lyzed τ^+ and τ^- events and correcting for the apparatus efficiency as determined from ~230 000 Monte Carlo events. The Y projection of $|M|^2$ is shown in Fig. 3(c), in which phase space has been weighted to account for final-state Coulomb interactions,[8] to allow comparison with other 3π decay modes. A linear fit of the form $1+aY$ yields $a=0.283\pm0.005$ (statistical error only). Without correcting for Coulomb interactions we obtained $a=0.247\pm0.005$. Complete results will be presented when possible biases have been thoroughly investigated to the level of a few million Monte Carlo-generated events.

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Observation of Coherent Interference Pattern Between ρ and ω Decays*

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We report a high-statistics experiment measuring the structure of e^+e^- mass spectrum from photoproduction of ρ and ω mesons. At 5.1 GeV, based on 4000 events, analysis of the spectra yields a ratio of vector-meson-photon coupling constants $\gamma_\omega^2/\gamma_\rho^2 = 9.4^{+2.6}_{-1.6}$ and a ρ-ω phase difference $\varphi_{\omega\rho}=41°\pm20°$.

We report the observation of interference in the e^+e^- final state from the leptonic decay of ρ and ω mesons, diffractively photoproduced off beryllium:

$$\gamma+\text{Be}\to\text{Be}+V^0(\rho,\omega)$$
$$\qquad\qquad\quad \lfloor\!\!\longrightarrow e^+e^-. \tag{1}$$

Near the mass region $m_{ee}\cong m_\rho\cong m_\omega$, the total amplitude of the e^+e^- pairs is

$$A_T=A_{\text{BH}}+A_\rho+A_\omega+A_x. \tag{2}$$

where A_{BH} is the Bethe-Heitler amplitude,[1] A_ρ (A_ω) is the diffractive photoproduction amplitude of ρ

(ω) meson decaying into e^+e^- pair, and A_x is the incoherent ρ, ω production amplitude.[2] This experiment is designed to measure the e^+e^- contribution from $A = A_\rho + A_\omega$ and thereby investigate the superposition phenomenon between these two amplitudes.

The contribution to the e^+e^- yield from coherent ρ and ω production[3] is

$$A_V = \frac{e}{2\gamma_v} A_{VA\to VA} \frac{1}{m_V^2 - m^2 - i m_V \Gamma_V} \frac{e m_V^2}{2\gamma_V} \frac{1}{-m^2} A_{\gamma\to e^+e^-}$$

$$|A|^2 = |A_\rho + A_\omega|^2 = \frac{\alpha^2\pi^2}{\gamma_\rho^4} |A_{\rho A\to\rho A}|^2 \frac{m_\rho^4}{m^4} \left| \frac{1}{m_\rho^2 - m^2 - i m_\rho \Gamma_\rho} + \frac{\gamma_\rho^2 m_\omega^2}{\gamma_\omega^2 m_\rho^2} \frac{|R| e^{i\varphi_{\omega\rho}}}{m_\omega^2 - m^2 - i m_\omega \Gamma_\omega} \right|, \qquad (3)$$

where $e m_V^2/2\gamma_V$ are the vector-meson-photon coupling constants, Γ_V the width of the resonance, and we have set $A_{\omega A\to\omega A}/A_{\rho A\to\rho A} = |R| e^{i\varphi_{\omega\rho}}$ with $\varphi_{\omega\rho}$ the relative production phase of the ω and the ρ mesons.

It has long been a puzzle that all the experiments on photoproduction of $\rho \to l^+l^-$ failed to observe the expected enhancement.[4] Part of the reason is statistics. For example, the DESY experiment on $\rho \to ee$ has twelve events near the ω mass. It was also possible, however, that since none of the experiments had observed the expected peak, our understanding of vector dominance needed a major modification.

The purpose of the present experiment is to search, with high statistics (4000 events) and good mass resolution (±4 MeV), for the expected peak and compare the result with predictions of the vector dominance model.

