

## 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. A clear picture of the two  $\pi^+\pi^-$  resonances interfering with the  $\rho(770)$  was also reported by BaBar using the ISR method [19].

The structure of these  $\rho$  states is not yet completely clear. Barnes [20] and Close [21] 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 [22] argues that hybrid states could have a  $4\pi$  decay mode dominated by the  $a_1\pi$ . Such behavior has been observed by [23] in  $e^+e^- \rightarrow 4\pi$  in the energy range 1.05–1.38 GeV, and by [17] in  $\tau \rightarrow 4\pi$  decays. CLEO [24] and Belle [25] observe the  $\rho(1450) \rightarrow \omega\pi$  decay mode in  $B$ -meson decays, however, do not find  $\rho(1700) \rightarrow \omega\pi^0$ . A similar conclusion is made by [26], 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 [27,28], 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 [29] (referred to as  $C(1480)$ ) and recently confirmed by [30]. While [31] shows that it may be a threshold effect, [5] and [32] suggest two independent vector states with this decay mode. The  $C(1480)$  has not been seen in the  $\bar{p}p$  [33] and  $e^+e^-$  [34,35] experiments. However, the sensitivity of the two latter is an order of magnitude lower than that of [30]. Note that [30] 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 [36–42] may be interpreted in terms of either  $J^P = 1^-$

$\rho(770) \rightarrow \omega\pi$  production [43], or  $J^P = 1^+$   $b_1(1235)$  production [41,42]. We argue that no special entry for a  $\rho(1250)$  is needed. The LASS amplitude analysis [44] showing evidence for  $\rho(1270)$  is preliminary and needs confirmation. For completeness, the relevant observations are listed under the  $\rho(1450)$ .

Recently [45] 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. [46–48] suggest its exotic structure (molecular or multiquark), while [49] and [50] explain it by the interference between the  $\rho(1450)$  and  $\rho(1700)$ . We quote [45] as  $X(1575)$  in the section “Further States.”

Evidence for  $\rho$ -like mesons decaying into  $6\pi$  states was first noted by [51] in the analysis of  $6\pi$  mass spectra from  $e^+e^-$  annihilation [52,53] and diffractive photoproduction [54]. Clegg [51] 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  $f_1(1285)\pi^+\pi^-$  [55]. The relativistic quark model [56] predicts the  $2^3D_1$  state with  $J^{PC} = 1^{--}$  at 2.15 GeV which can be identified with the  $\rho(2150)$ .

We no longer list under a separate particle  $\rho(1900)$  various observations of irregular behavior of the cross sections near the  $N\bar{N}$  threshold. Dips of various width around 1.9 GeV were reported by the E687 Collaboration (a narrow one in the  $3\pi^+3\pi^-$  diffractive photoproduction [57,58]) , by the FENICE experiment (a narrow structure in the  $R$  value [59]) , by BaBar in ISR (a narrow structure in  $e^+e^- \rightarrow \phi\pi$  final state [60], but much broader in  $e^+e^- \rightarrow 3\pi^+3\pi^-$  and  $e^+e^- \rightarrow 2(\pi^+\pi^-\pi^0)$  [61]) , by CMD-3 (also a rather broad dip in  $e^+e^- \rightarrow 3\pi^+3\pi^-$  [62]) . Most probably, these structures emerge as a threshold effect due to the opening of the  $N\bar{N}$  channel [63,64].

