OBSERVATION OF ρ-ω INTERFERENCE IN THE PHOTOPRODUCTION OF ELECTRON-POSITRON PAIRS FROM CARBON AND A MEASUREMENT OF THE ρ-ω PHASE

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The electron-positron mass spectrum has been studied in the process $\gamma + \mathrm{C} \to e^+ + e^- + \mathrm{C}$ in the invariant-mass region between 675 and 850 MeV/c^2. An enhancement in the region of the ω mass due to ρ-ω interference is clearly observed, and from a fit to the data we find $\gamma_\rho^2/4\pi = 0.50^{+0.12}_{-0.10}$ and $\gamma_\omega^2/4\pi = 3.5 \pm 1.2$. The value of the relative phase of the ρ-ω photoproduction amplitudes is found to be 100^{+38}_{-30} deg. The errors quoted are purely statistical.

Measurements of the branching ratios for the leptonic decay of ρ mesons, by photoproduction of lepton pairs at the Cambridge Electron Accelerator,[1] Cornell,[2] and DESY,[3] and by the related process of ρ-meson production by electron-positron colliding beams,[4,5] are in good agreement. However, it has recently been pointed out by several authors[6,7] that the photoproduction of lepton pairs in the mass region of the ρ and ω mesons, where it was assumed that only the ρ would contribute, should contain a strong enhancement at the ω mass due to the interference between the coherent ρ and ω amplitudes. If this interference effect is taken into account, then the value for the branching ratio of the ρ into lepton pairs from photoproduction has to be modified.

The photoproduction of vector mesons in the high-energy region can be described by the vector-dominance model together with the diffraction mechanism. The diagram for the photoproduction of lepton pairs on a complex nucleus by this process is shown in Fig. 1(a). The amplitude is given by

$$M \propto \frac{e m_V^2}{2\gamma_V} A_{VN} \frac{1}{m^2 - m_V^2 + i m_V \Gamma_V} \frac{e m_V^2}{2\gamma_V} \frac{1}{m^2} \langle e^+ e^- | H | \gamma \rangle,$$

where A_{VN} is the amplitude for $V^0 + A \to V^0 + A$, m is the invariant mass of the electron pair, $e m_V^2/2\gamma_V$ is the photon-vector-meson coupling constant, and the two final terms represent the transition through a virtual photon to the electron pair. The Bethe-Heitler (BH) process also gives a contribution to the electron pair spectrum and the corresponding diagrams are shown in Fig. 1(b). The shape of the mass spectrum due to the ρ and ω mesons can be written as

$$R(m^2) \sim \frac{1}{m^2} \left| \left(\frac{m_\rho^2}{\gamma_\rho}\right)^2 \frac{|A_{\rho N}|}{m^2 - m_\rho^2 + i m_\rho \Gamma_\rho} + \left(\frac{m_\omega^2}{\gamma_\omega}\right)^2 \frac{|A_{\omega N}| e^{i\varphi}}{m^2 - m_\omega^2 + i m_\omega \Gamma_\omega} \right|^2,$$

where φ is the phase difference between the ρ and ω scattering amplitudes. This experiment, in which electron pairs were detected with high mass resolution, was designed to measure the phase angle φ.[8]

The experimental apparatus has been described in detail elsewhere,[9] so only a brief outline of the essential details will be given here. The electron pairs were detected by identical magnetic spectrometers using a combination of Cherenkov and shower counters to identify the electrons. The efficiency for detecting pion pairs was about 10^{-8}. However, modifications were made to the spectrometers to increase the momentum acceptance to 14% and the solid angle to 0.67 msr, to give an overall gain in the counting rate of a factor of 3. These modifications were checked by measuring yields of electron pairs at 500 MeV/c^2, where essentially only the BH process contributes. The mass resolution of the spectrometers, including the effects of bremsstrahlung and multiple scattering, was ±6 MeV/c^2. The total mass acceptance was of the order of 140 MeV/c^2.

The ρ and ω mesons were produced in the forward direction by allowing a photon beam from the accelerator NINA, of maximum energy 4.1 GeV, to strike a carbon target. Carbon was chosen for several reasons: (a) It gives a good ratio of vector-meson to BH production; (b) for a target of zero isospin, one-pion-exchange effects are small; and (c) the vector-meson cross sections are strongly coherent in the forward direction.

