REACTION $\gamma p \to p\rho^0$ WITH LINEARLY POLARIZED PHOTONS AT 2.8 and 4.7 GeV: CROSS SECTIONS AND THE ρ^0 MASS SHIFT*

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Rho photoproduction is studied at 2.8 and 4.7 GeV using a linearly polarized photon beam in a hydrogen bubble chamber. The dependence of the ρ^0 mass shape on the momentum transfer is inconsistent with the Ross-Stodolsky factor. The production of $\pi^+\pi^-$ pairs in the s-channel c.m. helicity-conserving p-wave state accounts for almost all events in the ρ region. Evidence is presented for an interference of ρ^0 production with background. The data are compared with the Söding model and total and differential cross sections for ρ^0 production are presented.

Previous studies of ρ^0 photoproduction in the reaction

$$\gamma p \to p\pi^+\pi^- \tag{1}$$

have shown that the rho shape is skewed with respect to a p-wave Breit-Wigner resonance, resulting in an apparent mass shift of the order of 40 MeV.[1,2] These observations have necessitated the use of models to fit the data, and because no model has been preferred experimentally, the ρ^0-production cross section has been uncertain to ~20%. We present model-independent cross sections for production of $\pi^+\pi^-$ pairs from Reaction (1) in the s-channel c.m. helicity-conserving p-wave state which dominates in the ρ region.[3] We also determined the ρ^0-production cross sections using the Söding model,[4] which was found to agree with the data.

The results published here are part of a detailed study of photoproduction with a bubble chamber using a linearly polarized photon beam. We obtained 90 ± 4 and 149 ± 6 events/μb at 2.8 and 4.7 GeV, respectively. Measurements of the total γp cross section at 1.4, 2.8, and 4.7 GeV have already been reported[5]; the analysis of the ρ^0 decay distributions and results on ω and Δ^{++} production are given elsewhere.[3]

I. Experimental setup. – The 82-in. hydrogen bubble chamber at the Stanford Linear Accelerator Center (SLAC) was exposed to a photon beam obtained by Compton backscattering a linearly polarized ruby-laser beam on high-energy electrons. By collimating both the electron and the backscattered photon beam to less than 10^{-5} rad, the width at half-maximum of the photon energy spectrum is ±2.6 and ±3.3% at 2.8 and 4.7 GeV, respectively. The average degree of linear polarization as calculated for the Compton scattering process is 94 and 92%, respectively. Most of the film was taken with 70 to 80 photons per picture. More details of the beam can be found elsewhere.[5,6]

II. Analysis of the film. – Approximately 292 000 and 454 000 photographs were taken, resulting in a total of 11 000 and 19 000 events at 2.8 and 4.7 GeV, respectively. All pictures were double scanned and the combined scanning efficiency was found to be greater than 99% for all topologies. Half the film was measured on conventional measuring machines at SLAC and half at Lawrence Radiation Laboratory (LRL) (the last two-thirds at LRL were processed by the Spiral Reader II). The events were analyzed using the programs TVGP and SQUAW. After three measurement passes, less than 2% of the three-prong events remained to be measured. The fraction of three-prong events which could not be measured due to secondary scatters or track obscuration was 5%. The calculated effective-mass error for $\pi\pi$ pairs of Reaction (1) near the ρ mass was ±5 MeV. There were 2854 and 2910 events at 2.8 and 4.7 GeV, respectively, which gave a

Table I. Total cross sections for $\gamma p \to p\pi^+\pi^-$; total and forward differential cross sections and slope A for production of $\pi^+\pi^-$ pairs in the s-channel c.m. helicity-conserving p-wave state (Π) and for ρ^0 production as determined from fits with the Söding model.

