Predictions of Charged Charmoniumlike Structures with Hidden-Charm and Open-Strange Channels

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(Received 27 March 2013; published 5 June 2013)

We propose the initial single chiral particle emission mechanism, with which the hidden-charm dikaon decays of higher charmonia and charmoniumlike states are studied. Calculating the distributions of differential decay width, we obtain the line shape of the $J/\psi K^+$ invariant mass spectrum of $\psi_i \to J/\psi K^+ K^-$, where $\psi_i = \psi(4415)$, $Y(4660)$, and $\psi(4790)$. Our numerical results show that there exist enhancement structures with both hidden-charm and open-strange channels, which are near the $D\bar{D}_s^*/D^*\bar{D}_s$ and $D^*\bar{D}_s^*/\bar{D}^*D_s^*$ thresholds. These charged charmoniumlike structures predicted in this Letter can be accessible in future experiments, especially BESIII, BelleII, and SuperB.

DOI: 10.1103/PhysRevLett.110.232001 PACS numbers: 13.25.Gv, 13.75.Lb, 14.40.Pq

It is exciting to notice that the BESIII Collaboration has, for the first time, reported the observation of a charged charmoniumlike structure $Z_c(3900)$ in $e^+e^- \to J/\psi\pi^+\pi^-$ at $\sqrt{s} = 4260$ MeV [1]. As an enhancement structure around 3.9 GeV with statistical significance 9.0σ, $Z_c(3900)$ exists in the $J/\psi\pi^\pm$ invariant mass spectrum [1]. This observation confirms one of our predictions by the initial single pion emission (ISPE) mechanism [2], where we indicated that a charged charmoniumlike structure near the $D\bar{D}^*$ threshold is observable in the $Y(4260) \to J/\psi\pi^+\pi^-$ process (see Ref. [2] for details). In addition, we also need to indicate that the study of the exotic molecular states composed of $D^{(*)}$ and $\bar{D}^*$ and the relevant prediction of the isovector $D\bar{D}^*$ molecular state was given in Ref. [3] before BESIII's observation [1].

The ISPE mechanism was first proposed to explain Belle's observations of two charged bottomoniumlike structures $Z_b(10610)$ and $Z_b(10650)$ appearing in the hidden-bottom dipion decays of $\Upsilon(5S)$ [4]. Via the ISPE mechanism, two Z_b structures near the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds can be understood [5]. In addition, our results also naturally answer the question of why the charged bottomoniumlike structures near the $B\bar{B}$ threshold was not found by Belle. In Ref. [5], we further indicated that the ISPE mechanism can be applied to the hidden-charm dipion decays of the higher charmonia $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, and charmoniumlike state $Y(4260)$, which is due to the similarity between charmonium and bottomonium processes. Later, by studying the line shapes of the differential decay widths for $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, and $Y(4260)$ decays into $J/\psi\pi^+\pi^-$, $\psi(2S)\pi^+\pi^-$, and $h_c(1P)\pi^+\pi^-$, we predicted the sharp peak structures close to the $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds in the corresponding $J/\psi\pi^+$, $\psi(2S)\pi^+$, and $h_c(1P)\pi^+$ invariant mass spectra [2]. Thus, the charged charmoniumlike structure $Z_c(3900)$ newly observed by BESIII can be an important test for the ISPE mechanism.

Besides these theoretical predictions relevant to the hidden-charm dipion decays of higher charmonia, via the ISPE mechanism we have also predicted the charged bottomoniumlike structures near the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds in the hidden-bottom dipion decays of $\Upsilon(11020)$ [6], and two charged strangeoniumlike structures observable in the $Y(2175) \to \phi(1020)\pi^+\pi^-$ process [7]. We expect more experimental progress to test these predictions of ours presented in Refs. [2,6,7].

Indeed this new experimental observation given by BESIII [1] not only brings us excitement, but also further stimulates us to think about how to incorporate the ISPE mechanism with other phenomena, i.e., its application to more decay processes, and make more theoretical predictions.

Along the way, we notice that both the pion and kaon can be categorized as chiral particles. Thus, the hidden-charm dikaon decays of a higher charmonium are intriguing processes, and the initial single chiral particle emission (ISChE) mechanism can play an important role in these decays, which is a natural extension of the ISPE mechanism. To some extent, the ISPE mechanism can be included in the ISChE mechanism proposed in this work.

