$Y(4260)$ as a four-quark state

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We treat the $Y(4260)$ resonance as a four-quark state in the framework of the covariant confining quark model. We study two choices of the interpolating current, either the molecular-type current which effectively corresponds to the product of D and $\bar{D}_1$ quark currents or tetraquark one. In both cases, we calculate the widths of decays $Y(4260) \to Z_c(3900) + \pi$ and $Y(4260) \to D^{(*)} + \bar{D}^{(*)}$. It is found that in both approaches the mode $Y \to Z_c^+ + \pi^-$ is enhanced compared with the open-charm modes. However, the absolute value of the $Y \to Z_c^+ + \pi^-$ decay width obtained in molecular picture is arguably too large. On the other hand, the value obtained in tetraquark picture is reasonable.

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I. INTRODUCTION

In 2005, *BABAR* Collaboration observed a broad resonance around 4.26 GeV in analyzing the mass spectrum of $\pi^+\pi^- J/\psi$ in initial-state-radiation (ISR) production $e^+e^- \to \gamma_{\rm ISR}\pi^+\pi^- J/\psi$ [1]. Since this resonance was found in the e^+e^- annihilation through ISR, its spin-parity is $J^{PC} = 1^{--}$. However, its mass does not fit any mass of charmonium states in the same mass region, such as the $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$. Moreover, $Y(4260)$ has strong coupling to the $\pi^+\pi^- J/\psi$ final state, but no evidence was found for coupling to any open-charm decay modes as $D^{(*)}\bar{D}^{(*)}$, $D_s^{(*)}\bar{D}_s^{(*)}$ where $D^{(*)} = D$ or D^* [2–6]. These properties perhaps indicate that the $Y(4260)$ state is not a conventional state of charmonium [7].

In addition to $Y(4260)$, the BESIII Collaboration reported on the observation of another exotic state named as $Z_c(3900)$ in the reaction $e^+e^- \to \pi^+\pi^- J/\psi$ [8]. It carries an electric charge and couples to charmonium. A fit to the $\pi^\pm J/\psi$ invariant mass spectrum results in a mass of $M_{Z_c} = 3899.0 \pm 3.6(\text{stat}) \pm 4.9(\text{syst})$ MeV and a width of $\Gamma_{Z_c} = 46 \pm 10(\text{stat}) \pm 20(\text{syst})$ MeV. This state was confirmed by Belle [9] and CLEO [10] Collaborations. Then the BESIII Collaboration observed a distinct charged structure in the $(D\bar{D}^*)^\mp$ invariant mass distribution of the process $e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp$ [11]. Assuming this structure and the $Z_c(3900) \to \pi J/\psi$ signal are from the same source, the ratio of partial widths is $\Gamma(Z_c \to D\bar{D}^*)/\Gamma(Z_c \to \pi J/\psi) = 6.2 \pm 2.7$. That means that the $Z_c(3900)$ state has a much stronger coupling to DD^* than to $\pi J/\psi$ [12].

Now we go back to $Y(4260)$ and shortly review some theoretical efforts to understand the underlying structure of this state. We refer to Refs. [7,13–20] for more complete review of this subject. Probably, one of the first attempts to analyze the possible interpretations of $Y(4260)$ was undertaken in Ref. [21]. The conclusion has been done that only the hybrid charmonium picture is not in conflict with available experimental data from *BABAR* measurement. The interpretation of $Y(4260)$ as a charmonium hybrid has been also explored in Refs. [22,23].

The three-body $J/\psi\pi\pi$ and $J/\psi K\bar{K}$ systems have been treated as coupled channels in Ref. [24]. It was found by solving the Faddeev equations that the resonance $Y(4260)$ can be generated due to the interaction between these three mesons. $Y(4260)$ has been identified as the low member of the pair $\psi(4S) - \psi(3D)$ charmonium by using a simple quark model [25].

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In the paper [26], it was suggested that $Y(4260)$ is a $\chi_{c1} - \rho^0$ molecule. In that picture, one can show that the width of decay $Y(4260) \to \pi^+\pi^- J/\psi$ is larger than $Y(4260) \to D\bar{D}$ which has not been observed.

It was proposed in Ref. [27] to interpret $Y(4260)$ as the first orbital excitation of a diquark-antidiquark state $([cs][\bar{c}\,\bar{s}])$. In this case, $Y(4260)$ should decay predominantly to $D_s\bar{D}_s$.

Masses of heavy tetraquarks have been calculated in the relativistic quark model [28]. It was found the P-wave state of the tetraquark combination $(([cq]_{S=0}[\bar{c}\,\bar{q}]_{S=0})$ has a mass of 4244 MeV which is close to the $Y(4260)$ mass. At the same time, the mass of charm-strange diquark-antidiquark was found to be more than 200 MeV heavier than the $Y(4260)$ mass. It was concluded that a more natural tetraquark interpretation of $Y(4260)$ is charm-nonstrange diquark-antidiquark state. Then the dominant decay mode of $Y(4260)$ would be in $D\bar{D}$ pairs.

