Rev. 112, 568 (1958), and W. L. Faissler, F. M. Pipkin, and K. C. Stanfield, Phys. Rev. Letters 19, 1202 (1967).

[8]Including a 2% correction for bremsstrahlung by the incident or recoil electron elsewhere in the target along the flight path in the spectrometer.

[9]For a discussion of possible modifications of quantum electrodynamics see N. M. Kroll, Nuovo Cimento 45A, 65 (1966). A model which would predict a spectacular deviation from conventional quantum electrodynamics for timelike electrons has been suggested by F. E. Low, Phys. Rev. Letters 14, 238 (1965).

BREAKDOWN OF THE VECTOR DOMINANCE RELATION BETWEEN ρ^0, ω PRODUCTION AND POLARIZED PHOTOPRODUCTION*

L. J. Gutay, F. T. Meiere, J. H. Scharenguivel, D. H. Miller, R. J. Miller, S. Lichtman, and R. B. Willmann
Purdue University, Lafayette, Indiana 47907
(Received 8 January 1969)

The validity of vector-meson dominance is tested by comparing our high statistics ρ^0 and ω production experiments at 2.7 and 4 GeV/c with the results of polarized photopion production experiments. Our results suggest the breakdown of the vector-dominance model even after taking into account the strong S-wave $\pi\pi$ interaction in the ρ^0 region.

It was suggested by Gell-Mann and Zachariasen[1] that the hadronic electromagnetic currents are dominated by the vector mesons ρ, ω, and φ. (Hereafter the vector-meson–dominance assumption will be abbreviated by VMD.) Although this model has a wide range of applicability, we restrict our attention to the study of certain aspects of the reactions

$$\pi^- p \to \pi^+\pi^- n, \tag{1a}$$

$$\pi^+ d \to \pi^+\pi^- p p_s, \tag{1b}$$

$$\pi^+ d \to \pi^+\pi^-\pi^0 p p_s \tag{1c}$$

observed in bubble chambers.[2,3] Our results on Reactions (1) are compared with those of a counter experiment of Geweniger et al.[4] who studied the reactions

$$\gamma n \to \pi^- p, \tag{2a}$$

$$\gamma p \to \pi^+ n, \tag{2b}$$

where the incident photon was linearly polarized. Their results gave the first indication of the breakdown of VMD. Our comparison supports this conclusion.

We have analyzed 4477 events of Reaction (1a) and 3256 events of Reaction (1b) both at 2.7 GeV/c. The production and decay angular distributions of the di-pion system agreed within errors and the data from Reactions (1a) and (1b) were combined and used as a single sample in the following analysis. In addition we analyzed 3348 events of Reaction (1c) at 2.7 GeV/c and 7916 events of Reaction (1a) at 4 GeV/c. The 4-GeV/c data are the result of the Purdue–Notre Dame–Stanford Linear Accelerator Center–Lawrence Radiation Laboratory Collaboration.[3] The density matrix elements for ω production (1c) at 3.65 GeV/c were taken from Benson.[5]

The photoproduction experiment of Geweniger et al.[4] was done with an incident photon energy of 3.4 GeV. Thus the center-of-mass system energy for the photoproduction reactions (2) is bracketed by our data on vector-meson production.

By VMD we mean the assumption that the photoproduction amplitude is related to the amplitude for production of transverse vector mesons by[6]

$$\langle \pi N | T | \gamma N \rangle = \sum g_V \langle \pi N | T | VN \rangle, \tag{3}$$

where g_V are the known photon–vector-meson coupling constants. We keep only the ρ^0 and ω contribution to Eq. (3). The φ contribution is negligible.[7] The $\rho^0\omega$ interference terms are eliminated by considering the following sum of cross sections:

$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt}(\gamma p \to \pi^+ n) + \frac{d\sigma}{dt}(\gamma n \to \pi^- p). \tag{4}$$

The ρ^0 contribution is determined by the differential cross section for the reaction $\pi N \to \pi\pi N$ which is given by[8]

$$\frac{\partial^4\sigma}{\partial s\,\partial\Delta^2\,\partial\cos\theta\,\partial\varphi} = \frac{1}{4\pi}\{R_{00}^{00} + 2R_{11}^{11} + R_{00}^{11} + (R_{00}^{11} - R_{11}^{11})(3\cos^2\theta - 1) - 3\sqrt{2}\,\mathrm{Re}(R_{10}^{11})\sin 2\theta\cos\phi - 3R_{1-1}^{11}\sin^2\theta\cos 2\phi$$
$$- 2\sqrt{6}\,\mathrm{Re}R_{10}^{10}\sin\theta\cos\phi + 2\sqrt{3}R_{00}^{10}\cos\theta\}, \tag{5}$$

where $\sqrt{s}$ denotes the $\pi\pi$ effective mass, Δ^2 the squared four-momentum transfer to the nucleon, and θ, ϕ the polar and azimuthal angles of one of the pions in the helicity frame, respectively. This is the rest frame of the di-pion in which the z axis is antiparallel to the final nucleon and the y axis is normal to the production plane. Analogous results hold for ω production.[2,5]

