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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 $\gamma+\mathrm{Be}\rightarrow\mathrm{Be}+e^++e^-$ 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

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

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 section

$$\sigma_i = \frac{d\hat{\sigma}}{dE_+dE_-d\Omega_+d\Omega_-} = \frac{Z\alpha^2}{\pi^2}G_E(t)E_+E_-\frac{e^{\alpha t/2}}{t}\frac{g_{\gamma\rho}m_\rho^2}{m^2}S(k)D(k)\,\mathrm{Re}(\Lambda_1)\Lambda_2, \tag{3}$$

with

$$\Lambda_1 = ie^{i\varphi}\Lambda_0, \quad \Lambda_0 = D_\rho + \frac{\gamma_\rho^2 m_\omega^2}{\gamma_\omega^2 m_\rho^2}D_\omega e^{i\varphi_{\omega\rho}}, \quad D_V = (m_V^2 - m^2 - im_V\Gamma_V)^{-1},$$

$$\Lambda_2 = 2m^2\left(\frac{E_-}{k\cdot p_+} - \frac{E_+}{k\cdot p_-}\right) + 2\left(\frac{1}{k\cdot p_+} + \frac{1}{k\cdot p_-}\right)\left[\frac{m^2}{2}(E_+ - E_-) + E_-k\cdot p_+ - E_+k\cdot p_-\right]$$
$$-\frac{2}{M}(p_{+x}p_{-x} + p_{+y}p_{-y})\left(\frac{Q\cdot p_+}{k\cdot p_-} - \frac{Q\cdot p_-}{k\cdot p_+}\right),$$

where z is the charge of the target; k, the photon four-momentum; $p_\pm$, the four-momentum of the $e^\pm$; $E_\pm$, the energy of the $e^\pm$; P, the initial four-momentum of nucleus; $Q = k + P - p_+ - p_-$ is the recoil four-momentum of nucleus; $t = (k - p_+ - p_-)^2$; $S(k)$, the bremsstrahlung energy spectrum; and $G_E(t)$, the elastic form factor of the target. The metric is $g_{00} = 1$, $g_{ii} = -1$ ($i = 1, 2, 3$) with the z axis defined to be the beam direction.

The direct comparison of the asymmetric data with Eq. (3) is complicated because of the following: (1) There is no theory for wide resonances; the ρ line shape is not well known. (2) The forward differential cross section of ρ production is known only to ±10% and therefore $D(k)$ to ±5%. (3) The diffraction slope a is known to ±10%. (4) The coupling constant $g_{\gamma\rho}$ is uncertain to ±10%.

To reduce or remove dependence on these parameters we considered (instead of σ_i) the quantity

$$\frac{\sigma_i}{(\sigma_{BH}\sigma_C)^{1/2}} = \frac{\mathrm{Re}(\Lambda_1)}{|\Lambda_1|}\eta(p_+,p_-) \equiv \sin(\varphi + \psi)\eta(p_+,p_-), \tag{4}$$

where

$$\tan\psi = \frac{\mathrm{Im}\Lambda_0}{\mathrm{Re}\Lambda_0} \simeq \frac{m_\rho\Gamma_\rho}{m_\rho^2 - m^2}$$

if the ω contribution is small;

$$\eta(p_+,p_-) = \left(\frac{p_+\cdot P + p_-\cdot P - p_+\cdot p_-}{p_\rho M\Lambda_3(p_+\cdot p_-)_{3,4}}\right)^{1/2}\Lambda_2, \quad \Lambda_3 = \frac{m_e^2 t}{(k\cdot p_-)^2} - 2\left(\frac{k\cdot p_+}{k\cdot p_-} + \frac{k\cdot p_-}{k\cdot p_+} + \frac{tp_+\cdot p_-}{k\cdot p_+ k\cdot p_-}\right)$$
$$+ \frac{2}{\tilde{P}^2}\left[\frac{2m_e^2(p_+\cdot\tilde{P})^2}{(k\cdot p_-)^2} - \frac{t[(p_+\cdot\tilde{P})^2 + (p_-\cdot\tilde{P})^2]}{k\cdot p_+ k\cdot p_-}\right],$$

$$p_\rho = [(p_{+x}+p_{-x})^2 + (p_{+y}+p_{-y})^2 + (p_{+z}+p_{-z})^2]^{1/2}, \quad \tilde{P} = P + Q, \quad (p_+\cdot p_-)_{3,4} = E_+E_-(1 - \cos\theta_+\cos\theta_-).$$

$\sigma_{BH}(m)$ is the BH contribution, calculated with the measured elastic form factor of beryllium, and $\sigma_C(m)$ is the contribution of the Compton term, including both ρ and ω mesons. The determination of the production phase angle φ is thus independent of the following parameters: a, $D(k)$, $G_E(t)$, $S(k)$, and $g_{\gamma\rho}$, and the dependence on m_ρ, Γ_ρ, m_ω, Γ_ω, $\gamma_\rho^2/\gamma_\omega^2$, $\varphi_{\omega\rho}$, and normalization is minimized.

