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PHOTOPRODUCTION OF ω MESONS IN A
HYDROGEN BUBBLE CHAMBER BY 3 AND 5 GeV
LINEARLY POLARIZED PHOTONS

William Jesse Podolsky
(Ph. D. thesis)

May 4, 1971

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TABLE OF CONTENTS

ABSTRACT.	v
I. INTRODUCTION	1
II. THEORETICAL BACKGROUND	4
A. Vector Dominance and Vector-Meson Photoproduction.	4
B. Total Photoproduction Cross Section.	13
C. One-Pion Exchange.	14
D. Are There More Vector Mesons?.	17
E. Summary.	18
III. EXPERIMENTAL PROCEDURE	19
A. The SLAC Backscattered Photon Beam	19
B. Beam and Chamber Characteristics	24
C. Scanning and Measuring	28
IV. CHANNEL CROSS SECTIONS	34
A. General Procedure.	34
B. Four-Body Channels	34
C. Multineutral Channels, Especially Five-Body.	38
V. OMEGA PRODUCTION	44
A. The $\pi^+ \pi^- \pi^0$ channel; ω and η production.	44
B. Omega Decay and Density Matrix	49
C. Discussion of ω Results.	54
D. Comparison with Vector Dominance	64
VI. PRODUCTION OF ρ , Δ , and A_2 IN FOUR-BODY FINAL STATES	67
A. The Channel $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$	67
B. The Channel $\gamma p \rightarrow \pi^+ \pi^- \pi^+ n$	70
VII. B-MESON PRODUCTION	74
VIII. CONCLUSIONS.	87
ACKNOWLEDGMENTS	89
APPENDIX A: CROSS SECTIONS FOR ZERO-CONSTRAINT CHANNELS.	91
APPENDIX B: TWO SHORT PROOFS: Φ AND P_0	100
APPENDIX C: APOTHEOSIS OF VECTOR DOMINANCE	104
REFERENCES	105
FIGURES	115

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PHOTOPRODUCTION OF ω MESONS IN A
HYDROGEN BUBBLE CHAMBER BY 3 AND 5 GeV
LINEARLY POLARIZED PHOTONS.*

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May 4, 1971

ABSTRACT

We have studied photoproduction at 2.8 and 4.7 GeV with a mono-energetic, linearly polarized photon beam in a hydrogen bubble chamber. Since this experiment was the first to use the backscattered-laser-beam facility at SLAC, we describe the beam in some detail. At our energies the beam polarization is greater than 90%. The beam is virtually free of bremsstrahlung background, and the energy resolution (FWHM) is 0.15 GeV at $\bar{E}_\gamma = 2.8$ GeV and 0.35 GeV at $\bar{E}_\gamma = 4.7$ GeV. Our exposure produced 92 events/ μb cross section at 2.8 GeV and 151 events/ μb at 4.7 GeV.

We have made a detailed study of the reaction $\gamma p \rightarrow \omega p$ in the channel $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$. Knowledge of the beam energy allowed us to obtain a clean sample of this channel, including 700 ω events with very little background. We find $\sigma(\gamma p \rightarrow \omega p) = 5.3 \pm 0.5 \mu\text{b}$ at 2.8 GeV and $3.0 \pm 0.3 \mu\text{b}$ at 4.7 GeV.

With polarized photons we have been able to determine nine independent parameters of the ω density matrix (compared with three parameters measured in previous experiments with unpolarized beams). We employ a linear combination of the parameters to project cross sections from natural-parity exchange (σ^N) and from unnatural-parity exchange (σ^U). For $|t| < 1.0 \text{ GeV}^2$, we find

$$\sigma^N = 2.3 \pm 0.4 \mu\text{b}, \sigma^U = 2.6 \pm 0.4 \mu\text{b} \text{ at } 2.8 \text{ GeV},$$

$$\sigma^N = 1.7 \pm 0.3 \mu\text{b}, \sigma^U = 1.2 \pm 0.25 \mu\text{b} \text{ at } 4.7 \text{ GeV}.$$

*Work done under the auspices of the U. S. Atomic Energy Commission.

[†]NSF graduate fellow.

Our results agree with predictions of a hybrid model employing both diffractive ω production and one-pion exchange.

Comparing ω photoproduction with our Söding-model fits for $\gamma p \rightarrow \rho^0 p$,⁸⁹ we find that $\sigma^N(\rho^0)/\sigma^N(\omega) = 7.3 \pm 1.2$ at 2.8 GeV and 9.3 ± 1.7 at 4.7 GeV, consistent with predictions of vector dominance (VDM) plus SU(3). However, assuming VDM and the quark model, we find the coupling $f_\omega^2/4\pi = 26 \pm 6$, compared with 14 ± 2.8 measured in the Orsay colliding rings.^{40c}

We also report cross sections for channels with zero, one, or more neutral particles, and for reactions with η , A_2^+ , f , ρ , Δ , and $\rho\Delta$.

We find evidence for production of a neutral meson decaying into $\pi^+ \pi^-$ (+neutrals), consistent with $\omega \pi^0$ (1534). The cross section for $|t| < 0.5 \text{ GeV}^2$ is $1.0 \pm 0.6 \mu\text{b}$ at 2.8 GeV and $1.4 \pm 0.6 \mu\text{b}$ at 4.7 GeV. This meson may be the B^0 or possible ρ'^0 .

I. INTRODUCTION

We report results from a bubble-chamber photoproduction study with linearly polarized monoenergetic photons at 2.8 and 4.7 GeV. Our experiment was the first to employ the backscattered photon beam¹ at the Stanford Linear Accelerator Center (SLAC). The SLAC 82-inch hydrogen bubble chamber (reborn from the LRL 72-inch chamber) served as target and detector. This experiment was carried out by a collaboration of groups from the Lawrence Radiation Laboratory at Berkeley (LRL), SLAC, Tufts University, and the University of California at Berkeley (UCB), and preliminary results have already been published.²⁻⁹

The thesis of Kenneth C. Moffeit⁹ concerned principally the 3-constraint (3-C) channel

$$\gamma p \rightarrow p \pi^+ \pi^-, \quad (\text{Channel 1})$$

including $\rho^0 p$ and $\Delta^{++} \pi^-$ production. In this work we treat the 0-C channels

$$\gamma p \rightarrow p \pi^+ \pi^- \pi^0, \quad (\text{Channel 2})$$

$$\gamma p \rightarrow \pi^+ \pi^+ \pi^- n, \quad (\text{Channel 3})$$

etc., with emphasis on ωp photoproduction.

In Part II we discuss some of the theoretical motivation for this work. Part III is devoted to a description of the experimental procedure and our unique photon beam. In part IV we compare our channel cross sections with other experiments and a simple isospin model. Part V deals with η and ω production in Channel 2. We describe the ω decay in terms of an extended density matrix which includes correlations with the beam polarization; from this analysis we separate the cross sections for ω produced by exchange of natural parity [$P = (-1)^J$] and unnatural parity [$P = -(-1)^J$] in the t channel. Part VI concerns ρ , $\Delta(1236)$, and A_2 production in channels 2 and 3. In Part VII we present evidence for photoproduction of a 1250-MeV meson, which may be the B^0 or the postulated ρ' . Because this meson decays into $\pi^+ \pi^- + 2$ or more neutrals, its decay cannot be completely reconstructed; however, it appears as a bump in the mass recoiling from the proton.

Our experiment has many unique advantages stemming from our polarized monochromatic beam and the bubble chamber technique. No counter group has yet tried to do a general study of photoproduction reactions with missing neutrals, though there have been missing mass experiments of the type $\gamma p \rightarrow p M$.¹⁰ Two groups¹¹⁻¹² have reported

cross sections for ω photoproduction from heavy nuclei (Be-Pb) as well as hydrogen,^{11b} but they were unable to separate ωp from inelastic (e.g., $\omega \Delta^0$) production. Further ω experiments are proposed at Daresbury.¹³

Some of our results can be compared with the bubble chamber¹⁴⁻¹⁹ and streamer chamber²⁰ experiments listed in Table I. Most of the beam flux in these experiments came from bremsstrahlung, so that there were many more low-energy than high-energy photons; the bremsstrahlung spectrum made it difficult to analyze final states with neutral particles. In contrast to the other experiments, our monoenergetic beam allowed a clean separation of these states. Moreover, for photon energies > 2.5 GeV we have substantially better statistics than the other bubble chamber experiments.

Our greatest advantage, however, was the high degree ($> 90\%$) of linear polarization for our beam. The full description of vector meson photoproduction requires 12 complex amplitudes, or 23 real numbers at a given energy and momentum transfer.* With our polarized beam we have measured 10[†] of the 23 parameters, vs only 4 measured with unpolarized beams.^{21, 22}

* We sketch the proof in terms of helicity amplitudes: there are (2 photon helicity states) x (2 initial proton states) x (2 final proton states) x (3 vector meson states), yielding 24 complex amplitudes, which are functions of energy and scattering angle or the Mandelstam variables (s, t). We will always assume parity conservation, so that only 12 of these are independent. The 12 amplitudes can be written in terms of 23 real parameters and an arbitrary overall phase. For a specific parameterization, see Schilling, Seyboth, and Wolf.²¹

† Nine density-matrix parameters and the differential cross section.

II. THEORETICAL BACKGROUND

A. Vector dominance and Vector-Meson Photoproduction

In this section we introduce a few of the elementary concepts of vector dominance, $SU(3)$, and diffraction scattering that appear frequently in the interpretation of photoproduction. Further details can be found in the many excellent review articles²³ and the references therein.

In classical electromagnetic (em) theory the em field and current transform like vectors under spatial rotation and parity. In second quantization the massless²⁴ quanta of the em field are called photons; according to the correspondence principle, the photon has spin $J = 1$ and negative parity P . Since the leptonic em current is odd under charge conjugation C , we assume the same for the hadronic current. The suggestion of a $C = +$ component has had no experimental verification.²⁵ The electric charge is given by the space-integral of the timelike component of the em current: $Q = e \int J_0 d^3 \vec{x}$. The proton-neutron charge difference then implies that the em current must have both isoscalar and isovector components. We will consider only isospin 0 and 1, although the possibility of an isotensor component has not been ruled out.^{26,9} We refer to the photon as a massless particle with $J^{PC} = 1^{--}$ and a definite mixture of isospin 0 and 1 (Eq. 3 below).

The theory of vector dominance predates the discovery²⁷ of vector mesons. In 1957 Nambu postulated an isoscalar vector meson²⁸ to explain the nucleon form factors observed in electron-nucleon scattering.²⁹ Frazer and Fulco showed in 1959 that an isovector vector meson was also needed to explain the data.³⁰ In 1960 Sakurai proposed yet another $I = 0$ vector meson.³¹ The discovery of the ρ ,³² ω ,³³ and ϕ ³⁴ mesons in 1961-62 fulfilled these predictions. Their quantum numbers are now well established as $J^{PC} = 1^{--}$,^{32,33,35,36} along with the $K^*(890)$,²⁷ they fill an $SU(3)$ nonet.³⁷ If we neglect the small $\rho^0 - \omega$ mixing,⁷ the isospin (G -parity) is $I^G = 1^+$ for the ρ and 0^- for the ω and ϕ .³⁶

Since the nonstrange neutral vector mesons and photon all have $J^{PC} = 1^{--}$, it is appealing to postulate that the photon interacts with hadrons like a coherent mixture of ρ^0 , ω , and ϕ :

Table I. Comparison of bubble and streamer chamber photoproduction experiments.

Reference	Laboratory, Chamber	Beam Energy (GeV)	Number events with energy > 2.5 GeV ^a	
			$\gamma p \rightarrow \pi^+ \pi^- p$	$\gamma p \rightarrow \omega p$
This paper	SLAC 82" HBC	2.8+4.7	5764	700
This group	SLAC 82" HBC	9.3	3000 (in progress)	
14	DESY 85-cm HBC	5.8 ^b	2307	250
15(a)	CEA 12" HBC	6.0 ^b	527	50
16, 19	SLAC 40" HBC	5.2 ^c	538	300
16(a), 19	SLAC 40" HBC	7.5 ^c	800	
17, 19	SLAC 40" HBC	4.3 ^c	≥ 372	
20(a)	SLAC Streamer	16.0 ^b	400	50
20(b)	SLAC Streamer	18.0 ^b	2500 (in progress) ^d	

^a The cross section for $\pi^+ \pi^- p$ decreases slowly from 30 μb at 2.8 GeV to about 15 μb at 14 GeV. The ωp cross section decreases more rapidly (see Fig. 13).

^b Bremsstrahlung end point.

^c Positron annihilation peak with bremsstrahlung background.

^d Events above 4.5 GeV. Since only half the 3-prong events have been measured, this comparison underestimates the 3-prong statistics.

$$\left\{ \begin{array}{c} \gamma \\ \text{hadrons} \end{array} \right\} = \sum \langle V | \gamma \rangle \begin{array}{c} V \\ \text{hadrons} \end{array}$$

where $V = \rho^0, \omega, \phi$. More formally, we can postulate the current-field identity,^{31, 38, 39}

$$J_\mu = \sum_V \frac{m_V^2}{f_V} V_\mu, \quad (1)$$

where J_μ is the hadronic contribution to the em current, and the V_μ are the renormalized ρ^0, ω , and ϕ fields. The f_V are constants (some authors use $2\gamma_V$) which must be determined, and the m_V are the vector-meson masses.

Equation 1 contains the essence of the vector dominance model (VDM). There are two implicit assumptions that may have to be relaxed:

(a) The known vector mesons ρ^0, ω , and ϕ saturate the em current.

In principle there could be more vector mesons (perhaps an infinite number) that contribute. There could also be contributions from a continuum of hadronic states or family of Regge trajectories (see Section II-D).

(b) The constants f_V vary slowly (or not at all) with the mass of the photon. That is, f_V should be about the same whether measured for real ($m_\gamma^2 = 0$), spacelike ($m_\gamma^2 < 0$), or timelike ($m_\gamma^2 > 0$) photons. Examples of such measurements can be found, respectively, in photoproduction, electroproduction, and vector-meson production in colliding electron-positron rings.

A variety of experiments have been performed to test VDM, with mixed success.²³ For many of these the interpretations involve further theoretical assumptions, so that it is often hard to determine whether VDM or the other assumptions have failed. The failure

of VDM to explain the nucleon isovector form factor (see Section II-D) brings assumption (a) into question. The different values obtained for f_ρ in some photoproduction experiments²³ and colliding-beam experiments⁴⁰ leave (b) vulnerable. However, if it should be necessary to abandon either (a) or (b), then VDM would lose much of its attractiveness.

From the current-field identity we can derive the relation between photon and meson amplitudes

$$A(\gamma X \rightarrow Z) = \sum_V \frac{e m_V^2}{f_V} \frac{1}{m_V^2 - m_\gamma^2} A(VX \rightarrow Z), \quad (2a)$$

where X and Z are hadronic states, $e = \sqrt{4\pi\alpha}$ = proton charge, $\alpha \approx 1/137$, and $(m_V^2 - m_\gamma^2)^{-1}$ is the meson propagator. (For our purposes we could take Eq. 2a as the VDM hypothesis and ignore the full implications of Eq. 1.³⁹) For photoproduction the photon is real, so that

$$A(\gamma X \rightarrow Z) = \sum_V \frac{e}{f_V} A(V_{tr} X \rightarrow Z), \quad (2b)$$

where the subscript (tr) means that we are to consider only transversely polarized vector mesons, since at $m_\gamma^2 = 0$ gauge invariance requires that the photon have only helicity ± 1 . For real meson processes, however, this prescription is ambiguous. There is an infinite family of reference frames differing in the choice of the quantization axis; only in the limit of zero rest mass are these

frames equivalent.^{23e} The correct choice of frame (if there is a correct choice) is still in theoretical limbo.*

We now consider what the constants f_v should be. The fraction of isospin 0 and 1 for the photon is given by SU(3), if we assume that the photon transforms like the U-spin singlet member of an SU(3) octet. Then the photon state is

$$|\gamma\rangle \propto \sqrt{3} |\rho^0\rangle - |8\rangle, \quad (3)$$

where $|8\rangle$ is the isosinglet member of the vector-meson octet.⁴¹ The proof follows.

*With Eq. 2b and time reversal we can derive

$$A(\gamma p \rightarrow \pi^+ n) = \sum_v \frac{e}{f_v} A(\pi^+ n \rightarrow v_{tr} p) \quad \text{and}$$

$$A(\gamma n \rightarrow \pi^- p) = \sum_v \frac{e}{f_v} A(\pi^- p \rightarrow v_{tr} n).$$

These VDM relations have been extensively studied (the literature can be traced from Ref. 23). They predict that the asymmetry for π^+ photo-production by polarized beams is simply related to the density-matrix elements for ρ^0 and ω produced by pion beams. These relations agree with experiment only if the density matrix is calculated in a special frame. Then the cross sections agree if $f_\rho^2/4\pi \approx 1.0-1.6$, somewhat smaller than the values obtained for colliding beams.⁴⁰

In this experiment we have not attempted to measure the $\pi^+ n$ production cross sections or asymmetry, because at 2.8 and 4.7 GeV

- (a) scanning efficiency for one-prong events is mediocre;
- (b) the cross section for $\gamma p \rightarrow \pi^+ n$ is small ($\sigma \approx 20 \mu\text{b GeV}^2/E_\gamma^2$) compared with the total one-prong cross section, making separation of $\pi^+ n$ from multineutral channels difficult; and
- (c) these measurements are well suited for counter experiments.

[The octet assumption is motivated by the Gell-Mann-Nishijima formula⁴² for the electric charge, $Q = e(I_3 + Y/2)$, where Y = hypercharge. The photon must have $U = 0$, since all members of a U-spin multiplet have the same charge (i.e., couple equally to the photon). Equation 3 can be derived most easily by noting that the isospin raising operator I_+ and U-spin lowering operator U_- commute.⁴³ We define the orthogonal linear combinations with $U = 0$ and 1 as

$$|\gamma\rangle \propto |U=0\rangle = \alpha |\rho^0\rangle - \beta |8\rangle$$

$$|U=1\rangle = \beta |\rho^0\rangle + \alpha |8\rangle,$$

where $\alpha^2 + \beta^2 = 1$. Then by a sequence of SU(2) operations we have

$$U_- I_+ |K^{*0}\rangle = U_- |K^{*+}\rangle = |\rho^+\rangle,$$

$$= I_+ U_- |K^{*0}\rangle = I_+ \sqrt{2} [\beta |\rho^0\rangle + \alpha |8\rangle] = 2\beta |\rho^+\rangle.$$

Therefore $\beta = 1/2$ and $\alpha = \sqrt{3}/2$.]

The state $|8\rangle$ is a linear combination of ω and ϕ :

$$|8\rangle = -\sin \theta_Y |\omega\rangle + \cos \theta_Y |\phi\rangle, \quad (4)$$

where the mixing angle θ_Y is given by Lipkin's quark model⁴⁴ to be $\arcsin \sqrt{1/3} = 35.3$ deg. The experimental value of θ_Y lies in the range 30 to 50 deg., depending on the model used in evaluation.³⁹ For ideal quark-model mixing, Eqs. 3 and 4 imply

$$|\gamma\rangle \propto 3 |\rho^0\rangle + |\omega\rangle - \sqrt{2} |\phi\rangle. \quad (5)$$

Comparing this with Eq. 1 or 2, we predict

$$f_\rho^{-2} : f_\omega^{-2} : f_\phi^{-2} \approx 9 : 1 : 2 \quad (6)$$

for ideal mixing. Symmetry breaking can alter this ratio, e.g., to 9 : 1.2 : 1 (Ref. 45) or 9 : 0.65 : 1.33 (Ref. 46) (see also Table 3 in Ref. 40b).

The experimental values of f_V have been derived by a variety of methods, with different answers (e.g., values for $f_V^2/4\pi$ range from 1 to 5). These constants can be measured "directly" in electron-positron collisions, since the cross section for $e^+e^- \rightarrow V$ is proportional to f_V^{-2} (evaluated at $m_V^2 = m_V^2$). Since colliding-beam experiments present perhaps the fewest problems with background or theoretical ambiguity, their results have become a standard for comparison. The values found at Orsay are⁴⁰:

$V =$	ρ	ω	ϕ
$\frac{f_V^2}{4\pi}$	1.99 ± 0.19	14.0 ± 2.8	11.0 ± 0.9 with finite-width factor
	1.86 ± 0.17	14.0 ± 2.8	12.9 ± 1.1 without finite-width factor.

(For comparison, Eq. 6 would predict

$$\frac{f_V^2}{4\pi} \approx 1.55 \quad 14 \quad 7 \quad \text{normalized to } f_\omega^2)$$

In this work we are especially concerned with the diffraction-dissociation model of vector meson photoproduction.^{47,48} Since high-energy πp and $K p$ scattering exhibit large forward elastic peaks, it is natural to expect (especially in the light of SU(6) or quark models) that vector mesons would show the same behavior. In classical wave theory a forward diffraction peak is imposed by absorption -- wave fronts reradiating from all parts of the scatterer add coherently in the forward direction to yield an amplitude proportional to the total scattering area. By analogy, forward elastic scattering is said to exhibit a "diffraction peak". The optical theorem states that

$$\frac{d\sigma}{dt}(t=0) = \frac{1+\beta^2}{16\pi} \sigma_T^2, \quad (7)$$

where t is the square of the four-momentum transfer, β is the ratio of the real to imaginary parts of the forward amplitude, and σ_T is the total cross section. For πp scattering the forward differential cross section decreases with $|t|$ roughly as e^{at} , where $a \approx 8 \text{ GeV}^{-2}$ and $t < 0$. Somewhat loosely, in Regge language we associate

diffraction scattering with "Pomeron (P) exchange", where P represents a trajectory with the quantum numbers of the vacuum: an SU(3) singlet with $C = +$ and signature $= +$. The P trajectory dominates elastic scattering at high energy, and if $\sigma_T \rightarrow \text{constant}$ as $E \rightarrow \infty$, then the Pomeron "spin" α_P is 1 at $t = 0$.

The early data on $\gamma p \rightarrow \rho^0 p$ (see, e.g., references given in Ref. 48) showed a forward peak like e^{at} . The reaction cross section fell only slowly with increasing energy, in contrast to the E_γ^{-2} behavior expected for one-pion exchange (OPE). This lent support to the picture that the photon "dissociates" into ρ^0 , ω , and ϕ , which then scatter "elastically" as in Fig. 1a,c (there is a minimum momentum transfer $P_{\min} \approx m_V^2/2E_\gamma$ for the meson V to scatter onto its mass shell.) By "elastic" scattering we mean the assumption that the ρ^0 , ω , and ϕ retain their identities in the scattering process (e.g., Fig. 1a,c). In particular, we neglect $Vp \rightarrow V'p$ for $V \neq V'$. Then by specializing Eq. 2b, we have*

$$A(\gamma p \rightarrow Vp) = \frac{e}{f_V} AA(Vp \rightarrow Vp). \quad (8)$$

Taking Eq. 8 at $t = 0$ (which is not quite physically accessible) and using Eq. 7, we have

$$\begin{aligned} \frac{d\sigma}{dt}(\gamma p \rightarrow Vp)_{t=0} &= \alpha \frac{4\pi}{f_V^2} \frac{d\sigma}{dt}(Vp \rightarrow Vp)_{t=0} \\ &= \alpha \frac{4\pi}{f_V^2} \frac{1+\beta_V^2}{16\pi} \sigma_T^2(Vp), \end{aligned} \quad (9)$$

where $\alpha = e^2/4\pi \approx 1/137$.

*For dipion photoproduction Ross and Stodolsky take the ρ^0 propagator to be $m_{\pi\pi}^{-2}$, where $m_{\pi\pi}$ is the mass of the final dipion, so that the amplitude on the right side of Eq. 8 is multiplied by $(m_\rho/m_{\pi\pi})^2$; the corresponding expression for the cross section is then multiplied by $(m_\rho/m_{\pi\pi})^4$. This factor was advanced as an explanation for the shift and skewing of the ρ^0 mass shape seen in photoproduction. We discuss this matter in detail elsewhere.^{3,9}

For ρ^0 photoproduction on beryllium, β has been measured to be -0.2 ± 0.1 ,⁴⁹ in agreement with β for $\pi^\pm p \rightarrow \pi^\pm p$.⁵⁰ We will assume that $\beta^2 \ll 1$ for ωp scattering as well, as suggested by the quark model.* Equation 9 can be used to determine either $f_V^2/4\pi$ [assuming we know $\sigma_T(Vp)$] or σ_T [assuming $f_V^2/4\pi$]. As a "simplest assumption" we might conjecture that $\sigma(\omega p) = \sigma(\omega p) = \sigma(\pi p) = \sigma(Kp)$. These equalities would follow from the picture of mesons as quark-antiquark pairs,^{44,52} where the scattering force (e.g., P exchange) treats all quarks equally. (The last equality, of course, is empirically false for energies < 40 GeV.) With Eqs. 6 and 9, then, this predicts that

$$\sigma(\gamma p \rightarrow \rho^0 p) : \sigma(\gamma p \rightarrow \omega p) : \sigma(\gamma p \rightarrow \phi p) = 9 : 1 : 2. \quad (10)$$

Harari^{23a,53} has given an alternative derivation of Eq. 10 which does not use the quark model or VDM. He assumed that the photon is described by Eq. 5 and is entirely SU(3) octet, that the t-channel exchange is pure SU(3) singlet, and that SU(3) is conserved at the photon vertex.[†]

* From $\pi^\pm p$ scattering Okada⁵¹ estimates that $\beta_\rho \approx -0.2$ and $\beta_\omega \approx -0.07$. His estimate of $\beta_\phi \approx -0.5$ is somewhat surprising, but the uncertainties in the $K^\pm p$ data make this result less firm.

† Note that the Ross-Stodolsky⁴⁸ and Harari^{23a,53} models are not quite consistent with each other. Ross and Stodolsky take the view that in photoproduction we study scattering of ρ^0 , ω , and ϕ -- states which include both SU(3) octet and singlet. That is, the ω - ϕ mass difference introduces an SU(3) singlet component "before" the scattering. The Harari model holds that only the octet state scatters. We have adopted the Ross-Stodolsky view in Fig. 1 and Eq. 9. For further discussion on this point see Section III of Ross and Stodolsky.

Early experiments showed that the ratios in Eq. 10 were badly violated.^{14,15} Not only was $\sigma(\gamma p \rightarrow \omega p)$ larger than $1/9 \sigma(\gamma p \rightarrow \rho^0 p) \approx 2 \mu b$, but also it decreased rapidly with increasing photon energy. This behavior was explained by assuming that both P-exchange (Fig. 1a) and OPE (Fig. 1b) contributions are important for ω photoproduction below 6 GeV.¹⁴ The diffractive cross section σ_D was assumed to be almost constant and the OPE cross section to fall as $E_\gamma^{-1.6}$; σ_D was found to be $1.9 \pm 0.9 \mu b$, consistent with $1/9 \sigma(\gamma p \rightarrow \rho^0 p)$.¹⁴

Somewhat harder to explain was the observation that $\sigma(\gamma p \rightarrow \phi p)$ was small ($\approx 0.5 \mu b$) and relatively constant from 2.5 to 18 GeV.^{10,14} This value is about 10% of that expected from Eq. 10. The explanation advanced was that $\sigma_T(\phi p)$ was smaller than $\sigma_T(\rho^0 p) \approx \sigma_T(\omega p)$. Using Lipkin's quark model,⁴⁴ Joos⁵⁴ derived (for our energies)

$$\begin{aligned} \sigma(\rho^0 p) &= \sigma(\omega p) = \frac{1}{2} [\sigma(\pi^+ p) + \sigma(\pi^- p)] \approx 30 \text{ mb}, \\ \sigma(\phi p) &= 2 \sigma(K^+ p) - 2 \sigma(\pi^+ p) + \sigma(\pi^- p) \approx 10 \text{ mb}. \end{aligned} \quad (11)$$

Lipkin assumed that the ϕ consists of a strange quark-antiquark pair, and that the ρ^0 and ω contain only nonstrange quarks. To break SU(3) symmetry he assumed that strange quarks have smaller cross sections than nonstrange. Similar conclusions were derived from Regge models by considering P' (identified with the f meson) and A_2 exchange as well as P exchange (see Fig. 1).⁵⁵ Since σ_T is squared in Eq. 9, a three-fold suppression in $\sigma_T(\phi p)$ results in a nine-fold suppression in $\frac{d\sigma}{dt}(\gamma p \rightarrow \phi p)$ at $t=0$.

With allowances for a smaller ϕp cross section and an OPE contribution to ω photoproduction (see Section II-C), the diffraction-dissociation model has been fairly successful. We will discuss this more quantitatively in Section V-D.

B. Total Photoproduction Cross Section⁵⁶

In VDM the Compton amplitude given by Eq. 2b is

$$A(\gamma p \rightarrow \gamma p) = \sum_V \frac{e}{f_V} A(\gamma p \rightarrow V_{tr} p).$$

At $t = 0$ the optical theorem gives*

$$\begin{aligned} \sigma_T(\gamma p) &= \sum_V \frac{e}{f_V} \left[\frac{16\pi}{(1+\beta_V^2)} \frac{d\sigma}{dt} (\gamma p \rightarrow V_{tr} p)_{t=0} \right]^{1/2} \\ &= \sum_V \pm \left[\frac{4\pi\alpha}{f_V^2} \frac{16\pi}{1+\beta_V^2} \frac{d\sigma}{dt} (\gamma p \rightarrow V_{tr} p)_{t=0} \right]^{1/2}. \end{aligned} \quad (12)$$

The η contribution is presumably negative, but since $\sigma(\gamma p \rightarrow \eta p) \ll \sigma(\rho^0$ or $\omega)$, its effect is small. The assumptions for Eq. 12 are

(a) only coherent amplitudes contribute to the forward cross sections (e.g., Figs. 1 a, c, d, but not Fig. 1b); and

(b) only transverse vector mesons (helicity ± 1) are included. These conditions are satisfied experimentally in ρ^0 photoproduction.^{4,9} The OPE contribution spoils this for the ω . However, in Section V we show that we can remove the OPE contribution; presumably the remaining ω cross section satisfies conditions (a) and (b). In this experiment we have determined all the cross sections in Eq. 12. If we take β , f_ω , and f_ρ as given, we can evaluate $f_\rho^2/4\pi$.

*In principle the terms in Eq. 12 could enter with arbitrary phase; but in the spirit of our simple models, we will assume that the relative ρ^0 , ω , η phases are 0, 0, π , respectively. See also Ref. 231.

C. One-Pion Exchange

We next use VDM to calculate the relative strengths of the coupling constants $g_{\pi V \gamma}$ for the vertices .

