

CONSERVATION OF s -CHANNEL HELICITY IN ρ^0 PHOTOPRODUCTION*

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An analysis was made of the decay angular distribution of rho mesons produced via $\gamma p \rightarrow p \rho^0$ by linearly polarized photons at 2.8 and 4.7 GeV. The reaction proceeds almost completely through natural-parity exchange, the contribution from unnatural-parity exchange for momentum transfers $|t| < 1 \text{ GeV}^2$ being $(3.1 \pm 2.2) \%$ at 2.8 GeV and $(-1.1 \pm 1.9) \%$ at 4.7 GeV. The behavior of the density-matrix elements shows that the rho-production mechanism conserves s -channel c.m. system helicity for $|t| < 0.4 \text{ GeV}^2$.

Previous studies of ρ^0 production via $\gamma p \rightarrow p \rho^0$ have shown that the cross section is essentially constant above 2 GeV, a characteristic of diffractive processes, and that the transverse part of ρ^0 production is dominated by natural-parity exchange¹⁻⁵; also it has been indicated that s -channel c.m. system helicity is conserved.² In this paper we establish that ρ^0 production is dominated by natural-parity exchange and that it conserves s -channel c.m. system helicity for $|t| < 0.4 \text{ GeV}^2$.

We studied rho production with linearly polarized photons by exposing the 82-in. hydrogen bubble chamber at the Stanford Linear Accelerator Center (SLAC) to the monochromatic Compton backscattered photon beam at 2.8 and 4.7 GeV. From 2854 events at 2.8 GeV and 2910 events at 4.7 GeV of the reaction



a sample of ~4000 ρ^0 events was obtained. Experimental details, mass distributions, a discussion of the ρ^0 mass shift, and ρ^0 -production cross sections for Reaction (1) are given elsewhere.⁶

In this paper we report the results from the study of the ρ^0 decay angular distribution. The analysis used the formalism of Schilling, Seyboth, and Wolf.⁷ We present the results in three reference systems which differ in the choice of the spin quantization axis (z axis): the Gottfried-Jackson system, where the z axis is chosen as the direction of the incident photon in the ρ^0 rest system; the helicity system where the z axis is opposite to the direction of the outgoing proton in the ρ^0 rest system; and the Adair system, where the z axis is along the direction of the incident photon in the overall c.m. system. The y axis is always normal to the production plane. For forward produced ρ^0 mesons, all three systems coincide.

We define the following angles⁸: Φ is the angle of the photon electric polarization vector with respect to the production plane and is the same in the total c.m. system and the ρ^0 rest system; θ and φ are the polar and azimuthal angles of the π^+ in the ρ^0 rest system. The decay angular distribution for rho mesons produced by linearly polarized photons can be expressed in terms of nine independent, measurable, spin-density matrix parameters $\rho_I^{\alpha 7\theta}$:

$$\begin{aligned} W(\cos\theta, \varphi, \Phi) = & (3/4\pi) \left\{ \frac{1}{2}(1 - \rho_{00}^0) + \frac{1}{2}(3\rho_{00}^0 - 1) \cos^2\theta - \sqrt{2} \text{Re}\rho_{10}^0 \sin 2\theta \cos\varphi - \rho_{1-1}^0 \sin^2\theta \cos^2\varphi \right. \\ & - P_\gamma \cos 2\Phi [\rho_{11}^1 \sin^2\theta + \rho_{00}^1 \cos^2\theta - \sqrt{2} \text{Re}\rho_{10}^1 \sin 2\theta \cos\varphi - \rho_{1-1}^1 \sin^2\theta \cos 2\varphi] \\ & \left. - P_\gamma \sin 2\Phi [\sqrt{2} \text{Im}\rho_{10}^2 \sin 2\theta \sin\varphi + \text{Im}\rho_{1-1}^2 \sin^2\theta \sin 2\varphi] \right\}. \quad (2) \end{aligned}$$

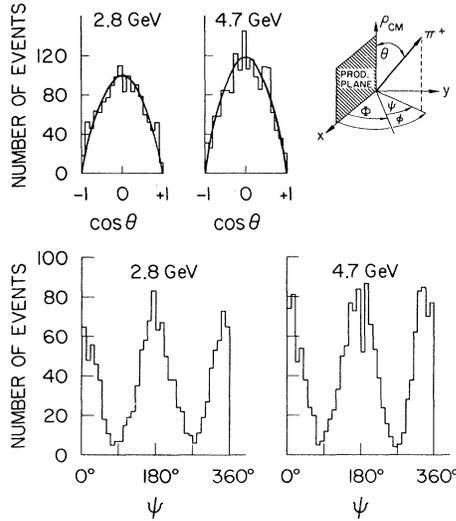


FIG. 1. Reaction $\gamma p \rightarrow p\rho^0$. Rho-decay angular distributions in the helicity system for $|t| < 0.4 \text{ GeV}^2$ and $0.6 < M_{\pi\pi} < 0.85 \text{ GeV}$ without background subtraction. The curves for the $\cos\theta$ distributions are proportional to $\sin^2\theta$.