		Helicity-conserving p wave (Π)			ρ^0 production		
E_γ (GeV)	$\sigma(\gamma p \to p\pi^+\pi^-)$ (μb)	σ (μb)	$d\sigma/dt$ ($t=0$) (μb/GeV^2)	A (GeV^{-2})	σ (μb)	$d\sigma/dt$ ($t=0$) (μb/GeV^2)	A (GeV^{-2})
2.8	31.4 ± 1.3	18.9 ± 1.1	144 ± 13	7.5 ± 0.6	16.4 ± 1.0	93 ± 7	5.4 ± 0.4
4.7	20.2 ± 0.8	13.5 ± 1.0	102 ± 8	7.2 ± 0.5	14.4 ± 0.7	80 ± 5	5.5 ± 0.3

three-constraint fit to Reaction (1) consistent with the observed ionization and with a fitted photon energy in the interval $2.4 < E_\gamma < 3.3$ GeV or $4.1 < E_\gamma < 5.3$ GeV. The effects of possible contamination by wide-angle electron-positron pair production and scanning losses of events with a short proton recoil track were estimated. The corrections were found to be negligible for events with $|t| > 0.02$ GeV^2 (t is the square of the four-momentum transfer between incoming and outgoing proton) and, consequently, for all further studies, only events with $|t| > 0.02$ GeV^2 were considered.

III. Results.—The corrected total cross sections for Reaction (1) are given in Table I and agree with other experiments.[2] Figure 1 shows the $\pi^+\pi^-$ mass distributions for various t intervals. The dominant feature is ρ^0 production; $\Delta^{++}(1236)$ production, which is also present in Reaction (1), is discussed elsewhere.[3] We have

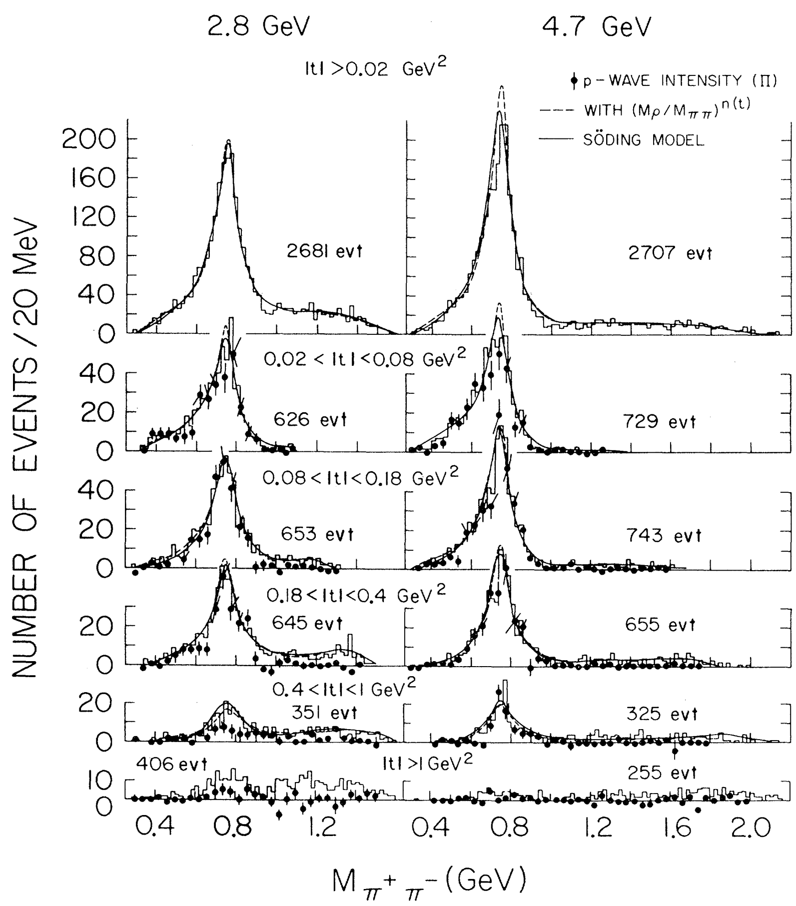

FIG. 1. $\pi^+\pi^-$ mass distributions for events of the reaction $\gamma p \to p\pi^+\pi^-$. The helicity-conserving p-wave intensity Π (see text) is shown by the closed circles. The curves give the results of a maximum-likelihood fit using for the ρ^0 the parametrization $(M_\rho/M_{\pi\pi})^{n(t)}$ (the dashed line) and the Söding model (the solid line).

looked in the $\pi^+\pi^-$ mass distributions for the production of higher mass mesons, in particular the vector mesons ρ' and ρ'' with masses of ~1.3 and ~1.7 GeV predicted by the Veneziano model.[7] The upper limits (1 standard deviation) on their production cross sections at 4.7 GeV are 0.5 and 0.4 μb, respectively, assuming for both ρ' and ρ'' a width of 200 MeV and decay into $\pi^+\pi^-$ only. These upper limits agree with other experiments[8] but are still consistent with a recent Veneziano-model calculation.[9]