Electron pairs were detected with the spectrometers set for a momentum of 1.802 GeV/c and at seven mean angles between 11.2° and 13.3° The spectrometers were positioned symmetrically with respect to the photon beam so that the in-

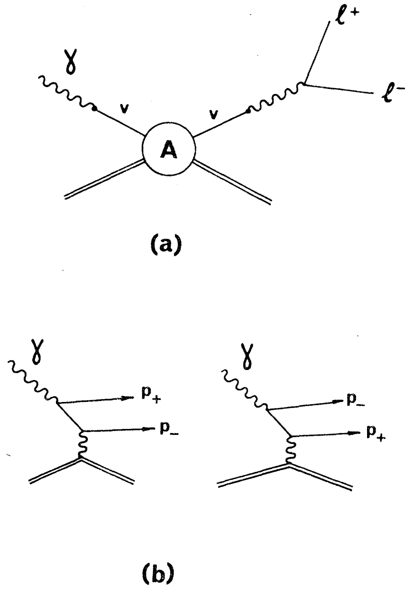

FIG. 1. (a) Diagram for production of vector mesons with decay into electron-positron pairs. (b) Diagram for Bethe-Heitler production of electron-positron pairs.

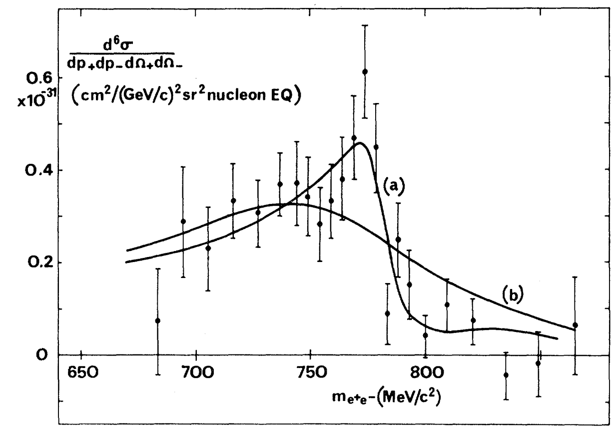

FIG. 2. Differential cross section $d^6\sigma/dp_+dp_-d\Omega_+d\Omega_-$ in $cm^2/[(GeV/c)^2 sr^2$ nucleon equivalent quantum]. The curves shown in the figure are best fits to the data assuming (a) ρ-ω interference and (b) no ω contribution. The values for the parameters used in these fits are given in the text.

terference between the BH and the vector-meson diagrams was zero. With these settings a mass range between 675 and 850 MeV/c^2 was covered.

Data on the reaction

$$\gamma + C \to \pi^+ + \pi^- + C$$

were also taken to normalize the electron-pair data and thus provide a value for the branching ratio $\rho \to e^+e^-$.

The invariant mass of the pair events which satisfied the Cherenkov- and shower-counter criteria[8] was calculated from the relation

$$m^2 \simeq 2p_+p_-[1-\cos(\theta_+ + \theta_-)],$$

where $p_\pm$ are the mean momenta defined by the momentum hodoscope bins through which the two particles pass, and $\theta_\pm$ are the corresponding angles relative to the photon beam, defined by the θ hodoscopes. Events with two nonadjacent counters or more than two counters in one hodoscope were rejected. These constituted about 20% of the total number of events as defined above. The number of unambiguous events defined as electron pairs was 1060, of which 45% were due to the BH process. The number of events in each run was corrected for dead-time effects, rejected events, and accidentals, which were never greater than 5%. Target-out rates were typically less than 1%. The events were grouped into mass bins of width 0.0075 (GeV/c^2)^2.

The acceptance of the pair spectrometer for a given mass bin was defined as $\sum \Delta p_+ \Delta p_- \Delta\Omega_+ \Delta\Omega_-$, where the combinations of momentum and θ counters involved defined a value of m^2 within the bin. The method for obtaining the individual acceptances is described in the accompanying paper.[10] From the acceptances, the differential cross section $d^6\sigma/dp_+dp_-d\Omega_+d\Omega_-$ was obtained.

A plot of the data after the calculated BH contribution had been subtracted is shown in Fig. 2. The differential cross section shown contains the data from all seven settings. This mass spectrum shows the broad ρ resonance as well as a clear peak corresponding to the ω meson.

Radiative corrections for vector-meson decay into electron pairs[11] and for the BH process were both less than 2%. The maximum energy of the photon beam was kept constant throughout the experiment so that the bremsstrahlung energy losses remained constant.

