Novel charged charmoniumlike structures in the hidden-charm dipion decays of \(Y(4360)\)

Dian-Yong Chen\textsuperscript{1,3} \textsuperscript{a}, Xiang Liu\textsuperscript{1,2} \textsuperscript{b} and Takayuki Matsuki\textsuperscript{3} \textsuperscript{c}

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

Studying the hidden-charm dipion decays of the charmoniumlike state \(Y(4360)\), we show that there exist charged charmoniumlike structures near \(D\bar{D}^{*}\) and \(D^*\bar{D}^{*}\) thresholds in the \(J/\psi \pi^+\pi^-\) invariant mass spectra of the corresponding hidden-charm dipion decays of \(Y(4360)\) using the Initial Single Pion Emission mechanism. We suggest to do further experimental study on these predicted charged enhancement structures, especially by BESIII, Belle, and the forthcoming BelleII.

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I. INTRODUCTION

Very recently, the BESIII Collaboration reported a charged charmoniumlike structure by studying the \(J/\psi \pi^\pm\) invariant mass spectra in \(e^+e^- \rightarrow J/\psi \pi^+\pi^-\) at \(\sqrt{s} = 4.26\) GeV \cite{1}. This newly observed charged structure around 3.9 GeV is referred to \(Z_c(3900)\), which was confirmed by the Belle Collaboration \cite{2}. Later, Xiao et al. also announced the observation of \(Z_c(3900)\) with a 6\(\sigma\) significance by analyzing 586 \(\text{pb}^{-1}\) data collected with the CLEO-c detector at \(\psi(4160)\) \cite{3}. As indicated in Ref. \cite{1}, this charged enhancement structure near the \(D\bar{D}^*\) threshold was predicted in Refs. \cite{4,5} before the observation of \(Z_c(3900)\). Among these pioneering theoretical investigations, the Initial Single Pion Emission (ISPE) mechanism was applied to study the hidden-charm dipion decays of higher charmonia, where there exist the charged charmoniumlike structures near the \(D\bar{D}^*\) and \(D^*\bar{D}^*\) thresholds in the distributions of the \(J/\psi \pi^\pm\), \(\psi(2S)\pi^\pm\) and \(h_1(1P)\pi^\pm\) invariant mass spectra \cite{4}.

The ISPE is a decay mechanism peculiar to the hidden-charm dipion decays of higher charmonia \cite{6} and the hidden-bottom dipion decays of higher bottomonia \cite{7,8}. The ISPE mechanism was first proposed to explain why the charged bottomoniumlike structures \(Z_b(10610)\) and \(Z_b(10650)\) exist in the \(T(nS)\pi^\pm\) (\(n = 1, 2, 3\)) and \(h_1(mP)\pi^\pm\) (\(m = 1, 2\)) invariant mass spectra of the hidden-bottom decay modes of \(Y(10860)\), which was reported by Belle \cite{9}. The authors adopted the ISPE mechanism further to study hidden-bottom decay modes of \(Y(11020)\) \cite{8}, and predicted the charged bottomoniumlike enhancement structures similar to \(Z_b(10610)\) and \(Z_b(10650)\). Recently, we have developed the ISPE mechanism to propose the Initial Single Chiral Particle Emission (ISChE) mechanism, where the charged charmoniumlike structures with the hidden-charm and open-charm channel were predicted \cite{10}.

