Understanding the newly observed $\Omega_c$ states through their decays

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The strong and radiative decay properties of the low-lying $\Omega_c$ states are studied in a constituent quark model. We find that the newly observed $\Omega_c$ states by the LHCb Collaboration can fit in well the decay patterns. Thus, their spin-parity can be possibly assigned as the following: (i) The $\Omega_c(3000)$ has $J^P = 1/2^-$ and corresponds to the narrow $1P$ mixed state $|1^P_{1/2}S_{1/2}^+\rangle$, its partner $|1^P_{3/2}S_{1/2}^+\rangle$ should be a broad state with a width of $\sim 100$ MeV. (ii) The $\Omega_c(3050)$ and $\Omega_c(3066)$ can be assigned to be two $J^P = 3/2^-$ states, $|1^P_{3/2}S_{1/2}^+\rangle$ and $|1^P_{3/2}S_{3/2}^+\rangle$, respectively. (iii) The $\Omega_c(3090)$ can be assigned as the $|1^P_{3/2}S_{3/2}^+\rangle$ state with $J^P = 5/2^-$. (iv) The $\Omega_c(3119)$ might correspond to one of the two $2S$ states of the first radial excitations, i.e. $|2^S_{1/2}S_{1/2}^+\rangle$ or $|2^S_{3/2}S_{1/2}^+\rangle$.

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I. INTRODUCTION

Although the existence of $\Omega_c$ states have been predicted by the quark model for a long time, experimental information about the $\Omega_c$ spectrum has been extremely limited during the past several decades. The status about the $\Omega_c$ spectrum can be found in the recent reviews [1-4]. Very recently, five new narrow $\Omega_c$ states, $\Omega_c(2695)1/2^+$, $\Omega_c(3050)1/2^+$, $\Omega_c(3066)1/2^+$, $\Omega_c(3090)1/2^+$ and $\Omega_c(3119)2^-$, were observed in the $\Xi_c^+K^-$ channel by the LHCb Collaboration [5]. This observation can be regarded as a significant progress towards a better understanding of the $\Omega_c$ spectrum and immediately attracts a lot of attention from the hadron physics community. Together with the two established ground states, $\Omega_c(2685)1/2^+$ and $\Omega_c(2770)3/2^+$ [6], the $\Omega_c$ spectrum, for the first time, allows a more quantitative analysis of the internal structures, quantum numbers, and decay modes for higher excited states.

These newly observed $\Omega_c$ states are good candidates for the low-lying $\Omega_c$ resonances. Since the $\Omega_c$ contains a heavy $c$ quark and two relatively light $s$ quarks, the low-lying internal excitations will favor excitations of the so-called "$\lambda$-mode" in one orbital excitation in a Jacobi coordinate between the light quarks and the heavy $c$ quark. Such a structure is illustrated in Fig. 1. According to the mass spectrum from various theoretical studies [7-18], these newly observed $\Omega_c$ states can be organized into the first orbital excitations ($1P$ states with $J^P = 1/2^-, 3/2^-$, $5/2^-$) and the first radial excitations ($2S$ states with $J^P = 1/2^+, 3/2^+$) of the $\lambda$ mode, which have been summarized in Table I. Stimulated by the newly observed $\Omega_c$ states from LHCb, some groups have discussed their nature and possible quantum numbers [19, 22]. The possible spin-parity quantum numbers suggested in the literature are collected in Table I and there are still different views on their properties.

It should be noted that most of these low-lying $\Omega_c$ states have masses in the vicinity of the $\Xi_c^+K^-$ and $\Xi_c^+\bar{K}$ threshold, to which the strong decay will almost saturate their total decay widths. Meanwhile, for these states, their decays will be dominated by the leading constituent quark model wavefunctions instead of detailed structures, e.g. due to hyperfine splittings, because of their relatively small mass differences. In other words, we anticipate that without detailed information about the mass orderings in their classification, one can still possibly identify the predominant feature of their strong decay patterns for given quantum numbers. This makes it possible for us to determine their quantum numbers based on the present available experimental information on the partial and total widths. In addition to the hadronic decay, we also show that the electromagnetic (EM) transitions are useful for providing further information about their internal structures. For the low-lying

