Dynamical study of the $X(3915)$ as a molecular $D^*\bar{D}^*$ 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 $S$-wave $D^*\bar{D}^*$ state in the Bhaduri, Cohler, and Nogami quark model by the Gaussian Expansion Method. Due to 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 state of $B^*\bar{B}^*$ with $J^{PC} = 0^{++}$ and $2^{++}$ are also predicted in this work.

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I. INTRODUCTION

Very recently, Belle Collaboration reported the newest charmonium like state, the $X(3915)$, which is observed in $\gamma \gamma \rightarrow \omega J/\psi$ with a statistical significance of $7.7 \sigma$ \cite{3940}. It has the mass $M = 3915 \pm 3 \pm 2$ MeV and width $\Gamma = 17 \pm 10 \pm 3$ MeV. Belle Collaboration determined the $X(3915)$ production rate

\[ \Gamma_\gamma(X(3915))B(X(3915) \rightarrow \omega J/\psi) = 61 \pm 17 \pm 8 \text{ eV} \] (1)

or for $J^P = 0^+$ or $2^+$, respectively. The $X(3915)$ is similar to the previously discovered $Y(3940)$ by Belle and confirmed by BaBar Collaboration in the process $B \rightarrow KY(3940)$, $Y(3940) \rightarrow \omega J/\psi$ \cite{3940}. The mass and width of the $Y(3940)$ obtained by Belle are: $M = 3943 \pm 11 \text{(stat)} \pm 13 \text{(syst)}$ MeV, $\Gamma = 87 \pm 22 \text{(stat)} \pm 26 \text{(syst)}$ MeV \cite{3940}. However, BaBar obtained $M = 3914.6^{+3.3}_{-3.4} \text{(stat)} \pm 2.0 \text{(syst)}$ MeV, $\Gamma = 34^{+12}_{-5} \text{(stat)} \pm 5 \text{(syst)}$ MeV \cite{3940}. 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 \cite{3940}. The $Y(3940)$ and $X(3915)$ have same mass and width, and are both seen in $\omega J/\psi$. Hence they might be same states pointed out in Refs. \cite{3940}. The $X(3915)$ as a conventional $c\bar{c}$ charmonium interpretation is disfavored \cite{3940}. The mass of this state is well above the threshold of $DD$ or $D\bar{D}$ \cite{3940}, hence open charm decay modes would dominate, while the $\omega J/\psi$ decay rates are essentially negligible, which is same as $Y(3940)$ \cite{3940}. However, according to the production rate obtained by Belle, Eqs. (1) and (2), we obtain the $\Gamma_{\omega J/\psi} \sim O(1 \text{ MeV})$ if we assume $\Gamma_{\gamma \gamma} \sim O(1 \sim 2 \text{ keV})$ which is typical for an excited charmonium state \cite{3915}. $\Gamma_{\omega J/\psi} \sim O(1 \text{ MeV})$ is an order of magnitude higher than typical rates between known charmonium states, which imply that there is intricate structure for the $X(3915)$. In our previous study \cite{3915}, the quantum number and mass of $\chi_0(2^3P_0)$ is 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 \cite{3940} suggested $Y(3940)$ is probably a molecular $D^*\bar{D}^*$ states with $J^{PC} = 0^{++}$ or $J^{PC} = 2^{++}$ in a meson-exchange model. Assuming the $D^*\bar{D}^*$ bound-state structure, Branz \cite{3940} studied the strong $Y(3940) \rightarrow \omega J/\psi$ and radiative $Y(3940) \rightarrow \gamma \gamma$ 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 \cite{3940} 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 SU(3) chiral quark model and solving the resonating group method equation, Liu and Zhang \cite{3940} 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 same state in the following study. In this work we study the $X(1915)$ with molecular $D^*\bar{D}^*$ structure by taking into account of the coupling of different color structures in the Bhaduri, Cohler and Nogami (BCN) quark model, since the color singlet tetraquark state $(cq)^* (cq)^*$ can be consisted of colorless or colored $(cq)^*$ and $(cq)^*$ two-quark mesons. The role of the hidden color in $qq \rightarrow q\bar{q}$ $(q = u, d)$ has been discussed by Brink and Stancu \cite{20}, and then extended to study other four-quark systems \cite{21, 22}.

The BCN quark model was proposed by Bhaduri, Cohler and Nogami \cite{24}. In this model, the interaction between 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 \cite{23} and four-quark system \cite{21, 22} range from light quark $u, d$ to heavy quark $b$. 

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with same set of parameters. The molecular state bound by a one-gluon exchange interaction in the BCN quark model can be depicted in Fig. 1. One-gluon exchange interaction exist between pair of quark-antiquark or quark-antiquark in color structure $8 \otimes 8$, while no interaction 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 hidden color channel (color structure $8 \otimes 8$, Fig. 1(B)).

![Diagram](A)  
![Diagram](B)

FIG. 1: The molecule 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.

