5- TO 16-GeV SINGLE-π^+ PHOTOPRODUCTION FROM HYDROGEN*

A. M. Boyarski, F. Bulos, W. Busza, R. Diebold,
S. D. Ecklund, G. E. Fischer, J. R. Rees, and B. Richter
Stanford Linear Accelerator Center Stanford University, Stanford California
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The differential cross sections for single-π^+ photoproduction from hydrogen have been measured over a range of momentum transfers from -2×10^{-4} to -2 $(GeV/c)^2$, and photon energies from 5 to 16 GeV. The differential cross section increases by roughly a factor of 2 as the magnitude of the square of the momentum transfer decreases from 0.02 $(GeV/c)^2$. The cross section falls approximately as $\exp(-3|t|)$ at large momentum transfers, with a similar momentum-transfer dependence of the cross section at all photon energies studied.

We report here our measurements of single-pion photoproduction from hydrogen at photon energies from 5 to 16 GeV.[1] The maximum energy is high enough to be above the region where π-N resonances are expected to dominate the interaction and allow us to determine the (hopefully) asymptotic behavior of the cross section. In addition, measurements at very small momentum transfer have an important bearing on the Reggeized-particle exchange model.

A 1-kW bremsstrahlung beam from the Stanford Linear Accelerator's 20-GeV electron linear accelerator was incident on a 30-cm liquid-hydrogen target. The bremsstrahlung beam was monitored by placing a 0.005−radiation-length converter in the beam upstream of a 1-m long helium-gas Cherenkov cell operated at atmospheric pressure, and monitoring the Cherenkov light produced by electron pairs made in the radiator. The Cherenkov monitor was calibrated against a precision calorimeter.

Particles produced at forward angles were momentum and angle analyzed with the Stanford Linear Accelerator Center (SLAC) 20-GeV/c spectrometer.[2] In the vertical plane particles were brought to a first focus at the center of the spectrometer, and then brought to a second focus in the detector housing. A counter hodoscope at the second focus of the spectrometer determined the momentum. In the horizontal plane, parallel rays were brought to a focus in the detector housing where a second counter hodoscope determined the horizontal angle relative to the axis of the system. The magnet system was corrected for chromatic aberrations by three sextupole magnets and the inherent resolution of the system was about $\pm0.05\%$ in momentum and ±0.2 mrad in angle.

The acceptance of the system is ±4 mrad in angle, $\pm1.8\%$ in momentum, and 1.2×10^{-4} sr in solid angle.

The detection system included, in addition to the momentum (P) and angle (θ) hodoscopes, two other hodoscopes (X and φ). Information from the P and φ hodoscopes was used to determine a particle's momentum and angle in the vertical plane, the vertical angle being determined to a resolution of ±0.7 mrad. Information from the X and θ hodoscopes was used to determine the horizontal production angle and to reject particles which had come from the magnet poles.

Particles were identified by use of a differential Cherenkov counter, a shower counter, and a muon-range telescope. The differential Cherenkov counter was the coincidence-anticoincidence type, and was used to identify protons, K mesons, or the group of pions, muons, and electrons. Electrons were identified by pulse height in a shower counter, and muons by range in the iron absorber of a range telescope. In operation, a criterion on range in the iron and pulse height in the shower counter was used to isolate the strongly interacting particles, and the differential Cherenkov-counter pulse heights were used to separate members of the strongly interacting group into p, K, or π.

An SDS 9300 computer was used on line to log data from the counters, scalers, and beam monitors; control and monitor the spectrometer magnets and other apparatus; provide on-line diagnostic displays; and analyze the data. The on-line data analysis programs provided a preliminary value of the cross section at the end of each run.

Data at the smallest momentum transfer point for each photon energy were taken with the

spectrometer set at 0°. In order to reject the very large background of electron-positron pairs coming from the target, a six-radiation-length thick slab of lead was placed at the first vertical focus in the spectrometer. This reduced the electron flux at the counters by the factor of 10^5 to 10^6, while reducing the strongly-interacting particle flux by a factor 5 to 10 due to multiple scattering in the lead. The correction factor for this loss of strongly interacting particles was experimentally determined for each photon energy. The single pion yield was measured both with and without the lead at a lab angle of 1° where the electron contamination was negligible, and the lead in-out ratio thus determined was then used to correct the 0° data. The error in the correction factor has been included in the error shown for the 0° points. For these runs the angular acceptance of the system was limited by a collimator placed in front of the spectrometer to ±3 mrad horizontally and vertically.