FIG. 1: (Color online) $ssc$ system with $\lambda$- or $\rho$-mode excitations. $\rho$ and $\lambda$ are the Jacobi coordinates defined as $\rho = \frac{1}{\sqrt{2}}(r_1 - r_2)$ and $\lambda = \frac{1}{\sqrt{2}}(r_1 + r_2 - 2r_3)$. $q_1$ and $q_2$ stand for the light $s$ quarks, and $Q_3$ stands for the heavy $c$ quark.
interactions in the SU(3) flavor basis are described by the effective quark-photon EM coupling in a non-relativistic form. In the initial-hadron-rest system, the non-relativistic form of the quark-photon EM coupling can be written as

\[ H_p = \sum_j e_j \bar{\psi}_j \gamma^\mu A^\mu(k, r_j) \psi_j, \]

(2)

where \( A^\mu \) represents the photon field with 3-momentum \( k \). \( e_j \) and \( r_j \) stand for the charge and coordinate of the constituent quark \( \psi_j \), respectively.

To match the non-relativistic harmonic oscillator wave functions adopted in our calculations, we should provide the quark-pseudoscalar and quark-photon EM couplings in a non-relativistic form. In the initial-hadron-rest system, the non-relativistic form of the quark-pseudoscalar-meson coupling can be written as

\[ H_m^p = \sum_j \left[ A \sigma_j \cdot q + \frac{\omega_m}{2\mu_q} \sigma_j \cdot (e \times \hat{k}) \right] e^{-imr_j}, \]

(3)

while the nonrelativistic form of the quark-pseudoscalar-meson coupling can be written as

\[ H_m^r = \sum_j \left[ A \sigma_j \cdot q + \frac{\omega_m}{2\mu_q} \sigma_j \cdot (e \times \hat{k}) \right] e^{-imr_j}, \]

(4)

where \( A \equiv - (1 + \frac{\omega_m}{2\mu_q}) \); \( \sigma_j \) and \( p_j \) stand for the Pauli spin vector and internal momentum operator for the \( j \)th quark of the initial hadron; \( q \) is three momentum of the emitted light meson; \( I_j \) is the flavor operator defined for the transitions in the SU(3) flavor space; and \( \mu_q \) is the reduced mass given by \( \frac{1}{\mu_q} = \frac{1}{m_j} + \frac{1}{m_f} \), with \( m_j \) and \( m_f \) for the masses of the \( j \)th quark in the initial and final hadrons, respectively.

For a light pseudoscalar meson emission in a hadron strong decays, the partial decay width can be calculated with [58, 59]

\[ \Gamma_m = \left( \frac{\delta}{f_m} \right)^2 \frac{(E_f + M_f)|q|^2}{4\pi M_f(2J_f + 1)} \sum_{J_c,f_c} |M_{J_f,J_c}|^2, \]

(5)

while for a photon emission in a hadron radiative decays, the partial decay width can be calculated with [60, 61]

\[ \Gamma_Y = \frac{|k|^2}{\pi} \frac{2}{2J_f + 1} \frac{M_f}{M_i} \sum_{J_c,f_c} |A_{J_f,J_c}|^2, \]

(6)

where \( M_{J_f,J_c} \) and \( A_{J_f,J_c} \) correspond to the strong and radiative transition amplitudes, respectively. The quantum numbers \( J_c \) and \( J_f \) stand for the third components of the total angular momenta of the initial and final heavy baryons, respectively. \( \delta \) as a global parameter accounts for the strength of the quark-meson couplings. It has been determined in our previous study of the strong decays of the charmed baryons and heavy-light mesons [58, 59]. Here, we fix its value the same as that in Refs. [58, 59], i.e. \( \delta = 0.557 \).