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 Expression Method (GEM), which is a high precision numerical method for few body system. The detail 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 BCN quark model. Section III is devoted to discuss the wave function of few-body systems. In this work, the spectra of energy of few-body systems. In this work, the spectra of

II. HAMILTONIAN

The Hamiltonian of BCN model takes the form,

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

with

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

$$V_{ij}^C = \lambda_i^C \cdot \lambda_j^C \left(-a_c r_{ij} - \Delta \right). \quad (4)$$

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

| Quark masses | Confined | Confinement | OGE |
|--------------|----------|-------------|-----|
| $m_u,d$ (MeV) | $a_c$ (MeV fm$^{-1}$) | $\Delta$ (MeV) | $\kappa$ |
| 337          | 176.738  | -171.25     | 0.390209 |
| 600          |          |             | 0.4545  |
| 1870         |          |             |         |
| 5259         |          |             |         |

TABLE I: Parameters of the BCN model.

III. WAVE FUNCTION

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

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

with

$$\Phi_{JJ_z} = \left( |\chi \rangle |\Phi \rangle \right)_{JJ_z}$$

where $|\xi \rangle$, $|\eta \rangle$, $|\chi \rangle$, $|\Phi \rangle$ represent color singlet, isospin with $I$, spin with $S$ and spacial with angular momentum $L_T$ wave functions, respectively.

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

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

The similar state composed of $b$ quark is

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

The spatial structure of the above states are pictured in Fig. 2. The relative coordinates are defined as following,

$$r = r_1 - r_2, \quad R = r_3 - r_4, \quad (9)$$

$$\rho = \frac{m_1 r_1 + m_2 r_2 - m_3 r_3 + m_4 r_4}{m_1 + m_2 - m_3 + m_4}, \quad (10)$$

and the coordinate of the center of mass is

$$R_{cm} = \frac{1}{4} \sum_{i=1}^{4} m_i r_i \sum_{i=1}^{4} m_i, \quad (11)$$

where $m_i$ is the mass of the $i$th quark.
The expression of \( \zeta \) wave functions of the possible molecular state can be obtained from Eq. (16).

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

Three relative motion wave functions are written as,

\[
\phi_{lm}^G(r) = \sum_{n=1}^{n_{max}} c_n N_n^l e^{-\nu_n r^2} Y_{lm}(\hat{r}) \quad (13)
\]

\[
\psi_{LM}^G(R) = \sum_{N=1}^{N_{max}} c_N N_N^L e^{-\zeta_N R^2} Y_{LM}(\hat{R}) \quad (14)
\]

\[
\varphi_{\beta\gamma}^G(\rho) = \sum_{\alpha=1}^{\alpha_{max}} c_{\alpha\beta\gamma} e^{-\omega_\alpha \rho^2} Y_{\beta\gamma}(\hat{\rho}) \quad (15)
\]

Gaussian size parameters are taken as geometric progression

\[
\nu_n = \frac{1}{r_n^2}, \quad r_n = r_1 a^{n-1}, \quad a = \left( \frac{r_{n_{max}}}{r_1} \right)^{-\frac{1}{n_{max}-1}} \quad (16)
\]

The expression of \( \zeta_N, \omega_\alpha \) in Eqs. (14) - (15) are similar to Eq. (10).

The physical state must be color singlet, so the color wave functions of the possible molecular state can be constructed by the following color structures,

\[
|\xi_1\rangle = |1_{12} \otimes 1_{34}\rangle, \quad |\xi_2\rangle = |8_{12} \otimes 8_{34}\rangle. \quad (17)
\]

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

![FIG. 2: The relative coordinate of a molecular state](image)

By GEM, the outer products of space and spin is

\[
\Phi_{JJ_z} = [\phi_{lm}^G(r)\chi_{s_1 m_{s_1}}] J_1 M_1
\]

\[
[\psi_{LM}^G(R)\chi_{s_2 M_2}] J_2 M_2 \varphi_{\beta\gamma}^G(\rho)] J J_z. \quad (12)
\]

The IV. NUMERICAL RESULTS AND DISCUSSION

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

\[
(H - E) \Psi_{JJ_z} = 0 \quad (18)
\]

with Rayleigh-Ritz variational principle. The results of 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.

| Meson | BCN   | Exp.     |
|-------|-------|----------|
| \( \pi \) | 137.5 | 139.57±0.00035 |
| \( K \) | 521.4 | 493.67±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 | 1019.42±0.02 |
| \( \eta(1s) \) | 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 |
| \( \eta(1s) \) | 9422.2 | 9388.9±2.3(stat) |
| \( Y(1s) \) | 9439.5 | 9460.30±0.26 |

Due to the threshold of four-quark system is governed by two corresponding meson masses, so a good fit of meson spectra, with the same parameters used in four-quark calculations, must be the most important criterion \[21\].

Therefore, the universal model parameters are also employed in this work to study the possible molecular state of the \( X(3915) \) and \( X_2 \).