It was not possible to unfold the bremsstrahlung corrections from the cross section to obtain a theoretical mass spectrum, so the data were fitted by generating a matrix by a Monte Carlo method which converted a theoretical mass spectrum into an experimentally observed cross section. This matrix allowed for experimental effects such as bremsstrahlung energy loss, multiple scattering, ionization loss, and the mass resolution of the apparatus, as well as effects related to the production and decay of the vector mesons. The production cross section was assumed to have the form[12]

$$d\sigma/d\Omega \propto k^2 e^{47t},$$

where k is the photon energy and t is the square of the four-momentum transfer to the nucleus. The decay angular distribution of the electrons in the ρ c.m. system was taken to be

$$W_e(\theta^*) \propto (1+\cos^2\theta^*),$$

where θ^* is the angle between one of the particles and the ρ direction. The same parameters were used to describe the production and decay of the ω. This matrix was calculated for each setting of the spectrometer. To fit the data with a given set of variable parameters, the theoretical spectrum was multiplied by the matrices.

The theoretical spectrum was written in the form

$$R(m^2) = aI_{\rm BH}(m^2) + \frac{c}{m^2}\left|\frac{1}{m^2-m_\rho^2+im_\rho\Gamma_\rho} + \left(\frac{m_\omega}{m_\rho}\right)^4 \frac{\eta}{9}\frac{e^{i\varphi}}{m^2-m_\omega^2+im_\omega\Gamma_\omega}\right|^2,$$

where

$$\Gamma_\rho = \Gamma_\rho^{\,0}\frac{m_\rho}{m}\left(\frac{m^2-4m_\pi^2}{m_\rho^2-4m_\pi^2}\right)^{3/2}, \quad \eta = 9\frac{\gamma_\rho^2}{\gamma_\omega^2}\frac{|A_{\omega N}|}{|A_{\rho N}|},$$

and c, η, φ, and m_ω were treated as free parameters. $I_{\rm BH}(m^2)$ is the Bethe-Heitler contribution to the spectrum. Initially the values of m_ρ, $\Gamma_\rho^{\,0}$, and Γ_ω were fixed, at 770, 140, and 12.6 MeV/c^2, respectively, because if they were allowed to vary they did not assume realistic values. The ω mass was left as a free parameter because a fixed value would impose a constraint on the value of the phase φ. The overall normalization of the BH contribution, a, was put equal to 1.0.

Our best fit to the data gives the following values:

$$\varphi = 100\,^{+38}_{-30}\,\text{deg}, \quad \eta = 1.28\,^{+0.35}_{-0.29}, \quad m_\omega = 782.5 \pm 3.0 \text{ MeV}/c^2 \quad (\chi^2 = 34.1, \text{ degrees of freedom} = 35).$$

This result for the phase agrees well with the value[1,13] of $100 \pm 35°$ derived by comparing existing photoproduction and storage-ring data for the ρ-branching ratio.

The pion data were analyzed in a similar way to the electron data, except that the decay angular distribution was given by $W_\pi(\theta^*) \propto \sin^2\theta^*$ and the m^{-2} term multiplying the (ρ, ω) term in $R(m^2)$ was replaced by m_ρ^{-2}. The differential cross section for ρ photoproduction as derived from the pion-pair spectrum is consistent with other experiments.[14]

These data give a value for the branching ratio $(\Gamma_{\rho\to e^+e^-}/\Gamma_{\rho\to\pi^+\pi^-})$, corrected for ω contributions, of $(4.9\,^{+1.2}_{-1.5})\times 10^{-5}$. This corresponds to a value[15] for $\gamma_\rho^2/4\pi$ of $0.50\,^{+0.12}_{-0.10}$, which is in agreement with the Orsay storage-ring value of 0.52 ± 0.02.[4] The error on $\gamma_\rho^2/4\pi$ is only statistical as the fit to the pion data is model dependent. This dependence can give variations in $\gamma_\rho^2/4\pi$ of up to 10%.

From the value of η, making the assumption that $|A_{\rho N}| = |A_{\omega N}|$,[16] we obtain $\gamma_\omega^2/\gamma_\rho^2 = 7.0\,^{+2.1}_{-1.5}$. Taking the above value for $\gamma_\rho^2/4\pi$, this gives

$$\gamma_\omega^2/4\pi = 3.5 \pm 1.2,$$

which is consistent with the value of 3.7 ± 0.7 from the Orsay storage ring,[17] but not with the CERN value of $7.1\,^{+4.5}_{-2.0}$.[18]

When the data were fitted without any ω contribution, the χ^2 rose to 67.1 for 37 degrees of freedom and the best-fit value for $\gamma_\rho^2/4\pi$ fell to 0.35 ± 0.01. This corresponds to a value of the ρ branching ratio of $(6.9 \pm 0.2)\times 10^{-5}$ which agrees with the results of all previous experiments, where no ω contribution was included. The above two fits to the data are shown in Fig. 2.