In the calculation, the standard quark model parameters are adopted. Namely, we set \( m_c = 450 \text{ MeV} \), and \( m_\psi = 1480 \text{ MeV} \) for the constituent quark masses. The harmonic oscillator parameter \( \alpha_p \) in the wave function \( \psi_{in} = R_n Y_{lm} \) of the \( \rho \)-mode excitation between the two \( s \) quarks is taken as \( \alpha_p = 0.44 \text{ GeV} \), which is slightly larger than that of the \( p \)-mode excitation between the two light nonstrange quarks (\( \alpha_p = 0.40 \text{ GeV} \)).
TABLE I: The spectrum of 1P and 2S-wave \(\Omega\) states in the constituent quark model. The total wave function of a \(\Omega\) state is denoted by \(|N^{2S+1}L_J, J^P\rangle\). The Clebsch-Gordan series for the spin and angular-momentum addition \(|N^{2S+1}L_J, J^P\rangle = \sum_{LL',S,S',JJ'}(2L+1)^{1/2}Y_{LL'}^{\ast J}\Psi_{LL'SS'}\phi_{\Omega}\rangle\) has been omitted. The details of the wavefunctions can be found in our previous work [39]. The unit of mass is MeV in the table.

| State \(|N^{2S+1}L_J, J^P\rangle\) | Wave function | Predicted mass [7] | Predicted mass [8] | Predicted mass [9] | Predicted mass [13] | Predicted mass [15] | Predicted mass [14] | Observed state |
|----------------|----------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|----------------|
| \(|0 \uparrow S, \frac{1}{2}\rangle\) | \(0^+\Psi_{00\lambda}^{\ast}, \phi_{\Omega}\) | 2698 | 2745 | 2718 | 2695 | 2731 | 2648(28) | \(\Omega_2(2695)\) |
| \(|0 \uparrow S, \frac{1}{2}\rangle\) | \(0^+\Psi_{00\lambda}^{\ast}, \phi_{\Omega}\) | 2768 | 2805 | 2776 | 2767 | 2799 | 2709(32) | \(\Omega_2(2770)\) |
| \(|1 \uparrow P, \frac{1}{2}\rangle\) | \(1^+\Psi_{11\lambda}^{\ast}, \phi_{\Omega}\) | 3055 | 3015 | 2977 | 3011 | 3030 | 2995(46) | \(\Omega_3(3016)\) |
| \(|1 \uparrow P, \frac{1}{2}\rangle\) | \(1^+\Psi_{11\lambda}^{\ast}, \phi_{\Omega}\) | 3029 | 3030 | 2986 | 2976 | 3033 | 3016(69) | \(\Omega_3(3066)\) |
| \(|1 \uparrow P, \frac{1}{2}\rangle\) | \(1^+\Psi_{11\lambda}^{\ast}, \phi_{\Omega}\) | 2966 | 3040 | 2990 | 3028 | 3048 | \(\Omega_3(3056)\) |
| \(|1 \uparrow P, \frac{1}{2}\rangle\) | \(1^+\Psi_{11\lambda}^{\ast}, \phi_{\Omega}\) | 3054 | 3065 | 2994 | 2993 | 3056 | \(\Omega_3(3056)\) |
| \(|1 \uparrow P, \frac{1}{2}\rangle\) | \(1^+\Psi_{11\lambda}^{\ast}, \phi_{\Omega}\) | 3051 | 3050 | 3014 | 2947 | 3057 | \(\Omega_3(3090)\) |
| \(|2 \uparrow S, \frac{1}{2}\rangle\) | \(2^+\Psi_{20\lambda}^{\ast}, \phi_{\Omega}\) | 3088 | 3020 | 3152 | 3100 | \(\Omega_3(3119)\) |
| \(|2 \uparrow S, \frac{1}{2}\rangle\) | \(2^+\Psi_{20\lambda}^{\ast}, \phi_{\Omega}\) | 3123 | 3090 | 3190 | 3126 | \(\Omega_3(3119)\) |

TABLE II: Spin-parity \((J^P)\) numbers of the newly observed \(\Omega\) states suggested in various works.