First we note that conservation of G-parity implies that the couplings $\pi V V$ and $\pi \omega \omega$ vanish. Moreover, the $\pi \rho \rho$ coupling must be much weaker than $\pi \omega \omega$ because from the measured decay rates³⁶ ($\Gamma = g^2 \times \text{K.F.}$, where K.F. is the appropriate kinematic factor⁴⁰) we find

$$\frac{\Gamma(\omega \rightarrow \pi^+ \pi^- \pi^0)}{\omega \text{ K.F.}} \approx 100 \frac{\Gamma(\phi \rightarrow \pi^+ \pi^- \pi^0)}{\phi \text{ K.F.}}.$$

(This weak ϕ coupling is also consistent with simple quark-model rules.) Neglecting $\pi \rho \rho$ coupling, we assume the VDM diagrams

$$\begin{aligned} \gamma \rightarrow \rho \pi &= \gamma \rightarrow \rho \pi \omega \rightarrow \rho \pi \\ [g_{\pi \rho \gamma} &= \frac{e}{f_\omega} g_{\pi \rho \omega}] \\ \gamma \rightarrow \omega \pi^0 &= \gamma \rightarrow \omega \pi^0 \rho^0 \rightarrow \omega \pi^0 \\ [g_{\pi \omega \gamma} &= \frac{e}{f_\rho} g_{\pi \omega \rho}] \end{aligned}$$

Then from Eq. 6 we find the ratios

$$g_{\pi \rho \gamma} : g_{\pi \omega \gamma} : g_{\pi \eta \gamma} \approx 1 : 3 : 0 \quad (13a)$$

where by isospin invariance and G-conservation we have

$$g_{\pi^+ \rho^+ \gamma} = g_{\pi^- \rho^- \gamma} = g_{\pi^0 \rho^0 \gamma} = g_{\pi \rho \gamma}. \quad (13b)$$

We note that the decay rate for $V \rightarrow \pi \gamma$ is given by⁵⁷

$$\Gamma(V \rightarrow \pi \gamma) = \frac{g_{\pi V \gamma}^2 (m_V^2 - m_\pi^2)^3}{4\pi \cdot 24m_V^3}. \quad (14)$$

From the ω width and branching fraction^{36*} we find $\Gamma(\omega \rightarrow \pi^0 \gamma) = 1.06 \pm 0.16 \text{ MeV}$, which implies $g_{\pi \omega \gamma}^2/4\pi = 0.06 \pm 0.01 \text{ GeV}^{-2}$ (or $23 \pm 4 \mu\text{b}$, in societies where $\hbar c = 1$).

*Assuming that $\pi^0 \gamma$ is the only neutral decay mode. Dakin finds, however, that $\pi^0 \gamma$ accounts for $65 \pm 7\%$ of all neutral decays.⁵⁸ His result disagrees with some earlier works (see references in Ref. 36).

Radiative decays for ρ and ϕ have not been seen. The upper limits are³⁶

$$\Gamma(\rho \rightarrow \pi \gamma) < 0.25 \text{ MeV},$$

$$\Gamma(\phi \rightarrow \pi \gamma) < 0.014 \text{ MeV},$$

consistent with Eq. 13.

If vector-meson photoproduction were dominated by OPE, we would expect $\sigma(\gamma p \rightarrow \omega p) \approx 9 \sigma(\gamma p \rightarrow \rho^0 p)$.^{*} This is in violent disagreement with experiments showing that $\sigma(\gamma p \rightarrow \rho^0 p)$ is larger than $\sigma(\gamma p \rightarrow \omega p)$. Moreover, the absolute magnitude of $\sigma(\gamma p \rightarrow \rho^0 p)$ is much too large for the upper limits on $\Gamma(\rho \rightarrow \pi \gamma)$, and the energy dependence is wrong.⁴⁸ We conclude that OPE cannot play a large role in ρ^0 photoproduction. Our study of the ρ^0 decay parameters confirms this conclusion.^{4,9}

However, since the diffractive cross section for ω is smaller than for ρ , and conversely for OPE, it seems very likely that OPE provides much of the ω photoproduction cross section for energies $< 5 \text{ GeV}$. In the Born approximation the OPE cross section is^{57a}

$$\frac{d\sigma^{\text{OPE}}}{dt}(\gamma p \rightarrow \omega p) = \frac{g_{\pi\omega\gamma}^2 g_{\pi\omega\rho}^2}{4\pi \cdot 4\pi} \frac{\pi}{4E_\gamma^2 4M_p^2} \left[\frac{t-m_\omega^2}{t-m_\pi^2} \right]^2 \quad (15)$$

This naive formula gives too large a cross section for large $|t|$ and must be modified by absorption⁵⁷ and (or) form factors.⁵⁹

For small $|t|$ it gives the correct order of magnitude: with $g_{\pi\omega\gamma}^2/4\pi = 23 \text{ } \mu\text{b}$ and $g_{\pi\omega\rho}^2/4\pi = 14.5$, it yields

$$\frac{d\sigma}{dt}(t = -m_\pi^2) = 48 \text{ } \mu\text{b/GeV}^2 \text{ at } 2.8 \text{ GeV and } 17 \text{ } \mu\text{b/GeV}^2 \text{ at } 4.7 \text{ GeV}.$$

* Note that this is the inverse of the prediction for Pomeron exchange (Eq.10).

A similar formula should hold for $\gamma p \rightarrow A_2^+ n$. Note that C forbids $\gamma p \rightarrow A_2^0 p$ by OPE or Pomeron exchange.

If we assume that OPE dominates the reactions $\gamma p \rightarrow V\Delta$, then Eq. 13 predicts

$$\sigma(\gamma p \rightarrow \omega\Delta^-) = 9 \sigma(\gamma p \rightarrow \rho^0\Delta^+). \quad (16)$$

From the isospin coupling constants,^{*} we have

$$\sigma(\gamma p \rightarrow \rho^-\Delta^{++}) = 3 \sigma(\gamma p \rightarrow \rho^-\Delta^0), \quad (17)$$

$$\sigma(\gamma n \rightarrow \omega\Delta^0) = \sigma(\gamma p \rightarrow \omega\Delta^+) = 6 \sigma(\gamma p \rightarrow \rho^-\Delta^{++}). \quad (18a)$$

Since we are really interested in specific decay modes of the Δ , we write

$$\sigma(\gamma n \rightarrow \omega\Delta^0, \Delta^0 \rightarrow \pi^- p) = 2 \sigma(\gamma p \rightarrow \rho^-\Delta^{++}). \quad (18b)$$

Alternatively, Eq. 16 can be derived from the quark model and ideal mixing (Eq. 6) without assuming OPE.⁶⁰ If we further assume that quark and antiquark cross sections are equal (as required by the Pomanchuk theorem at infinite energy), then Eqs. 17 and 18 also follow.⁶⁰

There is some evidence that these ratios do not hold,^{18,61} perhaps because of ρ exchange. Moreover, the reactions $\gamma p \rightarrow V\pi^0 p$ ($V\pi^+ n$, etc.) can be diffractive in the $\pi^0 p$ ($\pi^+ n$) state has $I = 1/2$.⁶² Therefore any test of OPE in $V\Delta$ photoproduction must separate the Δ from nonresonant background.

* The rates $\Delta^0 \rightarrow \pi^- p : \Delta^0 \rightarrow \pi^0 n : \Delta^+ \rightarrow \pi^0 p : \Delta^{++} \rightarrow \pi^+ p$ are in the ratio 1 : 2 : 2 : 3.

D. Are There More Vector Mesons?

In recent years there has been considerable theoretical and experimental interest in the possible existence of additional vector mesons.^{3,9,10,20b,63-66} For more than a decade it has been known that the nucleon isovector form factor falls away too rapidly at large momentum transfer,^{29b} proportional to $(0.71 \text{ GeV}^2 - t)^{-2}$ rather than the $(m_\rho^2 - t)^{-1}$ predicted by ρ^0 pole dominance. An additional $I = 1$ vector meson, the hypothetical ρ' , could couple to the photon with opposite sign and cancel the asymptotic $1/t$ formfactor from ρ^0 - dominance.⁶³ On the other hand, the cancellation may come from a nonresonant continuum.

In a related approach Di Vecchia and Drago⁶⁷ and Jengo and Remiddi⁶⁸ obtained good fits to the nucleon form factors⁶⁹ with the Veneziano formula.⁷⁰ The Veneziano theory implicitly contains an infinite family of linearly rising Regge trajectories which are parallel and separated by $\Delta J = 1$. Below the leading trajectory (e.g., the ρ trajectory) are an infinite number of "daughter" trajectories. The first daughter will cross $J=1$ at $m^2 \approx 3m_\rho^2$, corresponding to the ρ' pole; similarly, there would be a ρ'' near $5m_\rho^2$, etc.

Another suggestion comes from the quark model, where the known vector nonet is assumed to be a 3S_1 quark-antiquark state. Then the 3D_1 state could correspond to a second vector nonet.⁵²

Besides altering the nucleon and pion form factors, existence of a ρ' would modify many other VDM predictions. The ρ' would contribute to Eq. 12 and modify the mass dependence and energy dependence expected for photonuclear cross sections.

A number of photoproduction searches have looked for a ρ' decay into $\pi^+\pi^-$ ⁶⁵ or $\mu^+\mu^-$ ⁶⁶ (for a comparison of experiments, see Table V in Ref. 23k). No clear resonance has been seen; the product of cross section times branching ratio for these decay modes is $< 1\%$ of that for the ρ^0 . The only suggestive data come from the SLAC spectrometer¹⁰ and streamer chamber.^{20b} The former saw an enhancement in neutral

missing mass $\approx 1.24 \text{ GeV}$, or about the B mass. The streamer-chamber experiment found an enhancement near $m(2\pi^+2\pi^-) \approx 1.55 \text{ GeV}$ in the $\pi\pi^+\pi^-\pi^-$ final state. We will compare our data with these results in Section VII.

E. Summary

In the photodissociation model the photon "dissociates" into ρ^0 , ω , and ϕ mesons, which scatter diffractively from the target. In Regge language it is usual to associate diffraction with exchange of particle trajectories with natural parity, i.e., $P = (-1)^J$. On the other hand, the pion has unnatural parity $P = (-1)^{J+1}$. In Section V we show that our polarized photon beam allows us to determine separately the natural and unnatural parity exchange contributions to vector meson photoproduction. With our total and differential cross sections we then test the expected values of $f_V^2/4\pi$ and $\sigma_T(Vp)$ in Eq. 9.

Through VDM, Eq. 12 connects the total photoproduction cross section^{2,9} (which we were able to determine because of our monoenergetic beam) with vector-meson photoproduction cross sections measured in this experiment.

One-pion exchange is expected to contribute more to ωp photoproduction than to $\rho^0 p$, in contrast to diffractive photoproduction. Because $V\Delta$ and A_2^+ cannot be diffractively photoproduced (they require isospin exchange), we consider OPE as a possible mechanism. We have derived pion coupling constants (Eq. 13) and relative OPE cross sections (eqs. 16-18) to compare with our measurements.

There is reason to expect that additional vector mesons may exist, but they have not been found in $\pi^+\pi^-$ or $\mu^+\mu^-$ decays. With the bubble chamber technique we have investigated other decay modes, and the monoenergetic beam has enabled us to search for multineutral decay modes.

The reader who has endured through this dry review of vector dominance may prefer the one-page treatment in Appendix C.

III. EXPERIMENTAL PROCEDURE

A. The SLAC Backscattered Photon Beam

In 1962 Milburn⁷¹ and Arutyunian et al.⁷² concurrently suggested that high-energy polarized photon beams could be produced by the Compton scattering of laser light from energetic electrons. The high energy, large current, and narrow phase space of the SLAC electron beam were well suited to this method, and serious beam-building began in 1967. Useful photon fluxes at energies from 1.5 to 6.5 GeV were available in early 1969, and energies up to 10 GeV are now available. For this experiment 40% of the data were taken in January-February, 1969, and the remainder in May, 1969.

The beam energy is given by simple two-body kinematics. The initial photons of energy $K = 1.786$ eV collide nearly head-on with the primary electron beam (energy $E \gg m_e = \text{electron mass}$).

The photons which scatter through $\theta_r = 180^\circ$ have a recoil energy

$$K'_{\max} = \frac{4 E^2 K}{s}, \quad (19)$$

where $s = m^2 + 4EK$ is the square of the total energy in the center of mass. (This result can be easily understood in terms of two consecutive Lorentz transformations - from lab to center of mass and back to lab - each with

$$\gamma = \frac{E+K}{\sqrt{s}} \approx \frac{E}{\sqrt{s}} \quad \text{and} \quad \beta \approx 1.)$$

In the electron rest frame the process is ordinary Compton scattering for moderate-energy x-rays: the photon energy $K_r = \frac{2E}{m} K$ is about 100 keV. The cross section was derived from Dirac theory in 1929 by Klein and Nishina,⁷³ and has been well verified at these energies.⁷⁴ The total cross section is

$$\sigma \approx \frac{m^2}{s} \sigma_{\text{Thomson}},$$

where

$$\sigma_{\text{Thomson}} \approx 2/3 \text{ barn.}$$

The final photon energy and depolarization are given uniquely by the scattering angle.^{1a, 74} The energy is

$$K' \approx \frac{K'_{\max}}{1 + \left(\frac{E^2}{s}\right) \theta^2}, \quad (20)$$

where θ is the angle in the laboratory frame between the scattered photon and the incident electron direction. For linearly polarized incident light, the scattered photons retain most of the linear polarization at $\theta = 0$ (180° scattering).^{1a, 74} The energy and polarization of the scattered beam are determined by the collimation angle. We chose a collimator half-angle of 10^{-5} radian, which accepted about 10% of the scattered photons.

The energy resolution is discussed in Section III-B. The beam was easily able to supply 50-100 photons per pulse for optimum HBC exposures. The current system can supply about 10 times this flux.*

* The number of scattered photons accepted in each pulse is

$$N = N_e N_\gamma \frac{\sigma L}{A c t} f,$$

where

N_e = number electrons/pulse $\approx 3 \times 10^{11}$ for 30 mA instantaneous current for 1.5 μ sec,

N_γ = number photons/pulse $\approx 5 \times 10^{18}$ for 1.5 joules of red light in 50 to 100 nsec,

σ = Compton cross section $\approx 5 \times 10^{-25}$ cm²,

L = full length of the beam-beam interaction region ≈ 500 cm (the effective length is $L/2$),

A = area of larger beam in interaction region ≈ 1 cm²

c = 3×10^{10} cm/sec,

t = duration of longer pulse $\approx 1.5 \mu$ sec, and

f = fraction of scattered photons accepted by collimator $\approx 10\%$.

Then the maximum yield is about 1000 photons/pulse, consistent with observation. This margin of safety is largely eliminated for experiments requiring blue laser light -- the second-harmonic generation yields about 12% as many blue photons as red (24% energy efficiency).

Figure 2a is a simplified schematic of the beam facility. The initial photon beam was produced by a Q-switched ruby laser. Although details of the laser assembly were frequently altered, the essential elements are shown in Fig. 2b.* These were modified from a commercial system by Spacera, Inc.

Initially a voltage across the Pockels cell (potassium dideuterium phosphate) made it an effective quarter-wave plate. Spontaneous photons from the ruby were reflected from the rear mirror, but they then had the wrong polarization to pass back through the Brewster stack. About 1 msec before electron beam time, the xenon flash lamps in the laser cavity were fired. When the electrons approached the interaction region, the voltage on the Pockels cell was removed (through a krytron circuit) to permit lasing. The laser pulse was somewhat shorter than 10^{-7} sec, and yielded over 1 joule of red light ($\lambda = 0.6943 \mu$) into a "phase space" about $(0.75 \text{ mrad cm})^2$. Cooling and recharging capacity limited the repetition rate to 2 pps, about the same as the maximum rate for the 82-inch HBC. With the system operating properly there seemed to be no limit to ruby life (many million pulses). Flash lamps had to be changed about every 10^5 flashes.

The Brewster stack assured lasing in a single polarization plane. With the half-wave plate out, the photon beam was polarized vertically at the bubble chamber; when the half-wave plate was inserted, the polarization was horizontal. The polarization direction was alternated (either on every other picture or at intervals of 2600 pictures) to insure an equal flux of both polarization states. The polarization direction was recorded on the HBC film.

The laser light was reflected by two dielectric-coated mirrors into the electron beam pipe and focused to about 1 cm² at the interaction region. There the laser and electron beams collided head-on (the actual crossing angle of 3 mrad is negligible in the electron rest frame).

* The beam has now been used for 8×10^5 pictures with $K'_{\text{max}} = 9.7$ GeV. For these the second harmonic of the laser was necessary. Figure 2b was modified by inserting one or more crystals of ammonium dihydrogen phosphate (ADP) between the ruby and the partial mirror. When properly oriented, the ADP doubled the frequency of the laser output into the far blue ($\lambda = 0.347 \mu$). The conversion efficiency was about 12% blue photons/red photons.

The primary electron beam was collimated to 1 mm diameter at C60 (Fig. 2a); collimator C61 limited the phase space to $(10^{-5} \text{ rad cm})^2$. The horizontal focus at the bending magnet B61 was to minimize unwanted dispersion. Immediately before the interaction region a quadrupole doublet and small dipole magnets served to focus and steer the beam image onto the defining photon collimator QD. Then after colliding with the laser beam, the electrons were dumped by a permanent magnet.

The safety collimator SC4 insured that no bremsstrahlung from electron collimators could reach the HBC; the chamber "saw" only the residual gas (about 10^{-6} torr) in the interaction region. Along with the dispersion of the magnet transport, collimators SC4 and QD limited the acceptance in electron momentum to $\pm 0.5\%$.

In order to weaken the synchrotron radiation seen by the HBC, the final bending and focusing magnets (after B61) used weak fields; the first section of the dump magnet was also weak. The remaining synchrotron radiation was absorbed in 0.16 radiation length of uranium foils in the photon beam beyond the dump magnet.*

Figure 3 shows the profile of the backscattered beam 2 in. before the defining collimator QD. This "photograph" was made with personnel dosimetry (dental x-ray) film by G. Svensson of SLAC. A 2-mm sheet of lead (0.35 radiation length) was placed in front of the film to convert part of the beam into electron pairs. The beam conditions were similar to our 2.8 GeV experiment; the electron energy E was 12.5 GeV, but only one plane of linear polarization was employed. The photograph displays the characteristic azimuthal dependence of Compton scattering, namely $1 - \sin^2 \theta_r \cos^2 \phi$, where $\cot \frac{\theta}{2} = \frac{E}{m} \tan \theta$ and ϕ is the angle between the initial polarization plane and the

* The uranium foils were placed in a sweeping magnet just before SC4 in Fig. 2a. Although the foils reduced the backscattered beam intensity by 11%, they did not contribute bremsstrahlung background at the HBC: the foils produced 1% equivalent bremsstrahlung photons per beam photon, most of which were not directed along our beam line. Even in the absence of sweeping, the typical angles for pair production and bremsstrahlung were $\approx \frac{m}{K} > 10^{-4}$ rad, and multiple scattering angles were $\approx 10^{-3}$ rad. Thus only $\approx (10^{-5})^2 / (10^{-3})^2 = 10^{-4}$ of this background passed through the final collimator.

Compton scattering plane.⁷⁴ The portion of the beam passing through the collimator ($\theta \leq 10^{-5}$ rad) does not have a strong azimuthal dependence.

The defining photon collimator QD, located about 100 m past the interaction region, consisted of a 2-mm diameter hole through 6 inches of Hevimet (tungsten alloy). Four quadrant scintillators surrounded the hole behind the first inch of Hevimet. The showers in these scintillators were compared electronically to determine the beam steering to about 10^{-6} radian and to monitor the beam intensity. Our electronics vetoed picture-taking if the beam was missteered more than $3 \cdot 10^6$ rad or if the intensity was too high or too low. The photon beam was "steered" by steering the electron beam, and the intensity was adjusted by changing laser output or electron-beam current. Details of the collimator and beam control are given in Ref. 1c.

A final lead shield near the 82-inch HBC removed the "spray" and leakage from collimator QD. The beam entered the chamber through thin stainless steel windows (0.02 - 0.04 inches total, corresponding to 0.03 - 0.06 radiation length).

B. Beam and Chamber Characteristics

The 82-in. hydrogen bubble chamber incorporated most of the hardware from the 72-in. Alvarez chamber. A new body was installed with an omega bellows for liquid expansion. The vertical magnetic field had a central strength of 16.6 kG. Elliptically ground "coat hanger" reflectors provided dark-field illumination. The chamber was viewed from above by a three-view camera, which demagnified images 15 to 1 onto a single 16-mm film strip. We were able to take up to two pictures/sec.

Figure 4 shows half of a frame taken during our 2.8 GeV run. The photon beam (about 50 photons/frame) enters the chamber off the bottom of the picture. In this half frame there are three electron-positron pair vertices and a reaction $\gamma p \rightarrow (\omega p) \rightarrow \pi^+ \pi^- \pi^0 p$. The other long tracks are electrons and positrons from earlier pairs; the short tracks are delta rays and Compton electrons. Note that all the pair vertices and the reaction vertex lie along a thin "beam line."

The small diameter of the beam is demonstrated by Fig. 5. Figure 5(a) shows the beam profile head-on. The true beam is contained in a cylinder with a 3-mm diameter. Measuring errors broaden the

apparent Z coordinate (toward the camera) by ± 1 mm. For analysis we defined a fiducial volume for event vertices: an elliptical cylinder centered on the beam with an 8-mm major axis along Z and a 4-mm minor axis. Only a few events lay outside this volume, and they were mostly one-prong or low-energy $\pi^+\pi^-p$ events from secondary photons. Figure 5(b) shows a "side view" of the beam. This view is a sensitive test for uncompensated optical distortions.*

During each bubble chamber run a random sample of e^+e^- pairs was measured to verify the beam energy. Later a larger, more carefully selected⁷⁵ random sample was measured. Since the pair cross section varies only slightly with energy and is well known,⁷⁶ these measurements provided a complete spectrum of the beam energy. In addition they served as a convenient check on measurement quality and optical parameters and provided the dip, azimuth and apparent chamber position for the beam. We found, however, that the pair energy spectrum was broader than expected, because of bremsstrahlung along the $e^\pm$ tracks measured.

Our most reliable energy spectrum was obtained from the 3-C fits (with no constraint on beam energy) to reaction 1 ($\pi^+\pi^-p$). This cross section varies slowly with energy (above 1.5 GeV) and is sufficiently well known from our experiment^{3,9} and others.¹⁴⁻¹⁷ The $\pi^+\pi^-p$ statistics were adequate (about 3000 events at each energy) and were enhanced at lower energies, where we were most in need of statistics. The energy resolution for most fits was within less than 1%, and there was no distortion from bremsstrahlung. The spectrum was sampled uniformly over the experiment, since these were the same events found in our regular scans. For energies below 0.5 GeV (where the $\pi^+\pi^-p$ cross section is small) we relied on the pair spectrum; above 0.5 GeV the two methods were consistent. Figure 6 shows the complete spectrum at each energy.

*Wiggles in earlier plots like Fig. 5(b) and changes in beam dip vs vertex position warned us to improve reconstruction parameters. The chamber optical constants were determined separately for measurements at LRL and SLAC and for the two runs (January-February, 1969, and May, 1969). The apparent beam dip, azimuth, and position were also determined separately. The beam direction could be determined from electron pairs within less than 1 mrad.

Several factors enter into the width and shape of the spectra. The total width given by equation 20 is

$$\frac{\Delta K'}{K'_{\max}} = 1 - \left(1 + \frac{E^2}{s} \theta^2\right)^{-1} \approx \frac{E^2}{s} \theta^2.$$

If the electron beam were a point source, for our collimation angle of 10^{-5} radian the spectrum shape would be roughly trapezoidal with a base width of 4% (6.4%) at 2.8 (4.7) GeV. However, the effective electron source has a 1-mm diameter times a magnification of 1.8, so that there is a low-energy tail extending toward low energies with four times the nominal width. The spread in primary beam momentum ($\pm 0.5\%$) smears the maximum photon energy by $\pm 1\%$. In addition there were long-term changes in electron energy of $\pm 0.5\%$; this caused different parts of the 4.7 GeV run to vary by 0.1 GeV. Beam missteering ($\approx 10^{-6}$ rad) altered the spectrum slightly. And finally the shape reflects a random measurement error of about $\pm 1\%$.

The tail at still lower energies had a different origin. There were a few bremsstrahlung photons from the primary electron beam striking the residual gas of the interaction region. The spatial distribution and very-high-energy spectrum indicate that these account for only part of the low-energy tail. The rest came from secondary bremsstrahlung by beam-produced pairs in the hydrogen and the beam windows.

For fixed E and K, the degree of depolarization in Compton scattering is determined uniquely by θ , or using Eq. 20, by $K'/K'_{\max}$.^{1a} Using the spectra of Fig. 6 we determined that the average linear polarization was 95.6% (93.1%) of the original laser polarization* at 2.8 (4.7) GeV. The average effective linear polarization was 93.3% (91.5%) for the 2.8 (4.7) GeV beams. Most of the error (about 2%) in these numbers reflects uncertainty in the polarization of the red light.* The ρ^0 decay distributions confirm our polarization values to within a few per cent.^{4,9}

The beam and exposure parameters are summarized in Table II.

*The laser output was 100% linearly polarized. A defective half-wave plate (see Fig. 2b) was used for half of the January-February, 1969, data. This reduced the polarization of the laser light and altered its direction. We have compensated for these changes.

Table II. Beam parameters and exposure statistics.

Nominal beam energy E_γ (GeV)	Mean beam energy E_γ (GeV)	Full width at half maximum (GeV)	E_γ limits accepted (GeV)	Electron energy E (GeV)
2.8	2.88	0.15	2.4 - 3.3	12.0
4.7	4.66	0.45 ^a	4.1 - 5.3	16.0

E_γ	Average linear polarization P_γ	Number of pictures	Events per microbarn ^b
2.8	93.3%	293 000	92
4.7	91.5%	452 000	151

^aBroadened by electron energy shifts. For a constant electron energy, the FWHM was about 0.35 GeV.

^bEvaluated for well-measured 3-prong events.

C. Scanning and Measuring

As shown in Table II, we exposed 293 000 frames of film at 2.8 GeV and 452 000 at 4.7 GeV. Half of this film was scanned and measured at LRL, and half at SLAC. The two systems were rather independent, except for the checks described below. Comparisons between the two laboratories helped to improve both systems and to check systematic biases.

All film was scanned twice in independent scans (at the same laboratory), and conflicts were resolved on a third pass. About 10% of the film had four independent scans (two at each laboratory), as a further check on scan efficiency. The scanners recorded all events with three or more outgoing tracks (prongs), as well as two-prong events with nonzero opening angle or secondary scatters. All events with strange-particle decays were recorded, and for 10% of the film single-prong events were also recorded.

In order to allow at least 35 cm of measurable length for forward tracks and 8 cm for backward tracks, we scanned only a 150 cm fiducial volume. * The beam diameter was less than 3 mm (Fig. 5); by setting a straightedge along the line of pair vertices on the scan table, our scanners could determine the center of the beam to within 1 mm. To exclude events and pairs not associated with the beam, the scanning fiducial width was 7.5 mm at LRL and 15 mm at SLAC, centered on the beam line (secondary decays were recorded anywhere in the chamber). For later analysis we required the measured vertex position to fall in the smaller fiducial volume shown in Fig. 5(a).

Because of the narrow beam our scanners needed to look for events only in a small area of the film. However, the actual scan for hadronic tracks or secondary vertices included the whole chamber volume. The average scanning rate was 200 frames/hour.

The scanning background (see Fig. 4) consisted of electron-positron pairs (an average of 7.5 per frame inside the fiducial volume), Compton-scattered electrons, and knock-on electrons (delta rays). Most delta and Compton electrons had low energy and did little to hinder scanning and measuring; but energetic tracks from beam pairs

* All dimensions are given in chamber space. The image on the scan tables was 2/3 life-size.

reduced visibility near the beam line and limited the flux which we could accept. However, most hadronic events "stood out" rather well from the pair background. The pairs had zero opening angle and pointed in the beam direction; the $e^\pm$ tracks had minimum bubble density (the average bubble density of a track is proportional to β^{-2} , where β is the particle velocity). In contrast, most hadronic tracks had dip and (or) azimuth angles different from the beam direction; moreover, many were darker than electron tracks or had secondary scatters.

From our double and quadruple scans we determined that our combined scan efficiency was greater than 99% for all events with three or more prongs, with the exception of 3-prong events with short proton tracks. Most of the scanning loss was for proton tracks shorter than 1 cm, corresponding to a proton momentum of 0.14 GeV/c and $t = -0.02 \text{ GeV}^2$, where t is the square of the four-momentum transfer from target proton to recoil proton. For $|t| < 0.02 \text{ GeV}^2$ there is also some contamination by wide-angle pairs. Losses for $|t| < 0.02 \text{ GeV}^2$ have been corrected by extrapolation from $|t| > 0.02 \text{ GeV}^2$, assuming an exponential t -dependence for $\gamma p \rightarrow \pi^+ \pi^- p$ ⁹ and using Eq. 34 (Section V-C) for $\gamma p \rightarrow \omega p$.

For $0.02 < |t| < 0.1 \text{ GeV}^2$ the quadruple scans indicated that our double-scan losses were larger than calculated from the traditional Geiger-Werner formula. To improve our loss corrections we later made a third independent scan on 25% of the 4.7-GeV film. The extra scans indicated that double-scan losses for 4.7-GeV $\gamma p \rightarrow p^0 p$ were $13 \pm 7\%$ for $0.02 < |t| < 0.05 \text{ GeV}^2$ and much less for larger $|t|$. Within limited statistics we found smaller losses for $\gamma p \rightarrow \omega p$, so that we have corrected the interval $0.02 < |t| < 0.06 \text{ GeV}^2$ by $5^{+10}_{-5}\%$. The 2.8-GeV losses were smaller, requiring no corrections for $|t| > 0.02 \text{ GeV}^2$.

For $0.02 < |t| < 0.05 \text{ GeV}^2$, the p^0 losses were correlated with the beam polarization direction. However, since we have (roughly) equal numbers of events with vertical and horizontal polarization, the angular-distribution biases cancel to first order.

Although electron pairs were the principal background, they provided a means to calculate cross sections with very little bias. Since our beam was nearly monochromatic, and the pair cross section in hydrogen is known to $\pm 0.5\%$,⁷⁶ we were able to normalize our cross sections to the number of pairs counted - namely,

$$\sigma_{\text{event}} = \frac{N_{\text{event}}}{N_{\text{pair}}} \sigma_{\text{pair}}, \quad (21)$$

with only small corrections. Pairs were counted during the event scans in the same fiducial volume as events, and discrepant counts were resolved in a third pass. Counts were made on four frames per roll of 660 frames. More details are given by Moffeit.⁹

At SLAC all events were measured on "conventional" NRI film-plane digitizers. At LRL 80% of the first measurements were made on a Spiral Reader (SR); the remainder, including all remeasurements, were made on a "conventional" Franckenstein (FSN). Events were measured a second or third time if necessary.

Output from the SR was filtered by the program POOH;⁷⁷ the FSN and NRI measurements required little pre-editing. The tracks were reconstructed by TVGP⁷⁸ and fitted to reaction hypotheses in SQUAW.⁷⁹ The hypotheses tried are given in Table III. The fits assumed that the beam direction was known and the beam energy unknown. Consequently, hypotheses with no missing neutral had three kinematic constraints, and those with one neutral had no constraints.

About 5% of the events were unmeasurable, usually because of secondary scatters.* The event in Fig. 4 was easy to measure on either SR or FSN, but a few events were badly obscured by background. Because of scanning or measuring errors, 2.5% of our measurable events were never measured successfully; these we call "remeasurable." Fewer than 1% had no fit to an apparently correct measurement.