In the following, we will specify the concrete process to illustrate the physical picture of the ISChE mechanism. Under the ISChE mechanism, the hidden-charm dikaon decay of a higher charmonium occurs via the triangle loop constructed by charmed and charmed-strange mesons, which are shown in Fig. 1. The kaon with a continuous energy distribution emitted by an initial higher charmonium makes the intermediate charmed and charmed-strange mesons with low momenta easily interact with each other and then transform into a charmonium and a

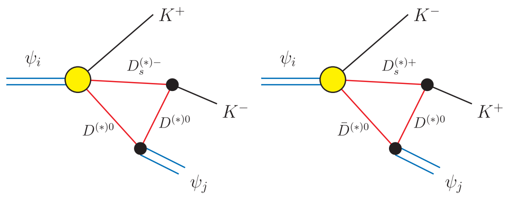

FIG. 1 (color online). Typical hadron-level diagrams of hidden-charm dikaon decay of higher charmonium by the ISChE mechanism. Here, ψ_i denotes the initial higher charmonium and ψ_j is a charmonium in the final state.

kaon. As nonperturbative QCD effects, the ISChE mechanism can be, in a word, the coupled-channel effect.

Applying the ISChE mechanism to the processes shown in Fig. 1, one requires two relations $m_{\psi_i} > m_K + m_{D^{(*)}} + m_{D_s^{(*)}}$ and $m_{\psi_i} > m_{\psi_j} + m_{K^+} + m_{K^-}$, which provide the criteria to choose suitable processes in Fig. 1. The minimum of the sum of masses of the kaon, $D^{(*)}$, and $D_s^{(*)}$ is about 4331 MeV. Thus, the mass of an initial higher charmonium must be higher than 4331 MeV, when we study the hidden-charm dikaon decays of a higher charmonium by the ISChE mechanism. Thus, in this work the hidden-charm dikaon decays of higher charmonia or charmoniumlike states include

$$\psi(4415) \to \bar{K}[D_s\bar{D}]/K[\bar{D}_s D] \to J/\psi K^+K^-, \quad (1)$$

$$Y(4660) \to \bar{K}[D_s^{(*)}\bar{D}^{(*)}]/K[\bar{D}_s^{(*)}D^{(*)}] \to J/\psi K^+K^-, \quad (2)$$

$$\psi(4790) \to \bar{K}[D_s^{(*)}\bar{D}^{(*)}]/K[\bar{D}_s^{(*)}D^{(*)}] \to J/\psi K^+K^-, \quad (3)$$

where $\psi(4415)$ is the first charmonium with mass above 4331 MeV listed by the Particle Data Group [8]. $Y(4660)$ is a charmoniumlike state reported by Belle [9] and recently confirmed by *BABAR* [10], which was reported in studying the $e^+e^- \to \psi(2S)\pi^+\pi^-$ process. In addition, $\psi(4790)$ was predicted as $n^{2s+1}L_J = 5\,^3S_1$ charmonium by using the resonance spectrum expansion model and analyzing the experimental data [11]. Studying these hidden-charm dikaon decays of $\psi(4415)$, $Y(4660)$, and $\psi(4790)$, we will answer the question of whether there exist charged charmoniumlike structures with both of hidden-charm and open-strange channels.

Via the ISChE mechanism, the hidden-charm dikaon decays of $\psi(4415)$, $Y(4660)$, and $\psi(4790)$ can be depicted by the schematic diagrams shown in Fig. 1. When calculating these diagrams, we adopt the effective Lagrangian approach, where the Lagrangians describing the interaction vertices are [12–15]