It follows from Eq. (3) that to observe the narrow interference peak the following features must be taken into consideration:

(1) To obtain maximum effective counting rate, the quantum-electrodynamics (QED) contribution $A_{\rm BH}$ must be kept small. Since coherent-diffraction production of vector mesons on nuclei behaves as

$$N_\rho \sim d\sigma/d\Omega \sim A^{1.7} p^2 e^{at} \qquad (4a)$$

with $t = (k - p_+ - p_-)^2$, $a = a_0 A^{2/3}$ with $a_0 \cong 8\ \mathrm{GeV}^{-2}$, whereas the BH contribution is

$$N_{\rm BH} \sim |A_{\rm BH}|^2 \sim Z^2 G_e^2(t) p^{-2} \theta^{-7}, \qquad (4b)$$

it follows that to reduce the relative BH contamination one should maximize the ratio

$$\frac{N_\rho}{(N_\rho + N_{\rm BH})^{-1/2}} = \frac{A^{1.7} p^2 e^{at}}{(p^2 A^{1.7} e^{at} + c Z^2 G_E^2(t) p^{-2} \theta^{-7})^{1/2}}, \qquad (5)$$

where c is a constant determined from earlier experiments.[4]

(2) In order to observe the interference term, the mass resolution of the detecting system must be comparable with the narrow ω width,[5] $\Gamma_\omega = 12.7$ MeV. The multiple scattering and bremsstrahlung loss of the e^+e^- pairs in the target are the main effects which deteriorate the mass resolution. To obtain good mass resolution one selects the momentum p_0 and the length of target X such that the multiple scattering and the bremsstrahlung loss are as small as possible.

(3) To facilitate direct comparison with theory, the contributions to ρ and ω production due to incoherent diffractive processes, σ^i, and the contributions to ω production from one-pion exchange, σ_ω^0, must be kept small (we denote the combined contribution by A_x). Explicitly one keeps the terms

$$\sigma_\omega^0 \sim E^{-1.6} \text{ and } \sigma^i \to 0 \quad (\theta \to 0°)$$

small.

Simultaneously optimizing the above requirements for the variables A and θ_0 (=half-pair opening angle) indicates the use of $A = 9$, a 2.1-cm Be target, and $7° \leq \theta_0 \leq 9°$ as the optimum condition to isolate the narrow ω peak from the QED background and to limit the unwanted contributions from noncoherent terms.

The double-arm magnetic spectrometer has the following properties which are essential to this experiment.

(I) Counting rate: To obtain maximum number of events (by a factor of 40 more than before)[4] the acceptance-defining scintillation counters are located only at the end section of the spectrometer. None of the counters faces the target directly. As a result the correction for dead time and accidentals is $\leq 6\%$ for the maximum 12 mA of circulating-beam current in the synchrotron.

(II) π rejection: Since the branching ratio for leptonic ρ or ω decays is about 10^{-5}, an experiment to 1% accuracy requires a pion rejection of 10^7:1 or better. To accomplish this, four large-aperture threshold Cherenkov counters and two shower counters are used. The total calibrated pion rejection of this system is 10^{10}:1.

(III) Mass resolution: The 202 500 hodoscope combinations defined the kinematical quantities of the e^+e^- pair, small hodoscopes being used to enable a mass resolution of $\Delta m = \pm 4$ MeV.

During the experiment many checks are made to ensure that the spectrometer behaves as designed and all systematic effects are understood. We list the following six examples:

(I) To keep radiative corrections and bremsstrahlung loss constant, the ratio $k/k_{\max}$ is fixed throughout the entire experiment at $k \cong 2p_0 = 2\times 2560$ MeV, $k_{\max}$ at 7.00 GeV. The mass spectrum is obtained by varying the pair-opening angle, i.e., $\theta_0 = 7.5°, 8.°, 8.4°$, and $8.8°$.

(II) To check that the acceptance of the spectrometer is not limited by edges of magnets or shielding, two sets of counters of different sizes are used and the change in counting rate agrees to $\pm 3\%$ with the expected difference due to counter sizes.

(III) To ensure that the contribution of the rescattering process is small, measurements with different target thicknesses are made. To an accuracy of $\pm 3\%$ the corrected yields increase linearly with the target thickness from 0.5 to 3.0 cm Be.

