SLAC-PUB-845
UCRL-19753
August 1970

# THE $\rho^0$-$\omega$ INTERFERENCE PARAMETERS IN DIFFRACTIVE PHOTOPRODUCTION OF VECTOR MESONS ON HYDROGEN*

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## ABSTRACT

We have examined the reaction $\gamma p \to \pi^+\pi^- p$ for evidence of $\rho^0$-$\omega$ interference. Assuming the ratio of the $\rho^0$ and $\omega$ photoproduction amplitudes

$$\left|\frac{A_\rho}{A_\omega}\right|^2 = 7.1 \pm 0.7,$$

we find

$$\mathrm{Re}(\delta e^{i\beta}) = 2.3 \pm 0.9 \text{ MeV and } \mathrm{Im}(\delta e^{i\beta}) = -0.4 \pm 0.9 \text{ MeV},$$

where $\delta(\approx 2.3$ MeV) is the mass mixing parameter and $\beta(\approx -9$ degrees) is the relative phase of the $\rho^0$-$\omega$ amplitudes. Our result, obtained using a hydrogen bubble chamber, agrees with the high-statistics Daresbury result using photoproduction on carbon.

The possibility of $\rho^0$-$\omega$ interference was proposed some time ago,[1] but interference effects amounting to two or more standard deviations in the $\pi^+\pi^-$ channel have been reported only recently.[2-8] These experimental results have stimulated new theoretical studies of $\rho^0$-$\omega$ mixing.[9-12] The magnitude of the observed $\omega \to \pi^+\pi^-$ amplitude agrees with these theoretical expectations, and its relative phase, as seen in the detailed shapes of the interference effects, can be interpreted in terms of simple models for $\rho^0$ and $\omega$ production in quasi-two-body reactions.

Clear evidence for $\rho^0$-$\omega$ interference has been observed in photoproduction on carbon by Biggs et al.[8] at Daresbury with 140 000 events, at a mean photon energy of 4.2 GeV. The $\rho^0$-$\omega$ interference is inferred from the shape of the $\pi^+\pi^-$ mass spectrum near $M_\omega$; they obtained constructive interference for $M_{\pi\pi} < M_\omega$ and destructive interference for $M_{\pi\pi} > M_\omega$ in agreement with the prediction of A. Goldhaber, Fox, and Quigg (GFQ).[9] The interference is determined by measuring the relative phase, $\beta$, of $\omega \to \pi^+\pi^-$ and $\rho^0 \to \pi^+\pi^-$ amplitudes. For photoproduction of $\rho^0$ and $\omega$, the value $\beta = 0$ is predicted assuming the vector dominance model

(Submitted to Nuclear Physics B)

(VDM) and that the photon transforms as the U-spin singlet member of an SU(3) octet. The Daresbury experiment obtained the value $\beta = 2.0 \pm 5.1°$.

Horn[11] and GFQ[9] have pointed out that the $\rho^0$-$\omega$ phase should be the same in $\rho^0$ and $\omega$ production from $e^+e^-$ colliding beams as in diffractive photoproduction (see also Ref. 8, 17). This follows from the observation that the production amplitudes shown in Fig. 1a, b, differ mainly by the presence or absence of a diffractive process, which does not distinguish between $\rho^0$ and $\omega$. For $e^+e^- \rightarrow \pi^+\pi^-$ the Orsay storage ring group[4] reported $\beta = 55 \pm 28°$, however, the disagreement with $\beta = 0$ is not statistically compelling.

We have analyzed events of the reaction

$$\gamma p \rightarrow \pi^+\pi^- p \qquad (1)$$

in terms of $\rho^0$-$\omega$ interference, as part of a detailed study of photoproduction using a hydrogen bubble chamber exposed to a monochromatic linearly polarized photon beam.[13] We obtained $90 \pm 4$ events/$\mu$b at 2.8 GeV and $149 \pm 6$ events/$\mu$b at 4.7 GeV. For the present study we combined the 2854 events at $E_\gamma = 2.8$ GeV and the 2910 events at $E_\gamma = 4.7$ GeV that fit reaction (1). The mass resolution, $\delta M_{\pi\pi}$, in the $\rho^0$ mass region was estimated to be $\pm 5$ MeV.

