Prediction of charmoniumlike structures in the hidden-charm di-eta decays of higher charmonia

Dian-Yong Chen1,2,3, Xiang Liu1,2,3 and Takayuki Matsuki4

1Research Center for Hadron and CSR Physics, Lanzhou University & Institute of Modern Physics of CAS, Lanzhou 730000, China
2School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China
3Nuclear Theory Group, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
4Tokyo Kasei University, 1-18-1 Kaga, Itabashi, Tokyo 173-8602, Japan

Via the single chiral particle emission mechanism, we study the hidden-charm di-eta decays of charmonium states Y(4660) and Y(4790), i.e., Y(4660)/ψ(4790) → η[D0+D−] or η[D∗s(s)D∗] → J/ψη and answer to the question whether there exist isoscalar charmoniumlike structures. Our results indicate that there are enhancement structures near DD∗, D D∗ and D D∗ thresholds in the M_{max}(J/ψη) distributions of Y(4660) → η J/ψ. The calculation of ψ(4790) → η J/ψ predicts the enhancement structures near D D∗, D D∗ and D D∗ thresholds in the corresponding M_{max}(J/ψη) distributions, which are accessible at future experiments, especially BESIII, Belle, BaBar and forthcoming BelleII.

PACS numbers: 13.25.Gv, 14.40.Pq, 13.75.Lb

In 2011, the charged charmoniumlike structures near the DD∗ and D D∗ thresholds were predicted in Ref. [1] by studying the hidden-charm dipion decays of higher charmonia and charmoniumlike states, where the initial single-pion-emission (ISPE) mechanism was adopted [3]. Recently, the BESIII Collaboration reported a charged charmoniumlike structure Z_{c}(3900) in e^+e^- → π^+π^- J/ψ at √s = 4.26 GeV [5], which was confirmed by the Belle Collaboration [4] and in Ref. [6] later. The observation of Z_{c}(3900) confirms our prediction of a charged charmoniumlike structure near the DD∗ threshold existing in the J/ψ π^+ invariant mass spectrum of Y(4260) → J/ψ π^+π^- [1], which provides a crucial test of the ISPE mechanisms.

Besides these predictions listed in Ref. [1], we have given abundant phenomena of charged charmoniumlike structures by applying the ISPE mechanism [3] and the initial single-chiral-particle-emission (ISChE) mechanism [5], which is an extension of the ISPE mechanism. The charged charmoniumlike structures with hidden charm and open-strange channels in the J/ψ K^+ invariant mass spectrum for the processes ψ(4415)/Y(4660)/ψ(4790) → J/ψ K^+K^- have been predicted in Ref. [8]. By studying the hidden-charm dipion decays of the charmoniumlike state Y(4660) with the ISPE mechanism, we have shown that there exist charged charmoniumlike structures near DD∗ and D D∗ thresholds in the J/ψ π^+, ψ(2S)π^+ and h_{c}(1P)π^+ invariant mass spectra of the corresponding hidden-charm dipion decays of Y(4600) [6]. The ISPE mechanism has been applied to the processes ψ(4160)/ψ(4415) → π D^0 D^0(s) to predict the enhancement structures near the thresholds of D D̅ and D D̅. [7] Very recently, the BESIII Collaboration has announced another charged charmoniumlike structure Z_{c}(4025) in the recoil mass spectrum of in e^+e^- → (D D̅ )^-π^+ at √s = 4.26 GeV [9].

These novel phenomena of charged charmoniumlike structures are of a common peculiarity, i.e., all of them are either isovectors or isodoublets. In the following, it is natural to ask whether there exists the corresponding isoscalar charmoniumlike structure as a partner of the predicted charged charmoniumlike structures. This question inspires our interest in further studying isoscalar charmoniumlike structures by choosing suitable decay processes.

Under the ISChE mechanism, the hidden-charm di-eta decays of higher charmonia and charmoniumlike states can be a good platform to search for isoscalar charmoniumlike structures since η, K and π are chiral particles. In this work, we choose the processes,

Y(4660)/ψ(4790) → η[D^0 D^0(s)] or η[D^0 D^0(s)] → J/ψη,

where both D^0 D^0(s) and D^0 D^0(s) are the intermediate states of Y(4660) and ψ(4790) which decay into J/ψη. As a vector charmoniumlike state, Y(4660) was reported by Belle in the ψ(2S)π^+π^- invariant mass spectrum of e^+e^- → ψ(2S)π^+π^- [10], which was later confirmed by BaBar [11] in the same process. ψ(4790) is a predicted charmonium with a quantum number n^2S_1 = 5^3S_1, which is derived from the analysis of the experimental data with the resonance spectrum expansion model [12].