Although we have already presented abundant phenomena of charged charmoniumlike/bottomoniumlike structures in the hidden-charm/bottomoniumlike structures near \(Z_b(10610)\) and \(Z_b(10650)\), it is not the end of the story. The fact that \(Y(4360)\) and \(Y(4260)\) observed in the \(e^+e^- \rightarrow J/\psi \pi^\pm\pi^-\) process \(Y(4360)\) was observed by BaBar \cite{11}. Later, both the CLEO and Belle Collaborations confirmed \(Y(4360)\) in the \(e^+e^- \rightarrow J/\psi \pi^\pm\pi^-\) process \cite{12,14}. \(Y(4360)\) was reported by BaBar \cite{15,16} after analyzing the \(\psi(2S)\pi^\pm\pi^-\) invariant mass spectrum of \(e^+e^- \rightarrow \psi(2S)\pi^\pm\pi^-\), which was confirmed by Belle \cite{17}. At present, \(Z_c(3900)\) was observed in the \(J/\psi \pi^\pm\) invariant mass spectrum of \(Y(4260)\rightarrow J/\psi \pi^\pm\pi^-\). The similarity between \(Y(4360)\) and \(Y(4260)\) just mentioned above provides us interest in studying whether a similar charged charmoniumlike structure can be found in \(Y(4360)\rightarrow J/\psi \pi^\pm\pi^-\) and other hidden-charm dipion decays of \(Y(4360)\). To answer to this question, we need to carry out a more in-depth study of the hidden-charm dipion decays of \(Y(4360)\).

This paper is organized as follows. After the introduction, we present the hidden-charm dipion decays of \(Y(4360)\) discussed above and the calculation of the corresponding decay amplitudes and the differential decay widths. In Sec. III, the numerical results are given. The last section devoted into a short summary.

II. THE HIDDEN-CHARM DIPION DECAYS \(Y(4360)\)

The involved hidden-charm dipion decays of \(Y(4360)\) include:

\[
Y(4360) \rightarrow \pi^\pm[D^{(*)}\bar{D}^{(*)}]_{\psi(2)}^\pm \rightarrow \begin{cases} 
J/\psi \pi^\pm \pi^- \\
\psi(2S)\pi^\pm \pi^- \\
h_1(1P)\pi^\pm \pi^-, \end{cases}
\]

where \(\pi^\pm\) is an initial single pion directly emitted from \(Y(4360)\) decay. With the pion emission, \(Y(4360)\) transits into intermediate \(D^{(*)}\bar{D}^{(*)}\). Then, via the exchanged \(D^{(*)}\) me-
FIG. 1: (color online). The typical diagrams depicting charm plus a pion. In Eq. (1), the subscript and superscript denote the total charge of the intermediate charmed mesons and the corresponding exchanged charm meson. These processes can be represented by the typical diagrams shown in Fig. 1.

Here, the initial single pion emission plays an important role to these processes, i.e., because the pion carries off some of the Q value, the intermediate $D^{(*)}$ and $D^\ast$ with low momenta can easily interact with each other and transit into final states. These typical diagrams reflect main physical picture of the ISPE mechanism.

First, we give a general expression of the differential decay width for $Y^\ast(4360)(p_0) \to \pi^+(p_3)[D^{(*)}(p_1)D^\ast(p_2)] \to \pi^+(p_3)\pi^\pm(p_4)\psi_j(p_5)$,  

$$d\Gamma = \frac{1}{3} \frac{1}{(2\pi)^3} \frac{1}{32M^2_{Y^\ast(4360)}} |M|^2 \rho_{\pi^\pm\pi}, d\phi_{\pi^\pm\pi},$$

(2)

where $m_{\pi^\pm}^2 = (p_3 + p_5)^2$ and $m_{\pi^\pm\pi}^2 = (p_3 + p_4)^2$. The overline denotes the average over the polarizations of $\psi_j$ in the final state. Thus, in the following our main task is to calculate $|M|^2$ corresponding different processes.

As shown in Fig. 1, $Y^\ast(4360)$ $\to \psi_j\pi^\pm\pi^\mp$ via the ISPE mechanism can be described by these hadron-level diagrams. Thus, we can write out the decay amplitude using the effective Lagrangian approach. The interaction Lagrangians involved in strong interaction vertexes, which are invariant under the isospin $SU(2)$ symmetry, are.

