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A STUDY OF THE CHANNEL $\gamma p \rightarrow p^+ \pi^-$ USING A LINEARLY
POLARIZED PHOTON BEAM OF ENERGY 9.3 GeV*

MASTER

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ABSTRACT

We present an analysis of ρ^0 and Δ^{++} production in the channel $\gamma p \rightarrow p^+ \pi^-$. Using the Söding model we obtain a ρ^0 cross section of $13.1 \pm 0.5 \mu\text{b}$ and a forward differential cross section of $83 \pm 8 \mu\text{b/GeV}^2$. The Δ^{++} cross section is $0.3 \pm 0.06 \mu\text{b}$. The parity asymmetry of the ρ is found to be 1.0 ± 0.09 indicating dominant natural parity exchange. A study of the ρ^0 decay distribution shows that ρ^0 production is consistent with s-channel helicity conservation at the γp vertex for

$$|t| < 0.8 \text{ GeV}^2.$$

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We report the results of the analysis of an exposure of the SLAC 82" hydrogen bubble chamber to a 9.3 GeV linearly polarized photon beam. We have analyzed 650,000 pictures (representing half our total exposure) yielding 138 ev/ μb in the energy interval $8 < E_\gamma < 10.3$ GeV. We present results on the channel $\gamma p \rightarrow p\pi^+\pi^-$ and compare them with our previous results at 2.8 and 4.7 GeV.^{1,2,3,4}

General characteristics of the reaction $\gamma p \rightarrow p\pi^+\pi^-$

In Fig. 1 we show the $\pi^+\pi^-$, $p\pi^+$ and $p\pi^-$ mass spectra⁵ for the channel $\gamma p \rightarrow p\pi^+\pi^-$. The channel is dominated by ρ^0 production and some Δ^{++} production also occurs. The channel cross section and the cross section for Δ^{++} production are $14.1 \pm 0.7 \mu\text{b}$ and $0.3 \pm 0.06 \mu\text{b}$, respectively. We find no evidence for higher mass vector mesons⁶; the upper limits (1 standard deviation) for production of the ρ' (ρ'') of mass 1.3 (1.7) GeV is 0.45 (0.2) μb for an assumed width of 200 MeV and a branching ratio of unity to $\pi\pi$.

We now discuss the general characteristics of the dipion system. The change in shape of the ρ^0 as a function of momentum transfer squared can be parameterized, as in our previous work, by the form Breit-Wigner $\times (M_p/M_{\pi\pi})^{n(t)}$.⁷ The fitted values of n are shown in Fig. 2(a); as at the lower energies the ρ^0 approaches a Breit-Wigner shape at larger momentum transfer. Fig. 2(b), (c) shows the result of a fit to the dipion mass ^{distribution} in intervals of 40 MeV using the form $d^2\sigma/dt dM = d^2\sigma/dt dM|_{t=0} e^{At}$ for the $|t|$ interval 0.05 - 0.4 GeV^2 .

ρ^0 cross sections

Following the procedures of our previous papers^{1,4}, we give four cross sections for ρ^0 production:

(1) a ρ^0 cross section derived from a fit of the Söding model⁸ to our data. In this cross section determination we are removing the influence of the coherent Drell background⁹ and giving a ρ^0 cross section proportional to the area of a rho Breit-Wigner. We use a Söding model with a Ferrari-Selleri form factor¹⁰ and include a double scattering correction to the Drell terms.

The model is described in detail in Ref. 4.

(2) A ρ^0 cross section is obtained from $d^2\sigma/dtdM|_{M=M_\rho} \pi \Gamma/2$. In this phenomenological application of the Söding model (based on the vanishing of the double-scattering corrected Drell-diagram at the ρ^0 mass) we determine $d^2\sigma/dtdM|_{M=M_\rho}$ from a fit of a smooth curve of the form Breit-Wigner $\chi(\frac{M}{M_\rho})^{n(t)}$ to the data. We take the mass, M_ρ , and width Γ_ρ , of the ρ to be the same as that determined in the fit in (1).¹¹ This approach takes a constant area for the rho Breit-Wigner in contrast to method (1) in which the ρ^0 Breit-Wigner depends on the available phase space. We refer to cross sections obtained using this technique as phenomenological Söding model cross sections.

(3) A parameterization cross section is obtained by fitting the Dalitz plot to a matrix element consisting of "phase space", Δ^{++} and a ρ^0 whose shape is given by the form Breit-Wigner $\chi(M/M_\rho)^{n(t)}$. Basically this yields a ρ^0 cross section through the assumption that the ρ^0 is all dipion pairs other than those originating through the Δ^{++} and 'phase' space parts of the matrix element.

