sequence

$$\pi^+p \rightarrow \pi^+p\eta, \quad \eta \rightarrow \pi^+\pi^-\pi^0, \tag{6}$$

$$\pi^0 \rightarrow e^+e^-\gamma. \tag{7}$$

(The e^+ and e^- are identified on the scanning table.) The film contains 140.8 (corrected) events of type (6) where the π^0 does not undergo Dalitz decay (7). We therefore expect about 140.8/80 = 1.8 associated Dalitz decays.[7]

C. Event with two Dalitz decays. The last six-pronged event (No. 2 182 402) corresponds to the reaction

$$\pi^+p \rightarrow \pi^+p\pi^0\pi^0, \tag{8}$$

where both neutral pions undergo single Dalitz decay (7). (The two positrons and two electrons are identified on the scanning table. The invariant mass recoiling against the final π^+p is 280 MeV.) In the same film we have observed about 50 examples of reaction (8) with a single Dalitz decay.[8] Therefore the expected number of events of type (8) with two Dalitz decays is about 50/80 = 0.6.

D. Events without electron pairs. No example was found of the reaction

$$\pi^+p \rightarrow \pi^+p\pi^+\pi^-\pi^+\pi^-. \tag{9}$$

The incident π^+ momentum is 1170 MeV/c, corresponding to a c.m. energy 120 MeV above threshold for this reaction. If we had found one event, it would have yielded a cross section of 0.35 μb.

We are grateful to Luis W. Alvarez for his interest and support.

[7] N. P. Samios, Phys. Rev. **121**, 275 (1961).

[8] F. S. Crawford, Jr., L. J. Lloyd, and E. C. Fowler, Phys. Rev. Letters **10**, 546 (1963).

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Photoproduction on Hydrogen of ρ^0 Mesons between Threshold and 6 BeV†

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Data are presented on the details of the interaction $\gamma+p \rightarrow p+\rho^0$ observed in a 12-in. hydrogen bubble chamber exposed to a bremsstrahlung photon beam of 6-BeV maximum energy at the Cambridge Electron Accelerator. The energy dependence of the cross sections, the production angular distributions, and the decay angular distributions of the ρ^0's are compared with the predictions of the one-pion-exchange (OPE) mechanism and with a diffraction or multiperipheral model proposed by Berman and Drell. These data, as well as a comparison with ω^0 and with $\rho^0+N^*(1238)$ production, reject the OPE model and favor a diffraction mechanism.

I. INTRODUCTION

THIS is the first of a series of papers reporting on the final results of the first bubble-chamber study of meson and hyperon production by photons of energy greater than 1 BeV. This experiment, performed at the Cambridge Electron Accelerator (CEA), utilized a 12-in. hydrogen bubble chamber exposed to bremsstrahlung beams of maximum energy varying between 4.8 and 6.0 BeV. The experimental conditions and some preliminary observations have previously been reported.[1] The details of the experiment and the analysis and interpretation of the events contained in 865 000

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[1] Crouch *et al.*, Phys. Rev. Letters **13**, 636 and 640 (1964); also Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Hamburg, 1965 (to be published), and Proceedings of the Second Topical Conference on Resonant Particles, Athens, Ohio, 1965, p. 476 (unpublished).

pictures will be reported in this and a forthcoming series of papers.

In examining the reaction

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

we have noted that ρ^0-meson production is one of the dominant channels for this reaction above the ρ^0 threshold of 1.05 BeV. We propose in this first paper to present the details of the observations relating to ρ^0 production and then to attempt a detailed comparison of these observations with the predictions of two theoretical models—the one-pion-exchange model (OPE), with and without absorption in the final state,[2,3] and the multiperipheral or diffraction model suggested by Berman and Drell.[4] The comparison with theory will utilize only those data corresponding to photon energies above 1.5 BeV, so as to avoid problems of intereference from $N^*(1238)$ production which is appreciable below this energy and very small above it.[1]

We find that our observations are in serious disagreement with OPE, while agreeing with diffraction-model predictions in those areas (mainly for extreme forward ρ^0 production) in which the diffraction calculation has thus far been carried out.[4]

In subsequent papers, we shall deal with the techniques of exposure and analysis, with cross sections and mechanisms for $N^*(1238)$ production, for ω^0 and η^0 production, for strange-particle production and for those events involving a multiplicity of pions in the final state.