$$\begin{aligned}\mathcal{L}_{\psi'\mathcal{D}^{(*)}\mathcal{D}^{(*)}\mathcal{P}} = & -ig_{\psi'\mathcal{D}\mathcal{D}\mathcal{P}}\varepsilon_{\mu\nu\alpha\beta}\psi'^{\mu}\partial^{\nu}\mathcal{D}\partial^{\alpha}\mathcal{P}\partial^{\beta}\mathcal{D}^{\dagger} + g_{\psi'\mathcal{D}\mathcal{D}^*\mathcal{P}}\psi'^{\mu}(\mathcal{D}\mathcal{P}\mathcal{D}_{\mu}^{*\dagger} + \mathcal{D}_{\mu}^{*}\mathcal{P}\mathcal{D}^{\dagger}) \\ & - ig_{\psi'\mathcal{D}^*\mathcal{D}^*\mathcal{P}}\varepsilon_{\mu\nu\alpha\beta}\psi'^{\mu}\mathcal{D}^{*\nu}\partial^{\alpha}\mathcal{P}\mathcal{D}^{*\beta\dagger} - ih_{\psi'\mathcal{D}^*\mathcal{D}^*\mathcal{P}}\varepsilon_{\mu\nu\alpha\beta}\partial^{\mu}\psi'^{\nu}\mathcal{D}^{*\alpha}\mathcal{P}\mathcal{D}^{*\beta\dagger}, \end{aligned} \quad (4)$$

$$\begin{aligned}\mathcal{L}_{\psi\mathcal{D}^{(*)}\mathcal{D}^{(*)}} = & ig_{\psi\mathcal{D}\mathcal{D}}\psi^{\mu}(\partial_{\mu}\mathcal{D}\mathcal{D}^{\dagger} - \mathcal{D}\partial_{\mu}\mathcal{D}^{\dagger}) - g_{\psi\mathcal{D}^*\mathcal{D}}\varepsilon^{\mu\nu\alpha\beta}\partial_{\mu}\psi_{\nu}(\partial_{\alpha}\mathcal{D}_{\beta}^{*}\mathcal{D}^{\dagger} + \mathcal{D}\partial_{\alpha}\mathcal{D}_{\beta}^{*\dagger}) \\ & - ig_{\psi\mathcal{D}^*\mathcal{D}^*}\{\psi^{\mu}(\partial_{\mu}\mathcal{D}^{*\nu}\mathcal{D}_{\nu}^{*\dagger} - \mathcal{D}^{*\nu}\partial_{\mu}\mathcal{D}_{\nu}^{*\dagger}) + (\partial_{\mu}\psi_{\nu}\mathcal{D}^{*\nu} - \psi_{\nu}\partial_{\mu}\mathcal{D}^{*\nu})\mathcal{D}^{*\mu\dagger} \\ & + \mathcal{D}^{*\mu}(\psi^{\nu}\partial_{\mu}\mathcal{D}_{\nu}^{*\dagger} - \partial_{\mu}\psi_{\nu}\mathcal{D}^{*\nu\dagger})\}, \end{aligned} \quad (5)$$

$$\mathcal{L}_{\mathcal{D}^{(*)}\mathcal{D}^{(*)}\mathcal{P}} = -ig_{\mathcal{D}^*\mathcal{D}\mathcal{P}}(\mathcal{D}\partial_{\mu}\mathcal{P}\mathcal{D}^{*\mu\dagger} - \mathcal{D}^{*\mu}\partial_{\mu}\mathcal{P}\mathcal{D}^{\dagger}) - g_{\mathcal{D}^*\mathcal{D}^*\mathcal{P}}\varepsilon^{\mu\nu\alpha\beta}\partial_{\mu}\mathcal{D}_{\nu}^{*}\mathcal{P}\partial_{\alpha}\mathcal{D}_{\beta}^{*\dagger}, \quad (6)$$

where $\mathcal{D}^{(*)} = (D^{(*)0}, D^{(*)+}, D_s^{(*)+})$. $\mathcal{P}$ is a pseudoscalar meson matrix.

In the heavy quark limit and using chiral symmetry, the coupling constants can be connected to one gauge coupling; the definite values of all the coupling constants are listed in Table I. In the present work, the initial vector charmonia are above the threshold of $D^{(*)}D_s^{(*)}K$, thus the coupling constants of $\psi'\mathcal{D}^{(*)}\mathcal{D}^{(*)}K$ should be evaluated from the corresponding partial decay widths. In addition, because we mainly concern ourselves with the line shape of the $J/\psi K$ invariant mass spectrum in the frame of the ISChE mechanism, the interferences between different intermediate states are not taken into account in the present calculations. Here, we assume $g_{\psi\mathcal{D}^*\mathcal{D}^*\mathcal{P}} = h_{\psi\mathcal{D}^*\mathcal{D}^*\mathcal{P}}$, which results from the heavy quark limit and $SU(4)$ symmetry [12].

