The structure of pentaquarks $\Omega^0_c$ in the chiral quark model

Gang Yang, Jialun Ping*

1Department of Physics and Jiangsu Key Laboratory for Numerical Simulation of Large Scale Complex Systems, Nanjing Normal University, Nanjing 210023, P. R. China

Recently, the experimental results of LHCb Collaboration suggested the existence of five new excited states of $\Omega^0_c$, $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$ and $\Omega_c(3119)^0$. The quantum numbers of these new particles are not determined now. To understand the nature of the states, a dynamical calculation of 5-quark systems with quantum numbers $I^J = 0(\frac{3}{2})^-$, $0(\frac{1}{2})^-$ and $0(\frac{1}{2})^-$ is performed in the framework of chiral quark model with the help of gaussian expansion method. The results show the $\Xi D$, $\Xi K$ and $\Xi^* K$ are possible the candidates of these new particles. The distances between quark pairs suggest that the nature of pentaquark states.

PACS numbers: 14.20.Lq, 14.40.Lb, 12.39.Jh

I. INTRODUCTION

Recently, CERN announced an exceptional new discovery that was made by the LHCb, which unveiled five new states all at once [1]. Each of the five particles were found to be the excited states of $\Omega^0_c$, a particle with three quarks, $css$. These particle states are named, according to the standard convention, $\Omega^0_c(3000)^0$, $\Omega^0_c(3050)^0$, $\Omega^0_c(3066)^0$, $\Omega^0_c(3090)^0$ and $\Omega^0_c(3119)^0$. Just after the announcement, the theoretical interpretations were proposed. S. S. Agaev et al. interpreted two of these excited charmed baryons ($\Omega^0_c(3066)^0$ and $\Omega^0_c(3119)^0$) as the first radial excitation with $J^P = 2^−$ and $J^P = 3^−/2^-$. In Ref. [2], Karlmer and Rosner suggested that the parity was negative for all of the five states, two $J^P = 1/2^−$ states ($\Omega^0_c(3000)^0$ and $\Omega^0_c(3050)^0$), two $J^P = 3/2^−$ states ($\Omega^0_c(3066)^0$ and $\Omega^0_c(3090)^0$), and the last one is $\Omega^0_c(3119)^0$, $J^P = 5/2^−$. These exciting announcements and the theoretical work along with the pentaquarks $P^+_c$ discovered also by the LHCb Collaboration in 2015 [3] have bring us lots of peculiar understanding to the world of microcosmic particles.

The quantum numbers of these new particles are not determined for the moment, and the explanation of them as the excited states of $q^3$ baryon is reasonable. However, the possibility of the multi-quark candidates of these excited states cannot be excluded. The ground states of $\Omega_c$ have been observed experimentally, $\Omega_c(2695)^0$ with $J^P = \frac{3}{2}^−$ and $\Omega_c(2770)^0$ with $J^P = \frac{5}{2}^−$. The excited energies of the newly reported states with respect to the ground states are $230-424$ MeV, which are enough to excite light quark-antiquark pair from the vacuum. From the masses of $\Xi_c$ baryon and $K$ meson, $2468$ MeV and $495$ MeV, we have the threshold for $\Xi_c - K$ state around $2963$ MeV. It is expected that the $5-q$ components will play a role in these $\Omega_c$’s. In Ref. [27], spectrum of low-lying pentaquark states with strangeness $S = -3$ and negative parity is studied in three kinds of constituent quark models. The results indicate that the lowest energy state $\Omega^*$ is around $1.8$ GeV, which is about $200$ MeV lower than predictions of various quenched three quarks models, and the energy cost to excite ground state of $\Omega$ to a $5$-quark state is less than that to an orbital excitation.

The interesting in pentaquark is revived after the observation of the exotic hadrons, $P^+_c(4380)$ and $P^+_c(4450)$ in the decay of $\Lambda^+_c(4140)$, $\Lambda^+_c(4150)$ and $\Omega^+_c(4380)$ by the LHCb Collaboration lately [27], there are lots of theoretical calculation have been performed to investigate these two exotic states [6–16], even though the $\Theta^+(1540)$ pentaquark was reported by several experimental groups [17–19] in 2003 and has been denied by JLab with more higher precision results [20] (LEPS Collaboration still insisted on the existence of pentaquark $\Theta^+(1540)$ [21]). Besides, it is shown that there should be notable five-quark components in the baryon resonances [22–24]. In addition, the valence-sea quark mixing (Fock space expansion) model $(q^2 + q^3 q\bar{q})$ of nucleon ground state had been used to explain the mysterious proton spin structure well [25]. Such a sea quark excitation model had also been used to show that the $q^3 q\bar{q}$ excitation is more favorable than the $p$-wave excitation in $q^3$ configuration for 1/2− baryons [26].

