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[14] C. Michael, Phys. Letters 29B, 230 (1969).

[15] The energy dependence will be given by $\alpha_{\text{eff}}=\alpha_N+\alpha_K-1$. Even taking the lowest trajectories, $N_\gamma$ and $K^*(890)$, one would get $\alpha_{\text{eff}}=-2.1$, which is much larger than the required $\alpha_{\text{eff}}\sim-4$.

[16] While the two models predict similar cross sections, they have quite different amplitudes. All acceptable resonance fits to $K^-p$ scattering have a large spin-flip amplitude whose vanishing at 180° causes the backward dip. On the other hand, in any single-trajectory Regge model without $\sqrt{u}$ terms in the residue function, the spin-nonflip amplitude dominates because of kinematic factors. The dip at 180° is caused by the nonsense wrong-signature zero in the Regge amplitude.

# PHOTOPRODUCTION OF $K^+\Lambda$ AND $K^+\Sigma^0$ FROM HYDROGEN AT BACKWARD ANGLES*

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We have investigated photoproduction of $K^+\Lambda$ and $K^+\Sigma^0$ from hydrogen at 4.3 GeV and for $u$ values between $-0.2$ $(\text{GeV}/c)^2$ and $-0.7$ $(\text{GeV}/c)^2$. The data were consistent with a smooth decrease in $d\sigma/du$ towards larger negative $u$ values. The $K^+$ backward photoproduction cross sections appear to be closely similar to the observed cross section for backward $\pi^+$ photoproduction. The ratio of $\Sigma^0/\Lambda$ is about 1.7, which rules out pure decuplet exchange in this region of $u$. The results are consistent with the SU(3) prediction.

At high energies the large-angle photoproduction of $K^+$ is expected to be dominated by $u$-channel exchange of baryons with hypercharge $Y=0$. In contrast to $\pi$ photoproduction, there are no large-angle data available for $K^+$ photoproduction above 1.5 GeV. We report here the results of a