To see what effect the variation of m_ρ, $\Gamma_\rho^{\,0}$, and Γ_ω would have on the fit, they were given the following values around the chosen settings:

$$m_\rho = 765,\ 775 \text{ MeV}/c^2, \quad \Gamma_\rho = 130,\ 150 \text{ MeV}/c^2,$$
$$\Gamma_\omega = 11.5,\ 13.7 \text{ MeV}/c^2.$$

The variation of Γ_ω between the two limits changed the value of η by ±10%, as would be expected, while the phase remained almost constant. The value of $\gamma_\rho^2/4\pi$ also changed by ±10% over the same interval. All the above parameters were insensitive to the change in m_ρ over the range considered. The only significant effect of varying Γ_ρ was to change the value of $\gamma_\rho^2/4\pi$ by 10%. For all these variations the χ^2 did not change by

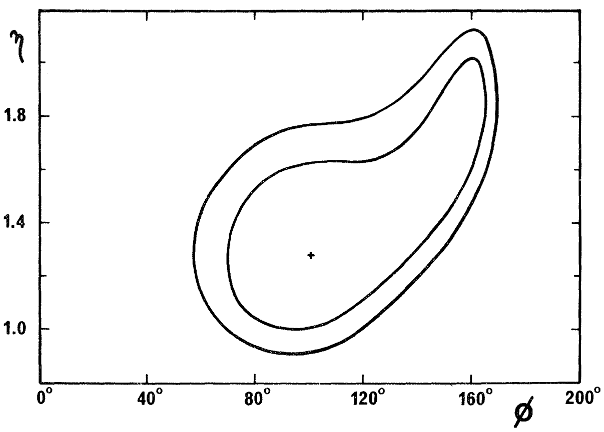

FIG. 3. χ^2 contours for the parameters η and φ. The central point indicates the best-fit values, corresponding to χ_{min}^2, and the two curves represent the contours for χ_{min}^2+1 and χ_{min}^2+2, respectively.

more than 1.0.

A fit was tried with the Ross-Stodolsky[19] factor, which multiplies the ρ Breit-Wigner factor by $(m_\rho/m)^4$. This had the effect of decreasing the phase angle to $76\pm31°$. The value of the mass decreased slightly to 780.0 ± 3.0 MeV/c^2 and $\gamma_\rho^2/4\pi$ increased to 0.72 ± 0.14. However, the theoretical basis for this modification is questionable.

A further fit to the data was tried under the same conditions as for the best fit except that the overall BH normalization a was allowed to vary. The best-fit value for this parameter was $a=0.91\,^{+0.20}_{-0.16}$ in agreement with quantum electrodynamics.

The errors on the values of η and φ are taken from the fitting program but, since these two parameters are strongly correlated, we show in Fig. 3 the χ^2 contours for values of χ^2 equal to χ_{min}^2+1 and χ_{min}^2+2. The first curve then corresponds to a one-standard-deviation error.

It is perhaps surprising that the value of the phase angle from the best fit should be so high. A preliminary result from DESY[20] indicates a value for the phase of $22\pm25°$ consistent with a diffraction model and a value of $\gamma_\omega^2/\gamma_\rho^2$ equal to 12 ± 4.[20] However, from the total cross-section measurements on hydrogen it can be deduced[21] that the real part of the ρ photoproduction amplitude is about 30% at 4 GeV. It has been shown that[22] ρ photoproduction data on complex nuclei also require a large real part, to give a value of $\gamma_\rho^2/4\pi$ consistent with the storage-ring value and a ρ-nucleon cross section in agreement with the quark-model prediction, so a nonzero phase is certainly to be expected, albeit quite small.

If we constrain our fit to have a zero phase, we find the following values for the parameters:

$$m_\omega=772.3\pm2.1\ \text{MeV}/c^2,\quad \gamma_\rho^2/4\pi=0.78\pm0.17,$$
$$\gamma_\omega^2/4\pi=5.7\pm2.1,$$

with a χ^2 of 44.5 for 36 degrees of freedom. This fit is not acceptable because of the low value of the ω mass. The error in the absolute mass calibration was ±1.5 MeV/c^2.[10]

From the point of view of the data, it is the extremely sharp falloff of the mass spectrum above the ω mass that is responsible for the large phase angle. The data reduction has been thoroughly checked and it is unlikely that any significant error has been made. The individual angle settings in this mass region also show the same behavior and agree with each other to within the experimental errors.

The acknowledgments given in the following Letter relate to this one also.

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

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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 under-