Relative Phase Angles in Leptonic Decay of Photoproduced Vector Mesons*

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Interference effects in the leptonic decay modes of photoproduced ρ, ω, and φ mesons are considered. Two experimental methods for determining the relative phase angles of the final-state muons are discussed. The phase-angle difference between the ρ and ω is estimated from existing data and appears to be in disagreement with the value of 0°.

RECENTLY, many data have been obtained on the leptonic decays of vector mesons, both in photoproduction[1,2] and in colliding-beam experiments.[3,4] The photoproduction experiments in the region of the ρ show little evidence for the ω, either in the shape of the resonance in the relatively high-resolution data, or when a comparison is made between the photoproduction leptonic branching ratios and those obtained in colliding-beam experiments. This was made more puzzling by an investigation of ρ-ω interference in photoproduction,[5] where it was found that for a relative phase of 0° between ρ and ω photoproduction, as predicted by the pure diffraction model where only Pomeranchon exchange is important, the interference effect is large (about 65%). We now extend the investigation of interference in the leptonic decays, emphasizing the possibility of a nonzero ρ-ω phase difference, and we also extend our considerations to ρ-φ interference, including the possibly nonzero ρ,φ phase.

Bethe-Heitler phase difference. The phase difference between the Bethe-Heitler and ρ photoproduction amplitudes has been measured by observing asymmetrically photoproduced electron pairs.[6] The result is $\Delta_{\mathrm{BH},\rho} = (15\pm25)°$, where, as in Ref. 6, $i\exp(i\Delta_{\mathrm{BH},\rho})$ is the phase of the ρ amplitude relative to the Bethe-Heitler amplitude. There is also evidence in a more recent experiment on the electroproduction of muon pairs[7] that $\Delta_{\mathrm{BH},\rho}$ is approximately $(22\pm14)°$. While these data are not conclusive, it appears likely that $\Delta_{\mathrm{BH},\rho}$ may not be zero but may instead be of the order of 15°–20°. We know of no *a priori* reason why $\Delta_{\mathrm{BH},\omega}$ should be fixed either in sign or magnitude near this value of $\Delta_{\mathrm{BH},\rho}$, and hence large ρ-ω phase-angle differences are possible.

Interference and phase difference. The Feynman diagram for the photoproduction of lepton pairs via a vector meson is shown in Fig. 1. We consider only the amplitudes where $V=V'$. The γ-V coupling is given by $em_V^2/2\gamma_V$ for both on- and off-shell photons. We assume that γ_V is not a function of the mass off the mass shell. We use $\gamma_\rho^{-2}:\gamma_\omega^{-2}:\gamma_\varphi^{-2}=9:(1.28\pm0.25):(1.72\pm0.27)$ as obtained in the colliding-beam experiments.[3] These data are within 1 standard deviation of the simple unbroken SU_3 values of 9:1:2. We use the central experimental values in this work, and our results should be scaled for later changes in these values. The amplitude corresponding to Fig. 1 is

$$\mathcal{A}_V=\frac{em_V^2}{2\gamma_V}A_{VV}\frac{1}{m^2-m_V^2+im_V\Gamma_V}\frac{em_V^2}{2\gamma_V}\frac{1}{m^2}\langle ll|V|\gamma\rangle, \quad (1)$$

where m is the invariant mass of the lepton pair and A_{VV} is the vector meson-nucleus elastic scattering amplitude. Experimentally, if the vector-dominance model is used, this amplitude can be written as

$$A_{VV}=a_V^{\frac{1}{2}}e^{\frac{1}{2}b_V t},$$

where t is the invariant squared momentum transfer

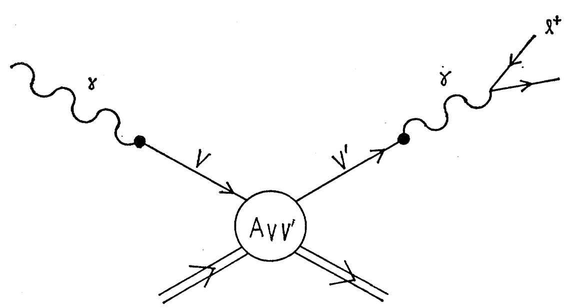

FIG. 1. Feynman diagram for the photoproduction of lepton pairs via a vector meson.

