Mass spectra of four quark states in hidden charm sector

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Masses of the low lying four quark states in the hidden charm sector (cq\bar{q}; q \in u, d) are calculated within the framework of a non-relativistic quark model. The four body system is considered as two two-body systems such as diquark-diantiquark (q_1q_2 - \bar{q}_3\bar{q}_4) tetraquark states and di-mesonic (q_1\bar{q}_2 - q_3\bar{q}_4) molecular states. Here, Cornell type potential has been used for describing the two body interactions among q - q, q - \bar{q}, \bar{q} - \bar{q}, q \bar{q} - q \bar{q}, q \bar{q} - q \bar{q}, with appropriate string tensions. Our present analysis suggests the following exotic states, X(3823), Z_c(3900), X(3915), X(3940), Z_c(4025), \psi(4040), Z_c(4050) and X(4110) as di-mesonic molecular states, while Z_c(3885) and Y(4140) as the diquark-diantiquark tetraquark state. We have been able to assign the J^{PC} values for many of the recently observed exotic states according to their structure.

I. INTRODUCTION

Over the past decade, the family of Exotic states has become more and more abundant due to the experimental development. It is a topic of current interest full of opportunities and challenges for theorists as well as experimentalists to reveal the internal mechanisms originating from these novel and complicated states. Many exotic states in the charm sector with \textit{c}\bar{c} content have been discovered by Belle and BESIII and others which provide challenges to theorists studying hadron spectroscopy. With the experimental progress, theorists have paid more attention to these observations by proposing different explanations. Due to the asymptotic property of the QCD, study of the hadron physics have to concern about the nonperturbative effect which is difficult in quantum field theory. It has been realized early on that quark models and QCD sustain a much richer pattern of different multi-quark and/or color network configurations, beyond the "non-exotic" standard q\bar{q} mesons and qqq baryons. There are growing evidences for the existence of exotic mesons containing both heavy and light quark-antiquark pairs i.e. c\bar{c}q\bar{q}. In the past few years, the experimental observations of so many X, Y and Z states have stimulated the study of exotic states greatly as they have induced a pre Gell- Mann like situation in our knowledge of the hadron spectroscopy.

Definite conclusions have not yet been reached about the internal structure of newly observed four quark systems. Models to accommodate the exotic states have been proposed over the last decades. Different attempts have been made for the interpretation of the internal structure of the exotic hadronic states of four quark system. These four quark state can in principle be composed of diquark-diantiquark (a tetraquark), a loosely bound state of two mesons (a molecular state), glueballs or q\bar{q} pair with gluons (hybrids). Here, we confine ourselves to a model of four quark exotic states with a diquark-diantiquark model and a di-mesonic molecular state. The study of such structures is important from the point of view of understanding interaction among hadrons at different energy scales related to their formation of bound states as well as decay processes. These interactions provide useful information to study fundamental problems of QCD such as color confinement. The first papers suggesting the existence of tetraquark configurations were given by way of the MIT bag model with color spin interaction. In the beginning, light flavor tetraquark states were predicted. Later on, Weinstein and Isgur extended this tetraquark picture into a variety of quark models. This means that tetraquarks with heavy quarks can also exist. In the last year, few exotic mesons in the charm sector were discovered. These exotic states can be the candidates for the tetraquark states. Moreover, these states can be dimesonic bound molecular states as was predicted more than twenty years ago. The calculation for the tetraquark state c\bar{c}q\bar{q} which was performed by Dias suggests that the newly discovered Z_c(3900) can be a tetraquark state. Another interesting possible interpretation of the Z_c(3900) proposed by Hong et al., is that it can be a molecular state of 1/(\sqrt{2})(D\bar{D}^* + D^*\bar{D}) resulting from the binding of two meson molecules. Thus, its interpretation as a tetraquark state or a di-mesonic molecular state remains unresolved. Here, we briefly review recent results for the masses of heavy tetraquarks in the framework of a non-relativistic quark model based on the potential approach. We use the diquark-diantiquark and the Di-meson approximation to reduce a complicated four-body problem to the subsequent more simple two two-body problems.

II. THEORETICAL FRAMEWORK

In this paper we shall take a different path and investigate different ways in which the experimental data can be reproduced. There are many methods to estimate the mass of a hadron, among which phenomenological potential model is a fairly reliable one.

