[12]F. M. Pipkin, in *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies Stanford Linear Accelerator Center, Stanford, Calif., 1967* (Clearing House of Federal Scientific and Technical Information, Washington, D. C., 1968), p. 289.

[13]G. Greenhut, R. Weinstein, and R. Parsons, 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), Abstr. No. 62.

[14]S. C. C. Ting, in *Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September 1968,* edited by J. Prentki and J. Steinberger (CERN Scientific Information Center, Geneva, Switzerland, 1968), p. 43.

[15]The value of $\gamma_\rho^2/4\pi$ is calculated from the equation $\Gamma_{\rho\to e^+e^-} = (m_\rho\alpha^2/12)(4\pi/\gamma_\rho^2)$.

[16]H. J. Behrend, F. Lobkowicz, E. H. Thorndike, A. A. Wehmann, and M. E. Nordberg, Jr., 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), Abstr. No. 93.

[17]J. E. Augustin, P. Benaksas, J. Buon, V. Gracco, J. Haissinski, D. Lalanne, F. Laplanche, J. LeFrancois, P. Lehmann, P. Marin, F. Rumpf, and E. Silva, Phys. Letters 28B, 513 (1969).

[18]D. Bollini, A. Buhler-Broglin, P. Dalpiaz, T. Massam, F. Navach, F. L. Navarria, M. A. Schneegans, and A. Zichichi, Nuovo Cimento 57A, 404 (1968).

[19]M. Ross and L. Stodolsky, Phys. Rev. 149, 1172 (1966).

[20]H. Alvensleben, U. Becker, W. K. Bertram, M. Chen, K. J. Cohen, T. M. Knasel, R. Marshall, D. J. Quinn, M. Rohde, G. H. Sanders, H. Schubel, and S. C. C. Ting, 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), Abstr. No. 163.

[21]H. Meyer, B. Naroska, J. H. Weber, M. Wong, V. Heynen, E. Mandelkow, and D. Notz, 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), Abstr. No. 154.

[22]J. Swartz and R. Talman, Phys. Rev. Letters 23, 1078 (1969).

MEASUREMENT OF THE MAGNITUDE AND PHASE OF ρ-ω INTERFERENCE IN $\pi^+\omega^-$ PHOTOPRODUCTION FROM CARBON

P. J. Biggs, R. W. Clifft, E. Gabathuler, P. Kitching,* and R. E. Rand
Daresbury Nuclear Physics Laboratory, Warrington, England
(Received 26 March 1970)

The reaction $\gamma + C \to \pi^+ + \pi^- + C$ has been investigated in the invariant-mass region of the ρ and ω mesons and shows distinct interference effects between the ρ and ω contributions to the cross section. The experiment was performed at a mean photon energy of 4.2 GeV with 140 000 events. A phenomenological analysis of the data yields the result $\Gamma_{\omega\to 2\pi} = 0.091\ {}^{+0.031}_{-0.025}$ MeV/c^2. The relative phase of the ρ and ω terms in the amplitude is obtained and discussed.

Several observations of the G-parity-nonconserving decay $\omega \to \pi^+\pi^-$ have been made for various production processes[1-3] by using interference between the ρ and ω channels. These have indicated that the decay width $\Gamma_{\omega\to 2\pi}$ is up to two orders of magnitude higher than that calculated for the pure electromagnetic decay. Such experiments have, however, been of limited statistical significance to date.

One of the earliest calculations of the effects to be expected is due to Greenberg[4] who gives references to earlier work. The first quantitative observation of the effect was made by Flatté et al.[1] who used the reaction $K^-p \to \Lambda\pi^+\pi^-$ and obtained $\Gamma_{\omega\to 2\pi}/\Gamma_{\omega\to 3\pi} \equiv B_{\omega\to 2\pi} > 0.2\,\%$. A later experiment ($\pi^+p \to \pi^+\pi^-\Delta^{++}$) by Goldhaber et al.[2] showed evidence for a dip at the ω mass in the π-pair invariant-mass spectrum. They deduced that $B_{\omega\to 2\pi} = (2.7\,{}^{+3.0}_{-2.0})\,\%$.

The production of charged pion pairs in electron-positron annihilation provides a means of observing ρ-ω interference in a reaction which is independent of strong interactions. Such an experiment has recently been performed[3] using the electron-positron storage rings at Orsay. An analysis of the mass spectrum obtained yielded the result $B_{\omega\to 2\pi} = (3.5\,{}^{+3.0}_{-2.1})\,\%$. The interference was destructive. The phase obtained will be discussed in the conclusions.