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[1] In the region of the ρ: J. K. de Pagter *et al.*, Phys. Rev. Letters **16**, 35 (1966) (muons); J. G. Asbury *et al.*, *ibid.* **19**, 869 (1967) (electrons).

[2] In the region of the φ: U. Becker *et al.*, Phys. Rev. Letters **21**, 1504 (1968) (electrons); C. Tank *et al.*, Bull. Am. Phys. Soc. **14**, 543 (1969); also K. M. Moy, thesis, Northeastern University, 1969 (unpublished) (muons).

[3] J. E. Augustin *et al.*, Phys. Letters **28B**, 508 (1969); **28B**, 513 (1969); **28B**, 517 (1969).

[4] V. L. Auslander *et al.*, Yadern. Fiz. **9**, 114 (1969) [English transl.: Soviet J. Nucl. Phys. **9**, 69 (1969)].

[5] R. G. Parsons and R. Weinstein, Phys. Rev. Letters **20**, 1314 (1968); M. Davier, Phys. Letters **27B**, 27 (1968).

[6] J. G. Asbury *et al.*, Phys. Letters **25B**, 565 (1967).

[7] D. Earles, thesis, Northeastern University, 1969 (unpublished).

to the nucleus. The experimental data[1,2] on *lepton* photoproduction in the region of the ρ do not give evidence for the Ross-Stodolsky[8] factor of $(m_V/m)^2$ and it has therefore not been included in (1).

We are interested in the interference between two amplitudes of the form (1). Following Parsons and Weinstein,[5] we consider the quantity

$$R_{uv}(m^2)=m_u^2\Gamma_u^2\left|\frac{1}{m^2-m_u^2+im_u\Gamma_u}+\frac{m_v^4}{m_u^4}\frac{\gamma_v^{-2}}{\gamma_u^{-2}}\left(\frac{a_v}{a_u}\right)^{\frac{1}{2}}\times e^{\frac{1}{2}(b_v-b_u)t}\frac{e^{i\Delta_{uv}}}{m^2-m_v^2+im_v\Gamma_v}\right|^2\frac{m_u^2}{m^2}. \quad (2)$$

R_{uv} is normalized to 1 at $m=m_u$ when the v contribution is absent. The over-all factor of m_u^2/m^2 in (2) takes into account the m dependence of the photon propagator and $\langle ll|V|\gamma\rangle$ when squared and integrated over phase space.

ρ-ω phase difference. We now consider ρ-ω interference in lepton pair production, setting $\mu=\rho$ and $v=\omega$ in (2). It is assumed that the t dependence of the amplitudes are similar, i.e., $b_\rho\approx b_\omega$, and that $a_\rho\approx a_\omega$.[9] The energy dependence of the ρ width is given by[10]

$$\Gamma_\rho=\Gamma_{\rho 0}\frac{m_\rho}{m}\left(\frac{m^2-4m_\pi^2}{m_\rho^2-4m_u^2}\right)^{3/2}. \quad (3)$$

The ρ-ω *interference term* obtained from (2) is plotted in Fig. 2(a) for various values of $\Delta_{\rho\omega}$. We see that information on $\Delta_{\rho\omega}$ may be obtained from a photoproduction experiment with good resolution, performed in the region of the ρ and ω mass peaks.[11] In such an experiment interference peaks such as in Fig. 2(a) are sought. These not only yield a measurement of $\Delta_{\rho\omega}$, but also independently measure $(a_\omega/a_\rho)\exp[(b_\omega-b_\rho)t]$, which is of additional interest. It is possible, however, to obtain information on $\Delta_{\rho\omega}$ from poor-resolution experiments as is done below.

