A possible explanation of a broad $1^{--}$ resonant structure around 1.5GeV

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Abstract

The broad $1^{--}$ resonant structure around 1.5GeV observed in the $K^+K^-$ mass spectrum in $J/\psi \rightarrow K^+K^-\pi^0$ by BESII is interpreted as a composition of $\rho(1450)$ and $\rho(1700)$. Various tests are investigated.
Recently, BESII has reported an observation of a broad resonant structure around 1.5GeV in the $K^+K^-$ mass spectrum in $J/\psi \to K^+K^0\pi^0$[1]. The quantum numbers of this structure are determined to be $1^{-+}$. In Ref.[1] single pole is used to fit the data

$$m = 1576^{+49+98}_{-55-91}\text{MeV} \quad \Gamma = 818^{+22+64}_{-23-133}\text{MeV}.$$ (1)

The branching ratio is determined to be

$$B(J/\psi \to X\pi^0)B(X \to K^+K^-) = (8.5 \pm 0.6^{+2.7}_{-3.6}) \times 10^{-4}.$$ (2)

Interpretation of this broad structure is a challenge. In Ref.[2] this structure is interpreted as a $K^*(892)-\kappa$ molecule. Tetraquark state[3] and diquark-antidiquark[4] are proposed to explain the broad width of this structure. It is pointed out in Ref.[5] that two broad overlapped resonances $\rho(1450)$ and $\rho(1700)$ are right at the region of the broad structure and have the same quantum numbers. The final state interactions of $\rho(1450, 1700) \to K^+K^-$ are studied in Ref.[5] and the $B(J/\psi \to \pi^0 \rho(1450, 1700))B(\rho(1450, 1700) \to K^+K^-) \sim 10^{-7}$ is obtained. This branching ratio is far less than the experimental value(2).

In the range $\rho(1600)$ there is complicated structure. A lot of strong evidences show that the 1600-MeV region actually contains two $\rho$-like resonances: $\rho(1450)$ and $\rho(1700)$[6]. In this letter the possibility that the broad structure mentioned above is caused by $\rho(1450)$ and $\rho(1700)$ is revisited. The arguments are following:

1. Their quantum numbers are $1^{-+}$ which are the same as the ones of the structure. They
are isovectors and can be produced in $J/\psi \to \rho(1450, 1700)\pi$.

2. Their masses are in the region of the structure.

3. The decay mode of $\rho(1450, 1700) \to \bar{K}K$ has been found[7]. Therefore, these two resonances do contribute to $J/\psi \to K\bar{K}\pi$.

4. Can the contributions of $\rho(1450, 1700)$ explain the $BR(J/\psi \to X\pi^0)B(X \to K^+K^-)(2)$?

This is a very important issue. In Ref.[1] the estimation of $BR(J/\psi \to \rho(1450)\pi^0)BR(\rho(1450) \to K^+K^-) = (5.0 \pm 0.4) \times 10^{-4}$ is obtained if the broad structure is from $\rho(1450)$. This value is within the lower end of the value(2). The contribution of $\rho(1700)$ should be included. $\rho(1450, 1700) \to K^+K^-$ are found in $\bar{p}p \to \rho(1450, 1700) \to K^+K^0\pi^0$ in Ref.[8] and $B(\bar{p}p \to \rho(1700)\pi \to K^+K^-\pi^0) = (2.9 \pm 0.8) \times 10^{-4}$ is reported[8]. In Ref.[9] $BR(\bar{p}d \to \pi^-\pi^-\pi^+p_{\text{spectator}}) = (1.1 \pm 0.1) \times 10^{-2}$ is presented. $\rho(770), \rho(1450), \rho(1700), f_2(1275)...$ are found in this process. The data in Ref.[7] leads to $BR(\rho(1700) \to \pi\pi) \sim 0.25 \times 10^{-2}$. Using all these data, the estimation $BR(\rho(1700) \to K\bar{K}) > 10^{-3}$ is obtained. Adding the contribution of $\rho(1700)$ to the estimation made in Ref.[1], the possibility that $BR(J/\psi \to \rho(1450, 1700)\pi^0 \to K^+K^-\pi^0)$ reaches the value presented in Eq.(2) is not impossible.