The reaction $\gamma + C \to \pi^+ + \pi^- + C$ is equally attractive for observing the decay $\omega \to \pi^+\pi^-$, since the production mechanism is reasonably well understood, and it has the advantage that good statistics are easily obtained. Previous experiments of this type[5] have failed to detect interference because of insufficient data at one setting or inadequate mass resolution.

The present experiment overcomes both these shortcomings. 140 000 events were observed at one photon energy with an experimental mass resolution of ± 4 MeV/c^2. The data show clear evidence of ρ-ω interference.

The apparatus consisted of two identical magnetic spectrometers and was basically the same as that described previously.[6,7] The mass resolution was improved by overlapping the scintillators of the momentum hodoscopes and by introducing extra counters into the θ hodoscopes. The effective number of bins in each hodoscope was doubled, resulting in a calculated mass resolution of ± 4 MeV/c^2. The acceptance of each spectrometer was defined by scintillation counters to avoid slit scattering effects. The solid angle of each spectrometer was 0.5 msr with a momentum bite $\Delta p/p = 0.11$. No discriminating devices were required to identify pion pairs since the production of other particle pairs at the settings used is negligible.

A collimated photon beam of maximum energy 4.6 GeV from the accelerator NINA was used to produce pion pairs in a thin carbon target. Carbon was chosen as a convenient zero-isospin nucleus, for which one-pion exchange effects are small. It also gives strongly coherent production of vector mesons in the forward direction and was suitable for the related electron-pair experiment.[7] The spectrometers were set symmetrically for a mean momentum of 2.1 GeV/c and at six angles between 8.0 and 10.5°.

The raw data were reduced analytically to produce a cross section $(d\sigma/dtdm)|_{t=0}$, as a function of mass, which could be compared with theory. This is in contrast to the electron-pair experiment,[7] where a Monte Carlo method was necessary.

For each angle setting, events were initially classified into invariant-mass-squared bins of width 0.006 (GeV/c^2)^2 using $m^2 = 2m_\pi^2 + 2E_+E_- - 2p_+p_- \cos(\theta_+ + \theta_-)$, where symbols have their usual meanings and p_+, p_-, θ_+, and θ_- were the mean values of these quantities for the appropriate momentum and angle bins. Events with a count in only one bin of each hodoscope were analyzed to produce the mass spectrum. Ambiguous events with not more than two counts per hodoscope were included in the final cross section. The total events in each run were corrected for dead times and accidentals.

Accurate relative acceptances of the momentum (Δp) and angle ($\Delta\theta$) bins were obtained using the pair data itself. The overall acceptance was calculated by a Monte Carlo method. Hence the acceptance in laboratory parameters $(\Delta p_+ \Delta p_- \Delta\Omega_+ \Delta\Omega_-)$ for every hodoscope combination was calculated.

Now assuming that (a) the photoproduction of ρ mesons is mainly diffractive,[8] (b) the pion-decay angular distribution in the ρ c.m. system is proportional to $\sin^2\theta^*$, where θ^* is the angle between one pion and the ρ direction, and (c) the photon spectrum is proportional to dk/k, one may show that

$$\left.\frac{d\sigma}{dtdm}\right|_{t=0} = \frac{1}{SJ}\frac{d\sigma}{dp_+dp_-d\Omega_+d\Omega_-},$$

where

$$S = \frac{3}{8\pi^2} k e^{bt} \sin^2\theta^*$$

and

$$J = \frac{\partial(\Omega_\rho, k, m, \Omega^*)}{\partial(p_+, p_-, \Omega_+, \Omega_-)}.$$

Here Ω_ρ is the solid angle in the laboratory into which the ρ meson is produced and Ω^* is the solid angle corresponding to θ^*. Hence for a given mass bin, the cross section is given by

$$\left.\frac{d\sigma}{dtdm}\right|_{t=0} = \frac{\sum \text{No. of events}}{N\sum SJ(\Delta p_+ \Delta p_- \Delta\Omega_+ \Delta\Omega_-)},$$

where the sums are taken over all hodoscope combinations defining a mass within the bin and N is a normalizing constant. The data were analyzed in this way using[8,9] $b = 47$ (GeV/c)$^{-2}$. Absolute normalization of the cross section took into account decay and absorption of the pions and absorption of the photon beam in the target. The measured cross section as a function of invariant mass is shown in Fig. 1. In Fig. 1(a) the data from the various angular settings of the spectrometers are shown separately to indicate their consistency while in Fig. 1(b) all the data are combined.

