Study of the ρ' (1600) Mass Region Using $\gamma p \rightarrow \pi^+\pi^- p$ at 20 GeV

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We have observed the $\pi^+\pi^-$ decay of the $\rho'(1600)$ in the production reaction $\gamma p \rightarrow \rho' p$ at 20 GeV. Using a calculation which takes into account the interference of the ρ' with the $\rho(770)$ and a Drell background, we find good evidence that this resonance is a radial excitation of the $\rho(770)$. The background interference strongly distorts the angular distributions predicted by a purely s-channel helicity-conserving production mechanism. We measure $m_0 = (1.55 \pm 0.07)$ GeV/c^2 and $\Gamma_0 = (0.28^{+0.03}_{-0.08})$ GeV/c^2.

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The study of radially excited $q\bar{q}$ states provides important information about the QCD force, especially its long-range confining character. In particular, the data available about vector mesons containing heavy quarks ($c\bar{c}$ or $b\bar{b}$) have led to the formulation of long-range, confining, linear potentials modified by short-range effects due to one-gluon exchange.[1] Although good information is available about the spectra of these ψ and Υ states, the radial excitations of vector mesons composed of light quarks ($u\bar{u}$, $d\bar{d}$, and $s\bar{s}$) have proved difficult to measure because of broad decay widths and interfering backgrounds.

We present new information about a possible radial excitation of the $\rho(770)$ produced in the reaction

$$\gamma p \rightarrow \rho' p, \quad \rho' \rightarrow \pi^+\pi^-. \tag{1}$$

Unlike previous photoproduction studies[2–6] of the $\pi^+\pi^-$ decay mode of the ρ', this experiment has full decay acceptance, and the analysis uses an interference of vector mesons with a Drell background to study the amplitude variation of the $\pi^+\pi^-$ system for $J^P = 1^-$ in the mass range up to 2.0 GeV/c^2.

The data used in this analysis were obtained from an experiment performed in the Stanford Linear Accelerator Center (SLAC) Hybrid Facility exposed to photons produced by backscattering laser light from a 30-GeV electron beam.[7] The photon beam had a linear polarization of 52% and an average energy of 19.3 GeV with a spread of 1.7 GeV (full width at half maximum). The photon flux was measured with an e^+e^--pair spectrometer and, independently, by a total-absorption lead-scintillator counter. Produced charged or neutral particles (ex-

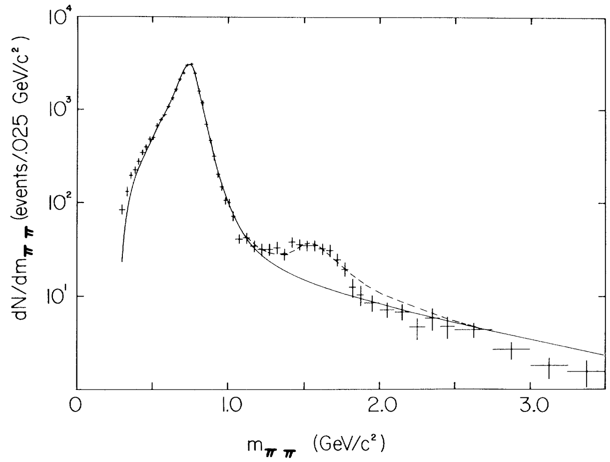

FIG. 1. The $\pi^+\pi^-$ invariant mass distribution corrected for all losses. The solid curve is the prediction of the Söding model with only the $\rho(770)$ resonance. The dashed curve shows the effect of adding a second resonance of mass 1.55 GeVc^2 and width 0.28 GeV/c^2.