II. THE EXPERIMENTAL RESULTS

1. Mass Distributions

The experimental data on reaction (1) have been divided into six photon-energy intervals between threshold and 6 BeV. Least-squares fits of the $(\pi^+\pi^-)$ invariant-mass distributions were made in each interval using a superposition of three-body phase space and an assumed Breit-Wigner resonance for the ρ^0 peak. These mass distributions are shown in Figs. 1(a)–1(f). All the intervals yield the same central value of the ρ^0 mass, within the experimental uncertainties. However, the best fit for the width varied from interval to interval (between $\Gamma\simeq125$ and ~225 MeV) to a degree rather inconsistent with the statistical uncertainties, an effect which is, we believe, attributable to some non-phase-space background contributions in the resonance wings. In any event, our widths appear to be definitely larger than the generally accepted value[5] of 124±4 MeV.

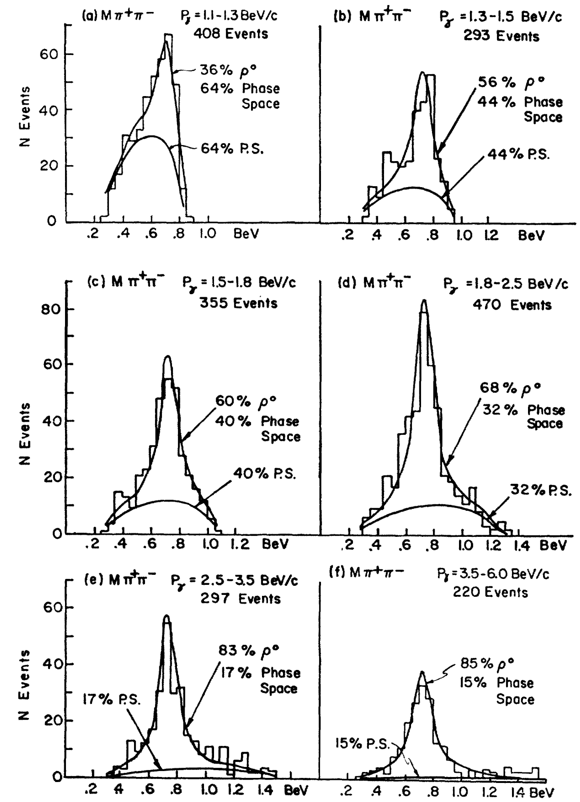

FIG. 1. Typical invariant-mass distributions for the $(\pi^+\pi^-)$ combination in the reaction $\gamma p\rightarrow p\pi^+\pi^-$. The curves represent best fits assuming a combination of three-body phase space and ρ^0 production, assumed to have a Breit-Wigner mass distribution.

Our data are best fitted by a mass of the ρ^0 of 728±8 MeV, with an average width $\Gamma=175$ MeV. We have checked for systematic errors in the measurement and analysis by determining the masses of other known particles and resonances which are photoproduced in the same experiment. The values we obtain for the masses of the K^0, Λ^0, ω^0, η^0, and N^{*++} are all in excellent agreement with those generally accepted.[5] Since we shall show in the following that the $(\pi^+\pi^-)$ system we observe has spin >0, we conclude that we are indeed observing the photoproduction of ρ^0 mesons in this experiment, and that the mass of the ρ^0 we observe is lower than that generally obtained in experiments[5] using other projectiles (765±3 MeV). The value reported by Lanzerotti *et al.* in a photoproduction experiment using counters,[6] $m_\rho=740\pm10$ MeV, $\Gamma=150\pm10$ MeV, and the preliminary results of the DESY bubble-chamber group[7] are in agreement with our mass value.

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[2] S. D. Drell, Rev. Mod. Phys. **33**, 458 (1961); F. Salzman and G. Salzman, Phys. Rev. **120**, 599 (1960); Phys. Rev. Letters **5**, 377 (1960).

[3] K. Gottfried and J. D. Jackson, Nuovo Cimento **34**, 735 (1964).

[4] S. M. Berman and S. D. Drell, Phys. Rev. **133**, B791 (1964).

[5] Rosenfeld *et al.*, Rev. Mod. Phys. **37**, 633 (1965). In a recently circulated report, P. Söding has shown how the apparent ρ mass could be shifted by as much as $\sim$25 MeV as a consequence of interference between the ordinary ρ-production amplitude and the amplitudes for two-pion production involving the $\gamma\pi^+\pi^-$ vertex, with one of the pions being scattered off the nucleon.

[6] Lanzerotti *et al.*, Phys. Rev. Letters **15**, 210 (1965).

[7] Aacnhe-Berlin-Bonn-Hamburg-Heidelberg-München Collaboration, Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Hamburg, 1965 (to be published); also private communications.