## References

1. C. Erkal, Z. Phys. **C31**, 615 (1986).
2. A. Donnachie and H. Mirzaie, Z. Phys. **C33**, 407 (1987).

3. A. Donnachie and A.B. Clegg, Z. Phys. **C34**, 257 (1987).
4. A. Donnachie and A.B. Clegg, Z. Phys. **C51**, 689 (1991).
5. A.B. Clegg and A. Donnachie, Z. Phys. **C40**, 313 (1988).
6. A.B. Clegg and A. Donnachie, Z. Phys. **C62**, 455 (1994).
7. T.J. Killian *et al.*, Phys. Rev. **D21**, 3005 (1980).
8. S. Fukui *et al.*, Phys. Lett. **B202**, 441 (1988).
9. D. Bisello *et al.*, Phys. Lett. **B220**, 321 (1989).
10. A. Antonelli *et al.*, Phys. Lett. **B212**, 133 (1988).
11. A. Abele *et al.*, Phys. Lett. **B391**, 191 (1997).
12. A. Abele *et al.*, Phys. Rev. **D57**, 3860 (1998).
13. A. Bertin *et al.*, Phys. Lett. **B434**, 180 (1998).
14. A. Abele *et al.*, Phys. Lett. **B468**, 178 (1999).
15. R. Barate *et al.*, Z. Phys. **C76**, 15 (1997).
16. S. Anderson, Phys. Rev. **D61**, 112002 (2000).
17. K.W. Edwards *et al.*, Phys. Rev. **D61**, 072003 (2000).
18. M. Fujikawa *et al.*, Phys. Rev. **D78**, 072006 (2008).
19. J.P. Lees *et al.*, Phys. Rev. **D86**, 032013 (2012).
20. T. Barnes *et al.*, Phys. Rev. **D55**, 4157 (1997).
21. F.E. Close *et al.*, Phys. Rev. **D56**, 1584 (1997).
22. A. Donnachie and Yu.S. Kalashnikova, Phys. Rev. **D60**, 114011 (1999).
23. R.R. Akhmetshin *et al.*, Phys. Lett. **B466**, 392 (1999).
24. J.P. Alexander *et al.*, Phys. Rev. **D64**, 092001 (2001).
25. D. Matvienko *et al.*, Phys. Rev. **D92**, 012013 (2015).
26. R.R. Akhmetshin *et al.*, Phys. Lett. **B562**, 173 (2003).
27. A. Abele *et al.*, Eur. Phys. J. **C21**, 261 (2001).
28. M. Bargiotti *et al.*, Phys. Lett. **B561**, 233 (2003).
29. S.I. Bityukov *et al.*, Phys. Lett. **B188**, 383 (1987).
30. B. Aubert *et al.*, Phys. Rev. **D77**, 092002 (2008).
31. N.N. Achasov and G.N. Shestakov, Phys. Atom. Nucl. **59**, 1262 (1996).
32. L.G. Landsberg, Sov. J. Nucl. Phys. **55**, 1051 (1992).
33. A. Abele *et al.*, Phys. Lett. **B415**, 280 (1997).
34. V.M. Aulchenko *et al.*, Sov. Phys. JETP Lett. **45**, 145 (1987).
35. D. Bisello *et al.*, Z. Phys. **C52**, 227 (1991).
36. P. Frenkiel *et al.*, Nucl. Phys. **B47**, 61 (1972).
37. G. Cosme *et al.*, Phys. Lett. **B63**, 352 (1976).
38. D.P. Barber *et al.*, Z. Phys. **C4**, 169 (1980).

39. D. Aston, Phys. Lett. **B92**, 211 (1980).
40. M. Atkinson *et al.*, Nucl. Phys. **B243**, 1 (1984).
41. J.E. Brau *et al.*, Phys. Rev. **D37**, 2379 (1988).
42. C. Amsler *et al.*, Phys. Lett. **B311**, 362 (1993).
43. J. Layssac and F.M. Renard, Nuovo Cimento **6A**, 134 (1971).
44. D. Aston *et al.*, Nucl. Phys. (Proc. Supp.) **B21**, 105 (1991).
45. M. Ablikim *et al.*, Phys. Rev. Lett. **97**, 142002 (2006).
46. G.-J. Ding and M.-L. Yan, Phys. Lett. **B643**, 33 (2006).
47. F.K. Guo *et al.*, Nucl. Phys. **A773**, 78 (2006).
48. A. Zhang *et al.*, Phys. Rev. **D76**, 036004 (2007).
49. B.A. Li, Phys. Rev. **D76**, 094016 (2007).
50. X. Liu *et al.*, Phys. Rev. **D75**, 074017 (2007).
51. A.B. Clegg and A. Donnachie, Z. Phys. **C45**, 677 (1990).
52. D. Bisello *et al.*, Phys. Lett. **107B**, 145 (1981).
53. A. Castro *et al.*, LAL-88-58(1988).
54. M. Atkinson *et al.*, Z. Phys. **C29**, 333 (1985).
55. B. Aubert *et al.*, Phys. Rev. **D76**, 092005 (2007).
56. S. Godfrey and N. Isgur, Phys. Rev. **D32**, 189 (1985).
57. P.L. Frabetti *et al.*, Phys. Lett. **B514**, 240 (2001).
58. P.L. Frabetti *et al.*, Phys. Lett. **B578**, 290 (2004).
59. A. Antonelli *et al.*, Phys. Lett. **B365**, 427 (1996).
60. B. Aubert *et al.*, Phys. Rev. **D77**, 092002 (2008).
61. B. Aubert *et al.*, Phys. Rev. **D73**, 052003 (2006).
62. R.R. Akhmetshin *et al.*, Phys. Lett. **B723**, 83 (2013).
63. A. Obrazovsky and S. Serednyakov, JETP Lett. **99**, 315 (2014).
64. J. Heidenauer *et al.*, Phys. Rev. **D92**, 054032 (2015).