Fit information was further checked for validity by computer or at the scan table. In addition to checking for measuring errors, the postfit scanner rejected any fit which required a track hypothesis inconsistent with its bubble density. Usually a track with momentum $< 1.4 \text{ GeV}/c$ could be unambiguously decided between a π^+ and a proton. Delta rays and π decays were occasionally used. All events processed at SLAC were checked by a scanner, as were about half those at LRL.

* We called an event unmeasurable if the error on the unfitted momentum of any track was greater than 20% of the momentum and greater than 50 MeV/c. This eliminated events with secondary scatters near the initial vertex. Examination of "almost measurable" events indicated that, except for larger errors, they showed no important difference from well-measured events.

Many of the LRL 3- and 5-prong events were resolved by automatic techniques.⁸⁰ The eligible events were of two classes:

- (a) events with a unique 3-C fit to $\pi^+\pi^-p$ (we required $\chi^2 < 25$, but events with $\chi^2 > 16$ were always examined by a scanner), and
- (b) events for which reliable pulse height data from the SR was available.

The SR pulse height was roughly proportional to bubble density and allowed us to decide fits with a sensitivity and accuracy similar to that for human scanners. Reference 80 details the LRL procedures and evaluates machine performance and fit selection reliability. We concluded that the SR and FSN provided roughly equal measurement quality. Errors in fit selection by human or computer were generally less than 5%. *

As a check on mass resolution, all K^0 decays measured at LRL were fitted with unconstrained mass. The mean K^0 mass was (497.86 ± 0.26) MeV, in excellent agreement with the accepted mass of 497.79 MeV.³⁶ Our actual resolution of ± 4.8 MeV compares with the calculated resolution of ± 4.1 MeV.

For an additional check on measurement quality, 4500 2.8 GeV three-prong events — originally measured at SLAC — were remeasured on the SR at LRL. The 3-C fits to $\pi^+\pi^-$ were compared in Appendix A of Kenneth Moffeit's thesis.⁹ He found generally excellent agreement; in particular, fewer than 1% of $\pi^+\pi^-$ events were "lost" to the O-C channel $\pi^+\pi^-\pi^0$, and vice versa. Although to some extent this was only a consistency check — showing that different measuring machines, optical parameters, and fit-selection procedures gave the same results — the conclusion agreed with our results from Monte Carlo studies.⁸¹

This 4500-event sample contained over 200 $\pi^+\pi^-\pi^0$ events with the $\pi^+\pi^-\pi^0$ invariant mass $m(+o)$ in the ω mass peak. On events which could be compared, less than 2% of the measurements had obvious errors. Only one event was fitted as $\pi^+\pi^-$ ($\chi^2 = 17$) at one lab and $\pi^+\pi^-\pi^0$ at the other. The ω mass measurements agreed well. Figure 8(a) shows the difference between the

*This was checked at LRL by a second postfit scan and comparing scanner-vs-scanner and scanner-vs-computer decisions.

Table III. Hypotheses fitted in SQUAW (events with no strange-particle decay).

Three prongs	Constraints
1. $\gamma p \rightarrow p\pi^+\pi^-$	3
2. $\gamma p \rightarrow p\pi^+\pi^-(\pi^0)^*$	0
3. $\gamma p \rightarrow \pi^+\pi^+\pi^-(n)^*$	0
4. $\gamma p \rightarrow pK^+K^-$	3
5. $\gamma p \rightarrow ppp$	3
Five prongs	
11. $\gamma p \rightarrow p2\pi^+2\pi^-$	3
12. $\gamma p \rightarrow p2\pi^+2\pi^-(\pi^0)^*$	0
13. $\gamma p \rightarrow 3\pi^+2\pi^-(n)^*$	0
14. $\gamma p \rightarrow p\pi^+K^+\pi^-K^-$	3
Seven prongs	
21. $\gamma p \rightarrow p3\pi^+3\pi^-$	3
22. $\gamma p \rightarrow p3\pi^+3\pi^-(\pi^0)^*$	0
23. $\gamma p \rightarrow 4\pi^+3\pi^-(n)^*$	0

*Includes multiple-neutral production.

LRL and SLAC values of $m(+\pi^0)$ for 198 events (chosen if either measurement gave $m(+\pi^0)$ in the mass interval 0.70 to 0.86 GeV). There is no systematic mass shift, and the spread is ± 6 MeV. Figure 7(b) shows the mass difference divided by $\delta m(+\pi^0)$, the expected error (standard deviation) in the LRL measurement. If all errors were uncorrelated (no Coulomb scattering), the width of Fig. 7(b) should be about $\pm \sqrt{2}$; in fact it is less than half that large. No two measurements of any event disagreed by more than $2.1 \delta m(+\pi^0)$. We conclude that there is very good agreement between LRL and SLAC measurements of ω events.

IV. CHANNEL CROSS SECTIONS

A. General Procedure

Of the 27 500 events found with 3, 5, or 7 prongs and no strange-particle decays, 92% were successfully measured and assigned to one or more of the hypotheses in Table III. The acceptance criteria are described in Appendix A and Ref. 80. Results of the assignments are given in Table IV.

The three-constraint fit assignments are virtually all unique. For events with a good 3-C fit ($\chi^2 < 25$ and bubble densities consistent with the hypothesis) no O-C hypotheses were accepted. Cross sections for $\gamma p \rightarrow p \pi^+ \pi^-$ are discussed in the thesis of Kenneth Moffeit;⁹ they include corrections for wide angle pairs and scanning losses (see Section III-C). Candidates for $\gamma p \rightarrow p K^+ K^-$, $\gamma p \rightarrow p p \bar{p}$, $\gamma p \rightarrow p K^+ \pi^+ K^- \pi^-$, and $\gamma p \rightarrow p 3\pi^+ 3\pi^-$ were given extra scrutiny at the scan table. Scanning losses were nil for events with five or more prongs. Events outside the fiducial volume (Fig. 5a) or energy range (Table II) were excluded, and similar corrections⁹ were made to the pair flux. Unmeasurable and remeasurable events were divided among all hypotheses for a topology in proportion to their occurrence in well-measured events. The corrected cross sections are given in Table V.

B. Four-Body Channels

The kinematically unconstrained hypotheses presented more difficulty. Some O-C events remained ambiguous after all selection criteria; the most common ambiguity was between $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$ and $\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$. Moreover, these "fits" contained many events with more than one neutral. Despite the ambiguities and multineutral events, we were able to use our knowledge of the beam momentum to separate the various channels. Our procedures are described in Appendix A, and the results are given in Table V.

Figure 8 compares our cross sections for the channel $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$ with the revised values¹⁹ from bubble chamber data taken with the SLAC positron-annihilation beam. The two experiments show good agreement.

TABLE IV

Fit results for events with 3-9 prongs

Hypothesis	Number Constraints	Number of Events ^a	
		$E_\gamma = 2.8 \text{ GeV}$	$E_\gamma = 4.7 \text{ GeV}$
1 $\gamma p \rightarrow p\pi^+\pi^-b$	3	2809	3082
2 $\rightarrow p\pi^+\pi^-\pi^0(m\pi^0)^c$	0	3357	4663
3 $\rightarrow n\pi^+\pi^+\pi^-(m\pi^0)^c$	0	1669	2248
4 $\rightarrow p\bar{K}^+K^-b\bar{c}$	3	79	102
5 $\rightarrow ppp$	3	0	9
Reactions 2, 3 ambiguous ^e	0	503	2780
No fit ^f		69	82
Remeasurable ^f		238	420
Unmeasurable ^f		387	737
<u>Total 3-prong</u>		<u>9111</u>	<u>14123</u>
11 $\gamma p \rightarrow p\pi^+\pi^+\pi^-\pi^-$	3	347	777
12 $\rightarrow p\pi^+\pi^+\pi^-\pi^0(m\pi^0)^c$	0	289	315
13 $\rightarrow n\pi^+\pi^+\pi^-\pi^-(m\pi^0)^c$	0	53	414
14 $\rightarrow pK^+\pi^+K^-\pi^-d$	3	1	43
Reactions 12, 13 ambiguous ^e		3	375
No fit ^f		21	25
Remeasurable ^f		50	140
Unmeasurable ^f		65	234
<u>Total 5-prong</u>		<u>829</u>	<u>3323</u>
21 $\gamma p \rightarrow p\pi^+\pi^+\pi^-\pi^-\pi^-$	3	4	42
22 $\rightarrow p\pi^+\pi^+\pi^-\pi^-\pi^0(m\pi^0)^c$	0	0	52
23 $\rightarrow n\pi^+\pi^+\pi^-\pi^-\pi^-(m\pi^0)^c$	0	0	10
Reactions 22, 23 ambiguous ^e		0	6
No fit ^f		0	2
Remeasurable ^f		0	13
Unmeasurable ^f		1	9
<u>Total 7-prong</u>		<u>5</u>	<u>134</u>
<u>Total 9-prong</u>		<u>1</u>	<u>1</u>

Footnotes to Table IV

- ^a The numbers of events are compatible with those in Table III of Moffeit's thesis,⁹ except that we have made different cuts and have used a kinematic condition (Equation A-2 of Appendix A) to reduce the number of ambiguous events. Events with only two prongs (i.e., proton track shorter than $\approx 1 \text{ mm}$) are not included in this table, but were included by Moffeit. Events which fell outside the fiducial volume (Section III-C and Fig. 5a) are not included here.
- ^b Two-prong events not included.
- ^c For $m \geq 0$.
- ^d Events with a visible K-decay not included.
- ^e In addition to the unique fits listed separately.
- ^f For definitions see Section III-C.

Table V. Channel cross sections

Number	Channel	$\sigma (\mu\text{b})$	
		2.8 GeV	4.7 GeV
	$\gamma p \rightarrow$		
1	$p\pi^+\pi^-$	30.6 ± 1.2	20.5 ± 0.8
4	$p K^+K^-^a$	1.0 ± 0.1	0.7 ± 0.1
5	$p p \bar{p}$	0	0.06 ± 0.03
2a	$p\pi^+\pi^-(\pi^0)$	24.6 ± 1.5	14.9 ± 1.5
2b	$p\pi^+\pi^-(\geq 2 \text{ neutrals})$	13.8 ± 2.0	20.4 ± 3.9
3a	$\pi^+\pi^+\pi^-(n)$	9.9 ± 1.3	7.1 ± 2.0
3b	$\pi^+\pi^+\pi^-(\geq 2 \text{ neutrals})$	11.0 ± 0.9	16.0 ± 2.3
11	$p2\pi^+2\pi^-$	4.1 ± 0.3	5.1 ± 0.3
14	$p\pi^+K^+\pi^-K^-^a$	0.01 ± 0.01	0.30 ± 0.06
12a	$p2\pi^+2\pi^-(\pi^0)$	3.2 ± 0.25	7.0 ± 0.6
12b	$p2\pi^+2\pi^-(\geq 2 \text{ neutrals})$	0.2 ± 0.15	3.1 ± 0.7
13a	$3\pi^+2\pi^-(n)$	0.4 ± 0.07	1.6 ± 0.5
13b	$3\pi^+2\pi^-(\geq 2 \text{ neutrals})$	0.2 ± 0.08	1.6 ± 0.3
21	$p3\pi^+3\pi^-$	0.05 ± 0.025	0.3 ± 0.05
22a	$p3\pi^+3\pi^-(\pi^0)$	0	0.3 ± 0.08
22b	$p3\pi^+3\pi^-(\geq 2 \text{ neutrals})$	0	0 ± 0.05
23a	$4\pi^+3\pi^-(n)$	0	0.07 ± 0.04
23b	$4\pi^+3\pi^-(\geq 2 \text{ neutrals})$	0	0 ± 0.03

^a Including events with visible K decay.

Figure 9 compares our cross sections for $\gamma p \rightarrow \pi^+\pi^+\pi^-n$ with revised values from the annihilation-beam experiments (SLAC-Weizmann-Tel Aviv).⁸² Again, the results agree. Also shown are cross sections for the "charge-symmetric" reaction $\gamma n \rightarrow \pi^-\pi^-\pi^+p$ from the Tel Aviv group.⁸³ The cross sections for the two reactions agree within errors. Likewise our cross section of $1.6 \pm 0.5 \mu\text{b}$ for 4.7-GeV $\gamma p \rightarrow 3\pi^+2\pi^-n$ agrees with the Tel Aviv value of $1.6 \pm 0.7 \mu\text{b}$ for 4.5 to 7.0-GeV $\gamma n \rightarrow 3\pi^-2\pi^+p$.*

In comparing their data with our preliminary data⁸ at 2.8 GeV[†] (the 4.7-GeV point was ignored) and with preliminary data from SLAC¹⁶ and Weizmann,¹⁷ the Tel Aviv group interpreted the difference between $\gamma p \rightarrow \pi^+\pi^+\pi^-n$ and $\gamma n \rightarrow \pi^-\pi^-\pi^+p$ as evidence for a large isoscalar-isovector interference.¹⁰² The revised cross sections for $\gamma p \rightarrow \pi^+\pi^+\pi^-n$ do not support their conclusion.

C. Multineutral Channels, Especially Five-Body

The cross sections for multineutral channels (Table VII) have been related to channels with one or no neutrals by a simple isospin model.^{84,85} The assumptions were that:

(a) The initial $|\gamma p\rangle$ state has the isospin composition

$$|\rho_p^0\rangle = \sqrt{2/3} |I = 3/2\rangle - \sqrt{1/3} |I = 1/2\rangle$$

* Because the photon is not an isospin eigenstate, the reactions $\gamma p \rightarrow \pi^+\pi^+\pi^-n$ and $\gamma p \rightarrow \pi^-\pi^-\pi^+p$, etc., are not truly charge-symmetric. In principle there may be substantial interference between amplitudes involving the isoscalar and isovector components of the photon; such an interference term would contribute to $\gamma p \rightarrow \pi^+\pi^+\pi^-n$ and $\gamma n \rightarrow \pi^-\pi^-\pi^+p$ with opposite sign.

† The cross section for 2.8 GeV $\gamma p \rightarrow \pi^+\pi^+\pi^-n$ reported here differs significantly from our preliminary value.⁸ Since the preliminary work we have found that the channel $\gamma p \rightarrow p\pi^+\pi^-\pi^0\pi^0$ produces substantial background under the neutron missing-mass peak (Fig. A-3b) for ambiguous events. In our new value this contamination has been subtracted (see Appendix A).

(this neglects the isoscalar component of the photon, but the results are not very sensitive to the exact initial isospin state).

(b) Resonance production can be neglected.

Although we have found substantial production of ρ and Δ resonances in the many-body channels, assumption (b) might be expected to be reasonable in an average sense, inasmuch as the ρ and Δ occur in all these channels but dominate none of them. The model then provides the expected charge ratios for nucleon + $\pi\pi$. These were given in H.

Spitzer's thesis⁸⁵ (Table 11) and are reproduced in Table VI for $m = 4$ to 7. Using these ratios and our well-measured cross sections for

$$\gamma p \rightarrow p 2\pi^+ 2\pi^-,$$

$$\gamma p \rightarrow p 2\pi^+ 2\pi^-(\pi^0),$$

$$\gamma p \rightarrow p 3\pi^+ 3\pi^-,$$

$$\gamma p \rightarrow p 3\pi^+ 3\pi^-(\pi^0),$$

we can predict the 5 to 8-body contributions to the multineutral channels. The predictions are compared in Table VII with the multineutral cross sections found in this experiment. The predictions agree fairly well for channels with no proton but are too small for proton channels. The discrepancies are even greater than they may appear, because the neutron and proton multineutral cross sections for a given topology are negatively correlated -- if we have overestimated the cross section for $\gamma p \rightarrow p n^+ \pi^-$ (≥ 2 neutrals), then we have underestimated $\gamma p \rightarrow \pi^+ \pi^+ \pi^-$ (≥ 2 neutrals). There are clearly more multineutral events than predicted by the model.

To determine the single-neutral and multineutral cross sections, a version of this isospin model was used to calculate the shapes of the missing-mass curves for multineutral events and to estimate the relative populations among ambiguous events. To what extent did we rely on a model which was not entirely correct? The answer is: not very heavily, and the model uncertainties are reflected in the errors. We applied the model to our 5- and 7-prong data to predict relative importance of 5 to 8 bodies in our 3- and 5-prong multineutral events. The predicted missing-mass shapes agreed well with the data, to which the predictions were then normalized. For unique fits, almost any model that resembles phase space with measuring errors could be used to correct the tails of multineutral events under the π^0 and neutron

TABLE VI. Relative isospin weights for the state

$$\sqrt{2/3} |I=3/2\rangle - \sqrt{1/3} |I=1/2\rangle$$

to decay into nucleon plus pions

(from Table 11 of Spitzer's thesis⁸⁵).

The symbols +, -, 0 refer to pion charge.

Channel	Weight (%)	Channel	Weight (%)
<u>5-body</u>		<u>6-body</u>	
p0000	2.0	p00000	0.8
p+-00	32.0	p+-000	18.7
p++--	20.0	p++--0	33.5
n+000	10.0	n+0000	4.2
n++-0	36.0	n++-00	30.4
		n++--	12.4
<u>7-body</u>		<u>8-body</u>	
p000000	0.3	p0000000	0.1
p+-0000	9.7	p+-00000	4.7
p++-000	33.8	p++-0000	26.7
p+++--	9.0	p+++--0	20.8
n+00000	1.8	n+000000	0.7
n++-000	20.8	n++-0000	12.5
n+++--0	24.6	n+++--00	28.8
		n++++--	5.7

Table VII. Comparison of measured multineutral cross sections with predictions of a simple isospin model (text and Refs. 84, 85).

Channel and energy	Measured cross section (μb)	Predicted cross section (μb)
2.8 GeV		
$\gamma p \rightarrow p\pi^+\pi^- (\geq 2 \text{ neutrals})$	13.8 ± 2.0	8.5 ± 0.05
$\gamma p \rightarrow \pi^+\pi^+\pi^- (\geq 2 \text{ neutrals})$	11.0 ± 0.9	10.4 ± 0.6
4.7 GeV		
$\gamma p \rightarrow p\pi^+\pi^- (\geq 2 \text{ neutrals})$	20.4 ± 3.9	12.5 ± 0.6
$\gamma p \rightarrow \pi^+\pi^+\pi^- (\geq 2 \text{ neutrals})$	16.0 ± 2.3	16.5 ± 0.7
$\gamma p \rightarrow p2\pi^+2\pi^- (\geq 2 \text{ neutrals})$	3.1 ± 0.7	1.6 ± 0.2
$\gamma p \rightarrow 3\pi^+2\pi^- (\geq 2 \text{ neutrals})$	1.6 ± 0.3	1.3 ± 0.2

peaks. The excess of proton multineutral events is especially obvious in these unique fits. For ambiguous fits, we used several methods to estimate the relative contribution from neutron and proton events, all of which agreed within errors. Details are given in Appendix A.

We speculate briefly on the cause of the model breakdown. The most plausible explanation is that resonances are produced which decay more strongly into multineutral channels than into the corresponding single-or no-neutral channels. Some possibilities for three charged prongs are

- (a) $\gamma p \rightarrow p\pi^+\pi^-\eta \rightarrow \text{neutrals} \quad (72\%)$
- (b) $\gamma p \rightarrow p B^0 \rightarrow \omega\pi^0 \rightarrow \pi^+\pi^-\pi^0\pi^0$
- $\gamma p \rightarrow \Delta^+\omega \rightarrow \pi^+\pi^-\pi^0$
- (c) $\rightarrow p\pi^0 \quad (67\%)$
- (d) $\rightarrow \pi\pi^+ \quad (33\%)$

From the $p\pi^+\pi^-\pi^0$ channel (see Section V-A) we estimate that the cross section for sequence (a) is about $1 \mu\text{b}$ at both energies. In Section VII we present evidence that the cross section for reaction (b) is also about $1 \mu\text{b}$ at both energies.

In Section II-C we showed that one-pion exchange predicts

$$\sigma(\gamma p \rightarrow \omega \Delta^+) = 6 \sigma(\gamma p \rightarrow \rho^- \Delta^{++}). \quad (16)$$

We measure $\sigma(\gamma p \rightarrow \rho^- \Delta^{++})$ to be $2.1 \mu\text{b}$ at 2.9 GeV and $1.3 \mu\text{b}$ at 4.7 GeV (Section VI). Reaction (c) could then be as large as $8 \mu\text{b}$ at 2.9 GeV and $5 \mu\text{b}$ at 4.7 GeV, and could account for most of the "excess" multineutral production. However, the Weizmann group¹⁸ has found that the OPE prediction

$$\sigma(\gamma n \rightarrow \omega \Delta^0, \Delta^0 \rightarrow \pi^- p) = 2 \sigma(\gamma p \rightarrow \rho^- \Delta^{++}) \quad (17)$$

is badly violated at 4.3 GeV: $\sigma(\gamma p \rightarrow \rho^- \Delta^{++}) = 1.8 \pm 0.4 \mu\text{b}$ and $\sigma(\gamma n \rightarrow \omega \Delta^0, \Delta^0 \rightarrow \pi^- p) \leq 0.5 \mu\text{b}$. The Weizmann results indicate that unless there is large isoscalar-isovector interference, $\sigma(\gamma p \rightarrow \omega \Delta^+, \Delta^+ \rightarrow \pi^0 p) < 1 \mu\text{b}$ at 4.3 GeV. However, at 4.7 GeV we might expect our $\gamma p \rightarrow \omega \pi^+ n$ cross section to equal the $1.4 \pm 0.5 \mu\text{b}$ for 4.3-GeV $\gamma n \rightarrow \omega \pi^- p$.⁶¹ If the $\pi^+ n$ state has $I = 3/2$, then we expect twice as much $\gamma p \rightarrow \omega \pi^0 p$; if $I = 1/2$, half as much.

We have been unable to explain the difference between model and experimental cross sections for $\gamma p \rightarrow p \pi^+ \pi^-$ (neutrals) in terms of a single simple reaction. Probably several reactions contribute significantly.

V. OMEGA PRODUCTION

A. The Channel $p \pi^+ \pi^- \pi^0$; ω and η Production

In this section we will consider events which "fit" the 0-constraint hypothesis

$$\gamma p \rightarrow p \pi^+ \pi^- \pi^0$$

and did not fit a 3-C hypothesis (Table III) with $\chi^2 < 25$. Using visual examination or pulse-height data (from Spiral Reader measurements) we selected only those fits with bubble densities consistent with the hypothesis. A fiducial-volume cut (Fig. 5a) removed events not produced by the beam (about 1%). Of the remaining 3860 (7443) candidates for $p \pi^+ \pi^- \pi^0$ at 2.8 (4.7) GeV, 503 (2780) were ambiguous with the hypothesis

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

The events for which the $\pi^+ \pi^+ \pi^- n$ hypothesis was ruled out (by bubble density or kinematics) were said to be "unique" $p \pi^+ \pi^- \pi^0$. However, both unique and ambiguous samples contained a substantial number of events with more than one neutral particle in the final state. By methods discussed in Appendix A, we estimate that 2260 ± 100 (2240 ± 200) of the candidates were true single- π^0 events at 2.8 (4.7) GeV.

Figure A-2(a, e) in Appendix A shows the beam energy K_{oc} (see Eq. A-1 in Appendix A) calculated for the unique $p \pi^+ \pi^- \pi^0$ candidates. Most of the events with K_{oc} much smaller than the true beam energy (shaded form) have more than one neutral particle. Experiments which use a bremsstrahlung beam have no way (except near the end point) of separating these multineutral events from single- π^0 events with lower energy. However, we were able to separate them easily by restricting K_{oc} to the energy intervals 2.4-3.3 (4.1-5.3) GeV. This cut removed most of the multineutral events and only a few of the single- π^0 events. The small loss of true events (with K_{oc} outside these intervals because of measuring and fitting errors) was determined by Monte Carlo calculations (see below). Surviving the energy cut were 2668 (3057) fits at 2.8 (4.7) GeV. Since a few events have two acceptable π^0 fits (with π^+ and p assignments reversed), these fits

correspond to 2661 (2882) events, of which 228 (774) were ambiguous.

In Fig. 10(a, c) we plot m_{+-0} , the invariant mass of the $\pi^+\pi^-\pi^0$, for all fits without the cut in K_{oc} . A sharp ω peak is visible at both energies. In Fig. 10(b, d) the same mass is plotted for events surviving the energy cut and a weak missing-mass cut.* The reduction in background beneath the ω is striking, especially at 4.7 GeV. In addition to the ω , a small η peak is visible at $m_{+-0} \approx 0.55$ GeV. No other clear structure is visible.† Most of the ω is contained in $|t| < 0.5$ GeV²; these events are shaded in Fig. 10(b, d).

The momentum-transfer distribution is exhibited more fully in the Chew-Low plots of Fig. 11, where $|t|$ is plotted against m_{+-0}^2 . The ω signal is very peripheral [see the "blow-up" plots for small $|t|$ in Fig. 11(c, d)] with at most a faint signal near $t = t_{\max}$ (backward ω production). The backward ω signal is very difficult to treat because of background and statistics. Since these events have fast protons in the laboratory, many are ambiguous with $\gamma p \rightarrow \pi^+\pi^+\pi^-n$. No such difficulties exist for forward ω production, where almost all fits are unique. Most of our analysis will concern the forward peak, which presumably comes from diffraction scattering and one-particle exchange (Section II).

* For Figs. 10-12, 17, and 19 we have applied both the energy cut and the missing-mass cut $MM^2 < 0.15$ (0.20) GeV² at 2.8 (4.7) GeV, where MM^2 is calculated from formula A-3 in Appendix A. As can be seen in Fig. A-4(a, c) of Appendix A, the MM cut leaves the π^0 signal virtually untouched; indeed, we used the stronger cut $MM^2 < 0.10$ (0.14) GeV² for the results of Section VI, and the "anti- π^0 " cut $MM^2 > 0.10$ (0.14) GeV² for Section VII.

We did not use a missing-mass cut in the determination of $\frac{d\sigma}{dt}(\omega)$, since the MM resolution is considerably broader for large $|t|$ than small. Equation A-3 suggests that the MM resolution is best for π^0 fast in the lab, and the K_{oc} resolution best for slow π^0 . Monte Carlo studies did not indicate a significantly greater loss of small- $|t|$ ω events because of the K_{oc} cut, however. Moreover, the determination of $\frac{d\sigma}{dt}$ for large t was not changed when we tried a MM cut. Although the number of events with $m_{+-0} \approx m_\omega$ decreased, most of the decrease could be attributed to background.

† We attach no significance to the small bump at 1.19-1.26 GeV near the peak of the 2.8 GeV phase space. It may be related to the much broader 1.0 to 1.3 GeV enhancement at 4.7 GeV. (See also Figs. 21j and 22j and brief discussion in Section VII.)

Figure 12 shows the mass resolution in more detail. At 2.8 (4.7) GeV the full width at half maximum (FWHM) of the ω peak is 25 (45) MeV, including the intrinsic width of $\Gamma = 11.4$ MeV.^{36*} The (standard deviation) uncertainty δm in the effective $\pi^+\pi^-\pi^0$ mass was calculated in SQUAW for each event. Most events near the ω mass had $\delta m \approx 5$ -30 MeV; the median was 10 (15) MeV at 2.8 (4.7) GeV. The shaded forms show the calculated resolutions folded into a symmetric Breit-Wigner with $\Gamma = 12$ MeV; the agreement with our data is good. The solid curves are our estimates of the background underneath the ω . The cross sections were determined by counting the number of events in the ω mass interval 0.70-0.86 GeV (at 2.8 GeV) or 0.67-0.90 GeV (at 4.7 GeV) and subtracting the background estimate. Corrections were made for ω events lost because they fit a 3-C hypothesis such as $\gamma p \rightarrow p\pi^+\pi^-$, had K_{oc} outside the accepted energy interval, or had m_{+-0} outside the ω mass interval (no missing mass cut was made). These corrections were determined with the aid of PHONY,⁸¹ which simulates track measurements and their errors. The PHONY events were processed through TVGP-SQUAW like real events. The corrections for these ω losses were $(+12 \pm 3)\%$ and $(+22 \pm 6.6)\%$ at 2.8 and 4.7 GeV, respectively.

In addition, by extrapolating our differential cross section to $t_{\min}$ (with Eq. 34 in Section V-C) we estimated that at 4.7 GeV about half the ω events for $t_{\min} = 0.005$ GeV² $< |t| < 0.02$ GeV² were lost in scanning or measurement reconstruction.† For $|t| > 0.02$ GeV² the losses

* The actual resolution function, which is a sum of Gaussian functions with different δm , resembles a simple Breit-Wigner for m (let $\Delta = \text{FWHM}$). Then the experimental ω peak should have a Breit-Wigner shape with $\text{FWHM} = \Delta + \Gamma$.⁸⁶

† At $t_{\min}$ the proton had momentum $70 \text{ MeV}/c \approx m_\omega^2/2E_y$ and range ≈ 0.5 mm, but events with proton range ≤ 2 mm were not adequately reconstructed in our 0-C fits.

were estimated from multiple scans. At 4.7 GeV we have used a scan correction of 5^{+10}_{-5} % for $0.02 < |t| < 0.06 \text{ GeV}^2$ and no correction for $|t| > 0.06 \text{ GeV}^2$. The scanning and reconstruction losses for $|t| < 0.06 \text{ GeV}^2$ constitute $7 \pm 3\%$ of the total ω photoproduction.

For 2.8-GeV $\gamma p \rightarrow \omega p$ the minimum momentum transfer is 0.014 GeV^2 , corresponding to a proton range of 5 mm. Events were also more visible at this energy, so that ω scanning losses were low ($< 2\%$) and required no correction.

The cross sections were also corrected for other decay modes of the ω , using

$$\Gamma(\omega \rightarrow \pi^+ \pi^- \pi^0) / \Gamma(\omega \rightarrow \text{all}) = 0.898. \quad {}^{36}$$

The final errors include the uncertainties in background, loss corrections, and flux, as well as statistical errors. The resulting cross sections are given in Table VIII and Fig. 13.

The differential cross sections were determined in like manner and are presented in Table IX and Fig. 14. The errors include statistics and the uncertainties in background and loss.

We delay discussion of the ω cross sections until Section V-C.

The η cross sections were determined by a similar method. We took as the η signal the events with $0.52 < m_{\pi^+ \pi^-} < 0.58 \text{ GeV}$, less a small background, and used the same loss correction factors as for ω (PHONY⁸¹ η events indicated that these were correct within errors). Only the $\pi^+ \pi^- \pi^0$ decay mode was detected (our energy and mass selections accept fewer than 10% of PHONY $\eta \rightarrow \pi^+ \pi^- \gamma$ decays as $\eta \rightarrow \pi^+ \pi^- \pi^0$), so that the visible cross sections were divided by the branching ratio $\Gamma(\eta \rightarrow \pi^+ \pi^- \pi^0) / \Gamma(\eta \rightarrow \text{all}) = 0.231. \quad {}^{36}$

The total cross sections for $\gamma p \rightarrow \eta p$ are given in Table VIII, and the differential cross sections are shown in Fig. 15. The η is not photoproduced as peripherally as the ω . Our η cross sections are a bit larger than we would expect from scaling the DESY⁸⁷ and CEA⁸⁸ 4-GeV counter data by $(4/E_Y)^2$, but within our large errors, we are consistent with them. Our total η cross sections are marginally compatible with those reported by the HBC experiment at DESY¹⁴ ($\sigma = 0.6 \pm 0.4$ for $1.5 < E_Y < 3.5 \text{ GeV}$ and $\sigma = 0 \pm 0.2$ for $3.5 < E_Y < 5.8 \text{ GeV}$) and CEA¹⁵ ($\sigma = 0.1 \pm 0.6$ for $2.5 < E_Y < 3.5 \text{ GeV}$).