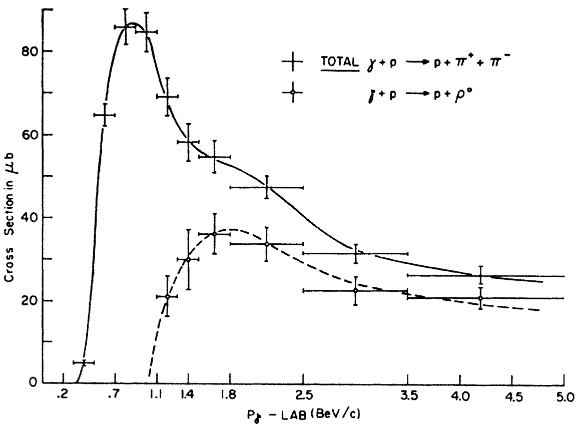

FIG. 2. Cross sections for $\gamma p \to p\rho^0$ derived from the mass distributions of Fig. 1. The curves represent a smooth joining of the experimental points. The total cross section for $\gamma p \to p\pi^+\pi^-$ is also shown.

2. Production Cross Section

Using our best mass value and width quoted above, the data shown in Fig. 1 can be fit with a Breit-Wigner ρ distribution plus phase-space background to determine the ρ-meson production cross section in each interval. The total cross sections for reaction (1), and those for the ρ^0-production portion are shown in Fig. 2. The photon flux and spectrum were obtained by measurement of 50 000 electron-positron pairs produced in the chamber according to a procedure previously described.[1]

3. Decay Angular Correlations

Decay angular correlations provide important information relating to the spin of the dipion system in question, as well as to the production mechanism. For obtaining the decay angular distributions shown in Fig. 3, we have designated as ρ^0's events in the mass interval 650–800 MeV, thereby avoiding the resonance wings and minimizing background effects. Subtraction of the (small) background of non-ρ^0 (phase-space) events does not alter these distributions in any statistically significant fashion. The angle α in Figures 3 (a)–(c) is the angle between the direction of the incident photon (in the lab or over-all c.m. system) and that of the emitted π^+ taken in the ρ^0 rest frame. (This is frequently referred to as the Adair angle.) Confining our attention to those ρ^0's produced in the forward direction, $\cos\theta_{\text{c.m.}} \geqslant 0.85$, best fits to the angular distributions of the form $a+\sin^2\alpha$ give the values

$$\begin{aligned} a &= 0.007 \pm 0.16, & E_\gamma &= 1.5\text{–}1.8 \text{ BeV} \\ &= -0.06 \pm 0.11, & E_\gamma &= 1.8\text{–}2.5 \text{ BeV} \\ &= 0.32 \pm 0.16, & E_\gamma &= 2.5\text{–}6 \text{ BeV}. \end{aligned}$$

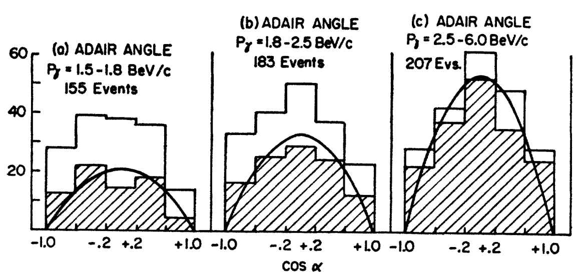

FIG. 3. Distributions of the Adair angle α between the incident-photon direction in the lab or c.m. system and the decay π^+ in the ρ^0 rest system for ρ^0 masses in the interval 650 MeV $\leqslant M_\rho \leqslant$ 800 MeV. The cross hatching corresponds to events produced within $\cos\theta_{\text{c.m.}} \geqslant 0.85$. The curves are for a $\sin^2\alpha$ distribution normalized to the cross-hatched events. In making the fits discussed in Sec. B.3, the data were broken down into ten intervals.

A pure $\sin^2\alpha$ Adair-angle distribution for forward-produced ρ^0's would result from the decay of a spin-one particle photoproduced without spin-flip of the target nucleon. Deviations from pure $\sin^2\alpha$ could result, even

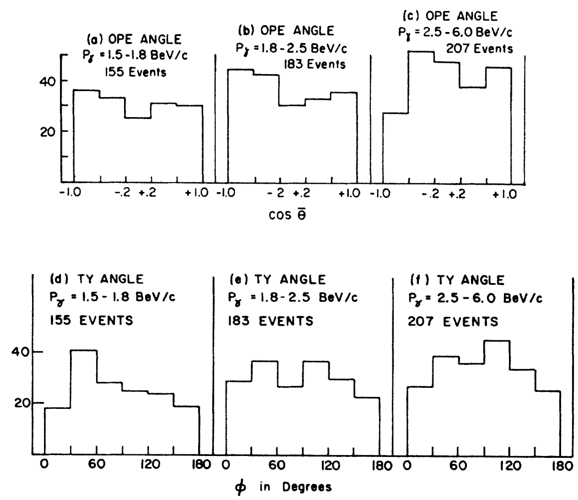

FIG. 4. (a)–(c) give the distribution of the angle θ between the photon and π^+, both transformed into the ρ^0 rest frame. (d)–(f) show the distributions in the angle ϕ between the production and the decay planes (the Treiman-Yang angle).

