Charged bottomoniumlike states $Z_b(10610)$ and $Z_b(10650)$ and the $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ decay

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Inspired by the newly observed two charged bottomoniumlike states, we consider the possible contribution from the intermediate $Z_b(10610)$ and $Z_b(10650)$ states to the $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ decay process, which naturally explains Belle's previous observation of the anomalous $\Upsilon(2S)\pi^+\pi^-$ production near the peak of $\Upsilon(5S)$ at $\sqrt{s} = 10.87$ GeV [K.F. Chen *et al.* (Belle Collaboration), Phys. Rev. Lett. **100**, 112001 (2008)]. The resulting $d\Gamma(\Upsilon(5S)\to\Upsilon(2S)\pi^+\pi^-)/dm_{\pi^+\pi^-}$ and $d\Gamma(\Upsilon(5S)\to\Upsilon(2S)\pi^+\pi^-)/d\cos\theta$ distributions agree with Belle's measurement after inclusion of these Z_b states. This formalism also reproduces the Belle observation of the double-peak structure and its reflection in the $\Upsilon(2S)\pi^+$ invariant mass spectrum of the $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ decay.

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Very recently, the Belle Collaboration announced the first observation of two charged bottomoniumlike states $Z_b(10610)$ and $Z_b(10650)$ in the hidden-bottom decay channels $\Upsilon(nS)\pi^\pm$ ($n = 1, 2, 3$) and $h_b(mP)\pi^\pm$ ($m = 1, 2$) of $\Upsilon(5S)$ [1]. The measured parameters of $Z_b(10610)$ and $Z_b(10650)$ are

$$M_{Z_b(10610)}/\Gamma_{Z_b(10610)} = 10608.4 \pm 2.0/15.6 \pm 2.5 \text{ MeV},$$
$$M_{Z_b(10650)}/\Gamma_{Z_b(10650)} = 10653.2 \pm 1.5/14.4 \pm 3.2 \text{ MeV}.$$

The analysis of the angular distribution indicates that the quantum numbers of both $Z_b(10610)$ and $Z_b(10650)$ are $I^G(J^P) = 1^+(1^+)$. Both $Z_b(10610)$ and $Z_b(10650)$ are charged hidden-bottom states. Moreover, they are very close to the thresholds of $B\bar{B}^*$ and $B^*\bar{B}^*$ [2], respectively. Thus, $Z_b(10610)$ and $Z_b(10650)$ are ideal candidates of the $B\bar{B}^*$ and $B^*\bar{B}^*$ S-wave molecular states, which were studied extensively in Refs. [3,4].

On the other hand, a new puzzle arises in the theoretical study [5,6] of the dipion invariant mass distribution and the $\cos\theta$ distribution of the anomalous $\Upsilon(2S)\pi^+\pi^-$ production near the peak of $\Upsilon(5S)$ [7]. While all the other calculations are well in accord with the Belle data, the predicted differential width $d\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)/d\cos\theta$ disagrees with the Belle measurement [5]. In this work, we will illustrate that the inclusion of these two Z_b states in the $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ decays explains the puzzling line shape of $d\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)/d\cos\theta$ very naturally.

In general, there exist three mechanisms for the $\Upsilon(5S)$ hidden-bottom decays with the dipion emission

$$\Upsilon(5S) \to \Upsilon(2S)(p_1)\pi^+(p_2)\pi^-(p_3).$$

The first one is the $\Upsilon(2S)\pi^+\pi^-$ direct production by $\Upsilon(5S)$ decay (see Fig. 1(a)). The so-called direct production of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ denotes that there does not exist the contribution from the intermediate mesons (such as $\sigma(600)$, $f_0(980)$, hadronic loop constructed by $B^{(*)}$ or $B_s^{(*)}$ mesons, Z_b) to $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$. Thus, the direct production of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ provides the background contribution.