Via the ISChE mechanism, the initial higher charmonium or charmoniumlike state first emits an η meson, which carries continuous energy distribution. Then, the charmonium or charmoniumlike state can dissolve into the intermediate D^0 D^0(s) and D^0 D^0(s). Due to the continuous energy distribution of the emitted η, the intermediate D^0 D^0(s) and D^0 D^0(s) with low momenta can easily transit into J/ψη by exchanging a proper charm or charm-strange meson. Taking Y(4660) → J/ψη as an example, we present the corresponding typical diagrams in Fig. [1].

To calculate the diagrams displayed in Fig. [1] we apply the effective Lagrangian approach, which is based on heavy quark limit and chiral symmetry. The effective Lagrangian describing interactions of Y(4660)/ψ(4790) with ηD^0 D^0(s) or ηD^0 D^0(s) is [13] [14]

\[ \mathcal{L}_{YD^0D^0(s)} = -ig_{YDD}e^{\mu\nu\rho\sigma}Y_{\mu\nu} \partial_{\rho}D_\sigma \partial_{\rho}D_\sigma \]
In the heavy quark limit, the coupling constants satisfy the relation

\[ g_{J/\psi DD} = g_{J/\psi D^*D^*} \sqrt{m_D m_{D^*}} = g_{J/\psi D^*D^*} \frac{m_D}{m_{D^*}} = \frac{m_{J/\psi}}{f_{J/\psi}}, \]

where \( f_{J/\psi} = 416 \text{ MeV} \) is the decay constant of \( J/\psi \), which can be evaluated by the leptonic decay width of \( J/\psi \) [20].

Considering chiral symmetry and heavy quark limit, we also have

\[ L_{D^*D^*\eta^\prime} = -ig_{D^*D^*\eta^\prime} \partial \bar{\eta}D^*\eta^\prime - \bar{D}^*\partial D^* \eta^\prime, \]

(4)

where \( \eta^\prime \) only operates on \( D^* \) and \( \bar{D}^* \) and the relevant coupling constants satisfy \( g_{D^*D^*\eta^\prime} = g_{D^*D^*\eta}/\sqrt{m_D m_{D^*}} = 2g/f_\eta \) and \( g_{\bar{D}^*D^*\eta^\prime} = \sqrt{m_{D^*} m_{D^*D^*\eta}/m_D m_{D^*}} \), where \( f_\eta = 132 \text{ MeV} \) is the pion decay constant and \( g = 0.59 \) is estimated from the partial decay width of \( D^* \rightarrow D \eta [20] \).

With the above effective Lagrangian, we can obtain the amplitudes corresponding to the diagrams in Fig. 1. In the following, we adopt a symbol \( M_{AB}^\omega \) to represent the amplitude of this process, i.e., the initial charmonium/charmioniumlike state dissolves into a meson pair \( AB \) with one \( \eta \) emission, which transits into \( J/\psi /\psi \) in the final state by exchanging a meson \( C \). We can express this process

\[ Y(4660)(p_0) \rightarrow \eta(p_3)[A(p_1)B(p_2)]_{L=0} \rightarrow \eta(p_3)[\eta(p_4)J/\psi(p_5)], \]

which is marked by the corresponding four momentum.

Taking \( Y(4660) \rightarrow \eta \eta J/\psi \) via the \( DD \) intermediate state as an example, we write out its decay amplitude, which is of the form

\[ A_{DD}^{\eta \eta} = (i^3 \int \frac{d^4 q}{(2\pi)^4}) \left[ -ig_{YD^*D^*\eta^\prime} \left( -i\gamma_5 q_\mu \right) \left( \gamma^\mu \right) \right] \times \left[ \frac{g_{\bar{D}^*D^*\eta} \left( -i\gamma_5 q_5 \right) \left( \gamma^5 \right)}{g_{\bar{D}^*D^*\eta^\prime}} \right] \frac{1}{p_1^2 - m_D^2} \frac{1}{p_2^2 - m_D^2} \frac{1}{q^2 - m_{D^*}^2} F(q^2, m_{D^*}^2), \]

(6)

where a monopole form factor \( F(q^2, m_{D^*}) = (\Lambda^2 - m_{D^*}^2)/(q^2 - m_{D^*}^2) \) is introduced, which plays an important role to describe the off-shell effect of the exchanged charm meson and reflect the vertex effect. Thus, the total amplitudes of \( Y(4660) \rightarrow \eta \eta J/\psi \) with the \( D \bar{D} \) intermediate state contribution can be expressed as

\[ M_{DD} = 2A_{DD}^{\eta \eta}, \]

