

## THE $\rho(1450)$ AND THE $\rho(1700)$

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In our 1988 edition, we replaced the  $\rho(1600)$  entry with two new ones, the  $\rho(1450)$  and the  $\rho(1700)$ , because there was emerging evidence that the 1600-MeV region actually contains two  $\rho$ -like resonances. Erkal [1] had pointed out this possibility with a theoretical analysis on the consistency of  $2\pi$  and  $4\pi$  electromagnetic form factors and the  $\pi\pi$  scattering length. Donnachie [2], with a full analysis of data on the  $2\pi$  and  $4\pi$  final states in  $e^+e^-$  annihilation and photoproduction reactions, had also argued that in order to obtain a consistent picture, two resonances were necessary. The existence of  $\rho(1450)$  was supported by the analysis of  $\eta\rho^0$  mass spectra obtained in photoproduction and  $e^+e^-$  annihilation [3], as well as that of  $e^+e^- \rightarrow \omega\pi$  [4].

The analysis of [2] was further extended by [5,6] to include new data on  $4\pi$ -systems produced in  $e^+e^-$  annihilation, and in  $\tau$ -decays ( $\tau$  decays to  $4\pi$ , and  $e^+e^-$  annihilation to  $4\pi$  can be related by the Conserved Vector Current assumption). These systems were successfully analyzed using interfering contributions from two  $\rho$ -like states, and from the tail of the  $\rho(770)$  decaying into two-body states. While specific conclusions on  $\rho(1450) \rightarrow 4\pi$  were obtained, little could be said about the  $\rho(1700)$ .

Independent evidence for two  $1^-$  states is provided by [7] in  $4\pi$  electroproduction at  $\langle Q^2 \rangle = 1$  (GeV/c)<sup>2</sup>, and by [8] in a high-statistics sample of the  $\eta\pi\pi$  system in  $\pi^-p$  charge exchange.

This scenario with two overlapping resonances is supported by other data. Bisello [9] measured the pion form factor in the interval 1.35–2.4 GeV, and observed a deep minimum around 1.6 GeV. The best fit was obtained with the hypothesis of  $\rho$ -like resonances at 1420 and 1770 MeV, with widths of about 250 MeV. Antonelli [10] found that the  $e^+e^- \rightarrow \eta\pi^+\pi^-$  cross section is better fitted with two fully interfering Breit-Wigners, with parameters in fair agreement with those of [2] and [9]. These results can be considered as a confirmation of the  $\rho(1450)$ .

Decisive evidence for the  $\pi\pi$  decay mode of both  $\rho(1450)$  and  $\rho(1700)$  comes from  $\bar{p}p$  annihilation at rest [11]. It has been shown that these resonances also possess a  $K\bar{K}$  decay mode [12–14]. High-statistics studies of the decays  $\tau \rightarrow \pi\pi\nu_\tau$  [15,16], and  $\tau \rightarrow 4\pi\nu_\tau$  [17] also require the  $\rho(1450)$ , but are not sensitive to the  $\rho(1700)$ , because it is too close to the  $\tau$  mass. A recent very-high-statistics study of the  $\tau \rightarrow \pi\pi\nu_\tau$  decay performed at Belle [18] reports the first observation of both  $\rho(1450)$  and  $\rho(1700)$  in  $\tau$  decays.

The structure of these  $\rho$  states is not yet completely clear. Barnes [19] and Close [20] claim that  $\rho(1450)$  has a mass consistent with radial  $2S$ , but its decays show characteristics of hybrids, and suggest that this state may be a  $2S$ -hybrid mixture. Donnachie [21] argues that hybrid states could have a  $4\pi$  decay mode dominated by the  $a_1\pi$ . Such behavior has been observed by [22] in  $e^+e^- \rightarrow 4\pi$  in the energy range 1.05–1.38 GeV, and by [17] in  $\tau \rightarrow 4\pi$  decays. Alexander [23] observes the  $\rho(1450) \rightarrow \omega\pi$  decay mode in  $B$ -meson decays, however, does not find  $\rho(1700) \rightarrow \omega\pi^0$ . A similar conclusion is made by [24], who studied the process  $e^+e^- \rightarrow \omega\pi^0$ . Various decay modes of the  $\rho(1450)$  and  $\rho(1700)$  are observed in  $\bar{p}n$  and  $\bar{p}p$  annihilation [25,26], but no definite conclusions can be drawn. More data should be collected to clarify the nature of the  $\rho$  states, particularly in the energy range above 1.6 GeV.

