the ratio of the two perturbation parameters is reduced to $\lambda'/\lambda=3.2$, and the particle states with $T=Y=0$ become

$$\eta=(3.89)^{-1/2}[\langle 11|+\langle 22|-1.37\langle 33|],$$
$$\delta=(4.13)^{-1/2}[\langle 11|+\langle 22|+1.46\langle 33|].$$

This change improves the accuracy of the approximate square array, Eq. (23).

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$K^+\Lambda$ Photoproduction from Hydrogen at 1200 MeV*

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Measurements of the angular distribution of the cross section for the photoproduction of the $K^+\Lambda$ system from hydrogen have been made in the c.m. angular interval from 15° to 85° at a photon energy of 1200 MeV. The reaction was identified by detecting the K^+ mesons with a magnet spectrometer and a velocity selection system consisting of two Čerenkov counters. The angular distribution at this energy is very similar to that at lower energies in that it is peaked forward and is easily fit with a quadratic in $\cos\theta_{\mathrm{c.m.}}$. Special emphasis was placed on the forward direction in an attempt to find evidence for the one-K-exchange pole. A Taylor-Moravcsik analysis of the data is presented, but the results are inconclusive.

I. INTRODUCTION

SINCE the original investigations[1] of the photoproduction of K^+ mesons, improvements in both detection schemes and electron synchrotron beam intensities have resulted in a significant increase in our knowledge of these reactions. Of the several possible associated photoproduction reactions, the simplest experimentally is

$$\gamma+p\rightarrow K^++\Lambda \quad [\text{threshold: } 911 \text{ MeV}]$$

and the experiment reported here concerns this process only. Recent work at Cornell[2,3] has yielded several angular distributions of the cross section for this reaction in the energy range from 934 to 1160 MeV. Furthermore, the polarization of the Λ at 90° in the center of mass for several energies up to 1160 MeV has been reported by the same group.[4] As was clear from the early measurements, the production near threshold is consistent with the $K^+\Lambda$ system being in an S state. However, at 1000 MeV the appearance of polarization of the Λ and a gentle rise of the angular distribution in the K^+ forward direction indicate that higher partial waves are beginning to be excited. As the photon energy is increased, the Λ polarization and the 90° cross section remain essentially constant[4] while the angular distribution of the cross section becomes more peaked[2,3] in the forward K direction. The results of the present investigation of the photoproduction of the $K^+\Lambda$ system from hydrogen show that this behavior of the cross section also obtains at a photon energy of 1200 MeV.

The K^+ photoproduction experiments are of some theoretical interest as they provide, in principle at

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] P. L. Donoho and R. L. Walker, Phys. Rev. **112**, 981 (1958); B. D. McDaniel, A. Silverman, R. R. Wilson, and G. Cortellessa, *ibid.* **115**, 1039 (1959); H. M. Brody, A. M. Wetherell, and R. L. Walker, *ibid.* **119**, 1710 (1960).

[2] R. L. Anderson, E. Gabathuler, D. Jones, B. D. McDaniel, and A. J. Sadoff, Phys. Rev. Letters **9**, 131 (1962).

[3] A. J. Sadoff, R. L. Anderson, E. Gabathuler, and D. Jones, Bull. Am. Phys. Soc. **9**, 34 (1964).

[4] H. Thom, E. Gabathuler, D. Jones, B. D. McDaniel, and W. M. Woodward, Phys. Rev. Letters **11**, 433 (1963).

least, a model-independent method of determining the K-nucleon-hyperon coupling constants by extrapolation of the cross section to the K-exchange pole in the forward direction. In the hope that such a program would prove feasible, special emphasis was placed on the cross sections in the forward direction. However, the results are inconclusive; the data give no indication of the photoelectric term. The long extrapolation distance and the statistical uncertainties render the method untrustworthy in this application.

II. EXPERIMENTAL METHOD

Since the reaction of interest has a two-body final state, the identification of the reaction and the measurement of the momentum and production angle of one of the products suffice to fully determine the kinematics. Since the Λ is the lowest mass particle which can be photoproduced from hydrogen in association with a K^+ meson, we can ensure the desired reaction by detecting the meson and maintaining the maximum photon energy in the bremsstrahlung beam below that required for the production of the $K^+\Sigma^0$ system. The momentum and angle requirements were moderately easily set with a magnetic spectrometer, so that the principal experimental problem was the accurate separation of K^+ mesons from a relatively large flux of pions and protons. The most obvious K^+ meson signatures are its characteristic decay and its velocity in the momentum-analyzed beam. In order to avoid the large nuclear absorption correction inherent in stopping the K mesons, we have not used the former possibility but have relied entirely upon velocity-dependent effects for meson identification.

a. The Beam and Target

The bremsstrahlung beam was generated by spilling the circulating electron beam in the Caltech synchrotron onto a tantalum radiator for a time of about 80 msec during which the magnetic field in the synchrotron was held constant. The typical photon beam intensity was 10^9 equivalent quanta per sec. The detailed energy spectrum of the bremsstrahlung has been measured by Boyden and Walker. The beam was defined by a lead collimator with a rectangular aperture and "scraped" by three lead walls before illuminating a liquid H_2 target about 10 m from the radiator. At the target, the beam was 3 cm high and 2 cm wide. The vacuum jacket surrounding the target extended 60 cm both upstream and downstream along the beam line to reduce empty target backgrounds for the small angle points. The target itself consisted of a hydrogen filled cylindrical cup of 0.005-in. Mylar, 7.5 cm in diameter, with axis vertical and normal to the production plane. In addition, several heat shields totaling 0.003-in. of Al extended into the photon beam. The liquid hydrogen was maintained at a constant pressure of 15 psi and had a density of 0.0707 g/cm³. Thus, the K^+ meson source consisted of 0.50 g/cm² H_2, 0.055 g/cm² of heavy nuclei inside the target vacuum system and, for angles smaller than 20° in the lab, the Mylar end windows of the vacuum chamber and part of the air path in the beam line. At the smallest lab angle used in this experiment, 6.3°, the total mass of heavy nuclei effective for producing K^+ mesons was estimated to be 0.19 g/cm².