For photons polarized either perpendicular to the production plane ($\perp$) or parallel to this plane ($\parallel$), VMD predicts

$$A \equiv \frac{d\sigma_\perp/dt - d\sigma_\parallel/dt}{d\sigma_\perp/dt + d\sigma_\parallel/dt}$$

$$= \frac{g_\rho^{\,2}R_{1-1}^{\;\;11}(\rho) + g_\omega^{\,2}R_{1-1}^{\;\;11}(\omega)}{g_\rho^{\,2}R_{11}^{11}(\rho) + g_\omega^{\,2}R_{11}^{11}(\omega)}. \quad (6)$$

It is clear from Eq. (5) that the relevant experimentally determined quantities are $2R_{11}^{11}+R_{00}^{11}+R_{00}^{00}$, $R_{00}^{11}-R_{11}^{11}$, and R_{1-1}^{11}. Thus R_{11}^{11} is not determined directly from experiment without further assumptions. In practice, R_{11}^{11} is determined from $R_{00}^{11}-R_{11}^{11}$ in a model-dependent way and depends upon the S-wave term. These methods are reviewed in detail in Ref. 8. There is a large isotropic term in the $\pi\pi$ angular distribution in the ρ region, and only after rather sophisticated analysis can one separate it into S wave and P wave. After this separation one can show that the S-wave correction to ρ_{11}^{11} is about 10%. We use the density matrix elements usually quoted in pion production,[8] $\rho_{\lambda\lambda'} \equiv R_{\lambda\lambda'}^{\;\;11}/(2R_{11}^{\;\;11}+R_{00}^{\;\;11}+R_{00}^{\;\;00})$. (Note that $\rho_{00}+2\rho_{11}<1$ due to S-wave effects.) Then

$$A = \frac{\rho_{1-1}(\rho) + r\rho_{1-1}(\omega)}{\rho_{11}(\rho) + r\rho_{11}(\omega)}, \quad (7)$$

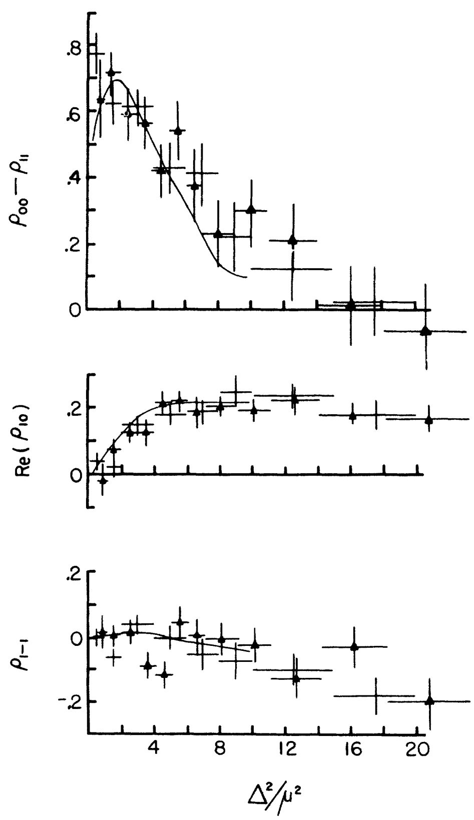

FIG. 1. The density matrix elements in the helicity frame for ρ production normalized to $2\rho_{11}+\rho_{00}+S$ wave $=1$. The triangles represent 2.7 Gev/c and the crosses represent 4.0 GeV/c. The error bars represent 90% confidence levels. The curve is from an absorption model calculation at 4 GeV/c.

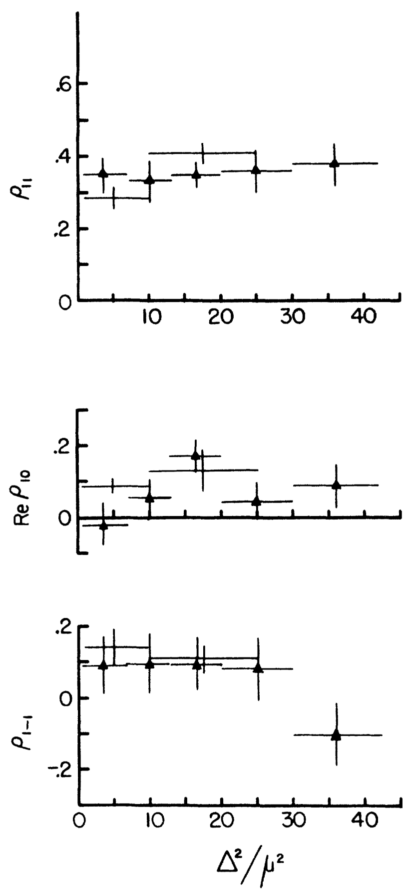

FIG. 2. The density matrix elements in the helicity frame for ω production normalized to $2\rho_{11}+\rho_{00}=1$. The triangles represent 2.7 GeV/c and the crosses represent 3.6 GeV/c. The error bars represent 90% confidence levels.

