Study of the heavy molecular states in the quark model with meson exchange interaction

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Abstract: Some charmonium-like resonances such as X(3872) can be interpreted as possible $D^{(*)}\bar{D}^{(*)}$ molecular states. Within the quark model, we study the structure of such molecular states and the similar $B^{(*)}\bar{B}^{(*)}$ molecular states by taking into account the light meson exchange (π, η, ρ, ω and σ) between two light quarks from different mesons.

Key words: molecular state, quark model, meson exchange

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1 Introduction

Some recently discovered narrow charmonium-like resonances have aroused great theoretical interest. The typical X(3872) state, which was discovered by the Belle collaboration [1] and subsequently confirmed by the CDF collaboration [2] and the BABAR collaboration [3], is summarized $M_{\rm X} = 3872.2\pm 0.8$ MeV, $\Gamma_{\rm X} = 3.0^{+1.9}_{-1.4}\pm 0.9$ MeV [4]. Previously, its quantum numbers were inferred most probably $J^{PC} = 1^{++}$, while the masses of the corresponding charmonium states in the quark model 2^3P_1 or 3^3P_1 are hundreds of MeV above $M_{\rm X}$. Recently, a study of the $\pi^+\pi^-\pi^0$ mass distribution from the X(3872) decay by the BABAR Collaboration was found to favor a negative parity assignment 2^{-+} [5]. However, the mass of the charmonium candidate in the quark model 1^1D_2 still disagrees with $M_{\rm X}$.

Since it is difficult to assign X(3872) to any conventional $c\bar{c}$ charmonium state in the quark model, other alternative explanations prevail. Because $M_{\rm X}$ is close to the $D^*\bar{D}$ threshold, X(3872) was interpreted as a loosely bound molecular $D^*\bar{D}$ state [6–9], or a molecular state with some admixtures of $\rho J/\psi$ and $\omega J/\psi$ [10]. It was also suggested as a tetra quark state dominated by a diquark-antidiquark structure [11], or a $c\bar{c}g$ hybrid state [12]. The proximity of the X(3872) to the $D^*\bar{D}$ threshold may also imply that the cusp scenario should be treated seriously [13].

The $D^{(*)}\bar{D}^{(*)}$ molecular states were proposed many years ago [14, 15]. To bind the two mesons together in a molecular state, additional interaction beyond the quark potential model should be introduced between the two mesons. Naturally, the meson exchanges were considered first. The inter-meson potentials from light meson exchanges can easily be treated in the frame of heavy quark effective theory. The studies showed that the cutoff parameters in the form factors are critical to the formation of the molecular states [7, 16–18]. Other interactions, such as the gluon exchanges, were also considered [10, 19, 20].

Basically, the form factor is related to the inner quark wave functions of the meson state. To avoid the uncertainty from the form factor, in this work we will investigate the possible molecular states directly using the quark wave function within the quark model. Our calculation is based on the multi-Gaussian function expansion of the quark wave function of the molecular state, which is a simple and efficient variational method to study many-body ground bound states [20–23].

We will assume that the light mesons (π, η, ρ, ω

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and σ) are exchanged between the light quarks from different hadrons. The mechanism can be understood from the chiral quark model [24], which was proposed by Weinberg [25] and formulated by Manohar and Georgi [24]. The key feature of the chiral quark model is that between the QCD confining scale and the chiral symmetry breaking scale, QCD can be roughly described by an effective Lagrangian of quarks and pseudo-scalar mesons of Numbu-Goldstone bosons. The strong interaction between hadrons is thus described mainly by the exchange of pseudo-scalar mesons at long range. In practice, the chiral quark model can be further extended with more mesons to account for the intermediate-range interaction. The light vector resonances ρ, K*, etc., can be realized as the dynamical gauge bosons of a hidden local symmetry [26]. The scalar meson σ can be explicitly introduced from the linear realization, as in the linear sigma model. The chiral quark model was widely used in the study of nuclear forces [27, 28], and was recently used to study the molecular states [29].

In Section 2 we will introduce the quark model with the meson exchange interactions used in our work. In Section 3 the multi-Gaussian function expansion method and the configuration space of the molecular states are presented. We will study both the $\mathrm{D}^{(*)}\bar{\mathrm{D}}^{(*)}$ and $\mathrm{B}^{(*)}\bar{\mathrm{B}}^{(*)}$ molecular states. Finally we will give a short summary.