Quark model is the most common approach to multi-quark system. With the recent experimental data on multi-quark states and the development of quark model, It is expected to perform a serious calculation of multi-quark state in the framework of quark model. In the present work, the chiral quark model (ChQM) is employed to study the pentaquark states $\Omega^0_c$. To find the structure of the pentaquark states, a general, powerful method of few-body system, gaussian expansion method (GEM) [28] is used to do the calculation. The GEM has been successfully applied to many few-body systems, light nuclei, hyper-nuclei, hadron physics and so on [28]. It suits for both of compact multi-quark systems and loosely bound molecular states. In this approach, the
four relative orbital motions of the system are expanded
by gaussians with various widths. By taking into account
of all the possible couplings for color-flavor-spin degrees
of freedom, the structure of the system determined by its
dynamics can be found.

The structure of the paper is as follows. In section II
the quark model, wave-functions and calculation method
is presented. Section III is devoted to the calculated re-

results and discussions. A brief summary is given in the
last section.

II. MODEL AND W A V E FUNCTION

The chiral quark model has achieved a success both
in describing the hadron spectra and hadron-hadron in-

teraction. In this model, the constituent quark and an-
tiquark interact with each other through the Goldstone
boson exchange and the effective one-gluon-exchange, in
addition to the phenomenological color confinement. Be-

sides, the scalar nonet (the extension of chiral partner
σ-meson) exchange are also introduced. The details of
the model can be found in Ref. [29]. So the Hamiltonian
in the present calculation takes the form

\[ H = \sum_{i=1}^{n} \left( m_i + \frac{p_i^2}{2m_i} \right) - T_{CM} + \sum_{j>i=1}^{n} \left[ V_{\text{CON}}(r_{ij}) + V_{\text{OGE}}(r_{ij}) + v_{\chi}(r_{ij}) + v_s(r_{ij}) \right], \]  

(1)

\[ V_{\text{CON}}(r_{ij}) = \lambda_\sigma^c \cdot \lambda_\sigma^c \left[ -a_c (1 - e^{-\mu r_{ij}}) + \Delta \right], \]

\[ V_{\text{OGE}}(r_{ij}) = \frac{1}{4} \alpha_s \lambda_i^c \cdot \lambda_j^c \left[ \frac{1}{r_{ij}} - \frac{1}{6m_{ij}} \sigma_i \cdot \sigma_j \frac{e^{-r_{ij}/r_0(\mu)}}{r_{ij}^2 r_0(\mu)} \right], \quad r_0(\mu) = r_0/\mu, \]

\[ v_{\chi}(r_{ij}) = v_\sigma(r_{ij}) \sum_{a=1}^{3} \lambda_i^a \cdot \lambda_j^a + v_{\nu}(r_{ij}) \sum_{a=1}^{7} \lambda_i^a \cdot \lambda_j^a + v_\eta(r_{ij}) [\lambda_i^8 \cdot \lambda_j^8 \cos \theta_P - \lambda_i^0 \cdot \lambda_j^0 \sin \theta_P], \]  

(2)

\[ v_s(r_{ij}) = \frac{g_{ch}^2}{4\pi} \frac{m_n^2}{12m_{ij}} \left[ \frac{\Lambda_n^2}{m_n^2} \right] \left( \frac{Y(m_n r_{ij}) - \frac{\Lambda_n^2}{m_n^2} Y(\Lambda_n r_{ij})}{m_n^2} \right) \sigma_i \cdot \sigma_j, \quad \chi = \pi, K, \eta, \]

\[ \chi = \pi, K, \eta, \]

\[ v_s(r_{ij}) = -\frac{g_{ch}^2}{4\pi} \Lambda_n^2 \left( \frac{\Lambda_n^2 - m_n^2}{m_n^2} \right) \left( \frac{Y(m_n r_{ij}) - \frac{\Lambda_n^2}{m_n^2} Y(\Lambda_n r_{ij})}{m_n^2} \right), \quad s = \sigma, a_0, \kappa, f_0. \]  

(3)

All the symbols take their usual meanings. \( \mu \) is the re-
duced mass of two interacting quarks. To simplify the
calculation, only the central parts of the interactions are
employed in the present work to consider the ground
state of multi-quark system. The model parameters are
fixed by fitting the spectrum of baryons and mesons and
their values are listed in Table I, the calculated masses
of baryons and mesons are shown in Table II. There are
two sets of parameters are given, the fixed quark-gluon
coupling constant is used in the set I, the set II has the
running coupling constants which are given as

\[ \alpha_s = \frac{\alpha_0}{\ln((\mu^2 + \mu_0^2)/\Lambda_0^2)}. \]

It is worth to mention that the above quark-quark in-
teraction is assumed to be universal according to the
"Casimir scaling" [30], it can be applied to the multi-
quark system directly. The possible multi-body interac-
tion in the multiquark system is not considered, although
it may give different spectra of multiquark states [30].