(IV) Because of the high π-rejection ratio needed in this experiment, we monitor the pion rejection, the Cherenkov-counter dead time, and the accidentals in the master trigger via a two-dimensional triggering system T_{ij} ($i = 2, 3, 4$ = the number of Cherenkov counters in the trigger, $j = 5, 7, 10, 15$ = the resolution time between the two arms in nanoseconds). In this way we monitor both the rejection and accidentals at the same time. Each counter had a measured efficiency on electrons of better than 99% and a measured π rejection of 10^3:1. Thus by controlling the beam intensity so that $T_{3j} \cong T_{4j}$ we were able to keep the pion contamination (<2%) and accidentals (<6%) small.

(V) To reduce the effect of any possible asymmetries in the spectrometer and to eliminate the interference term between BH and the Compton diagrams, half the data are taken at each polarity.

(VI) To check the absolute normalization of the detecting system and the mass resolution defined by the hodoscopes, we measured the QED yield (BH) at $\theta_0 = 4°$. The result, based on 12 000 events, is in good agreement with the predictions of QED in both shape and absolute normalization. This agreement verifies the mass resolution and shows that all systematic effects are small.

The data are corrected for target out, bremsstrahlung loss, dead time, accidentals, etc. In analyzing the data we subtract from the measured events in a given mass bin the expected BH contributions, which are calculated using measured elastic form factors[6] on Be and inelastic form factors from the Drell-Schwartz sum rule[7] (a 5% correction). The data are shown in Fig. 1(a) as black dots and the distribution of BH is shown as open circles. The total BH contribution near the mass peak is $\simeq 40\%$ of the total yield. After subtracting the BH contribution from the data, we obtained the event distribution corresponding to the Compton terms shown in Fig. 1(b). The mass spectrum as presented in Fig. 1(c) was obtained after dividing the event distribution in Fig. 1(b) by the production mechanism [Eq. (4a)] and by the acceptance of the spectrometer. As seen, the data exhibit a clear enhancement at the ω mass and follow the general features expected from vector-dominance model predictions [Eq. (3)].

To compare the observed spectrum of Fig. 1 with Eq. (3), we first subtract the contribution due to the term[8] $|A_x|^2$, estimated to be 5% of $|A|^2$.

To avoid systematic errors, fitting is done over the mass region $m > m_c$ where m_c is a cutoff parameter chosen such that a 3% variation in absolute normalization does not significantly affect the result of the fit. We then chose[5,9] $m_\rho = 765 \pm 10$, $\Gamma_\rho = 130 \pm 10$, $m_\omega = 783.7 \pm 2$, $\Gamma_\omega = 12.7 \pm 1.2$, $m_c = 700$ MeV, branching ratio of $\rho \to e^+e^- = (6.5 \pm 0.5)\times 10^{-5}$, $[d\sigma(\gamma\mathrm{Be} \to \rho\mathrm{Be})/dt]_{t=0} = 6.77$ mb/(GeV/c)^2, and the slope of the diffraction peak $a = 70$ GeV^{-2}. The unknown, or fit, parameters are $\gamma_\omega^2\sigma_{\rho N}/\gamma_\rho^2\sigma_{\omega N}$ and $\varphi_{\omega\rho}$. The best values are

$$\gamma_\omega^2\sigma_{\rho N}/\gamma_\rho^2\sigma_{\omega N} = 9.4^{+2.6}_{-1.6}$$

