QQ̅q̅q Four-quark Bound States in Chiral SU(3) Quark Model

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Abstract

The possibility of $QQ̅q̅q$ heavy-light four-quark bound states has been analyzed by means of the chiral SU(3) quark model, where $Q$ is the heavy quark ($c$ or $b$) and $q$ is the light quark ($u$, $d$ or $s$). We obtain a bound state for the $bb̅n̅n$ configuration with quantum number $J^P = 1^+, I = 0$ and for the $cc̅n̅n$ ($J^P = 1^+, I = 0$) configuration which is not bound but slightly above the $D^*D^*$ threshold ($n$ is $u$ or $d$ quark). Meanwhile, we also conclude that a weakly bound state in $bb̅n̅n$ system can also be found without considering the chiral quark interactions between the two light quarks, yet its binding energy is weaker than that with the chiral quark interactions.

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I. INTRODUCTION

A great interest in studying four-quark (4q) states has been triggered by the observations of some very narrow resonances, e.g., $D_{sJ}^*(2317)$ by BABAR [1], $D_{sJ}(2460)$ by CLEO [2], $X(3872)$ by BELLE [3], and $Y(4260)$ by BABAR [4]. Because almost all of these new states have the same special properties, which are narrow and their structures are difficult to be explained as the simple quark-antiquark pair, much attention has been paid and various theoretical explanations were proposed. Mostly, these new states were suggested as good candidates of 4q states [5]. In this work we will try to see if there are possibilities for the existence of the four-quark states with two heavy quarks which is also a significant problem in the new hadron state studies.

The possible existence of 4q states composed of two heavy quarks (anti-quarks) and two light anti-quarks (quarks) has been suggested and studied in the past few years in different ways [6, 7, 8]. For example, the work of Carlson et al. [7] based on the MIT bag model concluded that the state $b\bar{b}u\bar{d}$ with $J^P = 1^+$ is bound and the $cc\bar{u}\bar{d}$ is not bound. A different conclusion is obtained by Pepin et al. [8] using a pseudoscalar meson exchange interaction instead of the chromomagnetic potential, and their results indicated that such interaction binds the heavy-light 4q systems both for $Q = b$ and $Q = c$. Therefore, whether the bound state exists in heavy-light 4q systems is still an open question.

In this work, we focus our attention on the heavy-light 4q states and study their masses in the framework of chiral quark model (CQM). Since the heavy-light four-quark state contains two light quarks (anti-quarks) which are regarded as constituent quarks, the non-perturbative QCD effect should be considered between them. On the other hand we notice that the chiral quark model [9, 10] based on the idea that between the chiral symmetry breaking scale and the confinement scale, QCD may be formulated for the light-quark sector as an effective theory of constituent quarks interacting through Goldstone boson modes associated to the spontaneous breaking of chiral symmetry, and CQM has obtained great success in reproducing the energies of the baryon ground states, the binding energy of deuteron, the nucleon-nucleon phase shifts, and the nucleon-hyperon cross sections [10, 11]. Thus one can expect that the CQM is an effective approach to study the 4q systems with light quarks. In this work, the four-quark states with quark content $cc\bar{s}\bar{s}$, $cc\bar{n}\bar{n}$, $bb\bar{s}\bar{s}$ and $bb\bar{n}\bar{n}$ are studied in the chiral SU(3) quark (CSQ) model.

The parameters for the light quark pairs are taken from our previous work, and for the heavy-light pairs they are obtained from fitting the masses of $(D, D^*, D_s, D_s^*, \eta_c, J/\psi, h_c(1p))$, and
(B, B^*, B_s, B_s^*, η_b, Υ(1s)), the details will be introduced in the section II.B. By using these parameters, we obtain a bound state for bb-bar configuration and no bound state for cc-bar q-bar q.

Furthermore, we calculate the masses of QQ-bar q-bar without considering chiral quark interaction (CQI), and compare them with the masses of QQ-bar q-bar considering CQI. Through comparison we uncover that a bound state in bb-bar system can also be found without considering CQI, yet this bound state is not as strong as the bound state with CQI.