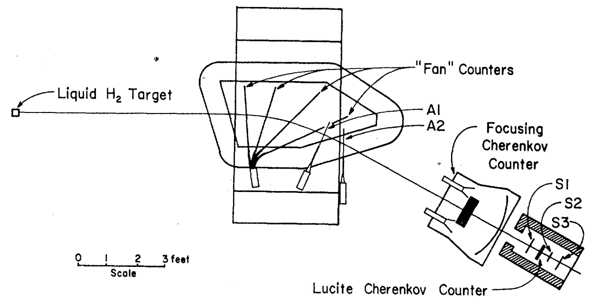

FIG. 1. A section through the median plane of the spectrometer showing the locations of the counters in the detection system. The photon beam line lay in a plane normal to that of this figure.

b. Momentum and Solid Angle Definition

Figure 1 shows the magnet spectrometer schematically and the arrangement of scintillation counters used to define the momentum and angular apertures of the instrument. The spectrometer was a wedge-shaped, uniform field, weak focusing magnet with a path length of 6.6 m between the conjugate points used. The magnetic field was set with a proton resonance magnetometer. The absolute momentum calibration was known to $\pm 1\%$ and the average angle to the photon beam could be set to better than 0.1°.

The solid angle of acceptance and angular resolution were determined principally by the counter A1 which was 12 in. long and 2.91 in. wide for all but two of the points measured. At the most forward point, it was necessary to stop down the aperture to maintain an angular resolution function similar to that of the larger angles, as well as for reasons given later; A1 was reduced to 6 in. in length. The 30° c.m. point was also measured with this configuration. This defining counter was situated behind the magnet to prevent it from flooding with counts at the beam intensities and small angles used. The lab angular resolution and solid angle were calculated to be $\pm 0.6°$ and 0.00176 sr, respectively. The solid angle was directly measured by setting up a small aperture in front of the magnet, whose solid angle is readily calculated, and observing its efficiency. The measurement agreed with the calculation to within the counting statistics of 1.5%.

The momentum acceptance window was defined by counter S2 to be 7.1% for most of the points. This resolution was divided into three channels by splitting S2 into three adjacent segments of equal width. For the two points taken with a stopped down aperture as well as the point at 85° c.m., the momentum window was

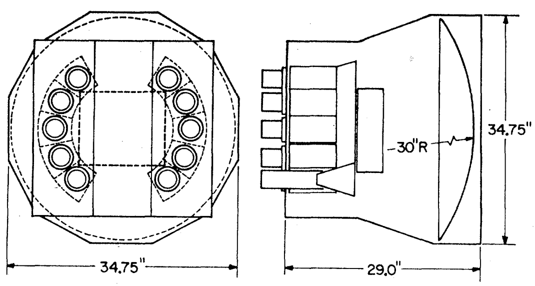

FIG. 2. The focusing Čerenkov counter.

increased to 9.4% to increase the yield. These momentum apertures were obtained by calculating orbits through the magnet based upon detailed measurements of the fringing fields; they agree to within 0.7% of the value one obtains by linear magnet theory. No experimental investigations with high-energy particles were made to corroborate these numbers.

Although the counter system so far described was sufficient to define the momentum and production angle (to within counter resolutions) of well-behaved particles, various spurious effects require a more complex system. First, three further counters, S1 and S3 near the momentum aperture and A2 near the angle aperture, were included in order to reduce accidental coincidences to a negligible rate. The second aperture counter A2 also eliminated a small but troublesome pion flux which fired A1 by making Čerenkov light in its Lucite light-pipe. Although they accounted for less than 0.5% of the total pion flux, these particles have a relatively large probability of firing the velocity selection system and contaminating the K rate. Finally, some particles with momenta far outside the acceptance window can scatter on the magnet pole pieces and be counted by the system. These were detected and electronically eliminated by a set of pole piece counters, the "Fans"; they were used in an earlier K experiment at this laboratory and have been described by Brody *et al.*[1]

c. Velocity Definition

In this experiment, the beam defined by the spectrometer consisted principally of pions, K mesons, and protons in the ratios, typically, of 300:1:300. Reference to earlier work[1] will show that these ratios are much more favorable than at the lower energies. On the other hand, at the higher momenta used in this experiment, the velocity separation between the various particles is significantly smaller.

