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Dynamical study of the $X(3915)$ as a $D^*\bar{D}^*$ bound state in a quark model

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Considering the coupling of color $1 \otimes 1$ and $8 \otimes 8$ structures, we calculate the energy of the newly observed $X(3915)$ as an S-wave $D^*\bar{D}^*$ state in the Bhaduri, Cohler, and Nogami quark model by the Gaussian expansion method. Because of the color coupling, the bound state of $D^*\bar{D}^*$ with $J^{PC} = 0^{++}$ is found, which is well consonant with the experimental data of the $X(3915)$. The bound states of $B^*\bar{B}^*$ with $J^{PC} = 0^{++}$ and 2^{++} are also predicted in this work.

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I. INTRODUCTION

Very recently, the Belle Collaboration reported the newest charmoniumlike state, the $X(3915)$, which is observed in $\gamma\gamma \to \omega J/\psi$ with a statistical significance of 7.7σ [1–5]. It has the mass $M = 3915 \pm 3 \pm 2$ MeV and width $\Gamma = 17 \pm 10 \pm 3$ MeV. The Belle Collaboration determined the $X(3915)$ production rate

$$\Gamma_{\gamma\gamma}(X(3915))\mathcal{B}(X(3915) \to \omega J/\psi) = 61 \pm 17 \pm 8 \text{ eV} \tag{1}$$

or

$$\Gamma_{\gamma\gamma}(X(3915))\mathcal{B}(X(3915) \to \omega J/\psi) = 18 \pm 5 \pm 2 \text{ eV}, \tag{2}$$

for $J^P = 0^+$ or 2^+, respectively. The $X(3915)$ is similar to the previously discovered $Y(3940)$ by Belle and confirmed by the *BABAR* Collaboration in the process $B \to KY(3940)$, $Y(3940) \to \omega J/\psi$ [6,7]. The mass and width of the $Y(3940)$ obtained by Belle are $M = 3943 \pm 11(\text{stat}) \pm 13(\text{syst})$ MeV and $\Gamma = 87 \pm 22(\text{stat}) \pm 26(\text{syst})$ MeV, respectively [6]. However, *BABAR* obtained $M = 3914.6^{+3.8}_{-3.4}(\text{stat}) \pm 2.0(\text{syst})$ MeV and $\Gamma = 34^{+12}_{-8}(\text{stat}) \pm 5(\text{syst})$ MeV [7]. The difference of the mass and width of $Y(3940)$ might be the attribute to the large data sample used by *BABAR* (350 fb^{-1} compared to Belle's 253 fb^{-1}), which enabled them to use smaller $\omega J/\psi$ mass bins in their analysis [2,3]. The $Y(3940)$ and $X(3915)$ have the same mass and width and are both seen in $\omega J/\psi$. Hence they might be same states pointed out in Refs. [1–5].

The $X(3915)$ as a conventional $c\bar{c}$ charmonium interpretation is disfavored [1–3]. The mass of this state is well above the threshold of $D\bar{D}$ or $D\bar{D}^*$ [8]; hence open charm decay modes would dominate, while the $\omega J/\psi$ decay rates are essentially negligible, which is the same as $Y(3940)$ [9]. However, according to the production rate obtained by Belle [Eqs. (1) and (2)], we obtain the $\Gamma_{\omega J/\psi} \sim \mathcal{O}$ (1 MeV) if we assume $\Gamma_{\gamma\gamma} \sim \mathcal{O}$ (1–2 keV), which is typical for an excited charmonium state [10–13]. $\Gamma_{\omega J/\psi} \sim \mathcal{O}$ (1 MeV) is an order of magnitude higher than typical rates between known charmonium states, which implies that there is an intricate structure for the $X(3915)$. In our previous study [14], the quantum number and mass of $\chi_0(2^3P_0)$ are compatible with the $X(3915)$. However, the calculated strong decay width is much larger than experimental data. Hence, the assignment of $X(3915)$ to the charmonium $\chi_0(2^3P_0)$ state is very unlikely.

