# HIGH-ENERGY PHOTOMESON PRODUCTION FROM HYDROGEN VIA THE "$u$ CHANNEL"*

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We have investigated the photoproduction process $\gamma+p\rightarrow\pi^{+}+n$ over a wide range of energies and $u$ values at the Stanford Linear Accelerator Center (SLAC) accelerator. We also have investigated $\gamma+p\rightarrow\pi^{-}+N^{*++}$ at one value of $u$, and $\gamma+p\rightarrow K^{+}+\Lambda^{0}, \Sigma^{0}$ at one $u$ value and three energies. Our results for $d\sigma/du$ for the photoproduction of $\pi^{+}$ mesons from hydrogen are roughly $\alpha/2\pi$ of the corresponding cross sections for the elastic scattering of $\pi^{-}$ mesons from hydrogen. The $u$ dependence of our cross sections is not dominated by nucleon exchange as it is in the case of $\pi^{+}p$ elastic scattering.

A large body of data now exists in the 3- to 16-GeV range on $\pi$-meson scattering at large center-of-mass angles.[1] In particular, $\pi^{+}p$ and $\pi^{-}p$ elastic scattering appear to be explained by the Regge exchange of the nucleon and $\Delta$ trajectories.[2] $\pi^{+}p$ elastic scattering appears to proceed in the $u$ channel, predominantly through the exchange of a nucleon, with a characteristic sharp dip in the cross section at $u=-0.2$ $(\mathrm{GeV}/c)^{2}$ corresponding to a nonsense value of the wrong signature of the nucleon Regge trajectory. For $\pi^{-}p$ only the $\Delta$ trajectory (isospin $\frac{3}{2}$) can be exchanged and this cross section shows no pronounced dip. For photoproduction, both nucleon and isobar exchange are permitted in the $u$ channel in principle, and accordingly similar dips might be expected in these cross sections. We have investigated the photoproduction process $\gamma+p\rightarrow\pi^{+}+n$ over a wide range of energies and $u$ values at the SLAC accelerator. We have also investigated $\gamma+p\rightarrow\pi^{-}+N^{*++}$ at one value of $u$, and $K$-meson production $\gamma+p\rightarrow K^{+}+\Lambda^{0}$ or $\Sigma^{0}$ at one $u$ value and three energies.

The experimental method consisted of running the electron beam of the SLAC accelerator through a variable copper radiator located just in front of a liquid-hydrogen target (see Fig. 1). The resulting beam of electrons and photons passed through the target. The thin-walled target cell containing the liquid hydrogen was a cylinder 12 in. long by 3 in. in diameter. The electron beam was monitored to ~2% precision with both a toroid monitor and a secondary emission monitor (SEM). The $\pi^{+}$ mesons were analyzed with a 100-in. radius, 90° vertical bend spectrometer.[3] The spectrometer focused the horizontal production angles and momenta onto a single focal plane. It was second-order corrected so that the focal plane was normal to the beam of particles. Five hodoscope counters were used to split up the focal plane. Four large scintillation counters, separated by the hodoscope and two variable absorbers, were used as trigger counters. The counter system was rotatable so that the hodoscope counters lay along lines of constant missing mass. Sufficient absorber was introduced between the trigger counters so that electrons were lost by radiation, protons could not penetrate, and only $\pi$ mesons were recorded. Geometric and absorption losses of the $\pi$ mesons were determined experimentally. Losses due to decay in flight were estimated by calculation.

For $K$-meson detection we used a differential Cherenkov counter and time-of-flight criteria. The time-of-flight information was obtained by chopping the primary electron beam and measuring the arrival times of the particles at the first trigger counter relative to the arrival time of the primary beam.

