π^0 PHOTOPRODUCTION FROM HYDROGEN AT BACKWARD ANGLES*

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Cross sections for π^0 photoproduction from hydrogen in the backward direction have been measured for photon energies of 6, 8, 12, and 18 GeV. The range of momentum transfer covered in these measurements is $-1\ (\mathrm{GeV}/c)^2 < u < 0\ (\mathrm{GeV}/c)^2$. $d\sigma/du$ is found to have a backward peak and decreases with energy as $s^{-3.0\pm0.2}$. Photoproduction of η^0 and ρ^0 mesons has also been observed.

High-energy backward processes are currently described as proceeding through the exchange of a Reggeized baryon. A simple pole model has been able to provide fits to the elastic pion-nucleon scattering.[1-3] The angular distributions and the energy dependence of the cross sections are primarily determined by the properties of the N_α and Δ_δ trajectories. It was expected that these trajectories would play a dominant role in nonstrange meson photoproduction at small u values. With this in mind, we have measured the cross section for π^0 photoproduction in the momentum transfer range $-1\ (\mathrm{GeV}/c)^2 < u < 0\ (\mathrm{GeV}/c)^2$ at several photon energies. Our results, taken together with the cross sections for π^+ production in the same kinematic region,[4] suggest that some modifications of present ideas are in order.

Description of the experiment.—The experiment was carried out at the Stanford Linear Accelerator Center (SLAC). A bremsstrahlung beam was produced by electrons of energy E_e impinging on a 0.03-radiation-length aluminum radiator. The photons passed through two collimators and sweep fields before striking a 40-in.-long hydrogen target. The beam flux was monitored to an accuracy of ±2% using a helium Cherenkov cell and a secondary-emission quantameter.[5] The momentum spectrum of protons emitted from the hydrogen at small angles was measured in the SLAC 20-GeV/c spectrometer.[6] The spectrometer accepts ±3 mrad horizontally, ±8 mrad vertically, and ±1.5% in $\Delta p/p$ over a distance of ±3 cm transverse to its axis. Protons were identified by a differential Cherenkov counter. Contamination from pions and kaons was not a problem, since the protons from π^0 production in this kinematic region have a momentum greater than the incident beam by several hundred MeV/c. A set of four scintillation-counter hodoscopes in the counter house were used to measure for each event the angle of emission from the target (with a resolution $\delta\theta_h = \pm 0.14$ mrad, $\delta\theta_v = \pm 1.2$ mrad), the horizontal displacement at the target relative to the spectrometer axis ($\delta x = \pm 2$ cm), and the momentum ($\delta p = \pm 5\times10^{-4}p$). The SDS-9300 computer facility[7] in the End Station A counting room was used to log these data on magnetic tape as well as to provide an on-line analysis.

From the angle and momentum measurements a "missing mass" was calculated for the event assuming that the photon energy was E_e. Single-meson production is recognized in this missing-mass spectrum as a step whose magnitude is proportional to the production cross section. The width of the step rise is determined by the experimental resolution. To provide a set of experimental resolution curves, we measured the forward π^+ momentum spectrum at four or five angles. Photoproduction cross sections for backward π^0 were measured at energies of 6, 8, 12, and 18 GeV. At each energy data were taken for eight or ten spectrometer angles. The spectrometer momentum was normally set to observe the step from π^0 production. Each such point represents 2 to 3 h of data taking. At two angles, the momentum spectrum was measured over a wider range (typically $\Delta p \simeq 0.8$ GeV/c or 1.5 GeV^2 in missing mass) in order to obtain more information about the background spectrum from multipion production. At these angles we have obtained cross sections for η^0 and ρ^0 production.

