Possible pentaquarks with heavy quarks

Hongxia Huang · Chengrong Deng · Jialun Ping · Fan Wang

Abstract Inspired by the discovery of two pentaquarks \( P_c(4380) \) and \( P_c(4450) \) at the LHCb detector, we study possible hidden-charm molecular pentaquarks in the framework of quark delocalization color screening model. Our results suggest that both \( N\eta_c \) with \( IJ^P = \frac{1}{2}^+ \) and \( NJ/\psi \) with \( IJ^P = \frac{1}{2}^+ \) are bounded by channels coupling. However, \( NJ/\psi \) with \( IJ^P = \frac{1}{2}^+ \) may be a resonance state in the \( D^- \) wave \( N\eta_c \) scattering process. Moreover, \( P_c(4380) \) can be explained as the molecular pentaquark of \( \Sigma^*_c D \) with quantum numbers \( IJ^P = \frac{1}{2}^+ \). The state \( \Sigma^*_c D^* \) with \( IJ^P = \frac{1}{2}^+ \) is a resonance, it may not be a good candidate of the observed \( P_c(4380) \) because of the opposite parity of the state to \( P_c(4380) \), although the mass of the state is not far from the experimental value. In addition, the calculation is extended to the hidden-bottom pentaquarks, the similar properties as that of hidden-charm pentaquarks system are obtained.

PACS 13.75.Cs · 12.39.Pn · 12.39.Jh

1 Introduction

Multiquark states were studied even before the advent of quantum chromodynamics (QCD). The development of QCD accelerated multiquark study because it is natural in QCD that there should be multiquark states, glueballs and quark-gluon hybrids. After more than 40 years of quark model study, the idea about baryon and meson is about to go beyond the naive picture: \( q^3 \) baryon and \( q\bar{q} \) meson. The proton spin puzzle could be explained by introducing the \( q^3 q\bar{q} \) component in the quark model \([1]\). In order to understand the baryon spectroscopy better, the five-quark component of proton was proposed \([2]\). The baryon resonance is certainly coupled to the meson-baryon scattering state and should be studied by coupling the \( q^3 \) with \( q^3 q\bar{q} \) scattering channel in a quark model approach. Although the strange pentaquark state \( \Theta^+ \) claimed by experimental groups thirteen years ago might be questionable (LEPS collaboration insists on the existence of pentaquark \( \Theta^+ \) \([3]\)) and the multi-quark states might be hard to be identified, the multi-quark study is indispensable for understanding the low energy QCD, because the multi-quark states can provide information unavailable in \( q\bar{q} \) meson and \( q^3 \) baryon, especially the property of hidden color structure.

In the past decade, many near-threshold charmonium-like states have been observed at Belle, BaBar, BESIII, and LHCb, triggering lots of studies on the molecule-like hadrons containing heavy quarks. In the heavy quark sector, the large masses of the heavy quarks reduce the kinetic of the system, which makes it easier to form bound states or resonances. So the heavy quarks play an important role to stabilize the multiquark systems. There were many theoretical studies of hidden-charm pentaquarks \([4,5,6,7]\), especially the prediction of nar-
row N* and Λ* resonances with hidden charm above 4 GeV by using the coupled-channel unitary approach [4], and the systematicat investigation of possible hidden-charm molecular baryons with components of an anticharmed meson and a charmed baryon within the one boson exchange model [5].