The paper is arranged as follows. In the next section, the theoretical framework of CSQ model, the determination of parameters and the wave functions for QQ-bar q-bar stats are briefly introduced. The calculated results are listed in Section III, where some discussions are made as well. Finally, the summary is given in Section IV.

II. THEORETICAL FRAMEWORK

A. The model

In the chiral SU(3) quark (CSQ) model, the Hamiltonian of a QQ-bar q-bar four-quark system can be written as

\[ H = \sum_i m_i + \sum_i T_i - T_G + V_{QQ}(12) + V_{q\bar{q}}(34) + \sum_{i=1,2, j=3,4} V_{Q\bar{q}}(ij), \]  

(1)

where \( m_i \) is the mass of the \( i \)th quark, \( T_G \) is the kinetic energy operator for the center-of-mass motion. Since the light quark is treated as constituent quark, and the non-perturbative QCD effect between them has to be considered, thus for the light quark pairs, besides the confinement potential and OGE interaction, the chiral quark interactions should be included also, but which is unnecessary to be considered for the heavy-heavy and heavy-light quark pairs. The expressions of the interactions are written as follows:

\[
\begin{align*}
V_{QQ}(12) &= V_{QQ}^{conf}(12) + V_{QQ}^{OGE}(12), \\
V_{q\bar{q}}(34) &= V_{q\bar{q}}^{conf}(34) + V_{q\bar{q}}^{OGE}(34) + V_{q\bar{q}}^{ch}(34), \\
V_{Q\bar{q}}(ij) &= V_{Q\bar{q}}^{conf}(ij) + V_{Q\bar{q}}^{OGE}(ij).
\end{align*}
\]

(2)

For the heavy quark pair (QQ), the confinement potential \( V_{QQ}^{conf}(12) \), which provides the non-perturbative QCD effect in long distance, is taken as linear form

\[ V_{QQ}^{conf}(12) = -(\lambda_1^i \cdot \lambda_2^j)(a_{12} r_{12} + a_{12}^0). \]

(3)
$V_{QQ}^{OGE}(12)$ is the one-gluon-exchange interaction, whose expression is

$$
V_{QQ}^{OGE}(12) = \frac{1}{4} g_1 g_2 (\lambda_1^c \cdot \lambda_2^c) \left\{ \frac{1}{r_{12}} - \frac{\pi}{2} \left( \frac{1}{m_1^2} + \frac{1}{m_2^2} + \frac{4(\sigma_1 \cdot \sigma_2)}{3m_1 m_2} \right) \delta(r_{12}) \right\}. 
$$

(4)

For the light anti-quark pair ($\bar{q}q$), we can obtain the forms of $V_{qq}^{OGE}$ and $V_{qq}^{conf}$ by replacing the $\lambda_i^c \cdot \lambda_j^c$ in Eq. (3) and Eq. (4) by $\lambda_i^{ae} \cdot \lambda_j^{ae}$, and the chiral quark interaction between two anti-quarks $V_{qq}^{ch}$ has the same form (only $\lambda_{3q}^a \cdot \lambda_4^a$ is replaced by $\lambda_{3q}^{ae} \cdot \lambda_4^{ae}$) as that of two light quarks $V_{qq}^{ch}$. In the CSQ model, $V_{qq}^{ch}$ includes the scalar boson exchanges and the pseudoscalar boson exchanges, thus

$$
V_{qq}^{ch}(34) = \sum_{a=0}^{8} V_{sa}(r_{34}) + \sum_{a=0}^{8} V_{psa}(r_{34}),
$$

(5)

and the expressions of these potentials are

$$
V_{sa}(r_{34}) = -C(g_{ch}, m_{sa}, \Lambda)(\lambda_{3q}^{ae} \cdot \lambda_4^{ae})X_1(m_{sa}, \Lambda, r_{34}),
$$

(6)

$$
V_{psa}(r_{34}) = C(g_{ch}, m_{psa}, \Lambda)(\lambda_{3q}^{ae} \cdot \lambda_4^{ae}) \frac{m_{psa}^2}{12m_3 m_4}X_2(m_{psa}, \Lambda, r_{34})(\sigma_3 \cdot \sigma_4),
$$

