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The $\rho'(1600)$ meson

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New high-energy photoproduction data on the two-pion and four-pion distributions in the region of 1600 MeV show evidence of resonance structure. The photoproduced two-pion final state is described by a resonance of mass ~ 1600 MeV and width of ~ 300 MeV whereas the four-pion distribution is characterized by a mass of ~ 1500 MeV and a width of ~ 600 MeV. The implications of these new data for colliding electron-positron beam measurements are presented using a simple theoretical model.

INTRODUCTION

The existence of the excited states of the ρ, ω, and ϕ mesons has been a long-standing question for meson spectroscopy. The existence of a ρ' meson was predicted as long ago as 1968 from analyses of the nucleon electromagnetic form factors[1] and from duality theory.[2] With the advent of quantum chromodynamics and the successes of the quark-model descriptions of the new ψ and Υ families, the existence of ρ', ω', and ϕ' states as radial excitations of the ρ, ω, and ϕ would seem to be necessary consequences of the theory. Indeed, as was shown in a recent paper,[3] radial excitations of the conventional low-mass mesons play an important role in obtaining a description of meson spectroscopy and, in particular, the mass of the pion.

The experimental verification of these ideas has been slowly building up. A recent publication[4] gives the best statistical evidence for a ρ' resonance at a mass of 1600 MeV with a total width of about 280 MeV with the two-pion final-state measurements. This result is in excellent agreement with a prediction[5] made some time ago in which the sum of the 4π and 2π widths was given to be about 280 MeV. The prediction was made on the basis of spontaneously broken gauge theory and vector dominance and the model may be considered as a natural extension of vector-dominance ideas. The new data show, however, that if the 2π distribution is assumed to determine the true width of the $\rho'(1600)$, then the four-pion distribution indicates the presence of major contributions from other than this resonance.[4] In the present note we shall discuss the experimental evidence for the $\rho'(1600)$ in the context of the gauge model and compare it with the collected data from the colliding-beam experiments.[6]

THE MODEL

The physical idea of the model[5] is that the proton couples to charged particles only through ρ and ρ' mesons, to lowest order in α. The scalar meson of the theory responsible for mass generation is identified with an ϵ meson. (Since the existence of an ϵ meson has been unclear for many years we will view the use of such a particle as a convenient way to parametrize the lowest-mass $\pi^+\pi^-$ pair within the 4π distribution.) The model may be described by analogy with the minimal electromagnetic-field substitution rule.[5] In the Lagrangian field theory corresponding to the vector-dominance hypothesis we replace the mass term $\frac{1}{2}m_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^\mu$, where $\vec{\rho}_\mu$ denotes the triplet ρ-meson field, by using the rules $m_\rho \to m_\rho + \frac{1}{2}f_\rho\phi(x)$ and $\vec{\rho}_\mu \to \vec{\rho}_\mu - (f_{\rho'}/f_\rho)\vec{\rho}\,'_\mu$. Here f_ρ ($f_{\rho'}$) correspond to a gauge coupling of the ρ (ρ') meson and $\phi(x)$ denotes the scalar field. A similar rule gives the coupling of the ρ' to the photon. The results of this procedure,[5] which will be given below in the expressions for cross sections and width formulas, are that traditional ideas of vector dominance are maintained as much as possible. Since the application of vector-dominance models to the radiative decays of mesons seems to be in a satisfactory state[7,8] and since the quark model may be put into a simple correspondence with the vector-dominance approach,[8] it is obviously useful to keep such a scheme viable. Furthermore, in dealing with the mesonic decays of higher-mass particles the quark model usually resorts to an elementary pion coupling, thus introducing a new phenomenological interaction, whereas our model gives a simple procedure for obtaining the 4π decays of the ρ'. However, in the quark model the ρ' is viewed as a radial excitation of the ρ meson so that the natural decay would be $\rho' \to \rho\pi\pi$ as incorporated in our present model.

The results of the model, relevant for the present discussion, are summarized in the following relations. The decay widths of the ρ' into 2π and 4π (the latter via a $\rho\epsilon$ final state) are[5]

$$\Gamma(\rho' \to 2\pi) = \frac{f_{\rho'}^2}{4\pi}\,\frac{m_\rho^4(m_{\rho'}^2 - 4m_\pi^2)^{3/2}}{12m_{\rho'}^2(m_{\rho'}^2 - m_\rho^2)^2}\,, \qquad (1)$$

$$\Gamma(\rho' \to \rho\epsilon \to 4\pi) = \frac{f_{\rho'}^2}{4\pi} \frac{m_\rho^2}{6m_\rho'}\left(1-\frac{(m_\rho - m_\epsilon)^2}{m_{\rho'}^2}\right)^{1/2}\left(1-\frac{(m_\rho + m_\epsilon)^2}{m_{\rho'}^2}\right)^{1/2}\left(\frac{m_{\rho'}^2}{m_{\rho'}^2 - m_\rho^2}\right)^2\left(1+\frac{(m_{\rho'}^2 + m_\rho^2 - m_\epsilon^2)^2}{8m_\rho^2 m_{\rho'}^2}\right). \tag{2}$$