(4) A cross section for s-channel helicity-conserving dipion pairs (II) calculated from

$$\Pi = \frac{1}{p_\gamma} \sqrt{\frac{40\pi}{3}} \Sigma \text{Re } Y_2^2(\theta, \psi)$$

Here we make use of our observation that the ρ^0 production mechanism is consistent with the conservation of c.m.s. s-channel helicity at the $\gamma\rho$ vertex and consequently yields dipion pairs with an angular distribution in the helicity frame given by $\text{Re } Y_2^2(\theta, \psi)^{12}$.

In Table I we give the total cross section, differential cross sections at $t = 0$, and the slope of the differential cross section from a fit of the form $B e^{At}$, determined using these four techniques. Differential cross sections are given in Table II.

From Tables I and II it may be seen that within errors, all techniques give the same cross sections and slopes¹³. This contrasts with our conclusions at 2.8 and 4.7 GeV where we found lower forward cross sections and slopes for the Söding model fit cross sections than for cross sections from the other three methods. The agreement of the Söding model fit and phenomenological Söding model cross sections at 9.3 GeV is due to the increased phase space available at low $|t|$.

We remark that the phenomenological Söding approach gives the same cross section as the Söding model fit only because we have used the mass and width of the ρ^0 that was obtained in the fit.¹¹ The phenomenological Söding approach gives a cross section which depends on M_ρ and is proportional to Γ_ρ ; the slope of $d\sigma/dt$ is, of course, independent of Γ_ρ and depends only slightly on M_ρ (see Fig. 2(c)). Further, the fitted Söding model cross sections depend on the form of the Drell background used. A different Drell background (one that was gauge invariant, for example) could lead to a different fitted ρ^0 mass and width and hence a different ρ^0 cross section. The only cross sections which are independent of the assumed ρ^0 mass and width and/or the form of the Drell background are the parameterization and $\pi\pi$ cross sections, but as we have emphasized⁴, these are not necessarily ρ^0 cross sections.

Comparison of Table I with the lower energy data⁴ shows that the ρ^0 cross section is decreasing with energy, but that the slopes of the phenomenological Söding, the parameterization and the π differential cross sections are independent of energy with the present statistics. The slope of the fitted Söding cross section is increasing with energy and this may be understood in terms of the increasing phase space at low $|t|$.

Dipion angular distribution

We describe the dipion angular distribution by the following angles ¹²: Φ , the angle of the photon electric polarization vector with respect to the production plane; θ and ϕ , the polar and azimuthal angles of the π^+ in the dipion rest frame. It is also convenient to introduce the angle $\psi = \phi - \Phi$, since a c.m.s. helicity conserving p-wave dipion pair has a decay angular distribution in the helicity frame given by $\sin^2\theta \cos^2\psi$ (assuming 100% linear polarization of the incident photon).

In order to show the general characteristics of the dipion system in the ρ region we show in Fig. 3 the θ and ψ distribution in the helicity frame for the dipion mass region 0.6 - 0.83 GeV and for $|t| > 0.05 \text{ GeV}^2$. The curves on the figure are calculated assuming helicity conservation and using the calculated⁴ photon polarization of 0.77.

A further general study of the dipion system was made using the moments $\Sigma Y_{\ell}^m(\theta, \psi)$ with θ, ψ defined in the helicity frame. In contrast to the lower energy studies⁴ in which significant non-zero $Y_1^0, Y_2^0, Y_2^2, Y_3^0, Y_4^0$, and Y_6^0 moments were found, here we find that only the Y_2^0 and Y_2^2 moments are different from zero with the present statistics. These two moments are given in Fig. 4 as a function of dipion mass. We conclude from the moments that the only significant angular momentum states in the dipion system are p-wave states and that these are confined to the ρ^0 mass region.

Having shown that the pion pairs in the ρ^0 region are in a p-wave state, we discuss next the dipion spin density matrix elements. 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 $\rho_{ik} \propto 14$:

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

Here, P_γ is the degree of linear polarization of the photon, which is calculated from the Compton scattering process to be 0.77 at 9.3 GeV.

The contributions σ^h , σ^u from natural parity ($P = (-1)^J$) and unnatural parity ($P = -(-1)^J$) can be obtained from the density matrix elements.