We define Area(u,v) as the area under the u, v interference curve obtained from (2), Area$(|u|^2)$ and Area$(|v|^2)$ as the areas under the curves obtained from the square of the first and second terms in (2), respectively, and Area(R_{uv}) as the area under the curve obtained from (2). We also define

$$r_{uv}\equiv\frac{\text{Area}(u,v)+\text{Area}(|v|^2)+\text{Area}(|u|^2)}{\text{Area}(|u|^2)}\equiv\frac{\text{Area}(R_{uv})}{\text{Area}(|u|^2)}. \quad (4)$$

This quantity is a measure of the expected ratio of the branching ratio for "u" $\rightarrow l^+l^-$ obtained in photoproduction, where the pure u is *not* being observed, to that obtained in colliding-beam experiments, where the pure u *is* being observed. A plot of $r_{\rho\omega}$ as a function of $\Delta_{\rho\omega}$ is shown in Fig. 2(b), where the areas are measured for $620\leq m\leq 910$ MeV. The diffraction model predicts $\Delta_{\rho\omega}=0°$. For this value, as previously pointed out,[5] the "ρ" branching ratio measured in lepton photoproduction is expected to be about 75% larger than the branching ratio measured in colliding-beam experiments because the photoproduction experiment includes both ρ,ω interference terms and $\omega\rightarrow l^++l^-$.

The experimental values of the ρ leptonic branching ratio in photoproduction are $(6.5\pm1.4)\times10^{-5}$ (electrons) and $(7.9\pm2.0)\times10^{-5}$ (muons),[1,12] and in colliding beams $(6.63\pm0.85)\times10^{-5}$ and $(5.0\pm1.0)\times10^{-5}$.[3,4] Taking an average for the photoproduction values as $(7.0\pm1.2)\times10^{-5}$ and for the colliding-beam values as $(5.9\pm0.7)\times10^{-5}$, the ratio of the photoproduction and colliding-beam values is 1.17 ± 0.23. The most favored values of $\Delta_{\rho\omega}$ from Fig. 2(b) are therefore between approximately 100° and 150° and between approximately 250° and 305°. We thus see that information on $\Delta_{\rho\omega}$ can be obtained from experiments of poor mass resolution. *These results are in relatively strong disagreement with the value of $\Delta_{\rho\omega}=0°$, predicted by the simple diffraction model.*

Based upon these considerations, we would therefore predict that a measurement of the ρ-ω interference in leptonic decay, with an apparatus of very good mass resolution, would yield a ρ-ω phase angle of $(125\pm25)°$ or $(278\pm28)°$. An experiment to be done at DESY[13] gives promise of measuring the interference terms directly. Such a high-resolution experiment would have the additional advantage that it would remove the ambiguity which results from a single value of r_{uv} corresponding to two values of Δ_{uv}.

φ-ρ interference. Because the φ photoproduction amplitude is small and the ρ width is large, there is a nonnegligible interference between the amplitudes for pair production via these two mesons. We again use expression (2), with $u=\varphi$ and $v=\rho$. By comparing the t dependence of the photoproduction data,[14,15] we find

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

[9] E. Lohrmann, in *Proceedings of the 1967 International Symposium on Electron and Photon Interactions at High Energies* (Clearinghouse for Federal and Technical Information, Springfield, Va., 1968).

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

[11] Preliminary results of two such experiments have been reported by G. R. Allcock, in Proceedings of the 1969 International Conference on Electron and Photon Interactions at High Energies, Daresbury (unpublished).

[12] The value of B_ρ for μ pairs is higher than that reported in Ref. 1 if one assumes that quantum electrodynamics is correct and the small observed deviations from quantum electrodynamics are due to systematic errors. P. Rothwell *et al.*, Phys. Rev. Letters **23**, 1521 (1969).

[13] S. C. C. Ting (private communication).

[14] S. C. C. Ting, Rapporteur's Summary, in *Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna, 1968*, edited by J. Prentki and J. Steinberger (CERN, Geneva, 1968): $(d\sigma/dt)_{\gamma+C\rightarrow C+\varphi}=(343\pm39)e^{(58\pm12)t}$ μb/(GeV$^2/c^2$) atom.