So long as the coupling constants f_ρ and $f_{\rho'}$ are of the same order, as one might have in an extended universality relation, it can be shown[5,9] that the cross-section formulas for production of 2π and 4π final states in colliding electron-positron beam experiments have no explicit dependence on them. Thus the cross section for the process $e^+e^- \to \pi^+\pi^-$ for center-of-mass energy near 1600 MeV is given by

$$\sigma(2\pi) = \frac{\pi\alpha^2}{3} \frac{m_\rho^4 m_{\rho'}^4}{q^5} \frac{(q^2 - 4m_\pi^2)^{3/2}}{(q^2 - m_\rho^2)^2[(q^2 - m_{\rho'}^2)^2 + m_{\rho'}^2\Gamma^2]}. \tag{3}$$

Similarly the cross section for $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ is given by

$$\sigma(4\pi^+) = \frac{4\pi\alpha^2}{9} \frac{m_{\rho'}^4 m_\rho^2}{q^2} \frac{\{[q^2 - (m_\rho - m_\epsilon)^2][q^2 - (m_\rho + m_\epsilon)^2]\}^{1/2}}{(q^2 - m_\rho^2)^2} \frac{1 + \dfrac{(q^2 + m_\rho^2 - m_\epsilon^2)^2}{8q^2 m_\rho^2}}{(q^2 - m_{\rho'}^2)^2 + m_{\rho'}^2\Gamma^2}. \tag{4}$$

The distribution of the lowest-mass $\pi^+\pi^-$ pair in the four-pion distribution has been given, for the photoproduction experiment, by Atiya *et al.*[4] We shall account for this distribution by considering the ϵ as a high-mass broad resonance and correcting for threshold effects by including contributions from the tail of the resonance.[10] The ρ meson we shall take in the narrow-width approximation.

RESULTS AND CONCLUSIONS

In addition to the photoproduction data there has been a steady accumulation of four-pion data from the electron-positron colliding-beam facilities[6]. It is these data and some, statistically poorer,[9] two-pion data to which we shall compare our model with parameters chosen from the photoproduction experiment. The comparison is done in two different cases as follows:

(i) We assume that the true width of the $\rho'(1600)$ is given by the two-pion photoproduction data. That is, the ρ' is a resonance of mass ~1600 MeV, total width of $283 \pm 14 \pm 40$ MeV and a cross section of 67 nb. We show in Fig. 1 the results of the model in such a case applied to the $4\pi^\pm$ colliding-beam data and in Fig. 2 the application to the 2π data. For these data the total ρ' width was taken to be 350 MeV to allow for possible π"A" type of events not included in the present analysis. The ratio $\Gamma(\rho' \to 2\pi)/\Gamma(\rho' \to 4\pi) \sim 20\%$ at an energy of 1600 MeV. This ratio is in rough agreement with previous estimates on the basis of this model and earlier data[5] or from the partial-wave analyses of the CERN-Munich data[11] on $\pi^-p \to \pi^+\pi^-n$. The integrated cross sections give a ratio of $\sim 10 \pm 5\%$, although if there are contributions other than from the resonance this value is not directly comparable to the ratio of the widths.

From the figures we see that the low-energy part of the $4\pi^\pm$ cross section exceeds the expected cross section in a manner not unlike that obtained in the photoproduction four-pion spectra. However, the two-pion colliding-beam cross section is poorly given in this case also.

(ii) The second case assumes that the two-pion photoproduction data underestimate the total ρ' width and that 600 MeV is more likely the correct

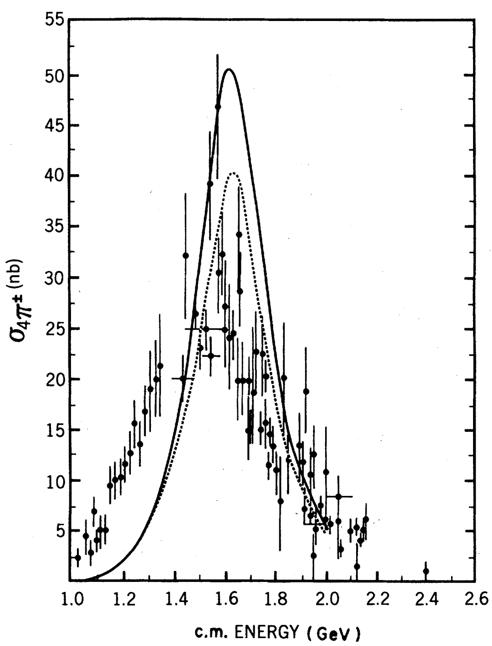

FIG. 1. The curves shown correspond to $m_{\rho' tot} = 1.6$ GeV and $\Gamma_{\rho' tot} = 0.35$ GeV and two slightly different ways of accounting for the low-mass $\pi^+\pi^-$ pair. The solid curve has $m_\epsilon = 0.75$ GeV and $\Gamma_\epsilon = 0.55$ GeV and the dashed curve corresponds to an increase of 200 MeV in this width. For the solid curve $\Gamma_{e\bar{e}}B(4\pi) = 4.6$ keV. The data are from the compilation given in Ref. 6.