Data were taken by holding the primary beam energy and the angle of the spectrometer fixed and varying the acceptance momentum of the spectrometer. Figure 2 shows a typical excitation curve as a function of spectrometer momentum at $u=0.19$ $(\mathrm{GeV}/c)^{2}$ for a 5-GeV peak energy incident bremsstrahlung beam. Even with the

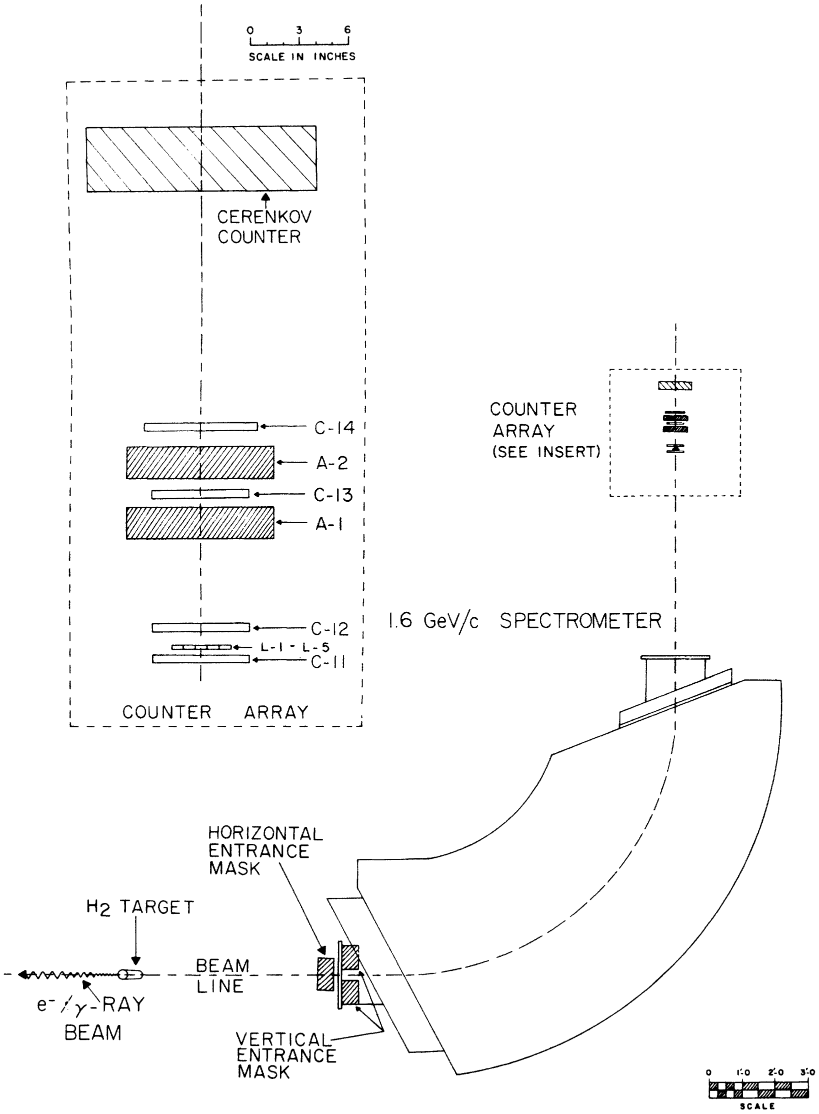


FIG. 1. Positioning of the spectrometer and counters relative to the beam line and target. The insert shows an enlarged picture of the counter array.

spectrometer set to accept momenta above the kinematic threshold for $\pi^+$ meson production there is still background due to double processes within the target. At the point at which it is kinematically allowed to produce $\pi^+$ mesons the cross section rises rapidly as the spectrometer momentum is decreased. At still lower momenta, pions associated with multiple-pion production contribute to the yield. At higher primary energies the backgrounds from double processes within the target became increasingly important relative to the direct single photoproduction of pions, and at primary energies above 12 GeV it was no longer possible to make significant cross-section measurements. The backgrounds were extensively studied as a function of momentum so that reliable background subtractions could be made. Cross sections were evaluated by taking into account the detection efficiency of the counters, the errors in background estimates, the effective photon fluxes, and the effective primary energy for $\pi^+$-meson production at the point at which the cross section was evaluated.

Figure 3 shows our $d\sigma/du$ values for $\pi^+$ production and $K^+$ production as a function of $u$ at various primary energies. The curves show little structure, and fall monotonically with energy for fixed $u$ values.

