Investigating the excited $\Omega_c^0$ states through $\Xi_cK$ and $\Xi_c\bar{K}$ decay channels

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Inspired by the five newly observed $\Omega_c^0$ states by the LHCb detector, we study the $\Omega_c^0$ states as the $S$-wave molecular pentaquarks with $I = 0$, $J^P = \frac{3}{2}^-$, and $\frac{5}{2}^-$ by solving the RGM equation in the framework of chiral quark model. Both the energies and the decay widths are obtained in this work. Our results suggest that $\Omega_c(3119)^0$ can be explained as an $S$-wave resonance state of $\Xi D$ with $J^P = \frac{3}{2}^-$, and the decay channels are the $S$-wave $\Xi_cK$ and $\Xi_c\bar{K}$. Other reported $\Omega_c^0$ states cannot be obtained in our present calculation. Another $\Omega_c^0$ state with much higher mass 3533 MeV with $J^P = \frac{5}{2}^-$ is also obtained. In addition, the calculation is extended to the $\Omega_c^0$ states, similar results as that of $\Omega_c^0$ are obtained.

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I. INTRODUCTION

There has been important experimental progress in the sector of heavy baryons in the past decade. Many heavy baryons have been reported. For example, the triplet of excited $\Sigma_c$ baryons, $\Sigma_c(2800)$, was observed by Belle \textsuperscript{[1]} in 2005, and they tentatively identified the quantum numbers of these states as $J^P = \frac{3}{2}^-$. In 2008, the same neutral state $\Sigma_c^0$ was also observed by the BABAR Collaboration with the mean value of mass higher than that obtained by Belle [2]. The charmed baryons $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ were observed by both BABAR and Belle Collaborations in 2007 [3, 4]. The charm-strange baryons $\Xi_c(2980)^+$ and $\Xi_c(3077)^0$ were reported by Belle [5] and later confirmed by BABAR [6]. $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$ were also investigated by BABAR [7]. Among the expected charmed baryons, the spectrum of the $\Omega_c^0$ baryons, which have quark content of $scs$, is still unknown. Only two states: $\Omega_c(2695)^0$ and $\Omega_c(2768)^0$ with $J^P = 1/2^+$ and $J^P = 3/2^+$ respectively have been observed before [8, 9]. Very recently, the LHCb Collaboration reported five new narrow $\Omega_c^0$ states in the $\Xi_c^+K^-$ invariant mass spectrum. They are: the $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$ [9]. Moreover, the decay widths of these states were also observed by the experiment, which are only a few MeV. However, the quantum numbers and the structures of these states are still unclear now.

All these experimental progress of heavy baryons have stimulated extensive interest in understanding the structures of the charmed baryons. A classical way to describe the charmed baryons is based on the assumption that they are conventional charmed baryons. And another way is treating them as candidates of molecular states. Take the $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$ states for example. Being considered as two traditional charmed baryons, the strong decays of these two states have been studied by using the heavy hadron chiral perturbation theory [10], the $\frac{3}{2}^+_0$ model [11], and the chiral quark model [12]. On the other hand, many work treat them as candidates of molecular states. J. R. Zhang found that $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$ as the $S$-wave $ND$ state and $ND^*$ state respectively by means of QCD sum rules. J. He and X. Liu explained the $\Lambda_c(2940)^+$ as an isoscalar $S$-wave or $P$-wave $D^*N$ system within the one-boson-exchange model [13]. For the newly observed $\Omega_c^0$ states, some work treat them as traditional charmed baryons. S. S. Aagaev et al. calculated the masses and the residues of these states with $J^P = 1/2^+$ and $J^P = 3/2^+$ in the framework of QCD two-point sum rules and they were inclined to assign the $\Omega_c(2066)^0$ and $\Omega_c(3119)^0$ states as the first radially excited $(2S, 1/2^+)$ and $(2S, 3/2^+)$ charmed baryons [14]. H. X. Chen et al. studied the decay properties of the $P$-wave charmed baryons within the light-cone QCD sum rules, including some $\Lambda_c$, $\Xi_c$, $\Omega_c$, $\Xi_c\bar{K}$ states, as well as these newly reported $\Omega_c^0$ states [15]. They interpreted one of these $\Omega_c$ states was a $J^P = 1/2^-$ state, two of them were $J^P = 3/2^-$ state and $J^P = 5/2^-$ state, another two may be with $J^P = 1/2^+$ and $3/2^+$. M. Karliner and J. L. Rosner explained these $\Omega_c^0$ baryons as bound states of a $P$-wave $ss$-diquark and a $c$-quark [16], and they predicted two of spin $1/2$, two of spin $3/2$, and one of spin $5/2$, all with negative parity. K. L. Wang et al. investigated the strong and radiative decay properties of the low-lying $\Omega_c$ states in a constituent quark model [17]. Their results show that the $\Omega_c(3000)^0$ and $\Omega_c(3090)^0$ can be assigned to have $J^P = 1/2^-$, $\Omega_c(3050)^0$ and $J^P = 2/2^-$, the $\Omega_c(3066)^0$, the $\Omega_c(3090)^0$ with $J^P = 5/2^-$, and the $\Omega_c(3119)^0$ might be one of the two $2S$ states of the first radial excitations. Another way to describe these states is assuming they are pentaquark states. G. Yang et al. did a dynamical calculation of 5-quark systems to study the structure of the pentaquarks $\Omega_c$ in the chiral quark model by taking the advantage of gaussian expansion method [18], and they pointed out that the $\Xi D$, $\Xi_c K$ and $\Xi_c\bar{K}$ are possible the candidates of these new parti-