(7)

where

$$
C(g_{ch}, m, \Lambda) = \frac{g_{ch}^2 \Lambda^2 m}{4\pi \Lambda^2 - m^2},
$$

(8)

$$
X_1(m, \Lambda, r) = Y(mr) - \frac{\Lambda}{m} Y(\Lambda r),
$$

(9)

$$
X_2(m, \Lambda, r) = Y(mr) - \left( \frac{\Lambda}{m} \right)^3 Y(\Lambda r),
$$

(10)

$$
Y(x) = \frac{1}{x} e^{-x},
$$

(11)

and $m_{sa}(m_{psa})$ is the mass of the scalar (pseudoscalar) meson.

The interactions of quark-antiquark pair ($Q\bar{q}$) include two parts: direct interaction and annihilation part

$$
V_{Q\bar{q}} = V_{Q\bar{q}}^{dir} + V_{Q\bar{q}}^{ann},
$$

(12)

$$
V_{Q\bar{q}}^{dir} = V_{Q\bar{q}}^{conf} + V_{Q\bar{q}}^{OGE}.
$$

(13)

The contribution of annihilation part is neglected in this work, and the expression of $V_{Q\bar{q}}^{dir}$ can be obtained from $V_{Q\bar{q}}^{conf}$. Concerning $V_{Q\bar{q}}^{conf}$ and $V_{Q\bar{q}}^{OGE}$, the transformation from $V_{Q\bar{q}}$ (the expressions of $V_{Q\bar{q}}^{conf}$ and $V_{Q\bar{q}}^{OGE}$ are the same as Eqs.(3) and (4)) to $V_{Q\bar{q}}$ is given by $\lambda_i^c \cdot \lambda_j^c \rightarrow -\lambda_i^c \cdot \lambda_j^c$, while for $V_{Q\bar{q}}^{ch}$ the alteration is $\lambda_i^a \cdot \lambda_j^a \rightarrow \lambda_i^a \cdot \lambda_j^a$. 

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B. Determination of the parameters

The interaction parameters include the OGE coupling constant $g_i$, the confinement strengths $(a_{ij}, a^0_{ij})$, and the chiral coupling constant $g_{ch}$. For the light quark pairs, the parameters are taken from our previous works [12, 13], which gave a satisfactory description for the energies of the light baryon ground states, the nucleon-nucleon scattering phase shifts the binding energy of the deuteron, where the chiral coupling constant $g_{ch}$ is fixed by

$$\frac{g_{ch}^2}{4\pi} = \frac{9}{25} \frac{g_{NN}^2}{4\pi} \frac{m_u^2}{M_N^2}$$

with $g_{NN}^2/4\pi = 13.67$ taken as the experimental value. The parameters for $cq$ or $cc$ quark pairs are taken from Ref. [12], which fitted the masses of $D, D^*, D_s, D^*_s, \eta_c, J/\Psi$ and $h_1(1p)$. Followed the same method, the model parameters for $bq$ and $bb$ quark pairs can be fixed by the masses of $B, B^*, B_s, B^*_s, \eta_b$ and $\Upsilon(1s)$. The complete set of the parameters is shown in Table I, and the corresponding theoretical results for the masses of $Q\bar{q}$ and $Q\bar{Q}$ mesons are shown in Table II, from which we can see that the theoretical masses of mesons are reasonably consistent with their experimental values, respectively.