Very recently, the LHCb Collaboration observed two pentaquark-charmonium states in the $J/\psi p$ invariant mass spectrum of $A_b^0 \rightarrow J/\psi K^- p$ [8]. One is $P_c(4380)$ with a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 66$ MeV, and another is $P_c(4450)$ with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred $J^P$ assignments are of opposite parity, with one state having spin $\frac{1}{2}^-$ and the other $\frac{3}{2}^-$. Then, a lot of theoretical work have been done to explain these two states. In Ref. [9], the current experimental progress and theoretical interpretations of the states were reviewed. R. Chen et al. [10] interpreted these two hidden-charm states as the loosely bound $\Sigma_c(2455)D^*$ and $\Sigma_c^*(2520)D^*$ molecular states by using the boson exchange model, and gave the spin parity $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively. While in Ref. [11], a Bethe-Salpeter equation approach was used to studied the $D\Sigma_c^*$ and $D^*\Sigma_c$ interactions, and then $P_c(4380)$ and $P_c(4450)$ were identified as $D\Sigma_c^*$ and $D^*\Sigma_c$ molecular states with the spin parity $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$, respectively. A QCD sum rule investigation was performed, by which the $P_c(4380)$ was suggested as a $D^*\Sigma_c$ hidden-charm pentaquark with $J^P = \frac{1}{2}^-$ and the $P_c(4450)$ was proposed as a mixed hidden-charm pentaquark of $D^*\Lambda_c$ and $D^*\Sigma_c$ with $J^P = \frac{5}{2}^+$ [12]. Also a coupled-channel calculation was performed to analyze the $A_b^0 \rightarrow J/\psi K^- p$ reaction and gave support to a $J^P = \frac{3}{2}^-$ assignment to the $P_c(4450)$ and to its nature as a molecular state mostly made of $D^*\Sigma_c$ and $D^*\Sigma_c^*$ [13]. In Ref. [14], Meißner and Oller suggested that the $P_c(4450)$ was almost entirely a $\chi_{c1p}$ resonance, coupling much more strongly to this channel than to $J/\psi p$. Kubarovskv and Voloshin [15] showed that the observed $P_c$ resonances are composites of $J/\psi$ and excited nucleon states with the quantum numbers of $N(1440)$ and $N(1520)$ within a simple "baryocharmonium" model. Moreover, some people proposed various rescattering mechanisms to show that the $P_c(4450)$ state might arise from the kinematical effect [16]17]. Besides, Burns [18] explored the phenomenology of the $P_c(4380)$ and $P_c(4450)$ states, and their possible partners. Several intriguing similarities were also discussed in Ref. [18], which suggested that the $P_c(4450)$ was related to the $X(3872)$ meson. Thus, different models may give different descriptions for the resonance structures. Clearly the quark level study of these two pentaquark-charmonium states is interesting and necessary.

It is well known that the nuclear force (the interaction between nucleons) are qualitative similar to the molecular force (the interaction between atoms). This molecular model of nuclear forces, quark delocalization color screening model (QDCSM) [19], has been developed and extensively studied. In this model, quarks confined in one nucleon are allowed to delocalize to a nearby nucleon and the confinement interaction between quarks in different baryon orbits is modified to include a color screening factor. The latter is a model description of the hidden color channel coupling effect [20]. The delocalization parameter is determined by the dynamics of the interacting quark system, thus allows the quark system to choose the most favorable configuration through its own dynamics in a larger Hilbert space. The model gives a good description of nucleon-nucleon and hyperon-nucleon interactions and the properties of deuteron [21]. It is also employed to calculated the baryon-baryon scattering phase shifts and the dibaryon candidates in the framework of the resonating group method (RGM) [22][23].

In this work, the resonating-group method (RGM) is employed to study the possible hidden-charm molecular pentaquarks in QDCSM, and the channel-coupling effect are considered. Extension to the bottom case is straightforward and is also included in the present work. The structure of this paper is as follows. After the introduction, we present a brief introduction of the quark model used in section II. Section III devotes to the numerical results and discussions. The summary is shown in the last section.

2 The quark delocalization color screening model (QDCSM)

The detail of QDCSM used in the present work can be found in the references [19][20][21][22][23]. Here, we just present the salient features of the model. The model
The quark delocalization in QDCSM is realized by specifying the single particle orbital wave function of QDCSM as a linear combination of left and right Gaussian, the single particle orbital wave functions used in the ordinary quark cluster model,

\[
\psi_\alpha(s_i, \epsilon) = (\phi_\alpha(s_i) + e\phi_\alpha(-s_i))/N(\epsilon),
\]

\[
\psi_\beta(-s_i, \epsilon) = (\phi_\beta(-s_i) + e\phi_\beta(s_i))/N(\epsilon),
\]

\[
N(\epsilon) = \sqrt{1 + e^2 + 2e\epsilon e^{-\epsilon^2/4\epsilon^2}}.
\]

\[
\phi_\alpha(s_i) = \left(\frac{1}{\pi b^2}\right)^{3/4} e^{-\frac{1}{2\pi^2}(r_o - s_i)^2}. \tag{3}
\]

\[
\phi_\beta(-s_i) = \left(\frac{1}{\pi b^2}\right)^{3/4} e^{-\frac{1}{2\pi^2}(r_o + s_i)^2}.
\]

Here \(s_i, i = 1, 2, ..., n\) are the generating coordinates, which are introduced to expand the relative motion wavefunction \([20]\). The mixing parameter \(\epsilon(s_i)\) is not an adjusted one but determined variationally by the
dynamics of the multi-quark system itself. This assumption allows the multi-quark system to choose its favorable configuration in the interacting process. It has been used to explain the cross-over transition between hadron phase and quark-gluon plasma phase [27].