The QCD Multipole Expansion method [8] is generally applied to deal with the dipion transition between heavy quarkonia. So far, there exist many theoretical efforts study the dipion transitions between the bottomonia [8–15] (see Refs. [16–18] for a detailed review). In this work, we do

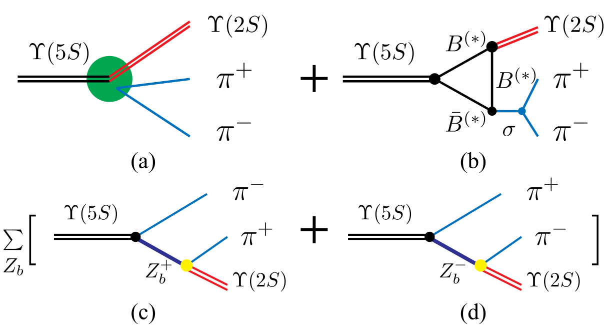

FIG. 1 (color online). The diagrams in the $\Upsilon(5S)$ hidden-bottom decay. Here, Fig. 1(a) represents the $\Upsilon(5S)$ direct decay into $\Upsilon(2S)\pi^+\pi^-$, while Fig. 1(b) denotes the intermediate hadronic loop contribution to $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$. (c) and (d) describe the intermediate $Z_b^\pm$ contribution to $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$, where $Z_b^\pm = \{Z_b(10610)^\pm, Z_b(10650)^\pm\}$.

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not intend to calculate the contribution from the direct transition under the framework of the QCD Multipole Expansion method, but alternatively follow the effective Lagrangian approach to describe $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ transitions. The transition amplitude of the direct production of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ can be written as

$$\mathcal{M}[\Upsilon(5S)\to\Upsilon(2S)\pi^+\pi^-]_{\mathrm{Direct}} = \frac{\mathcal{F}^{(n)}}{f_\pi^2}\epsilon_{\Upsilon(5S)}\cdot\epsilon_{\Upsilon(2S)}\bigg\{\bigg[q^2-\kappa^{(n)}(\Delta M)^2\bigg(1+\frac{2m_\pi^2}{q^2}\bigg)\bigg]_{S-\mathrm{wave}} + \bigg[\frac{3}{2}\kappa^{(n)}((\Delta M)^2-q^2)\bigg(1-\frac{4m_\pi^2}{q^2}\bigg)\bigg(\cos\theta^2-\frac{1}{3}\bigg)\bigg]_{D-\mathrm{wave}}\bigg\}, \tag{1}$$

which was suggested by Novikov and Shifman in the study of the $\psi' \to J/\psi\pi^+\pi^-$ decay [19], where the subscripts S-wave and D-wave denote the S-wave and D-wave contributions, respectively. ΔM is the mass difference between $\Upsilon(5S)$ and $\Upsilon(2S)$. $q^2 = (p_2 + p_3)^2 \equiv m^2_{\pi^+\pi^-}$ denotes the invariant mass of $\pi^+\pi^-$, while θ is the angle between $\Upsilon(5S)$ and π^- in the $\pi^+\pi^-$ rest frame. The pion decay constant and mass are taken as $f_\pi = 130$ MeV and $m_\pi = 140$ MeV, respectively. In Eq. (1), κ and $\mathcal{F}$ are free parameters to be determined when fitting the experimental data.

Different from the other low-lying bottomonia with $J^{PC} = 1^{--}$, $\Upsilon(5S)$ is above the $B^{(*)}\bar{B}^{(*)}$ thresholds and predominantly decays into $B^{(*)}\bar{B}^{(*)}$ pair, which may render the coupled channel effect quite important [20–22]. When exploring the $\Upsilon(5S)$ hidden-bottom decay, the coupled channel effect has to be taken into account. In other words, there also exists the second mechanism contributing to the $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ transitions as shown in Fig. 1(b), where the intermediate $B^{(*)}$ and $\bar{B}^{(*)}$ hadronic loop is the bridge to connect the initial state $\Upsilon(5S)$ and final state $\Upsilon(2S)\pi^+\pi^-$. Furthermore, $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ can be approximately expressed as a sequential decay process. $\Upsilon(5S)$ first transits into $\Upsilon(2S)$ and the scalar meson $\sigma(600)$. Then, $\sigma(600)$ couples with the dipion. Choosing $\sigma(600)$ as the intermediate state contribution to the $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ process is not only consistent with the Belle data [1,7], but also allowed by the phase space of the decay channel.

