Photoproduction of K^+ Mesons*

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The photoproduction in hydrogen of K^+ mesons in association with hyperons has been studied using an 1160-Mev bremsstrahlung beam from the Cornell Synchrotron. The K mesons were selected with a magnetic analyzer and counter telescope system. They were further identified by bringing them to rest in a stopping block and by the detection of the particles arising from their decay. The angular distribution for the associated production of K^+ mesons with Λ^0 hyperons at the photon energies of 980 and 1010 Mev has been studied. Measurements were also made of the cross section as a function of photon energy for the center-of-mass angle of 85 degrees. The results of these measurements are compatible with S-wave production. The photoproduction of Σ^0 hyperons in association with K^+ mesons has also been measured for one set of kinematical conditions. The measured $(K^+-\Sigma^0)$ cross section is comparable to that of the $(K^+-\Lambda^0)$ process.

INTRODUCTION

ONE of the problems available for study using the Cornell electron synchrotron, operating near 1.2 Bev, is the photoproduction of K mesons. Assuming the conservation of strangeness, the following reactions are possible at this energy when the target material is hydrogen:

$$\gamma+p \rightarrow K^+ + \Lambda^0, \tag{1}$$

$$\gamma+p \rightarrow K^+ + \Sigma^0. \tag{2}$$

The threshold for the first reaction is 910 Mev, and for the second reaction, it is 1040 Mev. In addition, neutral K mesons can be produced by the reaction

$$\gamma+p \rightarrow K^0 + \Sigma^+.$$

Both neutral and negative K mesons may also be produced when a complex nucleus is used as a target material.

Measurements of the angular distribution and cross section as a function of energy have been made by our group at Cornell. Preliminary results and a short summary of the present work[1,2] have already been reported. It is the purpose of the present paper to describe these measurements in more detail. We have confined our attention largely to process (1), though a single observation of process (2) is also included. Measurements of reaction (1) have also been reported by a group using the synchrotron at the California Institute of Technology (CIT).[3–5]

The work was undertaken in order to make an experimental determination of the cross sections for the above reactions and, in addition, it was hoped that it would be possible to make deductions from them concerning the parity of the K meson and the strength of the K-meson coupling to baryons. Because of the uncertainty and ambiguities of present theories, at present only limited conclusions can be drawn from the results.

A. EXPERIMENTAL ARRANGEMENT

The experiments were performed by identifying the K^+ meson produced in the reaction. Magnetic analysis was used to select the K-meson momentum and angle of production with respect to the direction of the photon beam. Because both reactions (1) and (2) have the kinematics of a two-body reaction, the measurement of the K-meson angle and momentum uniquely determines a photon energy corresponding to each reaction, the photon energy for reaction (2) being generally 120 Mev greater than that for reaction (1). The measurement of the K-meson yield as a function of the peak beam energy enables us to determine the cross section for both reactions. As will be seen in the section entitled "Identification of Reaction," the experimental data are consistent with the associated production by these two reactions.

The general experimental arrangement is shown in Fig. 1. The bremsstrahlung beam from the synchrotron is collimated by a lead collimator, and the collimated beam then passes through the hydrogen target and thence to the monitoring Quantameter,[6] a shower ionization chamber. The K mesons produced in the target pass out through the walls of the target and are selected in angle and momentum by the analyzing magnet. On leaving the magnet, the particles first traverse a series of counters which, together with their associated electronics, determine their specific ionization and reject light relativistic particles. The K mesons are then stopped in an aluminum absorber, and the secondaries are detected by a group of four counters, subsequently called "side counters," which surround the aluminum stopping block. A coincidence is required between at least one of the side counters and the output of the main telescope.

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1 Silverman, Wilson, and Woodward, Phys. Rev. **108**, 501 (1957).
2 McDaniel, Cortellessa, Silverman, and Wilson, Bull. Am. Phys. Soc. Ser. II, **3**, 24 (1958); McDaniel, Silverman, Wilson, and Cortellessa, Phys. Rev. Letters **1**, 109 (1958).
3 P. L. Donoho and R. L. Walker, Phys. Rev. **107**, 1198 (1957).
4 Brody, Wetherell, and Walker, Phys. Rev. **110**, 1213 (1958).
5 P. L. Donoho and R. L. Walker, Phys. Rev. **112**, 981 (1958).
6 R. Wilson, Nuclear Instr. **1**, 101 (1958).

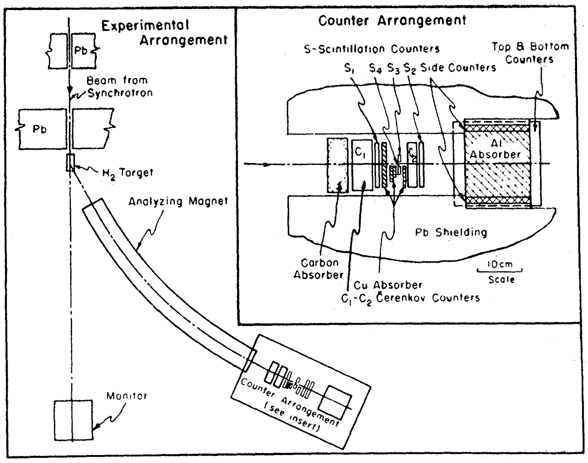

FIG. 1. Experimental arrangement and counter arrangement for the detection of the K^+ mesons produced in the liquid hydrogen target.

The lead collimator, 8 in. thick, restricts the beam dimensions at the hydrogen target to a rectangle of dimensions of about $\frac{1}{2}$ by 1 in. For all but one of the measurements, a liquid hydrogen target[7] was used which consisted of a thin-walled cylindrical container enclosed in a vacuum jacket with thin entrance and exit windows lying outside of the acceptance angle of the magnet. The cylinder has a diameter of $1\frac{1}{2}$ in. and is 3.10 in. long. The end walls of the cylinder, where the beam enters and leaves, are made of 0.001-in. stainless steel. The K particles leave the target through two thin walls of copper and brass whose total thickness corresponds to about 1.4 g/cm^2 of Cu. In the single measurement excepted above, a Styrofoam-insulated target, described in the literature,[8] was used.

