Reproducing the $Z_c(3900)$ structure through the initial-single-pion-emission mechanism

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Being stimulated by the recent BESIII observation of a charged charmoniumlike structure $Z_c(3900)$, in this work we study the distributions of the $J/\psi\pi^\pm$ and $\pi^+\pi^- J/\psi$ invariant mass spectra of the $Y(4260) \rightarrow \pi^+\pi^- J/\psi$ decay by the initial-single-pion-emission mechanism, where the interference effects of the ISPE mechanism with two other decay modes are also taken into account. The obtained $d\Gamma(Y(4260) \rightarrow \pi^+\pi^- J/\psi)/dm_{\pi^+\pi^-}$ and $d\Gamma(Y(4260) \rightarrow \pi^+\pi^- J/\psi)/dm_{J/\psi}$ marvelously agree with the BESIII data to reproduce the $Z_c(3900)$ structure.

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Very recently the BESIII Collaboration announced the observation of a charged charmoniumlike structure $Z_c(3900)$, which is near the $D\bar{D}^*$ threshold and comes from the analysis of the $J/\psi\pi^\mp$ invariant mass spectra in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4260$ MeV [1]. Before this interesting and important experimental observation, there were some theoretical predictions of charged charmoniumlike structures near $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds [2,4], which were mentioned in the BESIII paper on $Z_c(3900)$ [1].

The BESIII’s result on $Z_c(3900)$ has also inspired extensive discussions of its properties [5-12] and the prediction of a charged charmoniumlike structure with hidden-charm and open-charm [13]. What is more important is that the Belle Collaboration confirmed $Z_c(3900)$ in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4260$ MeV [14]. Later, the former CLEO-c group analyzed data of their own and observed the charged $Z_c(3900)$ structure in their analysis of $586\text{ pb}^{-1}$ data taken by their detector at $\psi(4160)$ [15], which is highly consistent with the BESIII’s observation [1]. In addition, the neutral $Z_c(3900)$ was also released at a $3\sigma$ significance [15].

Among many theoretical papers [2-4] on the predictions of charged charmoniumlike structures cited in BESIII’s paper [1], Ref. [2] has given the predictions of enhancement structures near $D\bar{D}^*$ and $D^*\bar{D}^*$ thresholds in the corresponding $J/\psi\pi^\pm$, $\psi(2S)\pi^\pm$, and $h_1(1P)\pi^\pm$ invariant mass spectra, where $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, and $Y(4260)$ decay into $\pi^+\pi^- J/\psi$, $\pi^0\pi^- J/\psi$, and $\pi^+\pi^- h_1(1P)$ via the initial-single-pion-emission (ISPE) mechanism [16], which was first proposed to understand the Belle’s observations of two charged bottomonium-like structures $Z_b(10610)$ and $Z_b(10650)$ appearing in the hidden-bottom dipion decays of $\Upsilon(5S)$ [17]. Later, the ISPE mechanism was applied to study the hidden-bottom dipion decays of $\Upsilon(11020)$, where the charged bottomonium-like structures near the $B\bar{B}$ and $B^*\bar{B}^*$ thresholds were predicted [18]. In addition, two charged straegonium-like structures observable in the $Y(2175) \rightarrow \pi^+\pi^- \phi$ (1020) process were predicted in Ref. [19] using the ISPE. These abundant theoretical results predicted by the ISPE mechanism [2-18] can be further tested in experiment.

Having more experimental information on the distribution of the $J/\psi\pi^\pm$ and $\pi^+\pi^- J/\psi$ invariant mass spectra of $Y(4260) \rightarrow \pi^+\pi^- J/\psi$ through the ISPE mechanism to get deeper understanding of a $Z_c(3900)$ structure discovered in the $J/\psi\pi^\pm$ invariant mass spectrum. Along this road, in this paper one will fit our model based on the ISPE mechanism to the experimental data of the $J/\psi\pi^\pm$ and $\pi^+\pi^- J/\psi$ invariant mass spectra of $Y(4260) \rightarrow \pi^+\pi^- J/\psi$. In this study, one would like to check whether the $Z_c(3900)$ structure can be reproduced through the ISPE mechanism. This will be helpful to deeply understand how to generate $Z_c(3900)$, which makes our study presented here an intriguing research work.

As for the hidden-charm dipion decay discussed here,

$$Y(4260)(p_0) \rightarrow \pi^+(p_1)\pi^-(p_2)J/\psi(p_3),$$

there exist different decay mechanisms as shown in Fig. 1 which play an important role in connecting the initial state $Y(4260)$ and final state $\pi^+\pi^- J/\psi$. Among these decay mechanisms, the first one is due to the $Y(4260)$ direct decay into $\pi^+\pi^- J/\psi$ (see Fig. 1(a)), where $Y(4260) \rightarrow \pi^+\pi^- J/\psi$ occurs without the intermediate state contribution and mainly provides the background for the distributions of the $\pi^+\pi^-$ and $J/\psi\pi^\pm$ invariant mass spectra. The intermediate state contributions come from $\sigma(600)$, $f_0(980)$, and the triangle hadronic loops composed of charmed mesons.