(7)

where the factor 2 is due to the isospin symmetry. If considering the intermediate charm-strange meson loop contribution for \( Y(4660) \rightarrow \eta \eta J/\psi \), this factor 2 should be replaced by the factor 1. In addition, the parameters in Eq. (6) should be changed as those relevant to the charm-strange meson, i.e., \( m_{D^*} \rightarrow m_{D_{s}} \).
Calculating in the similar way, we can construct the amplitudes for \( Y(4660) \rightarrow \eta\eta J/\psi \) via the intermediate \((D^* \bar{D} \rightarrow \eta \eta) / (D^\ast \bar{D}^\ast \rightarrow \eta \eta + h.c.) \) and \( D^\ast \bar{D}^\ast \rightarrow \eta \eta \). Finally, we obtain the general expression of the differential decay width for \( Y(4660) \rightarrow \eta\eta J/\psi \).

\[
d\Gamma(Y(4660) \rightarrow \eta\eta J/\psi) = \frac{|M|_i^2}{8(2\pi)^3 2m_1 m_2 m_3 m_4} d\omega_{\eta\eta} d\omega_{J/\psi} d\omega_{\bar{J}/\bar{\psi}}
\]

with the subscripts \( i = D\bar{D}, D_1\bar{D}_1, D_2\bar{D}_2, D_3\bar{D}_3, D_4\bar{D}_4, D_5\bar{D}_5 \) to distinguish different contributions form different intermediate states. Here, \( m_{\eta\eta} = (p_4 + p_5)^2 \) and \( m_{J/\psi} = (p_3 + p_2)^2 \). \( m_{Y(4660)} \) denotes the mass of \( Y(4660) \). To calculate the \( \eta\eta J/\psi \) decay, we only need to replace the parameters in the above decay amplitude and differential decay width in Eq. (8).

The input parameters including the masses and coupling constants adopted in this work are listed in Table I.

**TABLE I:** The concrete values of the coupling constants and masses involved in the present work. The masses are in unit of GeV.

| Coupling Value | Coupling Value | Coupling Value |
|----------------|----------------|----------------|
| \( g_{J/\psi DD} \) | 7.44 \( g_{J/\psi D^* D^*} \) | 3.84 GeV \( g_{J/\psi D^* D^*} \) |
| \( g_{J/\psi D D_1} \) | 7.84 \( g_{J/\psi D_1 D_1} \) | 4.04 GeV \( g_{J/\psi D_1 D_1} \) |
| \( g_{J/\psi D_2 D_2} \) | 9.95 \( g_{J/\psi D_2 D_2} \) | 5.14 GeV \( g_{J/\psi D_2 D_2} \) |
| \( g_{J/\psi D_3 D_3} \) | -5.48 GeV \( g_{J/\psi D_3 D_3} \) | -10.62 GeV \( g_{J/\psi D_3 D_3} \) |

| mass (GeV) | mass (GeV) | mass (GeV) |
|------------|------------|------------|
| \( m_D \) | 1.867 \( m_D \) | 2.009 \( m_D \) |
| \( m_{D^*} \) | 2.112 \( m_{D^*} \) | 0.548 \( m_{D^*} \) |
| \( m_{Y(4660)} \) | 4.660 \( m_{Y(4660)} \) | 4.790 |

As presented in Figures 2 and 3, the obtained lineshapes are not smooth since there exist turning points in each diagram, where the tuning points for the \( Y(4660) \rightarrow \eta\eta J/\psi \) and \( \psi(4790) \rightarrow \eta\eta J/\psi \) decays appear when \( M_{\max}(J/\psi \eta) = 3.918 \) GeV and \( M_{\max}(J/\psi \eta) = 3.996 \) GeV, respectively. These turning points are due to the maximum distribution of the \( J/\psi \eta \) invariant mass spectrum itself rather than the ISChE mechanism.

As for \( Y(4660) \rightarrow \eta\eta J/\psi \), we give important information:

1. Besides the tuning points mentioned above, there do not exist other turning points in Fig. 2 (a), (d) and (f).
2. Fig. 2 (b) indicates the existence of another tuning point appearing in the \( M_{\max}(J/\psi \eta) \) distribution.
3. There are explicit enhancement structures in Figs. 2 (c) and (e). As a broad structure, the enhancement in Fig. 2 (c) is around 4.018 GeV. While, this enhancement in Fig. 2 (e) is a sharp peak at \( M_{\max}(J/\psi \eta) = 4.081 \) GeV.