If comparing the dipion invariant mass spectrum of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ in Refs. [1,7], the data in Ref. [1] at the higher end of $m_{\pi^+\pi^-}$ are qualitatively different from those in Ref. [7], where the total events in Ref. [7] are at least one order of magnitude less than those in Ref. [1]. Such a large accumulation of events at $m_{\pi^+\pi^-} > 700$ MeV [1] might be due to the contribution from the tail of the intermediate $f_0(980)$. We did not include the $f_0(980)$ contribution when we analyzed the data in [7]. Considering the situation of the new data of the dipion invariant mass spectrum of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ [1], we also include the $f_0(980)$ contribution to the analysis of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ in the following.

The effective Lagrangians relevant to Fig. 1(b) include

$$\mathcal{L}_{\Upsilon\mathcal{B}\mathcal{B}} = ig_{\Upsilon\mathcal{B}\mathcal{B}}\Upsilon_\mu(\partial^\mu\mathcal{B}\mathcal{B}^\dagger - \mathcal{B}\partial^\mu\mathcal{B}^\dagger), \tag{2}$$

$$\mathcal{L}_{\Upsilon\mathcal{B}^*\mathcal{B}} = -ig_{\Upsilon\mathcal{B}^*\mathcal{B}}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu\Upsilon_\nu(\partial_\alpha\mathcal{B}^*_\beta\mathcal{B}^\dagger + \mathcal{B}\partial_\alpha\mathcal{B}^{*\dagger}_\beta), \tag{3}$$

$$\begin{aligned}\mathcal{L}_{\Upsilon\mathcal{B}^*\mathcal{B}^*} = -ig_{\Upsilon\mathcal{B}^*\mathcal{B}^*}\{&\Upsilon^\mu(\partial_\mu\mathcal{B}^{*\nu}\mathcal{B}^{*\dagger}_\nu - \mathcal{B}^{*\nu}\partial_\mu\mathcal{B}^{*\dagger}_\nu)\\ &+ (\partial_\mu\gamma_\nu\mathcal{B}^{*\nu} - \Upsilon_\nu\partial_\mu\mathcal{B}^{*\nu})\mathcal{B}^{*\mu\dagger}\\ &+ \mathcal{B}^{*\mu}(\Upsilon^\nu\partial_\mu\mathcal{B}^{*\dagger}_\nu - \partial_\mu\Upsilon_\nu\mathcal{B}^{*\nu\dagger})\},\end{aligned} \tag{4}$$

and

$$\mathcal{L}_{\mathcal{S}\mathcal{B}^{(*)}\mathcal{B}^{(*)}} = g_{\mathcal{B}\mathcal{B}\mathcal{S}}\mathcal{S}\mathcal{B}\mathcal{B}^\dagger - g_{\mathcal{B}^*\mathcal{B}^*\mathcal{S}}\mathcal{S}\mathcal{B}^*\mathcal{B}^{*\dagger}, \tag{5}$$

where $\mathcal{B} = (\bar{B}^0, B^-, B_s^-)$ and $(\mathcal{B}^\dagger)^T = (B^0, B^+, B_s^+)$. There are 4 diagrams. Thus, the concrete expressions of decay amplitudes are written as

$$\mathcal{M}^B_{B\bar{B}} = (i)^3\int\frac{d^4q}{(2\pi)^4}[ig_{\Upsilon(5S)BB}\epsilon^\mu_{\Upsilon(5S)}(ip_{2\mu} - ip_{1\mu})][ig_{\Upsilon(nS)BB}\epsilon^\rho_{\Upsilon(nS)}(-ip_{1\rho} - iq_\rho)][g_{BBS}] \times\frac{1}{p_1^2 - m_B^2}\frac{1}{p_2^2 - m_B^2}\frac{1}{q^2 - m_B^2}\mathcal{F}(q^2), \tag{6}$$

$$\mathcal{M}^{B^*}_{B\bar{B}^*} = (i)^3\int\frac{d^4q}{(2\pi)^4}[-g_{\Upsilon(5S)BB^*}\varepsilon_{\mu\nu\alpha\beta}(-ip_0^\mu)\epsilon^\nu_{\Upsilon(5S)}(ip_2^\alpha)][-g_{\Upsilon(nS)BB}\varepsilon_{\delta\tau\theta\phi}(ip_3^\delta)\epsilon^\tau_{\Upsilon(nS)}(iq^\theta)][-g_{B^*B^*S}] \times\frac{1}{p_1^2 - m_B^2}\frac{-g^{\beta\rho} + p_2^\beta p_2^\rho/m^2_{B^*}}{p_2^2 - m^2_{B^*}}\frac{-g^{\phi\rho} + q^\phi q^\rho/m^2_{B^*}}{q_2^2 - m^2_{B^*}}\mathcal{F}(q^2), \tag{7}$$