and

$$\varphi_{\omega\rho} = 41^{+20}_{-20}{}^\circ.$$

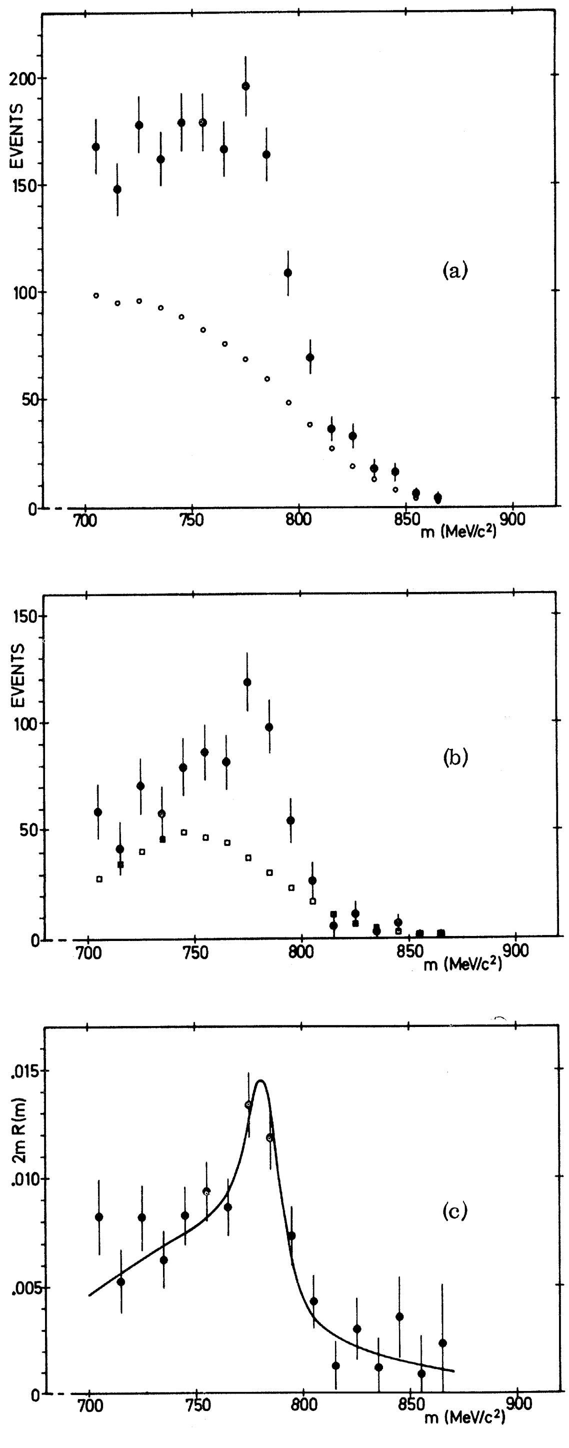

FIG. 1. (a) The black dots are the experimentally measured event distribution (2841 events). The open circles are the calculated contribution of the BH process (1618 events). (b) The black dots are the event distribution attributed to the Compton terms. The squares are the contribution from $\rho \to e^+e^-$ alone. (c) Experimentally measured mass spectrum $2mR(m)$. The curve is the best fit.

The errors quoted above mainly come from our estimation of uncertainties, such as the ρ line shape, the absolute normalization, and uncertainties in the parameters (Γ_ω, Γ_ρ, m_ω, etc.).

If $y = \Delta(\gamma_\omega^2\sigma_{\rho N}/\gamma_\rho^2\sigma_{\omega N})$ and $z = \Delta\varphi_{\omega\rho}$, the sensitivities of the fit results to the changes of input parameter x are, for $x = m_\rho$ (± 10 MeV), $y = \pm 0.5$ and $z = \mp 3°$; for $x = m_\omega$ (± 2 MeV), $y = \mp 0.3$ and $z = \pm 13°$; for $x = \Gamma_\omega$ (± 1.2 MeV), $y = \mp 0.5$ and $z = \mp 0.5°$; for $x = \Gamma_{\rho\to ee}$ ($\pm 10\%$ of $\Gamma_{\rho\to ee}$), $y = \pm 1.2$ and $z = \mp 2°$; for $x =$ Be radius ($\pm 10\%$), $y = \mp 0.4$ and $z = (-2°, +1°)$; and for $x =$ normalization ($\pm 2\%$), $y = \pm 0.4$ and $z = \mp 1°$.