With the effective Lagrangians listed in Eqs. (4)–(6), one can obtain the general form of the amplitudes of $\psi_i(p_0) \to K^+(p_3)[\bar{D}_s^{(*)}(p_1)D^{(*)}(p_2)] \to K^+(p_3)K^-(p_4)\psi_j(p_5)$ and $\psi_i(p_0) \to K^-(p_4)[D_s^{(*)}(p_1)\bar{D}^{(*)}(p_2)] \to K^+(p_3)K^-(p_4)\times \psi_j(p_5)$ corresponding to Figs. 1(a) and 1(b), respectively, i.e.,

$$\begin{aligned}&\mathcal{M}\{\psi_i \to K^+[\bar{D}_s^{(*)}D^{(*)}] \to K^+K^-\psi_j\} \\ &= \prod_i g_i \int \frac{d^4q}{(2\pi)^4}\frac{[p_3, p_4, p_5, q]_{\mu\nu}\epsilon_{\psi_i}^{\mu}\epsilon_{\psi_j}^{\nu}}{[(p_4+q)^2 - m_{D_s^{(*)}}^2][(p_5-q)^2 - m_{D^{(*)}}^2]} \\ &\times \frac{1}{q^2 - m_{D^{(*)}}^2}\mathcal{F}(q^2, m_{D^{(*)}}^2), \end{aligned} \quad (7)$$

TABLE I. Optimal values of the coupling constants involved in the present work. These coupling constants can be related to the gauge coupling g by $g_{\psi DD} = g_{\psi D^* D^*} m_{D^*}/m_D = g_{\psi D^* D} m_\psi \sqrt{m_D/m_D^*} = m_\psi/f_\psi$, $g_{\psi D_s^{(*)} D_s^{(*)}} = \sqrt{(m_{D_s}^{(*)} m_{D_s}^{(*)})/(m_D^{(*)} m_D^{(*)})} g_{\psi DD}$, $g_{D_s^* D^* K} = \sqrt{m_{D_s}^*/m_{D^*}} 2g/f_\pi$, and $g_{D_s^* DK}/\sqrt{m_{D_s^*} m_D} = g_{D^* D_s K}/\sqrt{m_{D^*} m_{D_s}} = 2g/f_\pi$ [15], where f_ψ is the decay constants of J/ψ, which is evaluated from the leptonic decay width of J/ψ. With $\Gamma_{J/\psi \to e^+ e^-} = 5.55$ keV [8], we have $f_\psi = 416$ MeV. $f_\pi = 132$ MeV is the pion decay constant and $g = 0.59$ is estimated from the partial decay width of $D^* \to D\pi$ [8].

Coupling	Value	Coupling	Value	Coupling	Value
$g_{\psi DD}$	7.44	$g_{\psi D^* D}$	2.49 GeV^{-1}	$g_{\psi D^* D^*}$	8.01
$g_{\psi D_s D_s}$	7.84	$g_{\psi D_s^* D_s}$	2.62 GeV^{-1}	$g_{\psi D_s^* D_s^*}$	8.42
$g_{D_s^* DK}$	17.76	$g_{D^* D_s K}$	17.78	$g_{D_s^* D^* K}$	9.16 GeV^{-1}

$$\mathcal{M}\{\psi_i \to K^-[D_s^{(*)}\bar{D}^{(*)}] \to K^+K^-\psi_j\} = \prod_i g_i \int \frac{d^4q}{(2\pi)^4} \frac{[p_3, p_4, p_5, q]_{\mu\nu} \epsilon^\mu_{\psi_i} \epsilon^\nu_{\psi_j}}{[(p_3+q)^2 - m^2_{D_s^{(*)}}][(p_5-q)^2 - m^2_{D^{(*)}}]} \times \frac{1}{q^2 - m^2_{D^{(*)}}} \mathcal{F}(q^2, m^2_{D^{(*)}}), \quad (8)$$