Data at the next three momentum transfer points at 8 and 11 GeV, and the next four momentum transfer points at 16 GeV were taken simultaneously at a spectrometer angle of 0.25°, the hodoscope information being used to subdivide the spectrometer acceptance.

In order to determine the yield of the reaction $\gamma p \rightarrow \pi n$, the spectrometer momentum was set to correspond to that of particles produced by photons of the maximum energy in the bremsstrahlung beam. The hodoscope information was used to compute the missing mass for each event assuming that the photon energy was equal to the bremsstrahlung maximum. Since the cross section does not vary significantly over the few-percent momentum acceptance of the spectrometer, the missing-mass distribution for single-π^+ production has the same shape as the bremsstrahlung spectrum folded with the over-all resolution of the system (0.6% full width from electron-beam energy spread, beam size at target, and spectrometer resolution). The missing-mass distribution was therefore fitted with a step function suitably smeared out at the beginning of the step to approximate closely the energy distribution of the photons near the tip of the bremsstrahlung distribution, plus a polynomial in the missing mass which began at the threshold for production of three-body final states. The resolution was sufficient to make an unambiguous separation of the sin-

gle-pion production from the multipion production background.

The results of the experiment are plotted in Fig. 1, together with lower energy data from Deutsches Elektronen-Synchrotron (DESY) and Cambridge Electron Accelerator (CEA).[3-5] The errors shown on our data represent the statistical uncertainties plus monitor fluctuations of about ±5%. In addition, there is a systematic uncertainty depending on energy. This uncertainty is largest at 5 GeV and when comparing the 5- and 16-GeV data, an uncertainty of ±8% should be added to the errors shown in Fig. 1; this uncertainty drops to ±4% when comparing 8 and 16 GeV. Finally, there is an additional uncertainty in over-all normalization of ±6%.

The data show a very sharp forward peak, the cross section increasing by a factor of 1.5 to 2 as |t| decreases from 0.01 GeV² to 0. This characteristic forward peaking has been previously observed[4,6] in single-π^+ photoproduction at photon energies between 0.6 and 3 GeV; it has been traditionally associated with the one-pion exchange diagram. The sharp rise is roughly ten times steeper than that of the usual elastic diffraction peak obtained off pro-
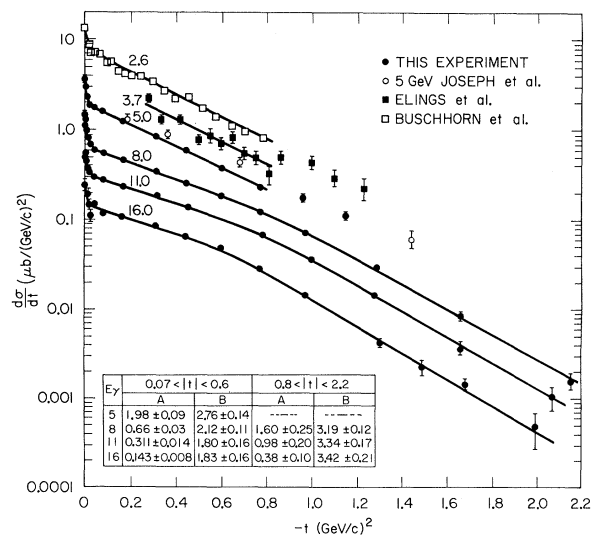

E_γ	$0.07 < |t| < 0.6$		$0.8 < |t| < 2.2$	
	A	B	A	B
5	1.98 ±0.09	2.76 ±0.14	------	------
8	0.66 ±0.03	2.12 ±0.11	1.60 ±0.25	3.19 ±0.12
11	0.311 ±0.014	1.80 ±0.16	0.98 ±0.20	3.34 ±0.17
16	0.143 ±0.008	1.83 ±0.16	0.38 ±0.10	3.42 ±0.21

FIG. 1. Photoproduction cross section for $\gamma p \rightarrow \pi^+ n$ vs t over our full range of t for $E_\gamma = 5$, 8, 11, and 16 GeV. The curves drawn are fits to the data of the form $A e^{Bt}$ for large and intermediate values of t. A break in the slope occurs at $|t| \approx 0.8$. Values for A and B are shown in the table. Also shown are the lower energy data of Elings et al., Jospeh et al., and Buschhorn et al.

tons. A similar sharp forward peak has also been observed in neutron-proton charge-exchange scattering.[7] At larger $|t|$ the rate of falloff is considerably slower, going as $e^{(2 \text{ to } 3)t}$, even slower than most forward peaks found in strong interactions. There appears to be a knee in the 8-, 11-, and 16-GeV data at $-t \approx 0.7$ GeV^2; the Fig. 1 caption gives a parametrization of the data. The small t region has been expanded in Fig. 2 by plotting the cross section as a function of $\sqrt{-t} \approx k\theta$.