We now list under a separate entry the  $\rho(1570)$ , the  $\phi\pi$  state with  $J^{PC} = 1^{--}$  earlier observed by [27] (referred to as  $C(1480)$ ) and recently confirmed by [28]. While [29] shows that it may be a threshold effect, [5] and [30] suggest two independent vector states with this decay mode. The  $C(1480)$  has not been seen in the  $\bar{p}p$  [31] and  $e^+e^-$  [32,33] experiments. However, the sensitivity of the two latter is an order of magnitude lower than that of [28]. Note that [28] can not exclude that their observation is due to an OZI-suppressed decay mode of the  $\rho(1700)$ .

Several observations on the  $\omega\pi$  system in the 1200-MeV region [34–40] may be interpreted in terms of either  $J^P = 1^-$   $\rho(770) \rightarrow \omega\pi$  production [41], or  $J^P = 1^+$   $b_1(1235)$  production [39,40]. We argue that no special entry for a  $\rho(1250)$  is needed.

The LASS amplitude analysis [42] showing evidence for  $\rho(1270)$  is preliminary and needs confirmation. For completeness, the relevant observations are listed under the  $\rho(1450)$ .

Recently [43] reported a very broad  $1^{--}$  resonance-like  $K^+K^-$  state in  $J/\psi \rightarrow K^+K^-\pi^0$  decays. Its pole position corresponds to mass of 1576 MeV and width of 818 MeV. [44–46] suggest its exotic structure (molecular or multiquark), while [47] and [48] explain it by the interference between the  $\rho(1450)$  and  $\rho(1700)$ . We quote [43] as  $X(1575)$  in the section “Further States.”

Evidence for  $\rho$ -like mesons decaying into  $6\pi$  states was first noted by [49] in the analysis of  $6\pi$  mass spectra from  $e^+e^-$  annihilation [50,51] and diffractive photoproduction [52]. Clegg [49] argued that two states at about 2.1 and 1.8 GeV exist: while the former is a candidate for the  $\rho(2150)$ , the latter could be a manifestation of the  $\rho(1700)$  distorted by threshold effects. BaBar reported observations of the new decay modes of the  $\rho(2150)$  in the channels  $\eta'(958)\pi^+\pi^-$  and  $f_1(1285)\pi^+\pi^-$  [53]. The relativistic quark model [54] predicts the  $2^3D_1$  state with  $J^{PC} = 1^{--}$  at 2.15 GeV which can be identified with the  $\rho(2150)$ .

The E687 Collaboration at Fermilab reported an observation of a narrow-dip structure at 1.9 GeV in the  $3\pi^+3\pi^-$  diffractive photoproduction [55]. A similar effect of the dip in the cross section of  $e^+e^- \rightarrow 6\pi$  around 1.9 GeV has been earlier reported by DM2 [51], where  $6\pi$  included both  $3\pi^+3\pi^-$  and  $2\pi^+2\pi^-2\pi^0$ . Later the dip in the  $R$  value (the total cross section of  $e^+e^- \rightarrow$  hadrons divided by the cross section of  $e^+e^- \rightarrow \mu^+\mu^-$ ) was observed by [56], again around 1.9 GeV. This energy is close to the  $N\bar{N}$  threshold, which hints at the possible relation between the dip and  $N\bar{N}$ , *e.g.*, the frequently discussed narrow  $N\bar{N}$  resonance or just a threshold effect. Such behaviour is also characteristic of exotic objects like vector  $q\bar{q}$  hybrids. Note that [57] failed to find this state in the reaction  $\bar{n}p \rightarrow 3\pi^+2\pi^-\pi^0$ . A reanalysis of the E687 data by [58] shows that a dip may arise due to interference of a narrow object with a broad  $\rho(1700)$  independently of the nature of the former. BaBar studied the processes  $e^+e^- \rightarrow 3\pi^+3\pi^-$  and  $e^+e^- \rightarrow 2\pi^+2\pi^-2\pi^0$  using the

radiative return, and observed a structure around 1.9 GeV in both final states [59]. The data are not well described by a single Breit-Wigner state, and a good fit is achieved while taking into account the interference of such a structure with a Jacob-Slansky amplitude for continuum. The mass of this state obtained by BaBar is consistent with [56] and [55], but the width is substantially larger. Recently [28] observed a structure at 1.9 GeV in the radiative return to the  $\phi\pi$  final state, with a much smaller width of  $48 \pm 17$  MeV consistent with that of [56,58]. We list these observations under a separate particle  $\rho(1900)$ , which needs confirmation.

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