Non-relativistic interaction potential we have used here is the Cornell potential consists of a central term V(r) which is being just a sum of the Coulomb(vector) and
linear confining(scalar) parts given by

\[ V(r) = V_V + V_S = k_s \frac{\sigma r}{r} + \sigma r \] (1)

\[ k_s = -4/3 \text{ for } q\bar{q} \]
\[ = -2/3 \text{ for } qq \text{ or } \bar{q}\bar{q} \] (2)

Different degenerate exotic states can be calculated by including spin-dependent part of the usual one gluon exchange potential discussed above but with different two-body system and the same form of the two-body nonrelativistic models of the hydrogen atom. In both to assume that they move in a static potential, much like quarks that comprise the exotic state is nonrelativistic

In this case, one uses the fact that the motion of the four quark state as a di-mesonic molecular state.

II.1. Four quark state as Diquark-Diantiquark system (Tetraquark)

We have calculated the masses of heavy tetraquarks considered as the bound states of a heavy-light diquark and diantiquark. We discuss the spectra in the framework of a non-relativistic hamiltonian including chromo-magnetic spin-spin interactions between the quarks (antiquarks) within a diquark(di-antiquark). We calculate the masses of ground state as well as excited heavy tetraquarks with hidden charm diquark-diantiquark (cq − \bar{c}\bar{q}) picture. The mass of diquark (diantiquark) is obtained by numerically solving the Schrödinger equation with the potential given by Eq.(1) and incorporating the spin interaction described by equation (3) perturbatively. Further, the same procedure is adopted to compute the binding energy of the diquark-diantiquark bound system but with a different potential strength \( \sigma \) of Eq.(1)

In the diquark-diantiquark model, the masses of the diquark/diantiquark system and tetraquark states are given by:

\[ M_d = m_{q_1} + m_{q_2} + E_d + \langle V_{SD} \rangle \] (7)

\[ m_d = m_{\bar{q}_3} + m_{\bar{q}_4} + E_{\bar{d}} + \langle V_{SD} \rangle \] (8)

\[ M_{d-\bar{d}} = m_d + m_{\bar{d}} + E_{d\bar{d}} + \langle V_{SD} \rangle \] (9)

Where \( m_{1,2} \) and \( m_{3,4} \) represents the masses of quarks, antiquarks respectively. In the present paper, \( d \) and \( \bar{d} \) represents diquark and diantiquark respectively. While \( E_d, E_{\bar{d}}, E_{d\bar{d}} \) are the energy eigen values of the diquark, diantiquark and diquark-diantiquark system respectively. The spin-dependent potential \( V_{SD} \) part of the hamiltonian described by Eq.(3) has been treated perturbatively.

II.2. Four quark state as di-mesonic molecular system

In the past thirty five years, theorists have been studying whether two charmed mesons can be bound into a molecular state, because the presence of the heavy quarks lowers the kinetic energy while the interaction between two light quarks could still provide a strong enough attraction. Voloshin and Okun studied the interaction between a pair of charmed mesons and proposed the possibilities of the molecular states involving charmed quarks \[ \bar{c}\bar{q} \]. In the present molecular framework, masses of meson molecules are determined by employing Coulomb plus Linear potential between heavy quark and light antiquark and vice-versa. Here, we have taken various combinations of spin and orbital angular momentum. We have considered the total spin \( J_1 \) and \( J_2 \) of the two mesons as spins \( S_1 \) and \( S_2 \) and these spins couple to \( J_{12} \) together
TABLE I. Mass spectra in tetraquark picture for $L_d=0$ and $L_{d\bar{d}}=0$ (In GeV).

| $S_d$ | $L_d$ | $S_{d\bar{d}}$ | $L_{d\bar{d}}$ | $J_d$ | $J_{d\bar{d}}$ | $J$ | $P$ | $C$ | $2S+1$ | $X_J$ | $M_{cw}$ | $\langle V_{SS} \rangle$ | $\langle V_{LS} \rangle$ | $\langle V_T \rangle$ | Mass |
|-------|-------|----------------|---------------|------|---------------|-----|-----|-----|---------|-------|----------|----------------|----------------|----------------|------|
| 0     | 0     | 0              | 0             | 0    | 0             | 0   | 0   | 0   | 0       | 0     | 0        | 0              | 0              | 0              | 3.906 |
| 1     | 0     | 0              | 1             | 0    | 1             | 1   | -   | -   | 1       | 3.910 | 0        | 0              | 0              | 0              | 3.910 |
| 1     | 0     | 0              | 1             | 1    | 0             | 0   | 0   | 0   | 0       | 0     | 0        | 0              | 0              | 0              | 3.914 |
| 2     | 2     | 2              | 2             | 2    | 2             | 2   | +   | +   | 2       | 4.156 | 0        | 0              | 0              | 0              | 4.156 |