By the effective Lagrangian approach, the decay amplitude of the direct decay of $Y(4260) \rightarrow \pi^+\pi^- J/\psi$ can be written as

$$M_{\text{Direct}}(Y(4260) \rightarrow \pi^+\pi^- J/\psi) = \frac{F}{f^2} \epsilon_{Y(4260)} \cdot \epsilon_{J/\psi} \left| q^2 - \kappa(M) \right| \left( 1 + \frac{2m_{D^*}^2}{q^2} \right) \left( 1 + \frac{m_{\pi^0}^2}{q^2} \right) \frac{3}{2} \kappa(M) \left( \cos \theta - \frac{1}{3} \right) \frac{m_{D^*}^2}{q^2},$$

which was once constructed by Novikov and Shifman to study $\phi' \rightarrow \pi^+\pi^- J/\psi$ transition [20]. In Eq. (1), the subscripts S-wave and D-wave represent the corresponding amplitudes.
from S-wave and D-wave contributions, respectively. \( \Delta M = m_{Y(4260)} - m_{J/\psi} \) is the mass difference between \( Y(4260) \) and \( J/\psi \). \( q^2 = (p_1 + p_2)^2 = m_{\pi^+\pi^-}^2 \) denotes the invariant mass of \( \pi^+\pi^- \) while \( \theta \) is the angle between \( Y(4260) \) and \( \pi^- \) in the \( \pi^+\pi^- \) rest frame. In addition, the pion mass and decay constants are taken as \( m_{\pi^+} = 139 \text{ MeV} \) and \( f_\pi = 130 \text{ MeV} \), respectively. Here, the amplitude of direct contribution is constructed to study the dipion transitions between spin \( \frac{1}{2}^+ \) states.

Besides these two decay mechanisms mentioned above, there is the third mechanism of \( Y(4260) \to J/\psi \pi^+\pi^- \) decay, i.e., the ISPE mechanism, via which the typical diagrams depicting \( Y(4260) \to J/\psi \pi^+\pi^- \) are shown in Figs. 1(c)-(d) corresponding to the \( \pi^- \) and \( \pi^+ \) emissions from \( Y(4260) \), respectively. Through the ISPE mechanism, \( Y(4260) \) first decays into a pair of intermediate charmed and anticharmed mesons with initial-single-pion-emission. Due to the continuous energy distribution of this pion, the intermediate charmed and anticharmed meson pair is of low momentum, which makes these intermediate mesons easily interact with each other to transform into \( J/\psi \) and \( \pi \). The diagram (c) in Fig. 1 will generate an enhancement structure near the threshold of \( D^*D^{*0} \) in the \( J/\psi \pi^+\pi^- \) invariant mass spectrum and a similar enhancement structure appears in the \( J/\psi \pi^- \) invariant mass spectrum resulting from diagram 1 (d). The latter enhancement can produce a bump when we project it into the Dalitz plot with \( J/\psi \pi^+ \) invariant mass distribution in abscissa, which we call the reflection in the \( J/\psi \pi^- \) invariant mass spectrum.

The detailed calculations of \( Y(4260) \to \pi^+\pi^- J/\psi \) via the ISPE mechanism are presented in Ref. [2], which shows that there are charged enhancement structures near \( D^0D^0 \) and \( D^*D^* \) thresholds. After performing the loop integrals, the decay amplitudes via the intermediate \( DD^0 \) and \( D^*D^{*0} \) can be parametrized as

\[
M_{\text{ISPE}}^{DD}(Y(4260) \to \pi^+\pi^- J/\psi) = g_{Y(4260)DD} e_{Y(4260)}^{\mu} e_{J/\psi}^{\nu} A_0 g_{\mu\nu} + (A_1 p_{1\mu} p_{1\nu} + A_2 p_{1\mu} p_{2\nu} + A_3 p_{2\mu} p_{1\nu} + A_4 p_{2\mu} p_{2\nu}),
\]

and

\[
M_{\text{ISPE}}^{D^*D^*}(Y(4260) \to \pi^+\pi^- J/\psi) = g_{Y(4260)D^*D^*} e_{Y(4260)}^{\mu} e_{J/\psi}^{\nu} B_0 g_{\mu\nu} + (B_1 p_{1\mu} p_{1\nu} + B_2 p_{1\mu} p_{2\nu} + B_3 p_{2\mu} p_{1\nu} + B_4 p_{2\mu} p_{2\nu}).
\]

respectively, where the coefficients \( A_i, B_i \), and \( C_i \) (\( i = 0 - 4 \)) in front of the di The ISPE mechanism can be evaluated by the loop integrals in the ISPE mechanism (see Ref. [2] for more details). As indicated in Ref. [2], the coupling constants of \( Y(4260) \), interacting with \( D^{(*)}D^{(*)} \), \( g_{Y(4260)DD}\), \( g_{Y(4260)D^*D^*}\), and \( g_{Y(4260)D^*D^{*0}}\), are unknown and become fitting parameters. The total decay amplitude of \( Y(4260) \to \pi^+\pi^- J/\psi \) is the sum over the subamplitudes, i.e.,