The analyzing magnet used is a two-lens, strong-focusing magnet. Two momentum channels, separated by about 13% in momentum, are defined by the target position, defining stops in the magnet, and two scintillation counters. The determination of the central momentum, the momentum resolution, and the aperture of the magnet is described below. (See Sec. E.)

The counter arrangement is shown in the inset in Fig. 1. Four scintillation counters are used in the main telescope. Counters S_1 and S_2 are plastic scintillators of $\frac{1}{8}$ in. thickness and cover the full output solid angle of the magnet. Counters 3 and 4 are counters which define the two momentum channels for the magnet. These are each of $\frac{3}{4}$-in. width, 3-in. length, and $\frac{1}{4}$-in. thickness. The amplified outputs of the photomultiplier tubes to which the scintillators are attached are passed through discriminators and taken in coincidence, to form the two coincidence channels, "123" and "124". In addition to the scintillators, either one or two Čerenkov counters are used in anticoincidence to reject particles of velocities greater than those of the K mesons being detected. The number of Čerenkov counters used depends on the amount of residual K range available to be used up in this manner. Generally the Čerenkov counters are of Plexiglas though for some of the measurements, a water-filled counter was used. In setting up the electronics, care was taken to ensure that the counting loss due to the anticoincidence rate would not be excessive. It is believed that losses due to this cause are less than 2%. In addition to the counters, various absorbers were used to reduce the residual range of the mesons and to increase the pulse height and discrimination in the scintillators.

A rather large thickness of aluminum stopping block is necessary for many cases because of the large range dispersion corresponding to the momentum channel width. Though the momentum dispersion is only about 13%, the corresponding range dispersion is about four times greater. This has also the effect of making precise discrimination in the telescope on a basis of pulse height difficult, since the corresponding dispersion in specific ionization is very great. The counters in which the K-meson decay particles are detected are each about $\frac{1}{2}$ in. of plastic scintillator. The dimensions of the top and bottom counters are $8\times7\frac{1}{2}$ in. while the two counters at either side are each 6×6 in. Separating the aluminum block and the side counters is an additional thickness of shielding corresponding to about $\frac{1}{2}$ in. of lead. The counters themselves are heavily shielded on the outside to decrease the accidental coincidence rate with the main telescope which would result from a high background rate of uncorrelated particles in the side counters.

In order to establish satisfactory discrimination levels in all counters, a relatively slow coincidence system (0.5×10^{-6} sec resolution) was used. However in order to obtain sufficient time resolution to suppress the accidental coincidence rate between the telescope and the very large side counters, an additional fast coincidence (5×10^{-8} sec) was provided between the side counters and one of the counters (S_2) of the telescope. Then by taking an additional coincidence between the output of the slow and the fast coincidence circuits, one effectively counts only those events which satisfy the slow discrimination criteria and at the same time appear in fast coincidence with the side counters. It was necessary, of course, to make certain that the discrimination level of the fast coincidence circuit was sufficiently lower than the discrimination of the slow system so that no coincidences were lost by the fast system because of pulse-height discrimination.

B. EXPERIMENTAL PROCEDURE

In principle, it should be possible to identify the K mesons without the requirement of the detection of the secondary particles arising from their decay. However, since there are a total of about 5000 protons and π mesons per K meson, a very small fraction of these

[7] R. Wilson, Rev. Sci. Instr. 29, 732 (1958).
[8] R. Littauer, Rev. Sci. Instr. 29, 178 (1958).

which succeed in satisfying the selection criteria will give rise to an unacceptably high background. If the telescope is used alone, a background rate about five times the K-meson rate is observed. It is believed that these background particles are protons or mesons which do not follow the main channel of the magnet but are scattered off the magnet faces and arrive at the telescope having an incorrect momentum. The addition of the side-counter requirement reduces this background to the range of 5 to 15% of the K-meson rate.

The process of establishing the correct biases for all the counters is very important. The operating point for the Čerenkov counters was adjusted so that the rejection of π mesons was essentially independent of the gain of the amplifier and yet was not such as to include a large number of background counts from the photomultiplier tube noise. One of the counters used rejected about 90% of the pions, while the other rejected about 98%. Both counters were examined for spurious counts due to scintillation by allowing protons to stop in them with a large energy loss. It was concluded that no significant fraction of the K mesons would produce scintillation pulse heights greater than the bias. Suitable absorbers were placed ahead of the Čerenkov counters so that the K-meson energy fell below the threshold for Čerenkov radiation in the counters.

The biases for the side counters were established by observing the pulse heights produced by relativistic cosmic-ray particles passing through the counters in coincidence with another counter provided especially for the purpose.

The thickness of absorbers placed in the two momentum channels 3 and 4 was computed so that the pulse heights in each of the telescope counters were at least 1.6 times those for a particle which passes through at minimum ionization. Generally, it was possible to arrange it so that they were appreciably larger than this, and in some cases as much as 2.5 times minimum. Though it is possible, in principle, to use fast mesons to establish the sensitivity of the scintillation counters, and to use protons to give another point of calibration, ultimately the biases were established by looking at the pulse-height distribution of the K mesons themselves. To do this, one sets the biases in the telescope at values which are conservatively low as estimated from the relativistic pions. Then runs are taken with the synchrotron beam incident on the hydrogen target and the pulse heights observed in each of the four telescope scintillation counters whenever a particle satisfying all the criteria passes through the system. After obtaining sufficient statistics, one may observe from the distribution, the proper location for the separate biases and adjusted them accordingly. It was of course necessary to make certain of the identification of the K mesons.