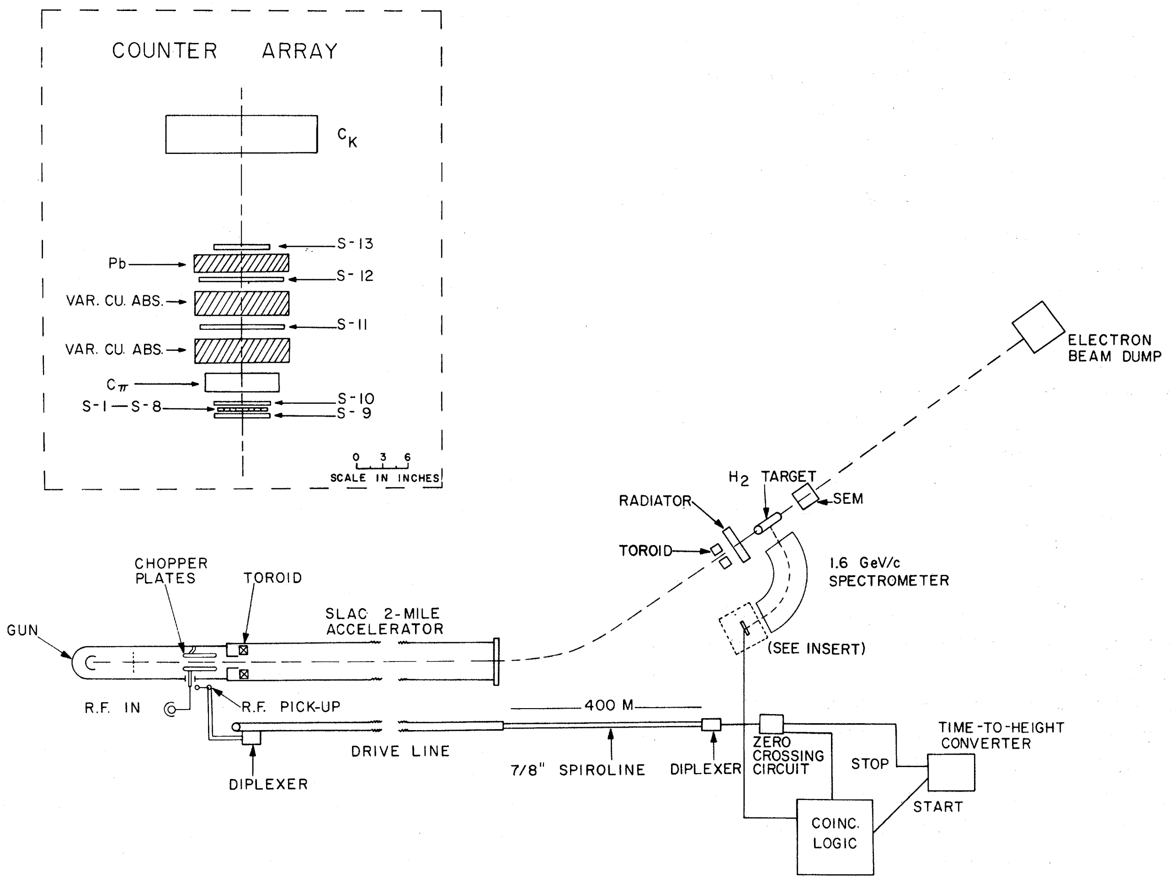

FIG. 1. The experimental setup including the time-of-flight system. The counter system is shown in the insert.

measurement of the photoproduction processes

$$\gamma + p \rightarrow K^+ + \Lambda,$$

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

at 4.3 GeV and in the $u$ range from $-0.2$ $(\mathrm{GeV}/c)^2$ to $-0.7$ $(\mathrm{GeV}/c)^2$.

The experimental apparatus is shown in Fig. 1 and is similar to the one described in earlier Letters.[1,2] The beam was prepared by passing the electrons through a set of chopper plates located near the electron gun and oscillating at 10 MHz with a peak rf voltage of several kV. A collimator situated downstream from the chopper plates intercepted the deflected electrons, permitting only electrons on the axis to be injected into the accelerator. The resulting beam consisted of 2-nsec-wide bunches spaced 50 nsec apart within the 1.6-$\mu$sec-long beam pulse. The electron beam was focused onto a copper radiator typically 0.14 radiation units thick, located just in front of a liquid-hydrogen target. The resulting beam of electrons and bremsstrahlung photons passed through the target. The thin-walled target cell containing the liquid hydrogen was a cylinder 15 in. long by 3.5 in. in diameter. The electron beam was monitored to an estimated 2% precision with two toroid monitors and a secondary emission monitor (SEM) located in front of the radiator. The momentum and angle of the $K^+$ mesons were determined with a 100-in.-radius, 90° vertical-bend spectrometer.[3] The acceptance of the spectrometer $(\Delta P/P)\Delta\Omega$ was $6.8\times 10^{-5}$ sr with an estimated uncertainty of ±3%. The spectrometer focused the horizontal production angles and momenta onto a single focal plane, permitting the eight hodoscope counters to be aligned along lines of constant missing mass.