In Fig. 2 we show the $\pi^+\pi^-$ mass distribution for the events of reaction (1) in the region of the $\rho^0$. In the reaction $e^+e^- \rightarrow \pi^+\pi^-$ a kinematical skewing of the dipion mass distribution proportional to $(M_{\pi\pi})^{-4}$ is caused by the photon propagator in Fig. 1(b). A somewhat similar skewing in reaction (1) is not so well understood. Our previous study[13] of the $\pi^+\pi^-$ mass shape has yielded an empirical formula[14] that adequately describes the observed skewing of the $\pi\pi$ mass distribution. In Fig. 2 we show by the dashed curve the results of a maximum-likelihood fit to the events of reaction (1) using the empirical formula to account for $\rho^0$ production; $\Delta^{++}$ and phase space were also allowed to contribute. Although the dashed curve accounts for the gross skewing of the $\rho^0$ shape, there is an excess of events just below $M_\omega$ and a depletion of events just above $M_\omega$.

To analyze our data we chose the mass mixing theory, and adopted the notation of GFQ.[9] Here we briefly re-derive their result. The informed reader may skip to Eq. (3).

In the spirit of the vector dominance model we assume that, before mixing, the $\rho$ and $\omega$ are produced (by diffraction scattering of the intermediate vector meson) in pure states which conserve G parity, i.e.,

$$\left.\begin{array}{l} |A_\rho\rangle \rightarrow 2\pi \text{ only} \\ |A_\omega\rangle \rightarrow 3\pi \text{ only} \end{array}\right\} \text{initial state.}$$

These states are then mixed by the G-violating term $\delta$ (assumed to be real[9]) in the propagator matrix P.

Using the usual abbreviation for the Breit-Wigner denominators, $\mu_\rho = m_\rho - m - i\frac{\Gamma_\rho}{2}$, $\mu_\omega$ = similar, and m for the dipion mass, we have

$$P = \begin{vmatrix} \mu_\rho & -\delta \\ -\delta & \mu_\omega \end{vmatrix}^{-1} = \frac{1}{\mu_\rho\mu_\omega - \delta^2} \begin{vmatrix} \mu_\omega & +\delta \\ +\delta & \mu_\rho \end{vmatrix}.$$

Dropping the $\delta^2$ term gives

$$P = \begin{vmatrix} \frac{1}{\mu_\rho} & \frac{\delta}{\mu_\rho\,\mu_\omega} \\ \frac{\delta}{\mu_\rho\mu_\omega} & \frac{1}{\mu_\omega} \end{vmatrix}.$$

After mixing, the $2\pi$ amplitude is

$$S(\pi^+\pi^-) = \Big(T(\rho \rightarrow 2\pi), \quad T(\omega \rightarrow 2\pi)\Big)\Big(P\Big)\begin{pmatrix} A_\rho \\ A_\omega \end{pmatrix},$$

where the T's are decay amplitudes in the absence of mass mixing [we take $T(\omega \rightarrow 2\pi) = 0$], and the A's are the vector meson production amplitudes,

$$S_{(\pi^+\pi^-)} = \frac{A_\rho T_\rho}{(m_\rho - m - i\frac{\Gamma_\rho}{2})} \left(1 + \left|\frac{A_\omega}{A_\rho}\right| e^{i\beta} \frac{\delta}{m_\omega - m - i\frac{\Gamma_\omega}{2}}\right), \qquad (2)$$

where $\beta = \mathrm{Arg}[A_\omega/A_\rho]$.