Experimental resolution was taken into account, by smearing the theoretical spectrum during the fitting procedure.

The general theoretical cross section used was of the form

$$\frac{d\sigma}{dtdm}\bigg|_{t=0} = \frac{d\sigma}{dt}\bigg|_{t=0} \frac{2m}{\pi} m_\rho \Gamma_\rho \left(\frac{m_\rho}{m}\right)^n \left| \frac{1}{m^2 - m_\rho^2 + i m_\rho \Gamma_\rho} + \frac{\xi e^{i\alpha}}{m^2 - m_\omega^2 + i m_\omega \Gamma_\omega} + U + iV \right|^2 + W, \tag{1}$$

where

$$\Gamma_\rho = \Gamma_\rho^0 \left(\frac{m_\rho}{m}\right)\left(\frac{m^2 - 4m_\pi^2}{m_\rho^2 - 4m_\pi^2}\right)^{3/2} \text{ and } W = \sum_{I=1}^{I_{\max}} C_I \left(\frac{m - m_\rho}{m_\rho}\right)^{I-1},$$

which incorporates the Jackson[10] form of the Breit-Wigner formula for the ρ propagator. The first two terms of the amplitude may be interpreted phenomenologically as due to contributions from the diagrams of Figs. 2(a) and 2(b). The parameter ξ is then given directly in terms of the partial width $\Gamma_{\omega\to 2\pi}$:

$$\xi \simeq \left(\frac{m_\omega}{m_\rho}\right)^2 \left|\frac{\gamma_\rho}{\gamma_\omega}\right| \left|\frac{A_{\omega N}}{A_{\rho N}}\right| \left(\frac{\Gamma_{\omega\to 2\pi}}{\Gamma_{\rho\to 2\pi}} \frac{m_\rho}{m_\omega}\right)^{1/2},$$

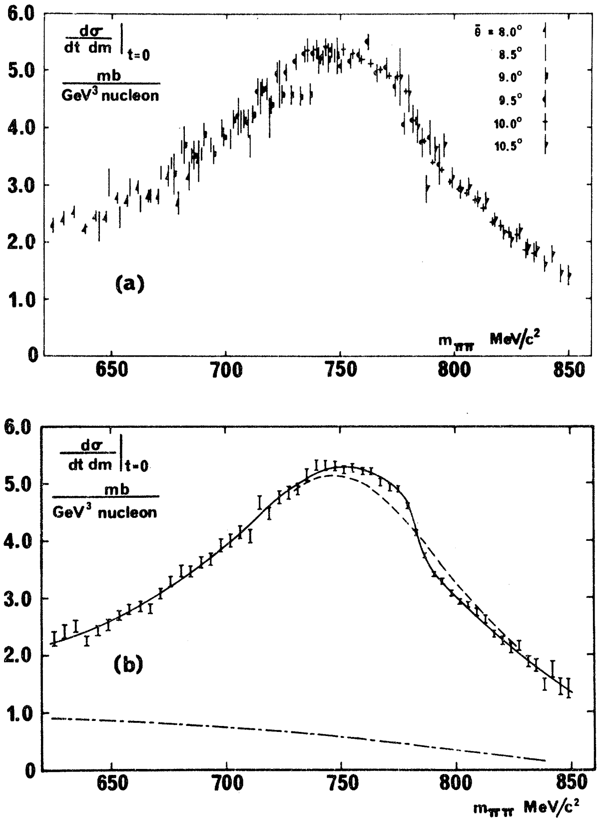

FIG. 1. (a) Differential cross section $d\sigma/dtdm|_{t=0}$ in mb GeV^{-3} nucleon^{-1} as a function of invariant mass. Data obtained at different angular settings of the spectrometers are compared. Some points are displaced 1 MeV/c^2 for clarity. The vertical scale includes a possible normalization error of ±5%. (b) The data of (a) combined. The solid line is the best fit to the data described in the text. The dashed line shows the same fit with $\xi = 0$ (no ω contribution) and the chain line shows the incoherent background.

where $(em_v^2/2\gamma_v)$ is the photon–vector-meson coupling constant and A_{VN} is the amplitude for vector meson-nucleus scattering.

