SLAC-PUB-527
November 1968
(TH)

EXPERIMENTAL INFORMATION ON THE $\pi^{\pm}$ PHOTOPRODUCTION AMPLITUDES*

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ABSTRACT

Recent data on $\pi^{\pm}$ photoproduction at 3.4 GeV are used to investigate the nature of the amplitudes contributing to these processes. It is found that a large amplitude corresponding to natural-parity G = +1 exchange is necessary to explain the data, even in the region $t \approx -0.6$ GeV^2 where Reggeized ρ exchange must vanish. This implies a large contribution from some ρ' trajectory or from cuts, absorption, etc. The large G = +1 exchange amplitude needed to explain the π^-/π^+ ratio is only marginally consistent with the vector dominance model.

(Submitted to Phys. Rev. Letters)

*Work supported by the U. S. Atomic Energy Commission.

Considerable experimental data have recently been obtained for the processes

$$\gamma p \rightarrow \pi^+ n, \tag{1}$$

$$\gamma n \rightarrow \pi^- p . \tag{2}$$

Differential cross sections have been measured from 2 or 3 GeV up to 16 GeV,[1] and polarized beam experiments[2] have measured the asymmetries (principally at 3.4 GeV)

$$\Sigma^+ = \left(\frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel}\right)_{\gamma p \rightarrow \pi^+ n} \tag{3}$$

$$\Sigma^- = \left(\frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel}\right)_{\gamma n \rightarrow \pi^- p} \tag{4}$$

where $\sigma_\perp$ ($\sigma_\parallel$) is the differential cross section measured with the γ ray linearly polarized perpendicular to (in) the plane of production. Although this is still far from being a complete set of experiments, the general character of the amplitudes can be determined and any theory hoping to describe these processes must show this character.

At high energies the parity-conserving amplitudes $\overline{f}^{\pm}_{\lambda_3\lambda_4,\lambda_1\lambda_2}$ of Gell-Mann et al.[3] correspond to definite quantum numbers when viewed from the t channel; these quantum numbers are found from the $N\overline{N}$ coupling[4] and the results are shown in Table I together with the corresponding A_i amplitudes of Ball.[5] Particles having these quantum numbers are also shown in Table I; since one unit of charge must be exchanged in the t channel for processes 1 and 2, only the $I = 1$ particles are shown. Elementary-particle-exchange or Regge-pole-exchange diagrams contribute to the amplitudes as indicated by Table I; absorption effects, Regge cuts, etc. will contribute terms to other amplitudes as well.

At high energies the differential cross section for $|t| \ll s$ is given by

$$\frac{d\sigma}{dt} = \frac{1}{32\pi}\left\{\left[|A_1|^2 + |t|\,|A_4|^2\right] + \left[|A_1 + tA_2|^2 + |t|\,|A_3|^2\right]\right\} . \qquad (5)$$

The terms in the first and second square brackets correspond to $P(-1)^J = +1$ and -1 (natural and unnatural parity) exchanges, respectively. At $t = 0$ only the A_1 amplitude contributes and it contributes equally to the natural and unnatural parity exchanges; this is just the famous conspiracy condition.

To better keep track of the amplitudes we introduce a set of mnemonics; for example, we denote by the symbol π that part of the $\overline{f}^{-}_{10\frac{1}{2}\frac{1}{2}}$ amplitude corresponding to $G = -1$ exchange in the t channel. This amplitude includes not only the one-pion-exchange term, but also other exchange terms for particles or trajectories with the appropriate quantum numbers as well as contributions from cuts, etc. We then rewrite the π^+ cross section as

$$\frac{d\sigma}{dt}(\gamma p \to \pi^+ n) = |\pi_c + \rho|^2 + |\pi + B|^2 + |A_1|^2 . \qquad (6)$$

Note that the natural parity amplitudes, π_c and ρ, are combinations of $\overline{f}^{+}_{10\frac{1}{2}\frac{1}{2}}$ and $\overline{f}^{+}_{10\frac{1}{2}-\frac{1}{2}}$; because of this there may be less $\pi_c\rho$ interference than implied by Eq. 6. Also, A_1 henceforth refers to A_1 meson exchange and not to Ball's amplitude. Equations 5 and 6 emphasize the fact that in general one does not expect the maximum interference between the $G = +1$ and -1 amplitudes which has been assumed[6] to explain the ratio

$$R = \frac{\frac{d\sigma}{dt}(\gamma n \to \pi^- p)}{\frac{d\sigma}{dt}(\gamma p \to \pi^+ n)} \qquad (7)$$

in terms of the vector dominance model. Indeed, to get this maximum interference not only must the $G = +1$ and -1 amplitudes have zero relative phase, but the relative amount of these amplitudes must be the same in all four terms of Eq. 5.