| State \(|\Omega\rangle\) | \([19]\) | \([20]\) | \([21]\) | \([22]\) | \([23]\) | \([24]\) | \([25]\) | \([26]\) | This work |
|----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| \(\Omega_2(3000)\) | \(1/2\) | \(1/2\) (3/2) | \(1/2\) | \(1/2\) | \(1/2\) | \(1/2\) | \(1/2\) | \(1/2\) | \(1/2\) |
| \(\Omega_2(3050)\) | \(1/2\) | \(1/2\) (3/2) | \(1/2\) | \(5/2\) | \(3/2\) | \(1/2\) | \(5/2\) | \(3/2\) | \(3/2\) |
| \(\Omega_3(3066)\) | \(1/2\) | \(1/2\) (3/2) | \(1/2\) | \(5/2\) | \(3/2\) | \(5/2\) | \(3/2\) | \(3/2\) | \(1/2\) |
| \(\Omega_3(3050)\) | \(1/2\) | \(1/2\) (3/2) | \(1/2\) | \(5/2\) | \(3/2\) | \(5/2\) | \(3/2\) | \(3/2\) | \(1/2\) |
| \(\Omega_3(3119)\) | \(3/2\) | \(5/2\) (3/2) | \(3/2\) | \(5/2\) | \(3/2\) | \(5/2\) | \(5/2\) | \(5/2\) | \(3/2\) |

III. RESULTS AND DISCUSSIONS

One important feature arising from the hadronic decays of the low-lying \(\Omega\) states is that their hadronic decay properties are determined by their dominant quark excitations. Within a local mass region containing several states, their decays are not sensitive to the local mass orderings which are determined by more detailed dynamics such as spin-dependent forces. Namely, the decay pattern should not change if the mass of such states vary within a small mass range. As a natural assumption for these observed \(\Omega\) states that they are most likely the 1P and 2S excited states, one can easily check that in most models the relative partial decay widths will not change dramatically if their masses change within 100 MeV (see figs. 3 and 4). In such a sense, the pattern arising from the relative partial widths should be more selective to their quantum numbers instead of their masses.

In Table III the calculations of the partial decay widths for the \(P\)-wave states into \(\Xi K, \Xi' K, \) and radiative decay channels are listed. It can be seen that although there are still some uncertainties with both the experimental and theoretical results, the magnitudes of the partial decay widths have indicated patterns determined by the three-body quark model wavefunctions.

A. \(\Omega_2(3000)\)

To be more specific, the relatively low mass of \(\Omega_2(3000)\) make it a good candidate for the \(J^P = 1/2^-\) states as the first orbital excitation states of \(|1^2P_{1/2}^-\rangle\) or \(|1^4P_{1/2}^-\rangle\). However, the quark model predicts rather broad widths for both \(|1^2P_{1/2}^-\rangle\) and \(|1^4P_{1/2}^-\rangle\) (see fig. 3) and suggest more profound configurations with the physical state. It could happen that these two \(J^P = 1/2^-\) states \(|1^2P_{1/2}^-\rangle\) and \(|1^4P_{1/2}^-\rangle\) can have significant mixings for the presence of the spin-orbit interaction. Thus, we further consider the \(\Omega_2(3000)\) as a mixed state of \(|1^2P_{1/2}^-\rangle\) and \(|1^4P_{1/2}^-\rangle\) by the following mixing scheme

\[
\begin{align*}
|1^2P_{1/2}^-\rangle_1 &= + \cos(\phi) \left|1^2P_{1/2}^-\right\rangle + \sin(\phi) \left|1^4P_{1/2}^-\right\rangle, \\
|1^4P_{1/2}^-\rangle_2 &= - \sin(\phi) \left|1^2P_{1/2}^-\right\rangle + \cos(\phi) \left|1^4P_{1/2}^-\right\rangle.
\end{align*}
\]
The solid lines stand for the total width of these two channels. At this moment we do not intend to determine the mass of the other mixed state with a width much larger than these observed states. At
doubling the mixing angle, it shows that with a mixing angle nearly 54◦, the measured decay width $\Gamma \approx 4.5 \pm 0.9$ MeV of $\Omega_c(3000)$ can be well explained. Note that an intrinsic sign between $|1^2P_{3/2}^{3/2}\rangle$ and $|1^4P_{3/2}^{3/2}\rangle$ is included which introduces the cancelation between the two transition amplitudes from these two configurations. In Ref. [25] a similar mixing mechanism for obtaining a narrow width for the $1/2^-$ state is also discussed in the basis of heavy quark spin symmetry (HQSS).

FIG. 3: The strong decay partial width as a function of mass. The dashed and dotted lines stand for the partial width of $\Xi^c K$ and $\Xi_c^*$ channels, respectively. The solid lines stand for the total width of these two channels.