However, as mentioned above, no evidence was found for the decays $Y(4260) \to D^{(*)}\bar{D}^{(*)}, D_s^{(*)}\bar{D}_s^{(*)}$ [2–6]. In Ref. [29], it was assumed that $Y(4260)$ is $D\bar{D}_1$ molecular state where $D = D(1870)$ is the pseudoscalar meson with the quantum numbers $I(J^P) = \frac{1}{2}(0^-)$, and $D_1 = D_1(2420)$ is the narrow axial meson $I(J^P) = \frac{1}{2}(1^+)$, $\Gamma = 27 \pm 3$ MeV. With this ansatz, the observation of $Z_c(3900)$ in the $\pi^+\pi^- J/\psi$ invariant mass distribution has an obvious explanation as well the absence of $Y(4260)$ in the decays with open charm.

However, in Ref. [30], it was argued that the production of an S-wave DD_1 pair in $\ell^+\ell^-$ annihilation is forbidden by the heavy quark spin symmetry. This argument is certainly not in the favor of considering $Y(4260)$ as S-wave DD_1 state. Despite this, there are many studies of $Y(4260)$ as DD_1 molecular state. We briefly mention some of them. By assuming that $Y(4260)$ is a DD_1 molecular state, some hidden-charm and charmed pair decay channels of $Y(4260)$ via intermediate DD_1 meson loops within an effective Lagrangian approach have been investigated in Ref. [31]. By treating $Y(4260)$ as a DD_1 weakly bound state and also $Z_c(3900)$ as a DD^* molecule [32], the two-body decay $Y(4260) \to Z_c(3900) + \pi$ has been studied. Moreover, the decay mode $Y(4260) \to J/\psi + \pi^+\pi^-$ was also computed. Further ideas related to $Y(4260)$ and $Z_c(3900)$ states can be found in [33–35].

The approach we propose is based on the covariant confining quark model (CCQM) [36–38] which represents an effective quantum field treatment of hadronic effects. The model is derived from Lorentz-invariant nonlocal Lagrangian in which a hadron is coupled to its constituent quarks. Hadrons are characterized by size parameters Λ_H from which the strength of the quark-hadron coupling can derived. It is done by using the so-called compositeness condition [39,40]; this condition requires the wave function renormalization constant of the hadron to be zero $Z_H = 0$. Besides reducing the number of free parameters (i.e., couplings), it also guarantees a correct description of bound states as dressed (with no overlap with bare states) and solves the double counting problem. The vertices are described by a Gaussian-type vertex functions which are supposed to effectively include contributions from gluons (which are not present). Thanks to the built-in confinement, based on a cutoff in the integration space of Schwinger parameters (stemming from representation of quark propagators), the model can be used for description of arbitrary heavy hadrons. The model should be understood as a practical tool for computing hadronic form factors from assumed quark currents, which is, in this text, applied to $Y(4260)$ and $Z_c(3900)$ states.

In our earlier papers devoted to description of the multiquark states, Refs. [41,42], first, we explored the consequences of treating the $X(3872)$ meson as a tetraquark, i.e., diquark-antidiquark bound state. We calculated the decay widths of the observed channels and concluded that for reasonable values of the size parameter of $X(3872)$ one finds consistency with the available experimental data. Then we critically checked in Ref. [43] the tetraquark picture for the $Z_c(3900)$ state by analyzing its strong decays. We found that $Z_c(3900)$ has a much stronger coupling to DD^* than to $J/\psi\pi$ which is in discord with the experiment. As an alternative, we employed a molecular-type four-quark current to describe the decays of the $Z_c(3900)$ state. We found that a molecular-type current gives the values of the above decays in accordance with the experimental observation. By using the molecular-type four-quark currents for the recently observed resonances $Z_b(10610)$ and $Z_b(10650)$, we calculated in Ref. [44] their two-body decay rates into a bottomonium state plus a light meson as well as into B-meson pairs. A brief sketch of our findings may be found in Ref. [45].

In the present paper, we treat the $Y(4260)$ resonance as a four-quark state. We study two choices of the interpolating currents either the molecular-type current which effectively corresponds to the product of D and $\bar{D}_1$ quark currents or tetraquark one. In both cases, we calculate the widths of decays $Y(4260) \to Z_c(3900) + \pi$ and $Y(4260) \to D^{(*)} + \bar{D}^{(*)}$.

The paper is organized as follows: two subsequent sections II and III are dedicated to the general formalism for describing $Y(4260)$ as a four-quark molecular state and tertaquark state, respectively; full expressions of studied quark currents and related amplitudes are provided. In the next, last section, the decay width formulas are written down and used to reach our numerical results which are presented together with our conclusion.

