Tetra-quark Systems in Heavy Mesons
– $D_{s0}^+(2317)$, $X(3872)$ and related –

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Typical candidates of open- and hidden-charm tetra-quark mesons are studied through their decays and productions, and are compared with conventional mesons. In addition, it is proposed how to confirm experimentally that they are tetra-quark mesons.

I. INTRODUCTION

Tetra-quark mesons can be classified into the following four groups in accordance with the difference of symmetry property of their flavor wavefunctions (wfs.) \[ \{qq\bar{q}q\} \[ \{qq\bar{q}q\} \[ \{qq\bar{q}q\} \[ \{qq\bar{q}q\}, \ (q = u, d, s, c), \] \] (I.1)

where parentheses and square brackets denote symmetry and anti-symmetry, respectively, of flavor wfs. under exchange of flavors between them. Each term on the right-hand-side (r.h.s.) of Eq. (I.1) is again classified into two groups with \[ 3_c \times 3_c \] and \[ 6_c \times 6_c \] of the color SU$_3$, which can provide colorless tetra-quark states. The force between two quarks is attractive (or repulsive) when they are of \[ 3_c \] (or \[ 6_c \] states), so that the \[ 3_c \times 3_c \] state is taken as the lower lying one. Narrow widths of the open- and hidden-charm tetra-quark mesons with \[ 3_c \times 3_c \] and \[ 6_c \times 6_c \] can be understood by a small overlap of color and spin wfs. On the other hand, the light scalar mesons \[ 3_c \] and \[ 6_c \] can be understood in the \[ J \leq 0 \] scheme. However, in this case, the corresponding small overlap of color and spin wfs. is not guaranteed, because QCD is non-perturbative and states with \[ 3_c \times 3_c \] and \[ 6_c \times 6_c \] can largely mix with each other at such a low energy scale, so that they are not necessarily narrow. When it is required that the total wfs. of \[ \{qq\} \] and \[ \{q\bar{q}\} \] are antisymmetric as in the flavor symmetry limit, their spins are 0 and 1, respectively, because the color wf. is antisymmetric for \[ \bar{q}q \]. Therefore, the spin and parity of (at least, dominant components of) \[ \{qq\bar{q}q\} \] and \[ \{qq\bar{q}q\} \] mesons with \[ 3_c \times 3_c \] are \[ J^P = 0^+ \] and \[ 1^+ \], respectively. For the same reason, \[ \{qq\bar{q}q\} \] can have \[ J^P = 0^+, 1^+, 2^+ \]. However, we ignore it, because no candidate of \[ (K\pi)_{I=3/2} \] state which can be given by the \[ \{qq\bar{q}q\} \] state has been observed in the region \[ \lesssim 1.8 \text{ GeV} \] in contrast with the theoretical expectation [1]. For more details, see Refs. [2–5].

II. OPEN-CHARM SCALAR MESONS

$D_{s0}^+(2317)$ was discovered through the $D^0_\pi^0$ channel in inclusive $e^+e^-$ annihilation, while no signal of resonance peak at the same energy in the radiative $D_s^+\gamma$ channel has been observed. Therefore, a severe constraint

$$ R(D^+_{s0}(2317))_{\text{CLEO}} = \frac{\Gamma(D^+_{s0}(2317) \rightarrow D_{s}^{*+}\gamma)}{\Gamma(D^+_{s0}(2317) \rightarrow D^0_{s}\pi^0)}_{\text{CLEO}} < 0.059 \quad (\text{II.1}) $$

was given by the CLEO [10]. In the case of $D_{s}^{*+}$, the ratio of decay rates has been measured as [4]

$$ R(D_{s}^{*+})_{\exp} = \frac{\Gamma(D_{s}^{*+} \rightarrow D_{s}^{+}\pi^0)}{\Gamma(D_{s}^{*+} \rightarrow D_{s}^{+}\gamma)}_{\exp} = 0.062 \pm 0.008. \quad (\text{II.2}) $$

This implies that isospin non-conserving interactions are much weaker than the electromagnetic ones which are much weaker than the isospin conserving strong ones. In fact, assuming that the isospin non-conservation is caused by the $\eta\pi^0$ mixing with the mixing parameter, $\epsilon \simeq 10^{-2}$, as usual [11], and applying the vector meson dominance