The instrument which made this experiment possible was a focusing Čerenkov counter[5] (FC) designed by R. L. Walker. Figure 1 shows its relative position in the apparatus, and Fig. 2, details of its construction. Čerenkov light produced in the 10-cm-thick radiator is focused by a large spherical mirror into a circular ring at the focal plane. To a good approximation, the radius of this ring of light is a function only of the particle's velocity while its position in the plane depends only upon the particle's direction. Thus, for a well-collimated beam of particles passing through the counter, a ring of phototubes viewing an annular aperture in the focal plane will respond only if the particle velocity lies within a well-defined range. For a poorly collimated beam, such as the spectrometer provides, the velocity window will be blurred. Figure 3 shows a typical resolution. With a fixed geometry, the velocity to which the counter is tuned depends only upon the refractive index of the radiator; mixtures of water and glycerine were used to adjust the index to that required by the K-meson velocity at each of the several momenta used.

The velocity range in which this counter is an effective tool for identifying K mesons is limited. As the velocity is lowered, the counter's momentum-window narrows and its detection efficiency deteriorates. For high velocities, the beam must be better collimated to provide a high pion rejection. For the momentum interval covered by this experiment, 557–812 MeV/c, the former limit caused no trouble, but at the highest momentum it was necessary to stop down the angle aperture of the spectrometer as mentioned above.

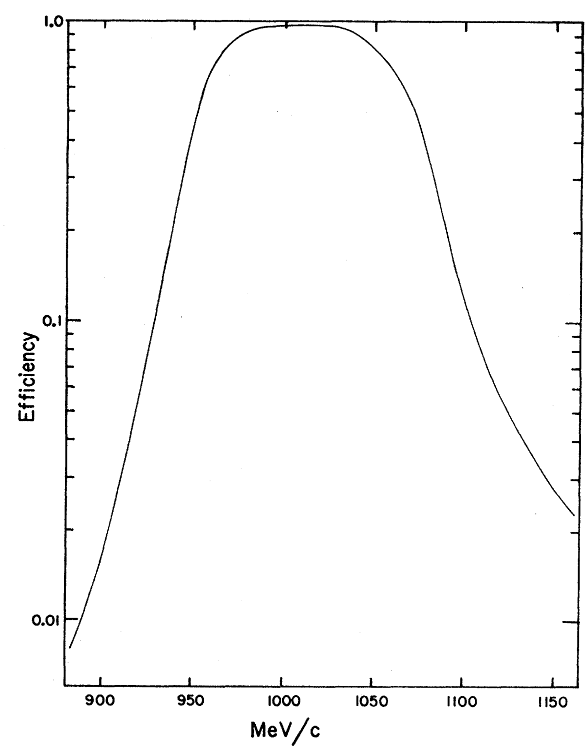

FIG. 3. A typical velocity window defined by the focusing counter. These data were taken by using a proton beam, momentum analyzed by the magnet with a resolution of 2.5%. The curve falls less steeply on the high-velocity side because the amount of Čerenkov light is increasing and the cone angle is opening less rapidly.

[5] A somewhat similar instrument has been described by M. Huq and G. W. Hutchinson, Nucl. Instr. Methods 4, 30 (1959).

In fact, over the entire momentum range, pions can make small signals in FC since small scatterings in the radiator of fast particles already somewhat off-axis can throw some of their Čerenkov light onto the phototubes. At the highest momentum, where the pion efficiency of the focusing counter is highest, it was observed to be 0.4% for the bias used in the data reduction. This rejection could have been significantly improved by setting a higher bias on the signal, but this would have reduced the K-detection efficiency and so made that efficiency crucial. Instead, a threshold type Lucite Čerenkov counter (LC) sensitive to pions (and electrons) but not to K mesons or protons in our momentum range was used in electronic anticoincidence to eliminate about 95% of the highly relativistic particles. This counter has been described by Brody *et al.*[1] Although the probability that a pion be not detected by this counter is, in principle, dependent upon its behavior in the focusing counter, the over-all pion detection efficiency of the system was observed to be consistent with a simple product; thus, in the worst case it was about 2×10^{-4}.

The focusing counter's rejection of protons with velocities far outside the nominal acceptance window is degraded by the existence of δ rays, nuclear reactions resulting in a fast, forward-going pion, and accidental coincidences. Estimates of the first two processes show them to be entirely negligible. The accidental coincidence rate was reduced to a negligible level by placing the focusing counter signal in 10 nsec coincidence with S1, carefully shielding it to reduce its background rate, and reducing the sensitivity of the rest of the system to protons. This latter was achieved by setting flight-time requirements with about 4 nsec resolution between each of the two aperture counters, A1 and A2, and S1. At the highest momentum, this reduced the effective proton rate by only a factor of 2 while at the lowest momentum the reduction was about a factor of 20. In the most unfavorable case in this experiment, an upper limit to the system's proton detection efficiency is 10^{-4}.

III. EXPERIMENTAL PROCEDURE

The procedure used for obtaining the K^+ yield from the hydrogen in the target will be described in this section. Ideally, at least three counting rates should be measured for each cross section to be determined: Rates with and without hydrogen in the target with the maximum photon energy E_0 greater than that necessary for the reaction, and one with full target but E_0 less than that required. This latter is essential to verify that one is indeed observing the reaction in question. However, with reasonable certainty that the reaction is being properly identified, the principal datum is the full target above threshold rate since the others will represent but small corrections. Accordingly, for a series of similar points the full complement need be obtained for a representative set only, and this procedure was followed.

