VECTOR DOMINANCE IN PHOTOPRODUCTION*

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It is shown that present data on photoproduction support the vector-dominance assumption for the hadron electromagnetic current, in direct tests which require almost no additional symmetry- or model-dependent assumptions. Agreement with predictions is obtained for both the angular distribution and the magnitude of the photoproduction cross section, over a wide energy range. New model-independent experimental tests of vector dominance in photoproduction are proposed.

In this work we examine experimental tests, in photoproduction, of vector dominance of the hadron electromagnetic current,[1] in view of new data and possible new experiments. It is shown that present data support vector dominance over a wide energy range in direct tests which require almost no additional symmetry- or model-dependent assumptions of the types necessary in previous analyses.[2] Agreement with vector-dominance predictions is obtained not only for the magnitude of the photoproduction cross section, but also for finer details of the angular distribution.

We consider experimental tests of the relation between a photoproduction amplitude on any target T and a linear combination of three amplitudes for the corresponding strong production by transversely polarized vector mesons $V_{\rm tr}$:

$$A(\gamma T \rightarrow \cdots) \approx \sum_{V=\rho,\,\omega,\,\varphi} g_{V\gamma} A(V_{\rm tr} T \rightarrow \cdots), \quad (1)$$

where the coupling constants $g_{V\gamma}$ can be determined from experimental electromagnetic decays of the mesons. This relation can be obtained as follows.[3] First, the hadron electromagnetic current J_μ is expressed as[1]

$$eJ_\mu = g_{\rho\gamma} m_\rho^{\;2} \rho_\mu + g_{\omega\gamma} m_\omega^{\;2} \omega_\mu + g_{\varphi\gamma} m_\varphi^{\;2} \varphi_\mu, \quad (2)$$

where ρ_μ, ω_μ, and φ_μ are the renormalized ρ, ω, and φ fields. Then using standard methods of field theory, Eq. (1) is derived from Eq. (2) for massless vector mesons and a smooth extrapolation is assumed from zero mass to the physical mass for the vector-meson ampltudes.

Because of the time-reversal invariance the processes on the right-hand side of (1) can be reversed so that any photoproduction amplitude is expressed as a linear combination of the corresponding three amplitudes for ρ, ω, and φ production. Experimental measurements, usually, give only cross sections and not the relative phases of the amplitudes, and consequently a critical check of (1) is not possible if there are appreciable contributions from more than one reaction on the right-hand side of (1), unless some reliable assumptions about the phases are possible.

In some cases isospin conservation can be used to eliminate the contribution from the isoscalar component of the photon and the isoscalar vector mesons to the relation (1). The sum on the right-hand side then reduces to a single term containing the ρ contribution. One case of this kind is pion photoproduction on an isoscalar target where the contribution of the isoscalar component of the photon vanishes by isospin conservation. For this case we have

$$\frac{d\sigma}{dt}(\gamma T_{I=0} \rightarrow \pi^0 T_{I=0}) \approx \tfrac{1}{2} g_{\rho\gamma}^{\;2} \frac{d\sigma}{dt}(\pi^\pm T_{I=0} \rightarrow \rho_{\rm tr}^{\;\pm} T_{I=0}),$$

where

$$\frac{d\sigma}{dt}(\pi^\pm T \rightarrow \rho_{\rm tr}^{\;\pm} T) = [1-\rho_{00}^{\;\pm}(t)] \frac{d\sigma}{dt}(\pi^\pm T \rightarrow \rho^\pm T).$$

$\rho_{00}^{\pm}(t)$ is the density matrix element for longitudinal $\rho^{\pm}$ production and the extra factor $\frac{1}{2}$ on the right-hand side of (3a) comes from averaging over photon polarizations. Experimental test of (3a) would provide the most direct check on the vector-dominance assumption for photoproduction, since the derivation of (3a) did not involve any specific reaction mechanism. Unfortunately, no experimental results are available at present on both sides of (3a). Experimental measurements with isosinglet targets like deuterium, helium, or carbon would be of interest.