For π^- photoproduction the relative signs of the G = -1 and G = +1 amplitudes change. Furthermore, at high energies only the natural-parity exchange terms contribute to $\sigma_\perp$ and unnatural-parity terms contribute only to $\sigma_\parallel$.[7] Normalizing the π^+ cross section to unity then yields the four equations

$$\begin{aligned} |\pi_c + \rho|^2 &= \frac{1+\Sigma^+}{2} \\ |\pi_c - \rho|^2 &= R\,\frac{1+\Sigma^-}{2} \\ |\pi + B|^2 + |A_1|^2 &= \frac{1-\Sigma^+}{2} \\ |\pi - B|^2 + |A_1|^2 &= R\,\frac{1-\Sigma^-}{2}\ . \end{aligned} \tag{8}$$

The experimental results[1,2] for R, Σ^+ and Σ^- are given in Table II for k = 3.4 GeV.

We first examine the unnatural-parity amplitudes. The width of the sharp forward peak in the π^+ cross section is about $\Delta t = m_\pi^2$ and it is natural to assume that one pion exchange is important in this region. It has been suggested[8] that B conspiracy as well as π conspiracy might be important at t = 0. The experimental value R = 1.05 ± 0.09 obtained by the DESY group at k = 3.4 GeV, t = -0.003 GeV shows that, to within experimental uncertainty, no G = +1 and -1 interference is necessary; if the π and B amplitudes were relatively real, the above number would give a ratio for the amplitudes $B/\pi = 0.01 \pm 0.02$. Table II shows that $|\pi + B|^2 - |\pi - B|^2 = 0$ to within the uncertainties at $|t| = 0.2$, 0.4 and 0.6 GeV^2; i.e., just as at t = 0, the data do not require interference between G = +1 and -1 unnatural-parity amplitudes in this t region. Although appreciable B exchange could be present 90° out of phase with the π amplitude, the vector dominance model suggests that this is not the case and certainly the simplest assumption is that the unnatural-parity,

$G = +1$ amplitude does not contribute, $B = 0$. This leaves $|\pi|^2 + |A_1|^2$ as the unnatural-parity contribution and at the moment we have no way of distinguishing the relative amount of the two amplitudes. Again, simplicity would argue $A_1 = 0$ and the π amplitude calculated under this assumption is listed in Table III.

Turning now to the natural-parity exchange amplitudes, $|\pi_c + \rho|^2 \neq |\pi_c - \rho|^2$ at all three momentum transfers (see Table II), a large $\pi_c \rho$ interference term being required to explain the data. A limit can be placed upon the relative phase ϕ between the π_c and ρ amplitudes:

$$\cos \phi_{max} = \frac{1 + \Sigma^+ - R(1 + \Sigma^-)}{1 + \Sigma^+ + R(1 + \Sigma^-)} . \qquad (9)$$

This maximum phase angle is shown in Table III; for $\phi = \phi_{max}$, $|\pi_c| = |\rho|$ and this value is also shown in Table III.

There are two reasons for believing the natural-parity $G = +1$ exchange amplitude to be small. In Regge-pole theory ρ-trajectory exchange would be expected to give the dominant contribution to this amplitude. Since the upper pion photoproduction vertex always involves a unit change of helicity, the ρ-exchange amplitude must go to zero at the point where $\alpha_\rho = 0$, which from the analysis[9] of other processes is between $|t| = 0.5$ and 0.6 GeV^2. The only other candidate listed in Table I for this amplitude is $\rho_N(1660)$; unfortunately this resonance may well be on the same trajectory as the ρ. Thus, a large natural-parity $G = +1$ exchange amplitude near $t = -0.6$ would force one to conclude that either some unknown ρ' trajectory is dominant[10] or that absorption or cuts, etc. are important.[11] The second reason for wanting a small ρ exchange amplitude comes from the vector dominance model in which the coupling of the photon to the ω (leading to $G = +1$ exchange) is much weaker[12] than the $\gamma\rho$ coupling ($G = -1$ exchange).