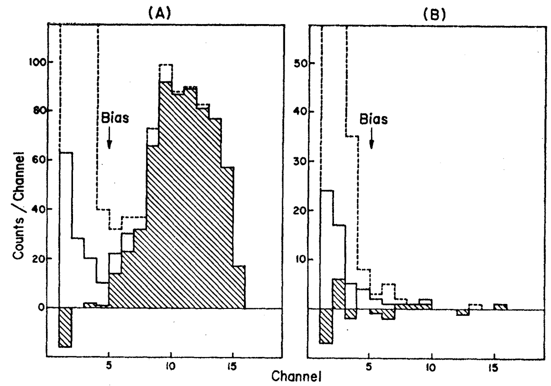

FIG. 4. (A) Pulse-height spectra observed in the focusing counter for the point at $k=1200$ MeV, $\theta_{c.m.}=30°$. The bremsstrahlung end-point energy was 1280 MeV. The dotted histogram shows the distribution when the signal from the Lucite Čerenkov counter was not used in the analyzer triggering logic. For the solid histogram, this signal was included in anticoincidence. The shaded histogram shows the residue remaining after subtracting a spectrum obtained with a carbon target as discussed in the text. The exposure was 0.77×10^{14} eq. quanta. (B) The same as Fig. 4(A) except that the bremsstrahlung end-point energy was set to 1130 MeV and the exposure was 0.35×10^{14} eq. quanta.

a. Full Target Rates

K^+ mesons passing through the system produced slightly greater than minimum ionizing pulses in the five scintillators A1, A2, S1, S2, S3, a large pulse in FC, no signal in the Fans, and none or a small one in LC. Electronic logic was arranged to require coincident signals from the scintillators greater than about one-quarter the average produced by a minimum ionizing particle, no signal in the Fans, and a signal greater than a very low bias in the focusing counter. When these conditions were satisfied, the signal from the focusing counter was measured in a TMC-401[6] pulse-height analyzer. The 400 word memory of this instrument can be segmented into four identical parts and the signal routed into one of these by suitable logic. Three of the four parts were used to accumulate the FC spectra when LC was not triggered, one memory section being used for each of the three momentum channels. This provided us with a sensitive running check on the tuning of the focusing counter. The remaining segment of the analyzer's memory was used to accumulate the pulse-height distribution in the focusing counter when the Lucite counter was triggered. This allowed us to monitor both the pion-detection efficiency of the focusing counter and, roughly, the K-detection efficiency of LC.

In Figure 4(A) a typical pulse-height distribution observed in the focusing counter is presented. The huge rise in the distribution at small pulse heights when the Lucite Čerenkov counter is not used is due to pions. However, when LC is included in anticoincidence, there still remains a contamination of small pulses spilling

[6] Technical Measurements Corporation, North Haven, Connecticut.

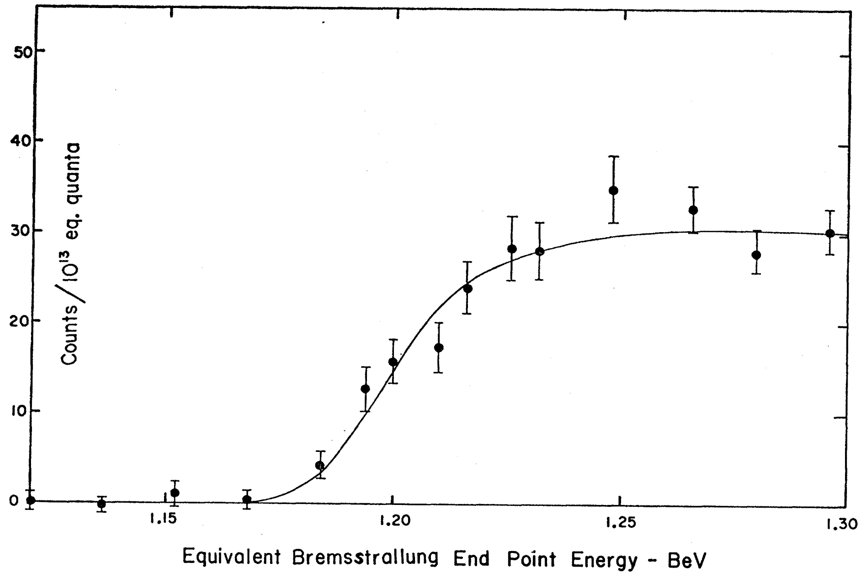

FIG. 5. The dependence of the K-meson counting rate upon the bremsstrahlung end-point energy. The 15 data points were actually taken at only five end-point energies, but the multiplexing of the momentum aperture allows the resolution shown. The shape of the smooth curve is that expected from the resolution of the spectrometer and the bremsstrahlung energy spectrum. The amplitude and horizontal position of this function were adjusted to fit the data. The *a priori* curve based upon the energy calibrations of the synchrotron and the spectrometer was 15 MeV (1.3%) higher than that shown. The origin of this discrepancy is not known but is currently under investigation.

into the K region. Similarly, when the maximum photon energy is set below that required for the $K^+\Lambda$ reaction, a distribution of small pulse heights appears, as is shown in Fig. 4(B). A detailed investigation of this contamination was made in the hope of finding its origin and either eliminating it or, at worst, discovering how to correct for it. In the most unfavorable kinematical regions, about 30% of the particles appeared to be properly momentum-analyzed pions and protons. We found that the remainder had velocities roughly equal to that for which the focusing counter was set by observing the pulse-height distributions which they made in the scintillation counters as well as by measuring their flight times. Thus, the fault was in inadequate energy selection by the spectrometer. Attempts to determine the mass of the offending particles by range measurements were inconclusive. The shielding of various parts of the apparatus with scintillators revealed no scattering