[15] F. M. Pipkin, Rapporteur's Summary, in *Proceedings of the 1967 International Symposium on Electron and Photon Interactions at High Energies* (Clearinghouse for Federal Scientific and Technical Information, Springfield, Va., 1968): $(d\sigma/dt)_{\gamma+C\rightarrow C+\rho}=(9600\pm770)e^{(47\pm3)t}$ μb/(GeV$^2/c^2$) atom.

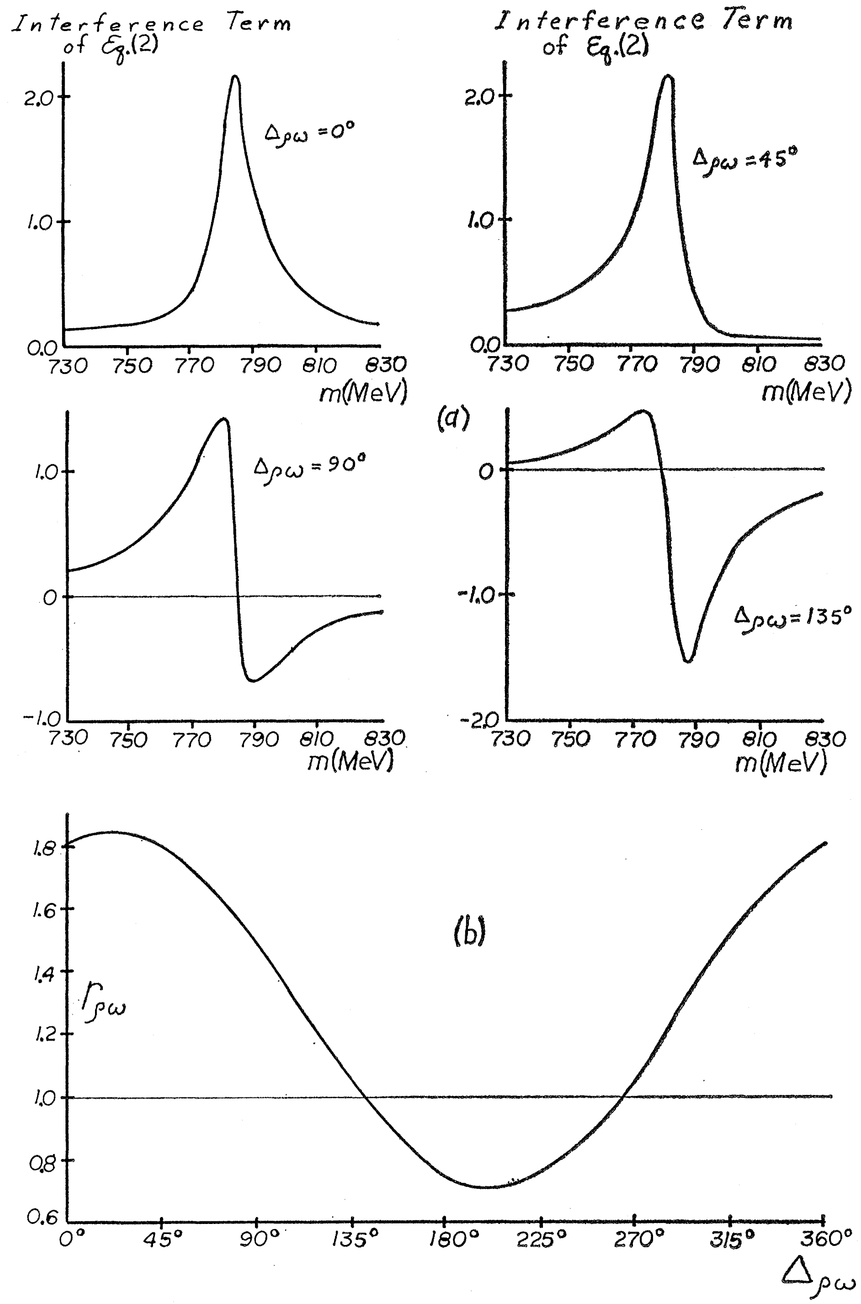

FIG. 2. (a) ρ-ω interference term in Eq. (2). (b) Ratio of the area under Eq. (2) for ρ and ω (i.e., the area under the ρ-ω interference term plus the square of the ω term plus the square of the ρ term) to the area under the square of the ρ term in Eq. (2), for $620\leq m\leq 910$ MeV, plotted versus $\Delta_{\rho\omega}$. Here $m_\rho=765$ MeV, $\Gamma_{\rho^0}=125$ MeV, $m_\omega=783$ MeV, and $\Gamma_\omega=12.2$ MeV.

$b_\varphi\approx b_\rho$ and $17a_\varphi\approx a_\rho$.[16] The uncertainty in the values for b_φ and b_ρ given in Refs. 14 and 15 would, if they were considered to reflect an actual difference in b_φ and b_ρ, make the scale of the ordinates in Fig. 3 uncertain to about 20%. The energy dependence of the ρ width as given in Eq. (3) is retained although our results are not sensitive to this choice, since for $m\approx m_\varphi$ the real part of the ρ Breit-Wigner denominator dominates the imaginary part. The resulting interference term in Eq. (2) is plotted in Fig. 3(a) for various values of $\Delta_{\varphi\rho}$. The quantity $r_{\varphi\rho}$ as defined in Eq. (4) is shown as a function of $\Delta_{\varphi\rho}$ in Fig. 3(b). The areas are taken for the mass values $1000\leq m\leq 1040$ MeV. Again, the diffraction model predicts $\Delta_{\varphi\rho}=0°$, implying that the branching ratios for $\varphi\to l^+l^-$ measured in photoproduction and in colliding-beam experiments should differ by about 5%. The extreme fluctuations in $r_{\varphi\rho}$ as a function of $\Delta_{\varphi\rho}$ are only about 10%. The accuracy of present photoproduction and colliding-beam work precludes using the existing data to comment on $\Delta_{\varphi\rho}$. The published values for the φ leptonic branching