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to the radiative decay, we can easily reproduce Eq. \( \text{(12)} \), i.e., \( R(D_s^{+}) \sim 0.06 \). Next, when \( D_s^{+}(2317) \) is assigned to the iso-triplet tetra-quark scalar \( \tilde{F}_1^* \sim [c\bar{s}]\bar{u}d \), Eq. \( \text{(11)} \) can be satisfied, i.e., \( R(D_s^{+}(2317) = \tilde{F}_1^*) \sim (4 - 5) \times 10^{-3} \ll 0.059 \). In contrast, if \( D_s^{+}(2317) \) were assigned to an iso-singlet state, (i) the conventional scalar \( D_s^{+} \sim \{cs\} \), or (ii) the iso-singlet tetra-quark \( F_1^* \sim [c\bar{s}]\bar{u}d \), Eq. \( \text{(11)} \) could not be satisfied, i.e., (i) \( R(D_s^{+}(2317) = D_s^{+}) \sim 70 \gg 0.059 \), and (ii) \( R(D_s^{+}(2317) = \tilde{F}_1^*) \sim 3 \gg 0.059 \), as expected above. In this way, it is seen that \( D_s^{+}(2317) \) should be assigned to an iso-triplet state \( \tilde{F}_1^* \). In addition, we have learned that \( \tilde{F}_1^* \) and \( D_s^{+} \) decay dominantly into radiative channels. For more details, see Refs. \( \text{[7]} \) and \( \text{[8]} \).

Just after the discovery of \( D_s^{+}(2317) \), charm-strange scalar mesons which are degenerate with \( D_s^{+}(2317) \) have been observed not only in the \( D_s^+\pi^0 \) but also the \( D^{*+}\gamma \) channels of \( B \) decays \( \text{[12]} \), \( Br(B \rightarrow D\bar{D}_s^{0}(2317)[D_s^+\pi^0]) \sim (8.5 \pm 2.1 \pm 2.6) \times 10^{-4} \) and \( Br(B \rightarrow D\bar{D}_s^{0}(2317)[D_s^+\gamma]) \sim (2.5 \pm 1.9 \pm 0.7 < 7.5) \times 10^{-4} \). (The above naming conventions, \( D_s^{+}(2317)[D_s^+\pi^0] \) and \( D_s^{+}(2317)[D_s^+\gamma] \), have been taken to distinguish the charm-strange scalar mesons observed in \( D \) decays from \( D_s^{+}(2317) \) in e^+e^- annihilation.) It should be noted that the above production rate of \( D_s^{+}(2317)[D_s^+\gamma] \) seems to be not much smaller than that of \( \tilde{D}_s^{+}(2317)[D_s^+\pi^0] \), in contrast with the e^+e^- annihilation. We now identify \( \bar{D}_s^{+}(2317)[D_s^+\pi^0] \) with \( \tilde{F}_1^* \) which has been assigned to \( \tilde{F}_1^* \), and \( \tilde{D}_s^{+}(2317)[D_s^+\gamma] \) is assigned to \( \tilde{F}_0^* \) which decays dominantly into the \( D_s^{+}\gamma \), as discussed above. It should be noted that \( \tilde{F}_1^* \) and \( \tilde{F}_0^* \) are degenerate with each other, in analogy to \( a_0(980) \) and \( f_0(980) \).

On the other hand, mass of the charm-strange \( (C = S = 1) \) scalar state has recently been calculated on the lattice \( \text{[14]} \), and the result has reproduced the measured mass of \( D_s^{+}(2317) \) which has been naturally assigned to the iso-triplet \( \tilde{F}_1^* \) in the above. This implies that the mass of the lowest \( C = S = 1 \) state which can contain not only the scalar \( \{cs\} \) but also the scalar \( [c\bar{s}]\bar{u}d \), etc. is much lower than that of the scalar \( \{cs\} \) which has been calculated in the quench approximation (i.e., with no multi-quark component) on the lattice \( \text{[12]} \), and hence the lowest \( C = S = 1 \) state cannot be dominated by the \( [c\bar{s}]\bar{u}d \) but could be by the \( [c\bar{s}]\bar{u}d \) component. It would be natural because \( a_0(980) \) and \( f_0(980) \) have been assigned \( \text{[1]} \) to the scalar \([ns][\bar{ns}]_{I=1} \) and \([ns][\bar{ns}]_{I=0} \), and are approximately degenerate with each other while \( f_0(1500) \) which is expected \( \text{[12]} \) to be dominated by the scalar \( ss \) is much heavier.