\[
M_{\text{Total}}(Y(4260) \to \pi^+\pi^- J/\psi) = M_{\text{Direct}} + e^{\phi_{D^0}} M_{\text{ISPE}} + e^{\phi_{D^*}} M_{\text{ISPE}} + e^{\phi_{D^*D^*}} M_{\text{ISPE}},
\]

where three phase angles \( \phi_{D^0}, \phi_{D^*}, \) and \( \phi_{D^*D^*} \) are introduced.
As discussed above, in our scenario we introduce ten free fitting parameters as

\[
F, \kappa, F_\sigma, F_{f_0(980)}, \phi_\sigma, \phi_{f_0(980)}, \phi_{\text{ISPE}}
\]

where \( \phi_{\text{ISPE}} \) are from PDG, and the other resonance parameters are from Ref. [21]. The resonance parameters involving in our calculation are listed in Table I.

Using Eq. (8), we fit the data from the BESIII and Belle collaborations and try to reproduce the enhancement in the \( J/\psi\pi^\pm \) invariant mass spectrum, whose peak is reported as \( Z_c(3900) \). The two red histograms in Fig. 2 are the results of our model with the ISPE mechanism. To obtain these histograms, we take the optimum values listed in Table II. Comparing our theoretical results with the data from the BESIII and Belle collaborations, we notice that the \( d\Gamma(Y(2460) \rightarrow \pi^+\pi^- J/\psi) \) distribution agrees well with the \( J/\psi\pi^\pm \) invariant mass spectrum. Here, two peaks, the \( Z_c(3900) \) structure and its reflection, can be nicely reproduced, where our fitting results indeed reflect the fact that \( Z_c(3900) \) is much sharper than its reflection. In addition, with the same fitting parameters, the theoretical distribution of \( d\Gamma(Y(2460) \rightarrow \pi^+\pi^- J/\psi) \) is also given and reproduces well the experimental data of the \( J/\psi \pi^\pm \) invariant mass spectrum again.

In summary, the charged charmoniumlike structure \( Z_c(3900) \) has been newly observed and reported by the BESIII Collaboration [1] and confirmed by Belle [14] and CLEO-c [15]. As this new observation, different theoretical groups have given different explanations for \( Z_c(3900) \) [5–12]. Among these explanations, the discussions on whether the structure of \( Z_c(3900) \) is due to an exotic state or not are very popular, where the exotic state explanation of \( Z_c(3900) \) includes a molecular state composed of \( D \) and \( \bar{D}^* \) mesons or a tetraquark state.

As mentioned in the BESIII experimental paper [1], there existed theoretical predictions of charmed charmoniumlike structures near the \( D\bar{D}^* \) threshold [2,4] before the observation of \( Z_c(3900) \). In Ref. [2], the ISPE mechanism was applied to study \( Y(2460) \rightarrow \pi^+\pi^- J/\psi, \pi^+\pi^- \phi, \pi^+\pi^- h_c \) decays, where two of the authors of this paper predicted the interesting phenomena of charged \( D\bar{D}^* \) structures existing in the \( J/\psi\pi^\pm \) invariant mass spectra. The BESIII observation of \( Z_c(3900) \) has inspired us to study the \( Y(2460) \rightarrow \pi^+\pi^- J/\psi \) decay process by the ISPE mechanism again together with other diagrams shown in Fig. 1 where we are able to fit our model completely, including a tree diagram as well as relative phases to the experimental data in our scenario, since BESIII now provides abundant information for the distribution of the \( J/\psi\pi^\pm \) invariant mass spectra.

As shown in Fig. 2, the \( Z_c(3900) \) structure has been remarkably reproduced under the ISPE mechanism that includes the interference effects. This fact affirmatively answers whether \( Z_c(3900) \) corresponds to the predicted charged charmoniumlike structure near \( D\bar{D}^* \) threshold via the ISPE mechanism in Ref. [2].

Besides the prediction and/or reproduction relevant to \( Z_c(3900) \) under the ISPE mechanism, there are other abundant predictions for the features of charged enhancement structures in the hidden-charm dipion decays of higher charmonia [2], the hidden-bottom dipion decays of \( \Upsilon(11020) \) [18], and the hidden-strange dipion decays of \( Y(2175) \) [19]. We hope that future experiments will carry out searches for these novel phenomena.

Given the experimental data, the present work has provided an important approach to test the ISPE mechanism. With more experimental observations, more phenomenological and theo-
FIG. 2: (color online). The distributions of the $J/\psi \pi^+$ and $\pi^+ \pi^-$ invariant mass spectra of $Y(4260) \rightarrow \pi^+ \pi^- J/\psi$. The blue dots and green triangles with error bars are the experimental data given by BESIII [1] and Belle [14], respectively. The red histograms are our results considering contributions of the ISPE mechanism to the $Y(4260) \rightarrow \pi^+ \pi^- J/\psi$ decay.

Theoretical efforts should be made by combining further experimental data, which will finally clarify what is the underlying mechanism behind the observed $Z_c(3900)$ structure and other exotic structures.

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