TABLE I. Comparison of full target counting rates C at two different synchrotron end-point energies E_0, one above the photon energy k required for the reaction $\gamma+p\rightarrow K^++\Lambda$, and the other below it. The rates are normalized to 10^{13} eq. quanta.

k (BeV)	$\theta_{\text{c.m.}}$	E_0 (BeV)	C
1.200	15°	1.280	90.1±4.3
		1.130	3.3±3.4
1.200	35°	1.280	85.5±3.0
		1.130	−0.2±0.8
1.200	55°	1.280	56.9±2.8
		1.130	0.5±0.8
1.200	70°	1.280	30.6±1.7
		1.130	−0.5±0.4
1.200	85°	1.280	18.8±1.9
		1.130	0.0±1.0
1.054	48°	1.130	36.6±2.7
		1.000	−0.2±1.0

source. Doubling the amount of matter at the positions of the aperture counters A1 and A2, as well as at the focusing-counter radiator did not change the contamination, thus ruling out nuclear interactions of pions, protons, or neutrons as the origin of the difficulty. Calculations of low-energy pions decaying in the magnetic field show that muons from this source cannot cause the trouble. In short, we were unable to attribute the contamination to any single source or simple combination of them. However, each test was made with but limited statistics so that each possibility may contribute something.

The simplest procedure of correcting for this contamination, in view of our ignorance of its origin, would be subtracting below threshold yields from those obtained above threshold. However, such a procedure is dangerous since it is known[7] that some types of contamination in K-meson photoproduction experiments show a dependence upon E_0. We found a purely empirical rule which appeared to effect the correction to a good approximation. With all logic and spectrometer settings the same as for a normal K run, the distribution in the focusing counter was observed with the hydrogen target replaced by carbon and the maximum photon energy set well below that required to produce K mesons. For the 1200-MeV data, the carbon distributions were taken with $E_0=1000$ MeV. When compared to the spectrum obtained from below threshold hydrogen runs, both spectra being normalized to the same total flux of particles through the spectrometer, the agreement in both size and shape was within the

[7] B. D. McDaniel, R. L. Anderson, E. Gabathuler, D. P. Jones, A. J. Sadoff, and H. Thom, in *1962 International Conference on High-Energy Physics at CERN* (Interscience Publishers, Inc., New York, 1962), p. 266.

statistical accuracy of the numbers. Similarly, when the spectrum from carbon, normalized as above, was subtracted from the above threshold hydrogen data the tail of small signals was essentially eliminated. In Fig. 4, the shaded histograms show typical residues after such a subtraction. Except for further small corrections to be discussed shortly, the full target yield was taken as the number of counts above a suitable bias on the focusing counter signal, chosen as a compromise between a small "carbon subtraction" and a high efficiency. The subtraction was largest at the most forward and most backward points, being 7% and 9%, respectively, while for the middle angles it was typically 3%.

Below-threshold rates were measured for six of the fourteen points. Table I compares these with the corresponding above-threshold yields. Also, for the 35° c.m. point, the yield as a function of E_0 was measured. Because of synchrotron energy limitations at the time this experiment was performed, we were unable to extend measurements to energies above that required for $K^+\Sigma^0$ production and display the plateau between these two sources of K^+ mesons in the *full* momentum-aperture counting rate. However, even with the end-point energy limitation, the resolution of a single one of the three momentum channels was sufficient to show the leveling off of its counting rate due to $K^+\Lambda$ production as the end point was raised. In Fig. 5, the equivalent yield in the central channel as a function of E_0 is presented along with the expected curve. The measured points actually fall on three adjacent similar curves, of course, one for each momentum channel, but these have been corrected for the different sensitivities of the three counters and suitably shifted along the horizontal axis to give a composite.

At small angles, the counting rate in each of the aperture counters A1 and A2 was large, reaching a maximum of 3×10^5 counts/sec for the 15° c.m. point. The rate in the Fans was almost an order of magnitude larger. Corrections were calculated to account for dead time in the coincidence circuits, and the accidental anticoincidence rate of the Fans was continuously measured using reduced logic requirements. In the worst case, these corrections amounted to 1% and 5%, respectively.

b. Empty Target Rates

During exploratory work prior to the principal running of this experiment, the empty-target yields at two wide-angle points were measured. These were found to be about 7% of the full-target yields, consistent with the known target construction and measured K^+ rates from Mylar. Except for the three smallest angles where the effective background target is not so well known, they were expected to be easily calculable from observed Mylar yields, and their direct measurement was left to the end of the experiment. Just after emptying the hydrogen, however, we found the target to be suddenly opaque, whereas it had been transparent throughout the experiment. Closer investigation revealed a thin layer of matter condensed on the heat shields as well as on the outside of the Mylar cup. Since this contaminant seemed to have appeared during emptying, the target was disassembled and cleaned before proceeding. A full-target check was immediately made and various monitoring rates were significantly smaller than before the incident. We were forced to conclude that the target had been contaminated to some extent during all but the earliest part of the experiment. However, the internal consistency of full-target K rates taken at various times during the experiment as well as a proton rate measured frequently to $\pm3\%$ statistical accuracy leads us to believe that the target contamination was stable. Since reaccumulation of the data was not feasible, full-target yields at four representative points, 15, 30, and 49° c.m. at 1200 MeV and the point at 1080 MeV, were remeasured. The assumption that the target contamination contributed a constant fraction of the full-target yields was consistent with these data and the correction factor was determined to be 0.933 ± 0.035. Two points, that at 85° c.m., 1200 MeV, and the wider angle one at 1054 MeV, were completed during the exploratory work so that their backgrounds were known directly. The statistical uncertainty of ±0.035 in this correction factor has not been included in the relative errors on the angular distribution but is rather combined with the systematic uncertainties.