From Table I we can see that the masses of \( P \end{equation}

\( \Omega_c \)'s are higher than 3200 MeV although the mass of \( P \)-
wave nucleon is close the experimental value (for the set
I). The parameters of set II is used to check the depen-
dence of the results on the model parameters. The results
show that the \( P \)-wave baryons have rather large masses,
comparing with the experimental data. So it is still dif-
ficult to have a good description of the negative parity
states of baryons in the quark model. In the following,
we use set I parameters to study the 5-quark states.

The wavefunctions for the system are constructed just
as the way in Ref. [6]. Here only the wavefunctions of
each degree of freedom for five-quark system and parts
of the sub-clusters of three-quark and quark-antiquark
TABLE I: Quark model parameters. The masses of mesons take their experimental values. $m_e = 0.7 \text{ fm}^{-1}$, $m_K = 2.51 \text{ fm}^{-1}$, $m_s = 2.77 \text{ fm}^{-1}$.

|                  | set I | set II |
|------------------|-------|--------|
| **Quark mass**   |       |        |
| $m_q = m_d$ (MeV) | 313   | 313    |
| $m_s$ (MeV)      | 555   | 555    |
| $m_c$ (MeV)      | 1752  | 1752   |
| **Goldstone boson** |      |        |
| $\Lambda_s = \Lambda_f$ (fm$^{-1}$) | 4.20  | 4.20  |
| $\Lambda_K = \Lambda_q$ (fm$^{-1}$) | 5.20  | 5.20  |
| $\theta_P(\circ)$ | -15   | -15    |
| $\eta_s/(4\pi)$  | 0.54  | 0.54   |
| **SU(3) Scalar nonet** |      |        |
| $s = \sigma, a_0, \kappa, f_0$ |       |        |
| $m_\sigma$ (fm$^{-1}$) | 4.97  | 4.97   |
| $\Lambda_\sigma$ (fm$^{-1}$) | 5.20  | 5.20   |
| $m_\sigma$ (fm$^{-1}$) | 3.42  | 3.42   |
| **Confinement**  |       |        |
| $\alpha_s$       | 0.69  | 1.293  |
| $\Lambda_0 = 1.5585 \text{ fm}^{-1}$ |       |        |
| $\mu_0 = 621.5 \text{ MeV}$ |       |        |
| $\hat{r}_0$ (MeV fm) | 28.170 | 43.882 |

TABLE II: Masses of baryon and meson in ChQM (unit: MeV).

$$\begin{array}{cccccc}
P & N(939) & \Delta(1232) & \Omega(1672) & \Lambda(1116) & \Sigma(1189) & \Xi(1315) \\
\hline
+ & 936 & 1208 & 1643 & 1154 & 173 & 1362 \\
- & 1575 & 1625 & 2203 & 1772 & 1777 & 1981 \\
\hline
+ & 939 & 1231 & 1671 & 1187 & 1209 & 1408 \\
- & 1661 & 1716 & 2301 & 1889 & 1895 & 2098 \\
\hline
\Sigma(1383) & \Xi^*(-1532) & \Omega^-&(2695) & \Omega^+(2765) & \Xi_c(2467) & \Xi_c^*(2645) \\
\hline
+ & 1342 & 1488 & 2675 & 2748 & 2541 & 2603 \\
- & 1805 & 1999 & 3257 & 3282 & 3086 & 3093 \\
\hline
+ & 1393 & 1539 & 2748 & 2818 & 2629 & 2727 \\
- & 1928 & 2119 & 3378 & 3389 & 3145 & 3166 \\
\hline
P & \pi(140) & \rho(775) & \eta(548) & \omega(782) & K(495) & K^*(892) \\
\hline
- & 93 & 800 & 611 & 705 & 326 & 965 \\
\eta(958) & \phi(1019) & D^0(1865) & D^*(2007) \\
- & 914 & 1056 & 1842 & 2043 & &
\end{array}$$

are listed. One need to notice that there are many different ways to construct the wave-functions of the system. However, it makes no difference by choosing any one configuration if all the possible coupling are considered.

For the $\Omega_0^+$ with quark content $ssc\bar{q}q$, $q = u, d, s$ in flavor SU(3) case, there are two types of separation, one is $(qss)\bar{q}c$ and the other is $(ssc)\bar{q}q$. The flavor wavefunctions for the sub-clusters constructed are shown below.