Defining P_σ by

$$P_\sigma = \frac{\sigma^h - \sigma^u}{\sigma^h + \sigma^u}$$

we find

$$P_\sigma = 2\rho_{1-1}^1 - \rho_{00}^1$$

to leading order in energy¹⁵.

The helicity frame density matrix for all dipion pairs was determined using eq. (1), by the method of moments. Fig. 5 shows these density matrix elements and P_σ plotted as a function of $M_{\pi\pi}$ for $0.05 < |t| < t_{\max}$. At the ρ^0 mass we find $P_\sigma \sim 1$, $\rho_{1-1}^1 = \rho_{1-1}^2 \sim 0.5$ with the other density matrix elements in $E_2(1)$ equal to zero; i.e. at the ρ^0 mass the data are consistent with a production mechanism which conserves c.m.s. s-channel helicity at the γp vertex. As in our 2.8 and 4.7 GeV exposures the data show indications of deviations from the values both below and above the ρ^0 mass.

The helicity frame density matrix elements for the rho mass region

are shown in Fig. 6 as a function of $|t|$. All the density matrix elements are consistent, within about two standard deviations, with the values to be expected for a ρ^0 produced by a mechanism conserving c.m.s. s-channel helicity. In addition, $P_0 = 1.01 \pm 0.09$ for $0.05 < |t| < t_{\max}$ showing that the ρ^0 is produced by natural parity exchange.

We have made two tests in an attempt to measure the degree of helicity conservation in ρ^0 production. Firstly, a maximum likelihood fit was made to determine the angle β , measured about the normal to the production plane, through which a non spin-flip density matrix must be rotated to give the best fit to the angular distribution in the helicity frame.¹⁶ Fig. 7 shows β as a function of t together with lines indicating where the data points should fall if the flip terms were minimal in the Gottfried-Jackson (GJ), helicity (H), or Adair system (A). For $|t| < 0.8 \text{ GeV}^2$, the helicity system is clearly preferred and, in contrast to the 2.8 and 4.7 GeV data, β is close to zero throughout the t -range. Secondly, we have fitted the helicity frame density matrix elements in the region $0.02 < |t| < 0.8 \text{ GeV}^2$ using a parameterization proposed by Hontebeyrie et al.¹⁷ (We find that in order to obtain a fit we have to include the region $0.02 < |t| < 0.05 \text{ GeV}$). Within 1.5 standard deviations all spin flip amplitudes were found to be zero in the t -range. This contrasts with our 4.7 GeV analysis in which we found that some amplitudes were four standard deviations away from zero for a fit in the same t -range. We conclude that at 9.3 GeV our data are consistent with c.m.s. channel helicity conservation at the γp vertex for $0.02 < |t| < 0.8 \text{ GeV}^2$. Thus, at 9.3 GeV, the t -range over which helicity conservation is a good approximation is extended by a factor two compared with the 4.7 GeV data.²⁰

Comparison with models

The curves drawn on Figs. 1, 4, and 5 are calculated from a fit⁴ of the Söding model to our data. As at the lower energies⁴, the Söding model gives a good quantitative description of the ρ^0 shape, its variation with t and the ρ^0 decay angular distribution. Except for the moments Y_2^0 , Y_2^2 the model predicts moments that are too small to be observed with our present statistics. The ρ^0 variables are also described well by a dual resonant model¹⁸; the model predicts the correct ρ^0 cross section within 15%, however more ρ' is predicted than is observed experimentally.¹⁹

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Footnotes and References

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2. J. Ballam et al, Phys Rev. Letters 24, 960 (1970); 1467(E) (1970)
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4. J. Ballam et al, (Bubble Chamber Study of Photoproduction by 2.8 and 4.7 GeV Polarized Photons: I. Cross Section Determinations and Production of ρ^0 and Δ^{++} in the Reaction $\gamma p \rightarrow \rho^+ \pi^-$) Submitted to this conference and to be published.
5. Data are given for $0.05 < |t| \leq t_{\max}$. We have still to make a study of scanning biases for $|t| < 0.05 \text{ GeV}^2$.