Data analysis procedure.—The π^+ data at forward angles as a function of squared missing mass x was fitted at each energy using a standard step function of the form

$$S_n(x)=\frac{1}{2}\left\{1+\frac{2}{\sqrt{\pi}}\int_0^x dy\,\exp\left[-\frac{(y-M_n^2)^2}{w_n^2}\right]\right\},$$

in order to fix the parameters w_n and M_n representing the step width and mass of the missing neutron. In addition to determining the step shape, the method checks the intercalibration of the incident beam energy E_e and the spectrometer momentum setting with a set of experimental points of high statistics. Having fixed the parameters of $S(x)$, we fitted the proton excitation spectra with a function of the form

$$F(x)=C_\pi S_\pi(x)+C_\eta S_\eta(x)+C_\rho S_\rho(x)+B(x),$$

which allows steps for π^0, η^0, and ρ^0 production. The C_i's were varied to fit the data. $B(x)$ is a term with a few more free parameters to represent the multiparticle production background. An early choice for this was

$$B(x)=C_1x+C_2x^2+C_3x^3.$$

In later stage of analysis $B(x)$ was made more complicated to approximate better our ideas about the appropriate form of the multiparticle background. Since protons were not observed at momenta above the threshold for π^0 production, it was not necessary to include terms in $B(x)$ which could give large contributions at $x=0$. Consequently, the cross sections obtained for π^0 production were insensitive to the specific background assumption. This was not the case for the η^0 and ρ^0 cross sections.

The spectrum at 8 GeV, $\theta_{\text{lab}}=1.9°$, which covers about three times the spectrometer momentum acceptance, is shown in Fig. 1(a). The same data are plotted in 1(b) with the fitted multiparticle background term subtracted from each point. Here the steps from single meson production are clearly seen. For this spectrum the background term $B(x)$ contributed about 20% of the total events below a missing mass of $x=0.3$ GeV^2. In some of the data this contribution was as much as 30%.

Cross sections for $\gamma+p\rightarrow\pi^0+p$.—The differential cross sections $-d\sigma/du$ vs u are shown in Fig. 2. The error bars represent the statistical errors, as determined from the fitting procedure, combined with 7% which reflects our estimate of the background uncertainties. The data have been corrected for absorption effects in the target [typically (12 ± 2)%] and in the detector [(6 to 10 ±3)%]. In view of these and the uncertainties in the spectrometer acceptance (±3%), detector efficiency (±3%), hydrogen density (±1.7%), photon monitor (±2%), and bremsstrahlung spectrum (±3%), we believe our normalization is reliable to ±10%.

This experiment does not distinguish the Compton effect from π^0 production, and the measured

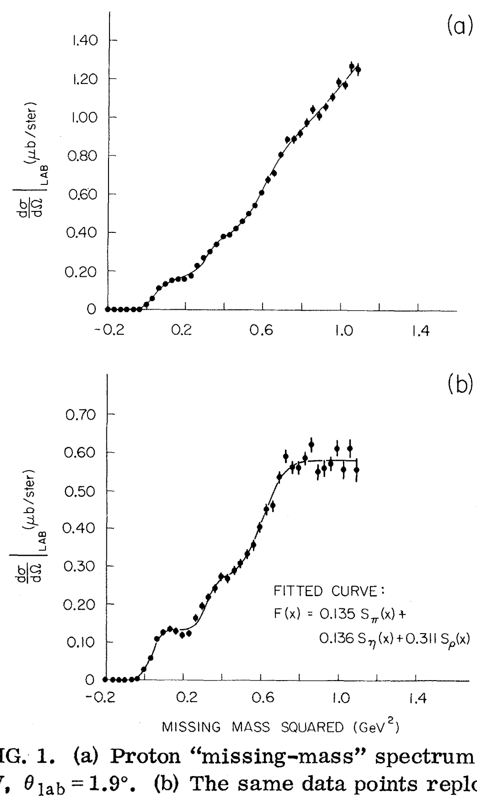

FIG. 1. (a) Proton "missing-mass" spectrum at 8 GeV, $\theta_{\text{lab}}=1.9°$. (b) The same data points replotted with the fitted background subtracted.