TABLE I: Model parameters for the systems with heavy quarks. The masses of $u (d)$ and $s$ quark: $m_{u,d} = 313MeV, m_s = 470MeV$. The OGE coupling constant $g_u = 0.886$.

| Parameter | Value (MeV) | Parameter | Value (MeV) |
|-----------|-------------|-----------|-------------|
| $m_c$     | 1430        | $m_b$     | 4717        |
| $g_c$     | 0.58        | $g_b$     | 0.52        |
| $a_{cu}$  | 275         | $a_{bu}$  | 275         |
| $a_{Cu}$  | -155.9      | $a_{Bu}$  | -141.1      |
| $a_{cu}$  | 275         | $a_{bs}$  | 275         |
| $a_{cu}$  | -124.7      | $a_{bs}$  | -112        |
| $a_{cc}$  | 275         | $a_{bb}$  | 275         |
| $a_{Ce}$  | -77.8       | $a_{Ce}$  | -39.5       |
TABLE II: The masses (MeV) of $Q\bar{q}$ and $Q\bar{Q}$ mesons. Experimental data are taken from PDG.

| Mesons       | $D$  | $D^*$ | $D_s$ | $D_s^*$ | $\eta_c$ | $J/\Psi$ | $h_c(1p)$ |
|--------------|------|------|-------|---------|----------|----------|-----------|
| Exp.         | 1867.7 | 2008.9 | 1968.5 | 2112.4 | 2979.6  | 3096.9   | 3526.2    |
| Theor.       | 1888  | 2009  | 1969  | 2130   | 2990    | 3098     | 3568      |

| Mesons       | $B$  | $B^*$ | $B_s$ | $B_s^*$ | $\eta_b$ | $\Upsilon(1s)$ |
|--------------|------|------|-------|---------|----------|---------------|
| Exp.         | 5279.2 | 5325 | 5369.6 | 5416.6 | 9300   | 9460.3       |
| Theor.       | 5288  | 5320  | 5317  | 5412  | 9404  | 9460          |

C. Four-quark wave function

For the description of a 4q state $(QQ\bar{q}\bar{q})$, the wave function can be written as the following form

$$\Psi(4q) = \psi_{4q}(0s^4)[(QQ)_{S_1,C_1}^{I_1}(\bar{q}\bar{q})_{S_2,C_2}^{I_2} \eta_{S,C}].$$  \hspace{1cm} (15)$$

where $S$ represents spin, $I$ represents isospin, and $C$ represents color. $\psi_{4q}(0s^4)$ is the orbital part and all the four quarks are in $(0s)$-wave state; $[(QQ)_{S_1,C_1}^{I_1}(\bar{q}\bar{q})_{S_2,C_2}^{I_2} \eta_{S,C}]$ is the flavor-spin-color part.

Since the wave function of $(QQ)_{S_1,C_1}^{I_1}$ and $(\bar{q}\bar{q})_{S_2,C_2}^{I_2}$ pairs should be antisymmetric \cite{14}, the possible configurations of $QQ\bar{q}\bar{q}$ are read as follows,

$$\Psi_A = \psi_{4q}(0s^4)[(QQ)_{0,6'}^{0}(\bar{n}\bar{n})_{1,6'}^{0}].$$  \hspace{1cm} (16)

$$\Psi_B = \psi_{4q}(0s^4)[(QQ)_{0,6'}^{0}(\bar{n}\bar{n})_{0,6'}^{1}].$$  \hspace{1cm} (17)

$$\Psi_C = \psi_{4q}(0s^4)[(QQ)_{1,3'}^{0}(\bar{n}\bar{n})_{0,3'}^{0}]_{1,1'}.$$  \hspace{1cm} (18)

$$\Psi_{D_j} = \psi_{4q}(0s^4)[(QQ)_{1,3'}^{0}(\bar{n}\bar{n})_{1,3'}^{1}]_{J,1'}. \hspace{1cm} (J = 0, 1, 2).$$  \hspace{1cm} (19)

$$\Psi_E = \psi_{4q}(0s^4)[(QQ)_{0,6'}^{0}(\bar{s}\bar{s})_{0,6'}^{0}].$$  \hspace{1cm} (20)

$$\Psi_{F_j} = \psi_{4q}(0s^4)[(QQ)_{1,3'}^{0}(\bar{s}\bar{s})_{1,3'}^{0}]_{J,1'}. \hspace{1cm} (J = 0, 1, 2).$$  \hspace{1cm} (21)
Thus for different quantum numbers \((J^P; I)\), the configurations of \(QQ\bar{q}\bar{q}\) states can be written as

\[
|0^+; 0\rangle = \Psi_E \text{ and } \Psi_{F_0},
\]

\[
|0^+; 1\rangle = \Psi_B \text{ and } \Psi_{D_0},
\]

\[
|1^+; 0\rangle = \begin{cases} 
\Psi_A \text{ and } \Psi_C \\
\Psi_{F_1},
\end{cases}
\]

\[
|1^+; 1\rangle = \Psi_{D_1},
\]

\[
|2^+; 0\rangle = \Psi_{F_2},
\]

\[
|2^+; 1\rangle = \Psi_{D_2}.
\]