$$B_{00}^1 = ssc, \quad B_{00}^2 = sss, $$
$$B_{1-1}^3 = \frac{1}{\sqrt{6}}(suss + usss - 2ssu), $$
$$B_{1-1}^0 = \frac{1}{\sqrt{6}}(sds + dss - 2ssd), $$
$$B_{1-1}^1 = \frac{1}{\sqrt{2}}(us - su)s, $$
$$B_{1-1}^2 = \frac{1}{\sqrt{2}}(ds - sd)s, $$
$$B_{1-1}^3 = \frac{1}{\sqrt{3}}(ssu + sus + uss), $$
$$B_{1-1}^4 = \frac{1}{\sqrt{3}}(ssd + sds + dss), $$
$$B_{1-1}^5 = \frac{1}{\sqrt{2}}(us + su)c, $$
$$B_{1-1}^6 = \frac{1}{\sqrt{2}}(ds + sd)c, $$
$$M_{1-1}^1 = \bar{c}d, \quad M_{1-1}^2 = -\bar{u}c, $$
$$M_{1-1}^3 = \bar{d}s, \quad M_{1-1}^4 = -\bar{s}d, $$
$$M_{1-1}^5 = \frac{1}{\sqrt{2}}((\bar{u}u + \bar{d}d), \quad M_{20}^2 = \bar{s}s, \quad M_{30}^3 = \bar{s}c. $$

The flavor wavefunctions for 5-quark system with isospin $I = 0$ are obtained by the following couplings,

$$\chi_1^f = \sqrt{\frac{1}{2}}(B_{1-1}^1 M_{1-1}^1 - B_{1-1}^1 M_{1-1}^1), $$
$$\chi_2^f = \sqrt{\frac{1}{2}}(B_{1-1}^2 M_{1-1}^2 - B_{1-1}^2 M_{1-1}^2), $$
$$\chi_3^f = \sqrt{\frac{1}{2}}(B_{1-1}^3 M_{1-1}^3 - B_{1-1}^3 M_{1-1}^3), $$
$$\chi_4^f = \sqrt{\frac{1}{2}}(B_{1-1}^4 M_{1-1}^4 - B_{1-1}^4 M_{1-1}^4), $$
$$\chi_5^f = \sqrt{\frac{1}{2}}(B_{1-1}^5 M_{1-1}^5 - B_{1-1}^5 M_{1-1}^5), $$
$$\chi_6^f = B_{00}^1 M_{00}^1, \quad \chi_7^f = B_{00}^2 M_{00}^2, \quad \chi_8^f = B_{00}^3 M_{00}^3. $$

In a similar way, the spin and color wavefunctions for 5-quark system can be constructed, which are the same as the expressions of Ref. [6]. Here we only give the expressions of 5-quark system, the wavefunctions for the sub-clusters can be found in Ref. [6].

$$\chi_{1-1}^f(5) = \sqrt{\frac{1}{3}}(\chi_{1-1}^f(3)) \chi_{1-1}^f(3) - \frac{1}{\sqrt{3}}(\chi_{1-1}^f(3)) \chi_{1-1}^f(3), $$
$$+ \sqrt{\frac{1}{2}}(\chi_{1-1}^f(3)) \chi_{1-1}^f(3) \chi_{1-1}^f(3).$$
where the Jacobi coordinates are defined as,

\[
\chi^a_{\frac{3}{2}, \frac{1}{2}}(5) = \sqrt{\frac{1}{3}} \chi^a_{\frac{1}{2}, \frac{1}{2}}(3) \chi^a_{00} - \sqrt{\frac{2}{3}} \chi^a_{\frac{1}{2}, \frac{1}{2}}(3) \chi^a_{11}
\]

\[
\chi^a_{\frac{1}{2}, \frac{1}{2}}(5) = \sqrt{\frac{1}{3}} \chi^a_{\frac{1}{2}, \frac{1}{2}}(3) \chi^a_{00} - \sqrt{\frac{2}{3}} \chi^a_{\frac{1}{2}, \frac{1}{2}}(3) \chi^a_{11}
\]

The size parameters of gaussians \( r_n \) are taken as the geometric progression numbers

\[
r_n = r_1 a^{n-1}.
\]

\( c_n \) is the variational parameters, which is determined by the dynamics of the system.

Finally, the complete channel wave function for the 5-quark system is written as

\[
\Psi_{JM,i,j,k,n} = A \left[ \chi^a_{S} (5) \psi_{L} \right]_{J,M} \chi_{L k}^f \chi_{L k}^t
\]

where \( A \) is the antisymmetry operator of the system. In the flavor SU(3) case, it has six terms for the system with three identical particles and it can be reduced to three terms, as follows, due to the symmetry between first two particles has been considered when constructing the wavefunctions of the 3-quark clusters. For the two types of separations, – (ussc)(uuc) + (ussd)(duc), (ussc)(ssc) (uuc + ddc), (ssc)(ssc), (ssc)(scc), we have the following antisymmetric operators,

\[
A_1 = 1 - (13) - (23), \quad A_2 = 1 - (15) - (25).
\]

The eigen-energy of the system is obtained by solving the following eigen-equation

\[
H \Psi_{JM} = E \Psi_{JM},
\]

by using variational principle. The eigen functions \( \Psi_{JM} \) are the linear combination of the above channel wavefunctions Eq. (14).