The fall off with energy of cross sections $d\sigma/du$ evaluated at fixed $u$ is proportional to $s^{-2.9\pm0.5}$

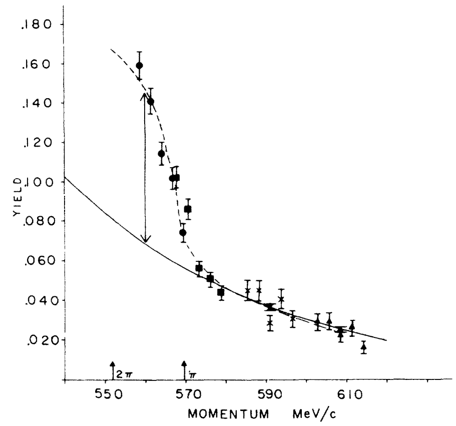


FIG. 2. Yield of $\pi$ mesons at a lab angle of 115° and a peak bremsstrahlung energy of 5.0 GeV, versus the momentum of the detected $\pi$ mesons. The calculated kinematic thresholds for the production of single $\pi$ mesons and the threshold for two-pion production are marked on the abscissa. The solid line represents our best background fit. The dashed line showing the rising yield is simply to guide the eye. The vertical arrow represents the contribution from single $\pi$-meson production.

over the range of $u$ values and energies measured. The data are thus consistent with a nonshrinking backward cross section. At fixed primary photon energies, $d\sigma/du$ as a function of $u$ shows no dip at $u=-0.2$ $(\mathrm{GeV}/c)^2$ as would have been expected if nucleon exchange played a dominant role in this photoproduction process.[1,2]

As a side product of some "parasite" runs we obtained a measurement for $\gamma+p\rightarrow\pi^-+N^{*++}$ and found its cross section to be in the range 0.5 to 1.5 of that for $\gamma+p\rightarrow\pi^++N^{*0}$ at an energy of 5 GeV and $u=+0.04$ $(\mathrm{GeV}/c)^2$. In our $K^+$ measurements, we did not separate $\gamma+p\rightarrow K^++\Lambda^0$ production from $K^++\Sigma^0$ production but measured the sum of the two processes. The combined cross sections for $K^++\Lambda^0$ and $K^++\Sigma^0$ production are shown plotted with dashed error bars in Fig. 3. The values obtained are close to those obtained for $\pi^+$ photoproduction.[4]

Our cross sections $d\sigma/du$ for photoproduction of $\pi^+$ mesons from hydrogen are roughly $\alpha/2\pi$ of the corresponding cross sections for elastic scattering of $\pi^-$ mesons from hydrogen. We conclude from our results on the photoproduction of $\pi^+$ mesons that, in the framework of Regge theory, the $u$ dependence of our cross sections is not dominated by nucleon exchange as it is in the case of $\pi^+p$ elastic scattering.[5]

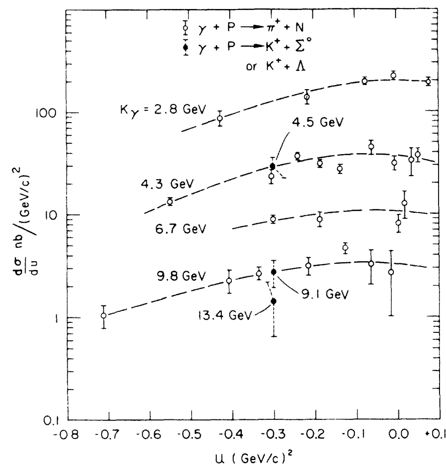


FIG. 3. Plot of $d\sigma/du$ in units nb/$(\mathrm{GeV}/c)^2$ vs $u$ in $(\mathrm{GeV}/c)^2$ at photon energies of 2.8, 4.3, 6.7, and 9.8 GeV. Also marked on the curve are points for the combined cross sections $d\sigma/du$ for $K^+\Lambda^0$ and $K^+\Sigma^0$ production at 4.5, 9.1, and 13.4 GeV. These $K\Lambda$, $K\Sigma$ points are marked with dashed error bars.