Table VIII. Total cross sections for the reactions $\gamma p \rightarrow \omega p$ and $\gamma p \rightarrow \eta p$, and parameters for fits of the differential ω cross sections to $C \exp(-At)$ for $0.02 < |t| < 0.4 \text{ GeV}^2$. Errors include statistics and uncertainties in flux, background subtraction, and loss corrections.

	$E_Y = 2.8 \text{ GeV}$	$E_Y = 4.7 \text{ GeV}$
$\sigma_T(\gamma p \rightarrow \omega p)$	$5.3 \pm 0.5 \text{ } \mu\text{b}$	$3.0 \pm 0.3 \text{ } \mu\text{b}$
C	$31.7 \pm 4.3 \text{ } \mu\text{b}/\text{GeV}^2$	$23.2 \pm 3.7 \text{ } \mu\text{b}/\text{GeV}^2$
A	$6.4 \pm 0.7 \text{ GeV}^{-2}$	$8.2 \pm 0.9 \text{ GeV}^{-2}$
$\sigma_T(\gamma p \rightarrow \eta p)$	$0.9 \pm 0.25 \text{ } \mu\text{b}$	$0.3 \pm 0.1 \text{ } \mu\text{b}$

Table IX. Differential cross sections $\frac{d\sigma}{dt} (\mu\text{b}/\text{GeV}^2)$ for $\gamma p \rightarrow \omega p$.

$ t (\text{GeV}^2)$	$E_Y = 2.8 \text{ GeV}$	$E_Y = 4.7 \text{ GeV}$
0.014 - 0.06	25.9 ± 3.1	19.6 ± 2.9
0.06 - 0.10	21.4 ± 3.0	10.8 ± 1.8
0.10 - 0.15	14.7 ± 2.3	8.1 ± 1.4
0.15 - 0.20	7.6 ± 1.6	5.6 ± 1.1
0.20 - 0.30	6.4 ± 1.1	2.8 ± 0.6
0.30 - 0.40	4.2 ± 0.8	1.9 ± 0.5
0.40 - 0.50	1.2 ± 0.6	0.8 ± 0.4
0.5 - 1.0	0.8 ± 0.2	0.3 ± 0.1
1.0 - 2.0	0.24 ± 0.12	0 ± 0.03
2.0 - $ t _{\text{max}}$	0.18 ± 0.10	
2.0 - 5.5		0 ± 0.01
5.5 - $ t _{\text{max}}$		0.04 ± 0.04

We remark in passing that η and ω are also photoproduced "inelastically" in the channel $\gamma p \rightarrow p 2\pi^+ 2\pi^- \pi^0$, as illustrated in Fig. 16. Correcting for other decay modes as before, we find

$\sigma(\gamma p \rightarrow \omega \pi^+ \pi^- p) \approx 1.3 (2.0) \mu\text{b}$ and $\sigma(\gamma p \rightarrow \eta \pi^+ \pi^- p) \approx 1.1 (1.2) \mu\text{b}$ at 2.8 (4.7) GeV.* At 4.7 GeV the inelastic ω cross section--in this channel alone--is comparable to that for elastic production $\gamma p \rightarrow \omega p$, and the inelastic η cross section is larger than that for elastic η . This illustrates the difficulty in interpreting results from counter experiments which detect only the ω .^{11b} The channel $\gamma p \rightarrow p 2\pi^+ 2\pi^- \pi^0$ will be treated in more detail in a future paper by our group.⁸⁹

B. Omega decay and density matrix

For our study of the ω decay parameters we selected those events with $0.73 < m_{\pi^+\pi^-} < 0.83$ GeV. This cut rejects fewer than 15% of the ω events (as determined by Monte Carlo calculations⁸¹), but rejects most of the non- ω background (cf. Fig. 12). Figure 17 shows the usual Dalitz plots for the decay $\omega \rightarrow \pi^+ \pi^- \pi^0$. The directions of increasing T_{π^0} , T_{π^+} , and T_{π^-} (where T_{π} is the π kinetic energy in the ω rest frame) point toward 12, 4, and 8 o'clock, respectively.[†] The decay distribution exhibits in general the expected $|\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}|^2$ density,⁹⁰ which is maximum at the center of the plot and zero at the edges. More specifically, we divided the Dalitz plot into 10 radial zones (cf. Flatté et al.^{90b}) and compared the number of events predicted by the simple $\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}$ matrix element with our data; the outermost two zones were added together to assure sufficient statistics. We found an excess of events near the periphery at 2.8 GeV ($\chi^2 \sim 20$ for 8 degrees of freedom); these were adequately accounted for by assuming 10% phase space background ($\chi^2 \sim 7$). At 4.7 GeV the radial fit was very good with no background necessary (although

*The cross sections include substantial $\gamma p \rightarrow \omega \pi^- \Delta^{++}$ and $\eta \pi^- \Delta^{++}$.

†For any physicist with a Dalitz plot on the face of his wrist watch.

5% phase space background would not be ruled out).

Azimuthally, the Dalitz plots obeyed sextant symmetry (i.e., the six sectors, created by dividing the plots along lines of equal T_{π^+} , T_{π^-} , and T_{π^0} , contained equal numbers of events within statistical errors). At 4.7 GeV there was a $(12 \pm 6)\%$ left-right asymmetry (i.e., there were more events with $T_{\pi^+} < T_{\pi^-}$), which we assume to be a statistical fluctuation. Measurements at both LRL and SLAC showed this small asymmetry.*

We conclude from the study of the Dalitz plots that our ω sample is indeed "clean" (with perhaps $\sim 10\%$ background at 2.8 GeV) and exhibits no gross manifestations of measurement or reconstruction errors.

The ω decay allows us to analyze the ω polarization state, since the decay matrix element is proportional to $\vec{P}_{\omega} \cdot \hat{n}$,[†] where $\vec{P}_{\omega}$ is the direction of the ω linear polarization (not the spin direction) and $\hat{n} \propto \vec{p}_{\pi^+} \times \vec{p}_{\pi^-}$ is the normal to the ω decay plane (in the ω rest system). (The analog for ρ^0 decay is $\vec{P}_{\rho} \cdot \hat{p}_{\pi^+}$, where $\hat{p}_{\pi^+}$ is the direction of the decay π^+ in the ρ^0 rest frame.) We take θ and ϕ to be the polar and azimuthal angles of the decay normal $\hat{n}$ in any coordinate system (to be specified below). Then the decay of a $J^P = 1^-$ state can be written in terms of its density matrix as

*We have considered and rejected a number of possible explanations for this small left-right asymmetry. The asymmetry persists for the (90% of all) ω events with $|t| < 0.5$ GeV²; for these the proton is always clearly identifiable on the scan table (cf. Fig. 4), so that the asymmetry could not have come from protons misidentified as π^+ .

All $\pi\pi$ mass combinations in ω decay are below the ρ mass, so that interference with $\rho\pi\pi$ or $\rho\Delta$ production would not cause such an effect. Since the "overlap" of phase space for ωp and $\pi\pi\Delta$ is comparatively less at 4.7 GeV than at 2.8 GeV, any influence of $\pi\pi\Delta$ would seem more likely at 2.8 GeV, where no asymmetry is observed.

No other deviations from the ideal decay distribution were observed; in particular, the distribution in T_{π^0} seems correct at both energies, even though we might expect it to be most sensitive to errors in measuring and reconstruction. The agreement strengthens our belief that we have no major biases in ω events.

†The caret $\hat{}$ implies a unit vector.

$$W^0(\cos \theta, \phi) = \frac{3}{4\pi} \left[\frac{1}{2} (1 - \rho_{00}) + \frac{1}{2} (3\rho_{00} - 1) \cos^2 \theta - \sqrt{2} \operatorname{Re} \rho_{10} \sin 2\theta \cos \phi - \rho_{1-1} \sin^2 \theta \cos 2\phi \right]. \quad (22)$$

The three parameters ρ_{00} , $\operatorname{Re} \rho_{10}$, and ρ_{1-1} have been measured in previous bubble chamber experiments.^{14, 15, 19*} However, the knowledge of our beam polarization allows us to define an additional angle and to determine 6 more parameters, which are important for understanding the ω production mechanism.

We follow the formalism of Schilling, Seyboth, and Wolf,²¹ as originated by Thews.²² We define Φ (see Fig. 18) as the angle between the photon polarization plane and the production plane.* Let $\hat{K}$ and $\hat{\epsilon}$ be the momentum and polarization (electric field) directions of the photon in the reaction center of mass, $\hat{\omega}$ the direction of the ω in the c.m., and $\hat{y} \propto \hat{K} \times \hat{\omega}$ the normal to the production plane. Then $\cos \Phi = (\hat{y} \times \hat{K}) \cdot \hat{\epsilon}$ and $\sin \Phi = \hat{y} \cdot \hat{\epsilon}$.

The density matrix of a photon with linear polarization P_Y can be written as²¹

$$\rho(\gamma) = \frac{1}{2} \begin{pmatrix} 1 & -P_Y e^{-2i\Phi} \\ -P_Y e^{2i\Phi} & 1 \end{pmatrix}, \quad (23a)$$

where the columns and rows correspond to helicity ± 1 (real photons do not have helicity 0). This can be decomposed into a unit matrix I and the Pauli spinors $\vec{\sigma}$ as

$$\rho(\gamma) = \frac{1}{2} (I + \vec{P}_Y \cdot \vec{\sigma}), \quad (23b)$$

where $\vec{P}_Y = P_Y (-\cos 2\Phi, -\sin 2\Phi, 0)$.

The density matrix for the ω can similarly be written as

$$\rho(\omega) = \rho^0(\omega) - P_Y \cos 2\Phi \rho^1(\omega) - P_Y \sin 2\Phi \rho^2(\omega), \quad (24)$$

* The angle Φ is invariant under Lorentz transformations in the production plane, so that it has the same meaning in the laboratory, total c.m., or ω rest frame. The proof is straightforward (see Appendix B).

$$\begin{aligned} \text{where } \rho_{jk}^0 &= \frac{1}{N} \sum_{\lambda=\pm 1} T_{j\lambda} T_{k\lambda}^\dagger, \\ \rho_{jk}^1 &= \frac{1}{N} \sum_{\lambda, \lambda'} T_{j\lambda} \sigma_{\lambda\lambda'}^1 T_{k\lambda'}^\dagger, \\ \rho_{jk}^2 &= \frac{1}{N} \sum_{\lambda, \lambda'} T_{j\lambda} \sigma_{\lambda\lambda'}^2 T_{k\lambda'}^\dagger, \end{aligned} \quad (24, \text{cont.})$$

$N = \sum_{j, \lambda} |T_{j\lambda}|^2$, T is the ω production amplitude,* and $T^\dagger$ is its Hermitian conjugate. The matrices ρ^α are Hermitian. If parity is conserved (as we shall assume) and $\hat{y}$ is the production normal, then

$$\begin{aligned} \rho_{\lambda\lambda'}^\alpha &= (-1)^{\lambda-\lambda'} \rho_{-\lambda-\lambda'}^\alpha, \quad \alpha = 0 \text{ or } 1, \\ \rho_{\lambda\lambda'}^2 &= -(-1)^{\lambda-\lambda'} \rho_{-\lambda-\lambda'}^2. \end{aligned}$$

The "decay" angular distribution can then be written as

$$\begin{aligned} W(\cos \theta, \phi, \Phi) &= W^0(\cos \theta, \phi) - P_Y \cos 2\Phi W^1(\cos \theta, \phi) \\ &\quad - P_Y \sin 2\Phi W^2(\cos \theta, \phi), \\ W^0(\cos \theta, \phi) &= \frac{3}{4\pi} \left[\frac{1}{2} (1 - \rho_{00}^0) + \frac{1}{2} (3\rho_{00}^0 - 1) \cos^2 \theta - \sqrt{2} \operatorname{Re} \rho_{10}^0 \sin 2\theta \cos \phi - \rho_{1-1}^0 \sin^2 \theta \cos 2\phi \right] \\ W^1(\cos \theta, \phi) &= \frac{3}{4\pi} \left(\rho_{11}^1 \sin^2 \theta + \rho_{00}^1 \cos^2 \theta - \sqrt{2} \operatorname{Re} \rho_{10}^1 \sin 2\theta \cos \phi - \rho_{1-1}^1 \sin^2 \theta \cos 2\phi \right) \\ W^2(\cos \theta, \phi) &= \frac{3}{4\pi} \left(\sqrt{2} \operatorname{Im} \rho_{10}^2 \sin 2\theta \sin \phi + \operatorname{Im} \rho_{1-1}^2 \sin^2 \theta \sin 2\phi \right). \end{aligned} \quad (25)$$

We must now define a coordinate system to specify θ and ϕ . We will consider only systems with $\hat{y}$ = the normal to the production plane, and $\hat{x} = \hat{y} \times \hat{z}$. We consider three different choices of $\hat{z}$ (see Fig. 18):

* For $T_{j\lambda}$ we may take, e.g., the usual helicity amplitudes $T_{jN\lambda}$, where $\lambda = \pm 1$ is the photon helicity and j is the ω helicity. For convenience we have suppressed the proton helicities N and N' , which are also summed in the definitions of the density matrix. For a more thorough description see Schilling, Seyboth, and Wolf.²¹

(1) the Gottfried-Jackson (GJ) system, where $\hat{z}$ is the direction of the photon in the ω rest system;

(2) the helicity (H) system, where $\hat{z} = \hat{\omega}$ is the direction of the ω in the c.m. system (or minus the direction of the recoil proton in the ω rest system); and

(3) the Adair (A) system, where $\hat{z} = \hat{K}$ is the c.m. photon direction. By definition, these systems differ only by a rotation around the y axis. The angle between helicity and Adair frames is Θ , the c.m. production angle; the angle between helicity and Gottfried-Jackson frames is $\cos^{-1} \left(\frac{v - \cos \Theta}{v \cos \Theta - 1} \right)$, where v = the ω velocity in the c.m.

If the production mechanism consists of simple t -channel exchange of spinless particles (e.g., OPE) with no absorption, then the spin-flip terms ρ_{00}^0 , etc., must vanish in the GJ system; this is referred to as t -channel helicity conservation. If the nuclear force is spin-independent as in the strong-absorption model (SAM),⁹¹ then the spin-flip terms vanish in the Adair system. If c.m. s -channel helicity is conserved, the helicity-flip terms vanish, so that ρ_{00}^0 , etc., are zero in the helicity system. [We have shown that in $\gamma p \rightarrow \rho^0 p$ ($|t| \leq 0.4 \text{ GeV}^2$) the ρ^0 retains the photon polarization. I.e., $\rho(\rho^0) \approx \rho(\gamma)$ (cf. Eqs. 23-24), so that all density-matrix parameters in Eq. 25, except ρ_{1-1}^1 and $\text{Im } \rho_{1-1}^2$, are small in the rho helicity frame.^{4,9}]

For convenience we also introduce the angle $\psi = \phi - \Phi$, which for forward-produced ω is the angle between the photon polarization $\hat{e}$ and the ω decay normal $\hat{n}$. For near-forward ρ^0 photoproduction, the ρ^0 decay distribution in the helicity frame is^{4,9}

$$W(\cos \theta_H, \psi_H) \approx (1 + P_Y \cos 2\psi_H) \sin^2 \theta_H. \quad (26)$$

Figure 19 shows the $\cos \theta_H$ and ψ_H distributions from the decay of forward-produced ω . The distribution in $\cos \theta_H$ is not $\sin^2 \theta_H = 1 - \cos^2 \theta_H$; this alone is sufficient proof that the ω does not conserve the photon helicity at our energies. Moreover, the distribution in ψ_H is relatively flat, in contrast to the $1 + P_Y \cos 2\psi_H$ distribution found for ρ^0 photoproduction (small histograms in lower left of Fig. 19).^{4,9} As we demonstrate in the next section, the $\psi_H(\omega)$ distribution is consistent with roughly equal amounts of helicity-conserving diffractive ω ($1 + P_Y \cos 2\psi_H$) and of ω from OPE ($1 - P_Y \cos 2\psi_{GJ}$).

We have determined the nine independent density-matrix parameters in Eq. 25 by a moment analysis. Since the background was so small, no subtraction was made.* Our results are presented in Table X and Fig. 20 for various $|t|$ intervals.

C. Discussion of ω Results

If s -channel helicity were conserved in ω photoproduction, the only nonzero density-matrix elements in the helicity frame would be

$$\left. \begin{aligned} \rho_{11}^0 &= \rho_{-1-1}^0 = (1 - \rho_{00}^0)/2 = 1/2, \\ \rho_{1-1}^1 &= 1/2, \\ \text{Im } \rho_{1-1}^2 &= -1/2. \end{aligned} \right\} \text{Helicity Frame} \quad (27)$$

Our results (Table X and Fig. 20) show clearly that at 2.8 and 4.7 GeV the ω does not retain the photon polarization. In fact ρ_{1-1}^1 and $\text{Im } \rho_{1-1}^2$ are both near zero, and there is substantial population of the helicity = 0 state (since $\rho_{00}^0 \neq 0$).

If the ω were produced entirely by OPE, we would expect (with no absorption)

$$\left. \begin{aligned} \rho_{00}^0 &= 0, \\ \rho_{1-1}^1 &= -1/2, \\ \text{Im } \rho_{1-1}^2 &= 1/2, \\ \text{all other parameters in Eq. 25 zero.} \end{aligned} \right\} \text{Gottfried-Jackson Frame} \quad (28)$$

From Table X we see that these values are clearly excluded.

* For $m_{+-0} < 0.73 \text{ GeV}$ and $0.83 < m_{+-0} < 1.23 \text{ GeV}$, we found that (in 0.1 GeV mass bins) the moments $Y_\ell^m(\cos \theta_H, \psi_H)$, $1 \leq \ell \leq 6$, were all zero within 2.5 standard deviations at both energies. This indicates that the "background" near the ω has no particular spin alignment. For the ω interval ($0.73 < m_{+-0} < 0.83 \text{ GeV}$) the moments Y_2^0 and Y_2^2 were nonzero, consistent with decay of a partially-aligned vector meson.

TABLE X : ω density matrix elements for the reaction $\gamma p \rightarrow p\omega$.a) $E_\gamma = 2.8$ GeV, Gottfried-Jackson system.

$ t $ (GeV ²)	0.014 - 0.05	0.06 - 0.15	0.15 - 0.4	0.4 - 1.0
ρ_{00}^0	0.15 $\pm$ 0.07	0.22 $\pm$ 0.06	0.33 $\pm$ 0.07	0.35 $\pm$ 0.12
Rep ₁₀ ⁰	0.06 $\pm$ 0.05	0.15 $\pm$ 0.04	0.04 $\pm$ 0.04	-0.23 $\pm$ 0.08
ρ_{1-1}^0	-0.01 $\pm$ 0.08	-0.03 $\pm$ 0.06	0.16 $\pm$ 0.06	-0.13 $\pm$ 0.10
ρ_{00}^1	0.10 $\pm$ 0.12	-0.01 $\pm$ 0.10	-0.04 $\pm$ 0.12	-0.40 $\pm$ 0.19
ρ_{11}^1	0.09 $\pm$ 0.08	0.02 $\pm$ 0.08	0.05 $\pm$ 0.07	0.11 $\pm$ 0.13
Rep ₁₀ ¹	-0.10 $\pm$ 0.07	0.04 $\pm$ 0.06	0.01 $\pm$ 0.06	0.22 $\pm$ 0.14
ρ_{1-1}^1	-0.03 $\pm$ 0.12	-0.11 $\pm$ 0.10	-0.08 $\pm$ 0.09	0.17 $\pm$ 0.16
Imp ₁₀ ²	0.01 $\pm$ 0.08	0.13 $\pm$ 0.06	0.19 $\pm$ 0.07	0.06 $\pm$ 0.09
Imp ₁₋₁ ²	-0.05 $\pm$ 0.13	0.09 $\pm$ 0.09	0.03 $\pm$ 0.10	0.13 $\pm$ 0.14

b) $E_\gamma = 2.8$ GeV, helicity system.

ρ_{00}^0	0.15 $\pm$ 0.07	0.09 $\pm$ 0.06	0.17 $\pm$ 0.06	0.37 $\pm$ 0.11
Rep ₁₀ ⁰	-0.02 $\pm$ 0.05	-0.05 $\pm$ 0.04	0.02 $\pm$ 0.05	0.24 $\pm$ 0.08
ρ_{1-1}^0	-0.01 $\pm$ 0.08	-0.10 $\pm$ 0.07	0.08 $\pm$ 0.07	-0.12 $\pm$ 0.11
ρ_{00}^1	0.21 $\pm$ 0.11	0.01 $\pm$ 0.09	0.08 $\pm$ 0.09	0.03 $\pm$ 0.20
ρ_{11}^1	0.03 $\pm$ 0.08	0.00 $\pm$ 0.08	-0.01 $\pm$ 0.08	-0.10 $\pm$ 0.12
Rep ₁₀ ¹	-0.07 $\pm$ 0.08	-0.05 $\pm$ 0.06	-0.06 $\pm$ 0.07	-0.21 $\pm$ 0.13
ρ_{1-1}^1	0.03 $\pm$ 0.12	-0.10 $\pm$ 0.10	-0.02 $\pm$ 0.10	0.39 $\pm$ 0.17
Imp ₁₀ ²	-0.02 $\pm$ 0.08	0.13 $\pm$ 0.05	0.09 $\pm$ 0.06	0.06 $\pm$ 0.10
Imp ₁₋₁ ²	-0.05 $\pm$ 0.13	-0.05 $\pm$ 0.10	-0.26 $\pm$ 0.10	-0.07 $\pm$ 0.14

c) $E_\gamma = 2.8$ GeV, Adair system.

$ t $ (GeV ²)	0.014 - 0.06	0.06 - 0.15	0.15 - 0.4	0.4 - 1.0
ρ_{00}^0	0.14 $\pm$ 0.07	0.09 $\pm$ 0.06	0.22 $\pm$ 0.07	0.74 $\pm$ 0.14
Rep ₁₀ ⁰	0.01 $\pm$ 0.05	0.04 $\pm$ 0.04	0.06 $\pm$ 0.04	0.01 $\pm$ 0.07
ρ_{1-1}^0	-0.01 $\pm$ 0.08	-0.10 $\pm$ 0.07	0.10 $\pm$ 0.07	0.06 $\pm$ 0.09
ρ_{00}^1	0.17 $\pm$ 0.11	-0.02 $\pm$ 0.10	-0.01 $\pm$ 0.11	-0.51 $\pm$ 0.28
ρ_{11}^1	0.05 $\pm$ 0.08	0.02 $\pm$ 0.08	0.03 $\pm$ 0.08	0.17 $\pm$ 0.11
Rep ₁₀ ¹	-0.09 $\pm$ 0.08	-0.02 $\pm$ 0.06	-0.06 $\pm$ 0.06	-0.17 $\pm$ 0.11
ρ_{1-1}^1	0.01 $\pm$ 0.12	-0.11 $\pm$ 0.10	-0.06 $\pm$ 0.10	0.12 $\pm$ 0.15
Imp ₁₀ ²	-0.01 $\pm$ 0.08	0.14 $\pm$ 0.06	0.17 $\pm$ 0.06	0.09 $\pm$ 0.11
Imp ₁₋₁ ²	-0.05 $\pm$ 0.13	-0.00 $\pm$ 0.10	-0.16 $\pm$ 0.10	0.00 $\pm$ 0.13

d) $E_\gamma = 4.7$ GeV, Gottfried-Jackson system.

ρ_{00}^0	0.15 $\pm$ 0.07	0.15 $\pm$ 0.07	0.46 $\pm$ 0.09	0.66 $\pm$ 0.15
Rep ₁₀ ⁰	0.17 $\pm$ 0.04	0.07 $\pm$ 0.05	0.07 $\pm$ 0.05	-0.18 $\pm$ 0.10
ρ_{1-1}^0	0.12 $\pm$ 0.07	-0.08 $\pm$ 0.07	0.14 $\pm$ 0.07	-0.04 $\pm$ 0.10
ρ_{00}^1	-0.26 $\pm$ 0.11	-0.22 $\pm$ 0.10	-0.42 $\pm$ 0.15	0.19 $\pm$ 0.34
ρ_{11}^1	0.18 $\pm$ 0.09	0.13 $\pm$ 0.09	0.19 $\pm$ 0.08	-0.00 $\pm$ 0.15
Rep ₁₀ ¹	0.04 $\pm$ 0.07	-0.03 $\pm$ 0.08	0.30 $\pm$ 0.07	-0.22 $\pm$ 0.17
ρ_{1-1}^1	-0.15 $\pm$ 0.12	0.11 $\pm$ 0.12	-0.39 $\pm$ 0.11	-0.06 $\pm$ 0.19
Imp ₁₀ ²	-0.02 $\pm$ 0.07	0.09 $\pm$ 0.06	0.13 $\pm$ 0.09	-0.13 $\pm$ 0.14
Imp ₁₋₁ ²	-0.08 $\pm$ 0.10	0.04 $\pm$ 0.11	-0.30 $\pm$ 0.12	-0.12 $\pm$ 0.18

e) $E_\gamma = 4.7$ GeV, helicity system.

$ t $ (GeV ²)	0.014 - 0.06	0.06 - 0.15	0.15 - 0.4	0.4 - 1.0
ρ_{00}^0	0.01 $\pm$ 0.06	0.20 $\pm$ 0.07	0.09 $\pm$ 0.07	0.25 $\pm$ 0.14
$\text{Re} \rho_{10}^0$	0.07 $\pm$ 0.04	-0.10 $\pm$ 0.05	0.03 $\pm$ 0.05	0.20 $\pm$ 0.10
ρ_{1-1}^0	0.05 $\pm$ 0.08	-0.06 $\pm$ 0.07	-0.05 $\pm$ 0.08	-0.25 $\pm$ 0.11
ρ_{00}^1	-0.17 $\pm$ 0.09	-0.09 $\pm$ 0.11	0.17 $\pm$ 0.11	-0.09 $\pm$ 0.08
ρ_{11}^1	0.13 $\pm$ 0.10	0.06 $\pm$ 0.09	-0.11 $\pm$ 0.09	0.15 $\pm$ 0.09
$\text{Re} \rho_{10}^1$	-0.16 $\pm$ 0.07	-0.06 $\pm$ 0.07	-0.18 $\pm$ 0.08	0.26 $\pm$ 0.17
ρ_{1-1}^1	-0.11 $\pm$ 0.13	0.18 $\pm$ 0.12	0.21 $\pm$ 0.12	-0.21 $\pm$ 0.09
$\text{Im} \rho_{10}^2$	-0.04 $\pm$ 0.06	0.09 $\pm$ 0.07	0.04 $\pm$ 0.07	-0.09 $\pm$ 0.03
$\text{Im} \rho_{1-1}^2$	-0.09 $\pm$ 0.10	-0.06 $\pm$ 0.10	-0.18 $\pm$ 0.14	0.19 $\pm$ 0.19

f) $E_\gamma = 4.7$ GeV, Adair system.

ρ_{00}^0	0.03 $\pm$ 0.06	0.15 $\pm$ 0.07	0.18 $\pm$ 0.08	0.58 $\pm$ 0.15
$\text{Re} \rho_{10}^0$	0.10 $\pm$ 0.04	-0.06 $\pm$ 0.05	0.12 $\pm$ 0.05	0.21 $\pm$ 0.09
ρ_{1-1}^0	0.06 $\pm$ 0.08	-0.08 $\pm$ 0.07	-0.01 $\pm$ 0.08	-0.09 $\pm$ 0.11
ρ_{00}^1	-0.23 $\pm$ 0.09	-0.13 $\pm$ 0.10	-0.06 $\pm$ 0.12	0.39 $\pm$ 0.31
ρ_{11}^1	0.16 $\pm$ 0.10	0.08 $\pm$ 0.09	0.01 $\pm$ 0.09	-0.09 $\pm$ 0.15
$\text{Re} \rho_{10}^1$	-0.11 $\pm$ 0.07	-0.07 $\pm$ 0.07	-0.25 $\pm$ 0.08	0.20 $\pm$ 0.17
ρ_{1-1}^1	-0.14 $\pm$ 0.13	0.16 $\pm$ 0.12	0.09 $\pm$ 0.11	0.03 $\pm$ 0.20
$\text{Im} \rho_{10}^2$	-0.03 $\pm$ 0.07	0.10 $\pm$ 0.06	0.08 $\pm$ 0.08	-0.14 $\pm$ 0.15
$\text{Im} \rho_{1-1}^2$	-0.09 $\pm$ 0.10	-0.03 $\pm$ 0.11	-0.14 $\pm$ 0.14	0.10 $\pm$ 0.17

For completeness we note that the spin-independence model⁹¹ would predict

$$\left. \begin{aligned} \rho_{00}^0 &= 0, \\ \rho_{1-1}^1 &= 1/2 \\ \text{Im} \rho_{1-1}^2 &= -1/2. \end{aligned} \right\} \text{Adair Frame} \quad (29)$$

These values are also excluded by our data.

We can actually draw a much stronger conclusion from the density-matrix elements. Let us define the parity asymmetry as

$$P_\sigma = \frac{\sigma^N - \sigma^U}{\sigma} \quad (30)$$

where σ^N is the ω cross section for natural-parity exchange, σ^U the cross section for unnatural-parity exchange, and $\sigma = \sigma^N + \sigma^U$. (Of the diagrams in Fig. 1, all but π -exchange are natural parity.) Schilling, Seyboth, and Wolf²¹ have shown that at high energies

$$P_\sigma = 2 \rho_{1-1}^1 - \rho_{00}^1 \quad (31)$$

The derivation (Appendix B) uses asymptotic relations between scattering amplitudes T from specific parity exchange.²¹ In the limit of high energy the interference between natural- and unnatural-parity amplitudes vanishes as E_γ^{-2} , allowing us to make the separation (Eq. 31) in terms of the density matrix, which is bilinear in T . Rough theoretical calculations⁹² suggest that the interference terms should be $\leq 20\%$ at 2.8 GeV and still smaller at 4.7 GeV. For ω photoproduction Cooper has estimated that the "unnatural-parity" contribution from Pomeron exchange is of the order of 5% of that from the pion.⁹³ But the real test of smallness must be empirical. We have shown that for ρ^0 photoproduction, the contribution from natural-parity exchange to the cross section

$$\sigma^U = (1 - P_\sigma) \sigma / 2 \quad (32)$$

is $\leq 5\%$ of σ^N at 2.8 GeV and $\leq 1\%$ at 4.7 GeV, when P_σ is calculated from Eq. 31. Consequently, we will assume that we have indeed reached asymptotia at our energies, * and henceforth will refer to the combination $2\rho_{1-1}^1 - \rho_{00}^1$ as P_σ .

We note further that the expression (Eq. 31) for P_σ is invariant under rotations in the production plane,²¹ so that (since the GJ, H, and A frames are related by rotations around $\hat{y}$ = the production normal). P_σ does not depend on the frame in which it is evaluated.