That is, in the presence of $\rho^0$-$\omega$ interference, the $\pi^+\pi^-$ mass distribution is given by the $\rho$ line shape (including kinematical dependences), multiplied by a modulating factor, $\mathcal{F}$, which characterizes the interference:

$$\mathcal{F} = \left|1 + \left|\frac{A_\omega}{A_\rho}\right| e^{i\beta} \frac{\delta}{m_\omega - m - i\Gamma_\omega/2}\right|^2. \qquad (3)$$

On the other hand, the Daresbury group analyzed the $\rho$-$\omega$ interference using the phenomenological parameterization

$$S(\pi^+\pi^-) \propto \left(\frac{1}{m^2 - m_\rho^2 + i\, m_\rho \Gamma_\rho} + \frac{\xi\, e^{i\alpha}}{m^2 - m_\omega^2 + i m_\omega \Gamma_\omega}\right). \qquad (4)$$

Factoring out the $\rho$ Breit-Wigner and comparing Eqs. (4) and (2), one obtains

$$\left|\frac{A_\omega}{A_\rho}\right| e^{i\beta}\,\delta \approx (m_\rho - m - i\frac{\Gamma_\rho}{2})\, \xi\, e^{i\alpha}.$$

Evaluating the right side at the $\omega$ mass yields the convenient approximation

$$\left|\frac{A_\omega}{A_\rho}\right| e^{i\beta}\,\delta \approx \frac{\Gamma_\rho}{2}\, \xi\, e^{i(\alpha - \phi_\rho)}, \qquad (5)$$

where $\tan\phi_\rho = \frac{\Gamma_\rho}{2(m_\rho - m_\omega)}$,

$$\delta \approx \left|\frac{A_\rho}{A_\omega}\right| \frac{\Gamma_\rho}{2}\, \xi \text{ and } \beta = \alpha - \phi_\rho.$$

The Daresbury group obtained $\xi = 0.0097 \pm 0.0008$, $M_\rho = 767.7 \pm 1.9$ MeV, $\Gamma_\rho = 146.1 \pm 2.9$ MeV, $M_\omega = 783.2 \pm 1.6$ MeV, $\alpha = 104.0 \pm 5.1$ deg, and $\left|\frac{A_\rho}{A_\omega}\right|^2 = 7.0^{+2.1}_{-1.5}$. These values, along with Eq. (5), give

$$\delta = 1.9 \pm 0.25 \text{ MeV},$$
$$\beta = 2.0 \pm 5.1 \text{ deg}.$$

To investigate $\rho^0$-$\omega$ interference in reaction (1) we assumed that the empirical formula[14] (discussed in Ref. 13) adequately represents the kinematical effects in $\rho^0$ production. We then made a maximum-likelihood fit, modulating the $\rho^0$ amplitude by the factor $\mathcal{F}$ of Eq. (3). Since $\beta$ is undefined for $\delta = 0$, we fit the real and imaginare parts of $\exp(i\beta)$. For convenience we define

$$\tau \equiv 3 \left|\frac{A_\omega}{A_\rho}\right| \delta. \qquad (6)$$

The solid line in Fig. 2 gives the best fit obtained with this form, which is better than that obtained without the factor $\mathcal{F}$ by $\approx 2.5$ standard deviations. The fit gives

$$\tau \cos\beta = 2.6 \pm 0.9 \text{ MeV},$$
$$\tau \sin\beta = -0.4 \pm 0.9 \text{ MeV},$$

resulting in a value of $\tau = 2.6 \pm 1.0$ MeV. Figure 3 shows contours of equal $\chi^2$ in the $\tau\cos\beta$ and $\tau\sin\beta$ plane, where $\Delta\chi^2 = -2\Delta[\ln(\text{likelihood})]$.

In order to relate $\tau$ to the $\rho^0$-$\omega$ interference parameter, $\delta$, we must make assumptions concerning the amplitudes $A_\omega$ and $A_\rho$. Figures 4 a-d shows the diagrams for the $\rho^0$ and $\omega$ photoproduction amplitudes resulting from natural-parity exchanges $[P = (-1)^J]$ and unnatural-parity exchanges $[P = (-1)^{J+1}]$. Analysis of the $\rho^0$ decay in this experiment[15] has shown that the reaction $\gamma p \to \rho^0 p$ proceeds almost completely through natural parity exchange; i. e., the amplitude corresponding to Fig. 4c can be neglected. Because the natural- and unnatural-parity exchange amplitudes are orthogonal, only the natural-parity exchange amplitude for the $\omega$ interferes with the $\rho^0$.