$M_{cw}$-center of weight mass

TABLE II. Mass spectra in tetraquark picture for $L_d=1$ and $L_{d\bar{d}}=0$ (In GeV).

| $S_d$ | $L_d$ | $S_{d\bar{d}}$ | $L_{d\bar{d}}$ | $J_d$ | $J_{d\bar{d}}$ | $J$ | $P$ | $C$ | $2S+1$ | $X_J$ | $M_{cw}$ | $\langle V_{SS} \rangle$ | $\langle V_{LS} \rangle$ | $\langle V_T \rangle$ | Mass |
|-------|-------|----------------|---------------|------|---------------|-----|-----|-----|---------|-------|----------|----------------|----------------|----------------|------|
| 0     | 1     | 0              | 0             | 1    | 0             | 1   | -   | -   | 1       | 4.156 | 0        | 0              | 0              | 0              | 4.156 |
| 1     | 1     | 0              | 0             | 0    | 0             | 0   | -   | -   | 0       | 4.156 | 0        | 0              | 0              | 0              | 4.156 |
| 2     | 2     | 2              | 2             | 2    | 2             | 2   | +   | +   | 2       | 4.156 | 0        | 0              | 0              | 0              | 4.156 |
| 1     | 1     | 0              | 0             | 1    | 1             | 1   | -   | -   | 1       | 4.156 | 0        | 0              | 0              | 0              | 4.156 |
| 1     | 1     | 0              | 0             | 1    | 1             | 1   | -   | -   | 1       | 4.156 | 0        | 0              | 0              | 0              | 4.156 |

with relative orbital motion $L_{12}$ presents the total spin $J$ of the di-mesonic system.

In the di-mesonic picture, we consider the masses of the quark-antiquark states as

$$M_1 = m_{q_1} + m_{\bar{q}_2} + E_{q_1 \bar{q}_2}$$

(10)

$$M_2 = m_{q_3} + m_{\bar{q}_4} + E_{q_3 \bar{q}_4}$$

(11)

to describe the two mesons and the di-mesonic molecular mass as

$$M = M_1 + M_2 + E_{M_{12}} + \langle V_{SD} \rangle$$

(12)

Where $M_1$, $M_2$ are two meson masses. Here, $E_{q_1 \bar{q}_2}$, $E_{q_3 \bar{q}_4}$ represent the binding energy of the quark-antiquark constituting the mesons and $E_{M_{12}}$ is the binding energy of the di-mesonic system. The interaction between the di-mesons are also assumed to be of the same form as given by Eq.(1) except that the string tension is assumed to be different.