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elements.

Actually, the hadron-hadron scattering is one of the important ways to generate and identify multi-quark states. Therefore, to provide the necessary information for experiment to search for the multi-quark states, we should not only calculate the mass spectrum but also study the corresponding scattering process. The scattering phase shifts will show a resonance behavior in the resonance energy region. By using the constituent quark models and the resonating group method (RGM) [10], we have obtained the $d^*$ resonance during the $NN$ scattering process, the energy and decay width of the partial wave are consistent with the experiment data [21]. Extending to the pentaquark system, we investigated the $N\phi$ state in the different scattering channels: $N\eta'$, $\Lambda K$, and $\Sigma K$ [21]. Both the resonance mass and decay width were obtained, which provide the necessary information for experiment searching at Jefferson Lab. Therefore, it is interesting to extend such study to the newly observed $\Omega^0_c$ states. In this work, we will assume $\Omega^0_c$ states are pentaquark states, calculate both the masses and decay widths of these states, and analyze if there are some $\Omega^0_c$ states which can be explained as pentaquarks by comparing with the LHCb data. Finally, we will also extend the study to the $\Omega^0_s$ states because of the heavy flavor symmetry.

The structure of this paper is as follows. A brief introduction of a constituent quark model used is given in section II. Section III devotes to the numerical results and discussions. The summary is shown in the last section.

II. CHIRAL QUARK MODEL

Here, we use the chiral quark model to study the $\Omega^0_c$ states. The Salamanca model was chosen as the representative of the chiral quark models, because the Salamanca group's work covers the hadron spectra, nucleon-nucleon interaction, and multiquark states. We also have used this model to study the nucleon-nucleon interaction, dibaryon resonance states, such as $d^*$ state [20], $N\Omega$ [22, 23], and so on. In this model, the constituent quarks interact with each other through the one-gluon-exchange and the Goldstone boson exchange in addition to the color confinement. For the system with strangeness, a version of chiral quark model [24, 25] had been used, where full SU(3) scalar octet meson-exchange was used. These scalar potentials have the same functional form like the one of SU(2) ChQM but a different SU(3) operator dependence [24]. The model details can be found in Ref. [20]. Here we only give the Hamiltonian:

$$H = \sum_{i=1}^{6} \left( m_i + \frac{p_i^2}{2m_i} \right) - T_{CM} + \sum_{j>i=1}^{6} \left( V_{ij}^C + V_{ij}^G + V_{ij}^\chi + V_{ij}^\sigma \right),$$

$$V_{ij}^C = -a_v \chi^c \cdot \chi^c_j (r_{ij}^2 + v_0),$$

$$V_{ij}^G = \frac{1}{4} \alpha_s \chi^c \cdot \chi^c_j \left[ \frac{1}{r_{ij}} - \frac{\pi}{2} \delta (r_{ij}) \left( \frac{1}{m_i^2} + \frac{1}{m_j^2} + \frac{4\sigma_i \cdot \sigma_j}{3m_i m_j} \right) - \frac{3}{4m_i m_j r_{ij}^2} S_{ij} \right],$$