The counter system is shown in more detail in the insert in Fig. 1. It consisted of a range telescope built up of five scintillation counters, with remotely variable amounts of absorbers between the counters; a Lucite threshold Cherenkov counter; and a differential Cherenkov counter. The light from $K$'s passing through an interchangeable radiator in the differential Chenenkov counter was focused onto a ring of 12 2-in.-diam RCA 8575 high-efficiency phototubes. The outputs of the tubes were added up in groups of six and a coincidence between the two groups was required to reduce the background. Since the electrons arrived in well-defined bunches, particles of equal mass arrived at the same time at the top of the spectrometer. Therefore by gating and timing the trigger system relative to the chopper plates the $K$'s could be selected.[4] At the lowest momentum the event gate to the hodoscope consisted of this time requirement in coincidence with the range telescope and in anticoincidence with the threshold Cherenkov counter. For all other momenta the differential Cherenkov counter was used as an additional requirement. The ratio of kaons to pions and protons at the top of the spectrometer was as unfavorable as 1:4000 just above the $\Lambda$ threshold. With the above requirements we achieved rejection ratios of more than 100 000:1. The efficiencies of the system were calibrated both with $K$ mesons and with protons of the same velocity. The efficiency of the trigger system including absorber and multiple-scattering losses varied between 45 and 75% with an estimated uncertainty around ±10%.

Data were taken by keeping the primary beam energy as well as the spectrometer momentum fixed and varying the angle of the spectrometer. Figure 2 shows an excitation curve traced out in this way. Plotted is the $K^+$ yield versus missing mass squared. For a fixed photon energy there is approximately a linear relation between the laboratory angle and missing mass squared. The steps due to the onset of $\Lambda$ and $\Sigma^0$ production are clearly seen and are well separated. Note that there is very little background beyond the kinematic limit.

The resolution functions and momentum calibration used in fitting the excitation curves had been well determined in a previous experiment[2] on $\pi^+$-meson production. Therefore the positions and shapes of the $K^+\Lambda$ and $K^+\Sigma^0$ yield were accurately predictable. From this previous experiment the momentum calibration was believed good to ±0.1%, corresponding to an error on the

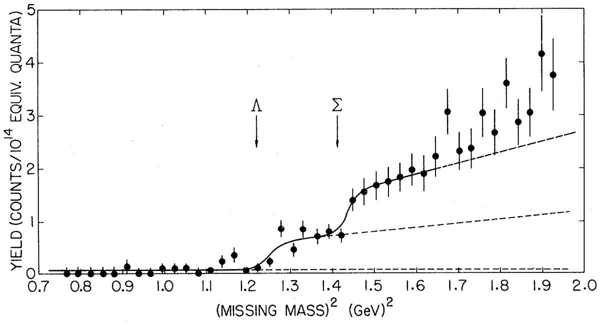

FIG. 2. The measured $K^+$ yield in counts per hodoscope element per $10^{14}$ equivalent quanta, normalized to standard spectrometer aperture, is plotted versus missing mass squared for an end-point energy of the bremsstrahlung spectrum of 4.5 GeV and for $u = -0.43$. The solid line is the result of the least squares fit to the data as described in the text.

order of 0.01 $(\mathrm{GeV}/c)^2$ in missing mass squared in the predicted positions of the steps in the yield curves. In fitting the yields we used a three-parameter fit: a constant background and two parameters for the "heights" of the $K^+\Lambda$ and the $K^+\Sigma^0$ yields. To obtain the correct shape of the yield curves we used the thick-target bremsstrahlung formulas, the previously measured[1] energy dependence $d\sigma/du \sim k^{-3}$ where $k$ is the photon energy, decay-in-flight corrections, the measured resolution of the apparatus, and the appropriate kinematic factors. The solid line in Fig. 2 represents this fit to the data. The derived value of the cross section is not very sensitive to the assumed energy dependence of $d\sigma/du$.

The cross sections $k^3(d\sigma/du)$ for $K^+\Lambda$ and $K^+\Sigma^0$ production are plotted versus $u$ in Fig. 3. The $k^3$ factor compensates for slight differences in the effective photon energy of the measurement and facilitates comparison with the $\pi^+$ data.[2] The error bars reflect the statistical errors combined with estimated uncertainties in the efficiency factors. For comparison the backward $\pi^+n$ cross section is shown as the dotted curve. The $K^+$ and $\pi^+$ cross sections are very similar, both decreasing smoothly with $u$. The ratio $\Sigma^0/\Lambda$ is consistent with the mean value of $1.7 \pm 0.15$ over the entire $u$ range covered in this experiment. This ratio is, of course, largely independent of systematic errors, and the error in its determination is mainly from counting statistics.