In order to test the Ross-Stodolsky factor[10] we have multiplied the p-wave Breit-Wigner factor for the ρ by a factor of $(M_\rho/M_{\pi\pi})^{n(t)}$. Maximum-likelihood fits have been made to the events of Reaction (1) allowing for ρ^0 and $\Delta^{++}(1236)$ production and a phase-space term,[11] and fitting these contributions together with the parameter $n(t)$ as a function of t. The fits describe the $\pi^+\pi^-$ mass spectra well, as shown by the dashed curves in Fig. 1. The fitted values for $n(t)$ are shown in Figs. 2(c) and 2(d). In contrast to the prediction of Ross and Stodolsky, namely $n(t=0) = 4$, the parameter n is ~5 near $t=0$; it drops to

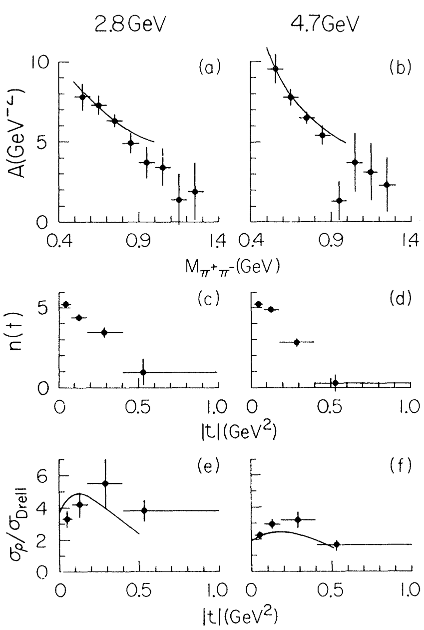

FIG. 2. Reaction $\gamma p \to p\pi^+\pi^-$: (a), (b) The exponential slope of the t distribution as a function of the $\pi^+\pi^-$ mass, taking all events in a given $\pi^+\pi^-$ mass bin and with $0.02 < |t| < 0.4$ GeV^2. The curves show the result of the Söding model. (c), (d) Fitted values for $n(t)$ using the parametrization $(M_\rho/M_{\pi\pi})^{n(t)}$. (e), (f) Ratio of the fitted ρ^0 production to Drell cross sections, $\sigma_\rho(t)/\sigma_D(t)$. The curves show the predictions of the Söding model.

zero around $|t| = 0.5$ GeV^2.

The analysis of the ρ^0 decay in this experiment has shown[3] that, for $|t| < 0.4$ GeV^2, the ρ^0-decay angular distribution is

$$W(\theta,\psi) = (3/8\pi)\{\sin^2\theta + P_\gamma \sin^2\theta \cos 2\psi\}. \quad (2)$$

Here θ is the polar angle of the decay π^+; ψ is the polarization angle defined as $\psi = \varphi - \Phi$, where φ is the azimuthal angle of the π^+ with respect to the production plane; Φ is the angle between the photon electric vector and the production plane; and P_γ is the degree of linear polarization of the photon. All angles are calculated in the $\pi^+\pi^-$ helicity system. Equation (2) can be expressed in terms of the moments $Y_0^0(\theta,\psi)$, $Y_2^0(\theta,\psi)$, and $\mathrm{Re}Y_2^2(\theta,\psi)$. Because of its ψ dependence, $\mathrm{Re}Y_2^2(\theta,\psi)$ is the least affected by background and therefore has been used to determine the intensity of the s-channel c.m. helicity-conserving p-wave $\pi\pi$ contribution, Π:

$$\Pi = \frac{1}{P_\gamma}\left(\frac{40\pi}{3}\right)^{1/2} \sum \mathrm{Re}Y_2^2, \quad (3)$$

where the summation is over all events. The dots marked on the histograms of Fig. 1 show Π as a function of $M_{\pi\pi}$ for different t intervals. We notice that (a) in the ρ region, Π accounts for almost all events and shows the same skewing as the mass distributions; (b) above $M_{\pi\pi} = 1$ GeV, Π is zero within errors, again emphasizing the absence of higher vector mesons; this also shows that the background which is present above 1 GeV does not contribute to $\mathrm{Re}Y_2^2$. The total helicity-conserving p-wave cross section (corrected for the interval $|t| < 0.02$ GeV^2) is given in Table I.