In evaluating the matrix elements of hamiltonian, the calculation is rather complicated, if the orbital angular momenta of relative motions of system are not all zero. Here a useful method named the infinitesimally-shifted gaussian are used [28]. In this method, the spherical harmonic function is absorbed into the shifted gaussians,

\[
\phi_{nlm}(r) = N_{nl} \lim_{\epsilon \to 0} \frac{1}{(\nu \epsilon)^{\frac{3}{2}}} \sum_{k=1}^{k_{max}} C_{lm,k} e^{-\nu_{n}(r-r_{k}D_{lm,k})^2},
\]

the calculation becomes easy with no tedious angular-momentum algebra required.

**III. RESULTS AND DISCUSSIONS**

In the present calculation, we are interested in the low-lying states of usssc, dissed pentaquark system, so all the orbital angular momenta are set to 0. Then the parity of five-quark system with one antiquark is negative. In this way, the total angular momentum \( J \) can take values 1/2, 3/2 and 5/2. The possible channels under the consideration are listed in Tables [III].

First, the single channel calculations are performed. The eigen-energies of each states with different quantum numbers are shown in Tables [VI] where the eigen-energies of the states are shown in column 2, along with

\[
\psi_{L M L} = \left[ \left[ \phi_{n_{1}l_{1}}(\rho) \phi_{n_{2}l_{2}}(\lambda) \right]_{L} \phi_{n_{3}l_{3}}(\nu_{e}) \phi_{n_{4}l_{4}}(R) \right]_{L M L}
\]

where the Jacobi coordinates are defined as,

\[
\rho = x_1 - x_2, \quad \lambda = x_3 - \left( \frac{m_1 x_1 + m_2 x_2}{m_1 + m_2} \right),
\]

\[
r = x_4 - x_5, \quad R = \left( \frac{m_1 x_1 + m_2 x_2 + m_3 x_3}{m_1 + m_2 + m_3} \right) - \left( \frac{m_4 x_4 + m_5 x_5}{m_4 + m_5} \right).
\]

To find the orbital wavefunctions, the gaussian expansion method (GEM) is employed, i.e., every \( \phi \) is expanded by gaussians with various sizes [28]

\[
\phi_{nlm}(r) = \sum_{n=1}^{n_{max}} c_n N_{nl} r^l e^{-(r/r_n)^2} Y_{lm}(\hat{r}),
\]

where \( N_{nl} \) is the normalization constant,

\[
N_{nl} = \left[ \frac{2l+2(2\nu_{n})^l+2}{\sqrt{\pi(2l+1)}} \right]^{\frac{1}{2}}.
\]
the theoretical thresholds in column 3 and experimental
thresholds in column 5, column 4 gives the binding energies, the difference between the eigen-energies and the
theoretical thresholds, $E_B = E - E_{th}^{exp}$. The corrected energies of the states (column 6), which are obtained by
-taking the sum of experimental thresholds and the binding energies. Namely, and $E' = E_B + E_{th}^{exp}$.

Secondly, the three types of channel coupling calculations are performed. The first is the channel coupling
between color-singlet and hidden-color channels with the same flavor-spin structures. The second is the coupling
among all color-singlet channels with different flavor-spin structures and the last is the full coupling, including all
channels for given $J^{P}$. Table[XI] gives the spacial configurations of the states by calculating the distances between
any two quarks or quark and antiquark in the full channel coupling calculation.

In the following we analyze the results in detail.

(a) $J^{P} = \frac{1}{2}^{-}$: The single channel calculations show that there are weak attractions for the most channels, the exceptions are $\Omega_c\eta_c, \Omega_c\omega, \Omega_c^*\omega$ and $\Xi_c^*K$. The coupling to hidden-color channels helps a little, increasing the attraction a few MeVs and pushing $\Omega_c^*\omega$ and $\Xi_cK$ below the corresponding thresholds. So the resonances can be formed. Most of the states have higher masses compared with that of the five new excited states of $\Omega_c$. For $\Xi D$, the second lowest state, it has the energy 3156 MeV, which is close to the biggest of $\Omega_c$, 3119 MeV. The lowest state $\Xi_c^*K$ has the energy 2949 MeV with the help of hidden-color channel coupling, which is a little smaller than the mass of the lowest excited state of $\Omega_c$, 3000 MeV.