The smallest value for the natural-parity G = +1 exchange amplitude is obtained under the assumption of maximum interference with the G = -1 amplitude; the results of this maximum $\pi_c \rho$ interference assumption are shown in Table III.[13] At all three t values a substantial natural-parity G = +1 amplitude is required; using the errors quoted by the experimentalists, $\rho \neq 0$ by 6 to 10 standard deviations. Near t = -0.6 the ratio of natural-parity amplitudes, G = +1/G = -1, is about 0.4 and does not show any rapid variation with t as would be expected from ρ-trajectory exchange.[14]

The vector-dominance-model comparison is made difficult by the lack of experimental data on the process $\pi^+ n \to \omega p$; in particular, there are no values for the density matrix as a function of momentum transfer. To test whether the present data are consistent in this model we have calculated[15]

$$\left(\rho^{hel}_{11}\right)_{\pi^+ n \to \omega p} = \frac{|\rho|^2 \frac{d\sigma}{dt}(\gamma p \to \pi^+ n)}{g^2_{\gamma\omega} \frac{d\sigma}{dt}(\pi^+ n \to \omega p)} \tag{10}$$

where $|\rho|^2$ is the maximum-interference value. As shown in Table III, the values so obtained for ρ^{hel}_{11} are larger than the maximum value of 1/2 at $|t| = 0.4$ and 0.6 GeV^2, but the errors are too large to allow a definite conclusion.[16] Additional data on $\pi^+ n \to \omega p$ are needed to determine whether a discrepancy exists.[17]

The principal conclusions which can be drawn from the present pion photoproduction data (k = 3.4 GeV) are the following:

1. Amplitudes corresponding to both natural and unnatural parity exchange in the t channel are required for $|t| \leq 0.6$ GeV^2.

2. No significant interference is observed between the amplitudes corresponding to G = +1 and -1 unnatural-parity exchange in the range $|t| \leq 0.6$ GeV^2. Since π exchange appears important near t = 0, the most economical assumption would be that there is no significant G = +1 unnatural-parity exchange.

3. Interference between amplitudes corresponding to G = +1 and -1 natural-parity exchanges is required by the data in the region $m_\pi^2 \leq |t| \leq 0.6\ \mathrm{GeV}^2$. The most prominent candidate for the G = +1 amplitude is ρ exchange, but in the Regge Model α_ρ goes through zero in this region and the ρ exchange amplitude goes to zero; this implies that some other contribution must be important: a ρ' trajectory or cuts, absorption, etc.

4. At $|t| = 0.4$ and $0.6\ \mathrm{GeV}^2$ the data require more G = +1 exchange than is predicted by the vector dominance model, but the uncertainties are large and more data on $\pi^+ n \to \omega p$ are required before a definite conclusion can be drawn.

The author is grateful for useful discussions with Drs. Frank Henyey, Haim Harari and Fred Gilman.

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9. See, for example, M. Barmawi, Phys. Rev. 166, 1857 (1968).
10. A ρ' trajectory has been used to explain other reactions; see, for example, H. Högaasen and W. Fischer, Phys. Letters 22, 516 (1966).
11. Similar conclusions have been reached by Haim Harari [Phys. Rev. Letters 21, 835 (1968)] for the amplitude corresponding to ω exchange in the reaction $\gamma p \to \pi^0 p$ where cuts or an ω' exchange are needed to avoid a gross violation of the vector dominance model; this conclusion has been reinforced by the polarized-beam results of Bellenger et al., contribution to Vienna Conference (1968).
12. S.C.C. Ting in his rapporteur talk at the Vienna Conference gave $g^2_{\gamma\omega}/g^2_{\gamma\rho} = (1.0 \pm 0.2)/9$.

13. Maximum interference not only requires the $G = +1$ and -1 exchange amplitudes to be relatively real, but also that they contribute in the same proportion to Ball's A_1 and A_4 amplitudes. The results are not sensitive to small phase differences between the amplitudes, however, and experiments involving the polarization of the initial and/or final nucleon are needed to pin down the relative phases.

14. At 5 GeV Σ^- has not been measured, but the small value $R \approx 0.3$ at $|t| = 0.4$ together with $\Sigma^+ = 0.45 \pm 0.17$ requires strong $\pi_c \rho$ interference independent of Σ^-.

15. The values

$$g^2_{\gamma\omega} = (0.39 \pm 0.08) \times 10^{-3} \quad \text{(ref. 12);}$$

$$\sigma(\pi^+ n \rightarrow \omega p) = 0.28 \pm 0.11 \text{ mb}$$

(estimated by comparing the results of several experiments under the assumption $\sigma \alpha\, p^{-2}_{lab}$) were used to evaluate Eq. (10). The ω angular distributions were obtained from H. O. Cohn *et al.* [Phys. Letters 15, 344 (1965)] and the Orsay-Bari-Bologne-Florence Collaboration [CERN Hadron Conference, vol. II, p. 134 (1968)] .