A more useful interpretation may be derived from the suggestion[4, 11-16] that the physical ρ and ω states are mixtures of pure isospin states ρ_0 and ω_0 so that one may write

$$|\rho\rangle = |\rho_0\rangle - \epsilon|\omega_0\rangle$$
$$|\omega\rangle = \epsilon|\rho_0\rangle + |\omega_0\rangle,$$

where ϵ is small and complex. Thus the ω meson may be considered as decaying to $\pi^+\pi^-$ through the ρ_0 channel is shown in Fig. 2(c). If the amplitude for the two diagrams 2(a) and 2(c) is written to lowest order in the ω-ρ coupling constant λ, each term contains a ρ propagator,

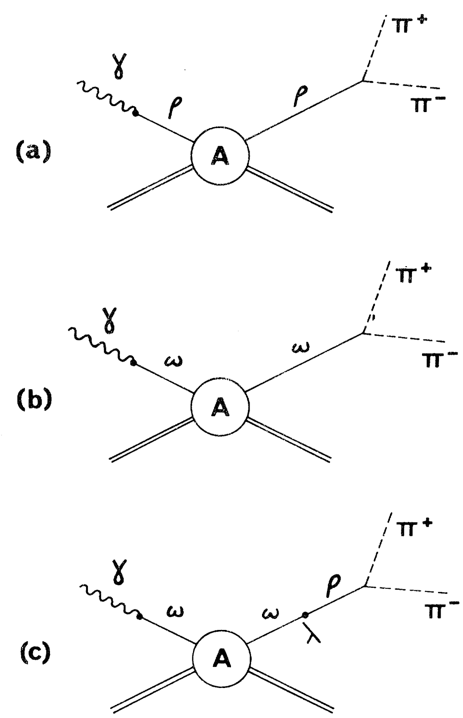

FIG. 2. Diagrams for the photoproduction of π pairs from a nucleus. (a) With intermediate ρ; (b) with intermediate ω decaying directly to 2π; (c) with intermediate ω coupled to ρ by a coupling constant λ.

but by suitable algebraic manipulation and assuming λ is small, it may be expressed[16] in the form of (1) with

$$\xi e^{i\alpha} \simeq \left(\frac{m_\omega}{m_\rho}\right)^2 \frac{\gamma_\rho}{\gamma_\omega} \left|\frac{A_{\omega N}}{A_{\rho N}}\right| \frac{|\lambda| e^{i(\varphi_N + \varphi_\lambda)}}{m_\rho^2 - m_\omega^2 - i(m_\rho \Gamma_\rho - m_\omega \Gamma_\omega)},$$

where φ_N and φ_λ are the arguments of $A_{\omega N}/A_{\rho N}$ and λ, respectively, and the mixing parameter ϵ is related to λ via

$$\epsilon \simeq \lambda/[m_\rho^2 - m_\omega^2 - i(m_\rho \Gamma_\rho - m_\omega \Gamma_\omega)].$$

Hence, assuming a positive value for $(\gamma_\rho/\gamma_\omega)$,

$$\alpha = \varphi_N + \varphi_\lambda + \tan^{-1}\left(\frac{m_\rho \Gamma_\rho - m_\omega \Gamma_\omega}{m_\rho^2 - m_\omega^2}\right). \quad (2)$$

If a negative value of $\gamma_\rho/\gamma_\omega$ is used, all experimental values of φ_λ in the following discussion should be changed by 180°.

The coherent background terms, U and V in (1), have been suggested[16] as a general modification to the Breit-Wigner formula and give an effect similar to that proposed by Söding.[17] The polynomial background term, W, simulates nonresonant and incoherent π-pair production which is assumed to vary smoothly over the mass range. The parameter n is set at 0, 2, or 4. The latter two values correspond to the models of Kramer and Uretsky[18] and Ross and Stodolsky,[19] respectively.

Formula (1) was fitted to the data with $n=0$, 2, and 4 and with coherent and incoherent background terms. Fits with $n=0$ were not acceptable because of the necessary magnitude of the background terms and high values of the ρ width and mass. The best fits were obtained with the Ross-Stodolsky factor ($n=4$). Fits with coherent background were not so good as those with incoherent background and gave rather high values for the ρ mass. The best fit to the data was obtained using $n=4$ and the previously defined background parameters C_1, C_2, and C_3 only. The other free parameters were $d\sigma/dt|_{t=0}$, m_ρ, Γ_ρ^0, m_ω, ξ, and α. This fit had $\chi^2 = 46.9$ for 47 degrees of freedom. The corresponding fits for $n=0$ and 2 had $\chi^2 = 54.5$ and 48.6, respectively. Apart from the values of χ^2, the only significant differences between the fits with $n=2$ and 4 were in the values of m_ρ and Γ_ρ^0. The best fit is shown in Fig. 1(b).