We solve the Schrödinger equation of the 4q system by using the variation method. The trail wave function is taken as an expression of the 4q states with several different harmonic oscillator frequencies \(\omega_i\),

\[
\psi_{4q}(0s^4) = \sum_i \alpha_i \phi_{4q}(b_i),
\]

where \(b_i^2 = \frac{1}{m\omega_i}\). Then the energies of these states can be obtained. For the 4q states with the same \((J^P; I)\), the configuration mixture has been considered in our calculation.

### III. RESULTS AND DISCUSSIONS

4q state will be stable under the strong interaction if their total energy lies below all the thresholds of the possible and allowed two-meson decay channels. Therefore, we use the quantity

\[
\Delta E = E(QQ\bar{q}\bar{q}) - E_{m_1}(Q\bar{q}) - E_{m_2}(Q\bar{q})
\]

(29)

to discriminate the stable 4q states.

We calculated the energies of the 4q states with the quantum numbers: \((J^P; I) = (0^+; 0), (0^+; 1), (1^+; 0), (1^+; 1), (2^+; 0), \text{ and } (2^+; 1)\). The results of \(cc\bar{q}\bar{q}\) and \(bb\bar{q}\bar{q}\) are listed in table III and IV, respectively. Our calculation predicts one bound state for the \(bb\bar{n}\bar{n}\) system with \((J^P; I) = (1^+; 0)\).
and no bound state for the $cc\bar{q}q$ system, both of which agree with the conclusion that for a ratio $M/m \geq 15$ ($M$ is the mass of the heavy quark $c$ or $b$, $m$ is the mass of light quark $n$ or $s$), a collective bound state appears, stable against spontaneous dissociation [15]. Meanwhile, we notice that the states $cc\bar{n}n$ and $bb\bar{n}n$ with $(J^P; I) = (1^+; 0)$ have the lowest energy than other $QQ\bar{q}q$ states. For the $(J^P; I) = (1^+; 0)$ state, we calculated the energies of the configurations $\Psi_A$ and $\Psi_C$ (Eqs. (16) and (18)) and also the configuration mixing between $\Psi_A$ and $\Psi_C$. The results show that the energy of the configuration $\Psi_C$ is lower and the mixture effect between $\Psi_A$ and $\Psi_C$ is very small, thus the component $\Psi_A$ can be neglected and component $[(QQ)_{1,3'}(\bar{n}\bar{n})_{0,3'}^0]_{1,1'}$ is dominate. In $\Psi_C$, the light anti-quark pair $(\bar{n}\bar{n})_{0,3'}$ contributes a strong attractive color magnetic force (CMF) which upholds Jaffe’s di-quark model [16], at the same time the pseudoscalar meson exchange interaction of $(\bar{n}\bar{n})_{0,3'}$ is also strongly attractive, thus $(\bar{n}\bar{n})_{0,3'}$ can be sufficiently attractive for forming a possible bound $4q$ state. On the other hand, in the state $[(QQ)_{1,3'}(\bar{n}\bar{n})_{0,3'}^0]_{1,1'}$, the heavy quark pair $(QQ)_{1,3'}$ contributes a repulsive CMF. When $Q = b$, the repulsive CMF is much weaker than that of the attractive force contributed by the light anti-quark pair component $(\bar{n}\bar{n})_{0,3'}$, because of the large heavy quark mass. Yet when $Q = c$, the repulsive CMF is not weak enough to counteract the attractive force. That is why for the same $(J^P; I) = (1^+; 0)$ state, a bound state in $bb\bar{q}q$ system can be found while there is no bound state in $cc\bar{q}q$ system.
Since CMF and the pseudoscalar meson exchange interaction can contribute enough attractive force to form a bound 4q state, it is interesting to find whether the existence of the bound state depends on the contribution of CQI or not. Following the above procedure, the parameters without considering CQI should be fixed firstly. Here we briefly give the procedure for the parameter determination. The one-gluon-exchange coupling constant $g_u$ is determined by the mass split between $N$ and $\Delta$, and the confinement strengths ($a_{uu}, a_{uu}^0$) are fixed by the masses of $N$ and $\Delta$. ($a_{cu}, a_{cu}^0$) are fixed by the masses of $D$ and $D^*$, while ($a_{bu}, a_{bu}^0$) are fixed by the masses of $B$ and $B^*$. Other parameters are taken from previous work [13]. The parameters without considering CQI are shown in Table V, and the theoretical results for the masses of $N$, $\Delta$ and $Q\bar{q}$ mesons without considering CQI are given in Table VI.