where $[p_3, p_4, p_5, q]^{\mu\nu}$ denotes the tensor function of p_3, p_4, p_5 and the integral momentum q, which can be constructed by the effective Lagrangians in Eqs. (4)–(6). In order to describe the internal structures of the exchange mesons and its off shell effects, we introduce a form factor in the form $\mathcal{F}(q^2, m_E^2) = (m_E^2 - \Lambda^2)/(q^2 - \Lambda^2)$. The parameter Λ is parametrized as $\Lambda = \alpha \Lambda_{\rm QCD} + m_E$ with $\Lambda_{\rm QCD} = 0.22$ GeV. In Ref. [7], we numerically proved that the line shapes are weakly dependent on the unique parameter α and hence $\alpha = 1$ is used in the present work.

In the following we use $\mathcal{M}_{AB}^C$ to indicate the process where an initial $\psi_i(p_0)$ decays into a meson pair $A(p_1)B(p_2)$ with $K^+(p_3)$ emission and the meson pair subsequently transits into $K^-(p_4)\psi_j(p_5)$ by exchanging a meson $C(q)$. Here, we consider the ISChE mechanism with different intermediate states and search for possible enhancement structures near the threshold of $D_s^{(*)}D^{(*)}$ in the invariant mass spectrum of $J/\psi K^+$. The total amplitudes from different intermediate states in the frame of ISChE are

$$\mathcal{A}^{\rm tot}_{DD_s} = \mathcal{M}^{D_s^*}_{D\bar{D}_s} + \mathcal{M}^{\bar{D}^*}_{\bar{D}_s D} + \ldots, \quad (9)$$

$$\mathcal{A}^{\rm tot}_{D^*D_s + DD_s^*} = \mathcal{M}^{D_s^*}_{D\bar{D}_s^*} + \mathcal{M}^{D_s}_{D^*\bar{D}_s} + \mathcal{M}^{D_s^*}_{D^*\bar{D}_s} + \mathcal{M}^{\bar{D}^*}_{\bar{D}_s D^*} + \mathcal{M}^{\bar{D}}_{\bar{D}_s^* D} + \mathcal{M}^{\bar{D}^*}_{\bar{D}_s^* D} + \ldots, \quad (10)$$

$$\mathcal{A}^{\rm tot}_{D_s^*D^*} = M^{D_s^*}_{D^*\bar{D}_s^*} + M^{D_s^*}_{D^*\bar{D}_s^*} + \mathcal{M}^{\bar{D}}_{\bar{D}_s^* D^*} + \mathcal{M}^{\bar{D}^*}_{\bar{D}_s^* D^*} + \ldots, \quad (11)$$

where "…" denotes the contributions from the ISChE mechanism with K^- emitted from initial charmonia.

With the above amplitudes, we can obtain the invariant mass distributions of $J/\psi K^+$ for $\psi_i \to J/\psi K^+K^-$ in the frame of the ISChE mechanism. In Figs. 2 and 3, we show the numerical results of the distribution of $d\Gamma/dm_{J/\psi K^+}$ dependent on the $J/\psi K^+$ invariant mass spectrum. In our calculation, we consider the intermediate $D\bar{D}_s$ + H.c., $D^*\bar{D}_s + D\bar{D}_s^*$ + H.c., and $D^*\bar{D}_s^*$ + H.c. contributions separately, and the line shape of the distribution of $d\Gamma/dm_{J/\psi K^+}$ is normalized to 1. The vertical lines are the corresponding thresholds. Based on these theoretical results, we find

1. The vector charmonium $\psi(4415)$ is below the thresholds of $D_s^*\bar{D}\bar{K}/D_s\bar{D}^*\bar{K}$ and $D_s^*\bar{D}^*\bar{K}$. Thus, under the ISChE mechanism, $\psi(4415) \to J/\psi K^+K^-$ occurs only via the intermediate $D\bar{D}_s$ + H.c. The $d\Gamma/dm_{J/\psi K^+}$ distribution is presented in Fig. 2. The line shape is smooth and does not show a sharp peak near the $D\bar{D}_s$ + H.c. threshold, which also holds for $Y(4660) \to J/\psi K^+K^-$ and $\psi(4791) \to J/\psi K^+K^-$ decays [see Figs. 3(a) and 3(d)].

