Predictions of charged charmonium-like structures with hidden-charm and open-strange channels

Dian-Yong Chen$^{1,3}$, Xiang Liu$^{1,2,4}$, and Takayuki Matsuki$^3$

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

We propose the initial single chiral particle emission mechanism, with which the hidden-charm di-kaon decays of higher charmonia and charmonium-like states are studied. Calculating the distributions of differential decay width, we obtain the line shape of the $J/\psi K^+\pi^-$ invariant mass spectrum of $\psi_j \rightarrow J/\psi K^+K^-$, where $\psi_j = \psi(4445), Y(4660), \psi(4770)$. Our numerical results show that there exist enhancement structures with both hidden-charm and open-strange decays, which are near the $D\bar{D}_s^*/D_s^*\bar{D}$ and $D^*\bar{D}_s^*/D_s^*\bar{D}_s^*$ thresholds. These charged charmonium-like structures predicted in this Letter can be accessible in future experiments, especially BESIII, BelleII, and SuperB.

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It is exciting to notice that the BESIII Collaboration has, for the first time, reported the observation of a charged charmonium-like structure $Z_c(3900)$ in $e^+e^\rightarrow J/\psi\pi^+\pi^-$ at $\sqrt{s} = 4260$ MeV [1]. As an enhancement structure around 3.9 GeV with statistical significance 9.0$\sigma$, $Z_c(3900)$ 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 charmonium-like structure near the $D\bar{D}^*$ threshold is observable in the $Y(4260) \rightarrow J/\psi\pi^+\pi^-$ process (see Ref. [2] for details). In addition, we also need to indicate that the study of the exotic molecular states composed of $D^{(*)s}$ and $D^{(*)}$ and the relevant prediction of the isovector $DD^*$ 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 bottomonium-like structures $Z_b(10610)$ and $Z_b(10650)$ appearing in the hidden-bottom di-kaon decays of $\Upsilon(5S)$ [4]. Via the ISPE mechanism, two $Z_b$ structures near the $B^+B^*$ and $B^*B^*$ thresholds can be understood [5]. In addition, our results also naturally answer the question of why the charged bottomonium-like 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 di-kaon decays of the higher charmonia $\psi(4040), \psi(4160), \psi(4445)$, and charmonium-like 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 $\psi(4040), \psi(4160), \psi(4445)$, 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 $DD^*$ 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 charmonium-like 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 di-kaon decays of higher charmonia, via the ISPE mechanism we have also predicted the charged bottomonium-like structures near the $BB^*$ and $B^*B^*$ thresholds in the hidden-bottom dipion decays of $\Upsilon(11020)$ [3], and two charged strangeonium-like structures observable in the $Y(2175) \rightarrow \phi(1020)\pi^+\pi^-$ process [7]. We expect more experimental progress to test these predictions of ours presented in Refs. [2, 3, 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 of the pion and kaon can be categorized as chiral particles. Thus, the hidden-charm di-kaon decays of a higher charmonium are the 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.

![FIG. 1: (color online). Typical hadron-level diagrams of hidden-charm di-kaon decay of higher charmonium by the ISChE mechanism. Here, $\psi_j$ denotes the initial higher charmonium and $\psi_i$ is a charmonium in the final state.](image-url)

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 di-kaon decay of a higher charmonium occurs via the triangle loop constructed by charmed and charmed-strange mesons, which are shown...
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 kaon. As non-perturbative 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 $m_q > m_K + m_{D^{s0}}, m_{D^{s0}}$, and $m_q > m_{D^s} + m_{K^*}$, which provide the criteria to choose suitable processes in Fig. 1. The minimum of the sum of masses of the kaon, $D^{s0}$, and $D^{s0}$ is about 4331 MeV. Thus, the mass of an initial higher charmonium must be higher than 4331 MeV, when we study the hidden-charm di-kaon decays of a higher charmonium by the ISChE mechanism. Thus, in this work the hidden-charm di-kaon decays of higher charmonia or charmonium-like states include

$$\psi(4415) \rightarrow K[D_sD]/[K[D_sD] \rightarrow J/\psi K^* K^*, \quad (1)$$
$$Y(4660) \rightarrow K[D^{s0}_sD^{s0}] K[D^{s0}_sD^{s0}] \rightarrow J/\psi K^* K^*, \quad (2)$$
$$\psi(4790) \rightarrow K[D^{s0}_sD^{s0}] K[D^{s0}_sD^{s0}] \rightarrow J/\psi K^* K^*, \quad (3)$$