Our results for P_σ are presented in Table XI and Fig. 20. P_σ is given both as a function of t and averaged over $|t| < 1 \text{ GeV}^2$. Likewise we give the differential cross sections for natural and unnatural parity exchange,

$$\frac{d\sigma^N}{dt} = \frac{1 + P_\sigma}{2} \frac{d\sigma}{dt}, \quad (32)$$

$$\frac{d\sigma^U}{dt} = \frac{1 - P_\sigma}{2} \frac{d\sigma}{dt}, \quad (33)$$

and their integrals for $|t| < 1 \text{ GeV}^2$ (Table XI and Figs. 13-14).

Integrated over $|t| < 1 \text{ GeV}^2$, $P_\sigma = -0.06 \pm 0.13$ at 2.8 GeV and 0.16 ± 0.14 at 4.7 GeV, indicating that at these energies both parity exchanges contribute to ω photoproduction with similar strength. However, while the total natural-parity cross section ($|t| < 1 \text{ GeV}^2$) decreases only slightly from $2.3 \pm 0.4 \text{ } \mu\text{b}$ at 2.8 GeV to $1.7 \pm 0.3 \text{ } \mu\text{b}$ at 4.7 GeV, the unnatural-parity cross section ($|t| < 1 \text{ GeV}^2$) drops from $2.6 \pm 0.4 \text{ } \mu\text{b}$ to $1.2 \pm 0.25 \text{ } \mu\text{b}$. These trends are continued in our preliminary data at 9.3 GeV (see Fig. 13).

The exponential form $C_N \exp(A_N t)$ fits $\frac{d\sigma^N}{dt}$ well for $0.014 < |t| < 0.4 \text{ GeV}^2$, but the errors on C_N and A_N are large (Table XI). Within errors C_N and A_N do not change from 2.8 to 4.7 GeV, but

* The error introduced by using Eq. 31 for P_σ should be even less than a few percent, since the interference terms will contribute both to the apparent σ^N and σ^U . But as we shall see, the natural and unnatural-parity exchanges are roughly equal at our energies, so that to first order the "leakage" from natural parity to σ^U and of unnatural parity to σ^N will cancel.⁹²

Table XI. Parity asymmetry P_σ for $\gamma p \rightarrow \omega p$ and the separate contributions σ^N (σ^U) of natural (unnatural) parity exchange to the ω cross sections. The values for C_N and A_N are for fits to $\frac{d\sigma^N}{dt} = C_N \exp(A_N t)$ within $0.014 < |t| < 0.4 \text{ GeV}^2$. Cross section errors include statistics and uncertainties in flux, background subtraction, and loss corrections.

$ t $ - interval (GeV^2)	P_σ	$\frac{d\sigma^N}{dt} \left(\frac{\mu\text{b}}{\text{GeV}^2} \right)$	$\frac{d\sigma^U}{dt} \left(\frac{\mu\text{b}}{\text{GeV}^2} \right)$
$E_Y = 2.8 \text{ GeV}$			
0.014-0.06	-0.15 ± 0.27	11.1 ± 3.8	14.8 ± 4.0
0.06-0.15	-0.21 ± 0.21	7.0 ± 2.1	10.6 ± 2.3
0.15-0.40	-0.13 ± 0.23	2.5 ± 0.7	3.25 ± 0.8
0.4 - 1.0	0.74 ± 0.40	0.75 ± 0.24	0.11 ± 0.18
$E_Y = 4.7 \text{ GeV}$			
0.014-0.06	-0.05 ± 0.27	9.4 ± 3.8	10.2 ± 3.9
0.06-0.15	0.45 ± 0.25	6.8 ± 1.5	2.6 ± 1.2
0.15-0.40	0.25 ± 0.27	1.9 ± 0.5	1.1 ± 0.3
0.4 - 1.0	-0.32 ± 0.45	0.13 ± 0.09	0.25 ± 0.11
Quantity, $ t $ - interval (GeV^2)	$E_Y = 2.8 \text{ GeV}$	$E_Y = 4.7 \text{ GeV}$	
P_σ average, $t_{\min} - 1.0$	-0.06 ± 0.13	0.16 ± 0.14	
σ^N integral, $t_{\min} - 1.0$	$2.3 \pm 0.4 \text{ } \mu\text{b}$	$1.7 \pm 0.3 \text{ } \mu\text{b}$	
σ^U integral, $t_{\min} - 1.0$	$2.6 \pm 0.4 \text{ } \mu\text{b}$	$1.2 \pm 0.25 \text{ } \mu\text{b}$	
C_N fit, 0.014-0.4	$12.4 \pm 4.2^a \text{ } \mu\text{b}/\text{GeV}^2$	$13.9 \pm 3.8^a \text{ } \mu\text{b}/\text{GeV}^2$	
A_N fit, 0.014-0.4	$5.9 \pm 2.1^a \text{ GeV}^{-2}$	$7.9 \pm 1.7^a \text{ GeV}^{-2}$	

^a Errors given are the more conservative correlated errors, where C_N and A_N are allowed to vary simultaneously.

there is a hint that A_N is larger at the higher energy. This steeper exponential fall-off is more evident in the full differential cross section (Table IX and Fig. 14).^{*} Within errors the values of A_N agree with those found for the reaction $\gamma p \rightarrow \rho^0 p$.^{9†}

In our discussion of diffraction dissociation and one-pion exchange (Section II) we indicated that diffraction and OPE contributions to ω photoproduction might be of comparable size at our energies. We will now hypothesize that in fact OPE accounts for all the unnatural-parity cross section and diffraction dissociation for all the natural-parity cross section (we will discuss A_2 exchange later).

As mentioned in Section II-C, simple OPE (Born approximation) does not predict a realistic cross section for large $|t|$, so that Eq. 14 must be modified by a form factor or absorption corrections. Accordingly, we have used a Benecke-Dürr form factor⁹⁵ with the radius parameters obtained by Wolf.^{59†} This form fits our values of $\frac{d\sigma}{dt}$ well if we leave $\Gamma(\omega \rightarrow \pi^0 \gamma) = \Gamma_{\omega\pi\gamma}$ as a free parameter. For the simultaneous fit at $E_\gamma = 2.8$ and 4.7 GeV and $|t| < 0.4$ GeV², we find $\Gamma_{\omega\pi\gamma} = 0.9 \pm 0.1$ MeV, close to the "world value" of 1.06 ± 0.16 (see Section II-C). We do not interpret this result as being an improvement on the world value, however, since our value of $\Gamma_{\omega\pi\gamma}$ is very dependent on the specific form factors used. Indeed, if we use an absorption-corrected OPE model^{57b} with absorption coefficient $C = 0.9$, we find $\Gamma_{\omega\pi\gamma} = 0.5 \pm 0.1$ MeV, which seems too small.

*The fit of $\frac{d\sigma}{dt}$ to $C \exp(At)$ yields the values of Table VIII. In principle this is not the best form to use (cf. Eq. 34 below), but with present statistics the fits are acceptable.

† The cross sections and exponential slopes for $\gamma p \rightarrow \rho^0 p$ depend on the model used to interpret dipion production.^{3,9}

The SLAC spectrometer group¹⁰ has fit their values for $\frac{d\sigma}{dt}$ ($\gamma p \rightarrow \rho^0 p$) to the (quadratic exponential) form found in $\pi^+ p$ scattering.⁹⁴ Our ρ^0 cross sections determined with the Söding model do not fit the πp form, but cross sections from a Ross-Stodolsky-like parameterization fit equally well to the πp form or a simple exponential (the πp form yields a larger cross section at $t=0$).⁸⁹ Our ω statistics are not large enough to choose between the two forms, so we use the simple $C \exp(At)$ parameterization for our ω differential cross sections; within errors the πp form gives the same ω cross sections at $t=0$.

‡ These parameters were determined from other reactions dominated by OPE. We used $R_{pp} = 2.86$ GeV⁻¹ at the πpp vertex and $R_{\pi\pi} = 2.31$ GeV⁻¹ at the $\omega\pi\gamma$ vertex.

We have not attempted a thorough search of models to fit the present data. However, we use the results of the Benecke-Dürr-Wolf OPE model to argue that it is plausible that OPE accounts for the entire unnatural-parity cross section. This model predicts that $\sigma^{\text{OPE}} (|t| < 1 \text{ GeV}^2)$ should decrease by a factor of 2.5 from 2.8 to 4.7 GeV; we find that $\sigma^{\text{U}} (|t| < 1 \text{ GeV}^2)$ has decreased by the factor 2.2 ± 0.6 .

We can use the energy and t dependence alone to fit $\frac{d\sigma}{dt}$ to a sum of OPE and diffractive contributions. We assume that the diffractive cross section has the form $D \exp(Bt)$ with D and B the same at both energies. For the OPE cross section we use Eq. 14 with Benecke-Dürr-Wolf⁵⁹ form factors, with the same $\Gamma_{\omega\pi\gamma}$ at both energies. Then by fitting our data to

$$\frac{d\sigma}{dt} = D e^{Bt} + \frac{d\sigma}{dt}^{\text{OPE}} \quad (34)$$

within $0.02 < |t| < 0.4$ GeV², we find $D = 11.9 \pm 1.9$ $\mu\text{b}/\text{GeV}^2$, $B = 5.8 \pm 0.6$ GeV², and $\Gamma_{\omega\pi\gamma} = 0.8 \pm 0.1$ MeV. These values, determined without using P_σ or the decay information, are quite consistent with $\Gamma_{\omega\pi\gamma} = 0.91 \pm 0.11$ MeV from the Benecke-Dürr-Wolf fit to $\frac{d\sigma^N}{dt} = C_N \exp(A_N t)$ (Table XI).

This model, of course, is capable of refinement. Not only is the parameterization of OPE a formidable task, but the assumption that σ^N comes entirely from Pomeron exchange is probably not entirely realistic: it seems likely that the A_2 trajectory should contribute substantially at our energies (Fig. 1d). If we associate the P' trajectory with the f meson and assume that the f , f' , and A_2 mesons are members of an SU(3) nonet with the same ideal mixing angle as the vector mesons, then the simple quark model⁴⁴ would suggest that f' exchange could be ignored in ρ^0 and ω photoproduction. Comparing Figs 1(c,d) with the related graphs for ρ^0 photoproduction,

we see that VDM and Eq. 5 predict that the contribution from A_2^0 exchange is ≈ 9 times larger for $\gamma p \rightarrow \omega p$ than for $\gamma p \rightarrow \rho^0 p$. Moreover, if the couplings $A_2^0 \rho^0 \omega$, $f \rho^0 \rho^0$, and $f \omega \omega$ are of similar size, then A_2^0 exchange is more important than f exchange in ω photoproduction, and conversely in ρ^0 photoproduction. However, since $\alpha_{A_2}(t=0) \approx \alpha_f(t=0) \approx 0.5$, we expect both the A_2 and f contributions to decrease with energy approximately as E_Y^{-1} . The values of $\sigma^N(\gamma p \rightarrow \omega p)$ (Table XI) of $\sigma^N(\gamma p \rightarrow \rho^0 p)$,⁹ and of $\frac{d\sigma}{dt}(\gamma p \rightarrow \rho^0 p, t=0)$,^{9,96} all show some decrease.

From the apparent difference between total photoproduction cross sections on protons and neutrons, Harari (p. 115 of Ref. 23h) has argued that at our energies the A_2^0 -Pomeron interference may contribute $40 \pm 20\%$ of $\sigma^N(\gamma p \rightarrow \omega p)$. However, the determination of $\sigma(\gamma n)$ from $\sigma(\gamma d)$ seems less than firm. Possible deuterium corrections tend to reduce the difference $\sigma(\gamma p) - \sigma(\gamma n)$,⁹⁷ so that less A_2^0 contribution is required. Wada⁹⁸ estimates that the $A_2^0 \omega \rho^0$ coupling is $\lesssim$ the $f \rho^0 \rho^0$ coupling; this would mean that A_2^0 exchange contributes no more to ω photoproduction than f exchange to ρ^0 photoproduction.

Finally, we show that this OPE + diffraction model is consistent with our results for the ω density matrix (Table X and Fig. 20). We assume that (like ρ^0 photoproduction) the diffractively produced ω retains the photon polarization, so that $\rho_{jk}^N(t)$ is given by Eq. 27. For the OPE contribution to the ω density matrix we assume that $\rho_{jk}^{\text{OPE}}(t)$ is given by Eq. 28, rotated by the angle $\beta = \cos^{-1} \left(\frac{v - \cos \Theta}{v \cos \Theta - 1} \right)$ from the

Gottfried-Jackson to helicity frame:

$$\rho_H = d^1(-\beta) \rho_{GJ} d^1(-\beta)^\dagger,$$

where d^1 is the standard rotation matrix for $J = 1$.⁹⁹ Then using our fit to Eq. 34, we calculate

$$\rho_{jk}(t) = \frac{\rho_{jk}^N(t) D \exp(Bt) + \rho_{jk}^{\text{OPE}}(t) \frac{d\sigma^{\text{OPE}}}{dt}}{D \exp(Bt) + \frac{d\sigma^{\text{OPE}}}{dt}}, \quad (35)$$

yielding the curves of Fig. 20, in fair agreement with our experimental values for the ω density matrix.

We remind the reader that Eqs. 34 and 35 used only the energy and t dependence of the ω cross sections to predict the density-matrix behavior. Within errors, we find that our model of OPE + (helicity-conserving) diffraction accounts for ω photoproduction at 2.8 and 4.7 GeV. When available, our 9.3-GeV data should provide a stricter test of the model.

D. Comparison with Vector Dominance

Ignoring the possibility of A_2 exchange, so that $\sigma^N(\gamma p \rightarrow \omega p)$ is given by diagrams like Fig. 1(a, c), we can use Eq. 9 from Section II-A,

$$\frac{d\sigma^N}{dt}(\gamma p \rightarrow \omega p)_{t=0} = \alpha \frac{4\pi}{f_\omega^2} \frac{1 + \beta_\omega^2}{16\pi} x_T^2(\omega p), \quad (9)$$

assuming $\beta_\omega \approx 0.07$.⁵¹ Our extrapolated measurement of $\frac{d\sigma^N}{dt}(t=0)$ allows us to determine either $i_\omega^2/4\pi = 4 \gamma_\omega^2/4\pi$ or $\sigma_T(\omega p)$, assuming we know the other. We will assume that for small $|t|$ we can extrapolate $\frac{d\sigma^N}{dt}$ by $C_N \exp(A_N t)$ (see second footnote on page 61). The values of C_N are given in Table XI. We take $\frac{d\sigma^N}{dt}(t=0)$ to be $C_N = 13.0 \pm 2.9 \mu\text{b}/\text{GeV}^2$, the average for both energies. If we take

$f_\omega^2/4 = 14.0 \pm 2.8$ from the colliding-beam experiments,^{40c} we find for our energies (total c.m. energy = 2.4 - 3.2 GeV) that

$$\sigma_T(\omega p) = 22 \pm 3 \text{ mb.}$$

On the other hand, if we take the quark-model prediction $\sigma_T(\omega p) = [\sigma_T(\pi^+ p) + \sigma_T(\pi^- p)]/2 \approx 30 \text{ mb}$ for this energy interval,¹⁰⁰ we find

$$f_\omega^2/4\pi = 25.5 \pm 5.6.$$

We conclude that Eq. 9, the Orsay value for $f_\omega^2/4\pi$, the quark-model prediction, and our ω photoproduction cross section extrapolated to $t = 0$ disagree by somewhat less than two standard deviations. Of course any one (or combination) of these inputs may be questioned.

Moffeit⁹ has used our Eq. 12 (Section II-B) to derive $f_\rho^2/4\pi$. Though this relationship is most sensitive to $\frac{d\sigma}{dt}(\gamma p \rightarrow \rho^0 p, t = 0)$, we shall restate his results here with revised values for the forward ρ^0 cross section, $C_N(\omega)$ from Table XI, and different vector-meson phases. For our Söding-model determination of $\frac{d\sigma}{dt}(\gamma p \rightarrow \rho^0 p, t = 0)$ ⁸⁹ and $\beta_\rho = \beta_\omega = \beta_\phi = 0$ (phase $(\phi) = \pi$ relative to ρ^0 and ω), we find $f_\rho^2/4\pi = 0.9 \pm 0.1$ at both energies. For $\beta_\rho = -0.2$, $\beta_\omega = -0.07$, and $\beta_\phi = -0.5$,⁵¹ the results are unchanged. These values differ by a factor of 2 from the Orsay results ($f_\rho^2/4\pi = 2.0 \pm 0.2$).^{40c} However, when we use different models to fit our ρ^0 data,⁸⁹ we find $\frac{d\sigma}{dt}(t = 0)$ larger by as much as 40% (this includes an uncertainty in extrapolating $\frac{d\sigma}{dt}$ from $t = -0.02 \text{ GeV}^2$ to $t = 0$). In view of these difficulties, the discrepancy with simple VDM is perhaps not too extreme.

From Tables VIII, IX, and XI of Moffeit's thesis,⁹ we find that $\sigma^N(\gamma p \rightarrow \rho^0 p, |t| < 1.0 \text{ GeV}^2) = 16.9 \pm 1.1 \mu\text{b}$ at 2.8 GeV, as determined with a Söding-model fit; at 4.7 GeV our revised value is $15.6 \pm 0.8 \mu\text{b}$.⁸⁹ Comparing $\sigma^N(\omega)$ from Table XI, we find $\sigma^N(\rho^0)/\sigma^N(\omega) = 7.3 \pm 1.2$ at 2.8 GeV and 9.3 ± 1.7 at 4.7 GeV.* These values are consistent with the 9 to 1 ratio predicted by simple VDM + SU(3) (Eq. 10) but are also consistent with $f_\omega^2/f_\rho^2 = 9/1.2$ predicted by Das, Mathur, and Okubo⁴⁵ or 7/1 found by the Orsay group.^{40c} Within the assumptions of Eq. 9, they do not seem to be consistent with 9/0.65 predicted by Oakes and Sakurai.⁴⁶ Further precision will require a better understanding of models to determine the ρ^0 cross section.^{3, 9, 89}

* With a Ross-Stodolsky-like parameterization for $\sigma(\rho^0)$,⁸⁹ we find $\sigma^N(\rho^0)/\sigma^N(\omega) = 8.3 \pm 1.3$ at 2.8 GeV and 9.5 ± 1.7 at 4.7 GeV.

VI. PRODUCTION OF ρ , Δ , AND A_2^+ IN FOUR-BODY FINAL STATES

In addition to prominent ω production, the four-body final states include substantial production of other quasi-two-body and quasi-three-body reactions. For completeness we describe briefly our results for these reactions, leaving further details to a future paper.⁸⁹

A. The Channel $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$

To remove multineutral contamination we applied the beam-energy selection of Table II and the missing-mass cuts^{*} $MM^2 < 0.10 \text{ GeV}^2$ at 2.8 GeV and $MM^2 < 0.14 \text{ GeV}^2$ at 4.7 GeV. The influence of the ω was removed by requiring $m_{+-} > 0.86 \text{ GeV}$. The remaining events were fitted by maximum likelihood¹⁰¹ to an incoherent sum of four-body phase space and the reactions in Table XII.

For the ρ resonance shape we used a p-wave Breit-Wigner^{3,9} with no mass-skewing term. The ρ mass was fixed at 770 MeV and the width at 140 MeV. The $\Delta(1236)$ shape was taken from phase shifts as in our analysis of the channel $p \pi^+ \pi^-$.^{6,9}

At 4.7 GeV there is an apparent excess of events with $\pi^+ \pi^-$ mass $m_{+-} \approx 1.25 \text{ GeV}$ (Fig. 22i). Our fit improved noticeably with the addition of the reaction $\gamma p \rightarrow f \pi^0 p$, with the f parameterized as a simple (symmetric) Breit-Wigner with mass = 1264 MeV and width = 150 MeV.³⁶

Our fits were substantially improved by "shaping" phase space with the ad hoc factors

$$(1 + a m_{p+}^2) / \left[(1 + b m_{+-}) (1 + c m_{+0}) \right] \quad (35)$$

Table XII. Total cross sections for reactions in the channel $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$. The cross sections for quasi-three-body states ($\pi \pi \Delta$ and $\rho \pi p$) do not include the cross sections for $\rho \Delta$ production.

Reaction	Total cross section (μb)	
	$E_\gamma = 2.8 \text{ GeV}$	$E_\gamma = 4.7 \text{ GeV}$
$\gamma p \rightarrow$		
$\rho^- \Delta^{++}$	2.1 ± 0.4	1.3 ± 0.2
$\rho^- \pi^+ p$	1.8 ± 0.5	2.0 ± 0.3
$\Delta^{++} \pi^- \pi^0$	1.5 ± 0.5	1.1 ± 0.2
$\rho^0 \Delta^+, \Delta^+ \rightarrow \pi^0 p$	0.3 ± 0.4	0.3 ± 0.1
$\rho^0 \pi^0 p$	1.3 ± 0.6	2.2 ± 0.3
$\Delta^+ \pi^+ \pi^-$	2.1 ± 0.5	0.7 ± 0.2
$\rho^+ \Delta^0, \Delta^0 \rightarrow \pi^- p^*$	0 ± 0.3	0 ± 0.1
$\rho^+ \pi^- p$	2.6 ± 0.5	2.1 ± 0.3
$\Delta^0 \pi^+ \pi^0^*$	0 ± 0.4	0 ± 0.2
$f \pi^0 p, f \rightarrow \pi^+ \pi^-$	---	0.5 ± 0.2
ωp	5.3 ± 0.5	3.0 ± 0.3
Parameters for phase-space modification (Eq. 35)		
a	$0.4 \pm 0.4 \text{ GeV}^{-2}$	$2.6 \pm 0.7 \text{ GeV}^{-2}$
b	$3.2 \pm 1.5 \text{ GeV}^{-1}$	$7.2 \pm 1.8 \text{ GeV}^{-1}$
c	$1.4 \pm 0.5 \text{ GeV}^{-1}$	$0.5 \pm 0.2 \text{ GeV}^{-1}$

* Excluded from the final fit. Errors were determined in a preliminary fit.

^{*} MM^2 is defined in Eq. A-3 of Appendix A. The MM cuts are partially redundant with the energy cuts. The uncut energy and MM distributions are shown in Figs. A-2 and A-4.

The parameters a , b , c were allowed to vary in the fit, with the results given in Table XII.

The fits agree well with all two- and three-body mass projections (Figs. 21-22) except m_{+-0} . There is no evidence for structure in the $\pi\pi$ effective masses.

The results of our fits are given in Table XII. These have been corrected for our energy and mass cuts, with the aid of Monte Carlo calculations.⁸¹ The errors include the fit errors (statistics and background) and correction uncertainty, but they do not reflect the systematic differences between possible forms that could have been used in the likelihood formula.

We can see from Figs. 21-22 and Table XII that ρ^0 , $\rho^\pm$, Δ^{++} , and Δ^+ are produced in quantity. In addition to independent ρ^- and Δ^{++} production, there is evidence for the reaction

$$\gamma p \rightarrow \rho^- \Delta^{++}$$

at both energies. This is illustrated by the "triangle plots" (m_{p^+} vs m_{0^-}) in Fig. 23. Where the ρ^- and Δ^{++} bands cross, there is substantial enhancement over that which could be accounted for by an incoherent sum of $\gamma p \rightarrow \rho^- \pi^+ p$ and $\gamma p \rightarrow \pi^- \pi^0 \Delta^{++}$.

Simple one-pion exchange (see Section II-C) predicts the relative cross sections

$$\sigma(\gamma p \rightarrow \rho^- \Delta^{++}) : \sigma(\gamma p \rightarrow \rho^0 \Delta^+) : \sigma(\gamma p \rightarrow \rho^+ \Delta^0) = 3 : 2 : 1.$$

Even allowing for the branching fractions of $2/3$ for $\Delta^+ \rightarrow \pi^0 p$ and $1/3$ for $\Delta^0 \rightarrow \pi^- p$, there is substantially more $\rho^- \Delta^{++}$ than $9/4$ $\sigma(\gamma p \rightarrow \rho^0 \Delta^+, \Delta^+ \rightarrow \pi^0 p)$. Also, the OPE relationship

$$\sigma(\gamma n \rightarrow \omega \Delta^0, \Delta^0 \rightarrow \pi^- p) = 2 \sigma(\gamma p \rightarrow \rho^- \Delta^{++}) \quad (18b)$$

fails badly. Our 4.7-GeV value of $2.6 \pm 0.4 \mu\text{b}$ for the right-hand side contrasts with the 4.3-GeV upper limit of $0.5 \mu\text{b}$ for the left-hand side.¹⁸

The SLAC-Weizmann-Tel Aviv groups^{19a} report that the cross sections for $\gamma p \rightarrow \rho^- \Delta^{++}$ (our preliminary data⁸ and their data for 3.7-8.2 GeV photons from the SLAC annihilation beam) are too large to agree with OPE for a reasonable value of $\Gamma_{\rho\pi\gamma}$. They also find that

the total cross section decreases with energy roughly as $E_Y^{-0.6}$. The latter is not necessarily in disagreement with OPE, however, since the requirement of a minimum momentum transfer can strongly modify the basic E_Y^{-2} dependence of simple OPE.

The "excess" $\rho^- \Delta^{++}$ production may be due to exchange of ρ or A_2 . These lie on Regge trajectories with $\alpha(t=0) \approx 0.5$, higher than the π trajectory, for which $\alpha(t=0) \approx 0$. If ρ or A_2 exchange is dominant, we might expect the forward cross section for $\rho^- \Delta^{++}$ to have a basic energy dependence more like E_Y^{-1} . For low energies the dependence would be somewhat weaker because of the minimum momentum transfer. This suggestion seems consistent with the data.^{19a}

The $f \pi^0 p$ production at 4.7 GeV also suggests ρ , ω , or B exchange, since neither f nor $f \pi^0$ can be photoproduced by $C=+1$ exchange (such as diffraction or OPE). In contrast to this channel, we found no evidence for $f p$ production in the channel $p \pi^+ \pi^-$.^{3,9}

B. The Channel $\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$

To remove multineutral contamination we applied the beam-energy selections of Table II and the missing-mass selections $0.52 < MM^2 < 1.08 \text{ GeV}^2$ at 2.8 GeV and $0.40 < MM^2 < 1.12 \text{ GeV}^2$ at 4.7 GeV. From Fig. A-3 we see that while most of the neutron signal is contained within the MM selections, some contamination from $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$ and $\gamma p \rightarrow p \pi^+ \pi^- \pi^0 \pi^0$ is also accepted. (Allowing 50% error in the curves of Fig. A-3, we estimate that the contamination is $\leq 10\%$ at 2.8 GeV and $\leq 40\%$ at 4.7 GeV.) Since these channels also contain some ρ^0 production (see Figs. 21-22 in Section VI-A and Fig. 26 in Section VII), the true values for the ρ^0 cross sections may be slightly smaller than those reported in Table XIII.

As in the preceding section, events surviving the cuts were fit to an incoherent sum of ρ^0 , Δ^+ , Δ^- , $\rho^0 \Delta^+$, and (unaltered) phase space. The fit results are shown in Fig. 24 for two-body mass combinations. There was no structure in the $\pi^+ \pi^+$ and $\pi^+ \pi^\pm n$ mass combinations (not shown). Corrections for the energy and MM cuts were made with the aid of Monte Carlo calculations.⁸¹ Errors include fit statistics (signal and background) and Monte Carlo uncertainties. The results are given in Table XIII.

Table XIII. Total cross sections for reactions in the channel $\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$. The cross sections for quasi-three-body states ($\pi\pi\Delta$ and $\rho\pi n$) do not include the cross sections for $\rho\Delta$ production, but the cross section for $\rho^0 \pi^+ n$ does include $A_2^+ n$.

Reaction	Total cross section (μb)	
	$E_\gamma = 2.8 \text{ GeV}$	$E_\gamma = 4.7 \text{ GeV}$
$\gamma p \rightarrow$		
$\rho^0 \Delta^+, \Delta^+ \rightarrow \pi^+ n$	0 ± 0.3	0 ± 0.2
$\rho^0 \pi^+ n$	2.2 ± 0.4	3.5 ± 0.3^a
$\Delta^+ \pi^+ \pi^-$	0 ± 0.3	0 ± 0.2
$\Delta^- \pi^+ \pi^+$	2.0 ± 0.3	1.0 ± 0.2
$A_2^+ n, A_2^+ \rightarrow \pi^+ \pi^+ \pi^-$	b	$1.0^{+0.6}_{-0.4}$

^a Contains some ρ^0 from $\gamma p \rightarrow p \pi^+ \pi^- \pi^0 (\pi^0)$.

^b Difficult to estimate, since phase space peaks near the A_2 mass.

Although there is sizable ρ^0 and Δ^- production, we find no evidence for Δ^+ production in this channel. Since $\sigma(\Delta^+ \rightarrow \pi^0 p) = 2 \sigma(\Delta^+ \rightarrow \pi^+ n)$, Table XII indicates that we should expect about $1.2 \pm 0.3 \mu\text{b}$ (total) of Δ^+ in 2.8-GeV $\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$; in fact we see no indication of Δ^+ production ($0 \pm 0.4 \mu\text{b}$). Since it seems unlikely that 10% contamination could change our fit results, the discrepancy should keep us from becoming too elated over the beauty of our fits.

Wolf⁶² has suggested that there should be substantial diffractive photoproduction of "inelastic" ρ^0 (i.e., ρ^0 plus any baryon state with $I = \frac{1}{2}$, other than the proton) at high energies. Since the ρ^0 signal in 4.7-GeV $\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$ is fairly strong ($\approx$ background), we have attempted to calculate its parity asymmetry P_σ , as in Section V-C. Corrections for background were made by extrapolating from neighboring $\pi^+ \pi^-$ mass intervals, and ρ^0 from A_2^+ decay (see below) were excluded. For $|t_{\gamma p}| < 0.5 \text{ GeV}^2$, we find $P_\sigma = 0.7 \pm 0.3$, consistent with natural parity exchange ($P_\sigma = 1$).

Groups from SLAC and the Weizmann Institute have reported photoproduction of $A_2^+ n$ at 4.3 and 5.3 GeV.^{16b, 102} In Fig. 25 we show the $\pi^+ \pi^+ \pi^-$ mass plots for the reaction $\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$. There is some indication of A_2^+ production, which is enhanced at 4.7 GeV for proton-neutron momentum transfer $|t_{pn}| < 1.0 \text{ GeV}^2$ (shaded events). The 2.8 GeV signal is near the peak of phase space. Although there appears to be A_2^+ production at this energy, we are unable to subtract background reliably.

We used two methods to determine the A_2^+ cross section at 4.7 GeV. A fit to a symmetric Breit-Wigner shape with mass = 1.3 GeV and width = 0.08 GeV gave $\sigma(\gamma p \rightarrow A_2^+ n) = 0.75 \pm 0.15 \mu\text{b}$ for $|t_{pn}| < 0.5 \text{ GeV}^2$. The value given in Table XIII was determined from a plot of the $\pi^+ \pi^+ \pi^-$ mass for events with at least one ρ^0 (not shown). The error limits correspond to "optimistic" and "pessimistic" background estimates.* Corrections were made for good

* The "optimistic" background assumed an A_1^+ "shoulder" near $m_{++-} \approx 1.06 \text{ GeV}$. While we do not claim to see A_1^+ photoproduction, we cannot rule out a cross section on the order of $0.5 \mu\text{b}$ at either 2.8 or 4.7 GeV.

events lost because of the ρ^0 cut (+20%) and energy and MM cuts (+31%, determined by Monte Carlo⁸¹).