for a spin-one particle, either from the occurrence of nucleon spin flip (which cannot be excluded on any *a priori* grounds) or from the introduction of a component of orbital angular momentum in the forward direction due to the inclusion in our sample of events with too-large production angles. On the other hand, these same phenomena could lead, quite by accident, to a $\sin^2\alpha$ distribution for a particle of spin $\geqslant 2$. The simplest and most likely explanation of our results is that we are observing the photoproduction of the vector ρ^0 meson; but in any event, these angular distributions exclude the possibility of spin zero for the dipion system here observed.

The decay angular correlations shown in Figs. 4(a)–4(c) are the ones appropriate to a comparison with OPE models.[3] Here, $\bar{\theta}$ is the angle between the π^+ and the photon, *both* taken in the ρ^0 rest frame. These distributions are consistent with isotropy in all the energy ranges. In addition, the distributions of the azimuthal angle, ϕ (the angle between the normals to the production and the decay planes, the Treiman-Yang angle) shown in Figs. 4(d)–4(f) are also consistent with isotropy for all photon energies.

Finally we looked for evidence of a forward-backward asymmetry in the ρ^0 decay; within statistics, there is none. Thus, in the energy intervals $E_\gamma=1.5$–2.5 BeV and $E_\gamma=2.5$–6 BeV, $(F-B)/(F+B)=(-0.11\pm0.06)$ and (0.024 ± 0.070), respectively. This decay symmetry agrees with the more limited counter observations of Lanzerotti *et al.*,[6] but differs from the results of experiments in which the ρ^0's are produced by pion beams.[8]

4. Differential Cross Sections

(a) *Production angular distributions* in the over-all c.m. system for the same ρ^0 sample and photon energy intervals are shown in Fig. 5. The angular distributions are strongly peaked in the forward direction, an effect which becomes more marked with increasing photon energy. Thus, at energies above 2.5 BeV [Fig. 5(c)]

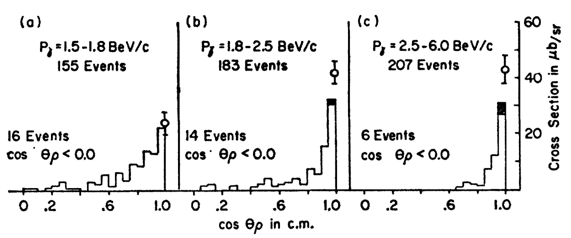

FIG. 5. Angular distributions for ρ^0 production in the $\gamma+p$ center-of-mass system, $d\sigma/d\Omega$ versus $\theta_{c.m.}$. The cross-hatched areas correspond to the correction for events missed because of short proton recoils. The points, with errors, at $\theta_{c.m.}=0$ are extrapolated values.

approximately 50% of all the ρ^0's are produced within $\cos\theta_{c.m.}\geqslant0.95$. These same angular distributions are also plotted in Figs. 6(a)–6(c) as a function of the invariant 4-momentum transfer to the ρ^0 in order to facilitate comparison with OPE models.

(b) *The differential cross sections in the forward direction* are of particular interest in attempting to distinguish between the different models. The extrapolated values of $d\sigma/d\Omega(\theta_{c.m.}=0)$ are shown in Figs. 5(a)–5(c) and summarized in Fig. 7. In order to perform these extrapolations, corrections had to be made for the events missed because of the reduced efficiency for observing short-range proton recoils corresponding to forward-produced ρ^0's. Our proton detection efficiency for short track lengths was obtained from a detailed study of the observed range distribution in approximately 5000 events involving protons and pions; the corrected numbers are indicated as cross-hatched areas

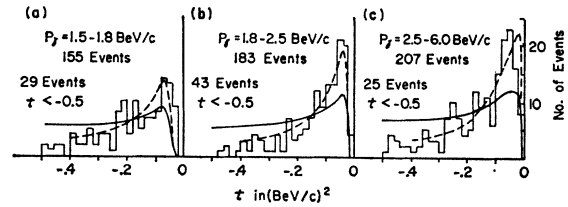

FIG. 6. The same data as in Fig. 5, but plotted against t, the invariant four-momentum transferred to the ρ^0. The curves represent the prediction of OPE theory without (solid) and with (broken) maximum absorption in the final state.

in Figs. 5(a)-5(c). In addition, the extrapolated cross section values depend on the assumed form of the angular dependence for small angles. A number of extrapolation procedures were employed (polynomial and exponential functions, with and without the point at the smallest angle) and the indicated errors on $d\sigma/d\Omega(\theta_{c.m.}=0)$ represent limits on the values obtained using different possible extrapolation procedures, as well as taking account of the uncertainty in the correction for missed short-range protons. Our quoted errors arise in approximately equal part from the two abovementioned sources.