The values of $d\sigma/dt$ measured in this experiment can be integrated to obtain a good estimate of the total $\gamma p \rightarrow \pi^+ n$ cross section. At 5 GeV one can use the CEA data[8] at $\theta_{c.m.} \approx 80°$ and the backward SLAC data[9] to estimate an additional contribution of ~10% from the large t region not measured in this experiment; at 8 GeV this contribution falls to ~3%. The DESY results[4] can similarly be integrated. To within 10% these results can be simply parametrized for laboratory photon energy k from the 1.8 to 16 GeV as

$$\sigma(\gamma p \rightarrow \pi^+ n) = 20 \ \mu b/k^2 \qquad (1)$$

with k in GeV.

Several authors[10] have shown that the conventional Regge model without conspiracy predicts a sharp decrease in the cross section as $t \rightarrow 0$ independent of the particle exchanged in the reaction. Jones and Frautschi find that the term in the conventional Regge model which gives the least rapid decrease as $t \rightarrow 0$ is given by

$$\left(\frac{d\sigma}{dt}\right)_{t \rightarrow 0} \propto \frac{-t/m_\pi^2}{(1-t/m_\pi^2)^2}. \qquad (2)$$
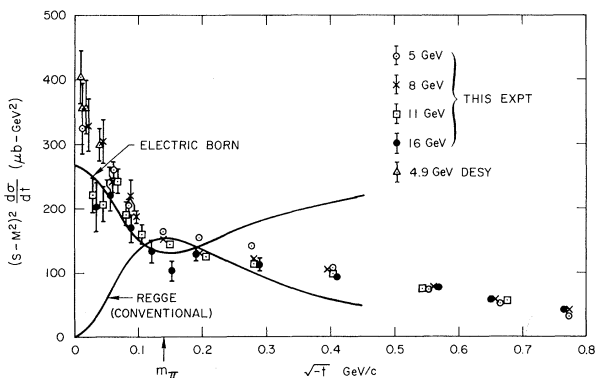
This form has been normalized to the data at $t = -m_\pi^2$ and is shown on Fig. 2. Our data are clearly inconsistent with this behavior and indicate that if the Regge model is applicable, conspiracy is strongly favored in π^+ photoproduction.[11]

An effective value of the Regge trajectory parameter $\alpha(t)$ can be obtained by assuming the cross section to go as

$$d\sigma/dt = f(t)s^{2\alpha(t)-2}, \qquad (3)$$

where $s = 2kM + M^2$ is the total center-of-mass energy squared. While this form is strictly applicable for single-trajectory exchange in the model without conspiracy,[12] the value of α determined from Eq. (3) gives some idea of where the simple model breaks down. Figure 3 shows values of $\alpha(t)$ obtained by fitting the 8-, 11-, and 16-GeV data at fixed t to Eq. (3). Where necessary, the data were interpolated to the same t value. Although some shrinkage appears at $|t| > 1$ GeV^2, it is considerably less than might be expected from a simple Regge picture. The low value of $\alpha(t)$ shown at very small t reflects the difference shown in Fig. 2 for the forward peak at 8 GeV and at 11 and 16 GeV. We expect to investigate this region in more detail in the next few months.

Finally, we should like to point out the agreement between the very forward cross section calculated in the Born approximation and the data. At small t, the electric Born approximation wherein the nucleon is treated as a Di-
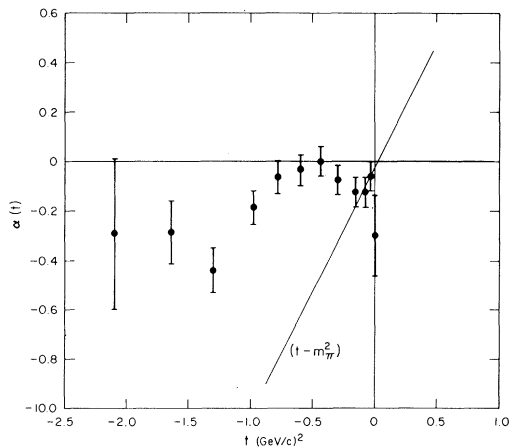

FIG. 2. Plot of the small momentum transfer data on an expanded scale. S is the square of the total energy in the center-of-mass system and M is the proton mass. The "Regge" curve is the most forward-peaked term in the Regge model without conspiracy [Eq. (1)].