In Fig. 2 is shown the pulse-height distributions observed in the four scintillation counters of the telescope. One sees that the pulse-height distributions are rather sharp and that it is possible to establish the biases

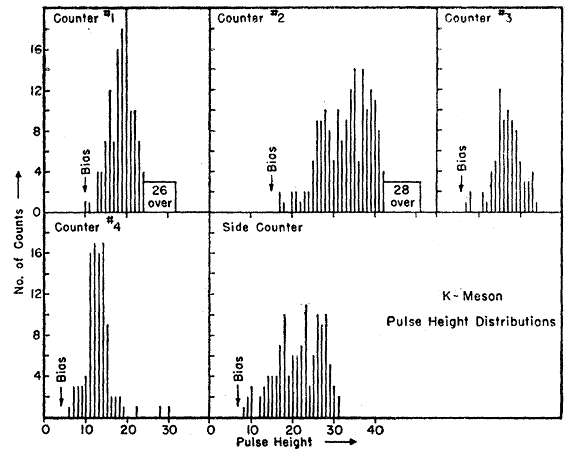

FIG. 2. Distribution of the K-meson pulse heights for each of the counters in the main telescope.

without ambiguity. The location of the arrow indicates the chosen operating points. It is believed that loss of counting rate due to small pulses which fall below the biases is generally at most two percent. Because of the low cross section for the reaction, a very long counting time was required to establish completely the correct operating point. As a result, preliminary biases were established and the runs were begun. Statistics on the pulse heights were gathered continuously through the run. In some cases it was necessary to readjust the biases and start again. In two other cases, it was necessary to make a correction of a few percent for pulses which fell below the bias in a single counter. The correction was determined by extrapolating the observed pulse-height distribution curve below the bias point.

C. IDENTIFICATION OF REACTION

The most important single check that the particles detected by the system described above are in fact K mesons arising from reactions (1) and (2) comes from the verification that the photon energies responsible for these particles are precisely those calculated assuming the validity of these reactions. This is confirmed by a set of measurements which were taken at a laboratory angle of 24.5° and momenta for channels 3 and 4 of 398 and 451 Mev/c, respectively. From the kinematics, K mesons produced by process (1) which are detected under these conditions are produced by photons of energies 982 and 1010 Mev. The corresponding photon energies for process (2) are 1110 and 1140 Mev. The measurements which were made consisted of observing the counting rate per equivalent beam quantum (see Sec. E) as a function of the peak energy of the bremsstrahlung spectrum. If these two processes are indeed the correct and important ones in this energy region, then at a peak energy of 900 Mev, we will measure only the background of the apparatus. As we increase the peak energy above 980 Mev, we should observe an

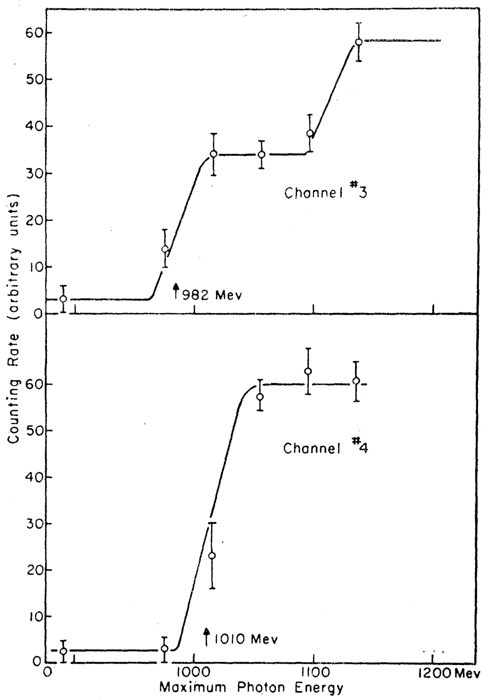

FIG. 3. Counting rate in channels 3 and 4 per equivalent beam quantum as a function of the maximum photon energy of the bremsstrahlung beam. In channel 3, one may see the increase in counting rate which occurs as photons of sufficient energy are available to produce K mesons in association with the Σ^0 hyperons at the same momentum and angle as for those K mesons produced in association with Λ^0 hyperons.

increase in the counting rate in channel 3 as we begin to obtain photons of sufficient energy to produce K mesons for which this apparatus is sensitive. As the energy is increased in the region from 980 Mev to about 1100 Mev, the counting rate should remain constant, but in the vicinity of 1100-Mev peak energy, it should again rise and level off if there is any contribution from process (2) by photons of 1110 Mev. The corresponding features should be observed in channel 4, but for correspondingly higher energies. Plotted in Fig. 3 are the results of these measurements. We note the expected rise in counting rate at 982 and 1010 Mev for channels 3 and 4, respectively. In addition, we note that in channel 3, the point at 1136 Mev lies much higher than the plateau region from 1000 to 1100 Mev for channel 3, indicating that reaction (2) has a cross section comparable to that of reaction (1). The corresponding second increase is not observed in channel 4 because of insufficient photon energy. The solid lines which have been drawn are computed curves based upon K-meson angle and momentum, and upon the measured peak photon energy in the bremsstrahlung distribution. The ordinates are normalized to the data. The computations have included the effects of the angular and momentum resolution of the magnet and the theoretical shape of the end of the bremsstrahlung spectrum. It is of interest to note that the location of the rapid increase in counting rate corresponding to process (1) is located to within one-half percent of the energy value predicted from the computed curves. We conclude that the reactions considered are indeed the correct ones and that they strongly confirm the principle of conservation of strangeness in strong interactions. The alternative reaction which one might expect to observe, in the event that strangeness is not conserved, is the reaction $\gamma+p\rightarrow K^{+}+n$, which has a threshold at 630 Mev. It is clear from the data that if such a reaction is possible, its cross section at an energy several hundred Mev above threshold is still less than 5% of the cross section for reactions (1) and (2). In the following treatment of the data we have assumed that the cross section for this latter reaction is zero.

D. BACKGROUNDS

There are three types of background: K mesons arising from the end windows of the target; particles other than K mesons which are detected; and accidental coincidences. Since the end windows of the target are only 0.001 in. of stainless steel, and the length of hydrogen in the chamber along the beam line is 3 in., the number of protons in the end windows is 3.3% of the number of protons in the hydrogen itself. Thus we see that the background due to the target is small. Measurements to examine the background were made at the laboratory angle of 16° with K-meson momenta of 471 and 520 Mev/c for channels 3 and 4, respectively. In this case, measurements were made both above threshold for K production in hydrogen, $k_{\max}=1060$ Mev, and below threshold, $k_{\max}=950$, and in each case, both with and without hydrogen in the target. The results are tabulated in Table I.