In the previous work, Liu and co-workers [15,16] suggested $Y(3940)$ is probably a molecular $D^*\bar{D}^*$ state with $J^{PC} = 0^{++}$ or $J^{PC} = 2^{++}$ in a meson-exchange model. Assuming the $D^*\bar{D}^*$ bound-state structure, Branz, Gutsche, and Lyubovitskij [17] studied the strong $Y(3940) \to \omega J/\psi$ and radiative $Y(3940) \to \gamma\gamma$ decay widths in a phenomenological Lagrangian approach. Their results are roughly compatible with the experimental data about $Y(3940)$. By the QCD sum rules, Zhang and Huang [18] also obtained the mass $M = 3.91 \pm 0.11$ GeV for $D^*\bar{D}^*$, which is consistent with $Y(3940)$ reported by *BABAR*. Using the SU(3) chiral quark model and solving the resonating group method equation, Liu and Zhang [19] also studied molecular $D^*\bar{D}^*$ states with color-singlet meson-meson structure; the bound state of $D^*\bar{D}^*$ may appear if the vector meson exchange between light quark and antiquark is considered.

Although at present the data for the $X(3915)$ and $Y(3940)$ are still preliminary, and whether the $X(3915)$ is the same as the $Y(3940)$ needs to be identified, it is worthwhile to discuss its possible assignments, especially in view of the great potential of finding new particles. We assume the $X(3915)$ and $Y(3940)$ as the same state in the following study. In this work we study the $X(1915)$ with $D^*\bar{D}^*$ structure by taking into account the coupling of different color structures in the Bhaduri, Cohler, and Nogami (BCN) quark model, since the color-singlet tetraquark state $(c\bar{q})^*(\bar{c}q)^*$ can consist of colorless or colored $(c\bar{q})^*$ and $(\bar{c}q)^*$ two-quark mesons. The role of the *hidden color* in $qq - \bar{q}\,\bar{q}$ ($q = u, d$) has been discussed by Brink

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and Stancu [20] and then extended to study other four-quark systems [21–23].

The BCN quark model was proposed by Bhaduri, Cohler, and Nogami [24]. In this model, the interaction between the quark pair is composed of linear color confinement, color Coulomb, and color magnetic interaction from one-gluon exchange. This model has been widely used to study $q\bar{q}$ meson, qqq baryon, [25] and four-quark systems [21,26–28] that range from light quark u, d to heavy quark b with the same set of parameters. The state $(c\bar{q})^*(\bar{c}q)^*$ bound by a one-gluon exchange interaction in the BCN quark model can be depicted in Fig. 1. One-gluon exchange interaction exists between pairs of quark-quark or quark-antiquark in color structure $8 \otimes 8$, while no interaction exists between meson-meson in color structure $1 \otimes 1$. Hence there is no bound state in Fig. 1(a). However, the bound state is possible within a hidden color channel [color structure $8 \otimes 8$, Fig. 1(b)].

The numerical method, which is able to provide reliable solutions, is very important for calculating the energy of few-body systems. In this work, the spectra of normal and exotic mesons are obtained by solving the Schrödinger equation using a variational method: Gaussian expansion method (GEM), which is a high precision numerical method for few-body systems. The details about GEM can be seen in Refs. [23,29].

The paper is organized as follows. In the next section we show the Hamiltonian and parameters of the BCN quark model. Section III is devoted to discussing the wave function of $X(3915)$ and similar state X_B with the c quark replaced by the b quark. In Sec. IV, we present and analyze the results obtained by our calculation. Finally, the summary of the present work is given in the last section.

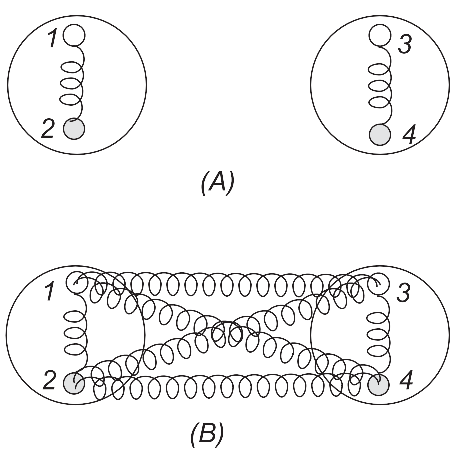

FIG. 1. The $(c\bar{q})^*(\bar{c}q)^*$ bound state by a one-gluon exchange interaction in color structures $1 \otimes 1$ (a) and $8 \otimes 8$ (b) in the BCN quark model. The darkened and open circles represent quarks and antiquarks, respectively.