3 The results and discussions

Here, we investigate the possible hidden-charm molecular pentaquarks with $Y = 1$, $I = \frac{1}{2}$, $J^P = \frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{3}{2}^−$. For the negative parity states, we calculate the $S$-wave channels with spin $S = \frac{1}{2}$, $\frac{3}{2}$ and $\frac{5}{2}$, respectively; and for the positive parity states, we calculate the $P$-wave channels with spin $S = \frac{3}{2}$, and $\frac{5}{2}$, respectively. All the channels involved are listed in Table 3. In the present calculation, we only consider the hidden-charm molecular pentaquarks which consist of two $S$-wave hadrons. The channel coupling effects are also taken into account. However, we find there is no any bound state with the positive parity within our calculations. There may exist other molecular structures, which contain excited hadrons, such as $\chi_{c1}P$ resonance [13], $J/\psi N(1440)$, $J/\psi N(1520)$ [15] and so on, which are out of range of present calculation. In the following we only show the results of the negative parity states.

Table 3 The channels involved in the calculation.

| $S$ | $N\eta_c$ | $NJ/\psi$ | $\Lambda_c D$ | $\Lambda_c D^*$ | $\Sigma_c D$ | $\Sigma^*_c D$ | $\Sigma^*_c D^*$ |
|-----|-----------|-----------|-------------|---------------|-------------|---------------|---------------|
| $\frac{1}{2}$ | $\frac{3}{2}$ | $\frac{5}{2}$ |
| $\frac{3}{2}$ | $\frac{5}{2}$ |

First, the effective potentials between two hadrons are calculated and shown in Figs. 1-3, because an attractive potential is necessary for forming a bound state or resonance. The effective potential between two colorless clusters is defined as, $V(s) = E(s) - E(\infty)$, where $E(s)$ is the energy of the system at the separation $s$ of two clusters, which is obtained by the adiabatic approximation. As mentioned in Sec. II, a phenomenological color screening confinement potential is introduced in our model. For the multiquark systems with heavy quark, because no experimental data is available, so we take three different values of $\mu_{cc}$ ($\mu_{cc} = 0.01, 0.001, 0.0001$), to check the dependence of our results on this parameter.

For the $J^P = \frac{1}{2}^−$ system (Fig. 1), one sees that the potentials are all attractive for the channels $N\eta_c$, $NJ/\psi$, $\Sigma_c D$, $\Sigma_c D^*$ and $\Sigma^*_c D^*$. While for the channels $\Lambda_c D$ and $\Lambda_c D^*$, the potentials are repulsive, so no bound states or resonances can be formed in these two channels. However, the bound states or resonances are possible for other channels due to the attraction nature of the interaction between two hadrons. The attraction between $\Sigma^*_c$ and $D^*$ is the largest one, followed by that of the $\Sigma_c D^*$ channel, which is a little larger than that of the $\Sigma_c D$ channel. In addition, the attraction of $N\eta_c$ is almost the same with that of $NJ/\psi$, which is the smallest one during these five attractive channels. Comparing figures (a), (b) and (c) in Fig. 1, we also find that larger values of $\mu_{cc}$ give rise lower energy, although the variation is not very significant.

For the $J^P = \frac{3}{2}^−$ system (Fig. 2), similar results as that of $IJ^P = \frac{1}{2}^−$ system are obtained. The potentials are all attractive for channels $NJ/\psi$, $\Sigma_c D^*$, $\Sigma^*_c D$ and $\Sigma^*_c D^*$, while for the $\Lambda_c D^*$ channel, it is strongly repulsive. For the dependence of potentials on the different values of $\mu_{cc}$, the behavior is the same as that for the $J^P = \frac{1}{2}^−$ system.

For the $J^P = \frac{3}{2}^+$ system (Fig. 3), there is only one channel $\Sigma^*_c D^*$, the potentials are attractive, and the dependence of potentials on $\mu_{cc}$ are similar with that in $J^P = \frac{1}{2}^−$ and $J^P = \frac{3}{2}^−$ system.

In order to see whether or not there is any bound states or resonances, a dynamic calculation is needed. The resonating group method (RGM), described in more detail in Ref. [28], is used here. Expanding the relative motion wavefunction between two clusters in the RGM by gaussians, the integro-differential equation of RGM can be reduced to algebraic equation, the generalized eigen-equation. The energy of the system can be obtained by solving the eigen-equation. In the calculation, the baryon-meson separation ($|s_n|$) is taken to be less than 6 fm (to keep the matrix dimension manageably small).

