Novel explanation of charmoniumlike structure in $e^+e^- \to \psi(2S)\pi^+\pi^-$

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We first present a nonresonant description to charmoniumlike structure $Y(4360)$ in the $\psi(2S)\pi^+\pi^-$ invariant mass spectrum of the $e^+e^- \to \psi(2S)\pi^+\pi^-$ process. The $Y(4360)$ structure is depicted well by the interference effect of the production amplitudes of $e^+e^- \to \psi(2S)\pi^+\pi^-$ via the intermediate charmonia $\psi(4160)/\psi(4415)$ and direct e^+e^- annihilation into $\psi(2S)\pi^+\pi^-$. This fact shows that $Y(4360)$ is not a genuine resonance, which naturally explains why $Y(4360)$ was only reported in its hidden-charm decay channel $\psi(2S)\pi^+\pi^-$ and was not observed in the exclusive open-charm decay channel or R-value scan.

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With the observations of charmoniumlike states X, Y, Z by experiment, studying charmoniumlike states X, Y, Z has became an intriguing and important research topic in hadron physics at present. The initial-state radiation (ISR) processes $e^+e^- \to \gamma_{\rm ISR} J/\psi\pi^+\pi^-$ and $e^+e^- \to \gamma_{\rm ISR}\psi(2S)\pi^+\pi^-$ are the ideal platform to carry out the study of charmoniumlike states with $J^{PC} = 1^{--}$. Besides the first observation of the $Y(4260)$ structure in $e^+e^- \to \gamma_{\rm ISR} J/\psi\pi^+\pi^-$ announced by *BABAR* [1] and confirmed by the CLEO and Belle Collaborations [2–4], a new charmoniumlike structure $Y(4360)$ was reported at *BABAR* [5] by analyzing the $\psi(2S)\pi^+\pi^-$ invariant mass spectrum of $e^+e^- \to \gamma_{\rm ISR}\psi(2S)\pi^+\pi^-$. Later, Belle confirmed *BABAR*'s result and also announced another structure $Y(4660)$ in $e^+e^- \to \gamma_{\rm ISR}\psi(2S)\pi^+\pi^-$ [6].

These observations of $Y(4360)$ and $Y(4660)$ not only make the vector charmoniumlike structures in ISR processes become abundant, but also stimulate the theorist's interest in revealing their underlying structure. Ding *et al.* indicated that $Y(4360)$ could be as a $n^{2S+1}J_L = 3^3D_1$ charmonium state or a charmonium hybrid, while $Y(4660)$ is a good candidate of charmonium with $n^{2S+1}J_L = 5^3S_1$ [7]. With these possible structure assignments, the corresponding decay behaviors of $Y(4360)$ and $Y(4660)$ are given [7]. Under the same charmonium assignments to $Y(4360)$ and $Y(4660)$ as that in Ref. [7], the dielectron widths of $Y(4360)$ and $Y(4660)$ are obtained [8]. With screened potential, Li and Chao calculated the mass spectrum of charmonium, which explained $Y(4360)$ and $Y(4660)$ as $\psi(3D)$ and $\psi(6S)$ charmonia, respectively, and predicted their decay behaviors [9]. In Ref. [10], $Y(4360)$ was also explained as a $4S$ charmonium state. The baryonium assignments to $Y(4360)$ and $Y(4660)$ were proposed in [11], where $Y(4360)$ might be the radial excited state of $Y(4260)$ and $Y(4660)$ is the radial excited state of the C-spin singlet with the flavor wave function $(|\Lambda_c^+\Lambda_c^-\rangle + |\Sigma_c^0\bar{\Sigma}_c^0\rangle)/\sqrt{2}$, which in fact are an extension of former $\Lambda_c^+\Lambda_c^-$ baryonium explanation to $Y(4260)$ [12]. Associated with the charmoniumlike state $Y(4630)$ in $e^+e^- \to \Lambda_c^+\Lambda_c^-$ [13] with $Y(4660)$, Cotugno *et al.* suggested that both $Y(4630)$ and $Y(4660)$ are from the same charmed baryonium state [14]. The authors in Ref. [15] indicated that the vector hybrid charmonium with strong coupling with D^*D_0 channel results in considerable threshold attraction related to $Y(4360)$. By the QCD sum rule, Albuquerque and Nielsen calculated the masses of $(c\bar{c}q\bar{q})$ or $(c\bar{c}s\bar{s})$ states with $J^{PC} = 1^{--}$, and found that $(c\bar{c}s\bar{s})$ state with obtained mass 4.65 GeV corresponds to $Y(4660)$, while $Y(4360)$ could be as a $D_0\bar{D}^{*0}$ molecular state [16]. Later, the mass of the P-wave cs-scalar-diquark $\bar{c}\,\bar{s}$-scalar-antidiquark state was computed in the framework of the QCD sum rule. The result 4.64 ± 0.25 GeV is in good agreement with the experimental value of $Y(4660)$ [17]. With the obtained effective potential of $D^*\bar{D}_1$ system in Refs. [18,19], Close *et al.* explained $Y(4360)$ as a $2S$ $D^*\bar{D}_1$ molecular state [20,21]. $Y(4660)$ as an $f_0(980)\psi(2S)$ bound state was proposed [22,23] and studied [24].

