lished); C. M. Ankenbrandt, A. R. Clark, B. Cork, T. Elioff, L. T. Kerth, and W. A. Wenzel, Phys. Rev. 170, 1228 (1968).

[3]C. T. Coffin, N. Dikmen, L. Ettlinger, D. Meyer, A. Saulys, K. Terwilliger, and D. Williams, Phys. Rev. 159, 1169 (1967).

[4]D. P. Owen, F. C. Peterson, J. Orear, A. L. Read, D. G. Ryan, D. H. White, A. Ashmore, C. J. S. Damerell, W. R. Frisken, and R. Rubinstein, Phys. Rev. 181, 1794 (1969); M. Fellinger, E. Gutman, R. C. Lamb, F. C. Peterson, L. S. Schroeder, R. C. Chase, E. Coleman, and T. G. Rhoades, Phys. Rev. Letters 23, 600 (1969).

[5]J. Orear, R. Rubinstein, D. B. Scarl, D. H. White, A. D. Krisch, W. R. Frisken, A. L. Read, and H. Ruderman, Phys. Rev. 152, 1162 (1966).

[6]Preliminary data for large angles at 3, 3.5, 4, and 5 GeV/c have recently been reported by H. W. Paik, B. B. Brabson, R. R. Crittenden, R. M. Heinz, R. C. Kammerud, H. A. Neal, and R. A. Sidwell, Bull. Am. Phys. Soc. 15, 41 (1970).

[7]W. F. Baker, K. Berkelman, P. J. Carlson, G. P. Fisher, P. Fleury, D. Hartill, R. Kalbach, A. Lundby, S. Mukhin, R. Nierhaus, K. P. Pretzl, and J. Woulds, Phys. Letters 28B, 291 (1968).

[8]J. P. Chandler, R. R. Crittenden, K. F. Galloway, R. M. Heinz, H. A. Neal, K. A. Potocki, W. F. Prickett, and R. A. Sidwell, Phys. Rev. Letters 23, 186 (1969).

[9]V. Barger and R. J. N. Phillips, Phys. Rev. Letters 22, 116 (1969); A. Beretvas and N. E. Booth, Phys. Rev. Letters 22, 113 (1969), and references cited therein.

[10]V. Barger and D. Cline, Phys. Rev. Letters 21, 392 (1968).

[11]E. L. Berger and G. C. Fox, Phys. Rev. 188, 2120 (1969); and private communication from E. L. Berger.

[12]R. L. Kelly, G. L. Kane, and F. Henyey, "A Strong-cut Reggeized Absorption Model for Backward Scattering" (to be published).

STUDY OF $\gamma p \to p\omega$ WITH LINEARLY POLARIZED PHOTONS AT 2.8 AND 4.7 GeV*

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The reaction $\gamma p \to p\omega$ was studied in a hydrogen bubble chamber using a linearly polarized photon beam. The total cross section was found to be 5.8 ± 0.5 μb at 2.8 GeV and 3.2 ± 0.3 μb at 4.7 GeV. From the decay angular distributions these cross sections have been separated into contributions from natural- and unnatural-parity exchange σ^N, σ^U in the t channel. For $|t| < 1$ GeV^2 $\sigma^N = 2.5 \pm 0.4$ μb, $\sigma^U = 2.7 \pm 0.4$ μb at 2.8 GeV and $\sigma^N = 1.8 \pm 0.3$ μb, $\sigma^U = 1.3 \pm 0.3$ μb at 4.7 GeV. The contributions from unnatural-parity exchange are consistent with the predictions of the one-pion–exchange model.

The energy dependence and the magnitude of the cross section for ω production by unpolarized photons measured[1,2] in the reaction

$$\gamma p \to p\pi^+\pi^-\pi^0 \tag{1}$$

suggests that ω production proceeds partly via one-pion exchange (OPE) and partly via diffraction scattering, with the dominant contribution at low energies (~2-4 GeV) coming from OPE. Using polarized photons, the contributions from natural parity $[P = (-1)^J]$ and unnatural parity $[P = -(-1)^J]$ exchange in the t channel can be separated, and the above conjecture can be tested.

We have analyzed ω production in Reaction (1) at 2.8 and 4.7 GeV exposing the 82-in. hydrogen bubble chamber at Stanford Linear Accelerator Center to the linearly polarized Compton-back-scattered laser beam. Table I summarizes the details of the beam and of the exposure.[3-6]

In Table I we list the number of events which gave a zero-constraint "fit" to Reaction (1) (the photon energy E_γ not being constrained) and

Table I. Beam parameters and exposure statistics.