For the $J^P = \frac{1}{2}^−$ system, the single channel calculation shows that both $\Lambda_c D$ and $\Lambda_c D^*$ are unbound, which agree with the repulsive nature of the interaction of these two channels. For the $N\eta_c$ and $NJ/\psi$ channels, the attractions are too weak to tie the two particles together, the calculation shows that they are also unbound. While, due to the stronger attractions, the obtained lowest energies of $\Sigma_c D$, $\Sigma_c D^*$ and $\Sigma^*_c D^*$ are below their corresponding thresholds. The binding energy of these three states are listed in Table 3, in which ‘ub’ means unbound. Here we should mention how we obtain the mass of a hidden-charm molecular pentaquark.

Generally, the mass of a molecular pentaquark can be written as $M^{the} = M_1^{the} + M_2^{the} + B$, where $M_1^{the}$ and $M_2^{the}$ stand for the theoretical masses of a charmed baryon and an anti-charmed meson respectively, and $B$
is the binding energy of this molecular state. In order to minimize the theoretical errors and to compare calculated results to the experimental data, we shift the mass of molecular pentaquark to \( M = M_1^{exp} + M_2^{exp} + B \), where the experimental values of charmed baryons and anti-charmed mesons are used. Taking the state \( J^P = \frac{1}{2}^+ \) \( \Sigma_cD \) as an example, the calculated mass of pentaquark is 4249 MeV, then the binding energy \( B \) is obtained by subtracting the theoretical masses of \( \Sigma_c \) and \( D \), \( 4249 - 2378 - 1890 = -19 \) (MeV). Adding the experimental masses of the hadrons, the mass of the pentaquark \( M = 2455 + 1864 + (-19) = 4300 \) (MeV) is arrived. In the present calculation, the resonance masses for \( \Sigma_cD \), \( \Sigma_cD^* \) and \( \Sigma_c^*D^* \) with \( J^P = \frac{1}{2}^- \) are 4300 ~ 4306 MeV, 4441 ~ 4444 MeV, and 4503 ~ 4506 MeV, respectively. These results are qualitatively similar with the conclusion of Ref. [4], in which they predicted two new \( N^* \) states (the \( \Sigma_cD \) molecular state \( N^*(4265) \) and the \( \Sigma_cD^* \) molecular state \( N^*(4415) \)) in the coupled-channel unitary approach. Meanwhile, the chiral quark model calculation also supported the existence of the \( S^- \) wave \( \Sigma_cD \) bound state [20].

At the same time, we also do a channel-coupling calculation. In this work, two kinds of channel-coupling are performed. The first one is the coupling of three closed channels \( (\Sigma_cD, \Sigma_cD^* \) and \( \Sigma_c^*D^*) \). The results, the lowest three eigen-energies and the percentages of coupling channels for the three eigen-states, are shown in Table 5. Taking the results of \( \mu_{cc} = 0.01 \) as an example, we can see that the main component of the lowest eigen-states is \( \Sigma_cD, \sim 95.5\% \), and the the energy is pushed down a little, compared with the single-channel
be coupled to other four open channels, is very weak. However, these three closed channels can small change of energy infer that the channel-coupling The large percentage of the main component and the olds of the corresponding main channels, and are stable against the change of the baryon-meson separations. The three eigen-energies are all smaller than the thresh-
hold of the corresponding main channel calculation, 4300 to 4296. The main component of the second lowest state is the \( \Sigma_c^*D^* \) with the percentage of 95.1%; and the main component of the third lowest state is the \( \Sigma_c^*D^* \) with the percentage of 94.4%. The three eigen-energies are all smaller than the thresholds of the corresponding main channels, and are stable against the change of the baryon-meson separations. The large percentage of the main component and the small change of energy infer that the channel-coupling is very weak. However, these three closed channels can be coupled to other four open channels, \( N\eta_c, NJ/\psi, \Lambda_cD \) and \( \Lambda_cD^* \). The results of this channel-coupling calculation are shown in Table 4. We obtain a stable state, the mass of which is lower than the threshold of \( N\eta_c \), and the main component of this state is \( N\eta_c \), with the percentage of 41.7%. This shows that the \( N\eta_c \) of \( J^P = \frac{3}{2}^- \) is bounded by channel-coupling in our quark model calculation, the energy is 3881 \( \sim \) 3884 (MeV). In addition, we also obtain several quasi-stable states, the masses of which are smaller than the thresholds of the corresponding main channels, but they fluctuate around the eigen-energies obtained in the three closed channel coupling calculation. For example, the energy of one quasi-stable state is 4296 MeV, it fluctuates around this energy with 2 MeV with the variation of the baryon-meson separation. To confirm whether the states of \( \Sigma_c^*D \), \( \Sigma_c^*D^* \) and \( \Sigma_c^*D^* \) can survive as resonance states after the full channel coupling, the study of the scattering processes of the open channels of \( N\eta_c, NJ/\psi, \Lambda_cD \) and \( \Lambda_cD^* \) is needed. This work is underway. From the fluctuation, we can estimate the partial decay widths of these states to \( N\eta_c, NJ/\psi, \Lambda_cD \) and \( \Lambda_cD^* \) around several MeVs, if they are resonances.