Standard backgrounds were measured from the uncontaminated empty target using the same procedure as for the full target runs. At the smallest angle, it was 17% of the full target rate while, for the angles greater than 35° c.m., it was about 7%. For four of the points, the background was calculated from K^+ rates observed with a 1-in.-thick Mylar target.

IV. CROSS-SECTION DETERMINATION AND RESULTS

For the conditions of this experiment, the relation connecting the hydrogen yield Y to the differential cross section: $d\sigma/d\Omega$ is one of simple proportionality

$$Y=K(d\sigma/d\Omega),$$

where K is a well-known product of kinematical factors, target and spectrometer constants, detection efficiencies, the exposure, and a photon energy spectrum factor. The kinematical factors are known with negligible uncertainty and the target and spectrometer constants are believed to be known to $\pm2\%$.

The detection efficiency consists of several factors: the decay correction, the nuclear absorption correction, and the efficiencies of the two Čerenkov counters. Other possible electronic losses, except as discussed earlier, were negligible. The decay correction factor varied from 0.20 to 0.33 for this experiment and is known to $\pm1.5\%$. To account for the fact that roughly 6% of the K mesons which decay between the two

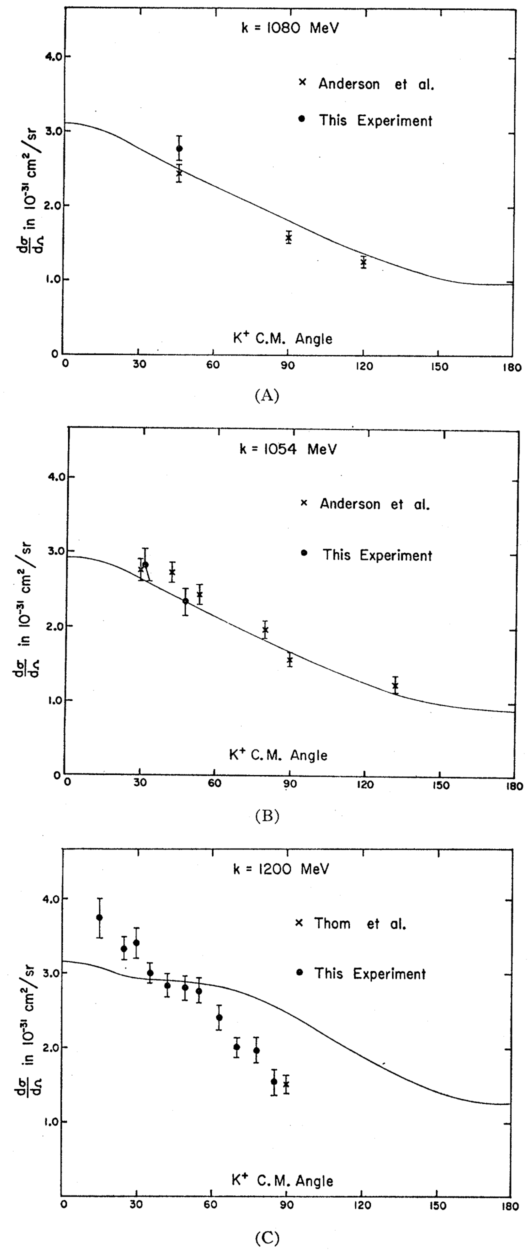

FIG. 6. Comparison of the results of this experiment with other work. (A) • This experiment; × Anderson *et al.*, Ref. 2. (B) • This experiment; × Ref. 2. (C) • This experiment; × Ref. 4. The smooth curves through the data were calculated from the model of Kuo (Ref. 13) and Beauchamp and Holladay (Ref. 14) with the parameters of the latter.

Čerenkov counters were in fact detected (as determined by a Monte Carlo calculation), this decay factor is slightly larger than the simple fraction of K mesons which traverse the system without decay. The nuclear absorption was taken to be independent of momentum and the optical model potential of Zorn and Zorn[8] for

[8] B. S. Zorn and G. T. Zorn, Phys. Rev. **120**, 1898 (1960).

TABLE II. The cross sections.

k (BeV)	$\theta_{\text{c.m.}}$	$d\sigma/d\Omega$ (10^{-31} cm^2)
1.200	15°	3.79±0.27
	25°	3.34±0.15
	30°	3.41±0.19
	35°	3.00±0.14
	42°	2.84±0.15
	49°	2.82±0.16
	55°	2.76±0.16
	63°	2.41±0.16
	70°	2.02±0.14
	78°	1.94±0.17
	85°	1.54±0.18
1.080	46.5°	2.79±0.18
1.054	31°	2.84±0.22
	48°	2.33±0.19