The A_2^+ cross section given in Table XIII is for the $\pi^+\pi^+\pi^-$ decay mode only. If we take the branching fraction for $A_2^+ \rightarrow \pi^+\pi^+\pi^-$ to be 39%,³⁶ we find $\sigma(\gamma p \rightarrow A_2^+ n) = 2.5^{+1.5}_{-1.0} \mu\text{b}$ at 4.7 GeV.

We note that $A_2^+ n$ photoproduction can proceed by OPE (see, e.g., Ref. 102), while OPE cannot contribute to $A_2^0 p$ because of C conservation. We find no evidence for A_2^0 production in $\gamma p \rightarrow p\pi^+\pi^-\pi^0$, although at 4.7 GeV there are more events with $1.0 < m_{+-0} < 1.3$ GeV than predicted by our fit (Fig. 22j). We find an upper limit (90% C. L.) of 1.2 μb for $\sigma(\gamma p \rightarrow A_2^0 p)$ at 4.7 GeV.

For $A_2^+ n$ production we have calculated the parity asymmetry $P_\sigma = 2\rho_{1-1}^1 - \rho_{00}^1 - 2\rho_{2-2}^1$ (see Appendix B). Background was subtracted by extrapolation from neighboring mass intervals. For 4.7 GeV and $|t_{\text{pr}}| < 0.5 \text{ GeV}^2$, we find $P_\sigma(A_2) = -1.3 \pm 0.8$, consistent with OPE ($P_\sigma = -1$).

VII. B-MESON PRODUCTION

In Sections V and VI we have studied resonance production in channels with one neutral particle in the final state. For these we were able to calculate all kinematic quantities, including the photon energy, without assuming prior knowledge of the beam energy. To remove multineutral background we applied cuts on the calculated beam energy and (sometimes) on the missing mass (MM).*

In this section we switch our attention to this "background," namely, the multineutral three-prong channel

$$\gamma p \rightarrow p \pi^+ \pi^- (\mathcal{M}), \quad (\text{Channel 2b})$$

where by $\mathcal{M}$ we mean a neutral state (e.g., $2\pi^0$) with mass $\text{MM} > m_{\pi^0}$. For the remainder of this section (with one exception) we consider only events with $\text{MM}^2 > 0.10 \text{ GeV}^2$ at 2.8 GeV and $\text{MM}^2 > 0.14 \text{ GeV}^2$ at 4.7 GeV (and no energy cut). These MM cuts remove most of the π^0 signal and few of the multineutral events, as seen in Figs. A-4(a, c).

Figure 26 shows effective mass distributions for $\pi^+\pi^-$, π^+p , and π^-p in Channel 2b. There is substantial Δ^{++} production at both energies and some (inelastic) ρ^0 production at 4.7 GeV.[†]

To analyze more of this channel we must again use our knowledge of the beam energy. Assuming a nominal energy, we calculate the mass M_x recoiling against the final proton in

$$\gamma p \rightarrow p X \quad | \rightarrow \pi^+ \pi^- \mathcal{M}$$

In Fig. 27 we illustrate our resolution in M_x by plotting events selected for $\mathcal{M} = \pi^0$ by requiring $\text{MM}^2 < 0.10$ (0.14) GeV^2 . The ω signal is quite clear, though somewhat broader than in the effective mass m_{+-0} calculated in 0-C fits (Figs. 10 and 12). The width of the $X = \omega$ peak is consistent with our calculated resolution $\text{FWHM} \approx 60 \text{ MeV}$.

*The MM is calculated from Eq. A-3 (Appendix A), which requires an assumed beam energy.

[†]Most, but not all, of the ρ^0 peak in Fig. 26d comes from events ambiguous with $\gamma p \rightarrow \pi^+\pi^+\pi^- (n \dots)$. The latter channel has a strong ρ^0 signal (cf. Fig. 24f).

Returning to channel 2b, defined by the cuts $MM^2 > 0.10$ (0.14) GeV^2 , we show the recoil mass M_x in Fig. 28. We plot separately events with $|t| < 0.5 \text{ GeV}^2$, $0.5 < |t| < 1.0 \text{ GeV}^2$, and $|t| > 1.0 \text{ GeV}^2$ (where t , as before, is the square of the four-momentum transfer from target to recoil proton). The samples for $|t| > 1.0 \text{ GeV}^2$ are heavily contaminated by events from

$$\gamma p \rightarrow \pi^+ \pi^+ \pi^- (+ \text{anything}). \quad (\text{Channel 3})$$

However the events with $|t| < 1.0 \text{ GeV}^2$ are almost never ambiguous with channel 3, since the slow proton leaves a dark track in the chamber (cf. Fig. 4).

For $|t| > 0.5 \text{ GeV}^2$ the M_x distributions resemble multibody phase space with no structure. For $|t| < 0.5 \text{ GeV}^2$, however, we find in the 4.7-GeV events a significant peak near $M_x \approx 1.25 \text{ GeV}$; also the 2.8-GeV events show a suggestive peak at the same mass. For these events ($M_x \approx 1.25 \text{ GeV}$) the resolution in M_x is calculated to be FWHM $\approx 70 \text{ MeV}$. For $E_\gamma = 2.8 \text{ GeV}$ the enhancement width (FWHM $\approx 100 \text{ MeV}$) seems not much larger than our resolution, but at $E_\gamma = 4.7 \text{ GeV}$ we see a FWHM $\approx 150 \text{ MeV}$.

We have checked the possibility that these peaks may come from low-energy events of

$$\gamma p \rightarrow p \pi^+ \pi^- \pi^0. \quad (\text{Channel 2a})$$

Consider an event from Channel 2a with true beam energy $<$ the nominal energy. Then according to Eq. A-3 (Appendix A), we would calculate a $MM > m_{\pi^0}$ and $M_x > m_{+-0}$. An anomalously large number of low-energy $\gamma p \rightarrow \omega p$ events* could create a false peak in $M_x > m_\omega$ that would be attributed to Channel 2b. However, in a 0-C fit to $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$, these events would still have $m_{+-0} \approx m_\omega$. For our sample of (supposedly) multineutral events we have plotted M_x vs m_{+-0} from the 0-C fit.

*Since our true beam spectra (Fig. 5) contain so few events with $E_\gamma \ll E_{\text{peak}}$, the type of effect discussed here would require a very large cross section at some lower energy.

The m_{+-0} spectrum shows no sign of (low-energy) ω events. Furthermore, the events with $M_x \approx 1.25 \text{ GeV}$ come from a wide band of (nominal) m_{+-0} , proving that the enhancement in M_x does not reflect an m_{+-0} peak from low-energy $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$.

We conclude that the 1.25-GeV enhancement consists of bona fide multineutral events. For convenience we will refer to the enhancement as $\tilde{B}$.

By observing the $\tilde{B}$ enhancement with the Δ^{++} removed ($m_{+p} < 1.16 \text{ GeV}$ or $m_{+p} > 1.30 \text{ GeV}$) we have satisfied ourselves that the $\tilde{B}$ is not a reflection of Δ^{++} production. On the other hand, Δ^{++} removal does not strengthen the $\tilde{B}$ signal, and the Δ^{++} signal/background is small (Fig. 26). Therefore we choose to make no Δ^{++} cuts for our subsequent analysis.

The distribution in t and M_x^2 is shown explicitly in the Chew-Low plots of Fig. 29. We see that both the $\tilde{B}$ signal and the background are rather peripheral. In Fig. 30 we plot $t' = t - t_{\min}$ for events near the $\tilde{B}$ ($1.15 < M_x < 1.35 \text{ GeV}$) and for "background" ($0.95 < M_x < 1.15 \text{ GeV}$ or $1.35 < M_x < 1.55 \text{ GeV}$). For the $\tilde{B}$ region the events are distributed roughly as $\exp(At')$, where $A \approx 4$ to 6 GeV^{-2} at both energies. This is also true of the "background" at 4.7 GeV, but at 2.8 GeV the background is less forward ($A \approx 3 \text{ GeV}^{-2}$). Because of the large background, we are unable to determine the $\tilde{B}$ differential cross section reliably. If helicity-flip* amplitudes were dominant, the cross section would fall near $t' = 0$ (forward production). Figures 30(a, c) show no indication of a forward dip, but background and lack of statistics make it difficult to state conclusively that there is no decrease in forward $\tilde{B}$ production.

The Review of Particle Properties³⁶ shows four nonstrange mesons with mass near 1.25 GeV: The B , $\bar{B}$, D , and A_2 . The A_2^0 has a somewhat higher mass ($\approx 1.3 \text{ GeV}$) and decays primarily into $\tau^+ \pi^- \pi^0$.

*I.e., $\lambda_{\tilde{B}} - \lambda_\gamma \neq \lambda_{p'} - \lambda_p$.

In $\gamma p \rightarrow \pi^+ \pi^- \pi^0$ there is some excess of events with $m_{+-0} \approx 1.24$ GeV at both energies (Figs. 10b, 21j, 22j),* but this mass seems too low to be A_2^0 . The only known A_2^0 decay sequence that would appear in Channel 2b is $A_2^0 \rightarrow \eta_c \pi^0$ ($\eta_c \rightarrow \pi^+ \pi^- \dots$), which is about 28% of 20% of $A_2^0 \rightarrow \rho \pi$.³⁶ As discussed below, the $\tilde{B}$ enhancement is not chiefly $\eta \pi^0$. Moreover, even if we assume at each energy a rather generous cross section of ≈ 1 μb for $\gamma p \rightarrow A_2^0 \rightarrow \rho \pi$, the $\eta_c \pi^0$ decay sequence would represent only ≈ 0.06 μb . Since our $\tilde{B}$ signals are ≈ 1 μb , they cannot come from A_2^0 .

The f meson decays principally into $\pi\pi$.³⁶ Since we see no f signal in $\gamma p \rightarrow p \pi^+ \pi^-$,^{3,9} the $\tilde{B}$ cannot be identified with the f .

The D meson is believed to decay largely into $\eta \pi^+ \pi^-$ ¹⁰³ or into $2\pi^+ 2\pi^-$.¹⁰⁴ We find no enhancement in either of these decay modes. For the $\eta \pi^+ \pi^-$ decay mode (corrected for unseen η decays³⁶), we find an upper limit (90% C. L.) for $\sigma(\gamma p \rightarrow D p, |t| < 0.5 \text{ GeV}^2)$ of 0.2 μb at 2.8 GeV and 0.05 μb at 4.7 GeV; these contrast with $\sigma(\tilde{B}) \approx 1$ μb , as discussed below.

Figures 31(b,d) show the 4π mass spectrum ($|t| < 0.5 \text{ GeV}^2$) from $\gamma p \rightarrow p 2\pi^+ 2\pi^-$. There is no evidence for a $\tilde{B}$ or D signal.[†] In the following paragraph we show that there are too few $2\pi^+ 2\pi^-$ events (at 4.7 GeV, near $M_{\tilde{B}} \approx 1.25$ GeV or $M_D \approx 1.29$ GeV) to be consistent with the 4π decay of the D or any other $I=0$ resonance.

*The appearance of this small bump in mass ($\pi^+ \pi^- \pi^0$) is qualitatively the same whether we use weak or stringent MM cuts, indicating that these events are probably genuine $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$ and not an artifact from multineutral events which survive the cuts.

[†]In Fig. 31e we give the 4π mass spectra for 4.7-GeV $\gamma p \rightarrow p 2\pi^+ 2\pi^-$ with no t cut, but with Δ^{++} removed. This corresponds to Fig. 4b in Ref. 10, where the SLAC streamer-chamber group, using bremsstrahlung photons with $E_\gamma = 4.5$ to 18 GeV, report a broad enhancement at mass (4π) ≈ 1.55 GeV (arrow in our Fig. 31e). We see no evidence for this enhancement at $E_\gamma = 4.7$ GeV (2.8 GeV is below threshold). Assigning an optimistic 45 events for the signal in $1.4 < M(4\pi) < 1.7$ GeV, we find an upper limit of 0.3 μb at 4.7 GeV, compared with the streamer-chamber result of 0.44 ± 0.2 μb for 4.5-18 GeV.

We assume what we wish to disprove: that $\tilde{B} \rightarrow \pi^+ \pi^- \pi^0 \pi^0$ and has $I = 0$. Consider the decay modes

$$\begin{array}{ll} \tilde{B}^0 \rightarrow \pi^+ \pi^+ \pi^- \pi^-, & \text{fraction } F_4, \\ \pi^+ \pi^- \pi^0 \pi^0, & F_2, \\ \pi^0 \pi^0 \pi^0 \pi^0, & F_0. \end{array}$$

If $I = 0$, there can be no preferred direction in isospace, so that a large number of $\tilde{B}$ decays would yield equal numbers of π^+ , π^- , and π^0 .¹⁰⁵ This implies that

$$F_2 = 2F_4 - 4F_0.$$

Since $F_0 \geq 0$, we see that F_4 can never be less than $F_2/2$. In Fig. 31 we compare the M_x signals with the $\pi^+ \pi^+ \pi^- \pi^-$ mass distributions from our $\gamma p \rightarrow p \pi^+ \pi^+ \pi^- \pi^-$. The latter show no sign of a 1.25-GeV enhancement. At 4.7 GeV we can state that the $\pi^+ \pi^+ \pi^- \pi^-$ decay mode for $\tilde{B}$ is less than one half of the $\pi^+ \pi^-$ (+ neutrals) mode. Therefore if $\tilde{B}$ is a 4π resonance, it has $I \geq 1$. (Of course if we could show that $\tilde{B}^0 \rightarrow \omega \pi^0$, $I = 1$ would follow trivially. This point is discussed below.)

By elimination we conclude that the enhancements, if genuine, result from production of B^0 or of a new meson, such as the ρ' (Section II-D).

The B meson has been observed only in the decay mode $\omega \pi$.¹⁰⁶⁻¹¹¹ For a while it was considered a possible $\omega \pi$ kinematic enhancement,¹⁰⁷⁻¹⁰⁸ but the observation of $\bar{p} p \rightarrow B^\pm \pi^\mp$ ¹⁰⁹ strengthened its claim as a bona fide resonance. The $\omega \pi$ decay mode determines $I^G = 1^+$ (and therefore $C = -1$ for the B^0), but J^P has not been firmly established. Ascoli et al.¹¹⁰ find evidence that $J^P = 1^+, 2^+$, or 3^- , but Bizzarri et al.¹¹¹ find best agreement with $J^P = 1^-$ (1^+ also acceptable). If J^P were 1^- , the B could decay into $\pi\pi$ or $K\bar{K}$; however, the experimental upper limit for the $\pi\pi$ decay rate is 30% of that for $\omega \pi$ decay.¹¹² In principle the B may even be the long-sought ρ' , but in this case it would be difficult to explain the small $\pi\pi$ decay rate.

"Consensus opinion" seems to favor the B as having $J^P = 1^+$ (decaying through an S or D wave into $\omega\pi$). In either case ($J^P = 1^-$ or 1^+) the B^0 could be diffractively photoproduced.^{113*} Our interest in the possibility of diffraction production is motivated by the observation of a missing-mass peak at 1240 MeV (width 100 MeV) in 14-GeV photoproduction.¹⁰ The cross section was of the order of $\sigma(\gamma p \rightarrow \phi p)$, perhaps a factor of 2 or 3 smaller than the cross sections for $\tilde{B}$ in our data. It seems likely that the same meson is produced at 2.8, 4.7, and 14 GeV.

Although we cannot reconstruct the complete decay sequence of the $\tilde{B}$, the distribution of $\pi^+\pi^-$ mass provides some useful information. We note that in 94% of our ω decays[†] the $\pi^+\pi^-$ mass is in the interval 0.33-0.60 GeV. In Fig. 32 we show M_x for events with $0.33 < m_{+-} < 0.60$ GeV; although the background is smaller, there is no decrease in $\tilde{B}$ signal. We conclude that these events are consistent with the decay $\tilde{B} \rightarrow \omega + \text{neutral}(s)$, but the decay $\tilde{B} \rightarrow \rho^0 + \text{neutrals}$ is excluded. Similarly, by selecting on $m_{+-} > 0.41$ GeV, we find little reduction in $\tilde{B}$ signal; this excludes $B \rightarrow \eta + \text{neutral}(s)$. We are not able to rule out $\tilde{B} \rightarrow \rho^\pm \pi^\mp \pi^0$.

Returning to the problem of "kinematic" enhancements, we recall the experiment of Chung et al.,¹⁰⁸ who studied the reaction $\pi^- p \rightarrow p \pi^- \omega$ at 3.2 and 4.2 GeV/c. For events with low momentum transfer ($|t| \leq 0.35 \text{ GeV}^2$) they found substantial production of B^- (i.e., an enhancement at mass $\pi^- \omega \approx 1.22 \text{ GeV}$) and (or) production of $\pi^- p$ resonances near 1.236, 1.518, and 1.688 GeV. The $\pi^- \omega$ and $\pi^- p$ enhancements, however, were associated mostly with the same events. This led the authors to suggest that the B was a "kinematic" enhancement of the type

* For the 1^+ assignment, the Pomeron would carry an "orbital angular momentum" $L = 1$.

† This fraction was determined for decays from $\gamma p \rightarrow \omega p$ (Section V) and agrees with that calculated for a $\vec{p}_+ \times \vec{p}_-$ matrix element.

where the π^- from N^* decay travels (roughly) in the ω direction. For the lower vertex, this corresponds to forward π^- production in the virtual reaction $\rho^- p \rightarrow \pi^- p$. For $N^* = N^*(1518)$ or $N^*(1688)$, the authors found such forward production, but it was not clear whether to interpret this as the cause or the effect of B production. Later experiments¹⁰⁹⁻¹¹¹ lend support to the B as a bona fide resonance.

A similar configuration could produce an artificial $\pi^0 \omega$ peak in our recoil mass spectrum. Consider the hypothetical diagram

Unfortunately, since there are two neutral particles in the final state, we cannot determine the $\pi^0 p$ mass. Let θ_H be the angle between the (lower vertex) π^0 and the ω in the N^* rest frame. Then for given c.m. energy and N^* mass, there is a linear relationship between $\cos \theta_H$ and the $\pi^0 \omega$ mass, the latter being smallest for $\cos \theta_H = 1$.

In this experiment we find evidence for $\Delta^+(1236)$ production in the channel $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$ (Table XII, Section VI) but no evidence for higher-mass baryon states in any channel. In principle the cross section for $\gamma p \rightarrow \omega \Delta^+$ could be fairly large (see Section IV-C), but we cannot measure this directly. We have generated Monte Carlo mass distributions for the $\pi^0 \omega$ mass from $\gamma p \rightarrow \omega \Delta^+$ assuming the most extreme angular distributions for $\Delta^+ \rightarrow \pi^0 p$, namely $W(\cos \theta_H) = \sin^2 \theta_H$ and $1 + 3 \cos^2 \theta_H$. The first distribution favors $\cos \theta_H \approx 0$ and produces a broad enhancement centered at $m(\pi^0 \omega) \approx 1.25 \text{ GeV}$ for $E_Y = 2.8 \text{ GeV}$ and at $m(\pi^0 \omega) \approx 1.55 \text{ GeV}$ for $E_Y = 4.7 \text{ GeV}$; the FWHM is 0.4 and 0.6 GeV, respectively. For the second distribution, favoring $\cos \theta_H \approx \pm 1$, there are broad dips at these masses, and enhancements at $m(\pi^0 \omega) \approx 1.0$ and 1.45 GeV for $E_Y = 2.8 \text{ GeV}$, and at 1.06 and 1.82 GeV for $E_Y = 4.7 \text{ GeV}$. In no way do these distributions resemble the M_x spectra in our experiment, but of course the true Δ^+ decay distributions need not be so extreme. We conclude that $\gamma p \rightarrow \omega \Delta^+$ cannot create the

narrow enhancements we see at $M_x \approx 1.25$ GeV, but that at 2.8 GeV our $\tilde{B}$ signal could be sitting atop a broad peak or valley from this reaction. The problem of background subtraction is thus worse at 2.8 GeV than at 4.7 GeV.

However, deuterium studies suggest that $\sigma(\gamma p \rightarrow \omega \Delta^+)$ may be $\lesssim 1 \mu\text{b}$ at 4.3 GeV¹⁸ (see Section IV-C), so that these distortions may not be significant.

At last, we attempt to determine the $\tilde{B}$ cross section. However, in order to estimate the background under the $\tilde{B}$ signal, we need some idea of the nature of events in channel 2b. Some probable contributors are

$$\gamma p \rightarrow \rho \omega \pi^0,$$

$$\gamma p \rightarrow p \pi^+ \pi^- 2\pi^0,$$

$$\gamma p \rightarrow p \pi^+ \pi^- 3\pi^0.$$

We have generated Monte Carlo distributions for these reactions with phase-space (PS) and $\exp(At)$ distributions. The five-body and six-body PS calculations yield M_x distributions which peak at large M_x , similar to our M_x distributions for $|t| > 0.5$ GeV² (Fig. 28). However, for $|t| < 0.5$ GeV², they do not account for the number of events with $M_x < 1.35$ GeV (including the $\tilde{B}$ and events with $M_x \approx 1.0$ GeV), even with a steep t dependence ($A = 6$ GeV⁻²). On the other hand, the $\rho \omega \pi^0$ PS distributions are rather flat and so predict many events with $M_x \approx 1.0$ GeV.

For an "objective" background curve we tried the simple isospin model described in Appendix A: We calculated M_x for our events from the channels $\gamma p \rightarrow p 2\pi^+ 2\pi^-$, $p 2\pi^+ 2\pi^- \pi^0$, etc., weighted according to the factors in Table VI, to estimate the M_x distributions in $\gamma p \rightarrow p \pi^+ \pi^- 2\pi^0$, etc. These provided a fair description of our M_x distributions, except for $M_x \approx 1.0$ and 1.25 GeV. It seems plausible that the events near $M_x \approx 1.0$ GeV are mostly $\rho \omega \pi^0$.*

* This is consistent with our observation (Appendix A) that the isospin model predicts too few multineutral events with small $|t|$. Since our model neglects resonance production, the $\rho \omega \pi^0$ channel is effectively beyond its scope.

For a "reasonable guess" background at 4.7 GeV we have drawn eyeball-normalized" curves representing 50% $p \pi^+ \pi^- 2\pi^0$, 30% $p \pi^+ \pi^- 3\pi^0$, and 20% $\rho \omega \pi^0$, where all distributions are phase space times $\exp(5t)$ with cuts appropriate to the plot. These are shown as solid curves in Fig. 31c and (with different fractions, due to the mass cut) in Fig. 32b. The dashed curve in Fig. 31c is 20% $\rho \omega \pi^0$, as before, plus 80% isospin model. For our "best guess" cross section we have used the average of these two curves, yielding $0.9 \mu\text{b}$ $\tilde{B}$ signal in the mass interval 1.04-1.44 GeV. If we assume that the natural width of the $\tilde{B}$ is 100 MeV and fold in ± 35 MeV resolution, we should increase this by 16% to account for signal lost in the tails of the distribution, giving for $E_\gamma = 4.7$ GeV and $|t| < 0.5$ GeV²,

$$\sigma(\gamma p \rightarrow \tilde{B} p) = 1.05 \pm 0.4 \mu\text{b}.$$

(The error is just a guess. The curves in Fig. 31c differ by $0.5 \mu\text{b}$.)

At 2.8 GeV the $\tilde{B}$ signal occurs near the peak of peripheralized 5-body phase space, so that it is possible to invent background curves which reduce its significance to less than two standard deviations. We have chosen to be somewhat more optimistic, though. The curve in Fig. 31a represents a mixture of 35% $p \pi^+ \pi^- 2\pi^0$ and 20% $p \pi^+ \pi^- 3\pi^0$ PS, both times $\exp(3t)$, and 45% $\rho \omega \pi^0$ PS times $\exp(5t)$. It coincides with that for 55% isospin model plus 45% $\rho \omega \pi^0$. The $p \pi^+ \pi^- 2\pi^0 + p \pi^+ \pi^- 3\pi^0$ mixture is also drawn in Fig. 32a (after applying m_{+-} cuts, so that fractions are different). The signal above background ($1.2 < M_x < 1.36$ GeV) is $0.8 \mu\text{b}$. The peak is somewhat more narrow than we would expect for the B (FWHM ≈ 100 MeV) with resolution of ± 30 MeV. We guess that 15% more events are in the tails of the distribution, so that at 2.8 GeV and $|t| < 0.5$ GeV²,

$$\sigma(\gamma p \rightarrow \tilde{B} p) = 0.9 \pm 0.5 \mu\text{b}.$$

We believe that our method of background subtraction (reasonable mixture of reactions with peripheral phase space, normalized by eye) is only slightly less prejudiced than drawing "smooth curves" under the $\tilde{B}$ peaks. Accordingly, we have set rather large errors on the $\tilde{B}$ cross sections to cover the possibilities of more optimistic and

more pessimistic background curves, including different widths for the tails of the $\tilde{B}$ distributions.

If we further assume that the signal consists entirely of the decay mode $\tilde{B} \rightarrow \omega\pi^0$, we should correct $\sigma(\tilde{B})$ for (10%) neutral decay modes of the ω .³⁶ The final cross sections are given in Table XIV.*

To summarize what we have learned about the $\tilde{B}$ enhancement:

(1) We observe the enhancement only in the recoil mass spectrum for $\gamma p \rightarrow pX$, $X \rightarrow \pi^+\pi^-$ (+ neutrals). This study was possible only because our beam is virtually monoenergetic.

(2) In this channel the $\tilde{B}$ signal is quite clean at $E_Y = 4.7$ GeV for $|t| < 0.5$ GeV². Because it appears near the peak of "phase space" at 2.8 GeV, its significance is more difficult to ascertain. (Moreover, a SLAC counter experiment¹⁰ has seen a similar enhancement in 14-GeV $\gamma p \rightarrow pX$, but they were unable to study the decay modes.)

(3) Our enhancement is quite peripheral, consistent with $\frac{d\sigma}{dt} \propto \exp(At)$, $A \approx 5$ GeV⁻². There is no signal visible for $|t| > 0.5$ GeV². Because of the large background we cannot study the differential cross section in detail.

(4) Because the channel involves two or more neutral particles, we cannot reconstruct the full decay sequence of the $\tilde{B}$. However, from the $\pi^+\pi^-$ mass spectrum we can show that the signal is consistent with 100% $\tilde{B} \rightarrow \omega\pi^0$ decay. From the effects of m_{+-} cuts we can set upper limits for decay modes $\tilde{B} \rightarrow \rho^0$ (+ neutrals) or η (+ one or more neutrals). In our five-prong events we find no evidence for $\tilde{B} \rightarrow \eta\pi^+\pi^-$, $\omega\pi^+\pi^-$, $2\pi^+2\pi^-\pi^0$, or $2\pi^+2\pi^-$. The upper limit for $\tilde{B} \rightarrow 2\pi^+2\pi^-$ shows that the $\tilde{B}$ is not an $I = 0$ object decaying predominantly into 4π . The upper limits for various decay modes are given in Table XIV.

Table XIV: Cross sections for $\gamma p \rightarrow \tilde{B} p$, assuming $\tilde{B}^0 \rightarrow \omega\pi^0$; upper limits for other decay modes. [Our $\tilde{B}$ signal is seen in the recoil mass spectrum for $\gamma p \rightarrow pX$, $X \rightarrow \pi^+\pi^-$ (+ neutrals). All of its measurable characteristics are consistent with those known for the B meson.^{36, 106-111}]

	$\sigma(t < 0.5 \text{ GeV}^2)$
$E_Y = 2.8 \text{ GeV}$	$1.1 \pm 0.6 \mu\text{b}$
$E_Y = 4.7 \text{ GeV}$	$1.4 \pm 0.6 \mu\text{b}$
Other decay modes: upper limits (90% C. L.) for $\tilde{B}$ decay rate divided by $\tilde{B} \rightarrow \pi^+\pi^-$ (+ neutrals).*	
$\tilde{B} \rightarrow \eta$ (+ one or more neutrals)	< 25%
ρ^0 (+ neutrals)	< 25%
$\pi^+\pi^-$	< 25%
$\pi^+\pi^-\pi^0$	< 50%
$2\pi^+2\pi^-$	< 25%
$2\pi^+2\pi^-\pi^0$	< 10%
$\eta\pi^+\pi^-$	< 10%
$\omega\pi^+\pi^-$	< 10%
* Upper limits were determined at 4.7 GeV for $ t < 0.5 \text{ GeV}^2$. Limits at 2.8 GeV are less stringent.	

* MM-cut losses were determined from Monte Carlo events⁸¹ (assuming B production $\propto e^5$, with S-wave decay into $\omega\pi^0$). The cross sections were corrected by +6.5% at 2.8 GeV and +17% at 4.7 GeV.

(5) At 4.7 GeV the $\tilde{B}$ signal appears to have the same mass (≈ 1235 MeV) and width (≈ 100 MeV, with resolution unfolded) as the B meson. At 2.8 GeV the mass is somewhat higher (≈ 1260 MeV) and the peak is narrower (≈ 70 MeV, unfolded). These differences should not be taken too seriously, though, in view of background uncertainties and limited statistics at 2.8 GeV.

(6) All our findings are consistent with interpreting the $\tilde{B}$ enhancement as the B^0 meson, with the photoproduction cross sections in Table XIV. Since similar cross sections are found at 2.8, 4.7, and 14 GeV, there is a good possibility that the $\tilde{B}$ is diffractively produced.*

In closing, we comment on the question of ρ' production. As mentioned in Section II-D, there have been abundant predictions for a ρ' with mass ≈ 1.3 GeV. Because the ρ^0 is so prominent in photoproduction, we might also hope to see ρ' photoproduction. If the dominant decay mode for ρ' is $\omega\pi$, our $\tilde{B}$ could be the ρ' . (In this case, the absence of a large $\pi^+\pi^-$ decay rate would provide useful employment for theorists. In fact the absence of $B \rightarrow \pi\pi$ ¹¹² seems to be the biggest obstacle to considering the B meson as the ρ' , since $J^P = 1^-$ has not been conclusively ruled out by the B decay distributions.)

We note that at 4.7 GeV and $|t| < 0.5 \text{ GeV}^2$,

$$\sigma(\gamma p \rightarrow \tilde{B} p) / \sigma(\gamma p \rightarrow \rho^0 p) = 10 \pm 4\%.$$

Using multi-Regge diagrams, Mickens has suggested that $\omega\pi^0$ photoproduction should be enhanced near $M(\omega\pi^0) \approx 1.24$ GeV.¹¹⁴ In the framework of Chew-Pignotti duality¹¹⁵ he interprets this enhancement as the ρ' . However, it would seem that his argument

* We see no evidence for $B^\pm$ production in $\gamma p \rightarrow \rho\omega\pi^+\pi^-$, but it would be interesting to check deuterium for the reaction $\gamma n \rightarrow B^+ p$. Both reactions require $I = 1$ exchange, so that evidence for them would weaken the argument for diffractive B^0 production.

is equally valid as a prediction of B^0 photoproduction.* By similar reasoning he predicts $\omega' \rightarrow \rho\pi$ near 1.24 GeV. Although we do find some excess $\pi^+\pi^-\pi^0$ production near this mass (see Figs. 21j and 22j), we make no claims on its significance.