Although different explanations for $Y(4360)$ and $Y(4660)$ were given from the point of view of conventional charmonium or exotic state just summarized in the above, the current situation regarding the 1^{--} charmoniumlike structures $Y(4360)$ and $Y(4660)$ produced through the ISR process is clearly unsettled [16]. No matter what explanations we proposed, we cannot avoid the fact that there is no evidence of these 1^{--} charmoniumlike structures produced through the ISR process in the exclusive open-charm decay channel [25–31] and R-value scan [32].

Recently, we proposed a new approach different from conventional charmonium and exotic state explanations to explain $Y(4260)$ structure, where $Y(4260)$ is not a genuine resonance [33]. $e^+e^- \to J/\psi\pi^+\pi^-$ can occur directly via e^+e^- annihilation. In addition, the intermediate charmonia can contribute to $e^+e^- \to J/\psi\pi^+\pi^-$, where we choose

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$\psi(4160)$ and $\psi(4415)$ as intermediate charmonia since the $Y(4260)$ structure is just sandwiched by two known charmonia $\psi(4160)$ and $\psi(4415)$. The interference effect from the above two production mechanisms for $e^+e^- \to J/\psi\pi^+\pi^-$ can reproduce the $Y(4260)$ structure in the $J/\psi\pi^+\pi^-$ invariant mass spectrum of the $e^+e^- \to J/\psi\pi^+\pi^-$ process well [33]. Such a nonresonant explanation can naturally answer why the experiment only reported $Y(4260)$ in its hidden-charm decay channel.

Successfully explaining the $Y(4260)$ structure stimulates our interest in extending the same picture to describe the charmoniumlike structures observed in $e^+e^- \to \gamma_{ISR}\psi(2S)\pi^+\pi^-$ since the experimental situation of $Y(4360)$ is similar to that of $Y(4260)$. If the $Y(4360)$ structure also be depicted by the nonresonant explanation similar to that proposed in our former work [33], it not only further supports the nonresonant explanation to $Y(4260)$, but also deepens our understanding of the underlying mechanism resulting in these charmoniumlike structures produced via the ISR process.