$$\mathcal{M}^B_{B\bar{B}^*} = (i)^3\int\frac{d^4q}{(2\pi)^4}[-g_{\Upsilon(5S)B^*B}\varepsilon_{\mu\nu\alpha\beta}(-ip_0^\mu)\epsilon^\nu_{\Upsilon(5S)}(ip_1^\alpha)][-g_{\Upsilon(nS)B^*B}\varepsilon_{\delta\tau\theta\phi}(ip_3^\delta)\epsilon^\tau_{\Upsilon(nS)}(-ip_1^\theta)][g_{BBS}] \times\frac{-g^{\beta\phi} + p_1^\beta p_1^\phi/m^2_{B^*}}{p_1^2 - m^2_{B^*}}\frac{1}{p_2^2 - m_B^2}\frac{1}{q^2 - m_B^2}\mathcal{F}(q^2), \tag{8}$$

$$\mathcal{M}^{B^*}_{B^*\bar{B}^*} = (i)^3 \int \frac{d^4q}{(2\pi)^4}[-ig_{\Upsilon(5S)B^*B^*}\epsilon^{\mu}_{\Upsilon(5S)}((ip_{2\mu} - ip_{1\mu})g_{\nu\rho} + (-ip_{0\rho} - ip_{2\rho})g_{\mu\nu} + (ip_{1\nu} + ip_{0\nu})g_{\mu\rho})]$$
$$\times [-ig_{\Upsilon(nS)B^*B^*}\epsilon^{\phi}_{\Upsilon(nS)}((-ip_{1\phi} - iq_{\phi})g_{\alpha\beta} + (ip_{3\beta} + ip_{1\beta})g_{\alpha\phi} + (iq_{\alpha} - ip_{3\alpha})g_{\beta\phi})][-g_{B^*B^*S}]$$
$$\times \frac{-g^{\rho\alpha} + p_1^{\rho}p_1^{\alpha}/m^2_{B^*}}{p_1^2 - m^2_{B^*}} \frac{-g^{\nu\tau} + p_2^{\nu}p_2^{\tau}/m^2_{B^*}}{p_2^2 - m^2_{B^*}} \frac{-g^{\beta\tau} + q^{\beta}q^{\tau}/m^2_{B^*}}{q^2 - m^2_{B^*}} \mathcal{F}(q^2). \tag{9}$$

The amplitude $\mathcal{M}^C_{AB}$ indicates that the initial $\Upsilon(5S)$ dissolves into intermediate AB, which transit into the final $\Upsilon(2S)$ and scalar meson by exchanging meson C. In the above expressions, the form factor is introduced by $\mathcal{F}(q^2) = (\Lambda^2 - m_E^2)/(q^2 - m_E^2)$. And m_E is the mass of the exchanged $B^{(*)}$ meson in the $B^{(*)}\bar{B}^{(*)} \to \Upsilon(2S)\mathcal{S}$ transitions shown in Fig. 1(b) and $\Lambda = m_E + \alpha\Lambda_{\rm QCD}$ with $\Lambda_{\rm QCD} = 220$ MeV. As indicated in Ref. [5], we can parameterize the decay amplitude of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ corresponding to Fig. 1(b) as

$$\mathcal{M}[\Upsilon(5S) \to \Upsilon(2S)\sigma(600) \to \Upsilon(2S)\pi^+\pi^-] = \frac{\epsilon_{\Upsilon(5S)} \cdot \epsilon^*_{\Upsilon(2S)} F_{\sigma}}{(p_2 + p_3)^2 - m_{\sigma}^2 + im_{\sigma}\Gamma_{\sigma}}, \tag{10}$$

if only considering the S-wave contribution. Here, we introduce F_{σ} as the fitting parameter.