[16] The photoproduction cross section is given by

$$d\sigma/dt=(emv^2/2\gamma v)^2 ave^{bvt}.$$

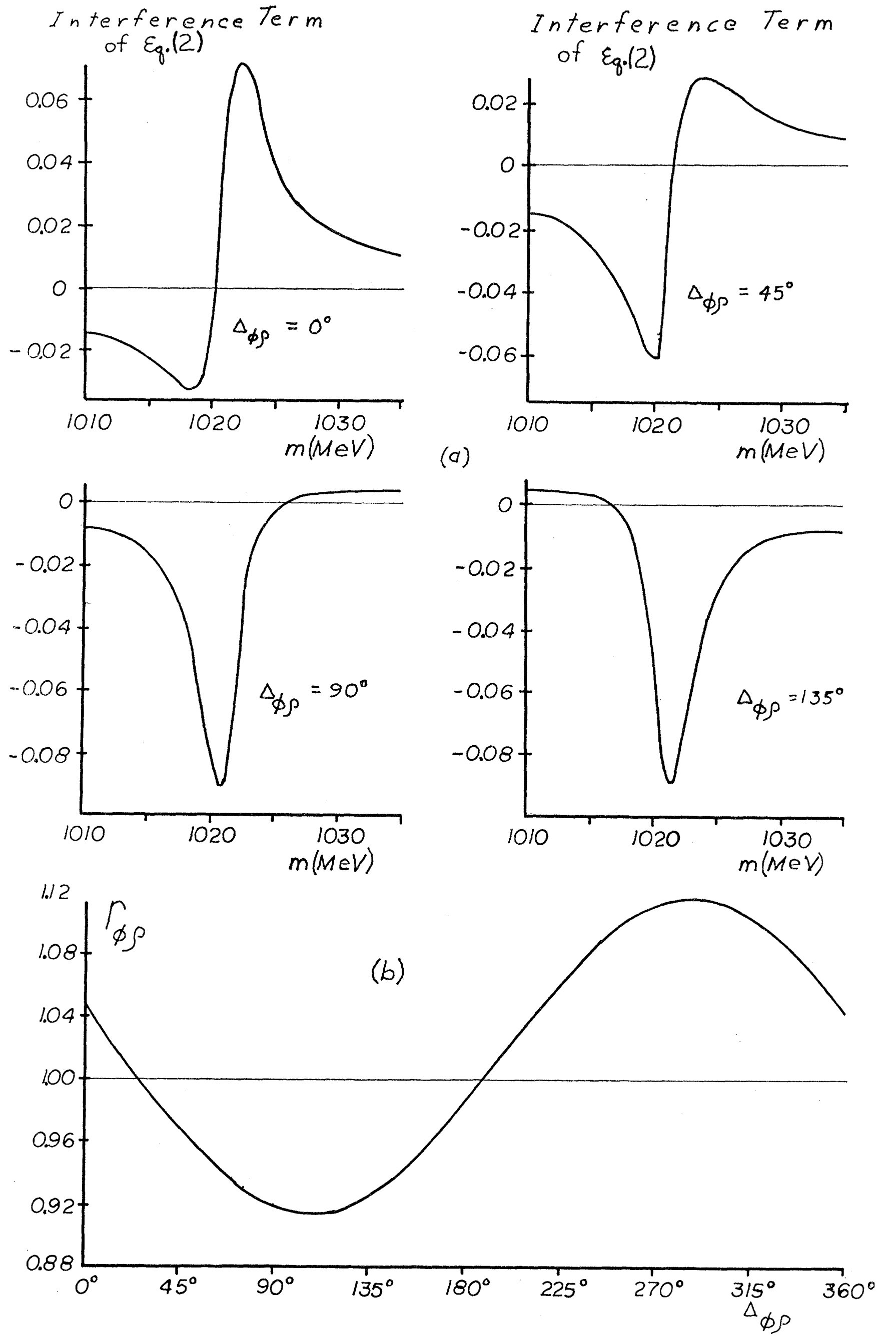

FIG. 3. (a) φ-ρ interference term in Eq. (2). (b) Ratio of the area under Eq. (2) for φ and ρ (i.e., the area under the φ-ρ interference term plus the square of the ρ term plus the square of the φ term) to the area under the square of the φ term in Eq. (2), for $1000 \leq m \leq 1040$ MeV, plotted versus $\Delta_{\varphi\rho}$. Here $m_\varphi = 1019.5$ MeV, $\Gamma_\varphi = 3.4$ MeV, $m_\rho = 765$ MeV, and $\Gamma_{\rho 0} = 125$ MeV.

ratio are $(2.9 \pm 0.8) \times 10^{-4}$ in photoproduction of electron pairs[2] and $(3.96 \pm 0.62) \times 10^{-4}$ in the colliding-beam experiment.[3] If we allow a small increase in the quoted errors, the ratio of these two values is such that all values of $\Delta_{\varphi\rho}$ are possible. The most recent determination of $B_\varphi = (2.3 \pm 1.2) \times 10^{-4}$ for muons[2] does not alter this situation. Conversely, the small values of $r_{\varphi\rho}$ result in only a small uncertainty in the leptonic branching ratio for φ's as measured via photoproduction experiments.[2] A significant decrease in the errors in measurements of the φ leptonic branching ratio would be needed for a good determination of $\Delta_{\varphi\rho}$.

In summary, the above results indicate that the relative phases between the ρ and ω amplitudes in lepton pair photoproduction from complex nuclei are quite probably not zero, in disagreement with the simple diffraction model. Higher accuracy in the measurement of the leptonic branching ratios for the φ, in both photoproduction and colliding beams, is needed to determine the values of the φ,ρ relative phase.