As expected, the measurements without hydrogen showed no statistically significant variation with the beam energy. This is of course simply because the intensities are not sufficiently high to enable one to make a statistically significant measurement in a reasonable length of time. Since the target walls consist of complex nuclei in which internal nuclear momenta are involved, one would expect to observe some K-meson yield at photon energies below the threshold for production in hydrogen. Rough measurements both at CIT and at Cornell indicate that the cross section for K production in hydrogen and in heavier elements is roughly the same, per proton, for energies of 50 to 100 Mev above threshold.

Most of the background arises from the contamination of the K-meson counting rate by other particles: protons, pi mesons, and electrons. Because we did not know of a more exact method of taking these backgrounds into account, we obtained the yield of K mesons from the hydrogen by subtracting the results of measurements taken with the target full, below threshold, from those taken with target full above threshold. This takes into account the contamination of the beam. This quantity was then further reduced by 3% to correct for the K mesons generated in the target walls.

TABLE I. Results of background measurements taken at the laboratory angle of 16°. Meson momentum for channels 3 and 4 are respectively 471 and 520 Mev/c. Measurements are shown for the hydrogen target full and empty, at 1060- and 950-Mev maximum photon energy. With these conditions, and assuming the kinematics for the reaction $\gamma+p \rightarrow K^+ + \Lambda^0$, no K mesons should be detected for the maximum photon energy of 950 Mev.

Peak photon energy	950 Mev Counts in channel	950 Mev Monitor	950 Mev (Counts/monitor) $\times 10^3$	1060 Mev Counts in channel	1060 Mev Monitor	1060 Mev (Counts/monitor) $\times 10^3$
Channel 3						
Target full	15	1350	11 ± 3	394	7702	51 ± 3
Target empty	4	700	5.7 ± 3	9	1670	5.4 ± 2
Channel 4						
Target full	4	1350	2.9 ± 2	426	7702	55 ± 3
Target empty	1	700	1.4 ± 2	4	1670	2.4 ± 2

It was necessary to make a small correction for accidental coincidences between the telescope and the side counters. This correction was less than two percent. A continuous monitor of the accidental coincidence rate was obtained by comparing the rate of slow coincidences only, with those combined with the fast coincidence. Basically, the accidental rate in the two channels should be in the ratio of the resolving times so that the difference between the two rates can be used to calculate the correction to the fast coincidence rate. Suitable checks were made to confirm the correctness of this assumption.

E. CROSS-SECTION DETERMINATION

Before being able to calculate a cross section from a measurement of yield under a given set of conditions, a number of quantities must be evaluated. The complete expression for the cross section in terms of parameters which may be directly evaluated is given in the following equation:

$$\frac{d\sigma}{d\Omega} = \frac{Y}{nMp\beta^2 GN(k)De_s e_i e_0},$$

where Y = yield in number of counts; n = atoms/cm^2 of hydrogen in the target;

$$M = \text{magnetic aperture} = \int \frac{dp}{p} d\Omega_{\text{lab}};$$

$p = K$-meson momentum; $\beta = K$-meson velocity/velocity of light;

$$G = G(p,k) = \frac{1}{\beta^2} \frac{\partial k}{\partial p} \frac{d\Omega}{d\Omega_{\text{lab}}},$$

with $d\Omega$ = differential solid angle in the center-of-mass system and $d\Omega_{\text{lab}}$ = differential solid angle in the laboratory system; $N(k) = (fcS/k_{\max}k)$ = number of photons per unit energy interval with S = number of monitor units, k = photon energy producing the reaction, $k_{\max}$ = maximum photon energy in bremsstrahlung beam, f = form factor for bremsstrahlung spectrum, c = total energy in photon beam per monitor count; D = fraction of K mesons remaining after decay in flight; e_s = efficiency of side counters for detecting one of decay products; e_i = efficiency factor arising from loss of K-mesons scattered or absorbed from the beam by absorbers and counters; e_0 = the product of all other efficiency factors.

We will discuss, in this section, each of the quantities that enter into the expression for the cross section and give some estimate of the accuracy with which each quantity is known.

The quantity Y is the directly measured yield of K particles, corrected for background, during a run in which S monitor units of integrated beam were recorded. The error ascribed to this quantity is simply the standard statistical error. The quantity $N(k) = (fcS/k_{\max}k)$ is the number of photons per unit energy interval at the photon energy k, which enter the target during the run. To understand this, we consider the following relations. The ionization chamber collects a total charge which is proportional to the total amount of energy carried by the photon beam. Thus the number of monitor counts, S, is related to the total energy in the beam by a calibration constant of the monitor, c. If $N(k)dk$ is the distribution of photon energies from the bremsstrahlung beam, for the run of length corresponding to S monitor counts, we have

$$\int_0^{k_{\max}} kN(k)dk = cS.$$

The product cS then gives the total energy carried by the beam during the run. This is usually called "Mev of beam." Now $N(k)dk$ can be written as

$$N(k)dk = (cS/k_{\max}) f(k,k_{\max}) dk/k,$$

where $f(k,k_{\max})$ is a form factor such that

$$\int_0^{k_{\max}} f(k,k_{\max})dk = 1.$$

The quantity $cS/k_{\max} = Q$ is usually called "number of equivalent quanta." The calibration constant, c, for our ionization chamber is 4.95×10^{12} Mev/monitor unit. This constant has been determined both by theoretical calculations and an intercalibration at 300 Mev with pair spectrometer measurements. It is believed to be determined with about 5% accuracy. Recent measurements in our laboratory[9] of the factor f indicate that in the region of the upper end of the spectrum, where we are working, the quantity f is about $(7\pm5)\%$ lower than that given by the Bethe-Heitler theory for a thin target bremsstrahlung. These measurements, made with a pair spectrometer, are preliminary. Similar measurements[10] made by the CIT group indicate very little deviation from the theoretical thin-target spectrum. Rather than make an uncertain correction for this effect, or wait for a more refined measurement, we have chosen to compute the cross section on the basis of the theoretical thin-target spectrum. If future measurements definitively show a deviation from this spectrum, then our cross section can be easily corrected for that deviation. The quantity $k_{\max}$ has also been measured by the pair spectrometer and is believed to be known to at least one percent. Actually, the data discussed under Sec. C yield a very precise calibration of the quantity $k_{\max}$, once one has concluded that the identification has been properly made. The determination of the energy, k, of the photon which produces the reaction is based on the kinematical relations between the K-meson momentum, p, and the laboratory angle of emission. As described below, p is known to about one percent. The angle $\theta_{\text{c.m.}}$ is determined to about 0.5 degree. This leads to an uncertainty of photon energy of less than one percent.