Avg. beam energy, E_γ (GeV)	FWHM[a] (GeV)	Avg. linear polarization P_γ	No. of pictures	Events/ μb	Events fitting $\gamma p \to p\pi^+\pi^-\pi^0$	E_γ limits accepted (GeV)	Fits to $\gamma p \to p\pi^+\pi^-\pi^0$ within E_γ limits	No. of ω events
2.8	0.15	94%	292 000	90 ± 4	3950	2.4–3.3	2687	411 ± 31
4.7	0.3	92%	454 000	149 ± 6	7660	4.1–5.3	3083	315 ± 24

[a] Full width at half-maximum.

which satisfied the following criteria: The mass assignments are consistent with ionization, and the event has no accepted fit to the hypothesis $\gamma p \to p\pi^+\pi^-$. Most of the multineutral events are removed by requiring the reconstructed photon energy to lie within the limits specified in Table I.

In Fig. 1 the $\pi^+\pi^-\pi^0$ mass distributions show a clear ω signal. In order to determine the cross section for ω production, corrections were made for ω events which (a) were excluded because they fit the three-constraint hypothesis $\gamma p \to p\pi^+\pi^-$ ($\chi^2 < 25$); (b) have a reconstructed photon energy outside the specified energy interval or a $\pi^+\pi^-\pi^0$ mass outside the ω region (0.67-0.90 GeV); (c) were lost because of short-recoil protons; or (d) have a decay mode other than $\pi^+\pi^-\pi^0$.[7] Corrections (a) and (b) were determined using the track and event simulation program PHONY[8] and amounted to 1.09 ± 0.02 at 2.8 GeV and 1.22 ± 0.06 at 4.7 GeV. For (c), because events with short-recoil protons connot be measured reliably, we disregarded all events with $|t| < 0.014$ GeV^2 (t is the square of the four-momentum transfer between incoming and outgoing proton). At 2.8 GeV the minimum value of $|t|$ is 0.014 GeV^2 and no correction of type (c) was applied. At 4.7 GeV we estimate the loss to be $(6 \pm 2)\%$ by extrapolating the t distribution according to Eq. (4) below. The scanning efficiency for events with $|t| > 0.02$ GeV^2 was found to be greater than 99%.

The corrected total ω-production cross sections are given in Table II and Fig. 2 together

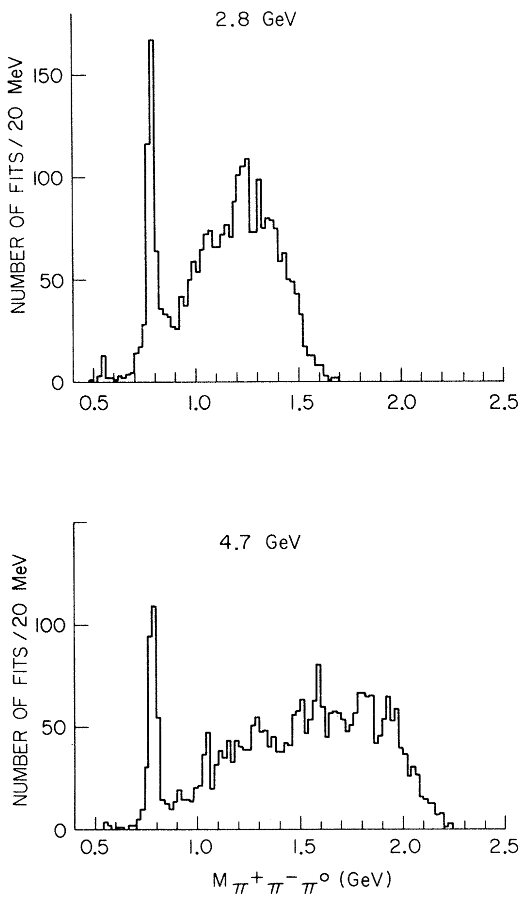

FIG. 1. $\pi^+\pi^-\pi^0$ mass distributions for the reaction $\gamma p \to p\pi^+\pi^-\pi^0$ at 2.8 and 4.7 GeV. There are 2687 and 3083 fits from 2678 and 2912 events at 2.8 and 4.7 GeV, respectively.