16. If one used $|\rho|^2$ as calculated for $\phi = \phi_{max}$, Eq. (10) would give ρ^{hel}_{11} about 6 times the maximum value of 0.5; even with the present uncertainty in the $\pi^+ n \rightarrow \omega p$ data this would be a strong violation of the vector dominance model. Harari (Ref. 11) found that large phase differences between $G = +1$ and -1 exchange amplitudes for the process $\gamma p \rightarrow \pi^0 p$ also lead to discrepancies in the vector dominance model.

17. A gross discrepancy presently exists between the polarized-beam data and the predictions of the vector dominance model; for details see
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TABLE I

PHOTOPRODUCTION AMPLITUDES AND PARTICLES CORRESPONDING TO THE t-CHANNEL QUANTUM NUMBERS OF THE AMPLITUDES

Parity Conserving Amplitudes	Ball Amplitudes	t-Channel Quantum Numbers $P(-1)^J$	$(-1)^I GP$	Corresponding Particles $G=-1$	$G=+1$
$\bar{f}^{+}_{10\frac{1}{2}\frac{1}{2}}$	$A_1 - 2MA_4$	+	+	$\pi_c, \pi_N(1016), A_2$	$\rho, \rho_N(1660)$
$\bar{f}^{-}_{10\frac{1}{2}\frac{1}{2}}$	$-A_1 + tA_2$	-	-	$\pi, \pi_A(1640)$	B
$\bar{f}^{+}_{10\frac{1}{2}-\frac{1}{2}}$	$2MA_1 - tA_4$	+	+	$\pi_c, \pi_N(1016), A_2$	$\rho, \rho_N(1660)$
$\bar{f}^{-}_{10\frac{1}{2}-\frac{1}{2}}$	A_3	-	+	A_1	

Note: (a) π_c may be identical to the $K\bar{K}$ state $\pi_N(1016)$

(b) The value of $(-1)^I GP$ for $\pi_A(1640)$ is not known and it could be associated with the A_1 instead of the π.

TABLE II

EXPERIMENTAL RESULTS FOR k = 3.4 GeV AND THE CORRESPONDING VALUES FOR THE AMPLITUDES $\left[\frac{d\sigma}{dt}(\gamma p \rightarrow \pi^+ n)\text{ NORMALIZED TO UNITY AT EACH } t\right]$

$-t$ GeV^2	R	Σ^+	Σ^-	$\lvert\pi_c+\rho\rvert^2$	$\lvert\pi_c-\rho\rvert^2$	$\lvert\pi+B\rvert^2 + \lvert A_1\rvert^2$	$\lvert\pi-B\rvert^2 + \lvert A_1\rvert^2$	$\lvert\pi+B\rvert^2 - \lvert\pi-B\rvert^2$
0.2	0.55±0.05	0.85±0.11	0.34±0.15	0.92±0.06	0.37±0.06	0.08±0.06	0.18±0.05	-0.10±0.08
0.4	0.32±0.03	0.63±0.11	-0.20±0.20	0.82±0.06	0.13±0.04	0.18±0.06	0.19±0.04	-0.01±0.07
0.6	0.37±0.03	0.77±0.13	-0.08±0.20	0.88±0.07	0.17±0.04	0.12±0.07	0.20±0.04	-0.08±0.08

TABLE III

RELATIVE PHOTOPRODUCTION AMPLITUDES UNDER VARIOUS ASSUMPTIONS

$\left[\frac{d\sigma}{dt}(\gamma p \to \pi^+ n)\right.$ NORMALIZED TO UNITY AT EACH t$\left.\right]$

-t GeV^2	π (B=A$_1$=0)	$(\phi_{\pi_c \rho})_{max}$	$\lvert\pi_c\rvert = \lvert\rho\rvert$ ($\phi=\phi_{max}$)	π_c (ϕ=0)	ρ (ϕ=0)	$\left(\rho_{11}^{hel}\right)_{\pi^+ n \to \omega p}$ (from eq. 10)
0.2	0.36±0.05	64°±4°	0.57±0.04	0.78±0.03	0.18±0.03	0.36±0.21
0.4	0.43±0.04	44°±6°	0.49±0.04	0.63±0.03	0.27±0.03	0.75±0.40
0.6	0.40±0.05	47°±6°	0.51±0.04	0.67±0.03	0.26±0.03	0.83±0.44