In general, the $e^+e^- \to \psi(2S)\pi^+\pi^-$ process occurs via two mechanisms. One is the direct production of $\psi(2S)\pi^+\pi^-$ by e^+e^- annihilation [Fig. 1(a)], which can be depicted by the production amplitude

$$\mathcal{A}_{NoR} = g_{NoR}\bar{u}(-k_1)\gamma_\mu u(k_2)\epsilon^{\mu}_{\psi(2S)}(k_5)\mathcal{F}_{NoR}(s), \quad (1)$$

where the form factor $\mathcal{F}_{NoR}(s)$ is introduced to represent the s-dependence of $\psi(2S)\pi^+\pi^-$ production directly via the e^+e^- annihilation, which can be represented as $\mathcal{F}_{NoR}(s) = \exp(-a(\sqrt{s} - \sum_f m_f)^2)$ with $\sum_f m_f$ as the sum of the masses of the final states for $e^+e^- \to \psi(2S)\pi^+\pi^-$. In Eq. (1), two parameters a and coupling constant $g_{\rm NoR}$ are introduced. $\sqrt{s}$ is the energy of center of mass frame of e^+e^-. k_1, k_2, k_5 correspond to the four momenta of e^+, e^-, $\psi(2S)$, respectively.

Another is from the intermediate charmonium contribution shown in Fig. 1(b), where e^+ and e^- annihilate into one virtual photon, which interacts with vector charmonium. Then, charmonium transits into $\psi(2S)\pi^+\pi^-$. Since two well-known charmonia $\psi(4160)$ and $\psi(4415)$ are most close to $Y(4360)$ among these observed charmonia, we choose $\psi(4160)$ and $\psi(4415)$ as the intermediate states to $e^+e^- \to \psi(2S)\pi^+\pi^-$ process. Under the vector meson

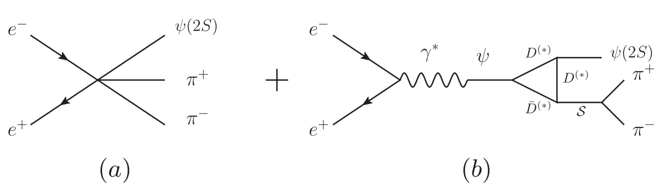

FIG. 1. The diagrams depicting the $e^+e^- \to \psi(2S)\pi^+\pi^-$ production process. (a) The e^+e^- annihilation directly into $\psi(2S)\pi^+\pi^-$. (b) The contributions from intermediate charmonia to $e^+e^- \to \psi(2S)\pi^+\pi^-$. Here, the hadronic loop effect plays an important role to the $\psi \to \psi(2S)\mathcal{S}$ transition.

dominance mechanism [34,35] for the $\gamma \to \psi(4160)/\psi(4415)$ coupling, the general amplitude of $e^+(k_1)e^-(k_2) \to \psi(2S)(k_5)\pi^+(k_3)\pi^-(k_4)$ via the intermediate charmonia reads as

$$\begin{aligned}\mathcal{A}_{\psi,\mathcal{S}} &= \bar{u}(-k_1)e\gamma^\mu u(k_2)\frac{em^2_\psi/f_\psi\epsilon^{\rho}_{\psi(2S)}}{(k_1+k_2)^2 - m^2_\psi + im_\psi\Gamma_\psi} \\ &\quad\times[g^\psi_A g_{\nu\rho}k_5\cdot(k_3+k_4) + g^\psi_B k_{5\nu}(k_{3\rho}+k_{4\rho})] \\ &\quad\times\frac{-g^\nu_\mu}{(k_1+k_2)^2}\frac{g_{\mathcal{S}\pi\pi}(k_3\cdot k_4)}{(k_3+k_4)^2 - m^2_{\mathcal{S}} + im_{\mathcal{S}}\Gamma_{\mathcal{S}}}, \end{aligned} \quad (2)$$