Similar to the above analysis of \( Y(4660) \rightarrow \eta\eta J/\psi \), in the following we also have some extra novel phenomena of \( \psi(4790) \rightarrow \eta\eta J/\psi \), which include:

1. There is an enhancement structure near \( M_{\max}(J/\psi \eta) = 4.081 \) GeV as shown in Fig. 3 (e). In addition, a small peak appears in the \( M_{\max}(J/\psi \eta) \) distribution in Fig. 3 (f). We also notice a tuning point at \( M_{\max}(J/\psi \eta) = 4.018 \) GeV in Fig. 3 (c), which is resulted from the ISChE mechanism and is different from the tuning point at \( M_{\max}(J/\psi \eta) = 3.996 \) GeV mentioned above.
2. The lineshapes listed in Figs. 3 (a), (b), and (d) show that the intermediate \( D\bar{D} \), \( D^* \bar{D}^* \), \( D_1 \bar{D}_1 \) cannot result in enhancement structures in the corresponding \( M_{\max}(J/\psi \eta) \) distributions.
In summary, in the past decade experiments have made big progress on searching for charmoniumlike states $XYZ$, which also stimulated extensive theoretical studies on their properties. At present, it is still a hot and interesting topic to carry out both theoretical and experimental investigations on these $XYZ$ states.

Recent experimental observation of $Z_c(3900)$ is a charged charmoniumlike state reported by BESIII [3] and confirmed by Belle [4] and Ref. [5]. It again draws our attention to a charmoniumlike state since a charged enhancement structure near the $D^*\bar{D}$ threshold was predicted in Ref. [1] before this experimental observation, where the ISPE mechanism was applied to study the hidden-charm dipion decay of $Y(4260)$ and other higher charmonia. Out prediction confirmed by BESIII [11] J. P. Lees [12] E. van Beveren, X. Liu, R. Coimbra and G. Rupp, Europhys. Lett. 85, 61002 (2009) [arXiv:0809.1151 [hep-ph]].

Although we already have given many predictions of charged charmoniumlike structures [4–8], we notice that the isoscalar charmoniumlike structures similar to the predicted charged ones are absent in experiment. Thus, in this work we have studied the hidden-charm di-eta decays of $Y(4660)$ and $\psi(4790)$ to theoretically give the prediction of the isoscalar charmoniumlike structure. Our results show that there are enhancement structures near $DD^*$, $D^*\bar{D}$ and $D_s\bar{D_s}$ thresholds in the $M_{\text{max}}(J/\psi\eta)$ distribution of $Y(4660) \to \eta\eta J/\psi$. The calculation of $\psi(4790) \to \eta\eta J/\psi$ predict the enhancement structure near $D^*\bar{D}$, $D_s\bar{D_s}$ and $D_s^*\bar{D}_s$ thresholds in the corresponding $M_{\text{max}}(J/\psi\eta)$ distributions. These theoretical studies provide abundant information on isoscalar charmoniumlike structure, which will be helpful for further experimental exploration in future, where the potential experiments to search for the predicted enhancements in this work include BESIII, Belle, BaBar, and forthcoming BelleII.

Acknowledgement

This project is supported by the National Natural Science Foundation of China under Grant No. 11222547, No. 11175073, No. 11005129 and No. 11035006, the Ministry of Education of China (FANEDD under Grant No. 200924, SRFDP under Grant No. 201202111000, and NCET), the Fok Ying Tung Education Foundation (No. 131006), and the West Doctoral Project of Chinese Academy of Sciences.

[1] D. -Y. Chen and X. Liu, Phys. Rev. D 84, 034032 (2011) [arXiv:1106.5290 [hep-ph]].
[2] D. -Y. Chen and X. Liu, Phys. Rev. D 84, 094003 (2011) [arXiv:1106.3798 [hep-ph]].
[3] M. Ablikim et al. [BESIII Collaboration], Phys. Rev. Lett. 110, 252001 (2013) [arXiv:1303.5949 [hep-ex]].
[4] Z. Q. Liu et al. [Belle Collaboration], Phys. Rev. Lett. 110, 252002 (2013) [arXiv:1304.0121 [hep-ex]].
[5] T. Xiao, S. Dobbs, A. Tomaradze and K. K. Seth, arXiv:1304.3036 [hep-ex].
[6] D. -Y. Chen, X. Liu and T. Matsuki, Phys. Rev. D 88, 014034 (2013) [arXiv:1306.2080 [hep-ph]].
[7] D. -Y. Chen, X. Liu and T. Matsuki, arXiv:1208.2411 [hep-ph].
[8] D. -Y. Chen, X. Liu and T. Matsuki, Phys. Rev. Lett. 110, 232001 (2013) [arXiv:1303.5842 [hep-ph]].
[9] M. Ablikim et al. [BESIII Collaboration], arXiv:1308.2760 [hep-ex].
[10] X. L. Wang et al. [Belle Collaboration], Phys. Rev. Lett. 99, 142002 (2007) [arXiv:0707.3699 [hep-ex]].
[11] J. P. Lees et al. [BaBar Collaboration], arXiv:1211.6271 [hep-ex].