* Mickens rejects the B^0 interpretation by claiming that $J^P = 1^+$ cannot be diffractively photoproduced. This statement seems incorrect, though. Since the vacuum trajectory allows exchange of "orbital angular momentum," only $J^P = 0^-$ is ruled out. See also Gilman et al.¹¹³

VIII. CONCLUSIONS

We have studied photoproduction at 2.8 and 4.7 GeV, using a linearly polarized photon beam in a hydrogen bubble chamber. The monoenergetic beam and 4π detection efficiency enabled us to measure cross sections for various photoproduction channels, including those with one or more neutral particles (Table V). Our total cross sections for hadron photoproduction and cross sections for $\gamma p \rightarrow \rho^0 p$ are published elsewhere.^{3,4,9,89}

We report here a study of $\gamma p \rightarrow \omega p$ in the channel $\gamma p \rightarrow p\pi^+\pi^-\pi^0$. The monoenergetic beam enabled us to separate single- π^0 from multi-neutral production, so that there is little background underneath the ω signal. Our cross sections for ω photoproduction are given in Tables VIII-IX and Figs. 13-14.

We have studied the ω decay in detail. Because our photon beam was $> 90\%$ linearly polarized, we have been able to determine nine independent parameters of the ω density matrix, compared with only three accessible to previous experiments. These parameters are given in Table X and Fig. 20. The greatest value of these parameters is that they allow separation of the cross sections for ω production by natural- and unnatural-parity exchange (Table XI and Figs. 13-14). We find that both parities are important at our energies, but that the unnatural-parity exchange decreases rapidly with increasing energy. The energy variation and t dependence of σ^U are consistent with one-pion exchange. The E_γ and t dependence of σ^N , however, resemble those for $\gamma p \rightarrow \rho^0 p$, which we believe to be a diffractive process.^{3,4,9} In fact, we find that the density matrix parameters are consistent with those calculated for a mixture of OPE and helicity-conserving diffractive ω production (curves in Fig. 20), though some helicity-flip contribution cannot be excluded.

Qualitatively, these features of ω photoproduction are well explained by the vector dominance model (Section II). If the cross sections for $\rho^0 p$ and ωp scattering are equal, as suggested by quark models,^{44,51,54} then the diffractive part of $\sigma(\gamma p \rightarrow \omega p)$ should equal $\sigma(\gamma p \rightarrow \rho^0 p) f_\rho^2/f_\omega^2$. With this assumption, and evaluating $\sigma(\rho^0)$ from our Söding-model fits,⁹ we find that $f_\omega^2/f_\rho^2 = 7.3 \pm 1.2$ at 2.8 GeV and 9.3 ± 1.7 at 4.7 GeV. (Other models for ρ^0 photoproduction give somewhat different values; see Section V-D.) These ratios are consistent

with those given by some SU(3) models, as discussed in Section V-D.

However, the absolute values of f_ρ^2 and f_ω^2 differ from those found in other experiments.^{23,40} If we take the quark-model predictions for $\sigma_{\pi^+}(\omega p)$, we find $f_\omega^2/4\pi = 26 \pm 6$, compared with 14 ± 2.8 found at Orsay.^{40c} This could be due to breakdown in VDM or the quark model or to extrapolation from $t \approx -0.02 \text{ GeV}^2$ to $t = 0$. Similarly, VDM connects the total photoproduction cross section with ρ^0 and ω photoproduction at $t = 0$, yielding $f_\rho^2/4\pi = 0.9 \pm 0.1$, in contrast to 2.0 ± 0.2 from Orsay.^{40c} Again, the fault could lie with VDM, with our ρ^0 photoproduction model, or with the extrapolation to $t = 0$.⁸⁹

We conclude that while VDM gives excellent qualitative agreement, some quantitative results lack explanation.

In the three-prong channels we also find production of η (Table VIII and Fig. 15), A_2^+ (Table XII), ρ , Δ , $\rho\Delta$, and perhaps f (Tables XII and XIII). The cross sections for $\gamma p \rightarrow \rho^-\Delta^{++}$ seem larger than we would expect from OPE.

With our monoenergetic beam we have been able to analyze the recoil mass spectrum for $\gamma p \rightarrow pX$, $X \rightarrow \pi^+\pi^-$ (+ neutrals). At both energies we find an enhancement ($\sigma \approx 1 \mu\text{b}$) near $M_X \approx 1.25 \text{ GeV}$. The enhancements are produced at $|t| < 0.5 \text{ GeV}^2$ and are consistent with $\omega\pi^0$ decay; the cross sections are given in Table XIV, along with upper limits on other decay modes. All characteristics are consistent with $\mathbb{B}^0$ photoproduction (perhaps diffractive), but we cannot exclude its interpretation as ρ' .

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APPENDIX A. CROSS SECTIONS FOR ZERO-CONSTRAINT CHANNELS

In this appendix we derive the cross sections for channels with three charged prongs,

$$2a. \gamma p \rightarrow p\pi^+\pi^- (\pi^0)$$

$$2b. \gamma p \rightarrow p\pi^+\pi^- (\text{neutrals})$$

$$3a. \gamma p \rightarrow \pi^+\pi^+\pi^- (n)$$

$$3b. \gamma p \rightarrow \pi^+\pi^+\pi^- (n + \text{neutrals})$$

with five prongs,

$$12a. \gamma p \rightarrow p2\pi^+2\pi^- (\pi^0)$$

$$12b. \gamma p \rightarrow p2\pi^+2\pi^- (\text{neutrals})$$

$$13a. \gamma p \rightarrow 3\pi^+2\pi^- (n)$$

$$13b. \gamma p \rightarrow 3\pi^+2\pi^- (n + \text{neutrals})$$

and with seven prongs,

$$22a. \gamma p \rightarrow p3\pi^+3\pi^- (\pi^0)$$

$$23a. \gamma p \rightarrow 4\pi^+3\pi^- (n)$$

(Our notation is to refer to channel 2 when we mean both 2a and 2b.

The a channels have a single neutral particle, and the b channels have more than one.)

We describe in detail the treatment of the three-prong channels; the corresponding five-prong and seven-prong channels were treated by an analogous method. All the cross sections are collected in Table IV (Section IV).

Since our initial fits did not fix the beam momentum, the a "fits" have zero constraints and the b "fits" are underconstrained. Most events had a nominal "fit" for both hypotheses 2 and 3. Our method was to use the bubble density to separate reactions 2 and 3 if possible, and then to exploit the narrow beam spectrum and kinematic models to complete the separation.

For each three-prong event* we attempted the hypotheses in Table III (Section III-C). The fits to hypotheses 2 and 3 include multi-neutral events. In addition, they may have some contamination from strange-particle reactions such as those in Table A-I, where neither of the strange-particle decays was visible in the chamber. (Corrections for this contamination are given in Table A-II.)

* With no visible strange-particle decay.

Table A-I.

Examples of strange-particle reactions which could contaminate the nonstrange channels. These hypotheses were not tried in SQUAW unless a strange-particle decay was seen.

$$6. \gamma p \rightarrow pK^+K^- (\pi^0)$$

$$7. \gamma p \rightarrow \pi^+K^+K^- (n)$$

$$8. \gamma p \rightarrow pK^+\pi^- (\bar{K}^0)$$

$$9. \gamma p \rightarrow \pi^+K^+\pi^- (\Lambda \text{ or } \Sigma^0)$$

$$10. \gamma p \rightarrow p\pi^+K^- (K^0)$$

Seven-prong events and all events which fit hypothesis 4, 5, or 14 (see Table III) were examined at the scan table by a physicist or expert scanner. A 3-constraint fit to reaction 1 ($p\pi^+\pi^-$) or 11 ($p\pi^+\pi^+\pi^-\pi^-$) was checked visually if $10^{-6} < CL < 10^{-3}$, where CL is the confidence level derived from the kinematic fit χ^2 with 3 degrees of freedom. Most $p\pi^+\pi^-$ fits with $CL > 10^{-3}$ ($\chi^2 < 16$) were accepted without visual examination.* Monte Carlo⁸¹ studies indicated that fewer than 1% of the 3-C events were lost to 0-C channels and vice versa. This "cross-feeding" is further discussed by Moffeit⁹ and Podolsky.⁸⁰

The remainder of this appendix concerns only those events which fit reaction 2 and (or) 3 and have no fit to reactions 1, 4, or 5 with $CL > 10^{-5}$.

About 25% of the 0-C fits (hypotheses 2, 3, 12 and 13) were compared with pulse-height data from the Spiral Reader, and the remaining 75% were examined at the scan table. If the bubble density of any track was not consistent with its interpretation, that fit was rejected; in a few cases criteria such as delta rays, neutron recoils, or π decays helped to establish the correct fit(s). A few events from reaction 6-10 (Table A-I) were identified in the rescanning; these were assigned to a "no-fit" category. Comparisons of postfit scans indicated that fewer than 5% of the fits were misassigned. Full details are given in an internal memo.⁸⁰

*Events with more than one 3-constraint fit were examined at the scan table; moreover, pulse-height data from the Spiral Reader provided confirmation for one-third of the sample. Special scans found no false $p\pi^+\pi^-$ introduced. For further details see References 9 and 80.

For tracks with momentum less than 1.25 GeV/c there were virtually no ambiguities between a proton and π^+ . For favorable events the choice could sometimes be made for momentum up to 1.7 GeV/c, for which (bubble density as proton) / (bubble density as pion) $\approx \beta_p^{-2} = 1.3$ (Figure A-1 shows the proton momentum distribution for reactions 1 and 2 and their 5-prong analogues.) After resolving as many track ambiguities as possible, we still had a number of events ambiguous between hypotheses 2 and 3. (Moreover, there were two different permutations of the positive tracks for $p\pi^+\pi^-\pi^0$ and three for $p\pi^+\pi^-\pi^-\pi^0$, so that the hypothesis $\pi^+\pi^+\pi^-\pi^0$ might be ambiguous with one or both of the $p\pi^+\pi^-\pi^0$ fits.)

It is instructive to review the O-C calculation for the apparent beam momentum K_{oc} where we assume a single neutral particle with mass m . We know the beam direction $\hat{K}$ and measure the lab momenta p_i of all charged particles in the final state. If we assign a mass (μ = pion mass or M = proton mass) to each charged track, we can calculate the charged energies $E_i = \sqrt{p_i^2 + m_i^2}$. Let $\vec{p} = \sum \vec{p}_i$, $E = \sum E_i$, and $q = \hat{K} \cdot \vec{p}$. Then

$$K_{oc} = (m^2 - B)/A, \quad (A-1),$$

where m^2 = square of neutral mass,

$$A = 2(M + q - E),$$

$$B = (E-M)^2 - p^2.$$

The calculated beam energy is linearly related to the value of m^2 assumed, though the coefficient A is different for each event. If the charged masses are assigned correctly, then (neglecting measurement error) we have

$$A = 2(E_{\text{neutral}} - q_{\text{neutral}}) \geq 0.$$

That is, if we assume a nominal m^2 which is smaller than the actual neutral mass², the calculated beam energy K_{oc} is smaller than the true energy.

Figure A-2(a, e) shows the beam energy calculated for 3350(4605) unique* events of hypothesis 2 at 2.8 (4.7) GeV; the energy was calculated assuming a single missing π^0 . The shaded area shows the true beam spectrum. The large excess of events at apparent low energies

* With proton identified or hypothesis 3 excluded kinematically.

comes from channels of the type 2b, e.g.,

- 2b₁. $\gamma p \rightarrow p\pi^+\pi^- (2\pi^0),$
- 2b₂. $p\pi^+\pi^- (3\pi^0),$
- 2b₃. $p\pi^+\pi^- (\pi \rightarrow \text{neutrals}),$
- 2b₄. $p\pi^+\pi^- (\omega \rightarrow \text{neutrals})$

As can be seen from Eq. A-1, the beam energy is badly determined for events with a high-energy π^0 in the forward direction ($A \approx 0$). Many of the events with $K_{oc} > K_{\max}$ are of this type. The rest may be mismeasures or events of

$$2b_5. \gamma p \rightarrow p\pi^+\pi^- (\gamma).$$

Hypotheses 3, 12, and 13 show similar distributions of apparent beam spectra; The unique fits to these reactions are shown in Figs. A-2 (b-c, f-h).

Up to this point the only kinematic criterion was that all masses and momenta be positive. Next we invoked the knowledge that the true beam energy had a sharp maximum $K_{\max}$ given by Eq. 19 (Sec. III-A; see also Fig. 6). Figure A-2(d) shows the beam spectrum calculated for $\pi^+\pi^+\pi^-\pi^0$ for events which were ambiguous with $p\pi^+\pi^-\pi^0$. The events with $K_{oc} \gg K_{\max}$ were mostly $p\pi^+\pi^-\pi^0$ and not genuine $\pi^+\pi^+\pi^-\pi^0$. For these we eliminated the $\pi^+\pi^+\pi^-\pi^0$ fit by imposing the cut

$$\frac{K_{oc} - K_{\max}}{\delta K_{oc}} < +5 \quad (A-2)$$

on all O-constraint fits. In effect this was like a 1-constraint χ^2 cut applied in one direction only. The cut reduced the number of ambiguous events to those remaining in Table IV (Sec. IV). This sample is the basis for the remaining calculations.

Finally we used the monochromatic properties of our beam in a much stronger way: Note that Eq. A-1 can be turned around to calculate the square of the missing mass, MM^2 , if we provide a nominal beam energy K_{nom} :

$$MM^2 = AK_{\text{nom}} + B. \quad (A-3)$$

We chose K_{nom} to be near the median beam energy, between the mean and mode of the true beam spectrum. Figures A-3, 4 show the MM^2 distributions for reactions 2, 3, 12, and 13. The π^0 and neutron peaks are quite prominent. The shapes and widths of these peaks

agree well with the resolution functions calculated either from SQUAW (real events) or by Monte Carlo methods.⁸¹

The greatest difficulty in determining the cross sections was how to assign the events which were ambiguous between hypotheses 2 and 3. For ambiguous events Fig. A-5 shows the MM^2 calculated as $p\pi^+\pi^-MM$ vs MM^2 for $\pi^+\pi^-MM$. The number of events in the overlap between π^0 and neutron peaks was small, so that the error introduced by assigning half to π^0 and half to neutron was not important. On the other hand there were many events which were ambiguous between channel 2b and either 3a or 3b. We had to devise a statistical method for separating 2b, 3a, and 3b.

We chose to use the 5-prong events as a model of 5-, 5-, and 7-body final states with three prongs. Thus channel 11 ($p\pi^+\pi^-\pi^-$) provided a very clean sample of a 5-body final state. Abandoning in turn the measurements of each of the four $\pi^+\pi^-$ combinations, we recalculated the events as $p\pi^+\pi^-$ ($MM=\pi^+\pi^-\approx\pi^0\pi^0$). Similarly we recalculated both of the two $\pi^+\pi^+$ ($MM=\pi^-\pi^-\approx\pi^0\pi^0$) combinations. The 5-prong 0-constraint events similarly served as models for 6- and 7-body final states (channels 12b, 13a, and 13b were sometimes ambiguous at 4.7 GeV, but this did not seriously affect our conclusions).

This method had several advantages over a completely artificial Monte Carlo. With no effort we had built in the correct beam spectrum and measurement errors. Despite some differences, the model provided a dynamical frame that was probably closer to truth than we could devise for Monte Carlo input. The momentum transfer distribution was relatively important. Figure A-1 indicates that the recoil proton momentum (P_{lab}) for $p\pi^+\pi^-$ (neutrals) is distributed much like that for $p2\pi^+2\pi^-$ (plus some $p2\pi^+2\pi^-\pi^0$), but with an excess of events having $P_{lab} < 0.8$ GeV/c. The excess may come from B^0p or $\omega\Delta^+$ production, as discussed in Sections IV and VII. This distortion is tolerable, though, since we relied more on the model for events with large P_{lab} (where the proton track was ambiguous with π^+).

Our model implicitly assumed that the 5-prong 5- and 5-body states contained the same mix of resonances as the 3-prong events. Clearly the ρ^0 , ω , η , and Δ^0 had different importance in the 3- and 5-prong events, and this is another shortcoming. However, the

multiplicity of combinations shaped the overall mass distributions much like phase space, and the fine features were smeared out by the MM resolution. Although detailed differences could be discerned, the weighted MM distributions from our model were in excellent agreement with the data.

The relative weights of the various multineutral channels were needed. Here the real 5-prong data also provided a handle not available in Monte Carlo methods. As an ansatz we adopted the isospin arguments of Shapiro¹⁰⁴ and Spitzer.¹⁰⁵ Spitzer approximated the initial γp state by $|\rho^0 p\rangle = \sqrt{2/3}|I=3/2\rangle - \sqrt{1/3}|I=1/2\rangle$ and assumed isospin invariance with no resonance production. In Table VI (Section IV) we repeat his branching ratios for the various 5-body charge states, 6-body, etc. We found that his method tended to underestimate the number of multineutral events (especially those $\pi^+\pi^-p$ MM events with slow protons), but that it was sufficient to provide reasonable relative weights. Multiplying his weights by our real 5 to 7 body 5-prong events, we estimated the relative importance of 5 to 7 bodies for our 3-prong MM. The combined multineutral distribution agreed well with our MM and was not sensitive to small differences in the weights. Only the 5-body distribution was important for correcting the tails underneath the π^0 and neutron MM peaks.

More difficult was the evaluation of false backgrounds in the ambiguous events - i.e., contamination from channels with the "other" choice (π^+ or proton) for the ambiguous track. Again we used the 5-prong events with Spitzer's weights, but this time we fitted the channel $p\pi^+\pi^-$ ($MM=\pi^+\pi^-$) and let the proton be misidentified as a π^+ . We used only those tracks which would be ambiguous on the basis of ionization (we required the momentum to be > 1.33 GeV/c - i.e., $\beta_p^{-2} < 1.5$). We found that this false MM peaked near the neutron mass (see Fig. A-3b), whereas the corresponding 6- and 7-body false MM gave a tail at larger MM. On the other hand, when we fitted $\pi^+\pi^+\pi^-$ ($MM=\pi^-p$) and pretended that the high-momentum π^+ was a proton, we found no false background near the π^0 mass.

Finally, we had to determine the amounts of ambiguous $p\pi^+\pi^-$ ($MM > \pi^0$), $\pi^+\pi^+\pi^-(n)$, and $\pi^+\pi^+\pi^-$ MM. We used several methods of

extrapolating from unique to ambiguous events. E.g., the 5-prong model gave expected rates for ambiguous $\pi^+\pi^+\pi^-$ MM and for false $\pi^+\pi^+\pi^-$ MM. The sum of these agreed well with the numbers of ambiguous candidates and shape of their MM distribution for $MM^2 > 1.5 \text{ GeV}^2$. The number of predicted multineutral events under the neutron peak was then subtracted. Alternatively, we first weighted the ambiguous $\pi^+\pi^+\pi^-$ MM by (unique/predicted) $\pi^+\pi^+\pi^-$ MM and the false $\pi^+\pi^+\pi^-$ MM by (unique/predicted) $p\pi^+\pi^-$ MM. This gave a slightly larger rate for reaction 2b at the expense of 3a and 3b. For the worst case the two approaches gave contamination estimates differing by 25 %. For our final values we used an average of the two background estimates with a generous uncertainty of ± 50 %.

Figures A-3 (a,c,e,f) show the MM^2 distributions for unique events fitting hypotheses 3 and 13. The solid curves show the shape of the multineutral backgrounds (reactions 3b and 13b) calculated from our model. (The curves were normalized to the number of events with $MM^2 > 1.5 \text{ GeV}^2$, requiring a factor 1.25 to 2 times the absolute predictions from the model.) Figures A-3 (b,d,g,) show the MM^2 distributions for fits to reaction 3(13) which are ambiguous with reaction 2(12). The light curves are the sum of estimated false events from 2a(12a) and false events from reaction 2b(12b). The amount of contamination from channel 2a ($p\pi^+\pi^-\pi^0$) was estimated from plots of MM^2 for competing proton and π^+ assignments (Fig. A-5). Only a fairly small shoulder at low MM^2 remained after our energy cut. The 5-body reaction $p\pi^+\pi^-\pi^0\pi^0$ created a false peak near the neutron mass, and the other multineutral reactions contributed to the high MM^2 tail. The light curves in Fig. A-3 are normalized to the amount of contamination (from channel 2) subtracted from the neutron cross sections — namely, the average of the unweighted predictions of our model and a modification with weights derived from the relative numbers of unique events in reactions 2b and 3b as discussed above. The heavy curves are the sum of this contamination and the multineutral background from channel 3b (13b). The excess of events near $MM^2 \approx 1.5 \text{ GeV}^2$ is partly from the neutron tail and partly $\Delta^0 \rightarrow n\pi^0$. The heavy curves agree well with the data for large MM^2 .

Figures A-4 show the MM^2 distributions for hypotheses 2 and 12; the solid curve is the sum of contamination from channel 3 and the distribution for events of channel 2b, as determined above. By counting the events that lay above this curve (cut off at $MM^2 \approx 0.15 \text{ GeV}^2$, with a correction for the higher mass tail), we determined the number of events in reaction 2a. The curve fitted large MM^2 well except for a slight excess of events near $MM^2 \approx 0.3 \pm 0.1 \text{ GeV}^2$. Part of this excess was from neutral decays of the η (see Sections IV and V).

In addition to these background subtractions, several smaller corrections (Table A-II) were applied to the cross sections. The largest was for events produced by photons from the low-energy tail of the true photon spectrum (Fig. 6). The number of single-neutral events was less affected than multineutral events (single-neutral events with $K_{oc} < K_{true}$ had an apparent MM^2 greater than the single-neutral peak, so that most were counted as multineutral events).

There was some scanning and (or) fitting loss for very peripheral (short proton) $\pi^+\pi^-\pi^0p$ events at 4.7 GeV/c (see Section III-C). For all other cases the scan efficiency was greater than 99 %.

From our events with strange-particle decay we estimated the number of events in reactions 6-10 (Table A-I) for which no strange particle was identified.

In the 5- and 7-prong events there may have been some 3- and 5-prong events with an e^+e^- pair from a π^0 Dalitz decay. When identified, the pair was not included in the number of prongs. However, if both e^+ and e^- had momentum $> 200 \text{ MeV}/c$, they could not usually be distinguished from pions. We calculated the number of Dalitz pairs expected and compared this with the number actually found. We concluded that at 2.8 GeV virtually all Dalitz pairs were identified and so do not contaminate reactions 12 and 13. However, at 4.7 GeV we found only about half as many Dalitz pairs as expected -- the remaining half had been included with the 5- and 7-prong reactions. These corrections are summarized in Table A-II.

There may be some true events of channel 2b₅ ($p\pi^+\pi^-\gamma$), which we cannot resolve from 2a ($p\pi^+\pi^-\pi^0$). We have not attempted any correction: the cross section given for 2a implicitly contains any

2b₅ that may exist.

The cross-section normalization was provided by the pair count (corrected for fiducial volume and energy tail) and the pair cross section.^{76,9} We assumed that events which were not successfully measured were populated like our well-measured events. The final cross sections are given in Table V, Section IV. Although the errors include statistics and the "minor" corrections of Table A-II, they are dominated by uncertainties in channel separation and background subtraction.

Table A-II. Additional corrections to cross sections for channels with neutral particles. All corrections are in percent.

Beam energy:	2.8 GeV			4.7 GeV			
	Wrong energy	Strange particle contam.	Dalitz pair contam.	Wrong energy	Strange particle contam.	Dalitz pair contam.	Scan eff.
2a.				-2.5±1			+1±1
2b.	-1.8±1	-2.5±2.5	0±2	-9.7±4	-5.5±5.5		
3b.	-1.1±0.5	-1.7±1.7	0±2	-9.1±3	-3.6±3.6	0±1	
12a.			0±2	-1.5±1		-1.2±0.7	
12b.			0±42	-7.8±4.5		-10±4	
13b.			0±25	-5.8±4		-9±4	
22a.						-12.5±12.5	
22b.						-100±60	
22c.						-100±200	

APPENDIX B. TWO SHORT PROOFS: Φ AND P_0 .

1. The angle Φ (Section V-B) is invariant under boosts in the production plane.

We assume that the photoproduction amplitudes are gauge-invariant, so that we can define Φ in terms of the electric field $\vec{E} = E \hat{\epsilon}$ of the photon. Let $\hat{Y}$ be the normal to the ωp production plane and $\hat{K}$ be the photon direction. We define

$$\cos \Phi = (\hat{Y} \times \hat{K}) \cdot \hat{\epsilon},$$

$$\sin \Phi = \hat{Y} \cdot \hat{\epsilon}$$

(Since $\hat{Y}$ and $\hat{\epsilon}$ are both normal to $\hat{K}$, Φ is obviously unchanged by a boost along $\hat{K}$; thus Φ has the same meaning in the laboratory and c.m. frames.)

For clarity we choose the reference axes $\hat{Z} = \hat{K}$ (c.m.) and $\hat{X} = \hat{Y} \times \hat{K}$, so that the photon fields are

$$\vec{E} = E \hat{\epsilon} = E (\cos \Phi, \sin \Phi, 0),$$

$$\vec{B} = \hat{K} \times \vec{E} = E (-\sin \Phi, \cos \Phi, 0).$$

We now consider the Lorentz transformation from c.m. to ω rest frame. Let Θ , E_ω , and p_ω be respectively the c.m. production angle (from $\hat{K}$), energy, and momentum of the ω . The strength of the boost is characterized by $\gamma = E_\omega/m_\omega$ and $\eta = p_\omega/m_\omega$, where $\gamma^2 = \eta^2 + 1$; and the direction is given by

$$\hat{\omega} = (\sin \Theta, 0, \cos \Theta).$$

For brevity we define $\alpha = \hat{\omega} \cdot \hat{\epsilon} = \sin \Theta \cos \Phi$.

Since none of the following depends on our choice of axes, on the direction Θ , or the strength of the boost, the proof is completely general for any boost in the production plane.

In the ω rest frame the transformed field is¹¹⁶

$$\vec{E}'_{\parallel} = \vec{E}_{\parallel} = \hat{\omega} \cdot \vec{E} = E\alpha,$$

$$\vec{E}'_{\perp} = \gamma \vec{E}_{\perp} + \eta \hat{\omega} \times \vec{B},$$

where

$$\vec{E}_{\perp} = \vec{E} - \hat{\omega}(\hat{\omega} \cdot \vec{E}) = \hat{\epsilon} \vec{E} - \hat{\omega} E\alpha$$

and

$$\begin{aligned} \hat{\omega} \times \vec{B} &= \hat{\omega} \times (\hat{K} \times \vec{E}) = \hat{K}(\hat{\omega} \cdot \vec{E}) - \vec{E}(\hat{\omega} \cdot \hat{K}) \\ &= \hat{K} E\alpha - \hat{\epsilon} E \cos \Theta. \end{aligned}$$

Since the $\hat{Y}$ direction is unchanged by the boost, we have

$$\sin \Phi' = \frac{\hat{Y} \cdot \vec{E}'_{\perp}}{E'}$$

$$\frac{\vec{E}'_{\perp}}{E'} = \gamma(\hat{\epsilon} - \hat{\omega}\alpha) + \eta(\hat{K}\alpha - \hat{\epsilon} \cos \Theta).$$

$$\hat{Y} \cdot \vec{E}'_{\perp}/E' = \sin \Phi (\gamma - \eta \cos \Theta).$$

$$\begin{aligned} \frac{E'^2}{E^2} &= \alpha^2 + [\hat{\epsilon}(\gamma - \eta \cos \Theta) - \hat{\omega}\gamma\alpha + \hat{K}\eta\alpha]^2 \\ &= \alpha^2 + (\gamma - \eta \cos \Theta)^2 + (\gamma^2 + \eta^2)\alpha^2 \\ &\quad - 2\gamma(\gamma - \eta \cos \Theta)\alpha^2 - 2\gamma\eta\alpha^2 \cos \Theta \\ &= 2\gamma^2\alpha^2 + (\gamma - \eta \cos \Theta)^2 \\ &\quad - 2\gamma^2\alpha^2 + 2\gamma\eta\alpha^2 \cos \Theta - 2\gamma\eta\alpha^2 \cos \Theta \\ &= (\gamma - \eta \cos \Theta)^2. \end{aligned}$$

$$E' = E(\gamma - \eta \cos \Theta).$$

$$\sin \Phi' = \frac{\hat{Y} \cdot \vec{E}'_{\perp}}{E'} = \sin \Phi$$

QED.

2. The parity asymmetry P_{σ} in terms of density matrix elements.

The spin (or helicity) state of any particle can be described by its density matrix ρ . As stated in Section V-B, if the particle is photoproduced from a beam with linear polarization $\vec{P}_Y = P_Y(-\cos 2\Phi)$,

$(-\sin 2\Phi, 0)$, this matrix can be written as²¹

$$\rho = \rho^0 - P_Y \cos 2\Phi \rho^1 - P_Y \sin 2\Phi \rho^2. \quad (24)$$

Our matrix is normalized so that $\text{Tr} \rho^0 = 1$. Schilling, Seyboth, and Wolf show that for photoproduction of a meson with spin-parity $= J^P$, it is possible at high energies to project out the components of the density matrix corresponding to natural (N) and unnatural (U) parity exchange:²¹

$$\left. \begin{aligned} \rho_{\lambda\lambda'}^0 N &= \frac{1}{2} (\rho_{\lambda\lambda'}^0 - P(-1)^{\lambda'+J} \rho_{\lambda-\lambda'}^1) \\ \rho_{\lambda\lambda'}^0 U &= \frac{1}{2} (\rho_{\lambda\lambda'}^0 + P(-1)^{\lambda'+J} \rho_{\lambda-\lambda'}^1) \end{aligned} \right\} \text{cf. Eq. 44 of Ref. 21}$$

$$\rho^0 = \rho^0 N + \rho^0 U.$$

The cross sections for natural and unnatural parity exchanges are given by

$$\sigma^N = \sigma \text{Tr} \rho^0 N,$$

where

$$\sigma^U = \sigma \text{Tr} \rho^0 U,$$

$$\sigma = \sigma^N + \sigma^U$$

is the (differential) cross section for production of the particle in question. The parity asymmetry is defined as

$$P_{\sigma} = (\sigma^N - \sigma^U) / \sigma = \text{Tr} \rho^0 N - \text{Tr} \rho^0 U.$$

Nothing we have said so far depends on the spin of the meson. Now we consider two special cases.

a. Vector meson photoproduction: $J^P = 1^-$ ($\text{Tr} \rho = 2\rho_{11} + \rho_{00}$).

$$\begin{aligned} P_{\sigma} &= \text{Tr} \rho^0 N - \text{Tr} \rho^0 U \\ &= (\rho_{11}^0 + \rho_{1-1}^1) + \frac{1}{2} (\rho_{00}^0 - \rho_{00}^1) \\ &\quad - (\rho_{11}^0 - \rho_{1-1}^1) - \frac{1}{2} (\rho_{00}^0 + \rho_{00}^1) \\ &= 2\rho_{1-1}^1 - \rho_{00}^1. \end{aligned}$$

b. Tensor meson photoproduction: $J^P = 2^+ (\text{Tr } \rho = 2\rho_{22} + 2\rho_{1-1} + \rho_{00})$.

$$P_G = \text{Tr } \rho^{0N} - \text{Tr } \rho^{0U}$$

$$= (\rho_{22}^0 - \rho_{2-2}^1) + (\rho_{11}^0 + \rho_{1-1}^1) + \frac{1}{2} (\rho_{00}^0 - \rho_{00}^1)$$

$$- (\rho_{22}^0 + \rho_{2-2}^1) - (\rho_{11}^0 - \rho_{1-1}^1) - \frac{1}{2} (\rho_{00}^0 + \rho_{00}^1)$$

$$= -2\rho_{2-2}^1 + 2\rho_{1-1}^1 - \rho_{00}^1$$

APPENDIX C. APOTHEOSIS OF VECTOR DOMINANCE

This appendix is reproduced in entirety from the Journal of Irreproducible Results, 18, 51 (1970).