Although the angular distributions, and the extrapolations to zero angle, look very different if done in the laboratory system (we have chosen to do them in the over-all c.m. system) the results should be the same if expressed in the form of $d\sigma/dt$. Since in the strictly forward direction ($\theta_{lab}=\theta_{c.m.}=0$) the simple relationship $\pi dt=P_\gamma P_\rho d\Omega$ holds in either system, the transformation of the forward cross section is especially simple. The relativistic invariance of $d\sigma/dt$ makes it useful to plot $d\sigma/d\Omega$ versus $P_\gamma P_\rho$, which we have done in Fig. 7. Our value of the average forward cross section in the interval 3.5 BeV$<E_\gamma<$6 BeV in the laboratory system, $d\sigma/d\Omega(\theta_{lab}=0)=(0.60\pm0.15)$ mb/sr is somewhat lower than the value 1.26 ± 0.17 for $E_\gamma=4.40$ BeV reported by Lanzerotti *et al.*[6] However, their ratio of 2.2 ± 0.6 between the 4.40-BeV and the 2.52-BeV

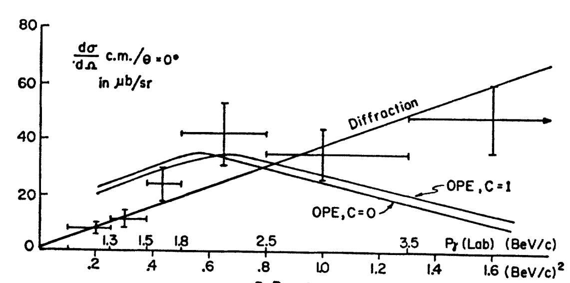

FIG. 7. The forward cross sections in the c.m. system. The curves shown compare the extrapolated values of $d\sigma/d\Omega(\theta_{c.m.}=0)$ with OPE without absorption, with maximum absorption and with the diffraction model. The OPE curves assume $\Gamma_{\rho\pi\gamma}=2.2$ MeV ($C=0$) and $\Gamma_{\rho\pi\gamma}=3.3$ MeV ($C=1$), respectively. The diffraction-model prediction is the best straight-line fit in $P_\gamma P_\rho$ to the experimental points.

[8] Derado *et al.*, Phys. Rev. Letters **14**, 872 (1965); G. Goldhaber, *Second Coral Gables Conference on Symmetry Principles at High Energy* (W. H. Freeman and Company, San Francisco, 1965), p. 34; Hagopian *et al.*, Phys. Rev. Letters **14**, 1077 (1965).

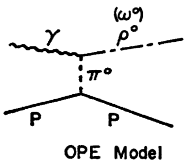

FIG. 8. Feynman diagram for $\rho^0(\omega^0)$ production through the OPE mechanism.

forward laboratory cross sections is in good agreement with our energy dependence.

III. COMPARISON WITH THEORY

Comparison with theoretical predictions are now given for the data described above. We shall consider the OPE model[2,3] (see Fig. 8) and the diffraction model (see Fig. 9). In particular, we shall refer to the results of the multiperipheral model [Fig. 9(b)] suggested by Berman and Drell[4] as the main mechanism for diffractive photoproduction of ρ mesons.

1. Total Cross Section

The total cross sections as observed in our experiment are compared in Table I with the predictions of the OPE model, both without final-state interaction (the parameter C of Ref. 3 equal to zero) and with complete absorption in the S state ($C=1$).[9] In making this comparison, we have confined ourselves to the portion of the data corresponding to $|t|\leqslant 20m_\pi^2$. The scale of the OPE predictions is determined by the assumed value of the width $\Gamma_{\rho\pi\gamma}$, which has been taken as 1 MeV in computing the numbers in Table I. However, the sharp disagreement between the observations and the predicted strong decrease in cross section with increasing photon energy cannot be repaired by any variation of this parameter. Thus, while the width $\Gamma_{\rho\pi\gamma}\simeq 1$ MeV ($\simeq 2$ MeV for $C=1$) is not in serious disagreement with the cross section in the lowest energy interval, widths of 4 and 10 MeV for $C=0$ and 1, respectively, are required to account for the observed cross section for $E_\gamma>3.5$ BeV.