Because \( D_s^{+}(2317) \) has been assigned to \( \tilde{F}_1^* \), its neutral and doubly charged partners, \( F_0^* \) and \( F_1^* \), should exist, although they have not been observed in inclusive e^+e^- annihilation \( \text{[17]} \). This implies that their production is suppressed in this process, as was understood within the framework of minimal \( q\bar{q} \) pair creation \( \text{[15]} \). In this way, it can be understood why experiments did not observe them \( \text{[19]} \). In addition, it has been discussed \( \text{[18]} \) that it is better to search for them in \( B \) decays, because the \( \tilde{D}_s^{+}(2317)[D_s^+\gamma] \) as a signal of \( \tilde{F}_0^* \) has already been observed in \( B \) decays, as mentioned above, and that their production rates are expected to be

\[
Br(B_{u} \rightarrow D^{-}\tilde{F}_1^{*+}) \sim Br(B_{u} \rightarrow D^{0}\tilde{D}_s^{0}(2317)[D_s^+\pi^0])_{\exp} \\
\sim Br(B_{d} \rightarrow D^{0}\tilde{F}_1^{*0}) \sim Br(B_{d} \rightarrow D^{-}\tilde{D}_s^{0}(2317)[D_s^+\pi^0])_{\exp} \sim 10^{-3-4},
\]

(II.3)

because all these decays can be described by similar quark-line diagrams, where more precise values of their measurements have been given in Refs. \( \text{[13]} \) and \( \text{[20]} \). In addition to \( \tilde{F}_0^{*+,++,+++} \) and \( \tilde{F}_0^{*0} \), the \( [c\bar{q}][q\bar{q}] \) states can have a narrow \( \text{[2]} \) \( \tilde{D} \sim [c\bar{s}][\bar{u}d] \). This, as well as the conventional \( D_s^{+} \), should be found in the observed \( D\pi \) enhancement just below the well-known \( D_s^{+} \) peak. Therefore, we now investigate the conventional open-charm scalar mesons, \( D_s^{+} \) and \( D_s^{0} \), to distinguish them from tetra-quark \( \tilde{D} \) and \( \tilde{F}_1^{*0} \). The most recent measurement of the \( D\pi \) enhancement \( \text{[21]} \) has provided \( m_{D_s^{0}} = 2297 \pm 32 \text{ MeV} \) and \( \Gamma(D_0) = 273 \pm 74 \text{ MeV} \). However, it is expected that the above very broad enhancement might have a structure \( \text{[22]} \) containing a broad conventional scalar \( D_s^{0} \) and a narrow tetra-quark \( \tilde{D} \). Although the latter seems to have already been observed as a narrow peak around the lower tail of the \( D\pi \) enhancement, it has not seriously been considered in Ref. \( \text{[21]} \). Because masses of \( D_s^{0} \) and \( D_s^{++} \) are not definitely known yet, as seen above, we tentatively take \( m_{D_s^{0}} \approx 2.3 \text{ GeV} \) and \( m_{D_s^{++}} \approx 2.4 \text{ GeV} \). The latter seems to be compatible with a prediction on the scalar \( \{cs\} \) mass in the quench approximation \( \text{[13]} \), as mentioned before. Taking the flavor \( SU_f(4) \) relation for the strong vertices with a \( 20 - 30 \% \) deviation of spatial \( w \)-overlap from unity (the symmetry limit) \( \text{[2]} \) and the experimental data \( \text{[4]} \) on the well-known light scalar \( F_0(980) \) as the input data, rates for their dominant decays, \( \tilde{D}_s^{0} \) and \( D_s^{++} \) to \( DK \), and hence their widths can be estimated to be \( \Gamma(D_0) \approx 50 - 60 \text{ MeV} \) and \( \Gamma(D_s^{++}) \approx 40 - 50 \text{ MeV} \). The latter leads to \( \Gamma(D_s^{0} \rightarrow D_s^{0}\gamma) \approx 0.2 - 0.3 \text{ keV} \), and hence \( R(D_s^{0}) \approx 70 \), as discussed before. Therefore, we expect that the observed broad \( D\pi \) enhancement can have a structure which includes the broad \( D_s^{0} \) and the narrow \( \tilde{D} \), as discussed before. The CDF \( \text{[24]} \) also observed peaks in \( D\pi \) mass distributions around 2.2 - 2.3 \text{ GeV} which can include \( \tilde{D} \) and \( D_s^{0} \). Besides, a clear peak in \( DK \) mass distribution around 2.4 \text{ GeV} which is degenerate with \( D_s^{++} \) has been observed by the CLEO \( \text{[23]} \). Because these peaks have been taken away as false peaks, however, we hope that experiments re-analyze more precisely the above mass distributions and find true signals of \( D_s^{++} \), \( D_s^{0} \) and \( \tilde{D} \) behind the false peaks.
III. HIDDEN-CHARM MESONS