with the decay constant f_ψ of intermediate charmonium and the coupling constant $g_{\mathcal{S}\pi\pi}$ of scalar state interacting with di-pion, where we assume $\pi^+\pi^-$ from scalar σ and $f_0(980)$ states which is consistent with the measurement result of the $\pi^+\pi^-$ invariant mass spectrum in $e^+e^- \to \psi(2S)\pi^+\pi^-$ [6]. Thus, in Eq. (2) we set $\psi = \{\psi_1 = \psi(4160), \psi_2 = \psi(4415)\}$ and $\mathcal{S} = \{\sigma, f_0(980)\}$. In Eq. (2), the coupling constants g^ψ_A and g^ψ_B are relevant to the transition of intermediate charmonium coupling to $\psi(2S)\mathcal{S}$, which are determined by evaluating hadronic loop mechanism [36–40]. Here, g^ψ_A and g^ψ_B are the functions of β_1 and β_2 respectively, where we adopt $\beta_1 = \beta_2 = 1$ [41], which are the parameters from the introduced form factor in hadronic loop calculation (see Ref. [33] for more details and the input parameters)

We write out the total amplitudes for $e^+e^- \to \psi(2S)\pi^+\pi^-$

$$\begin{aligned}\mathcal{A}_{\rm tot} &= \mathcal{A}_{NoR} + e^{i\phi_1}(\mathcal{A}_{\psi_1,\sigma} + e^{i\phi_s}\mathcal{A}_{\psi_1,f_0}) \\ &\quad + e^{i\phi_2}(\mathcal{A}_{\psi_2,\sigma} + e^{i\phi_s}\mathcal{A}_{\psi_2,f_0}) \\ &\equiv \mathcal{A}_{NoR} + \mathcal{A}_{\psi_1} + \mathcal{A}_{\psi_2} \end{aligned} \quad (3)$$

with three introduced phase angles ϕ_1, ϕ_2, ϕ_s. Generally speaking, the phases between different Feynman diagrams are fixed and not arbitrary as they are in this work. However, there maybe exist hadronic loop effects which generate different phases among the different diagrams (because the momentum flow is different). Hence, it is permissible to parameterize our ignorance of these interactions with these arbitrary phases to be fitted as is done in this work [33]. The observable is proportional to the modulus square of production amplitude $\mathcal{A}_{\rm tot}$, which includes the squared amplitudes ($|\mathcal{A}_{NoR}|^2, |\mathcal{A}_{\psi_1}|^2, |\mathcal{A}_{\psi_2}|^2$) and the cross terms ($2\,{\rm Re}(\mathcal{A}_{\psi_1}\mathcal{A}^*_{NoR})$, $2\,{\rm Re}(\mathcal{A}_{\psi_2}\mathcal{A}^*_{NoR})$, $2\,{\rm Re}(\mathcal{A}_{\psi_2}\mathcal{A}^*_{\psi_1})$), where such cross terms reflect the interference effect just mentioned above.

With the above preparation, in the following we investigate whether the experimental data given by *BABAR* and Belle [5,6] can be recovered by our model, where five parameters listed in Table I are applied to fit the experimental data of $e^+e^- \to \psi(2S)\pi^+\pi^-$ at *BABAR* and Belle.

As shown in the last diagram of Fig. 2, we obtain the best fit (red solid line) for the experimental data of $e^+e^- \to \psi(2S)\pi^+\pi^-$, where the obtained central values with errors

TABLE I. The values of parameters for the best fit (the red solid line shape in Fig. 2) to the experimental data. Here, GeV^{-2} and GeV^{-1} are as units of a and g_{NoR}, respectively.

Parameter	Value	Parameter	Value (Rad)
a	4.9248 ± 0.4105	ϕ_1	2.6770 ± 0.1260
g_{NoR}	0.0074 ± 0.0009	ϕ_2	1.8509 ± 0.3010
		ϕ_s	0.0003 ± 0.2467

of the fitting parameters are listed in Table I, which indicate that the theoretical line shape of $e^+e^- \to \psi(2S)\pi^+\pi^-$ is not sensitive to the changes of the fitting parameters. Thus, our theoretical study indicates that the $Y(4360)$ structure in the $\psi(2S)\pi^+\pi^-$ invariant mass spectrum is reproduced well under the interference effect proposed in this work.