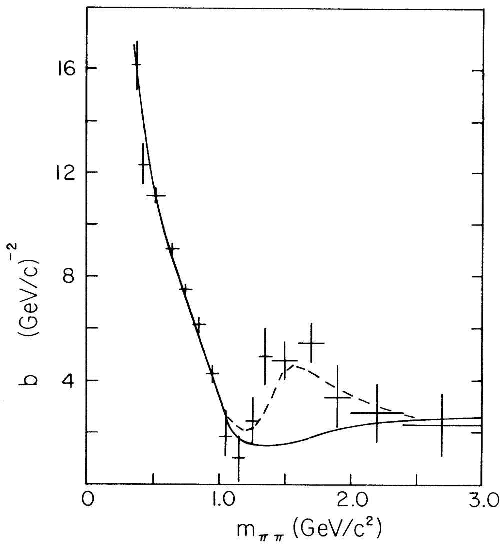

FIG. 2. Variation of the four-momentum slope parameter, b, with $\pi^+\pi^-$ mass. The curves are Söding model predictions with one (solid curve) and two (dashed curve) resonances as described in the text.

cept those in a narrow forward region dominated by $\gamma \rightarrow e^+e^-$ conversions) triggered the recording of hadronic interactions. A kinematic fit with three constraints was used to select the $\gamma p \rightarrow \pi^+\pi^- p$ events. Backgrounds were studied and found to be negligible after rejection of the events (1.4%) which had a better fit to $\gamma p \rightarrow \pi^+\pi^-\pi^0 p$, K^+K^-p, or $p\bar{p}p$. The data were corrected for experimental detection and selection losses as a function of the production and decay variables of the $\pi^+\pi^-$ system. An important feature of the experiment is that it has good acceptance for all decay angles of $\pi^+\pi^-$ pairs with masses between 0.4 and 2.5 GeV/c^2.

The final data sample consists of 20908 $\gamma p \rightarrow \pi^+\pi^- p$ interactions. This represents a cross section of 11.1 ± 0.9 μb. A small, well-isolated signal of $\Delta(1232)$ production was observed and removed by rejecting 133 events with $m_{p\pi^\pm} < 1.4$ GeV/c^2. The $\pi^+\pi^-$ mass distribution of the remaining events, presented in Fig. 1, shows that this channel is dominated by $\rho(770)$ production. The experimental mass resolution varies from 0.008 to 0.013 GeV/c^2 standard deviation for $\pi^+\pi^-$ masses between that of the ρ and 2.0 GeV/c^2. This is much smaller than the natural widths of the resonances studied in this experiment. We will briefly discuss the production and decay characteristics of the $\rho(770)$ and then show that a second resonance at a $\pi^+\pi^-$ mass of 1.55 GeV/c^2 is required to describe the data.

The cross section for the reaction $\gamma p \rightarrow \rho p$ is known to vary slowly with center-of-mass energy and rapidly with the square of the four-momentum transferred ($t' = t - t_{\rm min}$) from the photon to the ρ. The variation with $\pi^+\pi^-$ mass of the slope parameter, b, from fits of the form $Ae^{bt'}$ to the experimental distribution $d\sigma/dt'$, is shown in Fig. 2. We will return to a discussion of the dependence of b on the $\pi^+\pi^-$ mass, but note here that the slope is 7.5 ± 0.2 (GeV/c)$^{-2}$ at the ρ mass peak. This value is typical of elastic processes, and suggests that the ρ is produced by the diffractive, vector-meson dominance mechanism shown in Fig. 3(a).

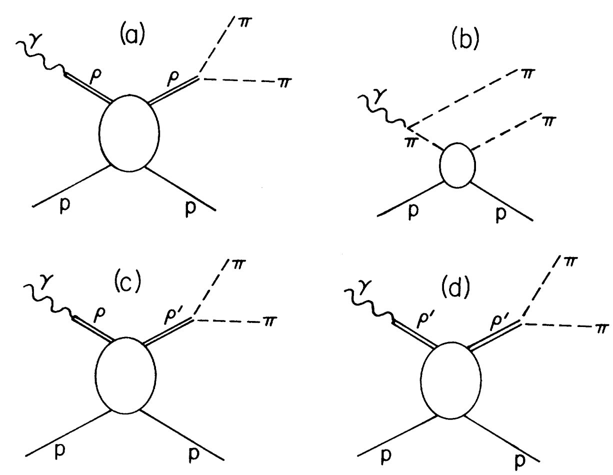

FIG. 3. (a) Diffractive production of the $\rho(770)$. (b) Nonresonant $\pi^+\pi^-$ production via a Drell amplitude as suggested by Söding. (c),(d) Diffractive ρ' production amplitudes.