Using VDM and assuming that the $\rho$ and $\omega$ elastic scattering amplitudes on protons are equal gives $|A_\omega/A_\rho| = \gamma_\rho/\gamma_\omega$, where $\gamma_V^{-1}$ is proportional to the photon-vector-meson coupling constant. Augustin <u>et al.</u>,[16] using the Orsay Storage Ring, obtained $\gamma_\omega^2/\gamma_\rho^2 = 7.1 \pm 0.7$. With this value and Eq. (6) our result for $\tau$ gives

$$\delta = 2.3 \pm 0.9 \text{ MeV}.$$

In comparing the results for diffractive photoproduction on carbon and on hydrogen, consideration must be given to nuclear effects. An indication of whether coherent nuclear effects are important in the interpretation of the Daresbury experiment can be obtained by comparing their determination[17] of the ratio $\gamma_\omega^2/\gamma_\rho^2$ with the Orsay storage ring results,[16] where nuclear effects are not present. As previously mentioned, the Daresbury group obtained $\gamma_\omega^2/\gamma_\rho^2 = 7.0^{+2.1}_{-1.4}$, whereas the Orsay results are $\gamma_\omega^2/\gamma_\rho^2 = 7.1 \pm 0.7$. Hence, neglecting differences in $\rho^0$ and $\omega$ coherent nuclear scattering appears to be justified within errors. If incoherent processes are also ignored,[8] the Daresbury result for the mass-mixing parameter, $\delta$, may be compared with the results from diffractive photoproduction on hydrogen and from colliding $e^+e^-$ beams.

Given in Table I are the values for $\delta$ and $\beta$. Because our value of $\delta$ is about 2.5 standard deviations from $\delta = 0$, we do not give an error for $\beta$. The results for $\delta$ and $\beta$ as determined by the colliding-beams experiment and by photoproduction from carbon are given in Table I for comparison. Our determination for $\delta$ corresponds[18] to $BR[\frac{\omega \to 2\pi}{\omega \to all}] = 1.3^{+1.2}_{-0.9}$ %. The parameter $\delta$ has been estimated by GFQ from the Coleman-Glashow model[19] to be about 2.5 MeV; this corresponds to $BR[\frac{\omega \to 2\pi}{\omega \to all}] = 1.45\%$.

## Conclusions

We have observed evidence for $\rho^0$-$\omega$ interference in diffractive photoproduction of vector mesons on hydrogen. Our results are consistent with the predictions by Goldhaber, Fox, and Quigg[9] and by Horn;[11] they are also in agreement with the results for $\rho^0$-$\omega$ interference in diffractive photoproduction of vector mesons on carbon.[8]

## Acknowledgment

We are particularly indebted to Dr. C. Quigg for encouragement and consultation during the progress of this paper.

## FOOTNOTES AND REFERENCES

*Work supported in part by the U. S. Atomic Energy Commission and the National Science Foundation.

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$$\left[\frac{m_\rho}{m_{\pi\pi}}\right]^{n(t)} e^{At},$$

was used to multiply the p-wave Breit-Wigner for the $\rho^0$, where $A = 6.6\ \mathrm{GeV}^{-2}$, and the t dependence of n (see Fig. 2c, d of Ref. 13) has been approximated by $n(t) = 5.6 + 8t$ for $|t| < 0.7\ \mathrm{GeV}^2$ at 2.8 GeV and $6 + 10t$ for $|t| < 0.6\ \mathrm{GeV}^2$ at 4.7 GeV (for $|t| >$ than these limits $n(t) = 0$).