Taking the $\Omega_c(3000)$ as the mixed state $|1^2P_{3/2}^{3/2}\rangle$, we plot the strong decay width into the $\Xi_c^* K$ channel as a function of the mixing angle $\phi$ in fig. [5] It shows that with a mixing angle $\phi \approx 24^\circ$ or $47^\circ$, the measured decay width $\Gamma \approx 4.5 \pm 0.9$ MeV of $\Omega_c(3000)$ can be well explained. Note that an intrinsic sign between $|1^2P_{3/2}^{1/2}\rangle$ and $|1^4P_{3/2}^{1/2}\rangle$ is included which introduces the cancelation between the two transition amplitudes from these two configurations. In Ref. [25] a similar mixing mechanism for obtaining a narrow width for the $1/2^-$ state is also discussed in the basis of heavy quark spin symmetry (HQSS).

If $\Omega_c(3000)$ corresponds to the mixed state $|1^2P_{3/2}^{1/2}\rangle$ indeed, the other mixed state $|1^4P_{3/2}^{1/2}\rangle$ should be a broad state with a width much larger than these observed states. At this moment we do not intend to determine the mass of the broad state but only discuss its width range near the mass of $\Omega_c(3000)$. It is found that with the mass of 2980 MeV, the decay width of $|1^4P_{3/2}^{1/2}\rangle$ is about ~ 70 MeV, while with the mass of 3020 MeV the width is about ~ 110 MeV. This presumably suggests the difficulty of identifying it from the background in the present data sets. One notices that in the LHCb data there are events excesses below $\Omega_c(3000)$ which are noted as the feed-down events from higher partially constructed $\Omega_c(X)$ states. It would be interesting to have more elaborate analysis of these event excesses to look for signals of the broad $1/2^-$. Moreover, it shows that that the lineshape of $\Omega_c(3000)$ has been distorted at the higher energy side and a broad structure is present below the narrow $\Omega_c(3000)$. Further analysis of the $\Xi_c^* K^-$ invariant mass spectrum may help clarify the status of the broad partner of $\Omega_c(3000)$.

The assignment of $\Omega_c(3000)$ as the narrow $1/2^-$ state naturally leads to the dominance of the $E1$ transition in the EM transitions of $\Omega_c(3000) \rightarrow \Omega_c(2695)\gamma$. It predicts an EM transition partial width of $200\sim 360$ keV, which is quite significant and can be searched for in experiments as further evidence for its assignment. We also take the ratio between the EM and hadronic decays as a guidance for its future studies:

$$\frac{\Gamma(\Omega_c(2695)\gamma)}{\Gamma(\Xi_c^* K)} \approx 5 \sim 9\%.$$ (9)

The EM transition of the state to $\Omega_c(2770)$ can also be calculated. Taking into account the phase space factor, it predicts a rather small partial decay width of about $10^5$ keV, which is much smaller than that for $\Omega_c(3000) \rightarrow \Omega_c(2695)\gamma$.

B. $\Omega_c(3050)$

The $\Omega_c(3050)$ is most likely to be the $J^P = 3/2^-$ state. It corresponds to $|1^4P_{3/2}^{3/2}\rangle$. If we assign the $\Omega_c(3050)$ as $|1^4P_{3/2}^{3/2}\rangle$, the two main decay channels will be $\Xi_c K$ and $\Omega_c(2770)\gamma$ with the latter dominated by the $E1$ transition. The partial decay width of $\Omega_c(3050) \rightarrow \Xi_c K$ is estimated to be about 0.61 MeV and the EM transition width of 0.33 MeV. The EM transition of $\Omega_c(3050) \rightarrow \Omega_c(2695)\gamma$ in the assignment of $|1^4P_{3/2}^{3/2}\rangle$ will be suppressed by the $M2$ transition which leads to a small partial width of $1.12 \times 10^{-3}$ MeV. The total width reads about 0.94 MeV which is also nearly saturated by the hadronic and EM decays. This value is consistent with the data. The large branching ratio of the radiative transition of $\Omega_c(3050)$ into the $\Omega_c(2770)\gamma$ channel

$$Br(\Omega_c(3050) \rightarrow \Omega_c(2770)\gamma) \approx 35\%,$$ (10)

indicates that the radiative transition of $\Omega_c(3050) \rightarrow \Omega_c(2770)\gamma$ should be accessible in future experiment.