Table XIII: The channels with $I^{J_P} = 0^{+}_{2}$.  

| index | $\chi_1^{n_1}$ | $\chi_j^{n_j}$ | $\chi_k^{n_k}$ | physical channel |
|-------|----------------|----------------|----------------|-----------------|
| 1     | $i = 1$       | $j = 3$       | $k = 1$       | $\Xi^*D^*$     |
| 2     | $i = 1$       | $j = 3$       | $k = 3$       | $\Xi^*D^*$     |
| 3     | $i = 1$       | $j = 4$       | $k = 1$       | $\Xi^*K^*$     |
| 4     | $i = 1$       | $j = 4.5$     | $k = 2.3$     | $\Xi_c^*K$     |
| 5     | $i = 1$       | $j = 6$       | $k = 1$       | $\Omega_c\omega$ |
| 6     | $i = 1$       | $j = 6$       | $k = 3$       | $\Omega_c\omega$ |
| 7     | $i = 2,3$     | $j = 1,2$     | $k = 1$       | $\Xi\bar{D}$ |
| 8     | $i = 2,3$     | $j = 1,2$     | $k = 2.3$     | $\Xi_c\bar{D}$ |
| 9     | $i = 2,3$     | $j = 4.5$     | $k = 1$       | $\Xi_c^*K^*$ |
| 10    | $i = 2,3$     | $j = 4.5$     | $k = 2.3$     | $\Xi_c^*K^*$ |
| 11    | $i = 2$       | $j = 6$       | $k = 1$       | $\Omega_c\omega$ |
| 12    | $i = 2$       | $j = 6$       | $k = 3$       | $\Omega_c\omega$ |
| 13    | $i = 4.5$     | $j = 1.2$     | $k = 1$       | $\Xi\bar{D}$ |
| 14    | $i = 4.5$     | $j = 1.2$     | $k = 2.3$     | $\Xi_c\bar{D}$ |
| 15    | $i = 4.5$     | $j = 4.5$     | $k = 1$       | $\Xi_c^*K^*$ |
| 16    | $i = 4.5$     | $j = 4.5$     | $k = 2.3$     | $\Xi_c^*K^*$ |
| 17    | $i = 4$       | $j = 6$       | $k = 1$       | $\Omega_c\omega$ |
| 18    | $i = 4,5$     | $j = 6$       | $k = 2.3$     | $\Omega_c\omega$ |

(b) $J^{P} = \frac{3}{2}^{-}$: We have similar results with that of $J^{P} = \frac{1}{2}^{-}$. Four channels, $\Omega_c\omega, \Xi_c^*K, \Xi_cK^*$ and $\Omega_c\omega$, have no attraction in single channel calculations, and the hidden-color channel-coupling induces a very weak

Table XIV: The channels with $I^{J_P} = 0^{+}_{2}$.  

| index | $\chi_1^{n_1}$ | $\chi_j^{n_j}$ | $\chi_k^{n_k}$ | physical channel |
|-------|----------------|----------------|----------------|-----------------|
| 1     | $i = 1$       | $j = 3$       | $k = 1$       | $\Xi^*D^*$     |
| 2     | $i = 1$       | $j = 3$       | $k = 3$       | $\Xi^*D^*$     |
| 3     | $i = 1$       | $j = 4$       | $k = 1$       | $\Xi^*K^*$     |
| 4     | $i = 1$       | $j = 4.5$     | $k = 2.3$     | $\Xi_c^*K$     |
| 5     | $i = 1$       | $j = 6$       | $k = 1$       | $\Omega_c\omega$ |
| 6     | $i = 1$       | $j = 6$       | $k = 3$       | $\Omega_c\omega$ |
| 7     | $i = 2$       | $j = 3$       | $k = 1$       | $\Xi^*D^*$     |
| 8     | $i = 2$       | $j = 3$       | $k = 3$       | $\Xi^*D^*$     |
| 9     | $i = 2$       | $j = 4$       | $k = 1$       | $\Xi^*K^*$     |
| 10    | $i = 2$       | $j = 4.5$     | $k = 2.3$     | $\Xi_c^*K$     |
| 11    | $i = 2$       | $j = 6$       | $k = 1$       | $\Omega_c\omega$ |
| 12    | $i = 2$       | $j = 6$       | $k = 3$       | $\Omega_c\omega$ |
| 13    | $i = 3.4$     | $j = 1.2$     | $k = 1$       | $\Xi^*D^*$    |
| 14    | $i = 3.4$     | $j = 1.2$     | $k = 2.3$     | $\Xi^*D^*$    |
| 15    | $i = 3.4$     | $j = 4.5$     | $k = 1$       | $\Xi_c^*K^*$ |
| 16    | $i = 3.4$     | $j = 4.5$     | $k = 2.3$     | $\Xi_c^*K^*$ |
| 17    | $i = 3$       | $j = 6$       | $k = 1$       | $\Omega_c\omega$ |
| 18    | $i = 3.4$     | $j = 6$       | $k = 2.3$     | $\Omega_c\omega$ |

The situation changes a lot after coupling all the color-singlet channels, the lowest energy we obtained is 2865 MeV. And the full channel-coupling calculation decreases the lowest energy further to 2769 MeV. Table[VII] shows the six lowest eigen-energies in the full-channel calculation. $E'$ denotes the corrected energy,

$$E' = E_{th}^{exp}(\Xi_c\bar{K}) - E_{th}^{exp}(\Xi_cK) + E.$$
attraction for $\Xi_{c}^{*}\bar{K}$. But, it introduces a large attraction for $\Xi_{c}^{*}\bar{K}$, $-158$ MeV, a good candidate of color structure resonance to be confirmed.