In Ref.[5] loop diagrams are calculated to determine the decay rates of $\rho(1450, 1700) \to K\bar{K})$. Very small branching ratios are found and the authors conclude that comparing
with the data(2), $BR(J/\psi \rightarrow \rho(1450, 1700)\pi^0 \rightarrow K^+K^−\pi^0)$ is too small. A different point of view is presented in this letter. $\rho(770)$ meson is made of u and d quarks. In a chiral field theory of pseudoscalar, vector, and axial vector mesons[10] it is shown that $\rho(770)$ is coupled to $K\bar{K}$ at the tree level[10]

$$
\mathcal{L}_{\rho K\bar{K}} = \frac{2}{g} f_\rho(q^2) f_{iab} \rho^i_\mu K_a \partial_\mu K_b,
$$

$$
\mathcal{L}_{\rho\pi\pi} = \frac{2}{g} f_\rho(q^2) \epsilon_{ijk} \rho^i_\mu \pi^j_\mu \partial_\mu \pi^k,
$$

$$
f_\rho(q^2) = 1 + \frac{q^2}{2\pi^2 m_\rho^2} \left\{ (1 - \frac{2c}{g})^2 - 4\pi^2 c^2 \right\},
$$

$$
c = \frac{f^2}{2gm_\rho^2}.
$$

(3)

where g is a universal coupling constant and determined to be 0.39. Eqs.(3) show that in the chiral limit the strengths of the couplings $\rho\pi\pi$ and $\rho K\bar{K}$ are the same at the tree level. In this chiral theory $\omega$ meson couples to $K\bar{K}$ at the tree level too. All $\rho K\bar{K}$, $\omega K\bar{K}$, and $\phi K\bar{K}$ couplings contribute to both the form factors of charged kaon and neutral kaon[11]. Theory agrees with data very well. The decay $\tau \rightarrow K\bar{K}\nu$ is dominated by the vertex $\mathcal{L}_{\rho K\bar{K}}$ at the tree level. Theory is in good agreement with data[12]. The vertex $\mathcal{L}_{\rho K\bar{K}}$ at the tree level contributes to $\pi K$ scatterings too[13] and good agreement with data is obtained[13]. Therefore, the coupling $\rho K\bar{K}$ at the tree level exists and is supported by experiments. In this chiral field theory meson vertices at the tree level are at the leading order in $N_C$ expansion and loop diagrams of mesons are
at higher order. Therefore, loop diagrams of mesons are suppressed by $N_C$ expansion. For example, $m_{\omega} - m_{\rho}$, $m_{f_1(1285)} - m_{a_1}$, $BR(\phi \rightarrow \rho\pi)$ are from one-loop diagrams of mesons and they are small. Comparing with $\rho(770)$, $\rho(1450, 1700)$ are isovectors too. There is no obvious reason why the couplings $\rho(1450, 1700)K\bar{K}$ at the tree level are forbidden. On the other hand, based on the arguments of Ref.[10], loop diagrams of mesons are at higher order in $N_C$ expansion. Therefore, $BR(\rho(1450, 1700) \rightarrow K\bar{K})$ obtained from loop diagrams of mesons in Ref.[5] are small. Adding tree diagrams which at the leading order in $N_C$ expansion, the increase of $BR(\rho(1450, 1700) \rightarrow K\bar{K})$ should be expected.

5. The experimental values of the widths of $\rho(1450, 1700)$ have a wide range[7]. The range of the width of $\rho(1450)$ is $60 - 547 \pm 86^{+46}_{-45}MeV$ and for $\rho(1700)$ it is $100 - 850 \pm 200 MeV$. In a high statistics study of the decay $\tau^- \rightarrow \pi^-\pi^0\nu_\tau$[14] both $\rho(1450, 1700)$ are found. In one fit $\Gamma(\rho(1450)) = 471 \pm 29 \pm 21MeV$ and $\Gamma(\rho(1700)) = 255 \pm 19 \pm 79MeV$ are determined. $\Gamma(\rho(1450)) = 553 \pm 31 \pm 21MeV$ and $\Gamma(\rho(1700)) = 567 \pm 81 \pm 79MeV$ are obtained in the second fit. Therefore, it is not a problem to use $\rho(1450, 1700)$ to understand the broad structure(1).

All the arguments provided above show it is possible that the broad structure observed in $J/\psi \rightarrow K^+K^-\pi^0$ is caused by $\rho(1450, 1700)$.

In this letter tests of this possibility are investigated. The decay mode of $\rho(1450, 1700) \rightarrow$
ππ has been found[7]. Therefore, the broad structure observed in \( J/\psi \to K^+K^-\pi^0 \) should be observed in the spectrum of \( \pi^+\pi^- \) of \( J/\psi \to \pi^+\pi^-\pi^0 \). The effective Lagrangians for \( J/\psi \to \rho(1450, 1700)\pi^0 \to K^+K^-\pi^0 \) are constructed

\[
\mathcal{L}_{J/\psi \to \rho\pi} = \frac{2g_J}{f_\pi} \epsilon^{\mu\nu\alpha\beta}(\partial_\mu J_\nu - \partial_\nu J_\mu)(\partial_\alpha \rho^i_\beta - \partial_\beta \rho^i_\alpha)\pi^i,
\]

\[
\mathcal{L}_{\rho \to K^+K^-} = g_\rho \rho^i_\mu f_{3ab} K_a \partial_\mu K_b,
\]