$$L_Y^{Y^\ast(4360)D^{(*)}D^\ast} = -ig_{YDD\pi}e^{\mu\nu\rho}Y_{\mu}D_{\nu}\partial_{\rho}\psi_j \bar{D} + g_{YD^\ast D}\eta^{\mu\nu\rho}(D^\ast_{\mu}\bar{D}_\rho + D_{\mu}\bar{D}_\rho)$$

$$-ig_{YD^\ast D\pi}e^{\mu\nu\rho}D_{\mu}\partial_{\nu}\partial_{\rho}\psi_j \bar{Y} + ig_{YD^\ast D}e^{\mu\nu\rho}\partial_{\mu}D_{\nu}\partial_{\rho}\psi_j \bar{Y},$$

which depicts the initial state $Y^\ast(4360)$ interacts with $D^{(*)}D^\ast\pi$, and

$$L_{D^{(*)}D^\ast} = \eta_{\mu\nu\rho}(D_{\mu}\partial_{\nu}\partial_{\rho}D^\ast - D_{\mu}\partial_{\nu}\partial_{\rho}D^\ast) - \eta_{\mu\nu\rho}(D_\mu\partial_{\nu}\partial_{\rho}D^\ast - D^\ast_{\mu}\partial_{\nu}\partial_{\rho}D),$$

$$L_{\phi D^{(*)}D^\ast} = ig_{\phi YDD\pi}(\partial_{\mu}D_\mu D^\ast - \partial_{\mu}D_\mu D) - g_{\phi D^*D}\eta^{\mu\nu\rho}\partial_{\mu}\psi_j(\partial_{\nu}\partial_{\rho}D),$$

which describes the coupling of $\phi$ to $D^{(*)}D^\ast\pi$, respectively.

In the heavy quark limit, the coupling constants among charmonia and charmed mesons satisfy $\Gamma_{\psi\to\pi^\pm\pi^\mp} = \frac{\Gamma_{\psi\to\pi^\pm\pi^\mp}}{2\Gamma_{\psi\to\pi^\pm\pi^\mp}}$. With the center values of the leptonic partial decay widths, i.e., $\Gamma_{\psi\to\pi^\pm\pi^\mp} = 5.55 \pm 0.14 \pm 0.02$ keV and $\Gamma_{\psi(2S)\to\pi^\pm\pi^\mp} = 2.35 \pm 0.04$ keV, one can obtain $f_\psi = 416$ MeV and $f_{\psi(2S)} = 298$ MeV. The gauge coupling $g_1$ can be related to the decay constant of $\psi$ through $g_1 = \sqrt{m_\psi/m_\psi}$, where the $\chi_{c0}$ decay constant $f_{\chi_{c0}} = 510$ MeV is estimated by the QCD sum rule analysis.

TABLE I: The relevant coupling constants involved in the present work.

| Coupling Value | Coupling Value |
|----------------|----------------|
| $g_{\phi \psi D^*D}$ | $g_{\phi \psi D^*D}$ |
| $g_{\phi \psi D^*D}$ | $g_{\phi \psi D^*D}$ |
| $g_{\phi \psi D^*D}$ | $g_{\phi \psi D^*D}$ |
| $g_{\phi \psi D^*D}$ | $g_{\phi \psi D^*D}$ |

As an example of $Y^\ast(4360)$ $\to J/\psi\pi^\pm\pi^\mp$, through intermediate $D^\ast + H.c.$, we illustrate how to obtain the corresponding decay amplitude. Although there are 12 diagrams for $Y^\ast(4360)$ $\to J/\psi\pi^\pm\pi^\mp$, we can find six independent diagrams since other diagrams can be obtained by considering the $SU(2)$ symmetry. Thus, the total decay amplitude reads as

$$M_{Y^\ast(4360) \to J/\psi\pi^\pm\pi^\mp} = 2 \sum_{a=1, \ldots, 6} |g_a|^2.$$
where the factor 2 is due to the isospin $SU(2)$ symmetry. Using the effective Lagrangian approach, we get sub-amplitudes $A_{DD^* + H.c.}^{(1)}$, $A_{DD^* + H.c.}^{(2)}$, and $A_{DD^* + H.c.}^{(3)}$, which correspond to the dipion transitions between $Y(4360)$ and $J/\psi$ with an initial single pion ($\pi^*$) emission, i.e.,