TABLE I. Parameters of the BCN model.

Quark masses	$m_{u,d}$ (MeV)	337
	m_s (MeV)	600
	m_c (MeV)	1870
	m_b (MeV)	5259
Confinement	a_c (MeV fm^{-1})	176.738
	Δ (MeV)	−171.25
One-gluon exchange	κ	0.390 209
	r_0 (fm)	0.4545

II. HAMILTONIAN

The Hamiltonian of the BCN model takes the form

$$H = \sum_{i=1}^{4}\left(m_i + \frac{\mathbf{p}_i^2}{2m_i}\right) - T_{\mathrm{c.m.}} + \sum_{j>i=1}^{4}(V_{ij}^C + V_{ij}^G), \quad (3)$$

with

$$V_{ij}^G = \frac{\lambda_i^c \cdot \lambda_j^c}{4}\left(\frac{\kappa}{r_{ij}} - \frac{\kappa}{m_i m_j}\frac{e^{-r_{ij}/r_0}}{r_0^2 r_{ij}}\sigma_i \cdot \sigma_j\right), \quad (4)$$

$$V_{ij}^C = \lambda_i^c \cdot \lambda_j^c(-a_c r_{ij} - \Delta), \quad (5)$$

where $r_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$ and $T_{\mathrm{c.m.}}$ is the kinetic energy of central mass of the whole system. σ and λ are the SU(2) Pauli and the SU(3) Gell-Mann matrices, respectively. The λ should be replaced by $-\lambda^*$ for the antiquark. The universal parameters of this model [24,27] are listed in Table I.

III. WAVE FUNCTION

The total wave function of the four-quark system can be written as

$$\Psi_{J,J_z}^{I,I_z} = |\xi\rangle|\eta\rangle^{II_z}\Phi_{JJ_z}, \quad (6)$$

with

$$\Phi_{JJ_z} = [|\chi\rangle_S \otimes |\Phi\rangle_{L_T}]_{JJ_z},$$

where $|\xi\rangle$, $|\eta\rangle^I$, $|\chi\rangle^S$, and $|\Phi\rangle_{L_T}$ represent the color singlet, isospin with I, spin with S, and spatial with angular momentum L_T wave functions, respectively.

Because the $X(3915)$ is observed in the invariant mass spectrum of $J/\psi\omega$ in $\gamma\gamma \to J/\psi\omega$ [1], the flavor wave function of the possible bound states is

$$X(3915) = \frac{1}{\sqrt{2}}(\bar{D}^{0*}D^{0*} + D^{-*}D^{+*}). \quad (7)$$

The similar state composed of the b quark is

$$X_B = \frac{1}{\sqrt{2}}(\bar{B}^{0*}B^{0*} + B^{-*}B^{+*}). \quad (8)$$

The spatial structures of the above states are pictured in Fig. 2. The relative coordinates are defined as follows:

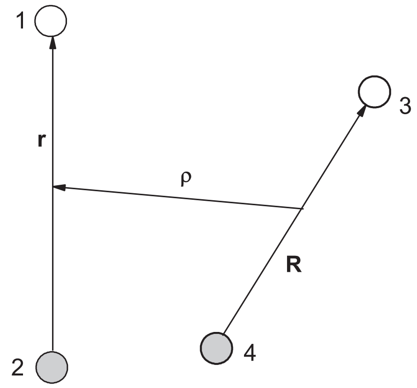

FIG. 2. The relative coordinate of a four-quark state. The darkened and open circles represent quarks and antiquarks, respectively.

$$\mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2, \qquad \mathbf{R} = \mathbf{r}_3 - \mathbf{r}_4, \tag{9}$$

$$\boldsymbol{\rho} = \frac{m_1\mathbf{r}_1 + m_2\mathbf{r}_2}{m_1 + m_2} - \frac{m_3\mathbf{r}_3 + m_4\mathbf{r}_4}{m_3 + m_4}, \tag{10}$$

and the coordinate of the center of mass is

$$\mathbf{R}_{\rm cm} = \sum_{i=1}^{4} m_i\mathbf{r}_i \Big/ \sum_{i=1}^{4} m_i, \tag{11}$$

where m_i is the mass of the ith quark.