(4)

where \( \rho \) is either \( \rho(1450) \) or \( \rho(1700) \). The distribution of \( J/\psi \to \rho(1450, 1700)\pi^0 \to K^+K^-\pi^0 \) is obtained

\[
\frac{d\Gamma}{dq^2} = \frac{1}{9f_\pi^2 m_{\pi}^4 (2\pi)^3} \frac{m_{\pi}^2}{q^2 - m_{\pi}^2} \frac{m_{\pi}^2}{q^2 - m_{\pi}^2} \frac{2}{\Gamma_1 + \frac{g_1}{\sqrt{q^2 \Gamma_1}}} + \frac{2}{\Gamma_1 + \frac{g_2}{\sqrt{q^2 \Gamma_2}}},
\]

(5)

where \( q \) is the momentum of \( \rho \), \( m_1 = 1.45 GeV \) and \( m_2 = 1.7 GeV \), \( g_{1,2} \) are two parameters, \( \Gamma_1 = 0.4 GeV \), \( \Gamma_2 = 0.4 GeV \), and \( g_1 = 1.495 g_2 \) are tried to fit the distribution obtained by BESII[1]. The width of the structure obtained by Eq.(5) is about 600MeV which is compatible with the data(1). In the chiral limit the effective Lagrangian of \( \rho(1450, 1700) \to \pi\pi \) is constructed as

\[
\mathcal{L}_{\rho(1450,1700)\to\pi\pi} = g_\rho \rho^i_\mu \epsilon_{ijkl} \partial_\mu \pi_k.
\]

(6)

Notice \( f_{3ab} = \frac{1}{2}(a, b = 4, 5, 6, 7) \). Substituting \( m_K^2 \) by \( m_{\pi^+}^2 \) in Eq.(5) and multiplying Eq.(5) by a factor of 4, the distribution of \( J/\psi \to \rho^0(1450, 1700)\pi^0 \to \pi^+\pi^-\pi^0 \) is obtained in the
resonance area of $\rho^0(1450,1700)$. Integrating this distribution, it is obtained

$$BR(J/\psi \rightarrow \rho^0(1450,1700)\pi^0 \rightarrow \pi^+\pi^-\pi^0) \sim 8BR(J/\psi \rightarrow \rho^0(1450,1700)\pi^0 \rightarrow K^+K^-\pi^0).$$

(7)

On the other hand, we can search for $\rho^{\pm}(1450,1700)$ in $J/\psi \rightarrow \pi^+\pi^-\pi^0$.

The decay mode $\rho(1450,1700) \rightarrow 4\pi$ has been found[7]. $\rho\pi\pi$ is the dominant decay channel of $\rho(1700)$. According to the chiral meson theory[11], $a_1$ strongly couples to $\rho\pi$. Therefore, $\rho(1700) \rightarrow \rho\pi\pi$ is dominant by $\rho(1700) \rightarrow a_1\pi$. Because of small phase space of $\rho(1450) \rightarrow a_1(1260)\pi$ $BR(\rho(1450) \rightarrow a_1(1260)\pi \rightarrow \rho\pi\pi)$ is small. $\rho(1700)$ can be searched in $J/\psi \rightarrow \rho(1700)\pi \rightarrow a_1\pi\pi$.

$\rho(1450,1700) \rightarrow \eta\rho,\omega\pi$ are discovered[7]. $\rho(1450,1700)$ can be found in $J/\psi \rightarrow \rho(1450,1700)\pi \rightarrow \eta\rho\pi,\omega\pi\pi$. $\rho(1450,1700) \rightarrow \phi\pi$ are OZI suppressed. Therefore, $BR(\rho(1450,1700) \rightarrow \phi\pi)$ are much smaller than $BR(\rho(1450,1700) \rightarrow \pi\pi,a_1\pi,\eta\pi,\omega\pi)$. However, if the broad structure is a four quark state $X[3,4]$ which via ”fall apart” decays, there is no suppression for this four quark state to decay to $\phi\pi$. Larger $BR(J/\psi \rightarrow X\pi \rightarrow \phi\pi\pi)$ and very small $BR(J/\psi \rightarrow X\pi \rightarrow \pi\pi\pi,a_1\pi\pi,\eta\rho\pi,\omega\pi\pi)$ should be expected if $X$ is a four quark state.

The nature of $\rho(1450,1700)$ is very interesting. In Ref.[15] the authors 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. In Ref.[16] it is argued that the inclusion of a isovector hybrid is essential to explain the $e^+e^- \rightarrow 4\pi$ data.
In summary, the possibility that the broad structure reported by BESII is caused by 
$\rho(1450,1700)$ is not ruled out. Various tests are proposed.

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