II. $Y(4260)$ AS A FOUR-QUARK STATE WITH MOLECULAR-TYPE CURRENT

We start with an assumption that both the $Y(4260)$ and $Z_c^+(3900)$ resonances are four-quark states with the molecular-type currents given in Table I.

TABLE I. Quantum numbers and molecular-type currents.

Title	$I^G(J^{PC})$	Interpolating current	Mass (MeV)	Width (MeV)
$Y(4260)$	$0^-(1^{--})$	$\frac{1}{\sqrt{2}}\{(\bar{q}\gamma_5 c)(\bar{c}\gamma^\mu\gamma_5 q) - (\gamma_5 \leftrightarrow \gamma^\mu\gamma_5)\}$	4230 ± 8	55 ± 19
$Z_c^+(3900)$	$1^+(1^{+-})$	$\frac{i}{\sqrt{2}}\{(\bar{d}\gamma_5 c)(\bar{c}\gamma^\mu u) + (\gamma_5 \leftrightarrow \gamma^\mu)\}$	3887.2 ± 2.3	28.2 ± 2.6

Their nonlocal generalizations are given by

$$J^\mu_{Y^{\rm mol}}(x) = \int dx_1 \ldots \int dx_4 \delta\left(x - \sum_{i=1}^4 w_i x_i\right)\Phi_Y\left(\sum_{i<j}(x_i - x_j)^2\right) J^\mu_{Y^{\rm mol};4q}(x_1, \ldots, x_4),$$
$$J^\mu_{Y^{\rm mol};4q} = \frac{1}{\sqrt{2}}\{(\bar{q}(x_3)\gamma_5 c(x_1)) \cdot (\bar{c}(x_2)\gamma^\mu\gamma_5 q(x_4)) - (\gamma_5 \leftrightarrow \gamma^\mu\gamma_5)\} \quad (q = u, d). \tag{1}$$

$$J^\mu_{Z_c^{\rm mol}}(x) = \int dx_1 \ldots \int dx_4 \delta\left(x - \sum_{i=1}^4 w_i x_i\right)\Phi_Z\left(\sum_{i<j}(x_i - x_j)^2\right) J^\mu_{Z^{\rm mol};4q}(x_1, \ldots, x_4),$$
$$J^\mu_{Z^{\rm mol};4q} = \frac{i}{\sqrt{2}}\{(\bar{d}(x_3)\gamma_5 c(x_1)) \cdot (\bar{c}(x_2)\gamma^\mu u(x_4)) + (\gamma_5 \leftrightarrow \gamma^\mu)\}. \tag{2}$$

The reduced quark masses are specified as

$$w_1 = w_2 = \frac{m_c}{2(m_c + m_q)}, \qquad w_3 = w_4 = \frac{m_q}{2(m_c + m_q)}, \tag{3}$$

where we assume no isospin violation in the $u - d$ sector, i.e., $m_u = m_d$. The Fourier-transform of the vertex function Φ may be written as

$$\Phi\left(\sum_{i<j}(x_i - x_j)^2\right) = \prod_{i=1}^3 \int \frac{d^4 q_i}{(2\pi)^4} e^{-iq_1(x_1-x_4)-iq_2(x_2-x_4)-iq_3(x_3-x_4)}\tilde{\Phi}\left(-\frac{1}{2}\sum_{i\le j} q_i q_j\right). \tag{4}$$

Because of convenience for performing calculations, the exponential form for the Fourier transform of the function Φ was adopted,

$$\tilde{\Phi}(-K^2) = \exp\left(\frac{K^2}{\Lambda^2}\right), \tag{5}$$

where K^2 is the combination of the loop and external momenta. The minus sign indicates that we are working in the Minkowski space, and the Wicked-rotated argument $K^2 \to -K_E^2$ makes explicit the appropriate fall-off behavior in the Euclidean region. Λ is an adjustable parameter of the CCQM which can be related to hadron size.

We consider two kinds of the strong Y decays: $Y \to D + \bar{D}$ where we imply the open-charm combinations as $D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}$, $D^*\bar{D}^*$, and $Y \to Z_c + \pi$. The Feynman diagrams describing these decays are shown in Fig. 1.