Cross sections are corrected for the interval $|t| < 0.05 \text{ GeV}^2$ by a linear experimental extrapolation of the differential cross section.
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7. The mass and width of the ρ^0 was fitted in each t interval.
8. P. Söding, Phys. Rev. Letters 19, 702 (1965).
9. S. D. Drell, Rev. Mod. Phys. 33 (1961) 458.
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11. $M_\rho = 770 \text{ MeV}$, $\Gamma_\rho = 150 \text{ MeV}$.
12. We analyse the ρ decay in the helicity frame, where the z axis is the direction of the ρ in the overall (γp) c.m.s.
The 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, $\hat{\epsilon}$, and the production plane in the total c.m. system is defined by: $\sin \phi = \hat{y} \cdot \hat{\epsilon}$ with the sign ambiguity defined by $\cos \phi = \hat{\epsilon} \cdot (\hat{y} \times \hat{k})$.
The decay angles θ, ϕ are the polar and azimuthal angles of the direction of flight, $\hat{k}_\pi$, of the $\pi^\pm$ in the ρ rest system:

$$\cos \theta = \hat{k}_\pi \cdot \hat{z}$$

$$\cos \phi = \hat{y} \cdot (\hat{z} \times \hat{k}_\pi) / |\hat{z} \times \hat{k}_\pi|$$

$$\sin \phi = -\hat{x} \cdot (\hat{z} \times \hat{k}_\pi) / |\hat{z} \times \hat{k}_\pi|$$

13. We interpret the low value of Π in the interval $0.05 < |t| < 0.075 \text{ GeV}^2$ as a statistical fluctuation. The cross section for Π in the interval $0.02 < |t| < 0.05 \text{ GeV}^2$ is in agreement with the parameterization cross section.

Note that the forward differential cross sections are obtained by a linear extrapolation from $|t| = 0.05 \text{ GeV}^2$. A quadratic extrapolation leads to essentially the same forward cross section but with errors increased by a factor two; of course, our forward cross sections may be in considerable error if the slope of the differential cross section changes below $|t| = 0.05 \text{ GeV}^2$.

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16. The density matrix elements used in this fit are given by

$$\rho_{ik} = d_{im}^1(\beta) \tilde{\rho}_{mn} d_{nk}^1(-\beta)$$

$$\text{with } \tilde{\rho}_{11}^0 = \tilde{\rho}_{-1-1}^0 = \frac{1}{2}; \quad \tilde{\rho}_{1-1}^1 = \tilde{\rho}_{-11}^1 = \frac{1}{2}; \quad \tilde{\rho}_{1-1}^2 = -\tilde{\rho}_{-11}^2 = -i/2$$

Other $\tilde{\rho}_{mn}$ are zero. The rotation matrices $d^1(\beta)$ describe a rotation through the angle β about the normal to the production plane.

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19. The dual resonant model gives $\chi^2 = 33$ for 3 bins in the ρ mass region $1.18 - 1.40 \text{ GeV}$ in contrast to $\chi^2 = 2.1$ for 3 bins obtained using the Söding model.

20. Lack of statistics prevents us from investigating helicity conservation for $|t| > 0.8 \text{ GeV}^2$.

Figure Captions

Fig. 1. Reaction $\gamma p \rightarrow p\pi^+\pi^-$. Two body mass spectra (a) $\pi^+\pi^-$, (b) $p\pi^+$, (c) $p\pi^-$, for $|t| > 0.05 \text{ GeV}^2$. The curve is from a fit of the Söding model. The shaded area in (b) and (c) is for $M_{\pi^+\pi^-} > 1 \text{ GeV}^2$ and for $t_p \rightarrow p\pi < 0.4 \text{ GeV}^2$.

Fig. 2. Reaction $\gamma p \rightarrow p\pi^+\pi^-$. (a) $n(t)$ from a fit of the form Breit-Wigner $\times (\frac{M_\rho}{M_{\pi\pi}})^n(t)$. (b), (c) $d\sigma/dtdM|_{t=0}$ and A from a fit of the form $d\sigma/dtdM|_{t=0} e^{At}$ to all dipion pairs in the region $0.05 < |t| < 0.4 \text{ GeV}^2$ shown as a function of dipion mass.

Fig. 3. Reaction $\gamma p \rightarrow p\rho^0$. The dipion angles θ, ψ in the helicity frame for $|t| > 0.05 \text{ GeV}^2$, $0.6 < M_{\pi\pi} < 0.88 \text{ GeV}$. The curves are the angular distributions expected for a c.m.s. s-channel helicity conserving ρ .

Fig. 4. Reaction $\gamma p \rightarrow p\pi^+\pi^-$. The dipion moments $Y_2^0(\theta)$, $\text{Re } Y_2^2(\theta, \psi)$ and $Y_4^0(\theta)$ in the helicity frame as a function of $M_{\pi\pi}$ for $|t| > 0.05 \text{ GeV}^2$.