a K^+ momentum of 670 MeV/c was used to evaluate this factor, 0.87±0.03. From the spectrum in the focusing counter of those particles which fired the Lucite Čerenkov counter, its K-detection efficiency was estimated to be about 5% and independent of momentum. A Monte Carlo calculation shows that about 3% of the detected K^+ yield should give large signals in both Čerenkov counters due to decays occuring between them, and so, this fraction has already been accounted for. Measurements with fast protons indicate that about 0.5% of the K^+ yield should trigger LC by scintillation and δ-ray emission. Finally, detailed considerations of the K^+ beam and the optics of this counter showed that, at the highest momentum used, another 0.5% should fire it by Čerenkov radiation. Thus, a 1% correction was included to account for the losses in this counter. The efficiency of the focusing counter could be determined directly using protons for only the two lowest K momenta. Pions are useless tools for this task since, for the velocities involved, they lose too much energy in the 10-cm-thick radiator. It was necessary, then, to calculate the K-detection efficiency. The optics of the counter and the K^+ beam were mathematically modeled and the expected pulse-height distributions from the counter were calculated with an IBM 7090 computer. The spectra so obtained agreed with observation quite well and were used to obtain the counter's efficiency for each point. These varied from 0.96 to 0.99 with an estimated uncertainty of 30% of the correction.

The total energy in the bremsstrahlung beam was normally measured with an ion chamber which was calibrated against a quantameter[9] several times during the experiment. However, for the three forward points, the magnet yoke intercepted the photon beam and a two element well-shielded counter telescope viewing the hydrogen target at 90° was used as the monitor; the statistical precision of this measurement was normally about 0.2%. The telescope was calibrated against the

[9] R. R. Wilson, Nucl. Instr. **1**, 101 (1957).

TABLE III. Statistical parameters from Taylor-Moravcsik analysis of 1.2-BeV cross sections. The observed cross sections are multiplied by $(1-\beta_K \cos\theta)^2$ and the resulting numbers are fitted with polynomials in $\cos\theta$. The evaluation of the polynomials at $\cos\theta = 1/\beta_K$ gives the "residue" at the one-K-exchange pole. In addition to the 11 cross sections at 1.2 BeV given in Table II, a "boundary condition" in the backward direction based upon unpublished data from Caltech[a] was imposed. The cross section at 127° was taken to be $1.34 \pm 0.40 \times 10^{-31}$ cm².

Order of polynomial	1	2	3	4	5
Degrees of freedom	10	9	8	7	6
χ_{obs}^2	8.24	7.17	7.05	3.73	3.60
"Residue" (10^{-31} cm²)	−0.07	−0.46	−0.81	7.31	15.4
Error on residue	0.09	0.38	1.11	4.59	22.2
Prob. $\chi^2 \geq \chi_{\mathrm{obs}}^2$	60%	62%	53%	81%	73%
F		1.34	0.14	6.24	0.21
F probability		28%	71%	5%	64%

[a] Melvin Drew Daybell, Ph.D. Thesis, California Institute of Technology, 1962 (unpublished).

ion chamber both before and after each small-angle run. The exposure, in number of equivalent quanta, is the total energy in the beam divided by E_0, and its over-all precision is thought to be 1.5%. The bremsstrahlung spectrum factor is known to $\pm 0.7\%$. The accumulation of these various uncertainties, including that of the target contamination, results in an over-all systematic uncertainty of $\pm 6\%$.

In summary, corrections which vary with the center-of-mass angle have been made for inadequate K-meson identification, empty target backgrounds, decays in flight, and electronic efficiencies. Uniform corrections to all the data have been made for nuclear absorption and target contamination although these effects may in fact be slightly angle-dependent.

In Table II, the results of this experiment are given. The errors indicated are statistical only and do not include the systematic uncertainties just discussed. In addition to the principal data at 1200 MeV, three measurements at lower energy were made in order to connect this work with the Cornell data. Figure 6 displays the comparison at the lower energies and the angular distribution at 1200 MeV. In view of the systematic uncertainties which are not included in the error bars, the two experiments seem to be in reasonable agreement.

V. DISCUSSION

The general behavior of the angular distribution at 1200 MeV is the same as that at 1054 MeV, for example. It shows a peaking in the forward direction and a maximum likelihood fit to the form $a_0 + a_1 \cos\theta + a_2 \cos^2\theta$ indicates a statistically significant positive quadratic term.

Although the precise physical mechanisms contributing to this photoproduction process are not as yet established, it seems safe to expect a contribution from

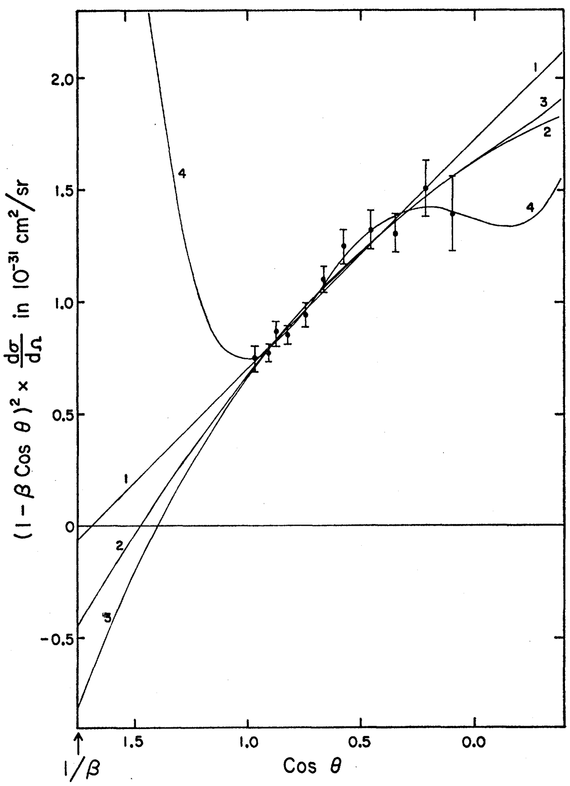

FIG. 7. Polynomial fits to the function $(1-\beta \cos\theta)^2 d\sigma/d\Omega$. The order of the polynomial is indicated on the curves. The intercept with the vertical axis on the left is the extrapolated value at the one-kaon-exchange pole.