Similar to Eq. (10), the parameterized decay amplitude of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ with $f_0(980)$ as the intermediate state can be expressed as

$$\mathcal{M}[\Upsilon(5S) \to \Upsilon(2S)f_0(980) \to \Upsilon(2S)\pi^+\pi^-] = \frac{\epsilon_{\Upsilon(5S)} \cdot \epsilon^*_{\Upsilon(2S)} F_{f_0}}{(p_2 + p_3)^2 - m_{f_0}^2 + im_{f_0}\Gamma_{f_0}}, \tag{11}$$

which corresponds to Fig. 1(b) with the replacement $\sigma \to f_0(980)$.

Regarding the contribution of these two newly observed Z_b states to the $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ process, we introduce the third mechanism depicted in Fig. 1(c) and 1(d), where $Z_b^{\pm}$s are the intermediate states and interact with $\Upsilon(5S)\pi^{\mp}$ and $\Upsilon(2S)\pi^{\pm}$. The general expressions of the amplitudes of Fig. 1(c) and 1(d) are

$$\mathcal{M}[\Upsilon(5S) \to Z_b^+\pi^- \to \Upsilon(2S)\pi^+\pi^-]_{Z_b^+} = F_{Z_b^+}\epsilon^{\mu}_{\Upsilon(5S)}\epsilon^{*\nu}_{\Upsilon(2S)} \frac{-g_{\mu\nu} + (p_1^{\mu} + p_2^{\mu})(p_1^{\nu} + p_2^{\nu})/m^2_{Z_b}}{(p_1 + p_2)^2 - m^2_{Z_b} + im_{Z_b}\Gamma_{Z_b}} \tag{12}$$

$$\mathcal{M}[\Upsilon(5S) \to Z_b^-\pi^+ \to \Upsilon(2S)\pi^-\pi^+]_{Z_b^-} = F_{Z_b^-}\epsilon^{\mu}_{\Upsilon(5S)}\epsilon^{*\nu}_{\Upsilon(2S)} \frac{-g_{\mu\nu} + (p_1^{\mu} + p_3^{\mu})(p_1^{\nu} + p_3^{\nu})/m^2_{Z_b}}{(p_1 + p_3)^2 - m^2_{Z_b} + im_{Z_b}\Gamma_{Z_b}}, \tag{13}$$

respectively, where we define $F_{Z_b^+} = g_{\Upsilon(5S)Z_b^+\pi}g_{Z_b^+\Upsilon(2S)\pi^+}$ and $F_{Z_b^-} = g_{\Upsilon(5S)Z_b^-\pi}g_{Z_b^-\Upsilon(2S)\pi^-}$. Since Fig. 1(c) and 1(d) are related to each other by charge conjugation, thus $F_{Z_b^-} = F_{Z_b^+} = F_{Z_b}$.

Thus, the total decay amplitude of the $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ decay is

$$\mathcal{M}_{\rm total} = \mathcal{M}[\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-]_{\rm Direct} + e^{i\phi_{\sigma}}\mathcal{M}[\Upsilon(5S) \to \Upsilon(2S)\sigma(600) \to \Upsilon(2S)\pi^+\pi^-]$$
$$+ e^{i\phi_{f_0}}\mathcal{M}[\Upsilon(5S) \to \Upsilon(2S)f_0(980) \to \Upsilon(2S)\pi^+\pi^-] + \sum_{Z_b} e^{i\varphi_{Z_b}}\{\mathcal{M}[\Upsilon(5S) \to Z_b^+\pi^- \to \Upsilon(2S)\pi^+\pi^-]_{Z_b^+}$$
$$+ \mathcal{M}[\Upsilon(5S) \to Z_b^-\pi^+ \to \Upsilon(2S)\pi^+\pi^-]_{Z_b^-}\}, \tag{14}$$

where we have introduced the phase angles ϕ_{σ}, ϕ_{f_0}, $\varphi_{Z_b(10610)}$, and $\varphi_{Z_b(10650)}$.

As a three-body decay, the differential decay width for $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ reads as,

$$d\Gamma = \frac{1}{3}\frac{1}{(2\pi)^3}\frac{1}{32m^3_{\Upsilon(5S)}}|\mathcal{M}_{\rm total}|^2 dm^2_{\Upsilon(2S)\pi}dm^2_{\pi\pi}, \tag{15}$$

with $m^2_{\Upsilon(2S)\pi^+} = (p_1 + p_2)^2$ and $m^2_{\pi^+\pi^-} = (p_2 + p_3)^2$. The relevant resonance parameters are listed in Table I.