TABLE V: Model parameters without CQI. The quark masses are as follows: $m_{u,d} = 313MeV$, $m_c = 1430MeV$, $m_b = 4717MeV$.

| Parameter | Value |
|-----------|-------|
| $g_u$ | 0.945 |
| $a_{uu}^0$ (MeV) | -181.68 |
| $a_{uu}$ (MeV) | 187.188 |
| $a_{cu}^0$ (MeV) | -153.5 |
| $a_{cu}$ (MeV) | 275 |
| $a_{bu}^0$ (MeV) | -138.8 |
| $a_{bu}$ (MeV) | 275 |

By using the variation method in section II.C, the masses of $QQ\bar{q}\bar{q}$ states can be obtained. Here we only show the numerical results for the states $cc\bar{c}\bar{n}$ and $bb\bar{c}\bar{n}$ with ($J^P; I$) = $(1^+; 0)$ in Table VII. From Table VII, we can see that without considering CQI, the configuration $bb\bar{c}\bar{n}$ with ($J^P; I$) = $(1^+; 0)$ is still a bound state and no bound state for $cc\bar{c}\bar{n}$ configuration. Meanwhile,

TABLE VI: The masses (MeV) of $P$, $\Delta$ and $Q\bar{q}$ mesons. Experimental data are taken from PDG.

| Mass | $P$ | $\Delta$ | $D$ | $D^*$ | $B$ | $B^*$ |
|------|-----|---------|-----|------|-----|------|
| Exp. | 939 | 1232    | 1967.7 | 2008.9 | 5279.2 | 5325 |
| Theor. | 939 | 1237 | 1879 | 2009 | 5287 | 5321 |
it should be noticed that this bound state is not as strong as that of the case with chiral quark interactions.

In order to see the differences between these two cases, we calculate the contribution of each part for the configuration $bb\bar{n}\bar{n}$ with $(J^P; I) = (1^+; 0)$. We find that without considering CQI, the strength of OGE interaction increases and it contributes enough attractive force to form a bound state, thus without CQI, $bb\bar{n}\bar{n}$ with $(J^P; I) = (1^+; 0)$ can also be bound. In comparison, when considering CQI, the OGE interaction and meson-exchange interaction both contribute attractive forces, and the contribution of the pseudoscalar meson exchange interaction is more favored to form a bound state. That is why for the configuration $bb\bar{n}\bar{n}$ with $(J^P; I) = (1^+; 0)$, the bound state considering CQI is stronger than without considering CQI.

IV. SUMMARY

In this work, we study the masses of $QQ\bar{q}\bar{q}$ heavy-light 4q system in the CSQ model, and try to see the possibilities of the existence of bound states. Our calculation shows the existence of only one bound four-quark state with $(J^P; I) = (1^+; 0)$ in the bottom sector and no bound state for the charm sector. Besides, by comparing the masses of the same four-quark state while considering CQI and without CQI, we find a similar result that $bb\bar{n}\bar{n}$ with $(J^P; I) = (1^+; 0)$ is bound but this binding energy is relatively weak.
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