2 The quark model with meson exchange

The Hamiltonian in a quark model can be written as

$$H = \sum_i \left(m_i + \frac{P_i^2}{2m_i}\right) - \frac{3}{4}\sum_{i<j}(F_i\cdot F_j V_{ij}^c + F_i\cdot F_j S_i\cdot S_j V_{ij}^s). \quad (1)$$

The first part is the non-relativistic kinetic energy, where m_i's are the constituent quark masses. The second part is the central potential, where $F_i = \frac{1}{2}\lambda_i$ are the well known $SU(3)_{\mathrm{c}}$ Gell-Mann matrices. Apart from a constant, the central potential is usually a combination of the one gluon exchange coulomb potential and the linear confinement:

$$V_{ij}^{\mathrm{c}} = -\frac{\kappa}{r_{ij}} + \frac{r_{ij}}{a_0^2} - M_0, \quad (2)$$

where $r_{ij} = |r_i - r_j|$ is the distance between quark i and quark j. The last part is the color-magnetic interaction, where $S_i = \frac{1}{2}\sigma_i$ are the Pauli matrices.

In our work we will use the Bhaduri quark model, which is a simple non-relativistic quark potential model [30]. The potential function V_{ij}^{s} of color-magnetic interaction reads

$$V_{ij}^{\mathrm{s}} = \frac{4\kappa}{m_i m_j}\frac{1}{r_0^2 r_{ij}}\mathrm{e}^{-r_{ij}/r_0}. \quad (3)$$

The model parameters are

$$\begin{aligned} &\kappa = 102.67\ \mathrm{MeV}, && a_0 = 0.0326\ (\mathrm{fm/MeV})^{\frac{1}{2}},\\ &M_0 = 913.5\ \mathrm{MeV}, && r_0 = 0.4545\ \mathrm{fm},\\ &m_{\mathrm{u}} = m_{\mathrm{d}} = 337\ \mathrm{MeV}, && m_{\mathrm{s}} = 600\ \mathrm{MeV},\\ &m_{\mathrm{c}} = 1870\ \mathrm{MeV}, && m_{\mathrm{b}} = 5290\ \mathrm{MeV}. \end{aligned} \quad (4)$$

The quark model is very successful in describing the hadron properties at low energy under the QCD confinement scale. As is well known, due to the color symmetry, the above quark potential does not provide direct interaction between hadrons. Here we will consider the exchange of the light mesons between the two light quarks from different hadrons based on the chiral quark model. At present, we will consider the exchanges of the π, η, ω, ρ and σ mesons only. The interaction Lagrangian densities are:

1) pseudoscalar

$$\mathcal{L}_{\mathrm{p}} = \mathrm{i}g_{\mathrm{p}}\bar{\psi}(x)\gamma_5\psi(x)\varphi(x), \quad (5)$$

2) scalar

$$\mathcal{L}_{\mathrm{s}} = g_{\mathrm{s}}\bar{\psi}(x)\psi(x)\phi(x), \quad (6)$$

3)vector

$$\mathcal{L}_{\mathrm{v}} = g_{\mathrm{v}}\bar{\psi}(x)\gamma_\mu\psi(x)v^\mu(x) + \frac{f_{\mathrm{v}}}{2m_{\mathrm{q}}}\bar{\psi}(x)\sigma_{\mu\nu}\psi(x)\partial^\mu v^\nu. \quad (7)$$

Here m_{q} is the constituent quark mass, $\psi(x)$ is the constituent quark Dirac spinor field and $\varphi(x)$, $\phi(x)$ and $v^\mu(x)$ are the pseudoscalar, scalar and vector intermediate meson fields, respectively. In the case of isovector mesons, the above meson fields should be replaced by $\boldsymbol{\tau}\cdot\boldsymbol{\varphi}$, $\boldsymbol{\tau}\cdot\boldsymbol{\phi}$ or $\boldsymbol{\tau}\cdot\boldsymbol{v}^\mu$, respectively, where $\boldsymbol{\tau}$ are the isospin Pauli matrices. From the effective Lagrangian we can obtain the effective potential between two quarks. In the coordinate space [31]:

1) pseudoscalar

$$V_{\mathrm{p}}(r) = \frac{g_{\mathrm{p}}^2}{48\pi}m_{\mathrm{p}}\left(\frac{m_{\mathrm{p}}}{m_{\mathrm{q}}}\right)^2 Y_1(m_{\mathrm{p}}r)\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2, \quad (8)$$

2) scalar

$$V_{\mathrm{s}}(r) = -\frac{g_{\mathrm{s}}^2}{4\pi}m_{\mathrm{s}}\left[Y(m_{\mathrm{s}}r) - \left(\frac{m_{\mathrm{s}}}{m_{\mathrm{q}}}\right)^2\frac{1}{4}Y_1(m_{\mathrm{s}}r)\right], \quad (9)$$