If considering only the contributions from Fig. 1(a) and 1(b) in our present scenario, we have four free parameters as listed in Table II, where the $\sigma(600)$ contribution is included to fit the Belle data [7]. With the help of the MINUIT package, we perform the global fit to the experimental data of the dipion invariant mass spectrum distribution and the $\cos\theta$ distribution of the $\Upsilon(2S)\pi^+\pi^-$

TABLE I. The resonance parameters adopted in our calculation [1,2,23].

State	Mass (GeV)	State	Mass (GeV)	Width (GeV)
$\Upsilon(5S)$	10.87	$\sigma(600)$	0.478	0.324
		$f_0(980)$	0.98	0.1
$\Upsilon(2S)$	10.023	$Z_b(10610)$	10.608	0.0156
		$Z_b(10650)$	10.653	0.0144

TABLE II. The values of the fitting parameters for the best fit to the Belle data of $\Upsilon(2S)\pi^+\pi^-$ production near the peak of $\Upsilon(5S)$ [7] without considering the contributions from $Z_b(10610)$ and $Z_b(10650)$. For the obtained central values of the parameters, the corresponding partial decay width of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ is 0.836 MeV.

Parameter	Value	Parameter	Value
$\mathcal{F}$	0.943 ± 0.071	κ	0.739 ± 0.034
F_σ	25.603 ± 2.175 GeV^2	ϕ_σ	2.623 ± 0.132 Rad

TABLE III. The values of the fitting parameters for the $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ decay after including the contributions from $Z_b(10610)$ and $Z_b(10650)$.

Parameter	Value	Parameter	Value
$\mathcal{F}$	1.404 ± 0.068	κ	0.301 ± 0.013
F_σ	20.037 ± 0.423 GeV^2	ϕ_σ	0.907 ± 0.132 rad
F_{f_0}	17.076 ± 3.563 GeV^2	ϕ_{f_0}	-0.753 ± 0.14 rad
$F_{Z_b(10610)}$	3.412 ± 0.385 GeV^2	$\varphi_{Z_b(10610)}$	-3.135 ± 0.03 rad
$F_{Z_b(10650)}$	2.994 ± 0.261 GeV^2	$\varphi_{Z_b(10650)}$	-2.836 ± 0.165 rad

production near the peak of $\Upsilon(5S)$ [7]. The best fit to the dipion invariant mass spectrum distribution is shown in the left panel in Fig. 2. Unfortunately, the corresponding $\cos\theta$ distribution of the $\Upsilon(2S)\pi^+\pi^-$ production strongly deviates from the Belle data, as shown in the right panel of Fig. 2. The values of the obtained fitting parameters are presented in Table II. Such discrepancy between theoretical and experimental results stimulates a *New Puzzle* first indicated in Ref. [5]. At present, solving this new puzzle becomes an important and intriguing research topic, which will be helpful to the underlying mechanism behind the $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ decay.

In contrast, we consider the contribution from $Z_b(10610)$ and $Z_b(10650)$ in the following and discuss the dependence of $d\Gamma/dm_{\pi^+\pi^-}$ and $d\Gamma/d\cos\theta$ of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ on $m_{\pi^+\pi^-}$ and $\cos\theta$, respectively. Under this scheme, we refit the Belle data [7] with Eq. (14). There are 10 fitting parameters as listed in Table III. In Fig. 3, we present a comparison between the Belle data (dots with error bars) and our best fit (histograms) to the Belle data [1], which indicates that the line shapes of the invariant mass spectra of $\pi^+\pi^-$ and $\Upsilon(2S)\pi^+$ for $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ describe the Belle data [1] well. The double-peak structure around 10.6 GeV and its reflection around 10.25 GeV are reproduced by our model well. With the central values of these parameters in Table III, we obtain the partial decay width of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ $\Gamma = 0.915$ MeV, which is consistent with the Belle measurement $\Gamma = 0.85 \pm 0.07(\text{stat}) \pm 0.16(\text{syst})$ MeV [7]. Thus, the contribution from these charged Z_b resonances provides a possible solution to the puzzle of why the $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ decay width is abnormally large [7].