All color-singlet channel-coupling calculation gives a very weak bound state with energy $3138$ MeV after correction. The full channel-coupling lowered the energy further to $3067$ MeV. Table IX shows the four lowest eigen-energies in the full-channel coupling calculation. After correction, their energies are below $3.2$ GeV.

(c) $J^P = \frac{3}{2}^-$: Only one channel, $\Xi_{c}^{*}\bar{D}^*$, has attractive in the single channel calculation. Coupling to the hidden-color channels, an additional channel, $\Xi_{c}^{*}\bar{K}^*$, is induced out an attraction. Channel-couplings, color-singlet and full, do not produce any bound state. The $D$-wave $\Xi_{c}\bar{D}$ and/or $\Xi_{c}\bar{K}$ scattering phase shift calculation is needed to check that the resonances, $\Xi_{c}^{*}\bar{D}^*$ and $\Xi_{c}^{*}\bar{K}^*$, can survive or not after the coupling.
investigated by means of Gaussian expansion method. The ssqc systems with quark contents two states are compact ones. Similar distances and all are smaller than 1.5 fm. So these calculation shows that there are several resonance states for \( I(J^P) = 0^+(\frac{1}{2}^-) \), \( 0^+(\frac{3}{2}^-) \) below 3.2 GeV, \( \Xi D \), \( \Xi K \) and \( \Xi^* K \) are possible the candidates of the newly announced excited states of \( \Omega_b \) by LHCb Collaboration. In the present calculation, the masses of the lowest states with quantum numbers \( I(J^P) = 0^-(\frac{1}{2}^-) \) and \( I(J^P) = 0^-(\frac{3}{2}^-) \) are 2769 MeV and 3067 MeV, respectively. And the distances between quark pairs suggest these two states are compact states or pentaquark structures. It manifests the effects of hidden-color channels. So it is interesting to identify the states experimentally. In this work, in fact we cannot identify the excited states of \( \Omega_b^0 \) reported by LHCb Collaboration with the pentaquarks we calculated. We want stress that the \( P \)-wave \( q^3 \) baryon will mix strongly with the \( S \)-wave pentaquark. The unquenched quark model, including the high Fock components, study of \( \Omega_c \) is needed to clarify the situation.

In the present calculation, the internal structures of the sub-clusters are not fixed, the structure of a 5-quark system is determined by the dynamics of the system, because all the possible coupling are included except the high orbital angular momentum. The further work of considering the high orbital angular momenta along with the spin-orbit and tensor interactions is expected.

Pentaquark involves two subcluster, \( q^3 \) and \( \bar{q}q \). If the two subclusters are colorless, they are corresponding to baryon and meson. To describe baryon and meson simultaneously in quark model with one set of parameters is still difficult. It is main source of the uncertainty of the model calculation of pentaquark. Unquenched quark model may be a solution for the unified description of baryon and meson, since the \( q\bar{q} \) cluster is always involved.

Multiquark states are ideal place to develop the quark model. Because the model approach is a phenomenological one, its development depends on the accumulated experimental data. We hope that the model description of the multiquark states will be improved with the accumulation of the experimental data on multiquark state.

### Acknowledgments

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

### IV. SUMMARY

In the framework of the chiral quark model, the 5-quark systems with quark contents \( sscc \), \( ssccd \) are investigated by means of Gaussian expansion method. The

---

**Table IX:** The eigen-energies of full channel-coupling calculation below 3.2 GeV with \( I(J^P) = 0^+(\frac{1}{2}^-) \). (unit: MeV).

| index | \( E \) | \( E_{ch} \) | \( E_{th} \) | \( E_{sh} \) | \( E' \) |
|-------|-------|-------|-------|-------|-------|
| 1     | 3508  | 3531  | -23   | 3569   | 3516  |
| 2     | 3507  |       | -24   | 3515   |       |
| 3     | 3568  | 3568  | 0     | 3537   | 3537  |
| 4     | 3646  |       |       |        |       |
| 5     | 3532  |       | -36   | 3501   |       |
| 6     | 3563  |       |       |        |       |
| 5+6   | 3453  | 3453  | 0     | 3548   | 3548  |
| mixed (singlet) | 3453 |
| mixed (full)     | 3453 |

**Table X:** The lowest eigen-energies of the \( sscc \) system with \( \frac{3}{2}^- \) (unit: MeV).

| Channel | \( E \) | \( E_{ch} \) | \( E_{th} \) | \( E_{sh} \) | \( E' \) |
|---------|-------|-------|-------|-------|-------|
| \( \Omega_b^0(2769) \) | 1.3   | 1.1   | 1.4   | 1.2   |       |
| \( \Omega_b^0(3067) \) | 1.4   | 1.1   | 1.2   | 1.4   |       |

Table XI gives the distances between quarks for two states, \( \Omega_b^0(2769) \) and \( \Omega_b^0(3067) \). All the quark-pairs have similar distances and all are smaller than 1.5 fm. So these two states are compact ones.