For the \( J^P = \frac{3}{2}^- \) system, the similar results with the case of \( J^P = \frac{1}{2}^- \) are obtained. The single channel calculation shows that \( NJ/\psi \) and \( \Lambda_cD^* \) are unbound, while \( \Sigma_c^*D^* \), \( \Sigma_c^*D \) and \( \Sigma_c^*D^* \) are all bound. The results are also listed in Table 5. These three states also exist when they are coupled together, the masses and the percentages of each channel of the lowest three eigen-states are shown in Table 6. We can see that the mass of the first eigen-state is about 4362 \( \sim \) 4368 MeV.

![Fig. 3 The potential of a single channel for the \( IJ^P = \frac{1}{2}^- \) system.](image)

| State     | \( \mu_{ec} \) | Mass (MeV) | State     | \( \mu_{ec} \) | Mass (MeV) |
|-----------|----------------|------------|-----------|----------------|------------|
| \( \Sigma_c^*D^* \) | 0.01 | 4362 | \( \Sigma_c^*D^* \) | 0.001 | 4368 |
| \( \Sigma_c^*D^* \) | 0.0001 | 4370 | \( \Sigma_c^*D^* \) | 0.0001 | 4372 |

Table 4 The binding energies and the masses (in MeV) of the hidden-charm molecular pentaquarks of \( I = \frac{1}{2}^- \).
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Table 5 The masses (in MeV) of the hidden-charm molecular pentaquarks of \( J^P = \frac{1}{2}^+ \) with three closed channels coupling and the percentages of each channel in the eigen-states.

| \( \mu_{cc} \) | 0.01 | 0.001 | 0.0001 | 0.01 | 0.001 | 0.0001 | 0.01 | 0.001 | 0.0001 |
|----------------|-------|-------|--------|-------|-------|--------|-------|-------|--------|
| \( M_{cc} \) | 4296  | 4437  | 4500   | 4300  | 4439  | 4501   | 4302  | 4440  | 4503   |
| \( \Sigma D \) | 95.5  | 2.9   | 4.8    | 96.0  | 2.5   | 4.5    | 96.7  | 2.1   | 4.2    |
| \( \Sigma c D^* \) | 3.6   | 95.1  | 0.8    | 3.2   | 95.3  | 1.0    | 2.7   | 95.7  | 1.1    |
| \( \Sigma c D^* \) | 2.9   | 94.4  |        | 0.8   | 92.2  | 4.4    | 0.6   | 2.2   | 94.7    |

Table 6 The masses (in MeV) of the hidden-charm molecular pentaquarks with all channels coupling and the percentages of each channel in the eigen-states.

| \( J^P = \frac{3}{2}^- \) | \( J^P = \frac{1}{2}^+ \) | \( J^P = \frac{3}{2}^- \) |
|----------------|----------------|----------------|
| \( M_{cc} \) | 3881  | 3883  | 3884   |
| \( \Sigma N c \) | 41.7  | 49.7  | 35.2   |
| \( N J/\psi \) | 23.1  | 24.4  | 29.3   |
| \( \Lambda c D \) | 14.6  | 11.7  | 14.5   |
| \( \Lambda c D^* \) | 0.9   | 0.4   | 2.0    |
| \( \Sigma c D \) | 0.1   | 4.8   | 6.0    |
| \( \Sigma c D^* \) | 4.5   | 6.4   | 12.4   |
| \( \Sigma c D^* \) | 15.1  | 2.6   | 0.6    |

Table 7 The masses (in MeV) of the hidden-charm molecular pentaquarks of \( J^P = \frac{3}{2}^- \) with three closed channels coupling and the percentages of each channel in the eigen-states.