The decay angular distributions[8] of the ρ in its helicity frame are shown in Figs. 4(a) and 4(b). As has been observed at lower energies, these angular distributions are consistent with ρ production via s-channel helicity conservation (SCHC) with natural spin-parity exchange.[9–11] The SCHC prediction for N_T events is given by $d^2N/d\cos\theta d\psi = (3N_T/8\pi)\sin^2\theta(1+P_\gamma\cos 2\psi)$, where $\psi = \phi_E - \phi$, θ and ϕ are the ρ helicity-frame polar and azimuthal angles, ϕ_E is the ρ azimuthal production angle with respect to the electric field vector of the photon, and P_γ is the degree of linear polarization of the incident photon. Fitting the data by this form yields $P_\gamma = 0.49 \pm 0.02$ for $t' < 0.4$ $(\text{GeV}/c)^2$ and $0.7 < m_{\pi\pi} < 0.75$ GeV/c^2. We expect $P_\gamma = 0.52$ from the backscattered laser beam. Therefore, near the ρ peak, the $\gamma p \to \rho p$ production process is essentially pure SCHC.

Away from the ρ peak, the data deviate from the prediction of pure diffractive ρ production. This may be due to the interference of the ρ amplitude with the Drell amplitude [shown in Fig. 3(b)], as has been suggested by Söding[12] and verified in several ρ photoproduction experiments.[10,11,13–16] This interference is constructive below the ρ peak and destructive above, leading to the asymmetric

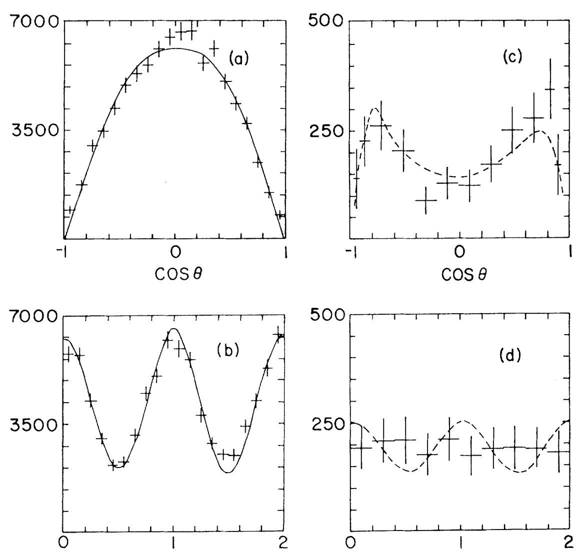

FIG. 4. Decay angular distributions of the $\pi^+\pi^-$ system in its helicity frame. (a) and (b) are for the $\rho(770)$ mass region, $0.70 < m_{\pi\pi} < 0.80$ GeV/c^2. (c) and (d) are for the ρ' mass region, $1.4 < m_{\pi\pi} < 1.8$ GeV/c^2. The $p\pi^+$ mass cut ($m_{p\pi} \pm > 1.4$ GeV/c^2) does not affect the $\cos\theta$ distribution in (a) but removes events with $|\cos\theta| > 0.95$ in (c). The curves are predictions of the Söding model as described in the text.

$\pi^+\pi^-$ mass distribution shown in Fig. 1 and the rapidly varying t' slope shown in Fig. 2.