Table I. Comparison of the photoproduction asymmetry parameter A with the predictions of vector-meson dominance.

t $(\mathrm{GeV}/c)^2$	A_{VMD} (2.7 GeV/c)	A_{exp} (3.4 GeV/c)	A_{VMD} (4 GeV/c)
−0.2	−0.06	+0.62	−0.28
	±0.32	±0.07	±0.34
−0.4	−0.49	+0.43	−0.43
	±0.35	±0.08	±0.37

where

$$r=\frac{g_\omega^{\;2}}{g_\rho^{\;2}}\frac{d\sigma}{dt}(\pi N\rightarrow\omega N)\left[\frac{d\sigma}{dt}(\pi N\rightarrow\rho N)\right]^{-1}.$$

The relevant density matrix elements are plotted on Fig. 1 and Fig. 2 for ρ^0 and ω, respectively. The errors represent 90% confidence levels. The ρ^0 and ω regions were taken as $0.70\ \mathrm{GeV}<\sqrt{s}<0.84$ GeV, respectively. The photon–vector-meson coupling constants can be evaluated from the leptonic (electromagnetic) decay of the vector mesons.[9,10] The ratio r is determined from the differential cross sections for vector-meson production,[2-5] where $g_\omega^{\;2}/g_\rho^{\;2}$ is taken from Ref. 10. The corresponding quantities for φ show that its contribution is negligible. Substituting r and the density matrix elements into Eq. (7) gives the asymmetry A. The results are shown in Table I. The errors of the density matrix elements and of the differential cross section (both at 90% confidence levels) have been propagated to obain the error in A. The ω contributions vary from 2 to 16%. The asymmetry, A, is relatively independent of some of the details of VMD such as g_ρ or the magnitude of $\sigma(\pi N\rightarrow\rho N)$ which enter in the comparisons for unpolarized photons.[6,11] Our results are compared with the photoproduction experiment of Geweniger et al.[4] in Table I and show a clear breakdown of VMD for polarized photopion production.

Geweniger et al.[4] have already come to the same conclusion along essentially the same line of argument. Our analysis which includes the effects of the ω contribution and the S-wave $\pi\pi$ interaction support their conclusion. The VMD in its present form is in sharp disagreement with pion production by polarized photons.

The authors wish to acknowledge discussions with Dr. P. Schmüser concerning the photoproduction data.

---

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

[1]M. Gell-Mann and F. Zachariasen, Phys. Rev. 124, 953 (1961); N. M. Kroll, T. D. Lee, and B. Zumino, Phys. Rev. 157, 1375 (1967); J. J. Sakurai, "Lectures in Theoretical Physics" (to be published).

[2]D. H. Miller, L. J. Gutay, P. B. Johnson, F. J. Loeffler, R. L. McIlwain, R. J. Sprafka, and R. B. Willmann, Phys. 153, 1423 (1967); R. J. Miller, S. Lichtman, and R. B. Willmann, Purdue University Report No. COO-1428-93 (unpublished).

[3]Purdue–Stanford Linear Accelerator Center–Lawrence Radiation Laboratory–Notre Dame Collaboration, to be published.

[4]Chr. Geweniger, P. Heide, U. Kötz, R. A. Lewis, P. Schmüser, H. J. Skronn, H. Wahl, and K. Wegener, Phys. Letters 28B, 155 (1968).

[5]G. C. Benson, thesis, The University of Michigan, 1966 (unpublished).

[6]See, for example, A. Dar, V. F. Weisskopf, C. A. Levinson, and H. J. Lipkin, Phys. Rev. Letters 20, 1261 (1968); M. Krammer and D. Schildknecht, Nucl. Phys. B7, 583 (1968).

[7]O. I. Dahl, L. M. Hardy, R. I. Hess, J. Kirz, and D. H. Miller, Phys. Rev. 163, 1377 (1967).

[8]L. J. Gutay, F. T. Meiere, D. D. Carmony, F. J. Loeffler, and P. L. Csonka, "Lectures in Theoretical Physics" (to be published), and Purdue University Report No. COO-1428-65, Revised (to be published).

[9]S. C. C. Ting, in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968 (CERN Scientific Information Service, Geneva, Switzerland, 1968).

[10]U. Becker, W. K. Bertram, M. Binkley, C. L. Jordan, T. M. Knasel, R. Marshall, D. J. Quinn, M. Rhode, A. J. S. Smith, and S. C. C. Ting, Phys. Rev. Letters 21, 1504 (1968).

[11]R. Diebold and J. A. Poirier, Phys. Rev. Letters 20, 1532 (1968); I. Derado and Z. G. T. Guiragossián, Phys. Rev. Letters 21, 1556 (1968).