A recent experiment done at Daresbury Nuclear Physics Laboratory[10] has measured the photoproduction of e^+e^- pairs on carbon at 3.6 GeV. The published results were

$$\gamma_\omega^2/\gamma_\rho^2 = 7.0^{+2.0}_{-0.9}, \quad \varphi_{\omega\rho} = 100^{+38°}_{-30}.$$

The difference between their result and ours is most likely due to statistics or difference in energy and target used.[11]

In conclusion, our data show that there is definitely a strong interference enhancement from ω superimposed on the leptonic-decay peak from ρ. Furthermore, if we assume $|A_{\omega N}| = |A_{\rho N}|$ our result for $\gamma_\omega^2/\gamma_\rho^2$ is $1\frac{1}{2}$ standard deviations away from the storage-ring measurements.[12] Thus we see that the mass spectrum is in reasonably good agreement with the predictions of the vector-dominance model.

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Determination of the Photoproduction Phase of ρ^0 Mesons*

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We have measured large-angle electron-positron pairs from the reaction $\gamma+\mathrm{Be}\to\mathrm{Be}+e^++e^-$ in the e^+e^- invariant-mass region $610<m<850$ MeV/c^2. The phase of the photoproduction amplitude of the ρ meson at 4.1-6.1 GeV was found to deviate from pure imaginary by 11.8°±4.4° which corresponds to a ratio of the real to imaginary ρ-nucleon amplitude of $\beta=0.2\pm0.1$.

Recent developments in the photoproduction of vector mesons[1] show that in order for the vector-dominance model to hold the ρ-nucleon amplitude in the GeV region must not be purely diffractive but should contain a substantial real part. Independently, the quark models of Joos,[2] Dar and Weisskopf,[3] and others predict an equality between the ρ-meson–nucleon amplitude $A_{\rho N}$ and the πN-scattering amplitude $A_{\pi N}$, so that at 4-6 GeV for ρ mesons the ratio of real to imaginary amplitude is $\beta\simeq-0.2$. The purpose of the present experiment is to measure directly the value β and compare it with the predictions of these models.

We determine β by studying the e^+e^- yields from the reaction

$$\gamma+\mathrm{Be}\to\mathrm{Be}+e^++e^- \tag{1}$$

in the energy region 4.1-6.1 GeV and the e^+e^- invariant mass region $610<m<850$ MeV/c^2. To second order, the amplitude for Reaction (1) is

$$A_T=A_\rho(\gamma)+A_\omega(\gamma)+A_{\mathrm{BH}}(2\gamma)+A_{\mathrm{BH}}(3\gamma)+A_x(\gamma),$$

where $A_\rho(\gamma)$ and $A_\omega(\gamma)$ are the diffractive photoproduction amplitudes of ρ and ω mesons decaying into e^+e^- via one photon. $A_{\mathrm{BH}}(2\gamma)$ is the ordinary Bethe-Heitler (BH) amplitude (which is real) where the final e^+e^- states are connected to two γ rays. $A_{\mathrm{BH}}(3\gamma)$ is the second-order BH pair amplitude in which the e^+e^- are connected to three γ rays. $A_x(\gamma)$ is the incoherent ρ, ω meson production amplitude.

It follows from charge-conjugation invariance that $2\langle A_{\mathrm{asy}}\rangle^2=\langle A_T(e^+,e^-)\rangle^2-\langle A_T(e^-,e^+)\rangle^2$ can come only from interference terms involving an odd number of photons:

$$\langle A_{\mathrm{asy}}\rangle^2=\mathrm{Re}[\langle A_\rho(\gamma)+A_\omega(\gamma)|A_{\mathrm{BH}}(2\gamma)\rangle+\langle A_{\mathrm{BH}}(2\gamma)|A_{\mathrm{BH}}(3\gamma)\rangle].$$

At high energy on complex nuclei in the region of the ρ mass, one has

$$\langle A_{\mathrm{asy}}\rangle^2\simeq\mathrm{Re}[\langle A_\rho(\gamma)|A_{\mathrm{BH}}(2\gamma)\rangle]. \tag{2}$$

Since $A_{\mathrm{BH}}(2\gamma)$ is real, the measurement of asymmetric e^+e^- pairs yields information on the phase $(ie^{i\varphi})$ of $A_\rho(\gamma)$.

The interference between the Bethe-Heitler[1,4] and Compton processes is described by the cross sec-