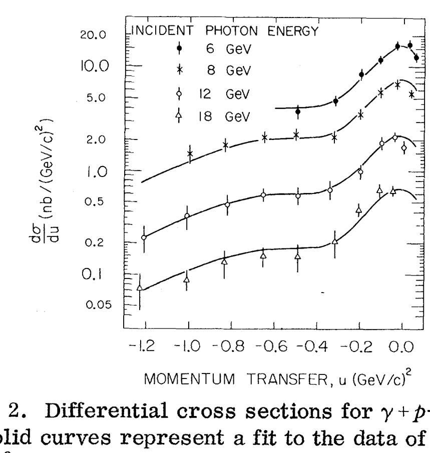

FIG. 2. Differential cross sections for $\gamma+p\rightarrow\pi^0+p$. The solid curves represent a fit to the data of the form $F(u)s^{-3}$.

cross sections are the sum of the two processes. However, from vector-meson dominance, we expect the Compton effect to be smaller than ρ^0 production by a factor of 250 to 500. Since the measured ρ^0 cross sections are approximately the same as those for π^0, we assume the Compton contribution is negligible.

The salient features of the cross section are the following: There is a backward peak which reaches a maximum near $u=0$ and decreases for positive u. The cross section falls rapidly out to $u\simeq-0.4$ $(\mathrm{GeV}/c)^2$ and then continues slowly downward as u becomes more negative. The dip found at $u=-0.15$ $(\mathrm{GeV}/c)^2$ in π^+p elastic scattering is not observed in π^0 photoproduction. Assuming that the energy dependence of the cross section can be represented by $-d\sigma/du=As^{-B}$, fits to the data at $u=0.0$, -0.2, and -0.5 $(\mathrm{GeV}/c)^2$ give, respectively, $B=3.2\pm0.13$, 2.9 ± 0.16, and 3.1 ± 0.25. Hence we conclude there is no indication of shrinkage. The integral of the cross section for $u>-1.0$ $(\mathrm{GeV}/c)^2$ is well approximated by $10(s/10)^{-3}$ nb.

Cross sections for η^0 and ρ^0.—Our main purpose in taking a few long momentum sweeps at each energy was to understand better how to evaluate the contribution of the multiparticle production spectrum under the π^0 step. However, we were also motivated toward obtaining information about the relative magnitude of other meson production processes at backward angles. Steps in the missing-mass spectra at the η^0 and ρ^0 mass appeared consistently at all energies. Attempts at fitting the data without an η^0 step gave an increase in χ^2 between 25 and 50 for most spectra taken at small angles. Fits in which the missing-mass value of the η^0 step was varied showed a narrow minimum in χ^2 $[\delta(m_\eta^2)\simeq\pm0.02$ $\mathrm{GeV}^2]$ at the η^0 mass. Although the cross section which we heuristically refer to as ρ^0 must be understood to be the sum of contributions from ρ^0 and ω^0 (since our resolution does not allow a separation), the fits indicated that the ω^0 contribution was certainly not more than that for the ρ^0. We give the results in Table I. The quoted errors include a contribution for variations in the fits obtained with different background assumptions. Since the η^0 and ρ^0 cross sections account for only 15 to 30% of the total number of events in the missing-mass range from which they are extracted, we would fold in an additional 25% uncertainty to the errors as an estimate of the reliability of the background subtraction technique.

The η^0 and ρ^0 cross sections are comparable with those for π^0 production. The energy dependence of the ρ^0 cross section is similar to that for the π^0 [a fit to the ρ^0 data at $u\simeq-0.06$ $(\mathrm{GeV}/c)^2$ gives $d\sigma/du\propto u^{-3.6\pm0.4}$], and one might assume that the same trajectories are exchanged. In this case the difference between the ρ^0 and π^0 cross sections would reflect the difference in structure of the meson-nucleon vertex. We have tried to estimate the relative importance of the N_α and Δ_δ Regge poles for ρ^0 production in comparison with π^0. For the N_α the coupling constants at the pole are known. The main contribution to ρ production comes from the coupling to

Table I. Cross sections for backward η^0 and ρ^0 photoproduction. (In addition to the errors listed above a 25% normalization uncertainty should be allowed.)