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18. By diagonalizing the $\rho^0$-$\omega$ mass-mixing matrix (see Refs. 9, 19) the relationship between $\delta$ and the $BR = \Gamma_{\omega\to 2\pi}/\Gamma_{\omega\to \mathrm{all}}$ is found to be

$$\frac{\Gamma_{\omega\to\pi\pi}}{\Gamma_{\omega\to \mathrm{all}}} = \left|\frac{\delta}{m_\rho - m_\omega - i(\Gamma_\rho - \Gamma_\omega)/2}\right|^2 \frac{\Gamma_{\rho\to 2\pi}}{\Gamma_{\omega\to \mathrm{all}}}.$$

In the maximum-likelihood fit we determined $M_\rho = 766 \pm 3$ MeV, $\Gamma_\rho = 145 \pm 6$ MeV, and have used $M_\omega = 784$ MeV, $\Gamma_\omega = 12.7$ MeV.

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Table I. Values of the phase angle ($\beta$) and mixing parameter ($\delta$).

| Source | $\beta$ (deg) | $\delta$ (MeV) |
|---|---|---|
| Theory (Refs. 9, 11 | 0 | 2.5 |
| $e^+e^- \to \pi^+\pi^-$ (Ref. 4) | 55 ± 28 | 3.5 ± 1.3 |
| $\gamma C \to \pi^+\pi^- C$ (Ref. 8) | 2.0 ± 5.1 | 1.9 ± 0.25 |
| $\gamma p \to \pi^+\pi^- p$[a] (this expt.) | ≈ -9 | 2.3 ± 0.9 |

a. No error quoted on $\beta$; $\mathrm{Re}(\delta^{i\beta}) = 2.3 \pm 0.9$ MeV and $\mathrm{Imag}(\delta e^{i\beta}) = -0.4 \pm 0.9$ MeV.

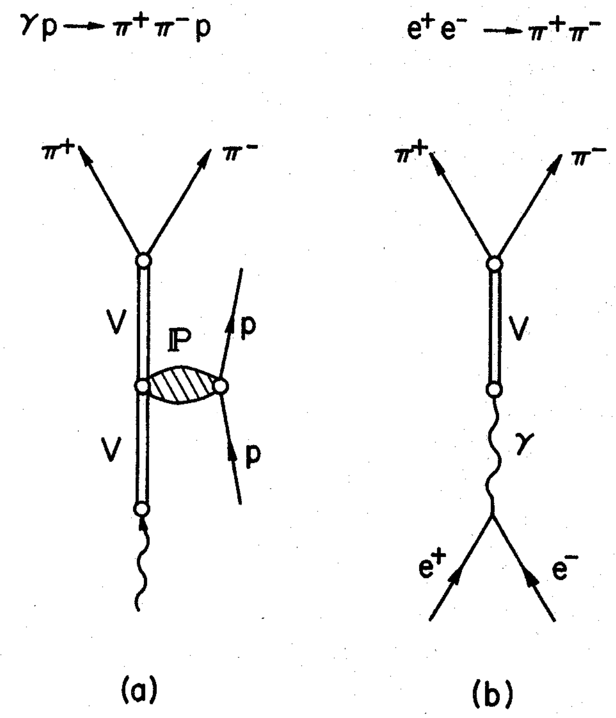


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Fig. 1. (a) Production mechanism assumed for $\gamma p \to \pi^+\pi^- p$. (b) Feynman diagram for $e^+e^- \to \pi^+\pi^-$.