$$A_{DD^* + H.c.}^{(1)} = (i)^3 \int \frac{d^4q}{(2\pi)^4} [g_{YD^* \pi^*}] g_{YD^* \pi^*}(ip_{1D}^*) \times [-ie^{i\phi}(ip_{2D} + ip_{3D}) + g_{YD^* \pi^*}(ip_{2D} + ip_{3D}) \times (-ie^{i\phi}(ip_{2D} + ip_{3D})) - g_{YD^* \pi^*}(ip_{2D} + ip_{3D}) - g_{YD^* \pi^*}(ip_{2D} + ip_{3D}) \times \frac{1}{p_{1D}^2 - m_{DD}^2} - \frac{1}{p_{2D}^2 - m_{DD}^2} - \frac{1}{p_{3D}^2 - m_{DD}^2} + \frac{1}{q^2 - m_{DD}^2}] F^2(q^2, m_{DD}^2).$$

$$A_{DD^* + H.c.}^{(2)} = (i)^3 \int \frac{d^4q}{(2\pi)^4} [g_{YD^* \pi^*}] g_{YD^* \pi^*}(ip_{1D}^*) \times [-ie^{i\phi}(ip_{2D} + ip_{3D}) + g_{YD^* \pi^*}(ip_{2D} + ip_{3D}) \times (-ie^{i\phi}(ip_{2D} + ip_{3D})) - g_{YD^* \pi^*}(ip_{2D} + ip_{3D}) - g_{YD^* \pi^*}(ip_{2D} + ip_{3D}) \times \frac{1}{p_{1D}^2 - m_{DD}^2} - \frac{1}{p_{2D}^2 - m_{DD}^2} - \frac{1}{p_{3D}^2 - m_{DD}^2} + \frac{1}{q^2 - m_{DD}^2}] F^2(q^2, m_{DD}^2).$$

$$A_{DD^* + H.c.}^{(3)} = (i)^3 \int \frac{d^4q}{(2\pi)^4} [g_{YD^* \pi^*}] g_{YD^* \pi^*}(ip_{1D}^*) \times [-ie^{i\phi}(ip_{2D} + ip_{3D}) + g_{YD^* \pi^*}(ip_{2D} + ip_{3D}) \times (-ie^{i\phi}(ip_{2D} + ip_{3D})) - g_{YD^* \pi^*}(ip_{2D} + ip_{3D}) - g_{YD^* \pi^*}(ip_{2D} + ip_{3D}) \times \frac{1}{p_{1D}^2 - m_{DD}^2} - \frac{1}{p_{2D}^2 - m_{DD}^2} - \frac{1}{p_{3D}^2 - m_{DD}^2} + \frac{1}{q^2 - m_{DD}^2}] F^2(q^2, m_{DD}^2).$$

Using Eqs. (7)-(9), we can obtain the sub-amplitudes $A_{DD^* + H.c.}^{(1)}$, $A_{DD^* + H.c.}^{(2)}$, and $A_{DD^* + H.c.}^{(3)}$, corresponding to the dipion transitions between $Y(4360)$ and $J/\psi$ with an initial $\pi^*$ emission, where we need to interchange $p_3 \rightarrow p_2$ in Eqs. (7)-(9). Here, $F(q^2, m_{DD}^2) = (\Lambda^2 - m^2_{DD})/(q^2 - m^2_{DD})$ denotes the monopole form factor with the parameterized $\Lambda$, which is taken as $\Lambda = m_E + \beta \Lambda_{QCD}$ with $\Lambda_{QCD} = 220$ MeV and $m_E$ is the exchanged meson mass in the triangle hadron loops. The parameter $\beta$ is expected to be of order unity [22]. In the present work we take $\beta = 1$. In Ref. [4], we have numerically shown that the corresponding lineshapes of the hidden-charm dipion decays of higher charmonia and charmoniumlike state $Y(4260)$ are weakly dependent on the parameter $\beta$. Considering the similarity between $Y(4260)$ and $Y(4360)$, we can conclude that the discussed lineshape of the hidden-charm dipion decays of $Y(4360)$ are also weakly dependent on the value $\beta$.