$X(3872)$ was discovered in the $\pi^+\pi^- J/\psi$ mass distribution by the Belle [25] and then confirmed [26] by the CDF, D0 and Babar. (Hereafter, we describe $J/\psi$ as $\psi$, for simplicity.) Experiments [23,29] favor $1^{++}$ as the $J^{PC}$ of $X(3872)$. However, it decays into two different final states with opposite G-parities,

$$R = \frac{Br(X(3872) \to \pi^+\pi^-\bar{\psi})}{Br(X(3872) \to \pi^+\pi^- \psi)} = 1.0 \pm 0.4 \pm 0.3.$$  \hspace{1cm} (III.1)

This is puzzling because the well-known strong interactions conserve G-parity. In addition, the Belle [25] and CDF [30] have noted that the decay $X(3872) \to \pi^+\pi^- \psi$ proceeds through $\rho^0 \psi$. If the isospin were conserved in the decay, there should exist charged partners of $X(3872)$, in contradiction to a negative result from an experimental search [31].

This would imply that $X(3872)$ is an isospin-singlet state, and hence the isospin conservation does not work in the $X(3872) \to \rho^0 \psi \to \pi^+\pi^- \psi$ decay. Besides, the Belle [32] has suggested that the $X(3872) \to \pi^+\pi^- \rho^0 \psi$ decay proceeds through the sub-threshold $X(3872) \to \omega \psi$. If isospin is conserved in this decay, $X(3872)$ would be an isospin-singlet state. This is consistent with the above negative result on the search for its charged partners.

Although various approaches [33] to solve the above puzzle have been proposed, they are unnatural, because the phenomenologically well-known $\omega \rho^0$ mixing [34] which can play an important role in the isospin non-conservation under consideration [35], has not been considered. Under the assumption that the above isospin non-conservation is caused by the $\omega \rho^0$ mixing with a mixing parameter [34], the isospin non-conserving $X(3872) \to \rho^0 \psi$ decay proceeds through two steps: the isospin conserving $X(3872) \to \omega \psi$ and the subsequent $\omega \rho^0$ mixing. $X(3872) \to \omega \psi \to \rho^0 \psi$. Here we consider the $X(3872) \to \gamma \psi$ in place of the $X(3872) \to \pi^+\pi^- \rho^0 \psi$ decay in Eq. (III.1), because the kinematics of the former is much simpler than the latter. As the result, we shall see below that existing data on the ratio

$$R_X' = \frac{Br(X(3872) \to \gamma \psi)}{Br(X(3872) \to \pi^+\pi^- \psi)}$$  \hspace{1cm} (III.2)

will select a realistic interpretation of $X(3872)$. When the above assumption is combined with the VMD [12], the $X(3872) \to \gamma \psi$ decay would proceed as

$$X(3872) \to \omega \psi \to \gamma \psi \text{ and } X(3872) \to \omega \psi \to \rho^0 \psi \to \gamma \psi.$$  \hspace{1cm} (III.3)

However, the contribution of the second decay is much smaller than that for the first one because $|g_{\omega \rho^0}/m_{\omega^0}^2| \ll 1$, while the role of the $\rho^0$ pole can be strongly enhanced [35] in the $X(3872) \to \omega \psi \to \rho^0 \psi \to \pi^+\pi^- \psi$ because $|g_{\omega \rho^0}/(m_{\omega^0}^2 - m_{\rho^0}^2)| \gg |g_{\omega \rho^0}/m_{\omega^0}^2|$.