By GEM, the outer products of space and spin are

$$\Phi_{JJ_z} = [[\phi^G_{lm}(\mathbf{r})\chi_{s_1m_{s_1}}]_{J_1M_1} \times [\psi^G_{LM}(\mathbf{R})\chi_{s_2m_{s_2}}]_{J_2M_2}]_{J_{12}M_{12}}\varphi^G_{\beta\gamma}(\rho)]_{JJ_z}. \tag{12}$$

The total angular momentum is 0 or 2 suggested by the Belle Collaboration [1].

Three relative motion wave functions are written as

$$\phi^G_{lm}(\mathbf{r}) = \sum_{n=1}^{n_{\max}} c_n N_{nl} r^l e^{-\nu_n r^2} Y_{lm}(\hat{\mathbf{r}}), \tag{13}$$

$$\psi^G_{LM}(\mathbf{R}) = \sum_{N=1}^{N_{\max}} c_N N_{NL} R^L e^{-\zeta_N R^2} Y_{LM}(\hat{\mathbf{R}}), \tag{14}$$

$$\varphi^G_{\beta\gamma}(\boldsymbol{\rho}) = \sum_{\alpha=1}^{\alpha_{\max}} c_\alpha N_{\alpha\beta} \rho^\beta e^{-\omega_\alpha \rho^2} Y_{\beta\gamma}(\hat{\boldsymbol{\rho}}). \tag{15}$$

Gaussian size parameters are taken as the geometric progression

$$\nu_n = \frac{1}{r_n^2}, \qquad r_n = r_1 a^{n-1}, \qquad a = \left(\frac{r_{n_{\max}}}{r_1}\right)^{(1/(n_{\max}-1))}. \tag{16}$$

The expression of ζ_N and ω_α in Eqs. (14) and (15) is similar to Eq. (16).

The physical state must be a color singlet, so the color wave functions of the possible four-quark state can be constructed by the following color structures:

$$|\xi_1\rangle = |\mathbf{1}_{12} \otimes \mathbf{1}_{34}\rangle, \qquad |\xi_2\rangle = |\mathbf{8}_{12} \otimes \mathbf{8}_{34}\rangle. \tag{17}$$

Clearly, it includes a color singlet-singlet and a color octet-octet state. The latter are called *hidden color* states by analogy to states which appear in the nucleon-nucleon problem [30].

IV. NUMERICAL RESULTS AND DISCUSSION

Using GEM and the universal model parameters listed in Table I, we also calculate the mass of a normal meson composed of a quark-antiquark by solving the Schrödinger equation

$$(H - E)\Psi^{I,I_z}_{J,J_z} = 0 \tag{18}$$

with the Rayleigh-Ritz variational principle. The results of the meson spectra are converged with the number of Gaussians $n_{\max} = 7$, and the relative distance of quark-antiquark ranges from 0.1 to 2 fm, which is determined by the convergence properties of the energies and discussed in detail in Ref. [23]. The calculated results are listed in Table II, which are in good agreement with the experimental data.

Because the threshold of the four-quark system is governed by two corresponding meson masses, so a good fit of meson spectra, with the same parameters used in four-

TABLE II. The normal meson spectra (MeV) in the BCN model. The last column is taken from Particle Data Group compilation [8], and the ground state of bottom $\eta_b(1s)$ is observed by the *BABAR* Collaboration from the radiative transition $\Upsilon(3S) \to \gamma\eta_b$ [31].