In a similar way, we can also write out the decay amplitudes of $Y(4360) \rightarrow J/\psi \pi^+ \pi^-$ through intermediate $D^* D^*$ and $DD$, and $Y(4360) \rightarrow \psi(2S) \pi^+ \pi^-$ and $Y(4360) \rightarrow h_c(1P) \pi^+ \pi^-$ through $D^{*0} D^{*+}$ (see Ref. [4] for more details).

We need to stress that in our work we calculate the individual contributions of the intermediates, $DD$, $D^*D^*$ + $H.c.$ and $D^*D^*$, to the hidden-charm dipion decays of $Y(4360)$ concerned, and that we do not include the interference effects among the decay amplitudes for different intermediate states. There are two main reasons for this. The first one is that it is difficult to obtain the concrete values of the coupling constants $g_{YD^* \pi^*}$ relevant to the internal structure of $Y(4360)$, i.e., too many ambiguities to determine these constants. The second is that the relative phases among different decay amplitudes cannot be also constrained by present experimental data. In other words, further experimental study of these novel phenomena discussed in this work can make us carry out the fit to the experimental data with our model. For example, after predicting the charged charmoniumlike structures in the hidden-charm dipion decays of $Y(4260)$ in Ref. [4], having the new experimental data of $Z_c(3900)$ observed by BESIII [1] we have succeeded in reproducing the structure of $Z_c(3900)$ by including all the mechanisms [23], tree and other diagrams and relative phases, among which the ISPE mechanism is the most dominant contribution to the structure. Hence, following the same analysis, we can perform the similar study on $Y(4360)$ if the detailed experimental data of the hidden-charm dipion decays of $Y(4360)$ is obtained. Considering the above reasons, in the present work we only concern only the lineshapes caused by the ISPE mechanism with individual intermediate states, where the maximum of the lineshape is normalized to 1 as shown in the next section.

### III. NUMERICAL RESULTS

With the formula derived in Sec. III we calculate the line shapes of the differential decay width of $Y(4360) \rightarrow J/\psi \pi^+ \pi^-$ dependent on the $J/\psi \pi^+ \pi^-$ invariant mass spectrum, which are shown in Fig. 2.

The results listed in Fig. 2 indicate:

1. For $Y(4360) \rightarrow J/\psi \pi^+ \pi^-$, there are two sharp peaks existing in the $J/\psi \pi^+ \pi^-$ invariant mass spectrum. The one is around the $D^*D^*$ threshold while another one is close to the $D^*D^*$ threshold (See Fig. 2(d) and (g)). There are two broad structures, which are the corresponding reflections of these two sharp structures.

2. The line shapes of $\psi(2S) \pi^+ \pi^-$ invariant mass spectrum of $Y(4360) \rightarrow J/\psi \pi^+ \pi^-$ show different behavior from (1). The intermediate $D^*D^* + H.c.$ can not result in sharp peak structures, instead there is a smooth curve (See Fig. 2(e)). When including only $D^*D^*$ as the intermediate state, we find that a small peak exists although the peak near the $D^*D^*$ threshold while another one is close to the $D^*D^*$ threshold (See Fig. 2(d) and (g)). There are two broad structures, which are the corresponding reflections of these two sharp structures.

3. For the $Y(4360) \rightarrow h_c(1P) \pi^+ \pi^-$ process, one irregular peak exists in the $h_c(1P) \pi^+ \pi^-$ invariant mass spectrum if only considering the intermediate $D^*D^* + H.c.$ contribution (See diagram Fig. 2(f)). The intermediate $D^*D^*$ contribution can produce a sharp peak near the $D^*D^*$ threshold (See Fig. 2(i)). Its reflection is a broad structure, which is around the $D^*D^*$ threshold. Comparing with the sharp peak structure shown in Fig. 2(d), the peak in Fig. 2(f) is more obvious.