| \( \mu_{cc} \) | 0.01 | 0.001 | 0.0001 | 0.01 | 0.001 | 0.0001 | 0.01 | 0.001 | 0.0001 |
|----------------|-------|-------|--------|-------|-------|--------|-------|-------|--------|
| \( M_{cc} \) | 4362  | 4445  | 4554   | 4365  | 4450  | 4553   | 4368  | 4451  | 4554   |
| \( \Sigma c D^* \) | 3.8   | 96.2  | 1.4    | 1.6   | 98.0  | 1.0    | 1.2   | 98.5  | 0.8    |
| \( \Sigma c D \) | 91.0  | 2.8   | 4.0    | 94.1  | 1.0   | 3.7    | 95.5  | 0.7   | 3.0    |
| \( \Sigma c D^* \) | 5.2   | 1.0   | 94.6   | 4.3   | 1.0   | 95.3   | 3.3   | 0.8   | 96.2   |

MeV and the main channel is \( \Sigma^* c D \) with the percentage of 91.0% \( \sim \) 95.5%; the mass of the second eigen-state is about 4445 \( \sim \) 451 MeV and the main channel is \( \Sigma D^* \) with the percentage of 96.2% \( \sim \) 98.5%; the mass of the third eigen-state is about 4551 \( \sim \) 4555 MeV and the main channel is \( \Sigma^* c D^* \) with the percentage of 94.6% \( \sim \) 96.2%. From the above results, we find that the mass of the first eigen-state is close to the mass of the observed \( P_c(4380) \), a pentaquark reported by LHCb collaboration. Therefore, in our quark model calculation the main component of the \( P_c(4380) \) is \( \Sigma^* c D \) with the quantum number \( J^P = \frac{3}{2}^- \). In addition, the mass of the second eigen-state is close to the mass of another reported pentaquark \( P_c(4450) \). Nevertheless, the opposite parity of the state to \( P_c(4380) \) may prevent this assignment. Moreover, all these closed channels can be coupled to the open channels \( N J/\psi \) and \( \Lambda c D^* \). The results of these five channels coupling are shown in Table 6. There is a stable state, the mass of which is lower than the threshold of \( N J/\psi \) and the main channel of this state is \( N J/\psi \), with the ratio of 80.8% \( \sim \) 62.1%. This shows that the \( N J/\psi \) of \( J^P = \frac{3}{2}^- \) is bounded by channel-coupling. However, it can couple to the \( D^- \) wave \( N \eta_c \). So further work should be done to check whether the \( J^P = \frac{3}{2}^- \) \( N J/\psi \) is a resonance state in the \( D^- \) wave \( N \eta_c \) scattering process. In fact, the possible existence of a nuclear bound quarkonium state was proposed more than 20 years ago by Brodsky, Schmidt and de Teramond [30]; Gao, Lee, and Marinov [31] also predicted the existence of the \( N \phi \) bound state, which is very similar with \( N J/\psi \) state; and the recent lattice QCD calculation also supported the existence of the strangenumium-nucleus and the charmonium-nucleus bound states [32]. Therefore, searching for the \( N J/\psi \) resonance state is the interesting work in future. In addition, there are also several quasi-stable states in the full channel-coupling calculation, the masses of which are lower than the thresholds of the corresponding main channels and they fluctuate several MeVs around their central values. It is just the behavior of a resonance. The amplitude of the fluctuation can be taken as the decay width of the quasi-states. In quark model calculation, the decay width of the \( P_c(4380) \) candidate is too small to match the experimental value. Further study is needed to check whether these eigen-states are resonance states in the \( N J/\psi \) and \( \Lambda c D^* \) scattering process and to calculate the widths of other decay modes.

As mentioned above, by taking into account the channel-coupling effect, a bound state \( N \eta_c \) is obtained for the \( J^P = \frac{3}{2}^- \) system; and another bound state
N\,J/\psi is obtained for the \( J^P = \frac{3}{2}^- \) system. In these two systems, the coupling between the calculated \( S^- \) wave channels is through the central force. In order to see the strength of these channel-coupling, we calculate the transition potentials of these channels. Here, we take the result of the \( J^P = \frac{3}{2}^- \) system with \( \mu_{cc} = 0.01 \) as an example. The transition potentials of five channels \( N\,J/\psi, A_s^*, \Sigma_s^*, \Sigma_s^* D, \) and \( \Sigma_s^* D^* \) are shown in Fig. 4. Obviously, it is a strong coupling among these channels that makes \( N\,J/\psi \) the bound state. The mechanism to form a bound state has been proposed before. Eric S. Swanson proposed that the admixtures of \( \rho J/\psi \) and \( \omega J/\psi \) states were important for forming \( X(3872) \) state [33], which was also demonstrated in Ref. [34] by T. Fernández-Caramés and collaborators. The mechanism also applied to the study of \( H^- \)-dibaryon [35], in which the single channel \( A \) is unbound, but when coupled to the channels \( N\Xi \) and \( \Sigma\Sigma \), it becomes a bound state. The effect of channel-coupling of the \( J^P = \frac{3}{2}^- \) system is the same as the one of the \( J^P = \frac{1}{2}^- \) system.