For explicitly illustrating the evolution of the line shape, we present how the $Y(4360)$ signal in $e^+e^- \to \psi(2S)\pi^+\pi^-$ is depicted by adding the intermediate charmonia $\psi(4160)/\psi(4415)$ and considering the interference effect in a stepwise fashion, which is given by the remaining five diagrams in Fig. 2. Here, the obtained fitting parameters (see Table I) corresponding to the best fit are adopted. We notice that the interference of production amplitudes of the $e^+e^- \to \psi(2S)\pi^+\pi^-$ processes via direct e^+e^- annihilation and through the intermediate charmonia $\psi(4160)/\psi(4415)$ plays a crucial role of fitting the experimental line shape of the $Y(4360)$ structure. Describing the $Y(4360)$ structure well in our model shows that the $Y(4360)$ structure in $e^+e^- \to \psi(2S)\pi^+\pi^-$ is not genuine resonance, which naturally explains why there is no evidence of $Y(4360)$ in the exclusive open-charm process and R-value scan. As announced by Belle, there is another structure $Y(4660)$ besides $Y(4360)$ in the $\psi(2S)\pi^+\pi^-$ invariant mass spectrum. Our study shows that the $Y(4660)$ structure cannot be described by the interference effect just mentioned in this work. Revealing the property of $Y(4660)$ is still an intriguing research topic.

The whole picture of the $Y(4360)$ structure proposed in this letter is an important extension of that for the $Y(4260)$ structure in $e^+e^- \to J/\psi\pi^+\pi^-$, where $Y(4260)$ is also not genuine resonance [33]. In comparing the experimental information of $Y(4360)$ and $Y(4260)$, one notices that both $Y(4360)$ and $Y(4260)$ were observed in an exclusive hidden-charm decay channel by the ISR process, where $Y(4360)$ and $Y(4260)$ correspond to $\psi(2S)\pi^+\pi^-$ and $J/\psi\pi^+\pi^-$ channels, respectively, which reflects the small difference between $Y(4360)$ and $Y(4260)$. To some extent, such a nonresonant picture for $Y(4360)$ not only embodies the similarity between $Y(4360)$ and $Y(4260)$, but also supports the $Y(4260)$ nonresonant explanation in Ref. [33].