Here, P_γ is the degree of linear polarization of the photon, which is calculated from the Compton scattering process to be 94% at 2.8 GeV and 92% at 4.7 GeV. The matrix elements ρ_{ik}^0 describe the rho decay in the case of an unpolarized beam; the additional terms ρ_{ik}^1 and ρ_{ik}^2 result from the linear polarization of the photon.

Matters are simplified if we use the angle $\psi = \varphi - \Phi$, which in the forward direction is the angle between the photon-polarization and ρ^0 -decay planes. If the rho is transverse and linearly polarized like the photon then in the helicity system, $\rho_{1-1}^1 = -\text{Im}\rho_{1-1}^2 = \frac{1}{2}$ and all other ρ_{ik}^α in Eq. (2) are zero. In this case the decay angular distribution is proportional to $\sin^2\theta \cos^2\psi$. Note that under these conditions ψ becomes the azimuthal angle of the decay π^+ with respect to the rho-polarization plane.

Figure 1 shows the distributions of the angle θ and the angle ψ in the helicity system for events in the rho mass region with $|t| < 0.4 \text{ GeV}^2$ where t is the square of the four-momentum transfer between incoming and outgoing proton. The $\cos\theta$ distributions are proportional to $\sin^2\theta$, i.e., the rho mesons are produced in Reaction (1) with c.m. system helicity ± 1 . The ψ distributions are $\sim \cos^2\psi$ and show that the rho is almost completely linearly polarized.

The matrices ρ_{ik}^0 , ρ_{ik}^1 , and ρ_{ik}^2 can be used to examine the production mechanism; for ex-

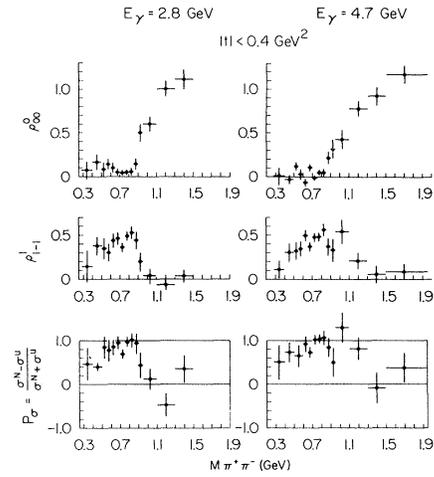


FIG. 2. Reaction $\gamma p \rightarrow p\pi^+\pi^-$. The density-matrix elements ρ_{00}^0 and ρ_{1-1}^1 and the parity asymmetry P_σ as a function of $M_{\pi\pi}$.

ample, the contributions σ^N , σ^U from natural-parity [$P = (-1)^J$] and unnatural-parity [$P = -(-1)^J$] exchanges in the t channel can be obtained by measuring

$$P_\sigma = (\sigma^N - \sigma^U) / (\sigma^N + \sigma^U), \quad (3)$$

which to leading order in energy is given by

$$P_\sigma = 2\rho_{1-1}^1 - \rho_{00}^1. \quad (4)$$

The expression (4) for P_σ is an invariant under rotations around the normal to the production plane.

We studied the influence of possible background by determining the ρ_{ik}^α as a function of the $\pi^+\pi^-$ mass, $M_{\pi\pi}$, with the method of moments using all events in a given $\pi^+\pi^-$ mass interval. Figure 2 shows the $M_{\pi\pi}$ dependence of ρ_{00}^0 and ρ_{1-1}^1 in the helicity system and that of P_σ . There is a pronounced difference between their values inside and outside of the rho region. The values $\rho_{00}^0 \cong 0$, $\rho_{1-1}^1 \cong 0.5$, and $P_\sigma \cong 1$ in the rho region are clearly associated with the production of the rho.

We took the background contribution into account by determining the rho density-matrix parameters through a maximum likelihood fit including ρ^0 , Δ^{++} , and phase space contributions.¹⁰ This method was checked by evaluating the ρ_{ik}^α inside and outside of the rho region and interpolating the contribution from the background. Within errors, the same result was obtained. Even if all events in the mass region $0.60 < M_{\pi\pi} < 0.85 \text{ GeV}$ are used without background subtraction, the values of the ρ_{ik}^α do not change by