Another possibility is photoproduction of pions on nucleons. From (1) we can write

$$A(\gamma N\to\pi N')\approx\sum_{V=\rho,\,\omega,\,\varphi}g_{V\gamma}A(\pi N'\to V_{\mathrm{tr}}N),\quad(4)$$

where N and N' are nucleon states and all possible pion charge states are considered. From the four reactions a suitable linear combination of cross sections can be found in which the isoscalar photon and vector-meson contributions cancel out. One then finds the relation

$$\begin{aligned}&\frac{d\sigma}{dt}(\gamma p\to\pi^0p)+\frac{d\sigma}{dt}(\gamma n\to\pi^0n)-\frac{1}{2}\frac{d\sigma}{dt}(\gamma p\to\pi^+n)-\frac{1}{2}\frac{d\sigma}{dt}(\gamma n\to\pi^-p)\\&\approx\tfrac{1}{2}g_{\rho\gamma}{}^2\left\{\frac{d\sigma}{dt}(\pi^0p\to\rho_{\mathrm{tr}}{}^0p)+\frac{d\sigma}{dt}[\pi^0n\to\rho_{\mathrm{tr}}{}^0n]-\frac{1}{2}\frac{d\sigma}{dt}[\pi^+n\to\rho_{\mathrm{tr}}{}^0p]-\frac{1}{2}\frac{d\sigma}{dt}(\pi^-p\to\rho_{\mathrm{tr}}{}^0n)\right\}\\&=\tfrac{1}{2}g_{\rho\gamma}{}^2\left\{2\frac{d\sigma}{dt}(\pi^0p\to\rho_{\mathrm{tr}}{}^0p)-\frac{d\sigma}{dt}(\pi^-p\to\rho_{\mathrm{tr}}{}^0n)\right\}\\&=\tfrac{1}{2}g_{\rho\gamma}{}^2\left\{\frac{d\sigma}{dt}(\pi^-p\to\rho_{\mathrm{tr}}{}^-p)+\frac{d\sigma}{dt}(\pi^+p\to\rho_{\mathrm{tr}}{}^+p)-2\frac{d\sigma}{dt}(\pi^-p\to\rho_{\mathrm{tr}}{}^0n)\right\},\end{aligned}\quad(5)$$

where isospin invariance has been used to simplify the right-hand side. However, there are insufficient data for photoproduction on neutron targets.[4]

Approximate tests of relation (4) are possible with presently available experimental data, if the φ contribution is neglected on the basis of the following relation between experimental values of cross sections[5] and vector-meson–photon couplings[6]:

$$g_{\rho\gamma}{}^2\frac{d\sigma}{dt}(\pi p\to\rho p)\gg g_{\omega\gamma}{}^2\frac{d\sigma}{dt}(\pi p\to\omega p)\gg g_{\varphi\gamma}{}^2\frac{d\sigma}{dt}(\pi p\to\varphi p).\quad(6)$$

Linear combinations of cross sections can be chosen in which the interference term between isovector and isoscalar contributions is absent. If the φ contribution is neglected, one obtains the approximate relations

$$\frac{d\sigma}{dt}(\gamma p\to\pi^+n)+\frac{d\sigma}{dt}(\gamma n\to\pi^-p)\approx g_{\rho\gamma}{}^2\frac{d\sigma}{dt}(\pi^-p\to\rho_{\mathrm{tr}}{}^0n)+g_{\omega\gamma}{}^2\frac{d\sigma}{dt}(\pi^-p\to\omega_{\mathrm{tr}}n),\quad(7a)$$

$$\frac{d\sigma}{dt}(\gamma p\to\pi^0p)+\frac{d\sigma}{dt}(\gamma n\to\pi^0n)\approx g_{\rho\gamma}{}^2\frac{d\sigma}{dt}(\pi^0p\to\rho_{\mathrm{tr}}{}^0p)+g_{\omega\gamma}{}^2\frac{d\sigma}{dt}(\pi^0p\to\omega_{\mathrm{tr}}p).\quad(7b)$$

Note that the interference terms between the ρ and ω contributions are equal and opposite for the two reactions on the left-hand side of each of Eqs. (7). This interference term accounts for the difference between the two cross sections and cancels out in the sum. A similar cancellation occurs for the ρ-φ interference term, which would otherwise be the dominant φ contribution. Thus the error in the approximate relation (7) is only of the order of the ω-φ interference term, which is less than a few percent of the ρ contribution.