This experiment was done on the modified DESY–Massachusetts Institute of Technology spectrometer.[5]

The target was chosen to be 2.1-cm Be. The apparatus and experimental procedure were the same as described earlier.[5] The data were collected with $k_{max} = 7.0$ GeV and $p_0 = 2.560$ GeV/c for the four angles $\theta_0 = 7.5°$, 8.0°, 8.4°, and 8.8°, p_0 and θ_0 being the central momentum and the angle of one spectrometer arm, respectively.

In order to describe the results of the measurements, we adopt the following notation: The subscript L (R) refers to the left (right) arm of the spectrometer. The subscripts "+" and "−" denote the sign of the charge of the lepton passing through the right arm of the spectrometer. The expression $N_+(\delta, m)$ with $\delta = p_R\theta_R - p_L\theta_L$ then represents the observed number of events with mass m and a pair transverse momentum δ. Figure 1(a) shows $N_+(\delta, m) - N_-(\delta, m)$. For purposes of

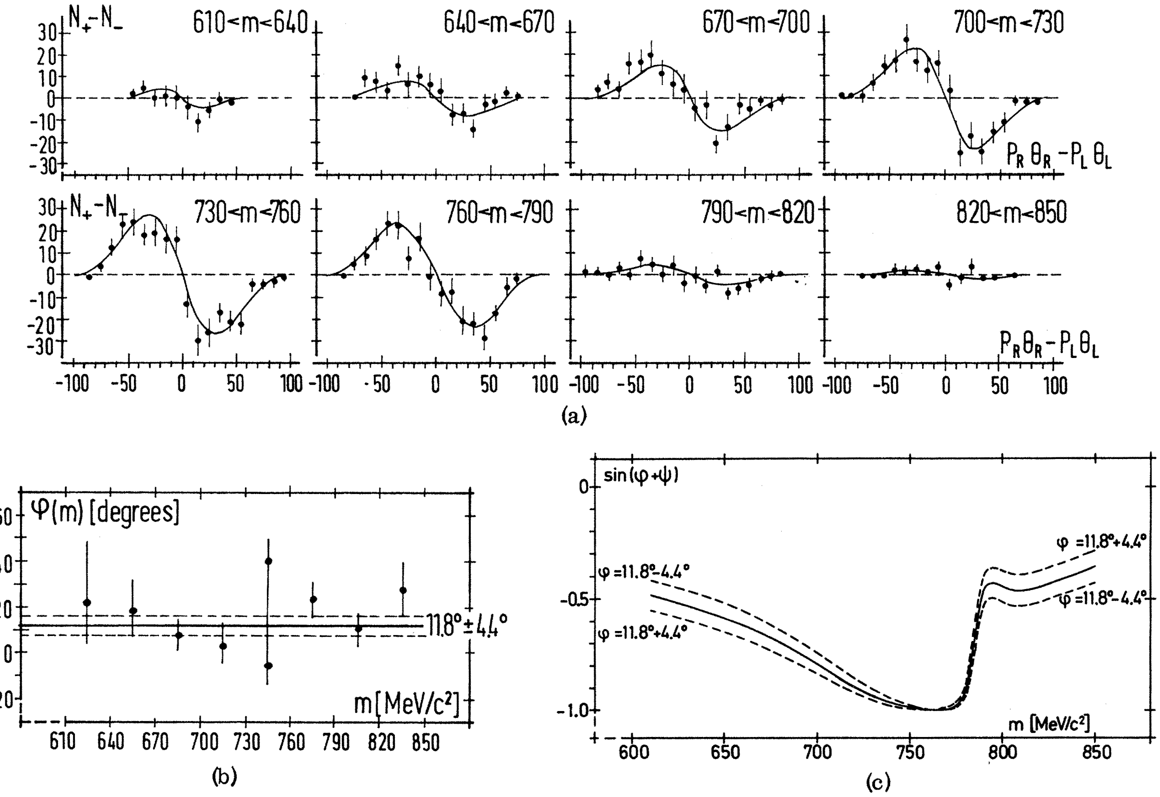

FIG. 1. (a) The measured asymmetric events $N_+(\delta, m) - N_-(\delta, m)$ as a function of $\delta = p_R\theta_R - p_L\theta_L$ for each mass bin of 30 MeV/c^2. The curves correspond to Eq. (6) with $\varphi = 11.8°$. (b) The fitted values of φ for each mass bin of 30 MeV/c^2. For the mass bin at 745 MeV/c^2, two local minima were found. (c) The quantity $\sin(\varphi + \psi)$ as a function of the e^+e^- pair mass. This quantity is independent of all parameters and is thus the most reliable result of this experiment.

analysis the experimental results were represented by the expression

$$R_{\mathrm{expt}}(\delta, m) = \frac{N_+(\delta, m) - N_-(\delta, m)}{[N_{\mathrm{BH}}(m) N_{\mathrm{C}}(m)]^{1/2}}, \tag{5}$$

as discussed above [Eq. (4)].