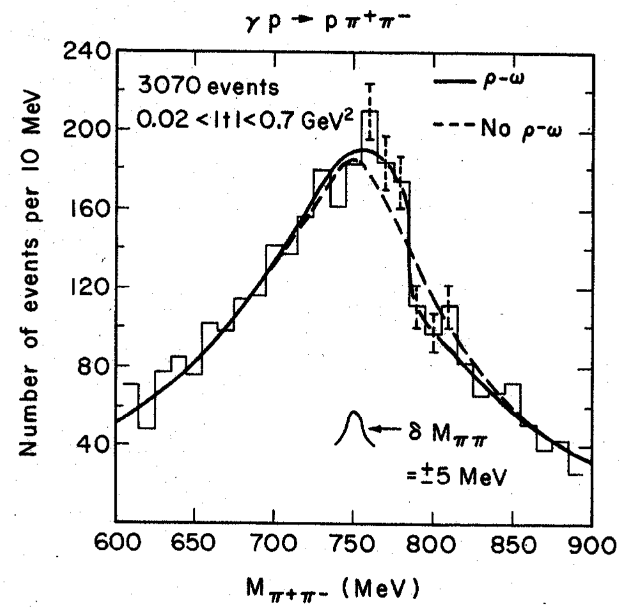


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Fig. 2. $\pi^+\pi^-$ Mass distribution for events of the reaction $\gamma p \to \pi^+\pi^- p$. The curves give the results of maximum-likelihood fits with (——) and without (-----) $\rho^0$-$\omega$ interference.

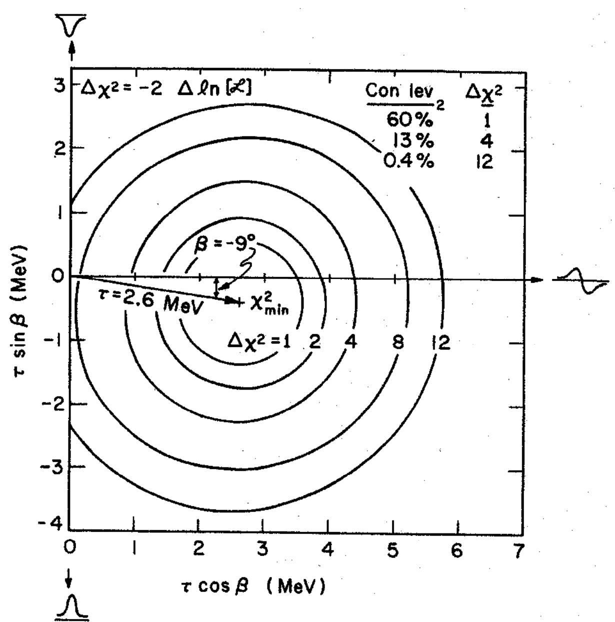


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Fig. 3. Contours of equal $\chi^2$ in the plane of $\tau \cos\beta$ and $\tau \sin\beta$ ($\tau = 3|\frac{A_\omega}{A_\rho}|\,\delta$, $\delta$ is the mass mixing parameter).

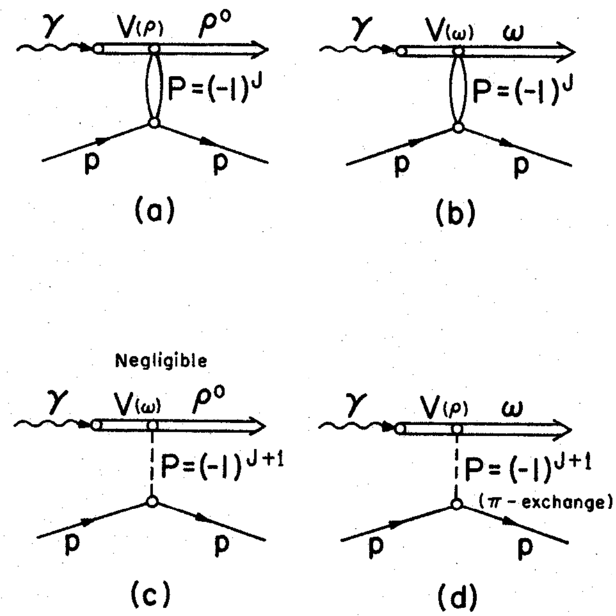


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Fig. 4. Production diagrams for $\rho^0$ and $\omega$ amplitudes resulting from (a, b) natural-parity exchanges, and (c, d) unnatural-parity exchanges.