We used the Söding model to examine these effects more quantitatively. The ρ production amplitude was taken to be purely imaginary and proportional to $e^{bt'/2}$. The ρ decay was described by a relativistic Breit-Wigner resonance with mass 0.769 GeV/c^2 and width 0.154 GeV/c^2.[17] The Drell amplitude was calculated using $\pi p \to \pi p$ phase-shift data.[18] The relative intensity of the two $\pi^+\pi^-$ production amplitudes and the t' slope b were treated as free parameters. The resulting predictions for the $m_{\pi\pi}$ and t' distributions, normalized to the total number of events, were fitted to the data. The results of this fit, with $b = 7.0 \pm 0.4$ $(\text{GeV}/c)^{-2}$, are given by the solid curves in Figs. 1, 2, 4(a), and 4(b). There is good agreement with the data except in the mass range between 1.3 and 1.8 GeV/c^2, where there is a large $\pi^+\pi^-$ mass enhancement above the predicted background and a rapid increases in the t' slope from about 1 $(\text{GeV}/c)^{-2}$ to about 5 $(\text{GeV}/c)^{-2}$. These features strongly suggest the diffractive production of at least one additional resonance.

We next modify the model by adding a second $J^P = 1^-$ resonance, ρ^-, that is assumed to be produced in the same diffractive SCHC manner as the $\rho(770)$. Within the context of the vector-meson dominance model, this amplitude represents a sum of the two diagrams shown in Figs. 3(c) and 3(d). The free parameters in this extended Söding calculation are the intensity, mass, and width of the ρ', and an overall sign of the ρ'-production amplitude.

The results of this fit to the $\pi^+\pi^-$ mass distribution are shown by the dashed curve in Fig. 1. The data are best fitted by a second resonance with $m_0 = 1.55 \pm 0.07$ GeV/c^2 and $\Gamma = (0.28^{+0.03}_{-0.08})$ GeV/c^2. The fit also requires that the sign of the ρ'-production amplitude be negative relative to that of the ρ.[19] The addition of the second resonance reduces the chi-square per degree of freedom from 9.4 to 0.8 for the $\pi^+\pi^-$ mass range between 1.1 and 1.8 GeV/c^2. Above 1.8 GeV the prediction is above the data. This could be an indication that the relativistic p-wave Breit-Wigner resonance forms[17] used for the ρ and ρ' are not adequate representations of the high mass tails of these resonances. The model reproduces the observed bump in the t' slope, as shown by the dashed curve in Fig. 2. The decay angular distributions in the ρ' mass region are shown in Figs. 4(c) and 4(d), as are the extended model predictions. The Drell background interference strongly distorts the pure SCHC prediction, and the model reproduces the decay angular distributions reasonably well. We can conclude from the $\cos\theta$ distribution shown in Fig. 4(c) that the ρ' is strongly aligned in the helicity frame. However, at the present statistical level, it is difficult to determine the extent of s-channel polarization from the ψ distribution shown in Fig. 4(d). We also note that earlier experiments with less than full angular acceptance would have had difficulty correcting for losses by simply assuming $d\sigma/d\cos\theta \propto \sin^2\theta$ in the ρ' mass region.

We have also calculated the $a_l^m(m_{\pi\pi})$ coefficients from a fit of our data to spherical harmonics. A comparison of these data with the extended Söding model shows a good agreement for $m_{\pi\pi}$ less than 2.0 GeV/c^2. In particular, no $\pi^+\pi^-$ partial waves with l greater than one are required in addition to those introduced by the Drell amplitude.

In conclusion, we have observed a resonance with mass 1.55 ± 0.07 GeV/c^2, width $0.28^{+0.03}_{-0.08}$ GeV/c^2, and $J^{PC} = 1^{--}$ in $\gamma p \to \pi^+\pi^- p$. The production characteristics of this state are similar to those of the $\rho(770)$. These facts suggest that this resonance is a radial excitation of the $\rho(770)$, although we can not rule out a $^3D_1$ $q\bar{q}$ meson. We find $\sigma(\gamma p \to \rho' p) \times BR(\rho' \to \pi^+\pi^-)/\sigma(\gamma p \to \rho(770)p) = (1.34 \pm 0.23) \times 10^{-2}$ at $E_\gamma = 19.3$ GeV. A future report will discuss our analysis of these data in more detail and include a measurement of the 4π decay of this resonance.

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