For $n=4$, the best-fit values of the various parameters were as follows[20]:

$$d\sigma/dt|_{t=0} = 0.98 \pm 0.05 \text{ mb GeV}^{-2} \text{ nucleon}^{-1},$$

$$m_\rho = 767.7 \pm 1.9 \text{ MeV}/c^2,$$

$$\Gamma_\rho^0 = 146.1 \pm 2.9 \text{ MeV}/c^2,$$

$$m_\omega = 783.2 \pm 1.6 \text{ MeV}/c^2,$$

$$\xi = 0.0097 \pm 0.0008, \quad \alpha = 104.0 \pm 5.1°.$$

The values for the cross section, masses, and width are in good agreement with previous results.[5,8,21]

The absolute value of ξ gives

$$\Gamma_{\omega\to 2\pi} = 0.091^{+0.031}_{-0.025} \text{ MeV}/c^2,$$

$$B_{\omega\to 2\pi} = (0.80^{+0.28}_{-0.22})\%.$$

Equivalently $|\lambda|/m_\rho = 3.4 \pm 0.5$ MeV$/c^2$.

These results[22] use the value of $(\gamma_\omega/\gamma_\rho)^2 = 7.0^{+2.1}_{-1.5}$ given in the preceding paper,[7] and assume $|A_{\omega N}/A_{\rho N}| = 1$. No account has been taken of incoherent ρ production but if the cross section for this is less than 10% of the total, the effect on the values of $\Gamma_{\omega\to 2\pi}$ and $|\lambda|$ is considerably less than the statistical errors. The above results may be compared with the Orsay[3] value $|\lambda|/m_\rho = 8 \pm 3$ MeV$/c^2$.

Assuming[13,14] that φ_N in Eq. (2) may be identified with the phase $\varphi = 100^{+38}_{-30}$ deg, measured in the electron pair experiment,[7] the result for α gives $\varphi_\lambda = -99^{+38}_{-30}$ deg. The corresponding phase from the Orsay result, $\alpha = 164 \pm 28°$, is, assuming $\gamma_\rho/\gamma_\omega = +1$, $\varphi_\lambda = 54 \pm 28°$ in direct contrast to the above. If, however, one takes the value of $\varphi_N = 22 \pm 25°$, as suggested by preliminary results from DESY,[23] which is consistent with the diffraction model, one obtains $\varphi_\lambda = -21 \pm 25°$. This is also not in agreement with the Orsay result but is compatible with the predictions of several authors,[11,15,16] based on both theoretical and experimental values for the magnitude of λ.

The imaginary part of λ, which is due to real intermediate states in the ω-ρ coupling (2π, 3π, $\pi^0\gamma$), has been estimated[16] to be approximately +0.2 MeV$/c^2$. The real part of λ, due to the self-energy contributions of virtual intermediate states, has been predicted[15] from the mass splitting of the meson states in SU(3) to be +5.0 MeV$/c^2$. Thus the theoretical estimate of $|\lambda|/m_\rho$ is in reasonable agreement with the experimental result, whereas the theoretical phase, $\varphi_\lambda \simeq 2°$, would agree with experiment only if φ_N were close to zero.

The authors greatly appreciate the tireless and enthusiastic support of M. W. Collins, K. Stephens, and A. E. Groome throughout these experiments. They are also indebted to A. J. Egginton and the Machine Group, for the efficient running of NINA, and to the technical services group. They would also like to thank Dr. G. R. Allcock for stimulating discussions and Dr. G. C. Fox and Professor R. H. Dalitz for their interest.

---

*Now at the University of Alberta, Edmonton, Alta., Canada.

[1]S. M. Flatté, D. O. Huwe, J. J. Murray, J. Button-Shafer, F. T. Solmitz, M. L. Stevenson, and C. Wohl, Phys. Rev. 145, 1050 (1966); S. M. Flatté, UCRL Report No. UCRL-18687 Rev., 1969 (to be published).

[2]G. Goldhaber, W. R. Butler, D. G. Coyne, B. H. Hall, J. N. MacNaughton, and G. H. Trilling, Phys. Rev. Letters 23, 1351 (1969).