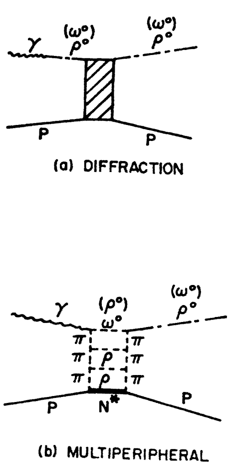

FIG. 9. Diffractive $\rho^0(\omega^0)$ production mechanisms. (a) A general diffraction diagram. (b) Multiperipheral model used by Berman and Drell (Ref. 4) to compute the forward ρ^0 production.

Although there has been no direct measurement[10] of $\Gamma_{\rho\pi\gamma}$, such large widths would be in very serious disagreement with several theoretical approaches currently in favor. For example, conservation of the A-quantum number of Bronzan and Low[11] predicts $\Gamma_{\rho\pi\gamma}\ll\Gamma_{\omega\pi\gamma}$, while the $SU(6)$ and $SU(6)_W$ symmetry schemes[12] require

$$\Gamma_{\rho\pi\gamma}=\tfrac{1}{9}\Gamma_{\omega\pi\gamma}. \tag{2}$$

Since recent observations,[13] on the decay $\omega^0\to$ neutrals, permit the conclusion $\Gamma_{\omega\pi\gamma}\leqslant 1$ MeV, our observations could be consistent with these theories only if the OPE contribution to the observed photoproduction of ρ^0 mesons should prove to be very small.

2. Decay Angular Correlations

The decay angular correlations provide another means of distinguishing between different models for ρ^0 photoproduction. In general, the angular distributions of the decay pion with respect to the photon direction in the ρ^0 rest system may be expressed in terms of the spin-density matrix elements.

$$W(\cos\bar{\theta})=\tfrac{3}{4}(1-\rho_{0,0})\left[1+\left(\frac{3\rho_{0,0}-1}{1-\rho_{0,0}}\right)\cos^2\bar{\theta}\right] \tag{3a}$$

$$2\pi W(\varphi)=1-2\rho_{1,-1}\cos 2\varphi. \tag{3b}$$

The predictions of OPE are compared in Table II with the results of least-squares fits to the data of Fig. 4. Although the effects of final-state interaction tend to bring the pure OPE predictions [$W(\cos\bar{\theta})=\sin^2\bar{\theta}$, $W(\varphi)=\text{const}$] into closer accord with the observations, the discrepancies are still quite substantial.

As previously noted, for vector mesons (ρ^0's) produced in the forward direction, observation of a $\sin^2\alpha$ distribution in the Adair angle implies no spin-flip for the target nucleon. We note that a diffraction mechanism would be consistent with this observation as long as the ρ^0-production angle is small enough so that no orbital angular momentum can be transmitted in the forward direction. However, there are many possible processes, including both OPE and diffraction, in which, for strictly forward ρ^0 production (which, as we have previously noted, comprises a large fraction of all the events in the higher photon energy interval), the ρ^0 will

[9] J. D. Jackson (private communication); P. C. M. Yock, Ph.D. thesis, MIT, 1965 (unpublished).

[10] The data reported in Ref. 13 on the reaction $K^-+p\to\Lambda^0$ +neutrals permit the setting of a conservative upper limit of $\sim$5 MeV on $\Gamma_{\rho\pi\gamma}$.

[11] J. B. Bronzan and F. E. Low, Phys. Rev. Letters **12**, 522 (1964).

[12] S. L. Glashow and R. H. Socolow, Phys. Rev. Letters **15**, 329 (1965); S. Meshkov (private communication); S. Badier and C. Bouchiat, Phys. Letters **15**, 96 (1965).

[13] Flatté *et al.*, Phys. Rev. Letters **14**, 1095 (1965). Assuming all the decay $\omega^0\to$ neutrals is in this mode, their results give $\Gamma_{\omega\pi\gamma}=0.82\pm0.20$ MeV.

TABLE I. Observed and calculated ρ^0 cross sections (μb) for $|t|\leq 20m_\pi^2$, $\Gamma_{\rho\pi\gamma}=1$ MeV.

E (BeV)	σ_{exp}	σ_{OPE} No absorption	σ_{OPE} Full absorption ($C=1$)
1.5–1.8	26.6±3.8	25.7	9.50
1.8–2.5	24.9±3.0	17.3	6.42
2.5–3.5	16.5±2.3	9.6	3.68
3.5–6.0	15.4±2.2	4.5	1.70

have the same helicity as the incident photon ($m=\pm 1$), leading to a pure $\sin^2\alpha$ decay distribution. As one goes off the forward direction, the OPE prediction very rapidly becomes different from $\sin^2\alpha$ (since θ soon is very different from α); our data favor a theory in which the distribution would tend to remain $\sin^2\alpha$, even for production angles well off zero degrees. We do not know what the off-zero predictions are for either the diffraction or multiperipheral diagrams [Figs. 8(b) and 8(c)], since the computations have until now been carried out for zero production angles only.[4] Computations on a multiperipheral model for production at larger angles are now in progress.