The matrix elements of the decays $Y_u \to D_1 + \bar{D}_2$ read as

$$M(Y_u(p, \epsilon^\mu_p) \to D_1^0(p_1) + \bar{D}_2^0(p_2)) = \frac{9}{\sqrt{2}} g_Y g_{D_1} g_{D_2}$$
$$\times \int \frac{d^4 k_1}{(2\pi)^4 i} \int \frac{d^4 k_2}{(2\pi)^4 i} \tilde{\Phi}_Y(-\Omega_q^2)\tilde{\Phi}_{D_1}(-\ell_1^2)\tilde{\Phi}_{D_2}(-\ell_2^2)$$
$$\times \{{\rm tr}[\gamma_5 S_c(k_1)\Gamma_2 S_u(k_3)] \cdot {\rm tr}[\gamma^\mu\gamma_5 S_u(k_2)\Gamma_1 S_c(k_4)]$$
$$- (\gamma_5 \leftrightarrow \gamma^\mu\gamma_5)\}. \tag{6}$$

Here, $\Gamma_1 \otimes \Gamma_2 = \gamma_5 \otimes \gamma_5$ for $D\bar{D}$ pair, $\epsilon^*_{\nu_1}\gamma^{\nu_1} \otimes \gamma_5$ for $D^*\bar{D}$ pair, and $\epsilon^*_{\nu_1}\gamma^{\nu_1} \otimes \epsilon^*_{\nu_2}\gamma^{\nu_2}$ for $D^*\bar{D}^*$ pair. The momenta are defined as

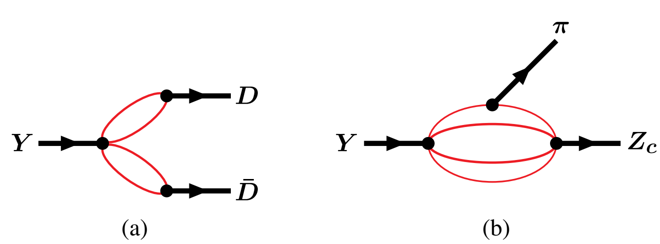

FIG. 1. Two modes of the $Y(4260)$ decay.

$$\Omega_q^2 = \frac{1}{2}\sum_{i\le j} q_i q_j, \qquad q_1 = -k_1 - w_1^Y p, \qquad q_2 = k_4 - w_2^Y p, \qquad q_3 = k_3 - w_3^Y p,$$
$$\ell_1 = k_2 + w_u^D p_1, \qquad \ell_2 = -k_1 - w_c^D p_2, \qquad k_3 = k_1 + p_2, \qquad k_4 = k_2 + p_1. \tag{7}$$

The calculation of the matrix element of the decay $Y \to Z_c + \pi$ is more involved because it is described by three-loop diagram as shown in Fig 1(b). One has

$$M(Y_u(p,\epsilon^\mu) \to Z_c^+(p_1,\epsilon^\nu) + \pi^-) = \frac{9}{2} g_Y g_{Z_c} g_\pi \prod_{j=1}^{3}\left[\int \frac{d^4 k_j}{(2\pi)^4 i}\right] \tilde{\Phi}_Y(-\Omega_q^2)\tilde{\Phi}_{Z_c}(-\Omega_r^2)\tilde{\Phi}_\pi(-\ell^2)$$
$$\times \epsilon_\mu(p)\epsilon_\nu^*(p_1)\sum_\Gamma \mathrm{tr}[\Gamma_1 S_c(k_1)\Gamma_2 S_u(k_2)]\cdot \mathrm{tr}[\Gamma_3 S_u(k_3)\Gamma_4 S_d(k_4)\Gamma_5 S_c(k_5)]. \tag{8}$$

Here

$$\sum_\Gamma [\Gamma_1\otimes\Gamma_2]\cdot[\Gamma_3\otimes\Gamma_4\otimes\Gamma_5] = [\gamma_5\otimes\gamma_5]\cdot[\gamma^\mu\gamma_5\otimes\gamma_5\otimes\gamma^\nu]$$
$$- [\gamma^\mu\gamma_5\otimes\gamma^\nu]\cdot[\gamma_5\otimes\gamma_5\otimes\gamma_5] - [\gamma^\mu\gamma_5\otimes\gamma_5]\cdot[\gamma_5\otimes\gamma_5\otimes\gamma^\nu]. \tag{9}$$

The momenta are defined as

$$\Omega_q^2 = \frac{1}{2}\sum_{i\le j} q_i q_j, \qquad q_1 = -k_1 - w_1^Y p, \qquad q_2 = k_5 - w_2^Y p, \qquad q_3 = k_2 - w_3^Y p,$$
$$\Omega_r^2 = \frac{1}{2}\sum_{i\le j} r_i r_j, \qquad r_1 = -k_5 + w_1^Z p_1, \qquad r_2 = k_1 + w_2^Z p_1, \qquad r_3 = k_4 - w_3^Z p_1,$$
$$\ell = k_3 + w_u^\pi p_2, \qquad k_4 = k_3 + p_2, \qquad k_5 = k_1 - k_2 + k_3 + p. \tag{10}$$