the exchange of a K^+ meson in the t channel. This gives rise to the well-known photoelectric term, whose importance was emphasized[10] long ago and which has been sought in earlier K^+ photoproduction[11] data. The existence of this term in the analogous pion reaction

$$\gamma + p \rightarrow \pi^+ + n$$

has been verified[12] by the Taylor-Moravcsik extrapolation method, and, accordingly, the present data have been analyzed in the same way. Table III gives the relevant parameters of the statistical analysis and Figs. 7 and 8 show the resulting fits and extrapolation values. The statistical tests indicate quartic to be preferred (but even the first-order polynomial fits the data quite well). This simply reflects the fact that a quadratic fits the angular distribution very well. Thus, contrary to the significant reduction in the order of the fitting polynomial when the pole is included in the

[10] J. G. Taylor, M. J. Moravcsik, and J. L. Uretsky, Phys. Rev. **113**, 689 (1959).

[11] M. J. Moravcsik, Phys. Rev. Letters **2**, 352 (1959); J. J. Sakurai, Nuovo Cimento **10**, 1212 (1961).

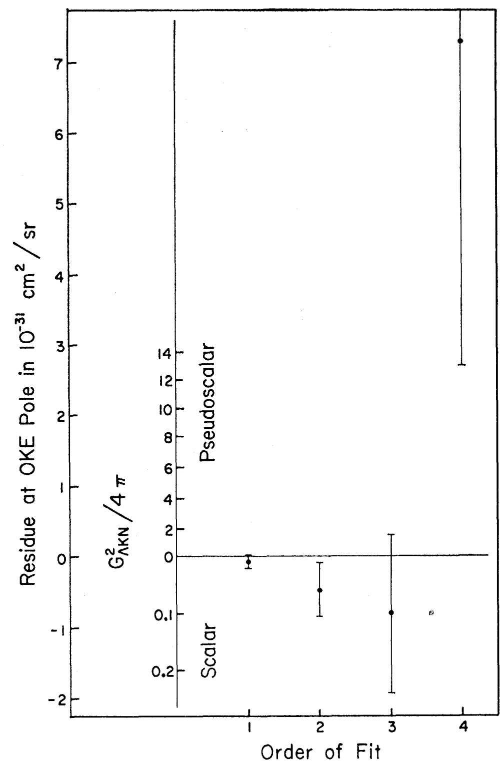

FIG. 8. The extrapolated value at the one-kaon exchange pole expressed in terms of the lambda-nucleon-K coupling constant.

analysis of π^+n photoproduction,[12] this $K^+\Lambda$ data does not suggest any need for its inclusion. Furthermore, at $k=1200$ MeV, the total c.m. energy (1770 MeV) is not very far from that of the $F_{5/2}$ nucleon resonance (1688 MeV) so that one might expect F waves to contribute to the angular distribution. This can be taken as evidence for the need of at least a sixth-order extrapolating polynomial, for which the data are quite inadequate. Accordingly, we do not place much confidence in the resulting extrapolated value.

[12] R. L. Walker, in *Proceedings of the Tenth Annual International Conference on High Energy Physics at Rochester, 1960* (Interscience Publishers, Inc., New York, 1960), p. 17.

Several specific models[13–16] have been proposed recently for strange particle photoproduction. These include contributions from the Born terms, the exchange of the $K^*(885)$, and various resonances. The model of Kuo[13] and Beauchamp and Holladay[14] incorporates a $P_{1/2}$ resonance that has been suggested[17] to explain the bump in the total cross section for the reaction $\pi^-+p \rightarrow K^0+\Lambda$. The parameters in this photoproduction model have been determined by fitting angular distributions at lower energies. However, it predicts the wrong sign for the Λ polarization[4] and gives too flat an angular distribution at 1200 MeV [Fig. 6(c)]. The models of Hatsukade and Schnitzer[15] and Gourdin and Dufour[16] are similar to each other in that they both take into account the $T=\frac{1}{2}$ nucleon resonances at 1512 and 1688 MeV. The relevance of at least the higher of these two states to the pionic associated production has been discussed by Rimpault[18], who finds that a resonant $F_{5/2}$ state is consistent with a partial wave analysis of this reaction. Work is in progress to make a multipole-partial wave analysis of the $K^+\Lambda$ photoproduction data as well as to test the adequacy of the detailed phenomenological models.

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[13] T. K. Kuo, Phys. Rev. **129**, 2264 (1963).
[14] N. A. Beauchamp and W. G. Holladay, Phys. Rev. **131**, 2719 (1963).
[15] S. Hatsukade and H. J. Schnitzer, Phys. Rev. **128**, 468 (1962); **132**, 1301 (1963).
[16] M. Gourdin, Nuovo Cimento **10**, 1035 (1961); M. Gourdin and J. Dufour, *ibid.* **27**, 1410 (1963).
[17] G. T. Hoff, Phys. Rev. **131**, 1302 (1963); A. Kanazawa, *ibid.* **123**, 993 (1961).
[18] M. Rimpault, Nuovo Cimento **31**, 56 (1964).