---

[1] R. Aaij et al. [LHCb Collaboration], arXiv:1703.04639 [hep-ex].
[2] S. S. Agaev, K. Azizi and H. Sundu, arXiv:1703.07091 [hep-ex].
[3] H. X. Chen, Q. Mao, W. Chen, A. Hosala, X. Liu and S. L. Zhu, arXiv:1703.07093 [hep-ph].
[4] M. Karliner and J. L. Rosner, arXiv:1703.07774 [hep-ph].
[5] R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett. 115, 072001 (2015).
[6] G. Yang, J. L. Ping and F. Wang, Phys. Rev. D 95, 014010 (2017).
[7] H. X. Huang, C. R. Deng, J. L. Ping and F. Wang, Eur. Phys. J. C 76, 624 (2016).
[8] R. Chen, X. Liu, X. Q. Li and S. L. Zhu, Phys. Rev. Lett. 115, 132002 (2015).
[9] J. He, Phys. Lett. B 753, 547 (2016).
[10] H. X. Chen, W. Chen, X. Liu, T. G. Steel and S. L. Zhu, Phys. Rev. Lett. 115, 172001 (2015).
[11] Z. G. Wang, Eur. Phys. J. C 76, 70 (2016).
[12] L. Roca, J. Nieves and E. Oset, Phys. Rev. D 92, 094003
(2015).
[13] R. L. Zhu, C. F. Qiao, Phys. Lett. B 756, 259 (2016).
[14] X. H. Liu, Q. Wang and Q. Zhao, Phys. Lett. B 757, 231 (2016).
[15] F. K. Guo, U. G. Meißner, W. Wang and Z. Yang, Phys. Rev. D 92 071502 (2015).
[16] H. X. Chen, W. Chen, X. Liu and S. L. Zhu, Phys. Rep. 639, 1 (2016).
[17] T. Nakano et al. [LEPS Collaboration], Phys. Rev. Lett. 91, 012002 (2003).
[18] V. V. Barmin et al. [DIANA Collaboration], Yad. Fiz. 66, 1763 (2003) [Phys. At. Nucl. 66, 1715 (2003)].
[19] S. Stepanyan et al. [CLAS Collaboration], Phys. Rev. Lett. 91, 252001 (2003).
[20] M. Battaglieri et al. [CLAS Collaboration], Phys. Rev. Lett. 96, 042001 (2006) and references therein.
[21] T. Nakano et al. [LEPS Collaboration], Phys. Rev. C 79, 025210 (2009).
[22] R. Bijker and E. Santopinto, Phys. Rev. C 80, 065210 (2009).
[23] E. Santopinto and R. Bijker, Phys. Rev. C 82, 062202(R) (2010).
[24] C. S. An and B. S. Zou, Eur. Phys. J. A 39, 195 (2009).
[25] D. Qing, X.S. Chen and F. Wang, Phys. Rev. C 57, R31 (1998), D 58, 114032(998).
[26] B. S. Zou, Chin. Phys. C (High Ener. Phys. Nucl. Phys.), 33, 1113 (2009).
[27] S. G. Yuan, C. S. An, K. W. Wei, B. S. Zou and H. S. Xu, Phys. Rev. C 87, 025205 (2013).
[28] E. Hiyama, Y. Kino and M. Kamimura, Prog. Part. Nucl. Phys. 51, 223 (2003).
[29] J. Vijande, F. Fernandez and A. Valcarce, J. Phys. G 31, 481 (2005).
[30] G. S. Bali, Phys. Rev. D 62, 114503 (2000).
[31] J.-M. Richard, Phys. Rev. C 81, 015205 (2010); M. W. Paris, Phys. Rev. Lett. 95, 202002 (2005); C. R. Deng, J. L. Ping, F. Wang and T. Goldman, Phys. Rev. D 82, 074001 (2010).
[32] M. Harvey, Nucl. Phys. A 352, 301 (1981); 326 (1981).
[33] F. Wang, Prog. Phys. 9, 297 (1989) (in Chinese).
[34] J. Vijande, A. Valcarce and N. Barnea, Phys. Rev. D 79, 074010 (2009); J. Vijande and A. Valcarce, Phys. Rev. C 80, 035204 (2009); D. Janc and M. Rosina, Few Body Syst. 35, 175 (2004).