Incident Energy (GeV)	Spectrometer Angle (degrees)	$\gamma+p\to\eta^0+p$		$\gamma+p\to\rho^0+p$	
		u $(\mathrm{GeV}/c)^2$	$-d\sigma/du$ nb/$(\mathrm{GeV}/c)^2$	u $(\mathrm{GeV}/c)^2$	$-d\sigma/du$ nb/$(\mathrm{GeV}/c)^2$
6	1.60	+0.011	6.82 ± 1.56	−0.010	33.2 ± 4.9
6	2.75	−0.046	9.91 ± 1.39	−0.075	40.2 ± 5.0
8	1.90	−0.050	4.46 ± 0.86	−0.063	11.7 ± 1.6
8	5.82	−0.670	2.10 ± 0.57	−0.670	10.3 ± 2.0
12	1.20	−0.045	0.92 ± 0.30	−0.055	3.83 ± 0.65
12	3.85	−0.645	0.47 ± 0.42	−0.645	2.53 ± 0.75
18	0.75	−0.042	0.26 ± 0.12	−0.051	0.83 ± 0.22
18	2.59	−0.670	0.053 ± 0.058	−0.670	0.26 ± 0.13

the isovector anomalous moment, $\kappa = 1.85$, of the nucleon. A calculation of the Born diagram for an elementary proton exchange gives for the high-energy cross section at backward angles

$$\frac{\sigma(\gamma p \to \rho^0 p)}{\sigma(\gamma p \to \pi^0 p)} = \frac{3f_{\rho NN}^2}{4g_{\pi NN}^2}\kappa^2.$$

Using $f_{\rho NN}^2/4\pi = 2.5$ and $g_{\pi NN}^2/4\pi = 14.5$, this ratio is 0.44. The experimentally observed ratio is 1.5 to 2, and we conclude that the N_α is important although not the only contributor. Backward ρ^- production has been observed in[8] $\pi^- p \to \rho^- p$ which is a pure $I=\frac{3}{2}$ baryon exchange. The cross sections for this reaction near $u=0$ are approximately 1.5 times larger than those for $\pi^- p \to \pi^- p$. Therefore Δ exchange is also likely to be important in ρ photoproduction.

The η meson is an isosinglet, and therefore only $I=\frac{1}{2}$ baryon exchange can contribute. The ηNN coupling constant[9,10] is thought to be more than an order of magnitude smaller than πNN; so the N_α Regge pole is ruled out. Since the $N^*(1550)$ has a large branching ratio into (ηN), the η photoproduction might be due to exchange of of the Reggeon associated with this particle. However, a fit to the energy dependence of the η cross sections gives $d\sigma/du \approx s^{-3.5 \pm 0.5}$, whereas a trajectory of unit slope through $N^*(1550)$ should give $s^{-5.8}$. Furthermore, in spite of the large branching ratio, the coupling to (ηN) is small ($g_{\eta NN^*(1550)}{}^2/4\pi$, defined for a scalar interaction, is $\simeq 0.3$ as determined from the partial width of 52 MeV). For these reasons the $N^*(1550)$ Reggeon is a poor choice. The N_γ Regge pole is a more likely candidate for understanding the η^0 cross section. The coupling of $N^*(1518)$, which is the lowest mass state on the N_γ trajectory, to both (γN) and (ηN) is large as evidenced from low-energy formation processes. Also, the observed energy dependence is consistent with the N_γ trajectory.

Discussion of results. —We have tried to understand to what extent the measured π^0 and[4] π^+ photoproduction cross sections are consistent with a Regge-pole model.[1-3] The photoproduction is more similar in u-dependent structure to $\pi^- p$ elastic scattering than to $\pi^+ p$. Paschos[3] suggested that π^+ photoproduction proceeds mainly through Δ_δ exchange. Using this as a starting point, the only remaining freedom to fit the π^0 cross sections is the amount of $I=\frac{1}{2}$ exchange. It is not possible to fit the data if this $I=\frac{1}{2}$ contribution is the N_α Regge pole. At $u \simeq -0.15$ (GeV/$c)^2$ the amplitude for N_α is supposed essentially to vanish because of a wrong-signature nonsense point. Only the isovector electromagnetic current contributes to $I=\frac{3}{2}$ exchange. Therefore, at this value of u, isospin symmetry requires the cross section for π^0 production to be twice that for π^+. The measured ratio is 0.8 ± 0.2 rather than 2. In general the π^0 cross section does not vary sufficiently in the region -0.2 (GeV/$c)^2 < u < 0.0$ (GeV/$c)^2$ to accommodate the N_α without a large contribution from some other $I=\frac{1}{2}$ exchange.