For the \( J^P = \frac{5}{2}^- \) system, it includes only one channel \( \Sigma_s^* D^* \), and it is a bound state with the mass of \( 4512 \sim 4517 \) (MeV), which is a little higher than that of \( P_s(4450) \). Although the width of \( S^- \) wave \( \Sigma_s^* D \) decaying to \( D^- \) wave \( N\eta \), and \( J/\psi \) (tensor interaction induced decay) is generally small, which can be used to explain why the width of \( P_s(4450) \) is much narrower than that of \( P_s(4380) \), the \( J^P = \frac{5}{2}^- \) may not a good candidate of \( P_s(4450) \) because of the opposite parity of the state to \( P_s(4380) \).

In the previous discussion, the hidden-charm molecular pentaquarks were investigated. We also extend the study to the hidden-bottom molecular pentaquarks because of the heavy flavor symmetry. Here we take the value of \( \mu_{bb} = 0.0001 \). The numerical results are listed in Table 8, Table 9 and Table 10. The results are similar to the hidden-charm molecular pentaquarks. For the \( J^P = \frac{3}{2}^- \) system, a bound state is obtained by all channels coupling, and the main channel is \( N\eta \) with the mass of 10304 MeV; the quasi-stable states with main components of \( \Sigma_b B, \Sigma_b^* B, \) and \( \Sigma_b^* B^* \), respectively should be confirmed by calculating the open channels scattering in future. For the \( J^P = \frac{3}{2}^- \) system, there is also a bound state of 10382 MeV, and the main channel is \( NT(1s) \), which also should be checked whether it is a resonance state or not in the \( D^- \) wave \( N\eta \) scattering process. Moreover, further work should be done to check whether the quasi-stable states of \( \Sigma_b B, \Sigma_b^* B, \) and \( \Sigma_b^* B^* \) are resonance states or not in the \( NT(1s) \) and \( A_b B^* \) scattering process. For the \( J^P = \frac{5}{2}^- \) system,

| \( J^P = \frac{1}{2}^- \) | \( J^P = \frac{3}{2}^- \) | \( J^P = \frac{5}{2}^- \) |
|-----------------|-----------------|-----------------|
| \( N\eta \) ub | \( NT(1s) \) ub | \( \Sigma_b^* B^* \) -14 |
| \( N\eta \) ub | \( NT(1s) \) ub | \( \Sigma_b^* B^* \) -14 |
| \( A_b B \) ub | \( \Sigma_b^* B^* \) -15 |
| \( A_b B^* \) ub | \( \Sigma_b^* B^* \) -16 |
| \( \Sigma_b B \) -15 |
| \( \Sigma_b B^* \) -21 |
| \( \Sigma_b^* B^* \) -24 |

**Table 9** The masses (in MeV) of the hidden-bottom molecular pentaquarks with three closed channels coupling and the percentages of each channel in the eigen-states.

| \( J^P = \frac{1}{2}^- \) | \( J^P = \frac{3}{2}^- \) | \( J^P = \frac{5}{2}^- \) |
|-----------------|-----------------|-----------------|
| \( N\eta \) 33.8 | \( NT(1s) \) 14.7 | \( \Sigma_b^* B^* \) 100.0 |
| \( N\eta \) 17.8 | \( A_b B^* \) 32.6 |
| \( A_b B \) 24.2 | \( \Sigma_b^* B^* \) 18.7 |
| \( A_b B^* \) 5.2 | \( \Sigma_b^* B^* \) 13.7 |
| \( \Sigma_b B \) 2.1 | \( \Sigma_b^* B^* \) 0.4 |
| \( \Sigma_b B^* \) 0.7 |
| \( \Sigma_b^* B^* \) 19.3 |

**Table 10** The masses (in MeV) of the hidden-bottom molecular pentaquarks of \( I = \frac{1}{2} \) and the percentages of each channel in the eigen-states.
a bound state $\Sigma_c^* B^*$ is obtained, with the mass of 11143 MeV.