FIG. 3. Plot of $\alpha(t)$ vs t for the process $\gamma p \rightarrow \pi^+ n$ by fitting the data for $E_\gamma = 8$, 11, and 16 GeV to the form $d\sigma/dt = Cs^{2\alpha(t)-2}$. The straight line shows a Regge trajectory passing through the pion pole with a slope 1 (GeV/c)$^{-2}$.

rac particle gives a cross section of

$$(s-M_p^2)^2 \frac{d\sigma}{dt} \approx 260 \frac{1+(t/m_\pi^2)^2}{(1-t/m_\pi^2)^2} \; \mu\text{b GeV}^2 \qquad (3)$$

(the π-N coupling constant has been taken as $g_{\pi NN}^2/4\pi = 14.7$), which is plotted in Fig. 2. The Born approximation gives a cross section which is much too large at all values of $-t \gg m_\pi^2$, and we have been unable to get good agreement with the data with absorption done in the fashion of Gottfried and Jackson.[13] It is interesting to note that the cross sections measured here can be fitted to within about 30% for all values of t and k by an unfashionable form factor model with

$$d\sigma/dt = e^{3t}(d\sigma/dt)_{\text{Born}}. \qquad (5)$$

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[1]Preliminary results were reported at the International Symposium on Electron and Photon Interactions at High Energies, Stanford, California, 1967 (to be published), and the Heidelberg International Conference on Elementary Particles, Heidelberg, Germany, 1967 (to be published).

[2]W. K. H. Panofsky, in Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Hamburg, Germany, 1965 (Springer-Verlag, Berlin, Germany, 1965), p. 138.

[3]P. M. Joseph, N. Hicks, L. Litt, F. M. Pipkin, and J. J. Russell, contributed paper to the International Symposium on Electron and Photon Interactions at

High Energies, Stanford, California, 1967 (to be published).

[4]G. Buschhorn, J. Carroll, R. D. Eandi, P. Heide, R. Hübner, W. Kern, U. Kötz, P. Schmüser, and H. J. Skronn, Phys. Rev. Letters 17, 1027 (1966), and 18, 571 (1967); G. Buschhorn, P. Heide, U. Kötz, R. A. Lewis, P. Schmüser, and H. J. Skronn, contributed paper to the International Symposium on Electron and Photon Interactions at High Energies, Stanford, California, 1967 (to be published).

[5]U. Elings, K. J. Cohen, D. A. Garelick, S. Homma, R. A. Lewis, P. D. Luckey, and L. S. Osborne, Phys. Rev. Letters 16, 474 (1966).

[6]J. T. Beale, S. D. Ecklund, and R. L. Walker, California Institute of Technology Report No. CTSL-42, 1966 (unpublished).

[7]G. Manning, A. G. Parham, J. D. Jafar, H. B. van der Raay, R. D. Reading, D. G. Ryan, B. D. Jones, J. Malos, and N. H. Lipman, Nuovo Cimento 41A, 167 (1966).

[8]L. S. Osborne, in Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Hamburg, Germany, 1965 (Springer-Verlag, Berlin, Germany, 1965), p. 91.

[9]R. Anderson, D. Gustavson, G. Jones, J. Johnson, D. Kreinick, R. Prepost, D. Ritson, and R. Weinstein, contributed paper to the International Symposium on Electron and Photon Interactions at High Energies, Stanford, California, 1967 (to be published).

[10]S. Frautschi and L. Jones, California Institute of Technology Report No. CALT-68-132, 1967 (to be published); S. D. Drell and J. D. Sullivan, Phys. Rev. Letters 19, 268 (1967); P. K. Mitter, Phys. Rev. 162, 1624 (1967); R. F. Sawyer, Phys. Rev. Letters 19, 137 (1967); M. B. Halpern, Phys. Rev. 160, 1441 (1967).

[11]We have received preprints from J. Frøyland and D. Gordon and from K. Dietz and W. Korth which give Regge-conspiracy fits in qualitative agreement with the small t data.

[12]G. Zweig, Nuovo Cimento 32, 659 (1964); P. Stichel, Z. Physik 178, 519 (1964).

[13]K. Gottfried and J. D. Jackson, Nuovo Cimento 34, 735 (1964); S. D. Drell and M. Jacob, Phys. Rev. 138, B1312 (1965).