Kane[11] has given an argument against a preponderance of Δ exchange in π^+ photoproduction. The total backward cross section for $\pi^- + p \to \rho^- + p$ at 8 GeV is 1.38 ± 0.14 μb.[8] Assuming all the ρ's are transverse and using vector-meson dominance, one obtains an upper limit for the square of the Δ exchange amplitude in photoproduction. For π^+ production the result is 0.6 nb with $\gamma_\rho{}^2/4\pi = 0.5$. The integral under the backward π^+ photoproduction peak at 8 GeV is greater than 3.5 nb, and one concludes that a consistent picture requires mainly nucleon exchange. Again, in view of the absence of a dip at $u = -0.15$ GeV^2 in the photoproduction data, the simple Regge-pole model must rely on some other $I=\frac{1}{2}$ trajectory in addition to the N_α.

The N_γ Regge pole is a possible choice for the additional $I=\frac{1}{2}$ exchange needed in the pole model. The importance of the N_γ in photoproduction, in contrast to backward elastic $\pi^+ p$ scattering, is not completely ad hoc, since the $N^*(1518)$ is a more distinguished resonance in low-energy photoproduction than in $\pi^- p$ elastic scattering. On the other hand there is a limit to the amount of N_γ amplitude that can be introduced, which is provided by the η cross sections measured in this experiment. From the partial widths of $N^*(1518) \to \pi N$ and ηN,[12] one estimates that the squared N_γ amplitude for backward η^0 photoproduction is $\simeq 6$ times that for π^0 production. Since the measured η^0 cross sections are smaller than those for π^0, this is a useful restriction.

Dashen and Lee[13] have suggested that backward pion photoproduction provides a sensitive test for the presence of right-signature fixed poles. A fixed nucleon pole at $J=\frac{1}{2}$ would contribute a term in the differential cross section $d\sigma/du$ proportional to s^{-1}. At high energies this term would dominate. In view of the observed s^{-3} energy dependence in this experiment, there seems to be no evidence for fixed poles.

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SEARCH FOR THE INTERMEDIATE VECTOR BOSON*

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A search for the vector boson (W particle), postulated as the mediator of the weak interaction, has been carried out by determining the intensity and polarization of muons originating very near the point of interaction of 28-GeV protons with nucleons. Bosons were not observed and the upper limit on the production cross section for W's with masses between 2.0 and 4.5 GeV/c^2 is $B\sigma \lesssim 6\times10^{-36}$ cm^2, where B is the branching ratio for the W decay to a muon and a neutrino.

It is attractive in many respects to consider that the weak interactions might be mediated by a vector boson, the W. Although no reliable method of calculating the mass of such a particle has been found, the small value of the K_1^0-K_2^0 mass difference suggests[1,2] that the W mass is less than 5 GeV/c^2, and the unsuccessful searches[3] for the W in neutrino experiments indicate that the mass must be greater than 2 GeV/c^2—if the W exists at all!

Though it is difficult to produce W's with masses greater than 2.0 GeV/c^2 with the secondary neutrino beams presently available from accelerators, the production of W's with masses up to 5 GeV/c^2 is kinematically accessible through the interaction of the primary proton beams with target nucleons. An examination of typical diagrams for the production of W's, shown in Fig. 1, shows that the nucleon-nucleon production of W's might be expected to be about $(137)^2$ times as probable as neutrino production, even as two electromagnetic vertices in the diagram of Fig. 1(a) are replaced by strong-interaction vertices in Fig. 1(b), provided that the weak-interaction form factors for the (p, W, n) vertex are not very much smaller than the unit form factor for the (ν, W, μ) vertex. If this timelike form factor is quite small for values of the square of the momentum transfer $q^2 = -M_W^2$, then previous measurements[4] of the W production cross section, σ, which place a limit such that $B\sigma \leq 2\times10^{-34}$ cm^2, might not be regarded as strong evidence that a W with a mass in this range did not exist. Here M_W is the mass of the W and B is the branching ratio for the decay of the W into a muon and a neutrino. Indeed, an estimate of the form factor for W pro-