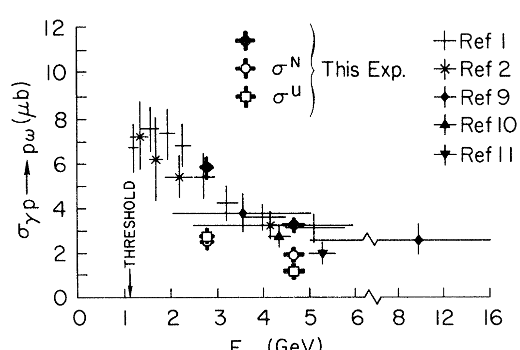

FIG. 2. Total cross sections for reaction $\gamma p \to p\omega$, from this experiment together with the values of Refs. 1, 2, 9-11. Cross section contributions σ^N, σ^U from natural- and unnatural-parity exchanges in the t channel for $|t| < 1$ GeV^2.

Table II. Parameters of the reaction $\gamma p \to p\omega$. Cross sections, P_σ, and production angular dependence for $0.02 < |t| < 0.4$ GeV^2 assuming $d\sigma/dt = C\exp(At)$ for all events, and for the contributions from natural-parity exchange in the t channel. Cross-section errors include statistical, flux, background, and loss-correction uncertainties.

	$E_\gamma = 2.8$ (GeV)	$E_\gamma = 4.7$ (GeV)
σ_{tot}	5.8 ± 0.5 μb	3.2 ± 0.3 μb
C	34 ± 4 μb/GeV^2	25 ± 3 μb/GeV^2
A	6.2 ± 0.7 GeV^{-2}	8.0 ± 0.8 GeV^{-2}
P_σ ($\lvert t\rvert < 1$ GeV^2)	-0.04 ± 0.13	0.19 ± 0.14
σ^N ($\lvert t\rvert < 1$ GeV^2)	2.50 ± 0.37 μb	1.84 ± 0.28 μb
σ^U ($\lvert t\rvert < 1$ GeV^2)	2.70 ± 0.39 μb	1.25 ± 0.27 μb
C_N	13.1 ± 4.1 μb/GeV^2	15.2 ± 3.8 μb/GeV^2
A_N	5.5 ± 1.6 GeV^{-2}	7.5 ± 1.5 GeV^{-2}

with those of other experiments.[1,2,9-11] The differential cross sections $d\sigma/dt$ are shown in Fig. 3. A fit of $d\sigma/dt$ for $0.02 < |t| < 0.4$ GeV^2 by the form $C\exp(At)$ leads to the values for A and C given in Table II.

For the analysis of the ω-decay angular distributions we adopt the formalism of Schilling, Seyboth, and Wolf.[12] Results will be presented in the helicity system, which was found to be the preferred system for the analysis of ρ^0 photoproduction.[5] In this frame the z axis is given by the ω direction of flight in the total c.m. system. The angles θ and φ are defined as the polar and azimuthal angles of the normal to the ω-decay plane in the ω rest system. The photon polarization plane in the total c.m. system makes an angle Φ with the production plane.[13] The decay angular distribution of the ω in terms of its spin density matrix is[12,14]

$$W(\cos\theta, \varphi, \Phi) = 3/4\pi\{\tfrac{1}{2}(1-\rho_{00}{}^0) + \tfrac{1}{2}(3\rho_{00}{}^0 - 1)\cos^2\theta - \sqrt{2}\,\mathrm{Re}\rho_{10}{}^0 \sin2\theta\cos\varphi - \rho_{1-1}{}^0\sin^2\theta\cos2\varphi$$
$$-P_\gamma\cos2\Phi\,[\rho_{11}{}^1\sin^2\theta + \rho_{00}{}^1\cos^2\theta - \sqrt{2}\,\mathrm{Re}\rho_{10}{}^1\sin2\theta\cos\varphi - \rho_{1-1}{}^1\sin^2\theta\cos2\varphi]$$
$$-P_\gamma\sin2\Phi\,[\sqrt{2}\,\mathrm{Im}\rho_{10}{}^2\sin2\theta\sin\varphi + \mathrm{Im}\rho_{1-1}{}^2\sin^2\theta\sin2\varphi]\}, \quad (2)$$

where P_γ is the degree of linear polarization. The nine independent measurable density-matrix parameters, which were determined by a moment analysis, are shown in Fig. 4 as a function of t. In ρ^0 photoproduction[5] we found for $|t| < 0.4$ GeV^2 that by choosing the helicity frame all $\rho_{ik}{}^\alpha$ in Eq. (2) reduced to zero except for two ($\rho_{1-1}{}^1 = -\mathrm{Im}\rho_{1-1}{}^2 = 0.5$) indicating no helicity flip. In contrast, for ω photoproduction our values for $\rho_{00}{}^0$ show that there is considerable helicity flip.