The quantity n gives the number of hydrogen atoms/cm^2 in the target. The target dimensions have been determined to a high degree of accuracy so that the principal uncertainty here is the hydrogen density. We have used the density 0.071.[11] We have measured the pion yield from the target and compared it with the pion yield from (CH_2-C). This measurement confirms the value given above to an accuracy of 3%.

The determination of the mean momentum p and the momentum dispersion was made by measuring the range distribution of protons which were passed by the magnet at a given setting of the magnet current. These range measurements were then converted into equivalent momenta after correction for loss of momentum in the air path of the magnet. It is believed the momentum p is determined to better than one percent. The quantity M, a constant of the magnet, involves the momentum and angular acceptance of the magnet. This quantity is given by $M=\int(dp/p)d\Omega_{\text{lab}}$, where dp is the differential momentum interval and $d\Omega_{\text{lab}}$ is the differential solid angle. The integral is taken over the entire angle and momentum acceptance interval. It was determined in several different ways. The most direct method involved the use of a simple proton telescope set at the same angle with respect to the beam as the magnet, but on the opposite side of the beam line. The counter telescope was adjusted to be sensitive to protons of the same range as for the magnet and to have a sensitive range interval of approximately the same value. Then from a knowledge of the accurately measurable solid angle and the range interval, it was possible to calibrate, by direct comparison from the same target, the value of M. This measurement was made on two separate occasions, and the values agree to within the statistical errors. This value is also in good agreement with another value obtained by comparison with another magnet of weak-focus design which had been carefully calibrated previously. We believe this parameter has been determined to about 4%. In making the magnet calibrations, a low-density Lucite target of the same dimensions as the hydrogen target was used. The sensitivity of the counting rate was also determined as a function of the beam height relative to the magnetic channel in order to establish the tolerance to beam location.

The factor G is a kinematical factor which we obtained from curves made by the CIT group.[12] The quantities which are important in determining this factor are the momentum of the K particle being detected and the energy of the photon producing the reaction. The uncertainties in these quantities give rise to an uncertainty in G of about 2%.

The quantity D is the fraction of K mesons which traverse the magnet without decaying in flight. Essentially all K mesons that decay before arriving at the stopping block are not detected. Decay products of a K meson that pass through the counter telescope system will be minimum-ionizing and so will be rejected as pi mesons or electrons, and those decaying immediately after will not have a very large probability for the detection of the secondaries in the side counters. One may estimate the efficiency in this intermediate region and then obtain an over-all efficiency using the measured mean life for the decay. The value of mean life which is used is $(12.2\pm0.13)\times10^{-9}$ sec.[13] The value of the quantity D varied from 0.35 to 0.58 depending on the momentum. An over-all estimate of the accuracy of this factor is about 3%, assuming no error in mean life.

The determination of the side-counter efficiency is one of the most difficult. It was assumed that the decay modes and ratios for K mesons produced by photoproduction are the same as those produced by particle interaction.[13] Then by calculating the solid angle efficiency for the detection of the various decay particles as they stop in the aluminum block, one may calculate an overall efficiency. Such a calculation must take into account the ranges of the secondary ionizing particles, the conversion efficiency for the π^0 gamma rays, and the spatial distribution of the decay events. Fortunately, the most favored mode, 58%, is the $K_{\mu2}$ in which the muon has an energy of about 150 Mev, and hence a long range with no other detectable particle accom-

[9] E. Malamud (private communication).
[10] J. Vette, Phys. Rev. **111**, 622 (1958).
[11] Wesley, Scott, and Brickweddie, J. Research Natl. Bur. Standards **41**, 379 (1948).
[12] R. L. Walker (private communication).
[13] M. Gell-Mann and A. Rosenfeld, *Annual Review Nuclear Science* (Annual Reviews, Inc., Palo Alto, California, 1957), Vol. 7, p. 407.

panying it. In this case, then, the geometrical detection efficiency is the principle uncertainty. The next most abundant mode is that of the $K_{\pi 2}$, 25%, which gives rise to a 109-Mev π^+ and a π^0. In this case the range becomes marginal and must be taken into consideration; in addition, the detection efficiency for the gamma rays from the π^0 must be estimated. The remaining modes contribute only about 10% to the over-all detection efficiency. In order to make the center of the K-meson range interval always come in the center of the side-counter array, the aluminum stopping block was varied in thickness from 2 to 6 in. as the selected K momentum was varied. The slight variation of the side-counter efficiency due to this cause is included in the calculation. The approximate over-all efficiency was 70% with an uncertainty of about 5%.

The efficiency factor e_i takes into account the counting rate loss of K mesons because of scattering and charge exchange reactions. Corrections for these effects are largest for high K-meson momentum because of the large thickness of the absorbers required for slowing them down. Calculation of the corrections for losses in the counters, absorbers, and stopping block was made on the basis of direct measurements for K mesons of 190-Mev energy.[14] In the most extreme case, the loss was about 24%. For most of the cases, the loss is less than 10%. It is believed that the maximum uncertainty introduced in the cross section due to the scattering correction is not greater than 5% for the worst cases.

The efficiency factor e_0 includes corrections for all other small effects. This includes the following effects: (a) Losses due to K-meson pulse heights which fall below the bias. This effect was important in only two cases and was only 5% in the worst case. (b) A correction for loss of counts due to mesons failing to stop in the absorber. This correction was only important in one case and amounted to 10%. (c) Dead time in the current integrator of the monitoring circuit. This correction never exceeded two percent. (d) Counting rate loss due to the anticoincidence circuit, amounting to 1.5%. (e) Correction to the effective range interval of the magnet due to the decrease of momentum in the target. This correction amounted to 10% in two cases, and on the average was about 5%. (f) Correction for loss of counts as a result of decaying secondaries occurring with a delay exceeding the resolving time of the fast coincidence. This correction is 0.5%. The error in the factor e_0 due to all these corrections combined is of the order of 3%.