The calculated BH mass spectrum corresponding to σ_{BH} is $N_{\mathrm{BH}}(m)$, and $N_{\mathrm{C}}(m)$ is the number of experimental events attributed to the diffractive Compton process. If $N_t(m)$ is the total number of experimental events at mass m and $N_i(m)$ is the incoherent and one-pion-exchange production part of the Compton process together with the inelastic BH contribution calculated using the Drell-Schwartz sum rule,[6] then

$$N_{\mathrm{C}}(m) = N_t(m) - N_{\mathrm{BH}}(m) - N_i(m).$$

The data were compared with

$$R(\delta, m) = \frac{\sigma_i(\delta, m) + \epsilon(\delta, m)}{[\sigma_{\mathrm{BH}}(m)\sigma_{\mathrm{C}}(m)]^{1/2}} = \sin(\varphi + \psi)\eta(p_+, p_-) + \frac{\epsilon(\delta, m)}{[\sigma_{\mathrm{BH}}(m)\sigma_{\mathrm{C}}(m)]^{1/2}}, \tag{6}$$

where $\epsilon(\delta, m)$ is the contribution of the interference of the BH term and the two-photon exchange process.[7] In our case $\epsilon(\delta, m)$ is small compared with σ_i. Variables other than δ and m were integrated over the spectrometer acceptance. The data were binned with $\Delta m = 30$ MeV/c^2. The quantity $R(\delta, m)$ depends on the spectrometer acceptance because σ_i, σ_{BH}, and σ_{C} vary rapidly and depend differently upon kinematic variables.

In order to reduce the dependence of the result on ω parameters, we only used $610 < m < 760$ and

$790 < m < 850$ MeV/c^2. Choosing $m_\rho = 765$, $\Gamma_\rho = 130$, $m_\omega = 783.7$, $\Gamma_\omega = 12.7$ MeV/c^2, $\gamma_\omega^2/\gamma_\rho^2 = 9.4$, and $\varphi_{\omega\rho} = 41°$,[5] comparison of the data with the theoretical expression $R(\delta, m)$ yields $\varphi = 11.8° \pm 4.4°$.

For light nuclei the effect of nuclear physics is small, and using the Margolis multiple-scattering theory[8] we relate the production phase angle φ of the ρ meson on Be to that on a nucleon. Thus β, the ratio of real to imaginary part of the ρ-nucleon amplitude, can be related to φ. From $\varphi = 11.8° \pm 4.4°$, we obtain $\beta = -0.2 \pm 0.1$ [Fig. 1(b)].

The measurement of the quantity $\sin(\varphi + \psi)$ in Eq. (6) is independent of parameters like m_ρ, Γ_ρ, m_ω, Γ_ω, $\gamma_\omega^2/\gamma_\rho^2$, etc. and thus is the most reliable result of this experiment [Fig. 1(c)].

The results of the fits are sensitive to the value of m_ρ used but are reasonably insensitive to all other variables. Furthermore, the fitting results are almost independent of the details of the ρ line shape, e.g., independent of the Ross-Stodolsky factor, etc. If $y = \Delta\varphi$, the sensitivities of φ to the changes of input parameter x are $x = m_\rho$ (±10 MeV), $y = \pm 4.6°$; $x = \Gamma_\rho$ (±20 MeV), $y = \mp 2.2°$; $x = m_\omega$ (±2.7 MeV), $y = \mp 0.5°$; $x = \gamma_\omega^2/\gamma_\rho^2$ (±1), $y = \pm 0.6°$; $x = \varphi_{\omega\rho}$ (±20°), $y = (-2.4°, +2.8°)$, and x = normalization (±8 %), $y = \mp 0.3°$. In order to see any mass-dependent effect on the phase angle φ, we also fit for φ in each 30-MeV bin. The result is shown in Fig. 1(b). No obvious mass dependence is noticed.

Photoproduction of ρ mesons and π elastic scattering are related according to the quark and vector-dominance models. Our result is in agreement with $\beta = -0.25$ obtained from the analysis of total cross sections[9] at 5.1 GeV and with the value of $\beta = -0.2$ obtained from the measurement of the $\pi^\pm p$ total cross section.[10]

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