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[3]The SLAC 1.6-GeV/$c$ spectrometer is described in the Stanford Linear Accelerator Center User's Handbook, 1966 (unpublished), Sec. E.

[4]It is worth noting that using SU(3) and assuming that only decuplet exchange was involved, the cross sections should be one-half of those obtained for $\gamma+p\rightarrow\pi^++n$. It therefore appears that both $U$-spin 0 and $U$-spin 1 exchange are involved in the photoproduction of $K$

mesons via the $u$ channel.

[5]E. A. Paschos, private communication. Paschos has analyzed our results in terms of $\Delta$-trajectory exchange and obtained good agreement with theory.

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# COMPARISON OF ELECTRON-PROTON AND POSITRON-PROTON ELASTIC SCATTERING AT FOUR-MOMENTUM TRANSFERS UP TO 5.0 $(\mathrm{GeV}/c)^2$ *

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Measurements of the ratio ($R$) of positron-proton and electron-proton elastic-scattering cross sections have been made, with the square of the four-momentum transfer ($q^2$) equal to 0.20, 0.69, 0.73, 1.54, 2.44, 3.27, 3.79, and 5.00 $(\mathrm{GeV}/c)^2$. The measurements, after radiative corrections, are consistent with $R=1$, with standard errors ranging from ±0.016 to ±0.123. The results give limits for the size of the two-photon effects.

Electron elastic-scattering experiments to date have been interpreted using the Rosenbluth formula based on the single-photon-exchange model. A measurement of $R$ is a test of this model because a deviation of $R$ from 1 is an indication of the size of the real part of the two-photon-exchange amplitude.[1] Because the interference between the single-photon amplitude and the two-photon amplitude occurs with opposite sign for electrons and positrons, one may write $R \approx 1+4 \times \mathrm{Re}B/A$, where $\mathrm{Re}B/A$ is the ratio of the real part of the two-photon amplitude ($\mathrm{Re}B$) to the single-photon amplitude ($A$). Earlier measurements of $R$ by other experimenters[2] for the most part gave $R \approx 1$. Past theoretical estimates[3,4] either make no definite prediction as to the size of $|R-1|$, or predict it to be $\lesssim 0.02$. A summary of previous investigations of $R$ has recently been given by Pine.[5]

Results.—The ratio $R$ was measured for the laboratory scattering-angle regions $12.5° \leq \theta \leq 35.0°$ and $2.6° \leq \theta \leq 15.0°$ with incident electron (and positron) energies of 4.0 and 10.0 GeV, respectively. The high-$q^2$ data extend to higher $q^2$ than earlier experiments, and the moderate-$q^2$ data include measurements at smaller angles than previously explored.

The results are displayed in Table I, and a comparison with previous measurements is given in Fig. 1. In the table, $R$ is the corrected experimental ratio with its uncertainty. The uncertainty in $R$ is the square root of the sum of the squares of the statistical uncertainty and the estimated uncertainty due to systematic errors, both of which are given in the table. The systematic error is dominated by the beam monitor uncertainty.

The difference in radiative corrections for $e^+$ and $e^-$ scattering was calculated using the results of Meister and Yennie,[6] with exponentation. The column labeled "Rad Corr" is the net correction to $R$ from radiative effects. No uncertainty is assigned to the radiative corrections. The column labeled "$\mathrm{Re}B/A$" in the table gives the 95% confidence limits for the quantity $\mathrm{Re}B/A$ defined earlier.

As can be seen in the table, all the elastic data are consistent with $R=1$. This result is in agreement with estimates by Drell, Ruderman, and others,[3] and supports the one-photon approximation over an enlarged kinematical region.

The inelastic measurements in the table, labeled "$N^*(1238)$," give $R$ for all scattered events in which the missing mass of the final-state particles other than the recoiling electron lay between 1110 and 1370 MeV. About 70% of the cross section leads to $N^*(1238)$ production. The remainder of the scattering in this region can be