2. If considering the intermediate $D^*\bar{D}_s + D\bar{D}_s^*$ + H.c. contribution to $Y(4660) \to J/\psi K^+K^-$, we notice that there exist two structures in the line shape shown in Fig. 3(b). The higher one is a sharp peak structure near the $D_s\bar{D}^*/\bar{D}_s^*D$ thresholds while the lower one is a broad structure as a reflection of the higher one. If only the intermediate $D^*\bar{D}_s^*$ + H.c. is included, the resultant distribution of $d\Gamma/dm_{J/\psi K^+}$ of $\psi(4660) \to J/\psi K^+K^-$ gives

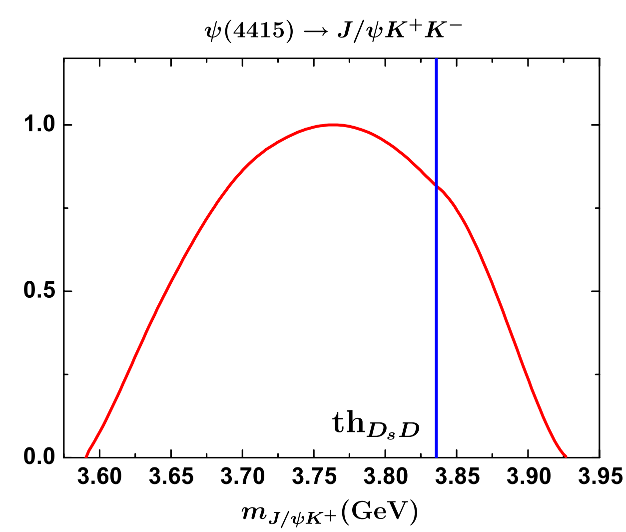

FIG. 2 (color online). The line shape of $\psi(4415) \to J/\psi K^+K^-$ in the ISChE frame with $D_s\bar{D}$ + H.c. intermediate state contributions.

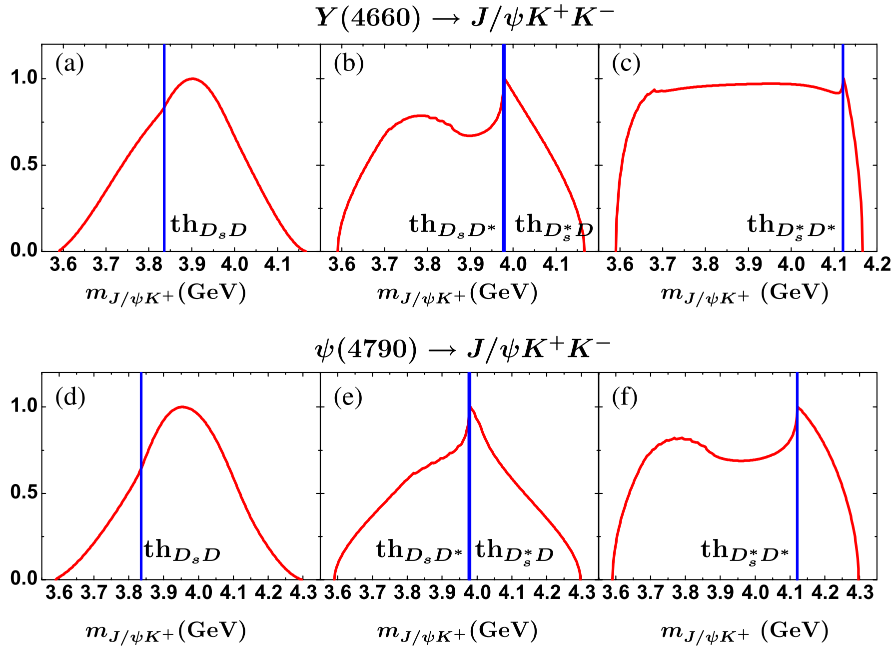

FIG. 3 (color online). Dependence of the distribution of $d\Gamma/dm_{J/\psi K^+}$ on the $J/\psi K^+$ invariant mass spectrum (red solid curves). The diagrams (a) and (d), the diagrams (b) and (e), and the diagrams (c) and (f), are the results considering the intermediate $D\bar{D}_s$ + H.c., $D^*\bar{D}_s + D\bar{D}_s^*$ + H.c., and $D^*\bar{D}_s^*$ + H.c. contributions, respectively. Here, the line shape of the distribution of $d\Gamma/dm_{J/\psi K^+}$ is normalized to 1.

a small sharp peak structure around the $D^*\bar{D}_s^*/\bar{D}^*D_s^*$ threshold. In addition, its reflection raised as 3.7 GeV is obscure [see Fig. 3(c) for more details].