Meson	BCN	Exp.
π	137.5	$139.57 \pm 0.000\,35$
K	521.4	493.677 ± 0.016
$\rho(770)$	779.6	775.49 ± 0.34
$K^*(892)$	907	896.00 ± 0.25
$\omega(782)$	779.6	782.65 ± 0.12
$\phi(1020)$	1018.5	1019.422 ± 0.02
$\eta_c(1s)$	3040	2980.3 ± 1.2
$J/\psi(1s)$	3098	3096.916 ± 0.011
D^0	1886.7	1864.84 ± 0.17
D^*	2021.3	2006.97 ± 0.19
D_s	1997	1968.49 ± 0.34
D_s^*	2102.3	2112.3 ± 0.5
$B^\pm$	5302	5279.15 ± 0.31
B^0	5302	5279.53 ± 0.33
B^*	5351.5	5325.1 ± 0.5
B_s^0	5373.1	5366.3 ± 0.6
B_s^*	5414.5	5412.8 ± 1.3
$\eta_b(1s)$	9422.2	$9388.9^{+3.1}_{-2.3}$(stat)
$\Upsilon(1s)$	9439.5	9460.30 ± 0.26

quark calculations, must be the most important criterion [21,26,27,32,33]. Therefore, the universal model parameters are also employed in this work to study the possible four-quark bound state of the $X(3915)$ and X_B.

Using GEM with the numbers of Gaussians $\alpha = 12$, $n = 7$, $N = 7$, and the magnitude of $\boldsymbol{\rho}$ ranges from 0.1 to 6 fm, and 0.1 to 2 fm for $\mathbf{r}$ and $\mathbf{R}$, respectively, in Eqs. (13)–(15), we obtain converged results for the four-quark systems, which are also discussed in detail in Ref. [23]. By taking the coupling of the color singlet and octet into account, the total energies of the possible four-quark state mentioned above are listed in Table III.

The $D^*\bar{D}^*$ with $J^{PC} = 0^{++}$ is bound and in good agreement with the mass of the $X(3915)$ and Ref. [18], while the $J^{PC} = 2^{++}$ with same flavor wave function is unbound. The results can be understood as follows. For convenience, the matrix elements of color operator are given in Table IV, where the (i, j) $(j > i = 1, 2, 3, 4)$ are the indices of quark pairs. The matrix elements of the spin operator for interacting quark pairs (i, j) are $((1, 2), (3, 4), (1, 3), (2, 4), (1, 4), (2, 3)) = (1, 1, -2, -2, -2, -2)$ and $(1, 1, 1, 1, 1, 1)$ for $J^{PC} = 0^{++}$ and 2^{++}, respectively. For the color singlet-singlet channel, because of no interaction between D^* and $\bar{D}^*$, the calculated energies of $D^*\bar{D}^*$ must converged to the threshold, the sum of the mass of D^* and $\bar{D}^*$; the distances between two quarks (or antiquarks) residing in the different color singlets are much larger than that of a quark and antiquark in the same color singlet. The results are demonstrated in Tables III and V. For the hidden color channel, according to the confinement interaction in Eq. (5) and color matrix element listed in Table IV, the interactions between quark-antiquark pairs (1, 2) and (3, 4) are repulsive, and anticonfinement appears [34]. However, the other four pairwise interactions are still attractive which govern the confinement of the whole four-quark system. The distance between quark-antiquark pair (1, 2) or (3, 4) is the competition result of the interaction between particle 1, 2 or (3, 4) and that between 1, 3, 1, 4, 2, 3, and 2, 4. The distances are converged to values given in Table V, and the energy of the four-quark system is also stable (see Table III). The color magnetic interactions are also important in the hidden color channel. For the state with $J^{PC} = 0^{++}$, the contributions from color magnetic interaction $-(\lambda_i^c \cdot \lambda_j^c)(\sigma_i \cdot \sigma_j)$ of each particle pair are all attractive. Hence, in the hidden color channel the energy of $D^*\bar{D}^*$ with $J^{PC} = 0^{++}$ is lower than the state with $J^{PC} = 2^{++}$, where the contributions from color magnetic interaction for particle pairs (1, 2) and (3, 4) are attractive, while those for the other four particle pairs are repulsive. The channel coupling increases the difference further, because the cross matrix elements between the color singlet-singlet and color octet-octet with $J^{PC} = 0^{++}$ is 2 times larger than with $J^{PC} = 2^{++}$.

TABLE III. The energy of the possible four-quark states. $E_{\rm th}$ and E_{4q} are the threshold and total energy of the four-quark state, respectively. The "cc" stands for channel coupling of color structures $1 \otimes 1$ and $8 \otimes 8$.