III. RESULTS AND DISCUSSIONS

The masses of the low lying hidden charm four quarks system as diquark-diantiquark (tetraquark) state as well as di-mesonic molecular states have been computed. For four quark system ($cq\bar{q}_q; q \in u,d$), we have used: $m_u = m_d = 0.323$ GeV, $m_c = 1.486$ GeV and the string tension (potential parameter) $\sigma = 0.030$ GeV$^2$ for diquark-diantiquark interaction and 0.018 GeV$^2$.
for di-meson interaction. The string tension $\sigma$ for intra $q - q$, $q - \bar{q}$ and $\bar{q} - \bar{q}$ are assumed as having same interaction strength 0.015 GeV$^2$. Various combinations of the orbital and spin excitations have been considered. The results obtained in both the cases are tabulated in Tables 1 to 5. Selected states for known experimental exotic states are identified and their $J^{PC}$ values are assigned. Their interpretations are shown in Table 6 as the summary of the present study. Finally, we find it interesting to compare our results with the newly discovered exotic charm states. For example, soon after the $Z_c^+(3900)$ observation, the BES-III reported the observation of three more charge states: $Z_c^+(4025)$, $Z_c^+(4020)$, and $Z_c^+(3885)$. Here, we have been able to identify the $X(3823), Z_c(3900), X(3915), X(3940), Z_c(4025), X(4160)$ and $\psi(4040)$ resonances as di-meson molecular states, while $Y(4140)$ as diquark-diantiquark tetraquark state. Though the parity of states $X(3823)$ and $Z_c(3900)$ $(J=1$ and $C=-1)$ is experimentally unknown, our predictions suggest $Z_c(3900)$ as $1^{++}$ state while $X(3823)$ state as $1^{--}$. There is a still question regarding the structure of two states $Z_c(3900)$ and $Z_c(3885)$ that whether they are two different states or the same state. Recently, BES-III group reported that $Z_c(3885)$ may have $1^{-}$ quantum number and if so then it can be in a S wave or and a D wave. Our present study predicts $Z_c(3885)$ as a diquark-diantiquark tetraquark state with $J^{PC} = 1^{+-}$. Although the $J^{P}$ quantum numbers of $Z_c(4025)$ still remain to be determined experimentally, it is assumed to have spin parity $J^{P} = 1^{+}$ by BES-III group. This assignment for $Z_c(4025)$ is in agreement with the interpretation of this state to be dimesonic molecular state having $J^{PC} = 1^{+-}$. Present identification of $\psi(4040)$ as a di-meson molecular state with $J^{PC} = 1^{+-}$ is in accordance with what was suggested by De Rujula, Georgi and Glashow. The state $Z_1(4050)$ is close to the interpretations of both diquark-diantiquark system and di-meson molecular state having same positive parity but with different J values. Thus, state $Z_1(4050)$ still needs more experimental confirmation of its J value. From our present prediction for $Z_1(4050)$, we suggest
TABLE IV. Mass spectra in molecular picture for \( L_1=1 \) and \( L_2=0 \) (In GeV).

| \( S_1 \) | \( L_1 \) | \( S_2 \) | \( L_2 \) | \( J_1 \) | \( J_2 \) | \( J_{12} \) | \( J \) | \( J^{PC} \) | \( 2S+1 \) | \( X \) | \( M_{\text{uw}} \) | \( \langle V_{SS} \rangle \) | \( \langle V_{LS} \rangle \) | \( \langle V_T \rangle \) | Mass |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|-------|-------|-------|-----|
| 0     | 1   | 0   | 0   | 1   | 0   | 1   | 1   | 1^-  | 3S1 |  3.927 | 0   | 0   | 0   | 3.927 |
|       | 0   | 0+  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 1     | 1   | 1   | 1^-  |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 2     | 2   | 2^+ |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
|       | 1   | 1^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 2     | 2   | 2^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 3     | 3   | 3^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 1     | 1   | 0   | 0   | 1   | 0   | 1   | 1   | 1^-  | 3S1 |  3.927 | 0   | 0   | 0   | 3.927 |
|       | 0   | 0+  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 1     | 1   | 0   | 1   | 1^-  | 5S2 |  3.927 | 0.034 | 0 | 0   | 0   | 3.927 |
|       | 2   | 2   | 2^+ |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
|       | 1   | 1^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 2     | 1   | 2   | 2^-  |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 3     | 3   | 3^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 0     | 1   | 1   | 1   | 0   | 0   | 0   | 1   | 0   | 1   | 0   | 1   | 0   | 1   | 0   | 1   | 0   | 3.858 |
|       | 1   | 1   | 1   | 1   | 1   | 1   | 1^-  |     |     |     |     |     |     |     |     |     |     | 4.023 |
| 2     | 2   | 2^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
|       | 1   | 1^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 2     | 1   | 2   | 2^-  |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 3     | 3   | 3^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 1     | 1   | 0   | 1   | 1   | 1   | 1   | 1^-  | 3P1 |  4.036 | -0.0009 | 0   | 0   | 0.0094 | 4.026 |
|       | 0   | 1^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 1     | 1   | 1   | 1^-  |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 2     | 2   | 2^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
|       | 1   | 1^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 2     | 1   | 2   | 2^-  |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 3     | 3   | 3^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 2     | 1   | 1   | 1   | 0   | 0   | 1   | 1   | 0   | 1   | 0   | 1   | 0   | 1   | 0   | 1   | 0   | 3.999 |
|       | 2   | 2^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
|       | 1   | 1^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 2     | 1   | 2   | 2^-  |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 3     | 3   | 3^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
| 3     | 2   | 2^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
|       | 3   | 3^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |
|       | 4   | 4^-  |     |     |     |     |     |     |     |     |     |     |       |       |       |       |     |

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TABLE V. Mass spectra in molecular picture for \(L_1=1\) and \(L_2=1\) (In GeV).