III. $Y(4260)$ AS A FOUR-QUARK STATE WITH TETRAQUARK CURRENT

Now we treat $Y(4260)$ as a four-quark state with the tetraquark current,

$$J^\mu_{Y^{\mathrm{tet}}} = \frac{1}{\sqrt{2}}\epsilon_{abc}\epsilon_{dec}\{(q_a C\gamma_5 c_b)(\bar{q}_d\gamma^\mu\gamma_5 C\bar{c}_e) - (q_a C\gamma^\mu\gamma_5 c_b)(\bar{q}_d\gamma_5 C\bar{c}_e), \tag{11}$$

where the charge conjugate matrix is chosen in the form $C = \gamma^0\gamma^2$ so that $C^T = -C$, $C^\dagger = C$, and $C^2 = C$. Its nonlocal generalization is given by

$$J^\mu_{Y^{\mathrm{tet}}}(x) = \int dx_1 \ldots \int dx_4 \delta\left(x - \sum_{i=1}^4 w_i^Y x_i\right)\Phi_Y\left(\sum_{i<j}(x_i - x_j)^2\right) J^\mu_{Y^{\mathrm{tet}};4q}(x_1,\ldots,x_4),$$
$$J^\mu_{Y^{\mathrm{tet}};4q} = \frac{1}{\sqrt{2}}\epsilon_{abc}\epsilon_{dec}\{(q_a(x_4)C\gamma_5 c_b(x_1))(\bar{q}_d(x_3)\gamma^\mu\gamma_5 C\bar{c}_e(x_2)) - (\gamma_5 \leftrightarrow \gamma^\mu\gamma_5)\}. \tag{12}$$

The matrix elements of the decays $Y_u \to D_1 + \bar{D}_2$ read as

$$M(Y_u^{\mathrm{tet}}(p,\epsilon_p^\mu) \to D_1^0(p_1) + \bar{D}_2^0(p_2)) = \frac{6}{\sqrt{2}} g_Y g_{D_1} g_{D_2} \int \frac{d^4 k_1}{(2\pi)^4 i}\int \frac{d^4 k_2}{(2\pi)^4 i}\tilde{\Phi}_Y(-\Omega_q^2)\tilde{\Phi}_{D_1}(-\ell_1^2)\tilde{\Phi}_{D_2}(-\ell_2^2)$$
$$\times \{\mathrm{tr}[\gamma_5 S_c(k_1)\Gamma_2^D S_u(k_3)\gamma^\mu\gamma_5 S_c(k_2)\Gamma_1^D S_u(k_4)] - (\gamma_5 \leftrightarrow \gamma^\mu\gamma_5)\}. \tag{13}$$

The momenta are defined as

$$
\Omega_q^2 = \frac{1}{2}\sum_{i\le j} q_i q_j, \qquad q_1 = -k_1 - w_1^Y p, \qquad q_2 = -k_2 - w_2^Y p, \qquad q_3 = k_3 - w_3^Y p,
$$
$$
\ell_1 = -k_2 - w_c^D p_1, \qquad \ell_2 = -k_1 - w_c^D p_2, \qquad k_3 = k_1 + p_2, \qquad k_4 = k_2 + p_1. \tag{14}
$$

The matrix element of the decay $Y \to Z_c + \pi$ is written down,

$$
M(Y_u^{\mathrm{tet}}(p,\epsilon^\mu) \to Z_c^+(p_1,\epsilon^\nu) + \pi^-(p_2)) = 3 g_Y g_{Z_c} g_\pi \prod_{j=1}^{3}\left[\int \frac{d^4 k_j}{(2\pi)^4 i}\right] \tilde{\Phi}_Y(-\Omega_q^2)\tilde{\Phi}_{Z_c}(-\Omega_r^2)\tilde{\Phi}_\pi(-\ell^2)
$$
$$
\times \epsilon_\mu(p)\epsilon_\nu^*(p_1)\sum_\Gamma \mathrm{tr}[\Gamma_1^Y S_c(k_1)\Gamma_2^Z S_u(k_2)\Gamma_2^Y S_c(k_3)\bar{\Gamma}_1^Z S_d(k_4)\gamma_5 S_u(k_5)], \tag{15}
$$

where $\bar{\Gamma} = C^{-1}\Gamma^T C$ and $\sum_\Gamma = [\gamma_5 \otimes \gamma^\mu\gamma_5 - \gamma^\mu\gamma_5 \otimes \gamma_5]^Y \otimes [\gamma_5 \otimes \gamma^\nu - \gamma^\nu \otimes \gamma_5]^Z$. The momenta are defined as

$$
\Omega_q^2 = \frac{1}{2}\sum_{i\le j} q_i q_j, \qquad q_1 = -k_1 - w_1^Y p, \qquad q_2 = -k_3 - w_2^Y p, \qquad q_3 = k_2 - w_3^Y p,
$$
$$
\Omega_r^2 = \frac{1}{2}\sum_{i\le j} r_i r_j, \qquad r_1 = k_3 + w_1^Z p_1, \qquad r_2 = k_1 + w_2^Z p_1, \qquad r_3 = -k_4 + w_3^Z p_1,
$$
$$
\ell = -k_4 - w_d^\pi p_2, \qquad k_4 = k_1 - k_2 + k_3 + p_1, \qquad k_5 = k_1 - k_2 + k_3 + p. \tag{16}
$$