[3]J. E. Augustin, D. Benaksas, J. Buon, F. Fulda, V. Gracco, J. Haissinski, D. Lalanne, F. Laplanche, J. Lefrancois, P. Lehmann, P. C. Marin, J. Perez-y-Jorba, F. Rumpf, and E. Silva, Lettere Nuovo Cimento 2, 214 (1969). Note that the sign convention for the phases in this reference is opposite to that used here.

[4]D. F. Greenberg, Nuovo Cimento 38, 1908 (1965).

[5]H. Alvensleben, U. Becker, W. K. Bertram, M. Chen, K. J. Cohen, T. M. Knasel, R. Marshall, D. J. Quinn, M. Rohde, G. H. Sanders, H. Schubel, and S. C. C. Ting, DESY Report No. DESY 69/50, 1969 (unpublished); F. Bulos, W. Busza, R. Giese, R. R. Larsen, D. W. G. S. Leith, B. Richter, V. Perez-Mendez, A. Stetz, S. H. Williams, M. Beniston, and J. Rettberg, Phys. Rev. Letters 22, 490 (1969); G. McClellan, N. Mistry, P. Mostek, H. Ogren, A. Silverman, J. Swartz, R. Talman, K. Gottfried, and A. I. Lebedev, Phys. Rev. Letters 22, 377 (1969).

[6]P. J. Biggs, D. W. Braben, R. W. Clifft, E. Gabathuler, P. Kitching, and R. E. Rand, Phys. Rev. Letters 23, 927 (1969), and Phys. Rev. (to be published).

[7]P. J. Biggs, D. W. Braben, R. W. Clifft, E. Gabathuler, P. Kitching, and R. E. Rand, preceding Letter [Phys. Rev. Letters 24, 1197 (1970)]. See also Ref. 1 of this paper.

[8]F. M. Pipkin, in *Proceedings of the Third International Symposium on Electron and Photon Interactions at High Energies, Stanford Linear Accelerator Center, Stanford, California, 1967* (Clearing House of Federal Scientific and Technical Information, Washington, D. C., 1968), p. 289.

[9]The t dependence of the present data will be presented in a later paper.

[10]J. D. Jackson, Nuovo Cimento 34, 1644 (1964).

[11]M. Gourdin, L. Stodolsky, and F. M. Renard, Phys. Letters 30B, 347 (1969).

[12]A. Donnachie, Phys. Letters 27B, 525 (1968); E. Etim and P. Picchi, Phys. Letters 28B, 272 (1968); R. G. Parsons, Center for Particle Theory, University of Texas, Report No. CPT-12, 1969 (unpublished).

[13]D. Horn, California Institute of Technology Report No. CALT-68-225, 1969 (unpublished).

[14]R. G. Sachs and J. F. Willemsen, Enrico Fermi Institute, University of Chicago, Report No. COO 264-531, 1969 (to be published).

[15]A. S. Goldhaber, G. C. Fox, and C. Quigg, Phys. Letters 30B, 249 (1969).

[16]G. R. Allcock, in *Proceedings of the 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), and to be published.

[17]P. Söding, Phys. Letters 19, 702 (1966).

[18]G. Kramer and J. L. Uretsky, Phys. Rev. 181, 1918 (1969).

[19]M. Ross and L. Stodolsky, Phys. Rev. 149, 1172 (1966).

[20]The error in the cross section includes a systematic error of $\pm 5\%$. Errors in the masses include a possible error in the mass calibration of ± 1.5 MeV/c^2. The value used for the ω width was $\Gamma_\omega = 12.6$ MeV/c^2 [N. Barash-Schmidt *et al.*, Rev. Mod. Phys. 41, 109 (1969)].

[21]Barash-Schmidt *et al.*, Ref. 20.

[22]Note that most of the error in $\Gamma_{\omega\to 2\pi}$ and $|\lambda|$ is due to uncertainty in the quantity $|\gamma_\rho/\gamma_\omega|$. ξ is determined much more accurately.

[23]H. Alvensleben, U. Becker, W. K. Bertram, M. Chen, K. J. Cohen, T. M. Knasel, R. Marshall, D. J. Quinn, M. Rohde, G. H. Sanders, H. Schubel, and S. C. C. Ting, in *Proceedings of the 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), Abstr. 163. This experiment was performed with a Be^9 target.