| \(S_1\) | \(L_1\) | \(S_2\) | \(L_2\) | \(J_1\) | \(J_2\) | \(J_{12}\) | \(J^{PC}\) | \(2S+1J\) | \(M_{cw}\) | \(\langle V_{SS}\rangle\) | \(\langle V_{LS}\rangle\) | \(\langle V_T\rangle\) | Mass |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | -0.076 | 0 | 0 | 3.960 |
| 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 3.998 |
| 2 | 2 | 2 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 4.075 |
| 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | -0.0093 | 4.133 |
| 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | -0.0022 | -0.018 | 4.122 |
| 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | -0.0005 | -0.0011 | -0.0046 | 4.137 |
| 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0011 | -0.010 | 4.134 |
| 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | -0.0033 | -0.029 | 4.112 |
| 3 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0005 | -0.0011 | 0.010 | 4.153 |
| 3 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0012 | -0.014 | 4.131 |

that its spin parity is \(4^{++}/1^{+-}\) if it is a tetraquark state or \(2^{++}/3^{++}\) as a molecular state. Up to now, the interpretation of the state \(X(4160)\) and \(X(3915)\) is still unclear. The state \(X(3915)\) clearly has \(C=+\), but \(J^P\) remains to be determined. T Branz et al. [15] predicted this state as a molecular state. But we have four possibilities for this state \(X(3915)\): it can be either one of the \(0^{++}/2^{++}/3^{++}\) molecular state or \(1^{+-}\) tetraquark state. If we follow experimental clue for \(C=+\), then it could be a \(0^{++}/2^{++}\) molecular state. For \(X(4160)\), we have predicted that it can be a either \(2^{+-}\) molecular state or \(1^{++}/1^{+-}\) tetraquark state. For \(Y(4140)\), we are having four different possible states \(0^{-+}, 1^{--}, 2^{+-}, 3^{---}\) in the energy range \(4.136 - 4.146\) GeV as diquark - diantiquark states while only \(1^{++}\) state in the di-mesonic molecular model. As per \(C=+1\) assignment provided by the experiment, then it can be interpreted as a molecular state only if its parity is positive. However, its experimental confirmation is awaited. Finally, We believe that strong experimental efforts aimed at determining the spin parity of the exotic states are required for understanding the status of many of the newly observed exotic states.

IV. ACKNOWLEDGMENTS

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### TABLE VI. Comparison of some predicted states with experimental results (In GeV)

| State  | Present Mass | $J^{PC}$ | $2S+1X_J$ | Model | Experimental Mass | $J^{PC}$ |
|--------|--------------|----------|-----------|-------|-------------------|----------|
| $X(3823)$ | $3.823\ 1^{--}$ | $^{3}S_1$ | Mole | $3.823\pm0.0019$ | $^{1+}_{?}$ |
| $Z_c(3885)$ | $3.882\ 1^{++}$ | $^{3}S_1$ | TQ | $3.883^{+0.0015}_{-0.0014}$ | $^{1+}_{?}$ |
| $Z_c(3900)$ | $3.897\ 1^{++}$ | $^{5}P_1$ | Mole | $3.899^{+0.0036}_{-0.0040}$ | $^{1+}_{?}$ |
| $X(3915)$ | $3.917\ 3^{++}$ | $^{5}P_3$ | Mole | $3.917\pm0.0027$ | $0/2^{++}$ |
| $X(3940)$ | $3.935\ 1^{--}$ | $^{1}P_3$ | Mole | $3.942^{+0.0009}_{-0.0008}$ | $^{1+}_{?}$ |
| $Y(4008)$ | $3.998\ 1^{--}$ | $^{3}S_1$ | Mole | $4.008^{+0.121}_{-0.049}$ | $^{1+}_{-0.0}$ |
| $Z_c(4025)$ | $4.026\ 0^{++}$ | $^{3}P_0$ | Mole | $4.026^{+0.0026}_{-0.0037}$ | $^{1+}_{?}$ |
| $Y(4140)$ | $4.136\ 1^{--}$ | $^{3}P_0$ | TQ | $4.143\pm0.003$ | $^{1+}_{+}$ |
| $X(4160)$ | $4.153\ 2^{++}$ | $^{5}P_2$ | Mole | $4.156^{+0.029}_{-0.025}$ | $^{1+}_{+}$ |

* Mole- molecular picture.
* [TQ]- tetraquark picture.

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