where $\psi(4415)$ is the first charmonium with mass above 4331 MeV listed by the Particle Data Group [3]. $Y(4660)$ is a charmonium-like state reported by Belle [9] and recently confirmed by BaBar [10], which was reported in studying $e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$ process. In addition, $\psi(4790)$ was predicted as $n_s^{3s1}L_J = 5^3S_1$ charmonium by using the resonance spectrum expansion model and analyzing the experimental data [11]. Studying these hidden-charm di-kaon decays of $\psi(4415), Y(4660)$, and $\psi(4790)$, we will answer the question of whether there exist charged charmonium-like structures with both of hidden-charm and open-charm decays.

Via the ISChE mechanism, the hidden-charm di-kaon 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]

$$L_{\psi(D^{s0}D^{s0}p)} = -ig_{\psi(D^{s0}D^{s0}p)}\bar{\psi}^{s0} \gamma^\mu D^{s0}_\mu \bar{D} \bar{D} + \text{H.c.},$$
$$L_{\psi(D^{s0}s^{3s1}p)} = -ig_{\psi(s^{3s1}p)}\bar{\psi}^{s0} \gamma^\mu D^{s0}_\mu \bar{D} \bar{D} + \text{H.c.},$$

where $D^{s0} = \{D^{s0}, D^{s0}, D^{s0} \}$. $\mathcal{P}$ is a pseudoscalar meson matrix.

### Table I: Optimal values of the coupling constants involved in the present work

| Coupling | Value | Coupling | Value | Coupling | Value |
|----------|-------|----------|-------|----------|-------|
| $g_{\psi D^{s0}D^{s0}p}$ | 7.44  | $g_{\psi D^{s0}D^{s0}p}$ | 2.49 GeV$^{-1}$ | $g_{\psi D^{s0}D^{s0}p}$ | 8.01 |
| $g_{\psi D^{s0}p}$ | 7.84  | $g_{\psi D^{s0}p}$ | 2.62 GeV$^{-1}$ | $g_{\psi D^{s0}p}$ | 8.42 |
| $g_{\psi D^{s0}D^{s0}p}$ | 17.76 | $g_{\psi D^{s0}D^{s0}p}$ | 17.78 | $g_{\psi D^{s0}D^{s0}p}$ | 9.16 GeV$^{-1}$ |

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 $D^{s0}_sD^{s0}_s$, thus the coupling constants of $\psi(D^{s0}_sD^{s0}_s)$ 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 intermediates states are not taken into account in the present calculations. Here, we assume $g_{\psi D^{s0}D^{s0}p} = h_{\psi D^{s0}p}$, which results from the heavy quark limit and $SU(4)$ symmetry [12].

With the effective Lagrangians listed in Eqs. 4, 5, one can obtain the general form of the amplitudes of $\psi(p_0) \rightarrow K^+(p_1)[D^{s0}_s(p_1)D^{s0}_s(p_2)] \rightarrow K^+(p_3)K^- (p_4)\psi(p_5)$ and $\psi(p_0) \rightarrow K^-(p_1)[D^{s0}_s(p_1)D^{s0}_s(p_2)] \rightarrow K^+(p_3)K^- (p_4)\psi(p_5)$ corresponding to Figs. 1(a) and 1(b), respectively, i.e.,

$$M(\psi_i \rightarrow K^+D^{s0}_sD^{s0}_s) = \int \frac{d^4q}{(2\pi)^3} \frac{\left[ (p_3 + p_4 + q)^2 - m_D^4 \right]}{q^2 - m_D^2} \times \mathcal{F}(q^2, m_D^2),$$

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, 5. In order to describe the internal structures of the exchange mesons and its off shell effects, we introduce a form factor in the form $\mathcal{F}(q^2, m_D^2) = (m_E^2 - \Lambda^2)/(q^2 - \Lambda^2)$. The parameter $\Lambda$ is parametrized as $\Lambda = \alpha_{NLOCD} + m_E$ with $\alpha_{NLOCD} = 0.22$ GeV. In Ref. 7, numerically proved that the line shapes are weakly dependent on the unique parameter $\alpha$ and hence $\alpha = 1$ is used in the
present work.