Figure 1 compares the photoproduction data on charged pions[7,8] with prediction (7a). The experimental average values from Ref. 6, $g_{\rho\gamma}{}^2=4.6\times10^{-3}$, $g_{\omega\gamma}{}^2=6.6\times10^{-4}$, were used. The results indicate agreement with experiment.

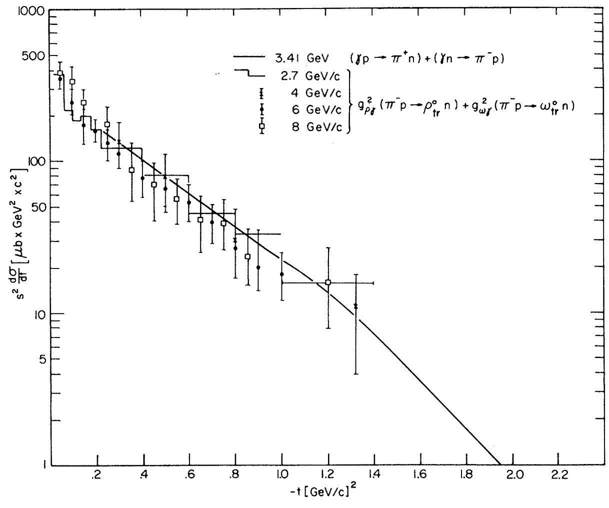

FIG. 1. A comparison between the sum rule (7a) and experiments. The smooth line represents the sum of the experimental cross sections for $\gamma p \to \pi^+ n$ and $\gamma n \to \pi^- p$. It was determined from the $\gamma p \to \pi^+ n$ cross section given in Ref. 8 and with the measured π^-/π^+ ratio of Ref. 9. The experimental results for the ρ and ω differential cross section and density matrix were taken from Refs. 7 and 12. The experimental average values $g_{\rho\gamma}^2 = 4.6 \times 10^{-3}$, $g_{\omega\gamma}^2 = 6.6 \times 10^{-4}$ were taken from Ref. 6.

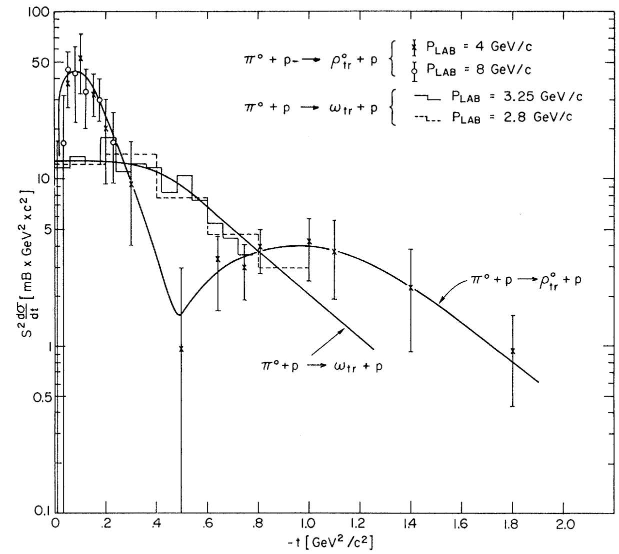

FIG. 2. Cross section $s^2(d\sigma/dt)$ for $\pi^0 p \to \rho_{\rm tr}{}^0 p$ and $\pi^0 p \to \omega_{\rm tr} p$ as determined from (9a) and (9b). The experimental points were taken from Ref. 7. ρ_{00} was taken to be s independent as indicated by the low-energy data. The smooth lines are interpolating lines through the experimental points.

Relation (7b) for π^0 photoproduction cannot be tested because only data on proton targets are available. Predictions for the individual cross sections on proton and neutron targets separately can be made with an additional assumption on the relative phase of the ρ^0 and ω contributions. Assuming the phase suggested by ρ and ω exchange (fixed or moving poles) with relative sign for the couplings as given by SU(6), and again neglecting the φ contribution, we obtain

$$\frac{d\sigma}{dt}(\gamma p \to \pi^0 p) \approx \tfrac{1}{2}\left\{ g_{\rho\gamma}\left[\frac{d\sigma}{dt}(\pi^0 p \to \rho_{\rm tr}{}^0 p)\right]^{1/2} + g_{\omega\gamma}\left[\frac{d\sigma}{dt}(\pi^0 p \to \omega_{\rm tr} p)\right]^{1/2}\right\}^2, \tag{8a}$$