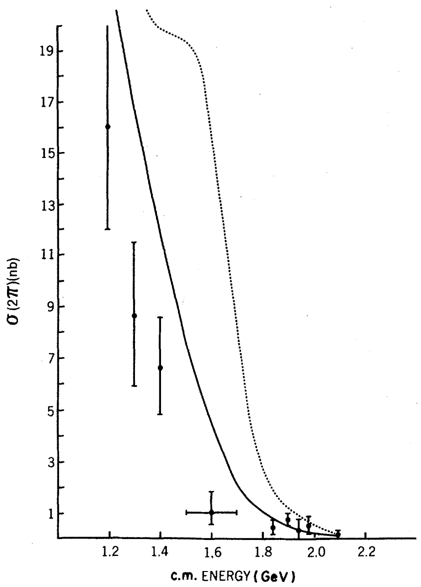

FIG. 2. The solid curve corresponds to $m_{\rho'} = 1.5$ GeV and $\Gamma_{\rho' \, \mathrm{tot}} = 0.6$ GeV; the dashed curve has $m_{\rho'} = 1.6$ GeV and $\Gamma_{\rho' \, \mathrm{tot}} = 0.35$ GeV. For the solid curve $\Gamma_{e\bar{e}} B(2\pi) = 733$ eV and for the dashed curve $\Gamma_{e\bar{e}} B(2\pi) = 974$ eV. The data are from Ref. 12.

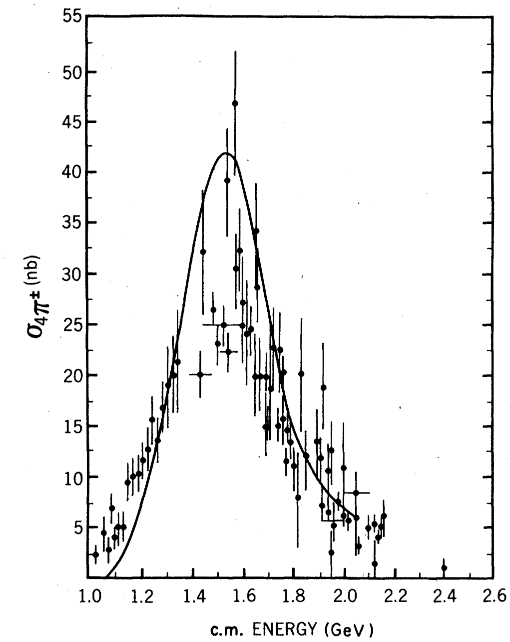

FIG. 3. This curve corresponds to $m_{\rho'} = 1.5$ GeV and $\Gamma_{\rho' \, \mathrm{tot}} = 600$ MeV. The low-mass $\pi^+\pi^-$ pair are accounted for with $m_\epsilon = 0.55$ GeV and $\Gamma_\epsilon = 0.55$ GeV. In this case we have $\Gamma_{e\bar{e}} B(4\pi) = 5.8$ keV. The data are from the compilation given in Ref. 6.

magnitude for the total width. The comparison with the electron-positron colliding-beam data is shown in Fig. 2 and 3. From Fig. 3 we see that the model can account very well for the $4\pi^\pm$ data. Furthermore, the data on two-pion production from the colliding beam are described somewhat better also. The ratio $\Gamma(\rho' \to 2\pi)/\Gamma(\rho' \to 4\pi) \sim 12\%$ at 1500 MeV. The analysis in this case is much more in line with the previous analyses[5] in which an assumption of universality $f_\rho^2/4\pi \sim f_{\rho'}^2/4\pi \sim 3$ gives about 300 MeV for the sum of two-pion and four-pion decays of the ρ'. This would leave about 30–40% of the total width due to decays into multiparticle events (6π or 8π states).

In summary then we have two possible outcomes of the new data. If we accept the photoproduction analyses of the two-pion spectra as a measure of the true width of the ρ', then the four-pion data of the photoproduction and the colliding-beam experiment seem to demand contributions from other than this resonance. Furthermore, the two-pion electron-positron colliding-beam cross-section results, meager though they are, must be ignored. Alternatively, if we assume that the total width of the ρ' is about 600 MeV, of which about 65% comes from two-pion and four-pion ($\rho\epsilon$) decay modes, then the cross section for four pions in the electron-positron colliding-beam experiments can be described very well and the two-pion description is improved relative to the first case.

Clearly one would need better two-pion data to settle this issue. Nevertheless, it is encouraging that the model accounts for the suppression of the two-pion relative to the four-pion decay of the ρ' since the model incorporates features that leave vector-dominance theory relatively unchanged and at the same time lends support, by its decay scheme, to quark-model descriptions of the ρ' as an excited state of the ρ.

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