IV. NUMERICAL RESULTS AND CONCLUSION

We remind the formulas for the two-body decay widths expressed via Lorentz form factors,

$$
M(V(p) \to P(p_1) + P(p_2)) = \epsilon_V^\mu q_\mu G_{VPP}, \qquad q = p_1 - p_2,
$$
$$
\Gamma(V \to PP) = \frac{|\mathbf{p_1}|^3}{6\pi m^2} G_{VPP}^2,
$$
$$
M(V(p) \to A(p_1) + P(p_2)) = \epsilon_V^\mu \epsilon_A^{*\nu}(g_{\mu\nu}A + p_{1\mu}p_\nu B),
$$
$$
\Gamma(V \to AP) = \frac{|\mathbf{p_1}|}{24\pi m^2}\left\{\left(3 + \frac{|\mathbf{p_1}|^2}{m_1^2}\right)A^2 + \frac{m^2}{m_1^2}|\mathbf{p_1}|^4 B^2 + \frac{m^2 + m_1^2 - m_2^2}{m_1^2}|\mathbf{p_1}|^2 AB\right\},
$$
$$
M(V(p) \to V(p_1) + P(p_2)) = \epsilon_V^\mu \epsilon_V^{*\nu_1}\varepsilon_{\mu\nu_1\alpha\beta}p^\alpha p_1^\beta G_{VVP},
$$
$$
\Gamma(V \to VP) = \frac{|\mathbf{p_1}|^3}{12\pi} G_{VVP}^2,
$$
$$
M(V(p) \to V(p_1) + V(p_2)) = \epsilon_V^\mu \epsilon_V^{*\nu_1}\epsilon_V^{*\nu_2}\{p_{1\mu}p_{1\nu_2}p_{2\nu_1}A + g_{\mu\nu_1}p_{1\nu_2}B + g_{\mu\nu_2}p_{2\nu_1}C + g_{\nu_1\nu_2}p_{1\mu}D\},
$$
$$
\Gamma(V \to V_1V_2) = \frac{|\mathbf{p_1}|^3}{24\pi m_1^2 m_2^2}\left\{m^2|\mathbf{p_1}|^4 A^2 + [|\mathbf{p_1}|^2 - 3m_1^2]B^2 + [|\mathbf{p_1}|^2 + 3m_2^2]C^2\right.
$$
$$
+ \left[|\mathbf{p_1}|^2 + 3\frac{m_1^2 m_2^2}{m^2}\right]D^2 + |\mathbf{p_1}|^2[m^2 + m_1^2 - m_2^2]AB
$$
$$
+ |\mathbf{p_1}|^2[-m^2 + m_1^2 - m_2^2]AC + |\mathbf{p_1}|^2[m^2 - m_1^2 - m_2^2]AD
$$
$$
+ [2|\mathbf{p_1}|^2 - m^2 + m_1^2 + m_2^2]BC + \left[2|\mathbf{p_1}|^2 + m_1^2 + \frac{m_1^2}{m^2}(m_2^2 - m_1^2)\right]BD
$$
$$
\left. + \left[-2|\mathbf{p_1}|^2 - m_2^2 + \frac{m_2^2}{m^2}(m_2^2 - m_1^2)\right]CD\right\}. \tag{17}
$$

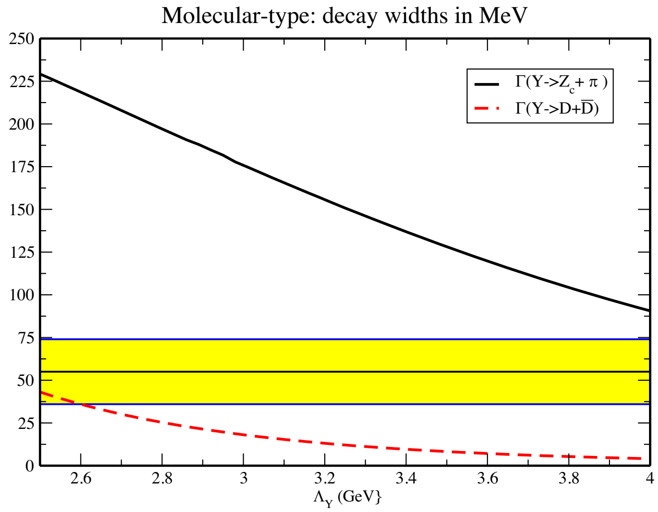

FIG. 2. Two modes of the $Y(4260)$ decay in molecular picture. The central value of the total decay width from experiment with error band is depicted as shadowed strip.