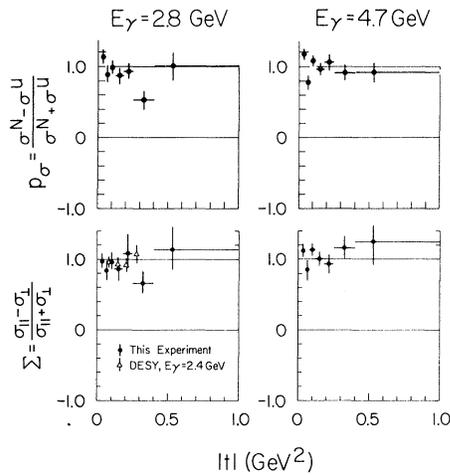


FIG. 3. Reaction $\gamma p \rightarrow p\rho^0$. The parity asymmetry P_σ and the asymmetry Σ as a function of t in the Gottfried-Jackson, helicity, and Adair systems.

more than one standard deviation.¹¹ We conclude that the rho density-matrix parameters are insensitive to the assumed form of the background.

In Fig. 3, P_σ is shown as a function of t . We see that rho production is completely dominated by natural parity exchange up to $|t| = 1$ GeV². Averaging P_σ over the range $|t| \leq 1$ GeV² we find the contribution from unnatural-parity exchange to be $(3.1 \pm 2.2)\%$ at 2.8 GeV and $(-1.1 \pm 1.9)\%$ at 4.7 GeV.

In Fig. 3 we also display the quantity Σ defined as⁷

$$\Sigma = \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}} = \frac{\rho_{11}^1 + \rho_{1-1}^1}{\rho_{11}^0 + \rho_{1-1}^0}, \quad (5)$$

which has been measured in counter experiments. Here σ_{\parallel} and σ_{\perp} are the cross sections for the pions from symmetric rho decay to emerge in the plane of the photon polarization and perpendicular to it ($\theta = \pi/2$, $\varphi = \pi/2$, $\Phi = 0$, and $\pi/2$). Our values of Σ at 2.8 GeV are in agreement with measurements at 2.4 GeV made at DESY.^{5,12}

Finally, Fig. 4 shows the density-matrix parameters themselves, evaluated in the Gottfried-Jackson, helicity, and Adair systems as a function of t at 4.7 GeV. The matrix parameters at 2.8 GeV show approximately the same behavior. We note that the density-matrix elements can be expressed in terms of bilinear combinations of helicity or spin amplitudes and that, for example, ρ_{00}^0 and ρ_{00}^1 receive only contributions from helicity-flip or spin-flip amplitudes.

We conclude the following from the behavior of the ρ_{ik}^α :

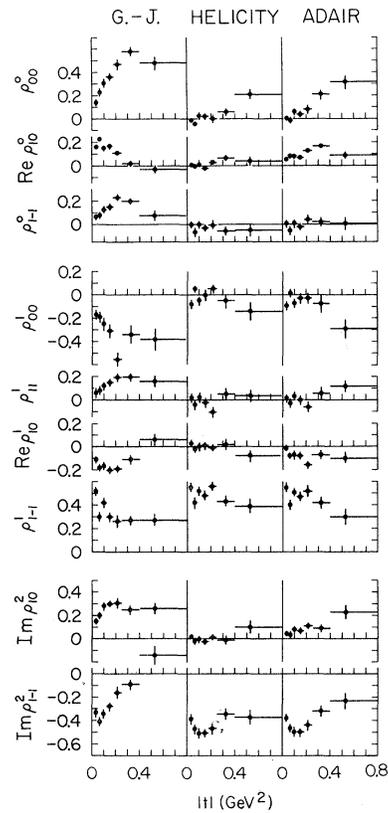


FIG. 4. Reaction $\gamma p \rightarrow p\rho^0$ at 4.7 GeV. The spin-density matrix parameters as a function of t in the Gottfried-Jackson, helicity, and Adair systems.

(1) The density matrix parameters vary rapidly in the Gottfried-Jackson system.^{1,13} The t -channel helicity-flip amplitudes increase rapidly with increasing $|t|$. This behavior rules out t -channel helicity conservation and also excludes a zero-spin particle exchange without absorption as the only contributor to rho production.

(2) The ρ_{ik}^α in the Adair system also vary significantly with t . This excludes² the hypothesis of spin independence in the total c.m. system for rho production.¹³

(3) In the helicity system the helicity-flip contributions are zero within errors up to $|t| = 0.4$ GeV², i.e., the rho behaves like a photon with the spin aligned along its direction of motion. In other words, the rho-production mechanism conserves s -channel c.m. system helicity. The fact that the flip contributions are minimum in the helicity system is further demonstrated in Fig. 5. The rho density matrix as calculated in the helicity frame was rotated by an angle β around the production normal and a least-squares fit made to find that value of β for which the flip terms