3. Production Angular Distributions

The c.m. production angular distributions predicted by OPE are shown in Fig. 6. Agreement with experiment can be obtained, but only on the assumption of almost complete absorption ($C\cong 1$) and then, as we have previously seen, only for excessively large values of $\Gamma_{\rho\pi\gamma}$. Although detailed calculations on the diffraction model have not yet been performed, Berman and Drell suggest[4] that the distribution at small angles should exhibit features similar to those of π-N elastic scattering. In the energy range 2–5 BeV, experiments on π-N scattering yield[14]

$$d\sigma/dt \propto e^{At} \tag{4}$$

with $A=(9.5\pm 2.0)$ (BeV/c)$^{-2}$. Equation (4) provides a satisfactory fit to the data plotted in Figs. 6(b) and 6(c) with $A=(8.8\pm 1.5)$ (BeV/c)$^{-2}$. The data of Lanzerotti *et al.*[6] are also consistent with Eq. (4) with $A\simeq 10$ (BeV/c)$^{-2}$.

TABLE II. Observed and calculated spin-density matrix elements from ρ^0-decay distributions.

E_γ (BeV)	Predicted $C=0$	Predicted $C=1$	Observed all t	Observed $\lvert t\rvert\leq 20m_\pi^2$
		$\rho_{0,0}$		
1.5–1.8	0	0.16	0.36±0.05	0.30±0.07
1.8–2.5	0	0.14	0.38±0.05	0.34±0.07
2.5–6.0	0	0.13	0.24±0.07	0.24±0.07
		$\rho_{1,-1}$		
1.5–1.8	0	0.015	0.14±0.07	0.12±0.08
1.8–2.5	0	0.02	0.10±0.07	0.12±0.08
2.5–6.0	0	0.02	0.10±0.04	0.08±0.05

[14] M. L. Perl, L. W. Jones, and C. C. Ting, Phys. Rev. **132**, 1252 (1963).

4. Forward Cross Sections

The differential cross sections in the forward direction provide perhaps the most striking evidence in favor of a diffractive model. The prediction of pure OPE, of a rapid decrease in $d\sigma/d\Omega(\theta=0)$ with increasing photon energy, is only slightly modified by the introduction of absorption effects. As may be seen in Fig. 7, these predictions are in serious disagreement with our experiment. The diffraction model, on the other hand, predicts the same behavior as in π-N scattering, i.e.,

$$d\sigma/dt(t=t_{\min})\simeq\text{constant} \tag{5a}$$

and hence

$$d\sigma/d\Omega(\theta=0)\propto P_\gamma P_\rho\,, \tag{5b}$$

where P_γ and P_ρ are the momenta, respectively, of the incident photon and emerging (forward) ρ^0. This prediction is in reasonable agreement with our data (Fig. 7).

5. Comparison with Other Processes

A detailed discussion of the production of resonances in the reaction

$$\gamma+p\to p+\pi^++\pi^-+\pi^0 \tag{6}$$

will be given in a paper to follow. However, a comparison between our observed cross sections for the photoproduction of ρ^0 in reaction (1) with ω^0 and $N^*+\rho$ in reaction (6) provides additional evidence relative to the problems under discussion. Assuming OPE is dominant for *both* ω^0 and ρ^0 production (see Fig. 8), we would have

$$\frac{\sigma(\gamma p\to\omega^0 p)}{\sigma(\gamma p\to\rho^0 p)}=\frac{\Gamma_{\omega\pi\gamma}}{\Gamma_{\rho\pi\gamma}}\,. \tag{7}$$

Taking the experimental value[13] of $\Gamma_{\omega\pi\gamma}\lesssim 1$ MeV, and the conclusions of the previous analysis, which require $\Gamma_{\rho\pi\gamma}=2-10$ MeV if OPE holds, we expect the cross section ratio (7) to be small. For the multiperipheral model [Fig. 9(b)] on the other hand, the predicted ratio is reversed,

$$\frac{\sigma(\gamma p\to\omega^0 p)}{\sigma(\gamma p\to\rho^0 p)}=\frac{\Gamma_{\rho\pi\gamma}}{\Gamma_{\omega\pi\gamma}}\,. \tag{8}$$

However, in the event of dominance of this mechanism, the ρ^0 production data provide no means of determining $\Gamma_{\rho\pi\gamma}$, so that the evaluation of Eq. (8) requires additional information [such as, for example, a theoretical prediction of the ratio of the widths, e.g., the $SU(6)$ or $SU(6)_W$ prediction of $\frac{1}{9}$].