Before showing the numerical results, one has to make some remarks concerning the difference between the molecular and tetraquark interpretations. The first obvious difference is the shape of the interpolating current as we have discussed above in great details. The second point is the choice of the vertex function $\tilde{\Phi}_Y$ which should be in principal related the relevant Bethe-Salpeter amplitude. For simplicity of the calculations, we use the

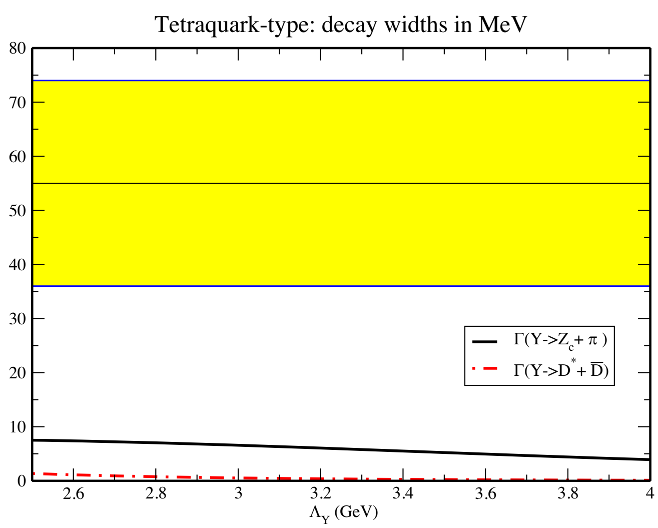

FIG. 3. Two modes of the $Y(4260)$ decay in tetraquark picture. The central value of the total decay width from experiment with error band is depicted as shadowed strip.

TABLE II. Decay widths in MeV.

Mode	Molecular-type current	Tetraquark current
$Y \to Z_c^+ + \pi^-$	146 ± 13	5.77 ± 0.39
$Y \to D^0 + \bar{D}^0$	11 ± 2	$(0.42 \pm 0.16) \times 10^{-3}$
$Y \to D^{*0} + \bar{D}^0$	$(0.39 \pm 0.14) \times 10^{-2}$	0.32 ± 0.09
$Y \to D^{*0} + \bar{D}^{*0}$	0	$(0.19 \pm 0.08) \times 10^{-3}$

Gaussian symmetric form in the configuration space as $\Phi_Y(\sum_{i<j}(x_i - x_j)^2)$ with the only adjustable parameter Λ_Y. Since we have in our hands only the value of the total Y-decay width 55 ± 19 MeV [46], we plot in Figs. 2 and 3 the calculated decay widths for both configurations as functions of Λ_Y. The allowed interval of $\Lambda_Y \in [2.5\text{–}4.0]$ MeV was found in our previous works by analyzing the known decays of exotic states.

Note that the widths of the modes $Y \to D^{*0} + \bar{D}^0$ and $Y \to D^0 + \bar{D}^{*0}$ are equal to each other; therefore, we will discuss only the first mode. It turned out that in the case of molecular configuration the mode $Y \to D^{*0} + \bar{D}^0$ is significantly suppressed compared with $Y \to Z_c^+ + \pi^-$ and $Y \to D^0 + \bar{D}^0$ modes, whereas the amplitude of the mode $Y \to D^{*0} + \bar{D}^{*0}$ is identical zero as follows from Eq. (6). In the case of tetraquark configuration, the dominant modes are $Y \to Z_c^+ + \pi^-$ and $Y \to D^{*0} + \bar{D}^0$. So we show the curves in Figs. 2 and 3 for the dominant modes only. One can see that in both approaches the mode $Y \to Z_c^+ + \pi^-$ is enhanced compared with the open-charm modes. Comparison with the total decay width of the $Y(4260)$ particle from the experiment [46] disqualifies the molecular picture. As a result, one can conclude that the CCQM model calculations favor the tetraquark picture of the $Y(4260)$ state since it leads to reasonable number of the decay width into $Z_c^+\pi^-$.

Finally, we have taken the value of Z_c size parameter to be equal $\Lambda_{Z_c} = 3.3$ GeV as was obtained in our paper [43]. We vary the value of Y size parameter in some vicinity of this average value $\Lambda_Y = 3.3 \pm 0.1$ GeV. The calculated decay widths are shown in Table II.