In addition, our calculation also shows that the intermediate $D^*D^*$ contribution to $Y(4360) \rightarrow J/\psi \pi^+ \pi^-$ cannot result in any enhancement structure close to the $D^*D^*$ threshold in the $J/\psi \pi^+ \pi^-$ invariant mass spectrum (See Fig. 2(a)-(c)).
the uncertainties of the coupling constants cannot result in the changes of our results. As for the $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$ process via the intermediate state $D\bar{D}^*$ as an example, a common factor $g_{YD^{(*)}D^*}/f_0$ can be extracted from the total decay amplitude, which is due to the constraint from Eqs. (3)-(5). Thus, the uncertainties of gauge coupling constants $g$ and $f_0$ cannot change the corresponding line shapes in the $J/\psi \pi^+$ invariant mass spectrum.

Indeed, although in our calculation we use the relations of the coupling constants that are obtained in the heavy quark limit, our qualitative conclusion does not depend on these relations but on the ISPE mechanism.

IV. SUMMARY

Heavy quarkonium physics is an intriguing and active research field full of challenges and opportunities [24, 26]. A newly observed charged charmoniumlike structure $Z_c(3900)$ was reported by BESIII [1] and confirmed by Belle [2] in the $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$ process. Before the BESIII’s observation, we have explored the hidden-charm dipion decays of $Y(4260)$ and have predicted charged charmoniumlike structures by the ISPE mechanism [3].

Stimulated by the similarity between $Y(4360)$ and $Y(4260)$ and the recent experimental observation of $Z_c(3900)$ by the BESIII and Belle Collaborations, we study the hidden-charm dipion decays of charmoniumlike state $Y(4360)$ in the present work. Our calculation shows that there exist charged structures in the $J/\psi \pi^+$ invariant mass spectrum, which are near the $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds (see Fig. 2(a) and (d)). A peak structure around the $D^*\bar{D}^*$ threshold appears in the $\psi(2S) \pi^+$ invariant mass spectrum (see Fig. 2(e)). In addition, we can also find a sharp peak structure in the $h_1(1P)\pi^+$ invariant mass spectrum near the $D^*\bar{D}^*$ threshold (see Fig. 2(f)).

Experimental search for these charged charmoniumlike structures predicted near the $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds is an interesting research topic, which will be helpful to further test our predictions presented in this work. What is more important is that the ISPE mechanism existing in the hidden-charm hidden-bottom dipion decays of higher charmonium/bottomonium can be tested again. BESIII, Belle, and forthcoming BelleII will be a good platform to carry out the experimental study on these hidden-charm dipion decays of charmoniumlike state $Y(4360)$. We would like to have more experimental progresses in this field.

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FIG. 2: (color online). The obtained differential decay widths of $Y(4360) \rightarrow \psi \pi^+ \pi^-$ dependent on the invariant mass spectrum $m_{\psi \pi^+}$.

Here, the line shapes in the first, second and the third columns correspond to the cases taking $\psi^j = J/\psi, \psi(2S)$ and $h_1(1P)$, respectively. The maximum of these line shapes are normalized to 1. In addition, the vertical dashed lines denote the $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds, which are marked in these figures. The red solid, blue dashed and black dotted curves are the results with $DD$ and $D^*\bar{D}$ as the intermediate states, respectively.

Since we only focus on the line shapes as shown in Fig. 2, the uncertainties of the coupling constants cannot result in the changes of our results. As for the $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$ process via the intermediate state $D\bar{D}^*$ as an example, a common factor $g_{YD^{(*)}D^*}/f_0$ can be extracted from the total decay amplitude, which is due to the constraint from Eqs. (3)-(5). Thus, the uncertainties of gauge coupling constants $g$ and $f_0$ cannot change the corresponding line shapes in the $J/\psi \pi^+$ invariant mass spectrum.

Indeed, although in our calculation we use the relations of the coupling constants that are obtained in the heavy quark limit, our qualitative conclusion does not depend on these relations but on the ISPE mechanism.
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