SU(3) theory[5] predicts the relation between the $K^+$ and $\pi^+$ photoproduction amplitudes to be

$$\sqrt{2}A(\pi^+n) = -\sqrt{3}A(K^+\Lambda) - A(K^+\Sigma^0).$$

With the angle $\varphi$ as defined in the insert to Fig. 3, we have the following relationship between the cross sections:

$$2\frac{d\sigma}{dt}(\pi^+n) = 3\frac{d\sigma}{dt}(K^+\Lambda) + \frac{d\sigma}{dt}(K^+\Sigma^0) + 2\cos\varphi\left[3\frac{d\sigma}{dt}(K^+\Lambda)\frac{d\sigma}{dt}(K^+\Sigma^0)\right]^{1/2}.$$

This relation is fulfilled over the whole $u$ range investigated. The angle $\varphi$ was always larger than 90° whereas in the forward direction $\varphi$ was measured[6] to be less than 90°.

From our previous data in the energy region from 4 to 13 GeV at one fixed $u$ value, the sum of the $K^+\Lambda$ and $K^+\Sigma^0$ cross sections was proportional to $k^{-3}$. These data would, if extrapolated, have passed close to the low-energy Cornell results[7] at 1.4 GeV. This is not surprising since the $u$-channel cross sections for $K^+$ production are similar to those for $\pi^+$ production, whereas $s$-channel resonances decay much more strongly into $\pi^+$ mesons than $K^+$ mesons and should be correspondingly less important for $K^+$ photoproduction. We would therefore expect the $K^+$-production channels to approach asymptotically their $u$-channel values at considerably lower energies than is the case for $\pi^+$-meson photoproduction. Large-angle $\pi^+$-meson production appears to show asymptotic behavior above 4 GeV,[1,2] and accordingly we believe that our 4.3-GeV $K^+$ measurements do indeed correspond to the asymptotic $u$-channel behavior.

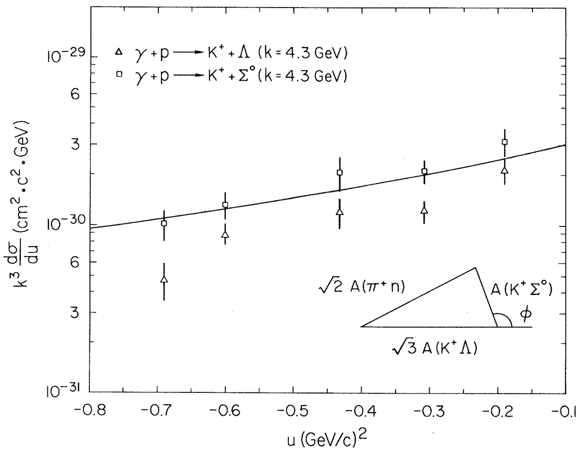

FIG. 3. $k^3(d\sigma/du)$ in $\mathrm{cm}^2\,c^2$ GeV is plotted versus $u$ for the reactions $\gamma + p \rightarrow K^+ + \Lambda$ and $\gamma + p \rightarrow K^+ + \Sigma^0$. The solid line indicates the measured cross section for the reaction $\gamma + p \rightarrow \pi^+ + n$. The angle $\varphi$ is defined in the insert.

The form of the backward photoproduction of $K^+$ as a function of $u$ is close to that for the process $\gamma + p \rightarrow \pi^+ + n$, as can be seen from the comparison in Fig. 3. As discussed in an earlier paper,[2] $\pi^+$ production probably involves only a small amount of decuplet exchange. $K^+$ production can proceed via the exchange of either the $U$-spin-1 or $U$-spin-0 members of the octet, or via decuplet exchange involving only $U$-spin 1. For $U$-spin-1 exchange the $\Sigma^0/\Lambda$ ratio should be 1 to 3.[5] The observed ratio of 1.7 to 1 therefore precludes any large decuplet contribution. This preference for octet exchange and the similar energy and $u$ dependences indicate that the $\pi^+$ and $K^+$ production processes proceed through closely related mechanisms.