3) vector

$$V_{\rm v}(r) = \frac{g_{\rm v}^2}{4\pi} m_{\rm v} \left\{ Y(m_{\rm v}r) + \left(\frac{m_{\rm v}}{m_{\rm q}}\right)^2 \frac{1}{2} Y_1(m_{\rm v}r) \right\} + \frac{g_{\rm v} f_{\rm v}}{4\pi} m_{\rm v} \left(\frac{m_{\rm v}}{m_{\rm q}}\right)^2 \left[\frac{1}{2} Y_1(m_{\rm v}r) + \frac{1}{3} Y_1(m_{\rm v}r) \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \right] + \frac{f_{\rm v}^2}{4\pi} m_{\rm v} \left(\frac{m_{\rm v}}{m_{\rm q}}\right)^2 \frac{1}{6} Y_1(m_{\rm v}r) \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2. \quad (10)$$

We have neglected the momentum dependence of all the potentials in the present work. The spin-orbit interaction and the tensor-force are also dropped out here since we only consider the molecular ground states. The functions Y, Y_1 are defined as follows:

$$Y(x) = \frac{{\rm e}^{-x}}{x}, \quad (11)$$

$$Y_1(x) = \frac{{\rm e}^{-x}}{x} - 4\pi\delta^3(\boldsymbol{x}). \quad (12)$$

Note that on the quark level, we do not need to introduce the form factors to treat the δ-interaction. The meson's quark wave functions will naturally smear out the singularity.

The $\rm q\bar{q}$ potentials are obtained from the above qq potentials by a G-parity transformation. Also, there should be an isospin factor $\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$ in the above effective potential if an isovector meson is exchanged.

From PDG [4], the masses of exchanged mesons are taken to be:

$m_\pi = 134.98$ MeV, $m_\eta = 547.85$ MeV,

$m_\rho = 775.5$ MeV, $m_\omega = 782.7$ MeV,

$m_\sigma = 600.0$ MeV.

The masses of relevant heavy flavor mesons are:

$m_{\rm D^0} = 1864.5$ MeV, $m_{\rm D^\pm} = 1869.3$ MeV,

$m_{\rm D^{*0}} = 2006.7$ MeV, $m_{\rm D^{*\pm}} = 2010.0$ MeV,

$m_{\rm B^0} = 5279.5$ MeV, $m_{\rm B^\pm} = 5279.1$ MeV,

$m_{\rm B^*} = 5325.1$ MeV.

The coupling constants are taken from Ref. [9]:

$g_\pi = 2.74$, $g_\eta = 2.05$, $g_\sigma = 3.30$,

$g_\rho = 3.46$, $f_\rho = 1.45$,

$g_\omega = 5.28$, $f_\omega = 0$,

which are extracted from the meson-nucleon coupling constants in the well-known Bonn model [31] using the single-quark operator approximation [32].

3 The heavy flavor molecular states

In this work, we consider the possible molecular states constructed from the pseudo-scalar heavy mesons (D, B) and their vector partners ($\rm D^*$, $\rm B^*$). The states involving strange mesons are not considered here. The corresponding charmed combinations are: D-$\bar{\rm D}$, $\rm D^*$-$\bar{\rm D}^*$, $\rm D^*$-$\bar{\rm D}$. Since the charmed mesons belong to the $I = \frac{1}{2}$ representation of isospin $SU(2)$, the possible isospins of the $\rm D^{(*)}$-$\bar{\rm D}^{(*)}$ system are $I = 0$, 1. Following Ref. [33], we label the D-$\bar{\rm D}$, $\rm D^*$-$\bar{\rm D}$ and $\rm D^*$-$\bar{\rm D}^*$ systems as $\Phi_{\rm IJ}$, $\Phi^*_{\rm IJ}$ and $\Phi^{**}_{\rm IJ}$, respectively, while the $\rm D^*$-$\bar{\rm D}$ system with negative charge conjugate ($C = -1$) is labeled as $\hat{\Phi}^*_{\rm IJ}$. Below we pick up the neutral state to represent the isospin multiplet:

1) $I = 0$

$$\Phi^0_{00} = \frac{1}{\sqrt{2}} \left(\bar{D}^0 D^0 - D^- D^+ \right), \quad (13a)$$

$$\Phi^{**0}_{0J} = \frac{1}{\sqrt{2}} \left(\bar{D}^{*0} D^{*0} - D^{*-} D^{*+} \right)_J, \quad (J = 0,1,2) \quad (13b)$$

$$\Phi^{*0}_{01} = \frac{1}{2} [D^0 \bar{D}^{*0} - D^+ D^{*-} - C(\bar{D}^0 D^{*0} - D^- D^{*+})], \quad (13c)$$