From Table III, we notice that the uncertainty of F_{f_0} is one order of magnitude larger than that of F_σ, which means the fit is less sensitive to the $f_0(980)$ than to the $\sigma(600)$. Using Eq. (14), we reanalyze the new Belle data in Ref. [1] with the obtained fitting parameters in Table IV, where we do not include the $f_0(980)$ contribution. The comparison between our fitting result and the experimental data are given in Fig. 4. By the scenario in Eq. (14), we reproduce the Belle data well, which confirms that the intermediate $f_0(980)$ contribution to $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ is small. If comparing the obtained values of the fitting parameter in Tables III and IV, we notice that the eight common parameters do not change much in the two schemes. With the parameters listed in Tables III and IV, we also present the $\cos\theta$ distribution with and without the intermediate f_0 contribution. The experimental measurement of the $\cos\theta$ distribution for $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ [7] can be described well with the scenarios in this work. This fact indicates that the two Z_b structures play an important role in the understanding of the Belle data, especially the $\cos\theta$ distribution of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$.

In summary, the Belle Collaboration announced an exciting observation of two charged bottomoniumlike states

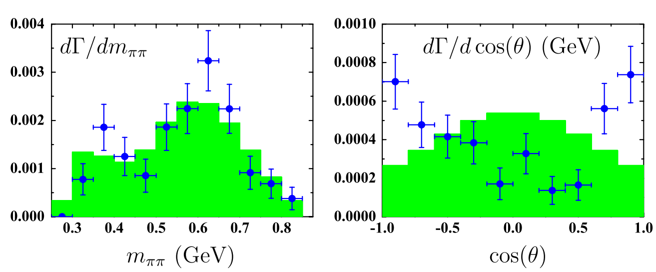

FIG. 2 (color online). (Color online). The dipion invariant mass ($m_{\pi\pi}$) distribution (left panel) and the $\cos\theta$ distribution (right panel) of the $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ decay. The dots with error bars are the results measured by Belle [7], while the green histograms are the best fit from our model without including the intermediate $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$ contribution to $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$. When fitting the experimental data [7], we only include the $\sigma(600)$ contribution.

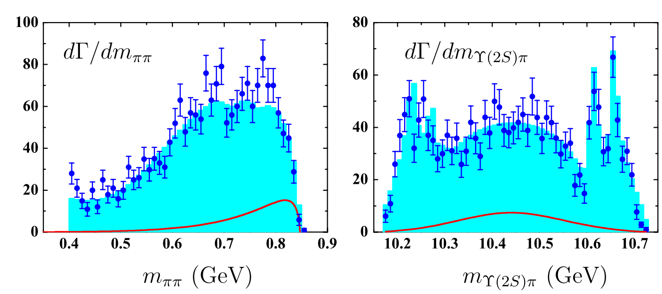

FIG. 3 (color online). (Color online). The invariant mass spectra of $\pi^+\pi^-$ and $\Upsilon(2S)\pi^+$ for $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$. Here, the histograms are theoretical results obtained in our scenario including the intermediate $f_0(980)$ contribution, while dots with error bars are the Belle data in Ref. [1]. We also plot the $f_0(980)$ contribution separately (red solid lines).

TABLE IV. The values of the fitting parameters for the $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ decay after including the contributions from $Z_b(10610)$ and $Z_b(10650)$. These parameters are obtained by fitting the new experimental data without including the contributions from $f_0(980)$.

Parameter	Value	Parameter	Value
$\mathcal{F}$	1.073 ± 0.064	κ	0.379 ± 0.034
F_σ	$23.833 \pm 2.503\ \mathrm{GeV}^2$	ϕ_σ	1.127 ± 0.128 rad
$F_{Z_b(10610)}$	$3.200 \pm 0.345\ \mathrm{GeV}^2$	$\varphi_{Z_b(10610)}$	-3.141 ± 0.076 rad
$F_{Z_b(10650)}$	$2.686 \pm 0.306\ \mathrm{GeV}^2$	$\varphi_{Z_b(10650)}$	-2.703 ± 0.225 rad

$Z_b(10610)$ and $Z_b(10650)$. These Z_b states are good candidates of exotic states, which calls for theoretical efforts in revealing their underlying structures. Carrying out the phenomenological study relevant to $Z_b(10610)$ and $Z_b(10650)$ is one of the important and valuable issues of heavy quarkonium physics, which is full of challenges and opportunities [24,25].