The combined systematic error due to all the causes enumerated above comes out to be approximately 10%, but one may conservatively set a value of 15%. The error affects all the measurements approximately equally and must be added to the statistical counting errors.

In Table II are given the pertinent data and cross sections for the various experimental conditions which

[14] Kerth, Kycia, and Van Rossum, Phys. Rev. **109**, 1784 (1958).

TABLE II. Experimental data and calculated cross section for reaction $\gamma+p\rightarrow K^++\Lambda^0$ and $\gamma+p\rightarrow K^++\Sigma^0$. The photon energy k and center-of-mass angle $\theta_{\mathrm{c.m.}}$, are calculated from the kinematical relations involving the K-meson momentum and angle in the laboratory. $k_{\max}$ is the maximum photon energy of the bremsstrahlung beam. The counts observed are tabulated for the corresponding "Mev of beam quanta." The differential cross section in the center-of-mass system is given by $d\sigma/d\Omega$.

k (Mev)	$\theta_{\mathrm{c.m.}}$ (degrees)	$k_{\max}$ (Mev)	Counts observed	(Mev of beam quanta) $\times 10^{-15}$	$d\sigma/d\Omega$ (10^{-31} cm²/sterad)[c]
		$\gamma+p\rightarrow K^++\Lambda^0$			
980	28	1085	234	26.3	0.73±0.10
		930[a]	38	14.1	
	46	1045	394	38.2	0.90±0.09
		920[a]	15	6.7	
	75	1060	176	27.6	0.99±0.10
		1100	78	11.3	
		895[a]	3	5.4	
	150				0.89±0.21
1010	26	1085	301	23.0	1.32±0.13
		930[a]	21	8.9	
	44	1045	426	38.2	1.32±0.07
		920[a]	4	6.7	
	68	1060	295	27.6	1.40±0.10
		1100	129	11.3	
		1140	187	17.4	
		895[a]	3	5.9	
		980[a]	2	3.5	
	89	1070	106	19.9	1.26±0.19
		1070[b]	7	7.9	
	116	1060	102	32.9	1.46±0.29
		920[a]	6	9.1	
935	85	1060	107	18.5	0.83±0.16
		880[a]	25	13.8	
963		1060	103	18.5	1.08±0.19
		880[a]	5	5.5	
1006		1070	106	19.9	1.23±0.20
		1070[b]	7	7.9	
1032		1140	128	20.2	1.25±0.18
		960[a]	3	5.1	
1066		1140	155	20.2	1.25±0.14
		960[a]	2	5.1	
		$\gamma+p\rightarrow K^++\Sigma^0$			
1111	85	1140	176	17.4	0.61±0.13
		1100[a]	78	11.3	
		1060[a]	176	27.5	

[a] Background measurement, target full but below threshold.
[b] Target-empty background. This run taken using Littauer target.[8] Background taken with no hydrogen, but above threshold because of dominant background due to wall thickness.
[c] Errors given include only the standard statistical errors based on the number of counts.

were studied. The results of the measurements are given in Fig. 4 and Fig. 5. Figure 4 plots the cross section, $d\sigma/d\Omega$, for process (1) as a function of the center-of-mass angle, $\bar{\theta}_{\mathrm{c.m.}}$, for the photon energies of 980 and 1010 Mev. The point at 150° in the 980-Mev angular

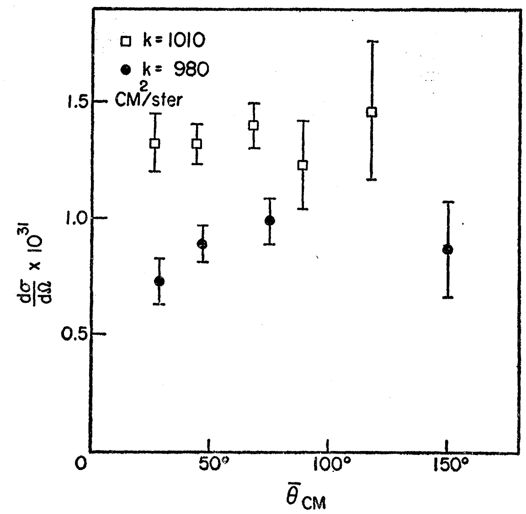

FIG. 4. The differential angular distribution, $d\sigma/d\Omega$, for the (K^+,Λ^0) process as a function of the center-of-mass angle, $\theta_{c.m.}$, for photons of 1010 and 980 Mev.

distribution is taken from the measurement reported in reference 1. The point at 26° cm for 1010 Mev has been corrected for a calculational error which was made in the earlier report.[2] The indicated errors include only the standard statistical errors. The scarcity of data and the large probable errors for measurements greater than 90° are a result of low intensity arising from unfavorable kinematical factors as well as a relatively higher background. Figure 5 shows the cross section as a function of photon energy for a center-of-mass angle of 85°.

It should be pointed out that there is probably an experimental inconsistency in the data given in Figs. 4 and 5. Smooth curves drawn through each of the sets display the fact that the difference in cross section at 85° for photons of 980 and 1010 Mev is somewhat greater as determined from the angular distributions of Fig. 4, than when it is determined from the curve, Fig. 5, which shows the dependence of the cross section on photon energy. It has not been found possible to resolve this discrepancy, though it is likely that it is a combination of poor statistics and some systematic error in the determination of the relative sensitivity of the two momentum channels.

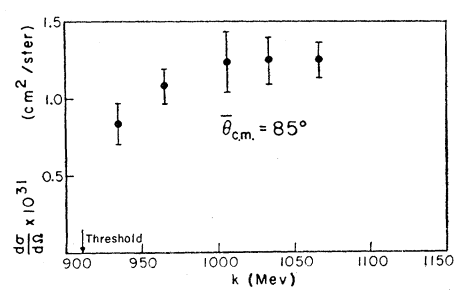

FIG. 5. The differential cross section, $d\sigma/d\Omega$, for the (K^+,Λ^0) process as a function of photon energy at the center-of-mass angle, $\theta_{c.m.}$, of 85°.