2) $I = 1$

$$\Phi^0_{10} = \frac{1}{\sqrt{2}} \left(\bar{D}^0 D^0 + D^- D^+ \right), \quad (13d)$$

$$\Phi^{**0}_{1J} = \frac{1}{\sqrt{2}} \left(\bar{D}^{*0} D^{*0} + D^{*-} D^{*+} \right)_J, \quad (J = 0,1,2) \quad (13e)$$

$$\Phi^{*0}_{11} = \frac{1}{2} [D^0 \bar{D}^{*0} + D^+ D^{*-} - C(\bar{D}^0 D^{*0} + D^- D^{*+})]. \quad (13f)$$

The states of the $\rm B^{(*)}$-$\bar{\rm B}^{(*)}$ combinations are constructed similarly but named after Ω.

To calculate the molecular state, we use the Rayleigh-Ritz variation principle. The test wave function is taken to be a series of Gaussian functions with various widths [21–23]. In our case of the $\rm Q\bar{q}q\bar{Q}$ molecular state, the test wave function between the

$Q\bar{q}$ and $q\bar{Q}$ mesons is expanded to [20]

$$\psi_{1234}(r_{12},r_{34},r_{1234}) = \sum_i \alpha^i_{1234}\psi_{12}(r_{12})\psi_{34}(r_{34}) \times \exp(-\beta^i_{1234}r^2_{1234}), \quad (14)$$

where $\boldsymbol{r}_1$, $\boldsymbol{r}_2$, $\boldsymbol{r}_3$ and $\boldsymbol{r}_4$ are the coordinates of Q, $\bar{q}$, q and $\bar{Q}$, respectively. $\boldsymbol{r}_{ij}=\boldsymbol{r}_i-\boldsymbol{r}_j$. r_{1234} is the distance between the two meson clusters

$$\boldsymbol{r}_{1234}=\frac{m_Q\boldsymbol{r}_1+m_q\boldsymbol{r}_2}{m_Q+m_q}-\frac{m_q\boldsymbol{r}_3+m_Q\boldsymbol{r}_4}{m_q+m_Q}. \quad (15)$$

Each of the meson wave functions $\psi_{ij}(r_{ij})$ is also taken to be a Gaussian function series

$$\psi_{ij}(r_{ij})=\sum_k \alpha^k_{ij}\exp(-\beta^k_{ij}r^2_{ij}). \quad (16)$$

Numerically, the above wave function is determined by the variational method in two steps. First the meson wave function (16) is determined from the potential quark model. Then the wave function (14) of the molecular state is obtained from the meson exchange potentials with the meson wave functions ψ_{ij} fixed.

To reduce the amount of computation, the parameters β^i and α^i in each Gaussian function series are also determined in two steps by one-dimensional minimization. We first search a central β value using a single Gaussian function. Then a set $\{\beta^i\}$ of $2N+1$ elements is generated by scaling the β value up and down by a scale factor s [23]:

$$\beta^i=\beta s^{i-N}, \quad (17)$$

where $i=0,1,...,2N$.

The bound energies and the mean squared radii (rms) $\langle \boldsymbol{r}^2_{1234}\rangle^{1/2}$ of the $D^{(*)}\bar{D}^{(*)}$ molecular states are listed in Table 1.

The calculation shows that the meson exchange interaction is strong enough to bind the molecular states. The typical Φ^*_{01} is the candidate molecular state for the X(3872). However, the bound energy of Φ^*_{01} is 30.7 MeV, which is larger than we expect, as X(3872) should be a loose bound molecular state.

However, there is some uncertainty in the meson coupling constants on the quark level. In the Bonn model for neucleon interaction, the form factors [31]

$$F_\alpha(\boldsymbol{k}^2)=\left(\frac{\Lambda^2_\alpha-m^2_\alpha}{\Lambda^2_\alpha+\boldsymbol{k}^2}\right)^{n_\alpha} \quad (18)$$

are also introduced in the description of the meson baryon couplings. Clearly from the meson mass dependence in the form factor, the effective meson coupling constants decrease as the mass of intermediate mesons increase.