From the density-matrix parameters one can deduce the parity asymmetry, $P_\sigma = (\sigma^N - \sigma^U)/(\sigma^N + \sigma^U)$, which measures the cross-section contributions σ^N, σ^U from natural- and unnatural-parity exchange in the t channel. In the high-energy limit P_σ is given by[12,15]

$$P_\sigma = 2\rho_{1-1}{}^1 - \rho_{00}{}^1. \quad (3)$$

In Table II the values of P_σ, $\sigma_\omega{}^N$, and $\sigma_\omega{}^U$ are given for ω production for $|t| < 1.0$ GeV^2 (see also Figs. 2 and 4). Natural- and unnatural-parity exchanges contribute in approximately equal amounts. The unnatural cross section $\sigma_\omega{}^U$ decreases from 2.8 to 4.7 GeV, whereas $\sigma_\omega{}^N$ does

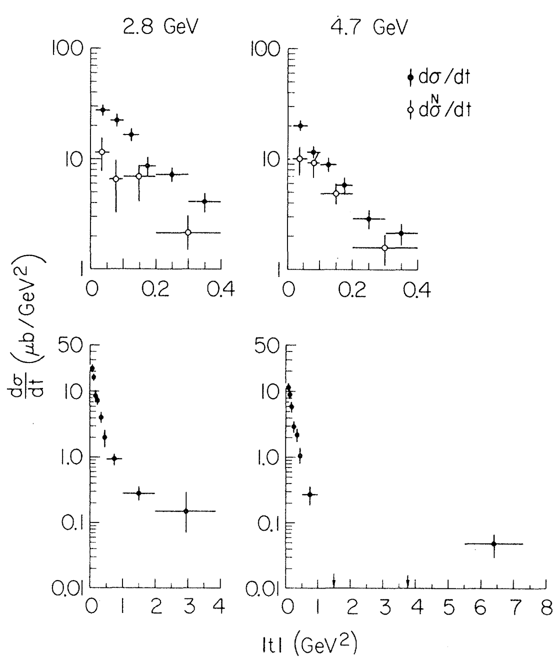

FIG. 3. Reaction $\gamma p \to p\omega$. Total differential cross sections and differential cross sections for contributions from natural-parity exchange at 2.8 and 4.7 GeV.

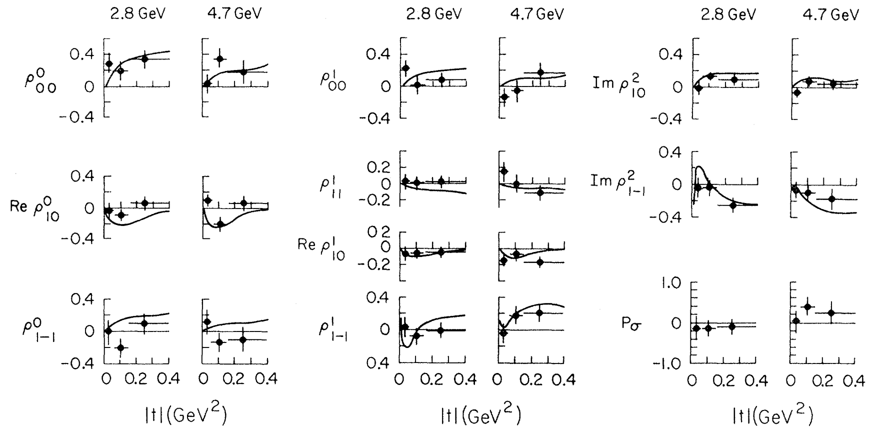

FIG. 4. Reaction $\gamma p \to p\omega$. The spin density matrix parameters in the helicity system and P_σ as a function of t at 2.8 and 4.7 GeV. The curves are calculated according to Eq. (5).

not change significantly. The natural differential cross section $d\sigma^N/dt$ for $0.02 < |t| < 0.4$ GeV^2 is shown in Fig. 3. A fit of $d\sigma^N/dt$ by the form $C_N \exp(A_N t)$ gave the values for A_N and C_N shown in Table II.