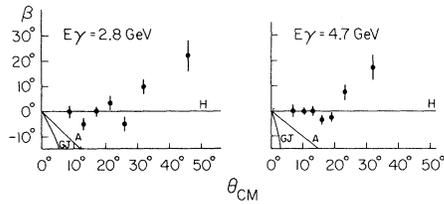


FIG. 5. Reaction $\gamma p \rightarrow p\rho^0$. The angle β for rotation into the "minimum flip" system as a function of the c.m. system rho-production angle $\theta_{c.m.}$. For the curves labeled G. J., A, and H, see text.

become minimal, i.e., for which the rho density matrix is closest to that of the photon (see above). Figure 5 shows β as a function of the rho c.m. system production angle $\theta_{c.m.}$, together with lines indicating where the data points should fall if the flip terms were minimal in the Gottfried-Jackson (G.J.), helicity (H), or Adair system (A), respectively. For $\theta_{c.m.} \lesssim 25^\circ$, the helicity system is clearly preferred.

In summary, rho photoproduction via $\gamma p \rightarrow p\rho^0$ proceeds almost completely through natural-parity exchange and conserves helicity in the s-channel c.m. system up to $|t| = 0.4 \text{ GeV}^2$. We remark that these features may be general characteristics of diffraction scattering.¹⁴

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[See also the data of these authors as quoted by E. Lohrmann, in *Proceedings of the Lund International Conference on Elementary Particles Held at Lund, Sweden, 25 June-1 July 1969* (Berlingska Bortryckeriet, Lund, Sweden, 1970), p. 11, and DESY Report No. 69-21 (1969).]

⁶H. H. Bingham *et al.*, preceding Letter [Phys. Rev. Letters **24**, 959 (1970)].

⁷K. Schilling, P. Seyboth, and G. Wolf, Stanford Linear Accelerator Center Report No. SLAC-PUB-683 (to be published).

⁸The y axis is the normal to the production plane, defined by the cross product $\hat{k} \times \hat{p}$ of the directions of the photon and the vector meson. The x axis is given by $\hat{x} = \hat{y} \times \hat{z}$. The angle Φ between the electric vector of the photon, ϵ , and the production plane in the total c.m. system is defined by $\cos \Phi = \hat{k} \cdot (\hat{\epsilon} \times \hat{y})$, $\sin \Phi = \hat{y} \cdot \hat{\epsilon}$. The decay angles θ , φ are the polar and azimuthal angles of the direction of flight of the π^+ in the ρ rest system:

$$\cos \theta = \hat{\pi} \cdot \hat{z}, \quad \cos \varphi = \hat{y} \cdot (\hat{z} \times \hat{\pi}) / |\hat{z} \times \hat{\pi}|,$$

$$\sin \varphi = -\hat{x} \cdot (\hat{z} \times \hat{\pi}) / |\hat{z} \times \hat{\pi}|.$$

⁹R. L. Thews, Phys. Rev. **175**, 1749 (1968).

¹⁰The following Dalitz-plot density distribution has been used:

$$\frac{a_\rho}{N_\rho} B_\rho W(\cos \theta, \varphi, \Phi) + \frac{a_\Delta}{N_\Delta} B_\Delta + \frac{a_{\rho s}}{N_{\rho s}} B_{\rho s}.$$

a_ρ , a_Δ , and $a_{\rho s}$ are the fractions of ρ^0 , $\Delta^{++}(1236)$, and phase-space-distributed events in each t interval; B_ρ is a p -wave Breit-Wigner distribution for the ρ^0 multiplied by a factor $(m_\rho/M_{\pi\pi})^4$ (see Ref. 2 for discussion); B_Δ is a p -wave Breit-Wigner distribution for the $\Delta^{++}(1236)$; $B_{\rho s} = \text{const}$ is the Lorentz-invariant phase-space distribution; N_ρ , N_Δ , and $N_{\rho s}$ are normalization factors. In these fits the values of the ρ_{IK}^α were not constrained. Consequently P_σ and Σ may be greater than unity.

¹¹A further check on the influence of the background on the values of the ρ_{IK}^α were made by using the Söding model, which has been found to describe ρ^0 production (Ref. 6). We have evaluated the Söding model assuming for the ρ^0 production the values obtained from the maximum likelihood fit for the density matrix parameters. An analysis of the resulting $\pi^+\pi^-$ angular distributions shows that the Drell term has no significant influence on the decay angular distribution of the rho.

¹² Σ has also been measured by Diambri-Palazzi *et al.*, as quoted in Ref. 4.

¹³This assumption was made in the "strong absorption model," Y. Eisenberg, *et al.*, Phys. Letters **22**, 217, 223 (1966); see also G. Kramer, DESY Report No. 67/32, 1967 (unpublished).

¹⁴See also F. J. Gilman, J. Pumplin, A. Schwimmer, and L. Stodolsky, Stanford Linear Accelerator Center, Report No. SLAC-PUB-719, 1970 (to be published).