Fig. 5. Reaction $\gamma p \rightarrow p\rho^0$. Dipion density matrix elements in the helicity frame and P_c for $0.6 < M_{\pi\pi} < 0.88 \text{ GeV}$ as a function of $M_{\pi\pi}$ for $0.05 < |t| < t_{\text{max}} \text{ GeV}^2$.

Fig. 6. Reaction $\gamma p \rightarrow p\rho^0$. (a) Dipion density matrix elements in the helicity frame and (b) P_c for $0.6 < M_{\pi\pi} < 0.88 \text{ GeV}$ as a function of $|t|$.

Fig. 7. Reaction $\gamma p \rightarrow p\rho^0$. The angle β for rotation, about the normal to the production plane, of the ρ^0 density matrix from the helicity frame into the "minimum flip" system as a function of $|t|$. The curves marked H, A, GJ show where the data points would be if the minimum flip system were the helicity, Adair and Gottfried-Jackson frame (as defined in Ref. 4), respectively.

TABLE I

Dipion total cross sections, σ , differential cross sections at $t = 0$, $d\sigma/dt|_{t=0}$, and the slope of the differential cross section, A , from a fit of the form Be^{At} in the $|t|$ interval $.02 - 0.5 \text{ GeV}^2$, determined using the four techniques described in the text.

	Söding Model Fit	Phenomenological Söding Model	Parameterization	II
$\sigma(\mu\text{b})$	12.4 ± 0.5	13.1 ± 0.6	12.7 ± 0.4	11.8 ± 0.7
$\left. \frac{d\sigma}{dt} \right _{t=0} (\mu\text{b}/\text{GeV}^2)$	79 ± 4	83 ± 8	90 ± 5	79 ± 8
$A(\text{GeV}^{-2})$	6.6 ± 0.3	6.3 ± 0.5	7.1 ± 0.3	7.1 ± 0.6

TABLE II

Dipion differential cross sections, $d\sigma/dt$, determined using the four techniques described in the text.

t (GeV ²)	$d\sigma/dt$ ($\mu\text{b}/\text{GeV}^2$)			
	Soding Model Fit	Phenomenological Soding Model	Parameterization	Π
0.02-0.05	65 $\pm$ 7	73 $\pm$ 12	79 $\pm$ 8	80 $\pm$ 12
0.05-0.075	61 $\pm$ 4	55 $\pm$ 8	61 $\pm$ 4	33 $\pm$ 8
0.075-0.10	39 $\pm$ 4	41 $\pm$ 7	47 $\pm$ 4	50 $\pm$ 7
0.10-0.15	32 $\pm$ 2	37 $\pm$ 5	33 $\pm$ 2	31 $\pm$ 4
0.15-0.20	29 $\pm$ 2	31 $\pm$ 4	27 $\pm$ 2	28 $\pm$ 6
0.20-0.25	21 $\pm$ 2	} 18 $\pm$ 2	20 $\pm$ 2	17 $\pm$ 3
0.25-0.30	23 $\pm$ 3		15 $\pm$ 2	11 $\pm$ 3
0.30-0.40	8.4 $\pm$ 0.9	} 6.4 $\pm$ 1.0	7.2 $\pm$ 0.8	5.9 $\pm$ 1.4
0.40-0.50	3.4 $\pm$ 0.6		3.5 $\pm$ 0.5	3.4 $\pm$ 0.9
0.50-0.70	1.0 $\pm$ 0.2	—	1.0 $\pm$ 0.2	1.3 $\pm$ 0.4

Fig. 1.

Fig. 2 (a)

$\gamma p \rightarrow p \pi^+ \pi^-$

Fig. 2 (b)

$\gamma p \rightarrow p \rho^0$
 $E_\gamma = 9.3 \text{ GeV}$
 $|t| > 0.02 \text{ GeV}^2$
 $0.6 < M_{\pi\pi} < 0.88 \text{ GeV}$

Fig. 4.

$$\gamma p \rightarrow p \pi^+ \pi^-$$

$$E_\gamma = 9.3 \text{ GeV}$$

DENSITY MATRIX ELEMENTS IN THE HELICITY SYSTEM

Fig 5.

$\gamma p \rightarrow p \rho^0$
 $E_\gamma = 9.3 \text{ GeV}$

DENSITY MATRIX ELEMENTS IN THE HELICITY SYSTEM

Fig. 6(a)

$\gamma p \rightarrow p \rho^0$
 $E_\gamma = 9.3 \text{ GeV}$

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Fig. 6(t)

$\gamma p \rightarrow p \rho^0$: Rotation into minimum flip system

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