$$V_{ij}^\chi = V_{\pi} (r_{ij}) \sum_{a=1}^{3} \lambda^a_i \cdot \lambda^a_j + V_{K} (r_{ij}) \sum_{a=1}^{7} \lambda^a_i \cdot \lambda^a_j + V_{\eta} (r_{ij}) \left[ (\lambda^8_i \cdot \lambda^8_j) \cos \theta_P - (\lambda^0_i \cdot \lambda^0_j) \sin \theta_P \right],$$

$$V_{ij}^\sigma = V_{a_0} (r_{ij}) \sum_{a=1}^{3} \lambda^a_i \cdot \lambda^a_j + V_{a_0} (r_{ij}) \sum_{a=1}^{7} \lambda^a_i \cdot \lambda^a_j + V_{f_0} (r_{ij}) \lambda^8_i \cdot \lambda^8_j + V_{\sigma} (r_{ij}) \lambda^0_i \cdot \lambda^0_j,$$

$$S_{ij} = \left\{ \frac{3}{r_{ij}} \left( \sigma_i \cdot r_{ij} \right) \left( \sigma_j \cdot r_{ij} \right) - \sigma_i \cdot \sigma_j \right\},$$

$$H(x) = (1 + 3/x + 3/x^2) Y(x), \quad Y(x) = e^{-x}/x.$$

Where $S_{ij}$ is quark tensor operator; $Y(x)$ and $H(x)$ are standard Yukawa functions; $T_{CM}$ is the kinetic energy of the center of mass; $\alpha_s$ is the quark-gluon coupling con-
The other symbols in the above expressions have their usual meanings. Generally, we use the parameters from our former work of dibaryons, only the mass of charm quark is adjusted to fit the charmed mesons and baryons used in this work. However, the former parameters can describe the ground baryons well, but cannot fit the ground mesons, especially the $K$ meson, the mass of which is much higher than the experimental value. This situation will lead to a consequence that some bound states cannot decay to the open channel $\Xi_c K$, because of the much larger mass of $K$. To solve this problem, we adjust the parameters which are related to $u$ and $d$ quarks. By doing this, the parameters can describe the nucleon-meson interaction well, and at the same time, it will lower the mass of $K$. All the parameters of Hamiltonian are given in Table II. The calculated masses of baryons and mesons in comparison with experimental values are shown in Table III.

\[
g_h^2 = \left(\frac{3}{5}\right)^2 \frac{g_{NN}^2}{4\pi} \frac{m_b^3}{m_N^3}. \tag{10}
\]

The results and discussions

In this work, we investigate the $S$–wave $\Omega^0$ states as the molecular pentaquarks with $I = 0, J^P = \frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$. Three structures are considered here, and they are structure 1: $uss - c\bar{u}$, 2: $usc - s\bar{u}$, and 3: $ssc - u\bar{u}$. All the channels involved are listed in Table III.

### A. Bound state calculation

As the first step, we do a dynamic calculation based on RGM to check whether or not there is any bound state. We expand the relative motion wavefunction between two clusters in the RGM equation by Gaussian bases. By doing this, the integro-differential equation of RGM can be reduced to algebraic equation, generalized eigen-equation. Then we can obtain the energy of the system by solving this generalized eigen-equation. In the present calculation, the baryon-meson separation is taken to be less than 6 fm (to keep the dimensions of matrix manageably small). The single channel calculation shows that the energy of each channel locates above the threshold of the corresponding channel, which means that there is no any singlet bound state. By coupling all the channels with different structures, there exist some bound states. The binding energies and the masses of the bound states, as well as the percentages of each channel in the eigen-states are listed in Table IV. Before discussing the features of the states, we should mention how we obtain the mass of these states. The binding energy $B = M_{\text{the}} - M_{\text{exp}} - M_{\text{M}}$, where $M_{\text{the}}, M_{\text{B}}$, and $M_{\text{M}}$ stand for the theoretical mass of the molecular state, a baryon and a meson, respectively. To minimize the theoretical errors and to compare calculated results to the experimental data, we shift the mass of a molecular state to $M = M_{\text{exp}} + M_{\text{M}}$, where the experimental values of a baryon and a meson are used. Taking the state $J^P = \frac{1}{2}^-$, $\Xi D$ an example, the calculated mass of this state is 3169 MeV, then the binding energy $B$ is obtained by subtracting the theoretical masses of $\Xi$ and $D$, 3169 – 1225 – 1980 = –36 (MeV). Adding the ex-