Next we try to decrease the coupling constants to the mesons σ, ρ, ω and η with heavier masses by a factor λ following Ref. [9]. The numerical results for the case of $\lambda=0.7$ are shown in Table 1 as calculation II. Now the bound energy of Φ^*_{01} is only 2.6 MeV and the rms is 2.47 fm, which meet the interpretation of X(3872) as a loose bound molecular state. Other possible molecular states that are left are iso-scalar $\Phi_{00}(0^{++})$, $\Phi^{**}_{01}(1^{++})$ and $\Phi^{**}_{02}(2^{++})$.

A similar calculation to the $B^{(*)}\bar{B}^{(*)}$ molecular states is shown in Table 2.

As we expect, the bound energies of the $B^{(*)}\bar{B}^{(*)}$ molecular states become larger. Even when the coupling constants are weakened by the scale factor $\lambda=0.7$ in calculation II, the meson exchange is still strong enough to bind the molecular states for all $B^{(*)}$-$\bar{B}^{(*)}$ combinations.

Table 1. The bound energies of the $D^{(*)}\bar{D}^{(*)}$ molecular states. In calculation II, all the meson coupling constants are reduced by a factor of 0.7, except the π meson.

$T=0$		Φ_{00}	Φ^*_{01}	Φ^{**}_{00}	Φ^{**}_{01}	Φ^{**}_{02}
rms/fm	I	1.34	1.37	0.94	1.28	1.48
	II	2.60	2.47	—	3.14	2.54
E/MeV	I	−29.7	−30.7	−45.1	−24.6	−24.6
	II	−1.9	−2.6	—	−1.2	−2.3
$T=1$		Φ_{10}	$\hat{\Phi}^*_{11}$	Φ^{**}_{10}	Φ^{**}_{11}	Φ^{**}_{12}
rms/fm	I	1.24	1.12	1.04	1.19	1.71
	II	—	—	—	—	—
E/MeV	I	−13.7	−18.3	−22.6	−15.6	−5.7
	II	—	—	—	—	—

Table 2. The bound energies of $B^{(*)}\bar{B}^{(*)}$ molecular states. In calculation II, all the meson coupling constants except the π meson are scaled by a factor of 0.7.

$T=0$		Ω_{00}	Ω^{*}_{01}	Ω^{**}_{00}	Ω^{**}_{01}	Ω^{**}_{02}
rms/fm	I	1.13	1.16	0.65	1.00	1.21
	II	1.39	1.32	1.11	1.38	1.42
E/MeV	I	−46.0	−49.2	−81.0	−44.6	−44.0
	II	−13.1	−17.3	−11.7	−9.5	−15.3
$T=1$		Ω_{10}	$\hat{\Omega}^{*}_{11}$	Ω^{**}_{10}	Ω^{**}_{11}	Ω^{**}_{12}
rms/fm	I	0.72	0.66	0.62	0.68	0.84
	II	1.01	0.90	0.84	0.93	1.29
E/MeV	I	−38.6	−48.9	−59.3	−46.6	−25.6
	II	−10.4	−14.8	−19.3	−13.7	−5.2

4 Summary

Based on the meson exchange interaction between light quarks, we investigated the heavy molecular states in the quark model. The molecular states are described by the four-quark wave function expanded as a series of Gaussian functions. The numerical results show that the light meson exchanges of π, η, ρ, ω and σ between the light u, d quarks are strong enough to bind the heavy molecular states.

However, the bound energies of the molecular states are tens of MeV (up to 80 MeV in $B^{(*)}\bar{B}^{(*)}$ cases) if we adopt the meson-quark coupling constants from the meson-nucleon coupling constants simply using the single-quark operator approximation. The results are unreliable because the bound energies are somehow close to $\Lambda_{\rm QCD}$, while only the long-range meson exchanges are considered in our calculation.

After we consider the uncertainty of the coupling constants, which are deduced from the Bonn potential of neucleon interaction by decreasing the η, ρ, ω and σ couplings by a factor of 0.7, the X(3872) is well interpreted as a loose molecular 1^{++} state. The calculation also shows that other possible molecular states, such as 1^{++} and 2^{++}, may exist on the threshold of $D^{*}\bar{D}^{*}$ (the 0^{++} scalar state on the threshold of $D\bar{D}$ is complicated by the scalar admixture). Since the bind energies of the $B^{(*)}\bar{B}^{(*)}$W molecular states increase with the heavy favor mass increase, there are more such molecular states near the $B^{(*)}\bar{B}^{(*)}$ thresholds, as we expected.

The main uncertainty in this work is the estimation of meson-quark coupling constants. To obtain a set of reliable coupling constants, we can use the model to study nucleon-nucleon interaction in the future.

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