Also shown in Table II is the result of the cross-section determination for $(K^++\Sigma^0)$ process. This cross section is calculated by subtracting the K yield at $k_{max}=1060$ and 1100 Mev from the yield for $k_{max}=1160$ Mev. It is interesting to note that the cross section for process (2) is about $\frac{2}{3}$ that of process (1) at a comparable energy above threshold.

F. CONCLUSIONS

The measurements above and below threshold, as shown in Fig. 3, beautifully confirm the associated production of the K mesons with baryons, in agreement with the theory of conservation of strangeness in strong interactions. Without relying strongly on detailed theoretical calculation, one may draw the conclusion that reaction (1) is dominantly S-wave near threshold. This is determined from Fig. 6 which shows a plot of the cross section as a function of center-of-mass momentum of the meson. This is to be compared to a linear dependence for S wave, or a p^3 dependence for P wave. The linear dependence seems to fit fairly well, and it is clear that the data cannot be fitted by a p^3 relation. In fact, as one might expect, in regions well above threshold, the cross section rises even less rapidly than that given by a linear dependence. Further, the angular distributions which are observed in Fig. 4 may also be interpreted as being essentially isotropic and consistent with S-wave production. S-wave production implies magnetic dipole interaction for a scalar K meson or electric dipole interaction for the pseudoscalar case.

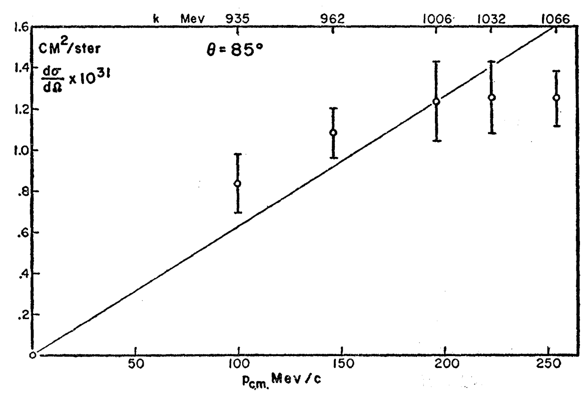

FIG. 6. The differential cross section, $d\sigma/d\Omega$, for the (K^+,Λ^0) process as a function of the momentum, $p_{c.m.}$, in the center-of-mass system, for the center-of-mass angle, $\theta_{c.m.}=85°$.

Because of the lack of any very reliable theory for the processes involved, it has not been possible to make further interpretation of the results very significant. Various theories[15–19] based on perturbation calculations

[15] M. Kawaguchi and M. Moravcsik, Phys. Rev. **107**, 563 (1957).
[16] A. Fujii and R. Marshak, Phys. Rev. **107**, 570 (1957).
[17] B. Feld and G. Costa, Phys. Rev. **110**, 968 (1958).
[18] D. Amati and B. Vitale, Nuovo cimento **6**, 394 (1957).
[19] R. Capps, Phys. Rev. **114**, 920 (1959).

have been made. Aside from questions of validity of perturbation methods, one of the large difficulties in trying to apply these calculations to assist in determination of the relative K-meson parity is that one does not know what values of the magnetic moments to use in the calculation. This leaves too many parameters undetermined for such an analysis to be very useful. The work by Fujii and Marshak and by Kawaguchi and Moravcsik may be used to attempt to fit the data but some choice for the magnetic moment must be made. In the paper by Capps, there is a discussion of the appropriate choice of magnetic moments which one should use, including the effect of the transition moment. By assuming the validity of the globally symmetric model for pion interactions, and making the reasonable assumption that the hyperon coupling constants are related so that $G_\Lambda^2 = G_\Sigma^2$, one may obtain a set of values for the moments to use in the calculations.

These values may be inserted in the equations of Capps to obtain an expression for the energy and angular dependence near threshold. However, for large energies above threshold, it is necessary to consider higher order terms which have been dropped in his calculation. Moreover, the calculations of Kawaguchi and Moravcsik may be used to provide a good approximation if, as described below, one includes the transition moment in their calculation. Using this theoretical approach, we have chosen parameters which give reasonable agreement with the experimental data. Possible values for the K-meson coupling constant, $G^2/4\pi$, which we have found are 0.063 and 2.2 for the scalar case and pseudoscalar case, respectively.

Several things must be kept in mind. First, these are perturbation calculations only. Second, the cross section and distribution with angle is very sensitive to the choice of values for the magnetic moments. Third, the choice of moments is based on the global symmetry model and on the value of G_Σ relative to G_Λ. This latter ratio, though it can probably be obtained through the measurement of K-meson scattering, seems most directly related to the measurement in this paper of the (K^+,Λ^0) and (K^+,Σ^0) cross sections at roughly equal distances above threshold. It is to be noted that there is also an ambiguity in the relative sign of G_Σ and G_Λ; thus even after making as many assumptions as indicated, there is still another parameter other than the K-meson parity to be determined by fitting the data.