VECTOR DOMINANCE AND THE SPIN OF THE PHOTON*

AABBCCDDEFGXYZ Collaboration

Vector Dominance¹ relates the two reactions

$$\gamma + p \rightarrow \pi + N \quad (1)$$

$$\pi + p \rightarrow V_{tr} + N. \quad (2)$$

However, the Lorentz frame in which the transverse polarization of the Vector meson V is defined has not been uniquely specified. Arguments have been proposed in favor of the helicity or frame², the conspiracy frame², the Brickwall-Jackson frame³, the Breit-Wigner frame, the Dar-Weiskopf frame¹, the Quark Model Additivity frame⁴, the Don'tknowwho-Youguessim frame⁵, the Infinite Momentum frame⁶ and the Picture frame.

We have settled this ambiguity experimentally by direct measurements of the reactions (1) and (2) in all frames⁷, using Reggeized colliding beams. Although the experiment was performed in the Feynman gauge, the results are assumed to be gauge invariant and show that vector dominance is seriously violated in all frames unless the photon is assumed to have spin 3/2. Since it seems very undesirable to discard the attractive vector dominance hypothesis⁸, we conclude that the spin of the photon is 3/2.

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Fig. 1. Vector dominance diagrams commonly considered for ω photoproduction. The vacuum trajectory, or "Pomeron", is denoted by P. Diagram (e) is assumed to have negligible contribution.

XBL 712-191

Fig. 2a. (Top) Important elements of the backscattered photon beam at SLAC. The primary electron beam enters at the left. (Bottom) The electron beam profile in the horizontal and vertical planes (not to scale).

Fig. 2b. Simplified schematic of the laser, excluding power supply, electronics and cooling system. The elements shown were mounted on a 10-ft. I-beam optical bench.

XBB 712-554

Fig. 3. Magnified x-ray film exposure of the backscattered photon beam 2 in. before the defining collimator QD (Fig. 2a). The electric polarization vector is indicated by the vertical line, and the circle indicates the relative size of the hole in QD, 2 mm in diameter.

Fig. 4. Photograph of the 82-inch HBC, showing an event of the reaction $\gamma p \rightarrow \omega p, \omega \rightarrow \pi^+ \pi^- \pi^0$, at 2.8 GeV. About half of the frame is shown. The high-energy background tracks are electrons and positrons from pair production; the low-energy (curled) tracks are delta rays or Compton electrons. Note that the reaction and pair vertices lie along a narrow beam line. Hadronic events are easily distinguished from electron pairs with zero opening-angle.

XBB 744-132B

XBL 712-177

Fig. 5(a). Head-on profile of the photon beam, inferred from location of events in the HBC. The coordinate X' is the horizontal and Z' the vertical distance from the beam center to the reaction vertex; Z' points toward the camera. (For clarity we shown only a typical subset of the data; events from the 2.8-GeV run of May, 1969, measured on Spiral Reader II at LRL. This sample includes equal numbers of events with horizontal and vertical polarization.) The 3-mm diameter circle is the nominal beam shape; the ellipse is the fiducial volume used for analysis. (b) Side profile of beam. The abscissa Y is the lengthwise distance from the center of the chamber to the vertex.

Fig. 6. Photon energy spectra obtained from events fitting the 3-C hypothesis $\gamma p \rightarrow \pi^+ \pi^- p$ (energy unconstrained), weighted by the inverse of the $\pi^+ \pi^- p$ cross section. Below 0.5 GeV the spectra were determined from $e^+ e^-$ pairs. The arrows indicate the energy ranges used for analysis. (a) Nominal $E_\gamma = 2.8$ GeV, primary electron energy $E = 12$ GeV; (b) $E_\gamma = 4.7$ GeV, $E = 16$ GeV.

XBL 706-3110

LRL MASS (+ - 0) - SLAC MASS (+ - 0)

LRL - SLAC MASS DIF / MASS ERROR

XBL 713-406

Fig. 7. (a) Difference between LRL and SLAC measurements of the $\pi^+ \pi^- \pi^0$ effective mass for 198 events of 2.8 GeV $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$. The sample includes all events for which this hypothesis was accepted at both LRL and SLAC, if either measurement gave $m_{\pi^+ \pi^-}$ in the ω interval 0.70-0.86 MeV. (b) Difference divided by the calculated (s.d.) mass error for the LRL measurement.

Fig. 8. Total cross sections for $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$ from this experiment and the annihilation-beam experiments (SLAC-Weizmann-Tel Aviv).¹⁹

Fig. 9 (next page). Total cross sections for $\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$ from this experiment and from the annihilation-beam experiments (SLAC-Weizmann-Tel Aviv).¹⁰¹ The latter errors are statistical only; our errors include substantial uncertainty in background subtraction. The Tel Aviv data¹⁰² for the "charge-symmetric" reaction $\gamma n \rightarrow \pi^- \pi^- \pi^+ p$ are shown for comparison.

Fig. 9

Fig. 10. Invariant mass of $\pi^+ \pi^- \pi^0$ for 2.8-GeV $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$. Figure (a) includes contamination from multineutral channels such as $\gamma p \rightarrow p \pi^+ \pi^- 2\pi^0$; in Fig. (b) we have removed most of this contamination by cuts on the calculated beam energy and missing mass (see Eqs. A-1 and A-3 in Appendix A).

Fig. 10 (cont.). Invariant mass of $\pi^+ \pi^- \pi^0$ for 4.7-GeV $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$. Figure (c) includes substantial contamination from multineutral channels; in Fig. (d) we have removed most of this contamination by cuts on the calculated beam energy and missing mass.

Fig. 11. Chew-Low plots for the channel $\gamma p \rightarrow p\pi^+\pi^-\pi^0$: the square of the $\pi^+\pi^-\pi^0$ mass is plotted against $|t|$, the square of the four-momentum transfer from target to recoil proton. The forward ω production is shown in more detail in Figs. 11(c,d) on the following page.

XBL 713-463

Fig. 11 (cont.). Chew-Low plots for the channel $\gamma p \rightarrow p\pi^+\pi^-\pi^0$ at small $|t|$, showing forward ω production.

XBL 713-460

Fig. 12. Mass of the $\pi^+ \pi^- \pi^0$ in the channel $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$, showing the mass resolution in greater detail. The shaded form indicates the mass resolution (as calculated in SQUAW) folded into a symmetric Breit-Wigner with $m = 783.7$ MeV and $\Gamma = 12$ MeV; our ω signals peak at the correct mass and agree well with the calculated shapes. The solid curves show the backgrounds subtracted in determining the ω cross sections.

XBL 713-416

Fig. 13. Total cross sections for $\gamma p \rightarrow \omega p$ for this experiment compared with other HBC results from DESY¹⁴ and SLAC.^{19b} Our 9.3-GeV results are preliminary, based on 1/3 of expected data. Also shown for this experiment are the separate cross sections for ω production ($|t| < 1 \text{ GeV}^2$) by natural (σ^N) and unnatural (σ^U) parity exchange (see Section V-C).

$\gamma p \rightarrow \omega p$

Fig. 14. Differential cross sections $\frac{d\sigma}{dt}$ for $\gamma p \rightarrow \omega p$. The upper graphs show the forward cross sections in more detail. Also shown are the cross sections $\frac{d\sigma^N}{dt}$ from natural parity exchange, as determined in Section V-C.

$\gamma p \rightarrow \eta p$

Fig. 15. Differential cross sections for $\gamma p \rightarrow \eta p$.

XBL 713-467

Fig. 16. Invariant mass of $\pi^+ \pi^- \pi^0$ (4 combinations/event) for the channel $\gamma p \rightarrow p 2\pi^+ 2\pi^- \pi^0$.

XBL 713-468

Fig. 17. Dalitz plots for ω decay, showing the kinetic energies T_π of the decay pions in the ω rest frame. The sum of the kinetic energies is $Q = m_{\omega} - 3m_\pi$.

DEFINITION OF QUANTIZATION AXIS (z):

GOTTFRIED-JACKSON

HELICITY

ADAIR

XBL 711-2645

Fig. 18. Definition of angles (in the ω rest frame) used in the study of ω photoproduction. The angle β depends on the specific choice of the z axis, e. g., those shown in lower diagrams. For the Gottfried-Jackson frame $\beta=0$; for other frames β depends on the production angle (Section V-B).

(a) Decay angles, 2.8 GeV $\omega \rightarrow \pi^+ \pi^- \pi^0$
 $|t| < 0.5 \text{ GeV}^2$, 313 decays

XBL 713-470

Fig. 19. Scatter plot and projections for the ω decay angles θ and ψ in the helicity frame (Section V-B). The curves are calculated from Eq. 25 with $\psi = \phi - \Phi$ and the experimental density matrix. The ω distribution in ψ_H is contrasted to that found for ρ^0 in this experiment⁹ (small plot at lower left, curve $\propto 1 + P_Y \cos 2\psi$).

Fig. 19 (cont.)

(b) Decay angles, 4.7 GeV $\omega \rightarrow \pi^+\pi^-\pi^0$
 $|t| < 0.5 \text{ GeV}^2$, 275 decays $\gamma p \rightarrow \omega p$

HELICITY FRAME

Fig. 20. The nine measurable density-matrix parameters (helicity system) for ω photoproduction, and the parity asymmetry $P_\sigma = 2\rho_{1-1}^1 - \rho_{00}^1$. The curves are calculated for an incoherent mixture of helicity-conserving diffractive production and simple OPE (Eq. 35 in Section V-C).

Fig. 21. Mass combinations for the channel $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$ at 2.8 GeV. The curves show results of the fit described in Section VI-A and Table XII.

Fig. 22. Mass combinations for the channel $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$ at 4.7 GeV. The curves show results of the fit described in Section VI-A and Table XII.

$\gamma p \rightarrow p \pi^- \pi^+ \pi^0, |t(\gamma \rightarrow \pi^- \pi^0)| < 0.5 \text{ GeV}^2$

Fig. 23. "Triangle" plots for the channel $\gamma p \rightarrow p \pi^- \pi^+ \pi^0$, indicating associated $\rho^- \Delta^{++}$ production.

Fig. 24. Mass combinations for the channel $\gamma p \rightarrow \pi^+ \pi^- \pi^0 n$. The curves show results of fits described in Section VI-B and Table XIII.

XBL 713-536

Fig. 25. Effective mass of $\pi^+ \pi^+ \pi^-$ for the channel $\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$ (with the energy cuts of Table II and $MM^2 < 1.4 \text{ GeV}^2$). The shaded events have the square of the proton-neutron momentum-transfer $< 1 \text{ GeV}^2$.

XBL 714-629

Fig. 26. Two-body mass combinations for the channel $\gamma p \rightarrow p \pi^+ \pi^- m$, where m consists of neutral particles with $\text{mass}(m) = MM > \text{mass}(\pi^0)$. Arrows indicate selection on $m(\pi^+ \pi^-)$ made for Fig. 32.

XBL 714-631

Fig. 27. Mass recoiling from the proton in the channel $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$ (no energy cut, but missing mass selected to include π^0 peak). The ω peaks are somewhat broader here than for the same events as 0-C fits (Figs. 10 and 12).

Fig. 28. Mass recoiling from the proton, for various t intervals, in the channel $\gamma p \rightarrow p \pi^+ \pi^- m, m \neq \pi^0$.

XBL 714-633

Fig. 29. Chew-Low plots for the state recoiling from the proton in $\gamma p \rightarrow p\pi^+\pi^-(M)$, where mass (M) $>$ mass (π^0). Events with $|t| \geq 1.4$ GeV² are mostly ambiguous with $\gamma p \rightarrow \pi^+\pi^+\pi^-$ (+ neutrals). The arrows indicate $M_X^2 = 1.25$ GeV². Figures (b) and (d) show the small - $|t|$ region in more detail.

XBL 714-632

Fig. 29 (cont.)

$$\gamma p \rightarrow pX, X \rightarrow \pi^+ \pi^- \eta$$

Fig. 30. Distributions in $t' = t - t_{\min}$: (a, c) for the $\tilde{B}$ enhancement region and (b, d) for "control" regions on either side of the $\tilde{B}$ mass.

Fig. 31. (a) Mass recoiling from the proton in 2.8-GeV $\gamma p \rightarrow p\pi^+\pi^-$ (+ neutrals) with $|t| < 0.5 \text{ GeV}^2$ (same as Fig. 28a). The background curve is described in the text. (b) Mass($2\pi^+2\pi^-$) in 2.8-GeV $\gamma p \rightarrow p2\pi^+2\pi^-$ with $|t| < 0.5 \text{ GeV}^2$.

Fig. 31 (cont.). (c) Mass recoiling from the proton in 4.7-GeV $\gamma p \rightarrow p\pi^+\pi^- (+\text{neutrals})$ with $|t| < 0.5 \text{ GeV}^2$ (same as Fig. 28d). The background curves are described in the text. (d) $M(2\pi^+ 2\pi^-)$ in 4.7-GeV $\gamma p \rightarrow p2\pi^+ 2\pi^-$ with $|t| < 0.5 \text{ GeV}^2$. (e) Same as (d), with no t cut, but with $\Delta^{++} (1.16 < m_{\pi^+\pi^-} < 1.32 \text{ GeV})$ removed. The arrow indicates position of enhancement seen in Ref. 20b.

Fig. 32. Mass recoiling from the proton in the channel $\gamma p \rightarrow p\pi^+\pi^- (+\text{neutrals})$. Same events as Figs. 31(a, c), with the additional selection $0.33 < m_{\pi^+\pi^-} < 0.60 \text{ GeV}$ to enhance events with $\pi^+\pi^-$ from ω decay.

XBL 714-634

2.8 GEV

LABORATORY MOMENTUM (GEV/C)

XBL 713-419

Fig. A-1. Laboratory momentum of the recoil proton for the channels $\gamma p \rightarrow p \pi^+ \pi^-$, $\gamma p \rightarrow p \pi^+ \pi^- (\pi^0)$, $\gamma p \rightarrow p \pi^+ \pi^-$ (neutrals $\neq \pi^0$), $\gamma p \rightarrow p 2\pi^+ 2\pi^-$ and $\gamma p \rightarrow p 2\pi^+ 2\pi^- (\pi^0)$ (a-e) $E_\gamma = 2.8$ GeV; (f-j) $E_\gamma = 4.7$ GeV. For the shaded events the "proton" is ambiguous with a π^+ .

4.7 GEV

LABORATORY MOMENTUM (GEV/C)

XBL 713-420

Fig. A-1 (cont.)

UNIQUE $\pi^+\pi^-\pi^0$ 2.8 GEV UNIQUE $\pi^+\pi^+\pi^-$ (N) 2.8 GEV

UNIQUE $2\pi^+2\pi^-\pi^0$ 2.8 GEV AMBIG $\pi^+\pi^+\pi^-$ (N) 2.8 GEV

XEL 713-421

Fig. A-2. (a-d) Nominal $E_\gamma = 2.8$ GeV. Beam energies K_{OC} (see Eq. A-1) calculated for zero-constraint hypotheses, assuming a single π^0 or neutron in the final state. The shaded form indicates the true beam spectrum (see Fig. 6a). By accepting only events in the K_{OC} interval 2.4 - 3.3 GeV (arrows) for the single-neutral analysis, we eliminated most of the multineutral background (events with K_{OC} below the true beam energy). Figures (a-c) contain events with no proton-pion ambiguity: (a) $\gamma p \rightarrow p \pi^+ \pi^- (\pi^0)$, (b) $\gamma p \rightarrow \pi^+ \pi^+ \pi^- (n)$, (c) $\gamma p \rightarrow p 2\pi^+ 2\pi^- (\pi^0)$. Figure (d) ambiguous $\gamma p \rightarrow \pi^+ \pi^+ \pi^- (n)$: the events with large K_{OC} came mostly from $\gamma p \rightarrow p \pi^+ \pi^- (\pi^0)$ with fast proton; the cross-hatched events were removed by a kinematic cut (Eq. A-2).

UNIQUE $\pi^+\pi^-\pi^0$ 4.7 GEV UNIQUE $\pi^+\pi^+\pi^-$ (N) 4.7 GEV

UNIQUE $2\pi^+2\pi^-\pi^0$ 4.7 GEV UNIQUE $3\pi^+2\pi^-$ (N) 4.7 GEV

XBL 713-422

Fig. A-2. (e-h) Nominal $E_\gamma = 4.7$ GeV. Beam energies K_{OC} (see Eq. A-1) for zero-constraint hypotheses, assuming a single π^0 or neutron in the final state. The shaded form indicates the true beam spectrum (see Fig. 6b). By accepting only events in the K_{OC} interval 4.1 - 5.3 GeV (arrows) for the single-neutral analysis, we eliminated most of the multineutral background (events with K_{OC} below the true beam energy). Only events with no proton-pion ambiguity are shown: (e) $\gamma p \rightarrow p \pi^+ \pi^- (\pi^0)$, (f) $\gamma p \rightarrow \pi^+ \pi^+ \pi^- (n)$, (g) $\gamma p \rightarrow p 2\pi^+ 2\pi^- (\pi^0)$, (h) $\gamma p \rightarrow 3\pi^+ 2\pi^- (n)$.

Fig. A-3. The square of the missing mass for the hypotheses $\gamma p \rightarrow \pi^+ \pi^+ \pi^-$ (MM) and $\gamma p \rightarrow 3\pi^+ 2\pi^-$ (MM). The ambiguous events include contamination from $\gamma p \rightarrow p\pi^+ \pi^-$ (+ neutrals), etc. The heavy curves are normalized model predictions (see text) for MM $\neq$ neutron, including $p\pi^+ \pi^-$ (+ neutrals) contamination; the light curves are the model predictions for proton-associated contamination alone. The arrows indicate the neutron mass².

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Fig. A-3 (cont.)

XBL 713-418

Fig. A-4. The square of the missing mass for the hypotheses $\gamma p \rightarrow p \pi^+ \pi^-$ (MM) and $\gamma p \rightarrow p 2\pi^+ 2\pi^-$ (MM). Ambiguous events (for which the proton could not be identified) are shaded. The curves are normalized model predictions for $MM \neq \pi^0$, including contamination from $\gamma p \rightarrow \pi^+ \pi^- \pi_2^0$ (+ neutrals), etc. The arrows indicate the π^0 mass.

Fig. A-4 (cont.)

XBL 713-407

Fig. A-5. Scatter plots of MM^2 calculated for $\gamma p \rightarrow p \pi^+ \pi^-$ (MM) (horizontal) vs MM^2 calculated for $\gamma p \rightarrow \pi^+ \pi^+ \pi^-$ (MM) (vertical), for events ambiguous between the two hypotheses; (a) 2.8 GeV; (b) 4.7 GeV.

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October 11, 1971

TO: Recipients of UCRL-20128 "Photoproduction of ω Mesons in
a Hydrogen Bubble Chamber by 3 and 5 GeV Linearly
Polarized Photons" by William Jesse Podolsky (Ph. D. Thesis)

FROM: Technical Information Division

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Table VIII. Total cross sections for the reactions $\gamma p \rightarrow \omega p$ and $\gamma p \rightarrow \eta p$, and parameters for fits of the differential ω cross sections to $C \exp(-At)$ for $0.02 < |t| < 0.4 \text{ GeV}^2$. Errors include statistics and uncertainties in flux, background subtraction, and loss corrections.

	$E_\gamma = 2.8 \text{ GeV}$	$E_\gamma = 4.7 \text{ GeV}$
$\sigma_T(\gamma p \rightarrow \omega p)$	$5.3 \pm 0.5 \text{ } \mu\text{b}$	$3.0 \pm 0.3 \text{ } \mu\text{b}$
C	$31.7 \pm 4.3 \text{ } \mu\text{b/GeV}^2$	$24.4 \pm 3.9 \text{ } \mu\text{b/GeV}^2$
A	$6.4 \pm 0.7 \text{ GeV}^{-2}$	$8. \pm 0.9 \text{ GeV}^{-2}$
$\sigma_T(\gamma p \rightarrow \eta p)$	$0.9 \pm 0.25 \text{ } \mu\text{b}$	$0.3 \pm 0.1 \text{ } \mu\text{b}$

Table IX. Differential cross sections $\frac{d\sigma}{dt} (\mu\text{b/GeV}^2)$ for $\gamma p \rightarrow \omega p$.

$ t (\text{GeV}^2)$	$E_\gamma = 2.8 \text{ GeV}$	$E_\gamma = 4.7 \text{ GeV}$
0.014 - 0.06	25.9 ± 3.1	19.6 ± 3.1
0.06 - 0.10	21.4 ± 3.0	10.8 ± 1.8
0.10 - 0.15	14.7 ± 2.3	8.1 ± 1.4
0.15 - 0.20	7.6 ± 1.6	5.6 ± 1.1
0.20 - 0.30	6.4 ± 1.1	2.8 ± 0.6
0.30 - 0.40	4.2 ± 0.8	1.9 ± 0.5
0.40 - 0.50	1.2 ± 0.6	0.8 ± 0.4
0.5 - 1.0	0.8 ± 0.2	0.3 ± 0.1
1.0 - 2.0	0.24 ± 0.12	0 ± 0.03
2.0 - $ t _{\text{max}}$	0.18 ± 0.10	
2.0 - 5.5		0 ± 0.01
5.5 - $ t _{\text{max}}$		0.04 ± 0.04

Table XI. Parity asymmetry P_σ for $\gamma p \rightarrow \omega p$ and the separate contributions σ^N (σ^U) of natural (unnatural) parity exchange to the ω cross sections. The values for C_N and A_N are for fits to $\frac{d\sigma^N}{dt} = C_N \exp(A_N t)$ within $0.014 < |t| < 0.4 \text{ GeV}^2$. Cross section errors include statistics and uncertainties in flux, background subtraction, and loss corrections.

$ t $ - interval (GeV^2)	P_σ	$\frac{d\sigma^N}{dt} \left(\frac{\mu\text{b}}{\text{GeV}^2} \right)$	$\frac{d\sigma^U}{dt} \left(\frac{\mu\text{b}}{\text{GeV}^2} \right)$
$E_\gamma = 2.8 \text{ GeV}$			
0.014-0.06	-0.15 ± 0.27	11.1 ± 3.8	14.8 ± 4.0
0.06-0.15	-0.21 ± 0.21	7.0 ± 2.1	10.6 ± 2.3
0.15-0.40	-0.13 ± 0.23	2.5 ± 0.7	3.25 ± 0.8
0.4 - 1.0	0.74 ± 0.40	0.75 ± 0.24	0.11 ± 0.18
$E_\gamma = 4.7 \text{ GeV}$			
0.014-0.06	-0.05 ± 0.27	9.4 ± 3.8	10.2 ± 3.0
0.06-0.15	0.45 ± 0.25	6.8 ± 1.5	2.6 ± 1.2
0.15-0.40	0.25 ± 0.27	1.9 ± 0.5	$1.1 \pm 0.$
0.4-1.0	-0.32 ± 0.45	0.13 ± 0.09	0.25 ± 0.11
Quantity, $ t $ - interval (GeV^2)	$E_\gamma = 2.8 \text{ GeV}$	$E_\gamma = 4.7 \text{ GeV}$	
P_σ average, $t_{\min} - 1.0$	-0.06 ± 0.13	0.16 ± 0.14	
σ^N integral, $t_{\min} - 1.0$	$2.3 \pm 0.4 \mu\text{b}$	$1.7 \pm 0.3 \mu\text{b}$	
σ^U integral, $t_{\min} - 1.0$	$2.6 \pm 0.4 \mu\text{b}$	$1.2 \pm 0.25 \mu\text{b}$	
C_N fit, 0.014-0.4	$12.4 \pm 4.2^a \mu\text{b}/\text{GeV}^2$	$13.9 \pm 3.8^a \mu\text{b}/\text{GeV}^2$	
A_N fit, 0.014-0.4	$5.9 \pm 2.1^a \text{ GeV}^{-2}$	$7.9 \pm 1.7^a \text{ GeV}^{-2}$	

^a Errors given are the more conservative correlated errors, where C_N and A_N are allowed to vary simultaneously.

VIII. CONCLUSIONS

We have studied photoproduction at 2.8 and 4.7 GeV, using a linearly polarized photon beam in a hydrogen bubble chamber. The monoenergetic beam and 4π detection efficiency enabled us to measure cross sections for various photoproduction channels, including those with one or more neutral particles (Table V). Our total cross sections for hadron photoproduction and cross sections for $\gamma p \rightarrow \rho^0 p$ are published elsewhere.^{3,4,9,89}

We report here a study of $\gamma p \rightarrow \omega p$ in the channel $\gamma p \rightarrow p\pi^+\pi^-\pi^0$. The monoenergetic beam enabled us to separate single- π^0 from multi-neutral production, so that there is little background underneath the ω signal. Our cross sections for ω photoproduction are given in Tables VIII-IX and Figs. 13-14.

We have studied the ω decay in detail. Because our photon beam was $> 90\%$ linearly polarized, we have been able to determine nine independent parameters of the ω density matrix, compared with only three accessible to previous experiments. These parameters are given in Table X and Fig. 20. The greatest value of these parameters is that they allow separation of the cross sections for ω production by natural- and unnatural-parity exchange (Table XI and Figs. 13-14). We find that both parities are important at our energies, but that the unnatural-parity exchange decreases rapidly with increasing energy. The energy variation and t dependence of σ^U are consistent with one-pion exchange. The E_γ and t dependence of σ^N , however, resemble those for $\gamma p \rightarrow \rho^0 p$, which we believe to be a diffractive process.^{3,4,9} In fact, we find that the density matrix parameters are consistent with those calculated for a mixture of OPE and helicity-conserving diffractive ω production (curves in Fig. 20), though some helicity-flip contribution cannot be excluded.

Qualitatively, these features of ω photoproduction are well explained by the vector dominance model (Section II). If the cross sections for $\rho^0 p$ and ωp scattering are equal, as suggested by quark models,^{44,51,54} then the diffractive part of $\sigma(\gamma p \rightarrow \omega p)$ should equal $\sigma(\gamma p \rightarrow \rho^0 p)f_\rho^2/f_\omega^2$. With this assumption, and evaluating $\sigma(\rho^0)$ from our Söding-model fits,⁹ we find that $f_\omega^2/f_\rho^2 = 7.3 \pm 1.2$ at 2.8 GeV and 9.3 ± 1.7 at 4.7 GeV. (Other models for ρ^0 photoproduction give somewhat different values; see Section V-D.) These ratios are consistent

comes from channels of the type 2b, e.g.,

- 2b₁. $\gamma p \rightarrow p\pi^+\pi^- (2\pi^0)$,
- 2b₂. $p\pi^+\pi^- (3\pi^0)$,
- 2b₃. $p\pi^+\pi^- (\eta \rightarrow \text{neutrals})$,
- 2b₄. $p\pi^+\pi^- (\omega \rightarrow \text{neutrals})$

As can be seen from Eq. A-1, the beam energy is badly determined for events with a high-energy π^0 in the forward direction ($A \approx 0$). Many of the events with $K_{oc} > K_{max}$ are of this type. The rest may be mismeasures or events of

$$2b_5. \gamma p \rightarrow p\pi^+\pi^- (\gamma) ..$$

Hypotheses 3, 12, and 13 show similar distributions of apparent beam spectra; The unique fits to these reactions are shown in Figs. A-2 (b-c, f-h).

Up to this point the only kinematic criterion was that all masses and momenta be positive. Next we invoked the knowledge that the true beam energy had a sharp maximum K_{max} given by Eq. 19 (Sec. III-A; see also Fig. 6). Figure A-2(d) shows the beam spectrum calculated for $\pi^+\pi^+\pi^-n$ for events which were ambiguous with $p\pi^+\pi^-\pi^0$. The events with $K_{oc} \gg K_{max}$ were mostly $p\pi^+\pi^-\pi^0$ and not genuine $\pi^+\pi^+\pi^-n$. For these we eliminated the $\pi^+\pi^+\pi^-n$ fit by imposing the cut

$$\frac{K_{oc} - K_{max}}{\delta K_{oc}} < +5 \quad (A-2)$$

on all 0-constraint fits. In effect this was like a 1-constraint χ^2 cut applied in one direction only. The cut reduced the number of ambiguous events to those remaining in Table IV (Sec. IV). This sample is the basis for the remaining calculations.

Finally we used the monochromatic properties of our beam in a much stronger way: Note that Eq. A-1 can be turned around to calculate the square of the missing mass, MM^2 , if we provide a nominal beam energy K_{nom} :

$$MM^2 = AK_{nom} + B. \quad (A-3)$$

We chose K_{nom} to be near the median beam energy, between the mean and mode of the true beam spectrum. Figures A-3, 4 show the MM^2 distributions for reactions 2, 3, 12, and 13. The π^0 and neutron peaks are quite prominent. The shapes and widths of these peaks

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Fig. 11. Chew-Low plots for the channel $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$: the square of the $\pi^+ \pi^- \pi^0$ mass is plotted against $|t|$, the square of the four-momentum transfer from target to recoil proton. The forward ω production is shown in more detail in Figs. 11(c,d) on the following page.

XBL 713-463

Fig. 11 (cont.). Chew-Low plots for the channel $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$ at small $|t|$, showing forward ω production.

XBL 713-468

Fig. 17. Dalitz plots for ω decay, showing the kinetic energies T_{π} of the decay pions in the ω rest frame. The sum of the kinetic energies is $Q = m_{\omega} - 3m_{\pi}$.

(a) Decay angles, 2.8 GeV $\omega \rightarrow \pi^+ \pi^- \pi^0$
 $|t| < 0.5 \text{ GeV}^2$, 313 decays

XBL 713-470

Fig. 19. Scatter plot and projections for the ω decay angles θ and ψ in the helicity frame (Section V-B). The curves are calculated from Eq. 25 with $\psi = \phi - \Phi$ and the experimental density matrix. The ω distribution in ψ_H is contrasted to that found for ρ^0 in this experiment⁹ (small plot at lower left, curve $\propto 1 + P_Y \cos 2\psi$).

(b) Decay angles, 4.7 GeV $\omega \rightarrow \pi^+\pi^-\pi^0$
 $|t| < 0.5 \text{ GeV}^2$, 275 decays

XBL 713-471

Fig. 19 (cont.)

XBL 714-633

Fig. 29. Chew-Low plots for the state recoiling from the proton in $\gamma p \rightarrow p\pi^+\pi^-(M)$, where mass (M) $>$ mass (π^0). Events with $|t| \gtrsim 1.4 \text{ GeV}^2$ are mostly ambiguous with $\gamma p \rightarrow \pi^+\pi^+\pi^-$ (+ neutrals). The arrows indicate $M_X^2 = (1.25 \text{ GeV})^2$. Figures (b) and (d) show the small - $|t|$ region in more detail.

XBL 714-632

Fig. 29 (cont.)

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