One can compare $\sigma_\omega{}^N$ with the corresponding quantity $\sigma_\rho{}^N$ for ρ^0 production in the reaction $\gamma p \to p\rho^0$.[4,5] For $|t| < 1$ GeV^2, we found the ratio $\sigma_\rho{}^N/\sigma_\omega{}^N$ to be between 6 and 9 depending on the models used to determine the ρ^0 cross section. Using the combination of vector dominance model, quark model, and SU(6) this ratio has been predicted[16] to be 9. However, there could be a large positive contribution (~40%) from A_2 exchange to $\sigma_\omega{}^N$ which would reduce the value of this ratio[17] (the A_2 exchange contribution to $\sigma_\rho{}^N$ is expected to be small).

Next we compare the contributions from unnatural-parity exchange with the predictions of OPE. A similar analysis has been given by Schilling and Storim[18] for ω production by unpolarized photons. The OPE model predicts a decrease of the ω cross section for $|t| < 1$ GeV^2 by a factor 2.5 between 2.8 and 4.7 GeV. This ratio is practically independent of whether form-factor or absorption corrections are used. Experimentally we found a value of 2.2 ± 0.6 for this ratio in agreement with the OPE prediction. The magnitude of the OPE cross section is proportional to the radiative decay width of the ω, $\Gamma_{\omega\pi\gamma}$; it also depends on the vertex or absorption corrections employed. From the values of $\sigma_\omega{}^U$ at 2.8 and 4.7 GeV in the interval $|t| < 1$ GeV^2 and using the parametrization of Benecke and Dürr[19] we obtained $\Gamma_{\omega\pi\gamma} = 0.98 \pm 0.12$ MeV. This value is consistent with the value obtained from the ω width and branching ratio,[7] $\Gamma_{\omega\pi\gamma} = 1.19 \pm 0.24$ MeV. On the other hand the absorption-corrected OPE model[18] with the absorption coefficient $C = 0.9$ led to $\Gamma_{\omega\pi\gamma} = 0.58 \pm 0.07$ MeV for our data.

Assuming that $\sigma_\omega{}^U$ is accounted for by OPE we fitted the differential cross section for $0.02 < |t| < 0.4$ GeV^2 by the form

$$D \exp(Bt) + d\sigma^{\text{OPE}}/dt \tag{4}$$

to obtain more information of the t dependence of $\sigma_\omega{}^N$. The OPE cross section was calculated using the Benecke-Dürr parametrization. The fitted variables were $\Gamma_{\omega\pi\gamma}$, D, and B and were assumed to be the same at both energies. The result of the fit was $D = 12.1 \pm 2.1$ μb/GeV^2, $B = 5.6 \pm 1.2$ GeV^{-2}, and $\Gamma_{\omega\pi\gamma} = 0.98 \pm 0.10$ MeV. The value of B is consistent with the slope for ρ^0 production[4] in the reaction $\gamma p \to p\rho^0$.

Finally, we calculate the predictions for the ω density matrix elements assuming that the natural-parity exchange contributions conserve helicity in the total c.m. system as in the reaction[5] $\gamma p \to p\rho^0$ and that the contributions from unnatural-parity exchange are due to OPE. As a function of t the ω density matrix is then given by

$$\rho_{ik} = \frac{(d\sigma^N/dt)\rho_{ik}{}^{(N)} + (d\sigma^{\text{OPE}}/dt)\rho_{ik}{}^{(\text{OPE})}}{d\sigma^N/dt + d\sigma^{\text{OPE}}/dt}. \tag{5}$$

In the helicity system $\rho_{1-1}{}^{1(N)} = -\text{Im}\rho_{1-1}{}^{2(N)} = \frac{1}{2}$, all other density matrix parameters in Eq. (2) are zero; for $\rho_{ik}{}^{(\text{OPE})}$ we use the predictions of elementary OPE which, in the Gottfried-Jackson system,[12] are $\rho_{1-1}{}^{1(\text{OPE})} = -\text{Im}\rho_{1-1}{}^{2(\text{OPE})} = -\frac{1}{2}$, all other density-matrix parameters in Eq. (2) equal to zero. The absorption corrections for $\rho_{ik}{}^{(\text{OPE})}$

were neglected. For $d\sigma^{N}/dt$ and $d\sigma^{OPE}/dt$ we used the results of the fit by Eq. (4). The curves in Fig. 4 show the values of the ρ_{ik} predicted by Eq. (5).