State	J^{PC}	$E_{\rm th}$ (MeV)	E_{4q} (MeV) $1 \otimes 1$	E_{4q} (MeV) $8 \otimes 8$	E_{4q} (MeV) cc
$D^*\bar{D}^*$	0^{++}	4042.6	4043.6	3941.9	3912.1
	2^{++}	4042.6	4043.6	4200.3	4043.6
$B^*\bar{B}^*$	0^{++}	10 703	10 703.4	10 388.74	10 298.5
	2^{++}	10 703	10 703.4	10 609.83	10 535.1

TABLE IV. Color matrix elements $\langle \xi_k | \lambda_i^c \cdot \lambda_j^c | \xi_l \rangle$, with $j > i = 1, 2, 3, 4$. Here $|\xi_k\rangle$ and $|\xi_l\rangle$, with $k, l = 1, 2$, represent the color wave functions defined in Eq. (17).

$(i, j) =$	(1,2)	(3,4)	(1,3)	(2,4)	(1,4)	(2,3)
$(k, l) = (1, 1)$	$-\frac{16}{3}$	$-\frac{16}{3}$	0	0	0	0
$(k, l) = (2, 2)$	$\frac{2}{3}$	$\frac{2}{3}$	$-\frac{4}{3}$	$-\frac{4}{3}$	$-\frac{14}{3}$	$-\frac{14}{3}$
$(k, l) = (1, 2)$	0	0	$\sqrt{\frac{32}{9}}$	$\sqrt{\frac{32}{9}}$	$-\sqrt{\frac{32}{9}}$	$-\sqrt{\frac{32}{9}}$

TABLE V. The distances between each quark pair in the configuration of $D^*\bar{D}^*$ in different color structures. r_{ij} stands for $\sqrt{\langle r_{ij}^2 \rangle}$ $(j > i = 1, 2, 3, 4)$ in this form (unit: fm).

J^{PC}	Color structure	r_{12}	r_{34}	r_{13}	r_{24}	r_{14}	r_{23}
0^{++}	$1 \otimes 1$	0.65	0.65	6.6	6.6	6.6	6.7
	$8 \otimes 8$	0.7	0.7	0.69	0.69	0.36	0.91
	Coupling	0.71	0.71	0.69	0.69	0.36	0.91
2^{++}	$1 \otimes 1$	0.65	0.65	6.63	6.63	6.6	6.6
	$8 \otimes 8$	0.8	0.8	0.78	0.78	0.39	1.03
	Coupling	0.65	0.65	6.62	6.62	6.59	6.64

From Table III, one can see that the $B^*\bar{B}^*$ with $J^{PC} = 0^{++}$ and 2^{++} are both bound states. The appearance of the state $B^*\bar{B}^*$ with $J^{PC} = 2^{++}$ is due to the larger mass of the b quark than the c quark, the kinetic energy of former is lower than the latter, and the repulsive color magnetic interaction in $B^*\bar{B}^*$ is also small (the interaction is inversely proportional to the square of quark mass) in the hidden color channel, which leads to the energy below the threshold of $B^*\bar{B}^*$.

V. SUMMARY

In summary, we have studied the possible four-quark states of $X(3915)$ and similar state X_B with the b quark replacing the c quark by taking into consideration the coupling of different color structures in the BCN model. In the quark model, there is no net interaction between two color-singlet mesons. To form the bound state, the hidden color channel must be introduced. By considering the hidden color channel and the coupling between the color-singlet channel and the hidden color channel, bounded states $D^*\bar{D}^*$ and $B^*\bar{B}^*$ are obtained. In our calculation, the $X(3915)$ can be interpreted as $D^*\bar{D}^*$ with $J^{PC} = 0^{++}$, which is in agreement with the discussion in Refs. [3,14–18].

Since the experimental data about the $X(3915)$ are preliminary, further confirmation by other experimental collaborations is necessary. The role of the hidden color can be tested in a multiquark system if the $X(3915)$ is identified as a bound state $D^*\bar{D}^*$ with $J^{PC} = 0^{++}$. At present, we only have a limited understanding for the puzzling state $X(3915)$. A systematical study of the role of hidden color in different four-quark configurations will help us to understand the effects of hidden color configurations. The work is in progress.

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