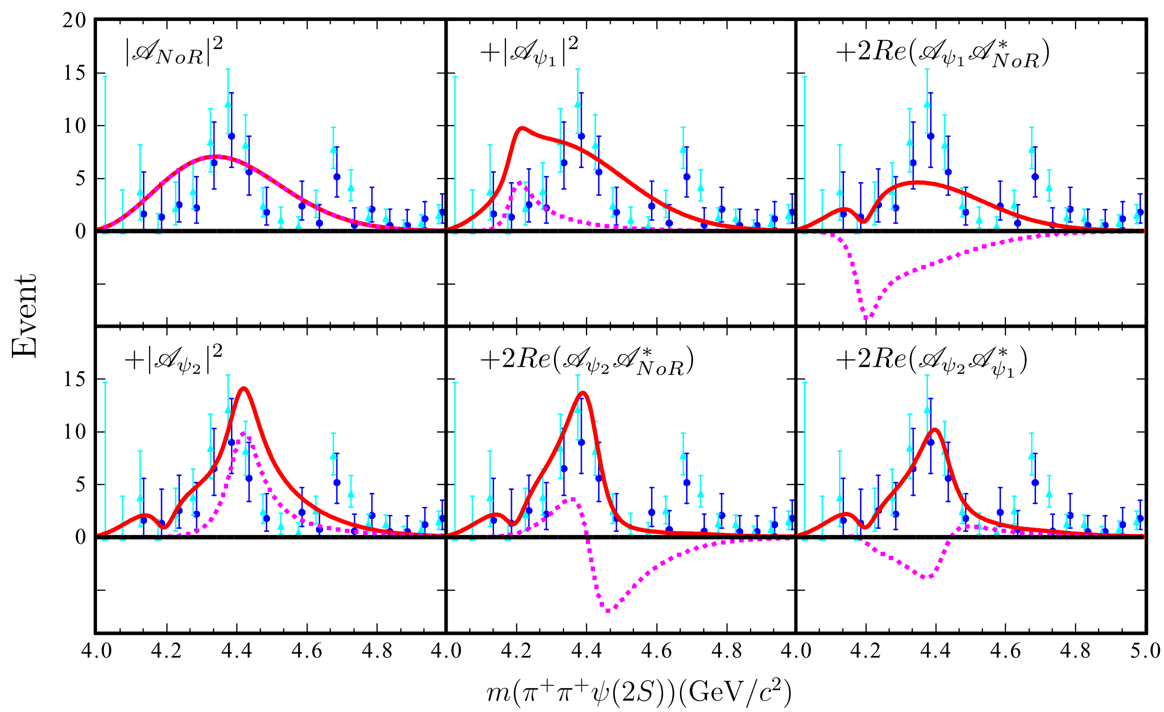

FIG. 2 (color online). The line shape of the cross section of the $e^+e^- \to \psi(2S)\pi^+\pi^-$ process dependent on $\sqrt{s} = m(\pi^+\pi^-\psi(2S))$. The blue dots and cyan triangles with the error bar are experimental data measured by *BABAR* and Belle, respectively. Our result is normalized to the experimental data. Here, one also presents the changes of the theoretical line shape (red solid line) by adding the contributions from these six terms ($|\mathcal{A}_{NoR}|^2$, $|\mathcal{A}_{\psi_1}|^2$, $2\,\mathrm{Re}(\mathcal{A}_{\psi_1}\mathcal{A}^*_{NoR})$, $|\mathcal{A}_{\psi_2}|^2$, $2\,\mathrm{Re}(\mathcal{A}_{\psi_2}\mathcal{A}^*_{NoR})$ and $2\,\mathrm{Re}(\mathcal{A}_{\psi_2}\mathcal{A}^*_{\psi_1})$) one by one. The sum of such six terms finally results in the total line shape of the cross section of the $e^+e^- \to J/\psi\pi^+\pi^-$ process just shown in the last diagram. The pink dashed line in each diagram reflects the contribution of each of six terms in $|\mathcal{A}_{\mathrm{tot}}|^2$.

In summary, stimulated by the observation of the charmoniumlike structure $Y(4360)$ in the $e^+e^- \to \psi(2S)\pi^+\pi^-$ process, in this paper we first propose a novel nonresonant explanation to the underlying structure of $Y(4360)$, which is different from the previous conventional charmonium or exotic explanations. The $Y(4360)$ structure is obtained by the interference effect of the production amplitude of $e^+e^- \to \psi(2S)\pi^+\pi^-$ via the intermediate charmonia $\psi(4160)/\psi(4415)$ and direct e^+e^- annihilation into $\psi(2S)\pi^+\pi^-$. Such a picture provides a natural explanation of why this experiment did not find any evidence of $Y(4360)$ in the exclusive open-charm decay process and R-value scan. Furthermore, the study presented in this paper further deeps our understanding of charmoniumlike structures observed in the hidden-charm process.

This study can be extended to include the theoretical study of other charmoniumlike structures appearing in other hidden-charm processes from e^+e^- annihilation by the ISR mechanism. Recently, the CLEO-c Collaboration announced a preliminary result by studying $e^+e^- \to h_c\pi^+\pi^-$, where there is a suggestive rise at 4260 MeV in the $h_c\pi^+\pi^-$ invariant mass spectrum [42]. Thus, we expect more experimental measurements especially to $e^+e^- \to h_c\pi^+\pi^-$. In addition, carrying out the study of the remaining charmoniumlike structure $Y(4660)$ [6] in the $\psi(2S)\pi^+\pi^-$ invariant mass spectrum will be also an intriguing and valuable research topic by associating with the charmoniumlike structure $Y(4630)$ in $e^+e^- \to \Lambda_c^+\Lambda_c^-$ [13].

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