Further analysis of the $\pi\pi$ angular distribution was made by studying the $M_{\pi\pi}$ dependence of other moments $Y_L^M(\theta,\psi)$. In Fig. 3 we show the moments Y_2^0 and Y_4^0 at 4.7 GeV. The moment Y_2^0 shows the behavior expected for the $\sin^2\theta$ decay of the ρ^0. The positive values of Y_2^0 above 1 GeV are due to the Δ^{++} reflection. The moment Y_4^0 shows a distinctive interference pattern in the ρ region which can be interpreted as an interference between the ρ^0 and a $\pi^+\pi^-$ state of spin $J \geq 3$.[12]

In view of the observed interference effect we compared our data with the model of Söding,[4,13] which explains the ρ-mass shift in terms of an interference between the ρ^0 production and a Drell-type background amplitude.[14] The solid lines shown in Figs. 1-3 were calculated from the Söding model after fitting the ratio of the total ρ^0 and Drell cross sections, σ_ρ/σ_D, and al-

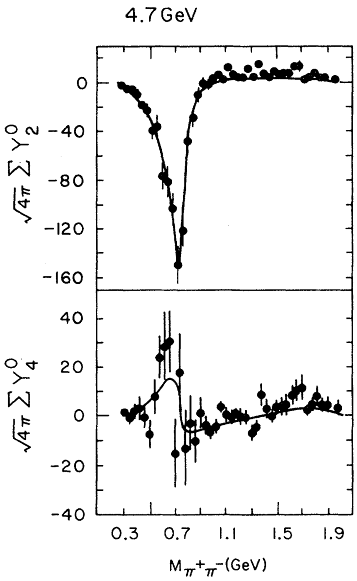

FIG. 3. Reaction $\gamma p \rightarrow p\pi^+\pi^-$: The moments $Y_2^0(\theta,\psi)$ and $Y_4^0(\theta,\psi)$ in the helicity frame as a function of $M_{\pi\pi}$ for $0.02<|t|<0.4$ GeV^2. The curves show the results of the Söding model.

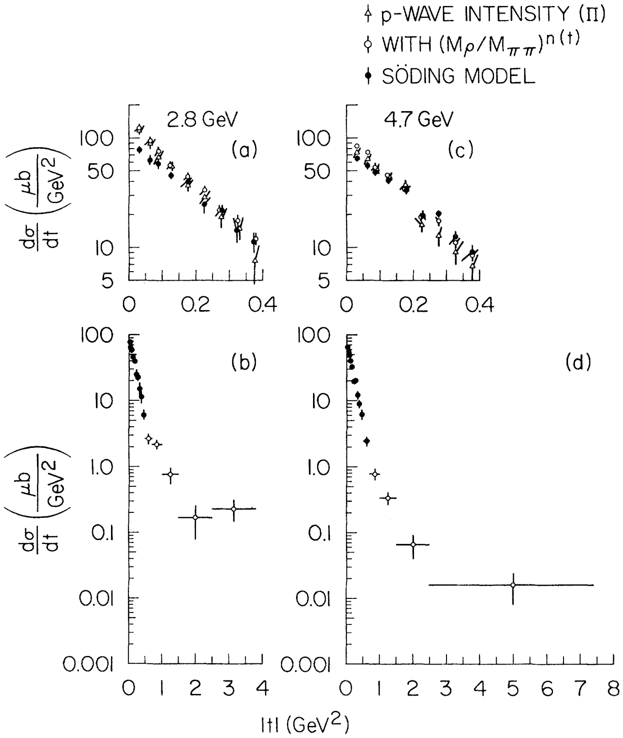

FIG. 4. Reaction $\gamma p \rightarrow p\pi^+\pi^-$: Differential cross sections as a function of t for the helicity-conserving p-wave contribution Π (open triangles), and for ρ^0 production as obtained from fits with the Söding model (closed circles) and using the parametrization $(M_\rho/M_{\pi\pi})^{n(t)}$ (open circles).

lowing for Δ^{++} production and an additional background term. At 2.8 GeV the Drell term did not include a Δ^{++} contribution. The fitted values of σ_ρ/σ_D are shown in Figs. 2(e) and 2(f) as a function of t. The Söding model describes the t dependence of the $\pi^+\pi^-$ mass distributions and of σ_ρ/σ_D and, consequently, the related dependence of the exponential slope of the t distribution on the $\pi^+\pi^-$ mass[2,15] [see Figs. 2(a) and 2(b)]. The shape of the interference pattern observed for Y_4^0 is also correctly predicted (see Fig. 3). The total ρ^0-production cross sections obtained by fitting the Söding model to our data (and correcting for the interval $|t|<0.02$ GeV^2) are given in Table I.