### TABLE I: Model parameters:

| $b$ (fm) | $m_u$ (MeV) | $m_d$ (MeV) | $m_s$ (MeV) | $m_c$ (MeV) | $m_b$ (MeV) |
|-----------|-------------|-------------|-------------|-------------|-------------|
| 0.518     | 313         | 313         | 450         | 1635        | 4988        |

### TABLE II: The calculated masses of baryons and mesons used in this work (in MeV).

| $\Xi$ | $\Xi^*$ | $\Xi_c$ | $\Xi_c^*$ | $\Omega$ | $\Omega_c$ |
|-------|--------|--------|----------|--------|----------|
| Exp. 1318 | 1533 | 2469 | 2577 | 2646 | 2695 | 2766 |
| ChQM 1225 | 1359 | 2448 | 2527 | 2543 | 2662 | 2672 |

### TABLE III: The channels calculated in this work.

| $J^P$ | Structure | Channels |
|-------|-----------|----------|
| $\frac{1}{2}^-$ | 1. $uss - c\bar{u}$ | $\Xi D, \Xi D^*, \Xi^* D^*$ |
| $\frac{3}{2}^-$ | 2. $usc - s\bar{u}$ | $\Xi c K, \Xi c K^*, \Xi c K^*, \Xi c K^*$ |
| $\frac{5}{2}^-$ | 3. $ssc - u\bar{u}$ | $\Omega_c, \Omega_c, \Omega_c, \Omega_c$ |

### TABLE IV: The calculated masses of $\Xi_c K$ channels.

| $\Xi_0$ | $\Xi_0^*$ | $\Omega_0$ | $\Omega_0^*$ | $B$ | $B^*$ |
|---------|-----------|---------|-----------|-----|------|
| Exp. 5795 | 5935 | 5949 | 6046 | ? | 5279 | 5325 |
| ChQM 5794 | 5880 | 6008 | 6011 | 5351 | 5358 |
TABLE IV: The binding energy and masses (in MeV) of the molecular pentaquarks with channel-coupling and the percentages of each channel in the eigen-states.

| $J^P = \frac{1}{2}^-$ | $J^P = \frac{3}{2}^-$ | $J^P = \frac{5}{2}^-$ |
|---------------------|---------------------|---------------------|
| $E_B$ | $E_B$ | $E_B$ |
| 36 | -1 | -7 |
| $M_{cc}$ | $M_{cc}$ | $M_{cc}$ |
| 3146 | 3324 | 3533 |

The threshold of $\Xi^*$ is too small. The channel-coupling to the $\Xi^*$ channel, which means there is no bound state by all channels coupling. However, we also obtain a quasi-stable state, the mass of which is smaller than the threshold of $\Xi D$, but it fluctuates around the 3146 MeV with about 1 MeV with the variation of the baryon-meson separation. To confirm whether or not the state $\Xi D$ can survive as a resonance state after the full channels coupling, the study of the scattering process of the open channels is needed, which is discussed in subsection B.

For the $J^P = \frac{1}{2}^-$ system, we only find a bound state $\Xi D^*$ with a binding energy of only $-1$ MeV by coupling channels of structure 1 and 3, as shown in Table IV. There is no bound state nor any quasi-stable state by the full channels coupling. However, we still need to calculate the scattering process of the open channel $\Xi c K$ to check if the state $\Xi D^*$ is a resonance or not. The result is also shown in subsection B.

For the $J^P = \frac{3}{2}^-$ system, it includes only one channel of each structure. Although it is not bound for each structure, there exists a bound state by three channels coupling. The binding energy and the mass of this system, as well as the percentages of each channel in the eigen-state are shown in Table IV from which we can see that the mass of the $J^P = \frac{5}{2}^-$ system is 3533 MeV. Moreover, this state can also decay to some open channels, but they are $D$-wave channels. This $S$- and $D$-wave channel-coupling, which is through the tenser force, is always very weak in our quark model calculation [21]. So we can estimate the effect of this kind of coupling is small here. We will do this $S$- and $D$-wave channel-coupling in future.