We are indebted to E. A. Paschos for numerous discussions of the theoretical aspects of backward photoproduction. J. Grant, J. Escalera, and J. Schroeder gave us invaluable support with the setup and the preparations for the experiment. We wish to acknowledge the help we received from the operation and support crew at Stanford Linear Accelerator Center, and especially to thank R. Bell, A. Golde, R. Miller, T. Jenkins, and D. Walz.

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[1] R. L. Anderson et al., Phys. Rev. Letters 21, 479 (1968).

[2] R. L. Anderson et al., Phys. Rev. Letters 23, 721 (1969).

[3] R. L. Anderson et al., Nucl. Instr. Methods 66, 328 (1968).

[4] R. L. Anderson and D. Porat, Nucl. Instr. Methods 70, 77 (1969).

[5] C. A. Levinson et al., Phys. Letters 7, 81 (1963).

[6] A. M. Boyarski et al., Phys. Rev. Letters 22, 1131 (1969).

[7] R. L. Anderson, in Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Hamburg, Germany, 1965 (Springer-Verlag, Berlin, Germany, 1965), Vol. I.

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# $n+p\to d+\gamma$ AND TIME-REVERSAL INVARIANCE*

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Measurements are reported of the differential and total cross section for $n+p\to d+\gamma$ for neutron energies between 160 and 640 MeV. A comparison is made with the differential and total cross sections for the inverse process.

We have measured the angular distribution and the total cross section for the reaction

$$n+p\to d+\gamma. \tag{1}$$

Results have been obtained for four intervals of neutron laboratory energy between 160 and 640 MeV. This study was prompted by the suggestion that time-reversal invariance may not be valid for the electromagnetic interaction of the hadrons.[1,2] A failure of time-reversal invariance could lead to a difference between the center-of-mass angular distribution of the deuteron in Reaction (1) and that of the proton in the inverse reaction

$$\gamma+d\to n+p. \tag{2}$$

To be sensitive, the comparison of angular distributions should be made at an energy where a nucleon has been excited to a state lying off the mass shell.[1] Reaction (2) has long been known to have a peak in the total cross section at a gamma-ray laboratory energy $k_\gamma\approx 300$ MeV.[3] Since this peak is generally ascribed to the influence of the $\Delta(1236)$ in an intermediate state, a study of Reaction (1) at an equivalent neutron energy $T_n=2k_\gamma=600$ MeV appeared worthwhile. We communicated our interest in this reaction to Barshay who was independently studying reciprocity relations. Using a specific model he then suggested that the effects of time-reversal violation are important only for neutron energies near 600 MeV.[4] There, the predicted difference between the angular distributions of Reactions (1) and (2) is symmetric about 90° and could be as great as 40%. The total cross sections are predicted to be insensitive to time-reversal-invariance violation.

Our study of $n+p\to d+\gamma$ at these energies was complicated by the presence of the kinematically similar reaction

$$\begin{array}{l} n+p\to d+\pi^0 \\ \qquad\qquad\ \llcorner\!\to 2\gamma. \end{array} \tag{3}$$

The cross section for this process rises sharply from zero at the threshold of 275 MeV to a broad peak of 1.5 mb at a neutron energy of 600 MeV. This peak is roughly 70 times higher than that expected for $n+p\to d+\gamma$.

In this experiment, neutrons were produced from an internal Pt target at the Princeton-Pennsylvania Accelerator (PPA). A beam of approximately 5000 neutrons/sec was defined at an angle of 34° relative to the circulating 3-GeV proton beam. A 2-in.-thick lead brick followed by a