If $X(3872)$ were an axial-vector charmonium, the radiative decay under consideration could have an extra contribution through the $\psi$ pole, $X(3872) \to \psi \psi \to \gamma \psi$, as the dominant one. In contrast, when $X(3872)$ is a tetra-quark state like [36] $\{(|cn|\bar{c}n) + (|cn|\bar{c}n)\}$ arising from the last term on the r.h.s. of Eq. (I.1), such a contribution is suppressed because of the OZI rule [37]. Therefore, we study if the above isospin non-conservation can be reconciled with the measured ratios, $(R_X')_{\text{Belle}} = 0.11 \pm 0.05$ [32] and $(R_X')_{\text{Babar}} = 0.33 \pm 0.12$ [38].

In the above $\omega \rho^0$ mixing model [35], the value of $R_X'$ in Eq. (III.2) can be estimated without any unknown parameter, if $X(3872)$ is a tetra-quark system, i.e., $(R_X')_{\text{tetra}} \simeq (R_X')_{\text{Babar}} \simeq (R_X')_{\text{Belle}}$, because all the parameters involved in the decays can be estimated by using the existing experimental data [4], except for the $X\omega \psi$ coupling $g_{X\omega \psi}$ which can be canceled by taking the ratio of decay rates in Eq. (III.2). The $\gamma V$ coupling strengths $X_V(0)$, $V = \rho^0, \omega, \phi, \psi$, on the photon-mass-shell have already been estimated [39]. In addition, the measured production of prompt $X(3872)$ seems to favor a more compact object (i.e., a tetra-quark meson) over a loosely bound meson-meson molecule [40]. In contrast, if $X(3872)$ were a charmonium, the estimated ratio would be much larger than the observation, i.e., $(R_X')_{\text{cqc}} \gg (R_X')_{\text{tetra}} \simeq (R_X')_{\text{Babar}} \simeq (R_X')_{\text{Belle}}$, because of the OZI rule. Therefore, the existing data on $R_X'$ favor a tetra-quark interpretation of $X(3872)$, although a small mixing of $\chi_{c1}'$ would be needed to understand the measured ratio [38], $\Gamma(X \to \gamma \psi')/\Gamma(X \to \gamma \psi)_{\text{Babar}} = 3.4 \pm 1.4$. See Ref. [35] for more details.

IV. SUMMARY

Comparing the ratio of rates for the $D^+_s(2317) \to D^{*+}_s \gamma$ decay to the $D^+_s \pi^0$ with the experimental constraint Eq. (III.1), we have seen that assigning $D^+_s(2317)$ to $D^{*+}_s \pi^0$ is favored by experiments. In this case, $F^+_0, F^+_1$ and $F^+_2$ should exist and be observed. However their production through inclusive $e^+e^- \to c\bar{c}$ is suppressed, so that their observation is likely to be quite difficult, although $D^+_s(2317)$ itself has already been observed. Therefore, we have
discussed that, to search for them, $B$ decays would be much better. In fact, an indication of $\hat{F}_0^+ = \hat{D}_{s0}^+(2317)[D_s^{*+}\gamma]$ has already been observed by the Belle [13].

We have studied the ratio of decay rates $R_{\gamma X}$ in Eq. (III.2), assuming that the isospin non-conservation is caused by the phenomenologically well-known $\omega\rho_0$ mixing. As the result, we have seen that the existing data on $R_{\gamma X}$ and production of the prompt $X(3872)$ favor a tetra-quark interpretation of $X(3872)$ like $\{[cn](\bar{c}\bar{n}) + (cn)(\bar{c}\bar{n})]\}_{I=0}$ over a meson-meson molecule and a charmonium. To confirm the above interpretation, observation of $\{[cn](\bar{c}\bar{n}) - (cn)(\bar{c}\bar{n})\}_{I=0}$ with a mass close to $m_{X(3872)}$ in the $\pi^0\pi^0\psi$ channel is awaited.

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