4 Summary

In summary, the possible hidden-charm molecular pentaquarks with $Y = 1$, $I = \frac{1}{2}$, $J^P = \frac{1}{2}^+, \frac{3}{2}^+$, and $\frac{5}{2}^+$ are investigated by solving the RGM equation in the framework of QDCSM. Our results show: (1) All the positive parity states are all unbound in our calculation. Some other molecular structures, which contain excited hadrons, such as $\chi_{c1} p$, $J/\psi N(1440)$, $J/\psi N(1520)$ and so on, would deserve further study. (2) For the $J^P = \frac{1}{2}^-$ system, there is a bound state of 3881 ~ 3884 MeV by seven channels coupling, and the main channel is $N\eta_c$; there are three quasi-stable states of $\Sigma_c^0 D$, $\Sigma_c^* D^*$ and $\Sigma_c^* D^*$ should be confirmed by investigating the scattering process of the open channels of $N\eta_c$, $NJ/\psi$, $\Lambda_c D$ and $\Lambda_c D^*$. (3) For the $J^P = \frac{3}{2}^-$ system, the main channel of the bound state is $NJ/\psi$ with the mass of 3997 ~ 3998 MeV, which may be a resonance state in the $D$-wave $\eta_c$ scattering process. There are also three quasi-stable states: $\Sigma_c^* D^*$ with the mass of 4362 ~ 4368 MeV, $\Sigma_c^* D^*$ with the mass of 4445 ~ 4451 MeV, and $\Sigma_c^* D^*$ with the mass of 4551 ~ 4555 MeV, of which the mass of $\Sigma_c^* D^*$ is close to the observed $P_c(4380)$. So in our quark model calculation $P_c(4380)$ can be explained as the molecular pentaquark $\Sigma_c^* D$ with the quantum number $J^P = \frac{3}{2}^-$. However, the partial decay width of $\Sigma_c^* D^*$ to $NJ/\psi$ is estimated to be several MeVs, which should be checked by further experiments. Similarly, the open channels of $NJ/\psi$ and $\Lambda_c D^*$ scattering process calculation is needed to confirm the resonance states of $\Sigma_c^* D^*$, $\Sigma_c^* D$ and $\Sigma_c^* D^*$. (4) For the $J^P = \frac{5}{2}^-$ system, there is a bound state $\Sigma_c^* D^*$ with the mass of 4512 ~ 4517 (MeV). However, it may not a good candidate of the observed $P_c(4450)$ because of the opposite parity of the state to $P_c(4380)$. Besides, the calculation is also extended to the hidden-bottom pentaquarks. The results are similar to the case of the hidden-charm molecular pentaquarks.

QDCSM, which was developed to study the multi-quark states, is an extension of the naive quark model. As we know, quark model plays an important role in the development of hadron physics. The discovery of $\Omega^-$ is based on the prediction of quark concept of Gell-Mann-Zweig. The naive quark model of Isgur et al. gave a remarkable description of the properties of ground-state hadrons. Applying to the excited states of hadron, hadron-hadron interaction and multiquark systems, extensions to the naive quark model have to be made. Based on the different extension of the naive quark model, a proliferation of bound states or resonances are predicted. The recent progresses of experiments on "$XYZ$" particles, $P_c^+$ pentaquarks and dibaryons such as $d^*$ [35], are encouraging. However, some precaution about the proliferation of quark-model bound states has to be posed. So far, there is no multiquark state identified by experiments unambiguously. For particular multiquark state, there exist different points of view. For example, J. Vijande and collaborators studied the four-quark system $c\bar{c}n\bar{n}$ in the constituent quark model by using different types of quark-quark potentials, and no four-quark bound states have been found [37], whereas diquark-antidiquark picture was used by Maiani et al. to explain the state $X(3872)$ [38]. J. Vijande et al. also searched for the doubly-heavy dibaryons in a simple quark model, but no bound or metastable state was found [39], whereas $H$-like dibaryons with heavy quarks were proposed in ref.[40]. More theoretical and experimental work are needed to distinguish the different extension of the quark model. The critical development of the quark model may be the unquenching quark model, where the valence quarks and real/virtual quark pair are treated equally. T. F. Carames and A. Valcarce have studied the possible multiquark contributions to the charm baryon spectrum by considering higher order Fork space components [41]. By incorporating new ingredients, the phenomenological quark model is expected to describe ordinary and exotic hadrons well.

Acknowledgment

The work is supported partly by the National Natural Science Foundation of China under Grant Nos. 11175088, 11535005 and 11205091.

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