In Fig. 4 we show the differential cross sections obtained from fits with the Söding model, those for Π, and also those resulting from the parametrization $(M_\rho/M_{\pi\pi})^{n(t)}$. Fitting the differential cross section values for $|t|<0.4$ GeV^2 with the form $d\sigma/dt=(d\sigma/dt)_{t=0}\exp(At)$, we obtain $(d\sigma/dt)_{t=0}$ and A as given in Table I. We remark that for $|t|<0.4$ GeV^2 the differential cross sections and the slopes obtained for $\Pi(t)$ and for the ρ^0 cross sections fitted with the parametrization $(M_\rho/M_{\pi\pi})^{n(t)}$ or with the Ross-Stodolsky factor agree within errors. The ρ^0 cross sections obtained from fitting the Söding model lead to smaller values for the forward differential cross section (by ~25%) and for the slope.

The forward ρ^0 cross sections obtained from fitting the Söding model are about 60 μb/GeV^2 smaller at both energies than the values quoted by the DESY-Massachusetts Institute of Technology group,[16] who used an interference model which is different from that of Söding.

IV. Conclusions.—The production of $\pi^+\pi^-$ pairs in the s-channel c.m. helicity-conserving p-wave state, determined in a model-independent way, accounts for almost all events in the ρ region and shows the same skewing as the $\pi^+\pi^-$ mass distributions. We have observed a variation of the ρ mass shape as a function of t, a variation of the exponential slope of the t distribution with $M_{\pi\pi}$, and an interference of the ρ^0 amplitude with background. These features are inconsistent with a model using only the Ross-Stodolsky factor to explain the ρ^0 mass shift, but are well described by the interference model of Söding. Since it is necessary to use a model to determine the ρ^0 differential cross section, we emphasize that an uncertainty is introduced which is much larger than our experimental errors.

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[11]For the density distribution on the Dalitz plot we use formula (A1) of Ref. 2 with the addition of the factors $\exp(7t)$ and $\exp(7.1t_\Delta)$ (t_Δ = square of four-momentum transfer between incoming proton and outgoing Δ^{++}) which multiply the ρ and Δ^{++} Breit-Wigner terms.

[12]At 2.8 GeV the moment Y_4^0 does not show a statistically significant interference effect. This is probably due to the large Δ^{++} production, which plays only a minor role at 4.7 GeV.

[13]The predictions of the Söding model have been calculated using a Monte Carlo program written by P. Söding. The formulas employed differ from those given in Ref. 4 in the following points: The pion-nucleon scattering is calculated from the phase shift data keeping only the spin-nonflip term (within errors the same ρ^0 cross sections are obtained when the extreme assumption is made that the πN elastic-scattering amplitude, A, is completely imaginary, i.e., $A = i|A|$); the rho amplitude is assumed to be helicity conserving in the s-channel c.m. system. The ρ mass, M_ρ, and width, Γ_ρ, used in the determination of the differential cross sections were obtained from fits to the events in the interval $0.02 < |t| < 0.5$ GeV^2. The resulting values were $M_\rho = 765 \pm 3$ MeV (760 ± 3 MeV) and $\Gamma_\rho = 132 \pm 6$ MeV (141 ± 5 MeV) at 2.8 GeV (4.7 GeV). We note that there are theoretical difficulties with the Söding model, namely, gauge invariance, uncertainties in the off-mass shell corrections, and neglect of a possible real part of the ρ^0 production amplitude. Double-counting corrections as proposed by D. R. Yennie and by J. Pumplin (private communications) lead to ρ^0 forward differential cross sections of 101 ± 7 and 90 ± 6 μb/GeV^2 and to slopes of 5.6 ± 0.3 and 5.8 ± 0.3 GeV^{-2} at 2.8 and 4.7 GeV, respectively.

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