The ω-production cross section decreases from 5.8 ± 0.5 μb at 2.8 GeV to 3.2 ± 0.3 μb at 4.7 GeV. Both natural- and unnatural-parity exchanges contribute to ω production. The energy dependence and the magnitude of the unnatural-parity-exchange cross section agree with the predictions for one-pion exchange. The natural-parity–exchange cross sections do not change significantly from 2.8 to 4.7 GeV.

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[1]Aachen-Berlin-Bonn-Hamburg-Heidelberg-München Collaboration, Phys. Rev. 175, 1669 (1968).

[2]Cambridge Bubble Chamber Group, Phys. Rev. 155, 1468 (1967).

[3]J. Ballam *et al.*, Phys. Rev. Letters 23, 498, 817(E) (1969).

[4]H. H. Bingham *et al.*, Phys. Rev. Letters 24, 955 (1970).

[5]J. Ballam *et al.*, Phys. Rev. Letters 24, 960 (1970).

[6]J. J. Murray and P. Klein, Stanford Linear Accelerator Center Report No. SLAC-TN-67-19, 1967 (unpublished); C. K. Sinclair, J. J. Murray, P. Klein, and M. Rabin, IEEE Trans. Nucl. Sci. 16, 1065 (1969).

[7]A. Barbaro-Galtieri *et al.*, Rev. Mod. Phys. 43, 87 (1970). A value of 0.87 was used for the branching ratio $\Gamma(\omega\to\pi^+\pi^-\pi^0)/\Gamma(\omega\to\text{all})$.

[8]E. Burns and D. Drijard, Technical Note No. 143, Trilling-Goldhaber Group, Lawrence Radiation Laboratory, 1968 (unpublished).

[9]M. Davier *et al.*, Phys. Letters 28B, 619 (1969).

[10]Y. Eisenberg *et al.*, Phys. Rev. Letters 22, 669 (1969).

[11]J. Ballam *et al.*, Phys. Letters 30B, 421 (1969).

[12]K. Schilling, P. Seyboth, and G. Wolf, Nucl. Phys. B15, 397 (1970).

[13]The y axis is the normal to the production plane, defined by the cross product $\hat{k}\times\hat{\omega}$ of the directions of the photon and the ω meson. The angle Φ between the electric vector of the photon ϵ and the production plane in the total c.m. system is defined by $\cos\Phi=\hat{\epsilon}\cdot(\hat{y}\times\hat{k})$, $\sin\Phi=\hat{y}\cdot\hat{\epsilon}$. The decay angles θ, φ are the polar and azimuthal angles of the normal $n=\pi^+\times\pi^-$ to the ω decay plane in the ω rest system $\cos\theta=\hat{n}\cdot\hat{z}$, $\cos\varphi=\hat{y}\cdot(\hat{z}\times\hat{n})/|\hat{z}\times\hat{n}|$, and $\sin\varphi=-\hat{x}\cdot(\hat{z}\times\hat{n})/|\hat{z}\times\hat{n}|$. The x axis is given by $\hat{x}=\hat{y}\times\hat{z}$.

[14]R. L. Thews, Phys. Rev. 175, 1749 (1968).

[15]The derivation of Eq. (3) in addition to the high-energy approximation involves in the case of Regge exchange processes an assumption on the relative size of the trajectories α^N, α^U of the natural- and unnatural-parity exchanges [cf. J. D. Jackson and G. E. Hite, Phys. Rev. 169, 1248 (1968)].

[16]F. Bucella and M. Collocci, Phys. Letters 24B, 61 (1967); H. Joos, Phys. Letters 24B, 103 (1967). Modifications due to symmetry breaking lead to ratios between 9:0.65 and 9:1.2 [see R. J. Oakes and J. J. Sakurai, Phys. Rev. Letters 19, 1266 (1967); T. Das, V. S. Mathur, and S. Okubo, Phys. Rev. Letters 19, 470 (1967)].

[17]H. Harari, in *International Symposium on Electron and Photon Interactions at High Energies, Liverpool, England, September 1969,* edited by D. W. Braben (Daresbury Nuclear Physics Laboratory, Daresbury, Lancashire, England, 1970), p. 107.

[18]K. Schilling and F. Storim, Nucl. Phys. B7, 559 (1968).

[19]J. Benecke and H. P. Dürr, Nuovo Cimento 56, 269 (1969); G. Wolf, Phys. Rev. 182, 1538 (1969). A value of 2.31 GeV^{-1} was used for the R parameter describing the $\omega\pi\gamma$ vertex, i.e., the same value obtained for the R parameter of the $\rho\pi\pi$ vertex.