The $Z_b(10610)$ and $Z_b(10650)$ states are related to the anomalous phenomena of $\Upsilon(2S)\pi^+\pi^-$ production near $\Upsilon(5S)$, previously reported by Belle [7]. Comparing the fitting results without and with the contributions from the newly observed states, we notice that the intermediate $Z_b(10610)$ and $Z_b(10650)$ play a crucial role in the behavior of $d\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)/d\cos\theta$. The inclusion of the $Z_b(10610)$ and $Z_b(10650)$ contribution to $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ provides a unique mechanism of understand the puzzling $\cos\theta$ distribution of $\Upsilon(2S)\pi^+\pi^-$ production near $\Upsilon(5S)$ [7]. The double-peak structure and its reflection in the $\Upsilon(2S)\pi^+$ invariant mass spectrum of $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ [1] are also reproduced by this mechanism. In this work, the values of the fitting parameters in our scenario are obtained by fitting Belle data [1,7]. To some extent, the interpretation of the values of these parameters is related to the understanding of background, the structures of two Z_b states, etc, which is an interesting research topic.

Besides finding the signals of $Z_b(10610)$ and $Z_b(10650)$ in the $\Upsilon(2S)\pi^\pm$ decay channel, Belle's analysis of its remaining four hidden-bottom decay channels $\Upsilon(nS)\pi^\pm$ ($n = 1, 3$) and $h_b(mP)\pi^\pm$ ($m = 1, 2$) also indicate the observation of $Z_b(10610)$ and $Z_b(10650)$ [1]. The present formalism can be extended to study the dipion invariant mass distribution and the $\cos\theta$ distribution of $\Upsilon(5S) \to \Upsilon(1S, 3S)\pi^+\pi^-$ and $\Upsilon(5S) \to h_b(1P, 2P)\pi^+\pi^-$ decay (see Fig. 5 for more details).

Additionally, Belle's measurement favors the $B\bar{B}^*$ and $B^*\bar{B}^*$ molecular explanation of the $Z_b(10610)$ and $Z_b(10650)$ resonances, respectively. The possible S-wave $B\bar{B}^*$ and $B^*\bar{B}^*$ molecular states were investigated extensively in Refs. [3,4]. Very recently, the authors in Ref. [26] discussed the special decay behavior of the J = 1 S-wave $B\bar{B}^*$ and $B^*\bar{B}^*$ molecular states based on the heavy quark symmetry. Future dynamical study of the mass and decay pattern of the S-wave $B\bar{B}^*$ and $B^*\bar{B}^*$ molecular states are very desirable.

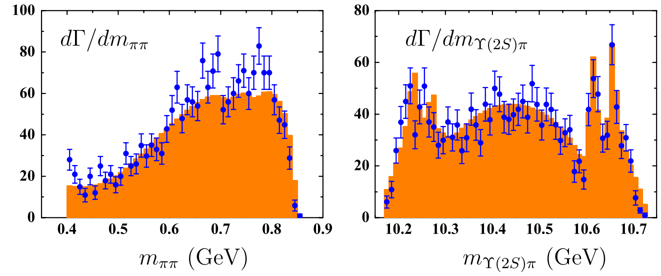

FIG. 4 (color online). (Color online). The distribution invariant mass spectra $m_{\pi\pi}$ and $m_{\Upsilon(2S)\pi}$ for $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ without including the contributions from $f_0(980)$. Here, we use Eq. (14) to redo the analysis. The histograms are the fitting results. The dots with errors correspond to the Belle data [1].

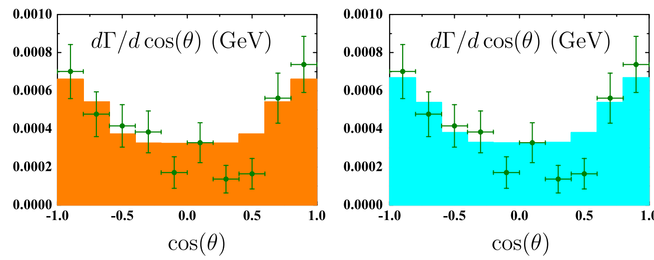

FIG. 5 (color online). (Color online). The $\cos\theta$ distributions for $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$. The histograms in the left-hand side and right-hand side diagrams are the fitting results without and with the contribution from $f_0(980)$. The dots with errors correspond to the Belle data [7].

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