B. Resonance states and decay widths

To find the resonance mass and decay width of the quasi-stable states discussed in subsection A, we calculate the phase shifts of the corresponding open channels. For the $J^P = \frac{1}{2}^-$ system, coupling to the $S$-wave open channel $\Xi c K$ cause the $\Xi D$ bound state to change into an elastic resonance, where the phase shift, shown in Fig. 1, rises through $\pi$ at a resonance mass. We find the resonance mass is 3146.8 MeV, which shows the energy of the bound state is pushed up a little. From the Fig. 1, the decay width is obviously very narrow, which is only 0.6 MeV. By coupling to another open channel $\Xi c K$, similar results are obtained. The $\Xi D$ bound state changes to a resonance state of the same resonance mass and decay width. Therefore, we can obtain a resonance state $\Xi D$ with $J^P = \frac{1}{2}^-$ in the decay channel $\Xi c K$ or $\Xi c K$, with the resonance mass 3146.8 MeV and decay width 0.6 MeV, which is consistent with the newly reported $\Omega_c (3119)^0$, the decay width of which is $1.1 \pm 0.8 \pm 0.4$ MeV. What’s more, this $\Omega_c (3119)^0$ were observed both in $\Xi c K$ and $\Xi c K$ in the LHCb experiment [9]. So in our quark model calculation, we can explain the $\Omega_c (3119)^0$ as a resonance state $\Xi D$ with $J^P = \frac{1}{2}^-$. 

Fig. 1: The phase shifts of the scattering channels $\Xi c K$ and $\Xi c K$ for the $J^P = \frac{1}{2}^-$ system.
FIG. 2: The phase shifts of the scattering channels $\Xi_b K$ and $\Xi^*_b K$ for the $J^P = \frac{3}{2}^-$ system.

the energy of $\Xi D^*$ above its threshold. So there is no resonance state with $J^P = \frac{3}{2}^-$ in our calculation.

In addition, we also extend the study to the $\Omega_b^0$ system because of the heavy flavor symmetry. The results are similar to that of $\Omega_c^0$ system. We obtain a resonance state $\Xi B$ with $J^P = \frac{1}{2}^-$ in the decay channels $\Xi_b K$ and $\Xi^*_b K$, with the same resonance mass of 6560 MeV and decay width 0.6 MeV (see Fig. 2). Besides, there is a bound state $\Xi^* B^*$ with $J^P = \frac{5}{2}^-$ and the energy of it is 6856 MeV.

IV. SUMMARY

In summary, we investigate the excited $\Omega_b^0$ states as the $S$–wave molecular pentaquarks with $I = 0$, $J^P = \frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$ by solving the RGM equation in the framework of chiral quark model. In this work, we study not only the energies of the $\Omega_c^0$ states but also the decay widths of them. Our results show that the $\Omega_b(3119)^0$ can be explained as an $S$–wave resonance state $\Xi D$ with $J^P = \frac{1}{2}^-$, and the decay channels are the $S$–wave $\Xi_c K$ and $\Xi_b K$. Other newly reported $\Omega_b^0$ states cannot be obtained in our present calculation. They maybe the conventional charmed baryons with $P$–wave or even higher partial waves. It is also possible that these states are mixing states with $q^3$ and $q^2 \bar{q}$. The unquenched quark model, which takes into account the high Fock components, is feasible to do this mixing. We also obtain another $\Omega_b^0$ state with much higher mass, which is 3533 MeV with $J^P = \frac{5}{2}^-$. Besides, the calculation is extended to the $\Omega_b^0$ states, similar results as that of $\Omega_c^0$ are obtained.

Our calculation also shows that the coupling of the structure $uss - \bar{c}u$ and $ssc - \bar{u}i$ is important to make the $\Xi D$ bound, and the coupling with structure $usc - \bar{s}u$ is very weak, which can be used to explain why the reported $\Omega_b(3119)^0$ has a narrow decay width. It also gives us some information that the decay width of these $\Omega_b^0$ states maybe somehow related to the structure of these states. More structures will be studied in future.

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