$$\frac{d\sigma}{dt}(\gamma n \to \pi^0 n) \approx \tfrac{1}{2}\left\{ g_{\rho\gamma}\left[\frac{d\sigma}{dt}(\pi^0 p \to \rho_{\rm tr}{}^0 p)\right]^{1/2} - g_{\omega\gamma}\left[\frac{d\sigma}{dt}(\pi^0 p \to \omega_{\rm tr} p)\right]^{1/2}\right\}^2. \tag{8b}$$

Note that the two expressions (8a) and (8b) set upper and lower bounds on these cross sections for an arbitrary choice of phases.

The cross section on the right-hand side of (8) can be determined from measured[9] cross sections for reactions initiated by charged pions by using the isospin relations

$$\frac{d\sigma}{dt}(\pi^0 p \to \rho^0 p) = \frac{1}{2}\left[\frac{d\sigma}{dt}(\pi^- p \to \rho^- p) + \frac{d\sigma}{dt}(\pi^+ p \to \rho^+ p) - \frac{d\sigma}{dt}(\pi^- p \to \rho^0 n)\right], \tag{9a}$$

$$\frac{d\sigma}{dt}(\pi^0 p \to \omega p) = \frac{1}{2}\frac{d\sigma}{dt}(\pi^- p \to \omega n) = \frac{d\sigma}{dt}(\pi^+ n \to \omega p). \tag{9b}$$

Figure 2 presents the experimental results for the vector-meson production reactions. Figure 3 compares the π^0 photoproduction data[10] with predictions (8). The results show good agreement with experi-

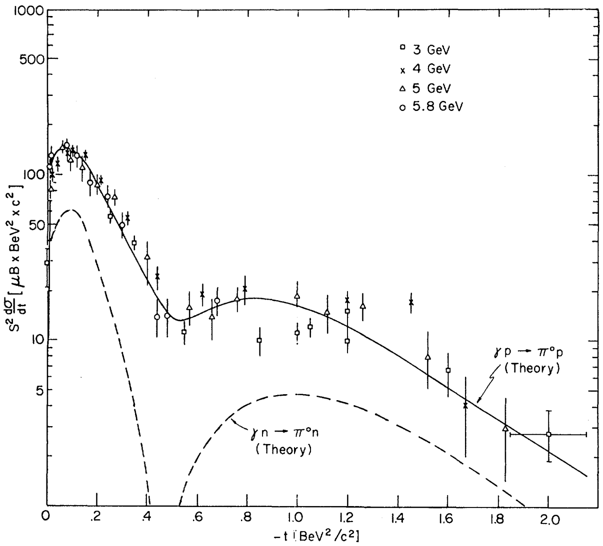

FIG. 3. Comparison between experimental cross sections $s^2(d\sigma/dt)$ of Ref. 10 for π^0 photoproduction and theoretical predictions obtained by substituting into Eq. (8a) the experimental average values $g_{\rho\gamma}{}^2=4.6\times10^{-3}$, $g_{\omega\rho}{}^2=6.6\times10^{-4}$ of Ref. 6 and experimental cross sections (Ref. 9) from curves drawn through the experimental points of Fig. 2.

ment and indicate that the ω contribution, although smaller than that of the ρ, is appreciable. Photoproduction of π^0 on neutrons would be of interest, in particular, the predicted dip around $-t=0.5$ $\{\mathrm{BeV}/c\}^2$.

Another example is Compton scattering. From (2),

$$A(\gamma T\to\gamma T)\approx\sum_{V=\rho,\omega,\varphi} g_{V\gamma}A(\gamma T\to V_{\mathrm{tr}}T). \quad (10)$$

In this case the phases of the amplitudes on the right-hand side of (10) can be measured by their interference with the Bethe-Heitler amplitude. Theoretical models[2] consistent with preliminary data[6] suggest that at high energy these photoproduction amplitudes have the same phase. In this case,

$$\frac{d\sigma}{dt}(\gamma T\to\gamma T)$$
$$\approx\left\{\sum_{V=\rho,\omega,\varphi} g_{V\gamma}\left[\frac{d\sigma}{dt}(\gamma T\to V_{\mathrm{tr}}T)\right]^{1/2}\right\}^2. \quad (11)$$

There are not yet any detailed data on high-energy Compton scattering to allow a significant experimental test of (11).