The attempt to fit the data was made with the calculations of Kawaguchi and Moravcsik, using the moments of Capps in the following way. Of the terms involving the magnetic moments, the dominant ones in the Kawaguchi and Moravcsik calculation involve the quantity

$$\mu = \mu_p \pm \mu_{\Lambda^0},$$

where μ_p is the static anomalous proton magnetic moment, μ_{Λ^0} is the hyperon moment, and the negative sign is associated with the scalar interaction while the posi-

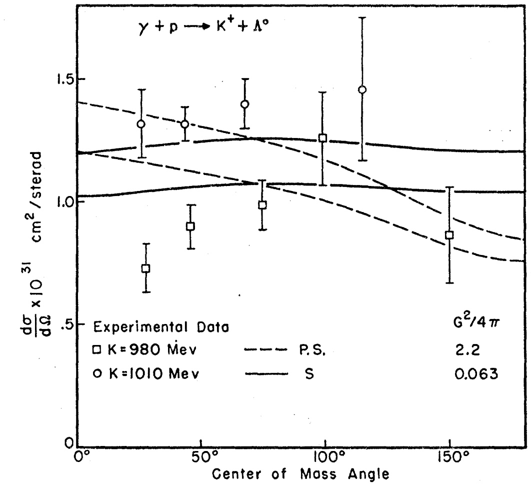

FIG. 7. The experimental angular distribution data fitted with the calculations of Kawaguchi and Moravcsik. See the text for the choice of magnetic moments.

tive sign goes with the pseudoscalar case. There is an additional term involving the cross product $\mu_p\mu_\Lambda$ but in relation to the data to be fitted, this term is negligible. Kawaguchi and Moravcsik have not included the effect of the $(\Lambda^0-\Sigma^0)$ transition moment. Near threshold, Capps shows that the transition moment may be included by writing

$$\mu = \mu_p \pm \mu_{\Lambda^0} \pm (G_\Sigma/G_\Lambda)\mu_T,$$

where μ_T is the transition moment and G_Σ and G_Λ are the Σ and Λ coupling constants. Thus by including the term containing μ_T in the Kawaguchi and Moravcsik calculation, a good approximation including the effect of the transition moments may be obtained. By the arguments of Capps, based on isotopic spin and global symmetry, we take the values $\mu_{\Lambda^0}=0$, $\mu_T=\mu_{\Sigma^+}=\mu_p=1.8$ nuclear

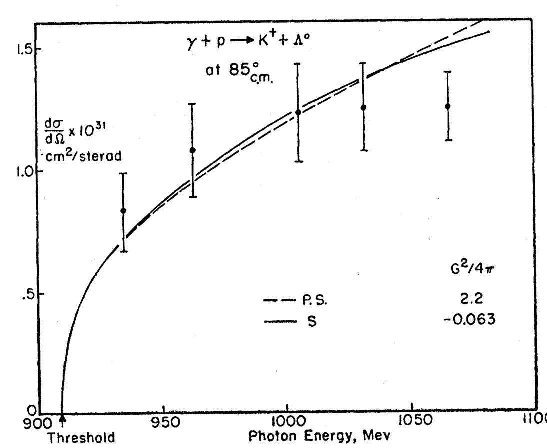

FIG. 8. The experimental data of cross section as a function of photon energy fitted with the calculations of Kawaguchi and Moravcsik. See the text for the choice of magnetic moments.

magnetons. Four combinations were considered: parity either even or odd and

$$G_\Sigma/G_\Lambda=\pm 1.$$

Of these, only the two cases with G_Σ/G_Λ corresponding to (-1) may be considered to fit the data at all. These two cases have been fitted to the data and are shown in Figs. 7 and 8. It is to be noted that the predominant term in the calculated cross section is that corresponding to an S wave, and that both cases give a nearly isotropic distribution in this energy region. Perhaps the case of even parity fits the angular distribution somewhat better than that for odd parity, but in view of the large statistical errors, there is little basis on which to choose between them. The curves which are shown correspond to a value of the coupling constant $G^2/4\pi$ of 0.063 and 2.2, for the scalar case and pseudoscalar case, respectively.

In order to make a definitive decision concerning the parity, it appears that it is necessary to make further measurements on processes such as the photon interaction with neutrons in (K^0,Λ^0), (K^0,Σ^0), and (K^+,Σ^-) production.

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Nuclear Interaction of θ_2 Mesons in Emulsion*

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Additional observations in emulsion on the nuclear interaction of neutral K mesons are reported. A total of 1 τ^+, 7 K^-, 7 Σ^+, 10 Σ^-, and 18 hyperfragments have been observed. The relative frequencies of different types of strange particles produced in the emulsion are consistent with the assumption that the neutral K meson is a particle admixture and that interactions in the θ and $\bar{\theta}$ modes are similar to interactions of K^+ and K^-, respectively.

1. INTRODUCTION

IN order to get a better insight into the modes of interaction of neutral long-lived K mesons in the complex nuclei of nuclear emulsions, it seemed worth while to continue the work reported by Baldo-Ceolin *et al.*,[1] hereafter referred to as paper I. Similar work has been reported by several groups working with emulsions,[2–5] and with other techniques.[6–8]

Additional plates of the stack reported in paper I have been scanned. These pellicles were exposed to a neutral beam coming from a 3-in. hole in the iron yoke of the magnet of the bevatron at 90° to the 6-Bev proton beam. Details of the exposure are given in paper I.

The scanning procedure was identical to that of the work in paper I; namely, area scanning. In this paper we report the results from the scanning of 50 cm³ of emulsion. The data reported here includes those events found in 13 cm³ described in paper I.

2. BACKGROUND CONSIDERATION

Nuclear interactions of neutral K mesons frequently give rise to charged strange particles. In what follows we will show that, in the emulsion stack under consideration, this is indeed the only important process leading to such particles. In order to do so, we will estimate the number of charged strange particles produced by processes other than the interactions of neutral K mesons. The most important of these can readily be seen to be the associated production by neutrons.

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1 Baldo-Ceolin, Dilworth, Fry, Greening, Huzita, Limentani, and Sichirollo, Nuovo cimento **6**, 130 (1957).

2 Fry, Schneps, and Swami, Phys. Rev. **103**, 1904 (1956).

3 Glasser, Seeman, and Snow, Phys. Rev. **107**, 277 (1957).

4 Ammar, Friedman, Levi-Setti, and Telegdi, Nuovo cimento **5**, 1801 (1957).

5 Bisi, Cester, Debenedetti, Garelli, Quassiati, Talone, and Vigone, Nuovo cimento **9**, 864 (1958).

6 Panofsky, Fitch, Motley, and Chesnut, Phys. Rev. **109**, 1353 (1958).

7 R. Lander, University of California Radiation Laboratory Report UCRL-3930, 1957 (unpublished).

8 Crawford, Cresti, Good, Gootstein, Lymon, Solmitz, Stevenson, and Ticho, University of California Radiation Laboratory Report UCRL-8298, 1958 (unpublished).