Our data on the photoproduction of ω^0 in reaction (6) will be discussed more fully in a subsequent paper.

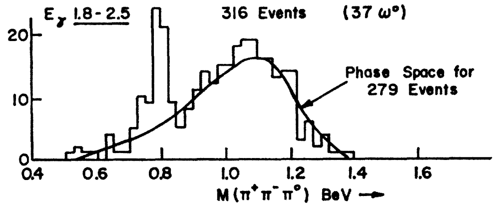

FIG. 10. Invariant $(\pi^+\pi^-\pi^0)$ mass distribution for events interpreted as reaction (6) in the photon-energy range 1.8–2.5 BeV. The solid curve is computed on the basis of pure 4-body phase space. This, and the distributions for other photon energies, is fitted by a Gaussian ω^0 peak at (786±2) MeV with $\sigma=(17\pm2)$ MeV, plus a phase-space background.

Figure 10 shows one example of the clear evidence for ω^0 production in our $(\pi^+\pi^-\pi^0)$ invariant mass distributions. Interpretation of events with a missing neutral is more difficult owing to a number of possible ambiguities. These include: possible interpretation as reaction (1) of cases where the π^0 emerges in the forward direction; our inability to distinguish between reaction (6) and reactions in which more than one π^0 is emitted (owing to our lack of knowledge of the incident photon momentum, events with missing neutrals have zero constraints and can be analyzed only by assuming knowledge of the missing neutral mass); there is a certain residual number of events in which, owing to the high momentum of the positive products, we are unable to decide by bubble counting between reaction (6) and the reaction in which the final products are $N\pi^+\pi^+\pi^-$. All these make the background, computed on the basis of pure 4-body phase space in Fig. 10, somewhat ambiguous. However, making reasonable estimates of these effects, and correcting for the neutral ω^0 decay modes, we obtain

$$\left.\frac{\sigma(\gamma p\to\omega^0 p)}{\sigma(\gamma p\to\rho^0 p)}\right|_{(\exp)} = (4.8\pm0.8)^{-1} \quad (E_\gamma<1.8\text{ BeV})$$
$$= (6.8\pm1.5)^{-1} \quad (E_\gamma=1.8\text{–}2.5\text{ BeV})$$
$$= (6.7\pm1.1)^{-1} \quad (E_\gamma=2.5\text{–}6\text{ BeV}). \tag{9}$$

In the absence of independent information on the magnitude of $\Gamma_{\rho\pi\gamma}$, these values could be consistent with either theory: the OPE model, requiring a large $\Gamma_{\rho\pi\gamma}$ [Eq. (7)], in contradiction to $SU(6)$; or the multiperipheral model, for which the requirement of a small $\Gamma_{\rho\pi\gamma}$ [Eq. (8)] agrees with $SU(6)$.

Another check on OPE, which has the advantage that it is entirely independent of the value of $\Gamma_{\rho\pi\gamma}$, may be obtained by comparing $\rho^0 p$ production in reaction (1) with $\rho^0 N^{*++}$ production in reaction (6). Considering only those events for which the 4-momentum transfer $|t|\leqslant 20m_\pi^2$, OPE theory predicts for this ratio (which is relatively insensitive to the assumed final state absorption)

$$\frac{\sigma(\gamma p\to\rho^0 N^{*+})}{\sigma(\gamma p\to\rho^0 p)}\geqslant 0.35 \tag{10}$$

depending on the particular theoretical technique adopted for treating the π-N^* vertex.[4,9] In fact, we find no evidence for $\rho^0 N^{*+}$ production in reaction (6), thus permitting us to establish an upper limit to this ratio of 0.05 for $E_\gamma>1.8$ BeV. It is thus unlikely that OPE can be the dominating mechanism in both of these reactions.

IV. SUMMARY AND CONCLUSIONS

Our observations on the photoproduction of ρ^0 mesons in reaction (1) suggest very strongly that the OPE mechanism does not play an important role. Besides those aspects (energy dependence of total and forward cross sections, decay angular distributions) in which the experiments clearly disagree with the OPE predictions, the value of $\Gamma_{\rho\pi\gamma}$ required to achieve the magnitude of observed cross sections seems unreasonably large.[15] On the other hand, the diffraction model, at least in those aspects for which theoretical predictions are available,[4] is supported by our experiment, a result which is concurred with by a recent counter experiment.[6]

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[15] We had already observed this in our earlier report (Ref. 1), but we had not at that time performed computations taking into account final-state absorption, nor did our then limited statistics at the highest energies permit an accurate analysis of the energy dependence. Hence, we underestimated there the magnitude of $\Gamma_{\rho\pi\gamma}$ needed.