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[1] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **95**, 142001 (2005).
[2] D. Cronin-Hennessy *et al.* (CLEO Collaboration), Phys. Rev. D **80**, 072001 (2009).
[3] G. Pakhlova, K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **98**, 092001 (2007).
[4] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **76**, 111105 (2007).
[5] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **79**, 092001 (2009).
[6] P. del Amo Sanchez *et al.* (*BABAR* Collaboration), Phys. Rev. D **82**, 052004 (2010).
[7] N. Brambilla *et al.*, Eur. Phys. J. C **71**, 1534 (2011).
[8] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **110**, 252001 (2013).
[9] Z. Q. Liu *et al.* (Belle Collaboration), Phys. Rev. Lett. **110**, 252002 (2013).
[10] T. Xiao, S. Dobbs, A. Tomaradze, and K. K. Seth, Phys. Lett. B **727**, 366 (2013).
[11] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **112**, 022001 (2014).
[12] Z. Liu, arXiv:1504.06102.
[13] H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, Phys. Rep. **639**, 1 (2016).
[14] R. F. Lebed, R. E. Mitchell, and E. S. Swanson, Prog. Part. Nucl. Phys. **93**, 143 (2017).
[15] A. Esposito, A. Pilloni, and A. Polosa, Phys. Rep. **668**, 1 (2017).
[16] F. K. Guo, C. Hanhart, U. G. Meißner, Q. Wang, Q. Zhao, and B. S. Zou, Rev. Mod. Phys. **90**, 015004 (2018).
[17] A. Ali, J. S. Lange, and S. Stone, Prog. Part. Nucl. Phys. **97**, 123 (2017).
[18] S. L. Olsen, T. Skwarnicki, and D. Zieminska, Rev. Mod. Phys. **90**, 015003 (2018).
[19] Y. R. Liu, H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, Prog. Part. Nucl. Phys. **107**, 237 (2019).
[20] N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C. P. Shen, C. E. Thomas, A. Vairo, and C. Z. Yuan, arXiv:1907.07583.
[21] S. L. Zhu, Phys. Lett. B **625**, 212 (2005).
[22] E. Kou and O. Pene, Phys. Lett. B **631**, 164 (2005).
[23] F. E. Close and P. R. Page, Phys. Lett. B **628**, 215 (2005).
[24] A. Martinez Torres, K. P. Khemchandani, D. Gamermann, and E. Oset, Phys. Rev. D **80**, 094012 (2009).
[25] F. J. Llanes-Estrada, Phys. Rev. D **72**, 031503 (2005).
[26] X. Liu, X. Q. Zeng, and X. Q. Li, Phys. Rev. D **72**, 054023 (2005).
[27] L. Maiani, V. Riquer, F. Piccinini, and A. D. Polosa, Phys. Rev. D **72**, 031502 (2005).
[28] D. Ebert, R. N. Faustov, and V. O. Galkin, Phys. Lett. B **634**, 214 (2006).
[29] Q. Wang, C. Hanhart, and Q. Zhao, Phys. Rev. Lett. **111**, 132003 (2013).
[30] X. Li and M. B. Voloshin, Phys. Rev. D **88**, 034012 (2013).
[31] G. Li and X. H. Liu, Phys. Rev. D **88**, 094008 (2013).
[32] Y. Dong, A. Faessler, T. Gutsche, and V. E. Lyubovitskij, Phys. Rev. D **89**, 034018 (2014).
[33] G. Li, C. S. An, P. Y. Li, D. Liu, X. Zhang, and Z. Zhou, Chin. Phys. C **39**, 063102 (2015).
[34] Z. G. Wang, Eur. Phys. J. C **79**, 29 (2019).
[35] Z. G. Wang, Eur. Phys. J. C **78**, 933 (2018).
[36] G. V. Efimov and M. A. Ivanov, Int. J. Mod. Phys. A **04**, 2031 (1989).
[37] G. V. Efimov and M. A. Ivanov, *The Quark Confinement Model of Hadrons* (CRC Press, Boca Raton, 1993).
[38] T. Branz, A. Faessler, T. Gutsche, M. A. Ivanov, J. G. Körner, and V. E. Lyubovitskij, Phys. Rev. D **81**, 034010 (2010).
[39] A. Salam, Nuovo Cimento **25**, 224 (1962).
[40] S. Weinberg, Phys. Rev. **130**, 776 (1963).
[41] S. Dubnička, A. Z. Dubničková, M. A. Ivanov, and J. G. Körner, Phys. Rev. D **81**, 114007 (2010).
[42] S. Dubnička, A. Z. Dubničková, M. A. Ivanov, J. G. Körner, P. Santorelli, and G. G. Saidullaeva, Phys. Rev. D **84**, 014006 (2011).
[43] F. Goerke, T. Gutsche, M. A. Ivanov, J. G. Körner, V. E. Lyubovitskij, and P. Santorelli, Phys. Rev. D **94**, 094017 (2016).
[44] F. Goerke, T. Gutsche, M. A. Ivanov, J. G. Körner, and V. E. Lyubovitskij, Phys. Rev. D **96**, 054028 (2017).
[45] M. Ivanov, EPJ Web Conf. **192**, 00042 (2018).
[46] M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018).