The importance of model-independent tests of vector dominance is illustrated by the following point. In a particle-exchange picture (fixed or moving pole) one assumes that ρ^0 and ω production in π^0 nucleon collisions are dominated by ω and ρ exchange, respectively. Then Regge theory makes the following predictions: (a) No production of longitudinal vector mesons; $\rho_{00}(t)=0$. (b) Energy variation typical of the exchanged trajectory

$$s^2\frac{d\sigma}{dt}\sim\beta(t)s^{2\alpha(t)};\quad \alpha_\omega\approx\alpha_\rho\approx0.5+t.$$

(c) Forward dip in the differential cross section and a second one around $-t=0.5$ $[\mathrm{BeV}/c]^2$. However, large longitudinal polarizations were observed in ρ and ω production in contradiction with (a); $s^2d\sigma/dt$ for both vector production and photopion production do not show any significant energy variation, in fact it is consistent with a fixed pole at $J=0$ $[\alpha(t)=0]$. Although the differential cross sections (8a) and (9a) show the expected dips,[11] they do not seem to appear in ω production.

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[4]Note that the separation of the isoscalar contribution to (4) would leave two isoscalar vector-meson contributions, those of ω and φ, and leave an additional phase to be determined. Furthermore, in photopion production on nucleons there is only one independent isospin amplitude produced by isoscalar photons, but two independent amplitudes produced by the isovector

photons, namely those corresponding to total isospin $I=\frac{1}{2}$ and $\frac{3}{2}$. It is possible with four measured cross sections to eliminate the three parameters associated with a single isosinglet amplitude, its magnitude and phase. However, one cannot eliminate both isovector amplitudes.

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[12]Additional data on $\pi^-p\to\rho^0n$ were taken from the following: 2.7 GeV/c, D. H. Miller et al., Phys. Rev. 153, 1423 (1967); 3.0 GeV/c, D. R. Clear et al., Nuovo Cimento 49A, 399 (1967); 4.16 GeV/c, R. L. Eisner et al., Phys. Rev. 164, 1699 (1967); 6.0 GeV/c, Brookhaven National Laboratory-City College of the City University of New York Collaboration, private communication from K. Lai through H. J. Lubatti [$\rho_{00}(t)$ was taken from the 8.0-GeV/c data of Poirier et al., Ref. 7]; 11.0 GeV/c, B. D. Hyams et al., to be published. We are grateful to H. J. Lubatti for discussing these experimental data.

FOURTH TEST OF GENERAL RELATIVITY: PRELIMINARY RESULTS

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Several years ago it became evident that a new test of general relativity was technically feasible.[1] The proposed experiment was designed to verify the prediction that the speed of propagation of a light ray decreases as it passes through a region of increasing gravitational potential. For a radar pulse transmitted from the earth and reflected by another planet, the increase in the round-trip time delay, attributable to the predicted gravitational influence of the sun on the propagation, would be ≈200 μsec if the path of the pulse were to graze the solar limb.

An intensive program was therefore undertaken early in 1965 to build a new transmitter and receiver system to provide the Lincoln Laboratory Haystack radar with the capability to measure to within 10 μsec the time delays of pulses traveling between the earth and Mercury or Venus when either planet was on the other side of the sun from the earth—the superior-conjunction alignment. The improved radar was put into operation shortly before the last such conjunction of Venus, which occurred on 9 November 1966. Time-delay measurements were made then and during the subsequent superior conjunctions of Mercury on 18 January, 11 May, and 24 August 1967. The most reliable of these data agree, on average, with the excess-delay predictions of general relativity to well within the experimental uncertainity of ±20%. The remainder of this Letter is devoted to a more detailed discussion of the data analysis and the novel experimental techniques required by the echo signal being sometimes as small as 10^{-21} W, i.e., about 10^{27} times weaker than the transmitted signal power of ≈300 kW.

The techniques are most easily explained by describing the experimental procedure. The ra-