3. As for $\psi(4790) \rightarrow J/\psi K^+K^-$ decay, we present the corresponding line shapes of the $d\Gamma/dm_{J/\psi K^+}$ distribution by considering the intermediate $D^*\bar{D}_s + D\bar{D}_s^*$ + H.c. and $D^*\bar{D}_s^*$ + H.c contributions in the diagrams of Figs. 3(e) and 3(f). Figure 3(e) shows an enhancement structure existing in the $d\Gamma/dm_{J/\psi K^+}$ distribution, which is composed of a sharp peak near the $D_s\bar{D}^*/\bar{D}_s^*D$ threshold and its reflection. This situation is different from that of $Y(4660) \rightarrow J/\psi K^+K^-$ just mentioned above. Figure 3(f) indicates a sharp peak structure close to the $D^*\bar{D}_s^*/\bar{D}^*D_s^*$ threshold and a broad structure corresponding to its reflection, which are more clear compared with the structures shown in Fig. 3(c).

In this work, we have extended the ISPE mechanism and have proposed the ISChE mechanism to study the hidden-charm dikaon decays of higher charmonia and charmoniumlike states, where we have chosen three typical processes $\psi(4415) \rightarrow J/\psi K^+K^-$, $Y(4660) \rightarrow J/\psi K^+K^-$, and $\psi(4790) \rightarrow J/\psi K^+K^-$. Under the ISChE mechanism, we have calculated their differential decay widths and presented their dependence on the $J/\psi K^+$ invariant mass spectrum. Our results have shown that there do not exist peak structures near $D\bar{D}_s/D_s\bar{D}$ for the decays of concern. However, we have found sharp enhancement structures around the $D_s^{(*)}\bar{D}^*/\bar{D}_s^{(*)}D^*$ and $D^*\bar{D}_s^*/\bar{D}^*D_s^*$ thresholds, where the expected enhancement structures in the $J/\psi K^+$ invariant mass spectra have charge and are with both hidden-charm and open-strange channels in the final state, which are very peculiar.

According to our study, we suggest future experiments to carry out the search for these charged charmoniumlike structures with hidden-charm and open-strange channels. If our predictions are confirmed in the future, the ISChE mechanism existing in the hidden-charm dikaon decays of higher charmonia or charmoniumlike states can be tested further, which will also show that the ISChE mechanism can be a universal mechanism for heavy quarkonia. At present, BESIII has already obtained beautiful experimental results, the observation of a charged charmoniumlike structure near the $D\bar{D}^*$ threshold in $e^+e^- \rightarrow J/\psi\pi^+\pi^-$ at $\sqrt{s} = 4260$ MeV. Among the hidden-charm dikaon decays discussed in this Letter, $\psi(4415) \rightarrow J/\psi K^+K^-$, $Y(4660) \rightarrow J/\psi K^+K^-$ is accessible at BESIII. It will be a good opportunity for BESIII to study charmoniumlike structures *XYZ*. In addition, the Belle and *BABAR* and forthcoming BelleII and SuperB Collaborations will be good platforms to carry out the search for these charged charmoniumlike structures with hidden-charm and open-strange channels.

X. L. would like to thank Shan Jin for a fruitful and inspired discussion. This project is supported by the National Natural Science Foundation of China under Grants No. 11222547, No. 11175073, No. 11005129, and No. 11035006, the Ministry of Education of China (FANEDD under Grant No. 200924, SRFDP under Grant

No. 20120211110002, NCET, the Fundamental Research Funds for the Central Universities), the Fok Ying Tung Education Foundation (No. 131006), and the West Doctoral Project of the Chinese Academy of Sciences.

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