In the following we use $M_{AB}^C$ to indicate the process where initial $\psi(p_0)$ decays into a meson pair $A(p_1)B(p_2)$ with $K^+(p_3)$ emission and the meson pair subsequently transits into $K^-(p_4)\psi(p_5)$ 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

$$\mathcal{A}_{D_s^*D_s^*}^{\text{tot}} = M_{D_s^*D_s^*}^{D_s^*} + M_{D_s^*D_s^*}^{D_s^*} + \ldots ,$$

$$\mathcal{A}_{D_s^*D_s^*+D_s^*}^{\text{tot}} = M_{D_s^*D_s^*+D_s^*}^{D_s^*} + M_{D_s^*D_s^*+D_s^*}^{D_s^*} + M_{D_s^*D_s^*+D_s^*}^{D_s^*} + \ldots ,$$

$$\mathcal{A}_{D_s^*D_s^*}^{\text{tot}} = M_{D_s^*D_s^*}^{D_s^*} + M_{D_s^*D_s^*}^{D_s^*} + \ldots ,$$

where '...' denotes the contributions from the ISChE mechanism with $K^-$ emitted from initial charmonia.

![Graph](image)

**FIG. 2**: (Color online). The line shape of $\psi(4415) \rightarrow J/\psi K^+K^-$ in the ISChE frame with $D_s^*+\text{H.C.}$ intermediate state contributions.

With the above amplitudes, we can obtain the invariant mass distributions of $J/\psi K^+$ for $\psi_i \rightarrow J/\psi K^+K^-$ 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 $DD_s^*$, $H.C.$, $D_s^*D_s^*$, $D_s^*D_s^*$, and $D_s^*D_s^*$, $H.C.$ 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 $D_s^*D_s^*/D_s^*D_s^*$ $D_s^*D_s^*$ $D_s^*D_s^*$ $D_s^*D_s^*$. Thus, under the ISChE mechanism, $\psi(4415) \rightarrow J/\psi K^+K^-$ occurs only via the intermediate $DD_s^*+\text{H.C.}$ 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 $D_s^*D_s^*$, $H.C.$ threshold, which also holds for $Y(4660) \rightarrow J/\psi K^+K^-$ and $\psi(4791) \rightarrow J/\psi K^+K^-$ decays (see Figs. 3(a) and 3(d)).

2. If considering the intermediate $D_s^*D_s^*/D_s^*D_s^*$, $H.C.$ contribution to $Y(4660) \rightarrow J/\psi K^+K^-$, 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 $D_s^*D_s^*/D_s^*D_s^*$ thresholds while the lower one is a broad structure as a reflection of the higher one. If only the intermediate $D_s^*D_s^*/H.C.$ is included, the resultant distribution of $d\Gamma/dm_{J/\psi K^+}$ of $Y(4660) \rightarrow J/\psi K^+K^-$ gives a sharp peak structure around the $D_s^*D_s^*/D_s^*D_s^*$ 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 $D_s^*D_s^*/D_s^*D_s^*$, $H.C.$ and $D_s^*D_s^*/H.C.$ contributions in the diagrams of Figs. 3(e) and 3(f). The 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 $D_s^*D_s^*/D_s^*D_s^*$ 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 $D_s^*D_s^*/D_s^*D_s^*$ 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 di-kaon decays of higher charmonia and charmonium-like state, 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 $DD_s^*/D_s^*D_s^*$ for the decays of concern. However, we have found sharp enhancement structures around the $D_s^*D_s^*/D_s^*D_s^*$ and $D_s^*D_s^*/D_s^*D_s^*$ 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 decays in the final state, which are very peculiar.

According to our study, we suggest future experiments to carry out the search for these charged charmonium-like structures with hidden-charm and open-strange decays. If our predictions are confirmed in the future, the ISChE mechanism existing in the hidden-charm di-kaon decays of higher charmonia or charmonium-like state 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 charmonium-like structure near $D_s^*$ threshold in $e^+e^- \rightarrow J/\psi K^+K^-$ at $\sqrt{s} = 4260$ MeV. Among the hidden-charm di-kaon 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 opportunities for BESIII to study charmonium-like 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 charmonium-like structures with hidden-charm and
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.

open-strange decays.

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