Using GEM with the numbers of gaussians \( \alpha = 12, n = 7, N = 7 \), and the magnitude of \( z \) ranges from 0.1 to 6 fm, and 0.1 to 2 fm for \( x \) and \( y \), respectively, in Eqs. (13) - (15), we obtain converged results for the four-quark systems which also discussed in detail in Ref. \[23\].
By taking the coupling of color singlet and octet into account, the total energy of the possible molecular state mentioned above are listed in Table III.

| Molecular state | $J^{PC}$ | $E_{th}$ (MeV) | $E_{b0}$ (MeV) | 1 ⊗ 1 | 8 ⊗ 8 | cc |
|-----------------|----------|----------------|--------------|-------|-------|----|
| $D^* D^*$       | 0$^+$    | 4042.6         | 4043.6       | 3941.9| 3912.1|    |
|                 | 2$^+$    | 4043.6         | 4200.3       | 4043.6|        |    |
| $B^* B^*$       | 0$^+$    | 10703.4        | 10388.74     | 10298.5|       |    |
|                 | 2$^+$    | 10703.4        | 10609.83     | 10535.1|       |    |

The $D^* D^*$ 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 spin operator for interacting quark pairs $(i, j)$ are $((1, 2), (3, 4), (1, 3), (2, 4), (1, 4), (2, 3)) = (1, -2, -2, -2, -2, -2) and (1, 1, 1, 1, 1, 1)$ for $J^{PC} = 0^+$ and $2^+$, respectively. For the color singlet-singlet channel, because of no interaction between $D^*$ and $D^*$, the calculated energies of $D^* D^*$ must converged to the threshold, the sum of the mass of $D^*$ and $D^*$; the distances between two quarks (or antiquarks) residing in the different color-singlets are much larger than that of quark and antiquark in the same color-singlet. The results are demonstrated in Table 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, anticonfinement appears [34]. However, the other four pairwise interactions are still attractive which govern the confinement of 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 (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 interaction are also important in the hidden color channel. For the state with $J^{PC} = 0^+$, the contributions from color magnetic interaction $-\langle\lambda_i^c \cdot \lambda_j^c\rangle (\sigma_i \cdot \sigma_j)$ of each particle-pair are all attractive. Hence, in hidden color channel the energy of $D^* D^*$ 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 that for other four particle-pair are repulsive. The channel coupling increases the difference further, because the cross matrix elements between color singlet-singlet and color octet-octet with $J^{PC} = 0^+$ is two times larger than it with $J^{PC} = 2^+$.

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

| Molecular state | $J^{PC}$ | $E_{th}$ (MeV) | $E_{b0}$ (MeV) | 1 ⊗ 1 | 8 ⊗ 8 | cc |
|-----------------|----------|----------------|--------------|-------|-------|----|
| $D^* D^*$       | 0$^+$    | 4042.6         | 4043.6       | 3941.9| 3912.1|    |
|                 | 2$^+$    | 4043.6         | 4200.3       | 4043.6|        |    |
| $B^* B^*$       | 0$^+$    | 10703.4        | 10388.74     | 10298.5|       |    |
|                 | 2$^+$    | 10703.4        | 10609.83     | 10535.1|       |    |

TABLE IV: Color matrix elements $\langle\xi_i^c | \lambda_i^c \cdot \lambda_j^c | \xi_l^c\rangle$ with $k, l = 1, 2$ and $j > i = 1, 2, 3, 4$.

| $(i, j)$ | $(1, 2)$ | $(3, 4)$ | $(1, 3)$ | $(2, 4)$ | $(1, 4)$ | $(2, 3)$ |
|----------|----------|----------|----------|----------|----------|----------|
| $(k, l)$ | $(1, 1)$ | $-\frac{15}{4}$ | $0$ | $0$ | $0$ | $0$ |
|          | $(2, 2)$ | $\frac{5}{4}$ | $\frac{5}{4}$ | $\frac{5}{4}$ | $\frac{5}{4}$ | $\frac{5}{4}$ |
|          | $(1, 2)$ | $0$ | $\sqrt{\frac{15}{4}}$ | $-\sqrt{\frac{15}{4}}$ | $-\sqrt{\frac{15}{4}}$ | $-\sqrt{\frac{15}{4}}$ |

TABLE V: The distances between each quark pair in the configuration of $D^* D^*$ in different color structure. $r_{ij}$ stands for $\sqrt{<r_{ij}^2 >}$ $(j > i = 1, 2, 3)$ 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     | 0.66     | 0.66     | 0.72     | 0.72     |
|          | $8 \otimes 8$   | 0.7      | 0.09     | 0.72     | 0.72     | 0.92     | 0.92     |
|          | Coupling        | 0.71     | 0.71     | 0.69     | 0.69     | 0.93     | 0.93     |
| $2^+$    | $1 \otimes 1$   | 0.65     | 0.65     | 0.63     | 0.63     | 0.88     | 0.88     |
|          | $8 \otimes 8$   | 0.65     | 0.65     | 0.73     | 0.73     | 0.85     | 0.85     |
|          | Coupling        | 0.65     | 0.65     | 0.62     | 0.62     | 0.69     | 0.69     |

V. SUMMARY

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

Since the experimental data about the $X(3915)$ is preliminary, further confirmation by other experimental collaborations is necessary. The role of the hidden color can be tested in multi-quark system if the $X(3915)$ is identified as a molecular state $D^* D^*$ 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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