C. $\Omega_c(3066)$

The $\Omega_c(3066)$ can be assigned to another $J^P = 3/2^-$ state, $|1^2P_{3/2}^{3/2}\rangle$. As the result, the $\Omega_c(3066)$ will mainly decay into $\Xi_c K$ and $\Omega_c(2695)\gamma$, while its decays into $\Omega_c(2770)\gamma$ will be suppressed due to the spin-flipping $M2$ transition. Our results
Following this scenario, its radiative decay rate into the \( \Omega \) of the radiative transition data of 3.

The \( \Omega \) data have been listed in Table III. One can see that the total width \( \Gamma \approx 4.96 \text{ MeV} \) is in good agreement with the experimental data of 3.5\( \pm \)0.4\( \pm \)0.2 MeV. In this scenario, the branching ratio of the radiative transition \( \Omega_c(3066) \rightarrow \Omega_c(2695)\gamma \) is predicted to be a fairly large value:

\[
Br[\Omega_c(3066) \rightarrow \Omega_c(2695)\gamma] \approx 7\%.
\] (11)

This makes the experimental measurement of the radiative decay of \( \Omega_c(3066) \rightarrow \Omega_c(2695)\gamma \) a possible way to further test its configuration.

D. \( \Omega_c(3090) \)

The \( \Omega_c(3090) \) can be assigned to the \( J^P = 5/2^- \) state, \( |1^+P_{1/2} \rangle \). Its decays are governed by the strong decay channel \( \Xi_c\bar{K} \), and the predicted partial width is

\[
\Gamma[\Omega_c(3090) \rightarrow \Xi_c\bar{K}] \approx 9.32 \text{ MeV}.
\] (12)

Following this scenario, its radiative decay rate into the \( \Omega_c(2770)\gamma \) is expected to be sizeable with a ratio of

\[
\frac{\Gamma[\Omega_c(3090) \rightarrow \Omega_c(2770)\gamma]}{\Gamma[\Omega_c(3090) \rightarrow \Xi_c\bar{K}]} \approx 2\%.
\] (13)

The total width is nearly saturated by the \( \Xi_c\bar{K} \) channel and with the EM transition the total width, \( \Gamma \approx 9.5 \text{ MeV} \), is in good agreement with the measured width 8\( \pm \)1.0\( \pm \)0.8 MeV. To confirm the nature of \( \Omega_c(3090) \), experimental measurements of the radiative decay \( \Omega_c(3090) \rightarrow \Omega_c(2770)\gamma \) are strongly recommended.

E. \( \Omega_c(3119) \)

The \( \Omega_c(3119) \) has the highest mass among these five states but has a narrow width of 1.1\( \pm \)0.8\( \pm \)0.4 MeV. It may be assigned to be one of the first radially excited states, i.e. either \( |2^2S_{1/2}^{1}\rangle \) or \( |2^4S_{1/2}^{3}\rangle \). These 2S radial excitation states are found to usually have a very narrow decay width, which is about 1 MeV (see Table IV). Considering the \( \Omega_c(3119) \) as the \( |2^2S_{1/2}^{1}\rangle \) state, we find that \( \Omega_c(3119) \) should have two main decay channels, i.e. \( \Xi_c\bar{K} \) and \( \Xi_c\bar{K} \), of which the calculated partial widths are listed in Table IV. By summing up these dominant partial widths, the total width amounts to about 1.2 MeV, which is consistent with the central value of the experimental data. In this assignment, one notices that partial decay widths of the \( \Xi_c\bar{K} \) and \( \Xi_c\bar{K} \) channels are compatible.

In contrast, by assigning \( \Omega_c(3119) \) as the \( |2^4S_{1/2}^{3}\rangle \) state, we find that it mainly decays into \( \Xi_c\bar{K} \) and \( \Xi_c\bar{K} \) channels. Also, the partial width into \( \Xi_c\bar{K} \) will be much larger (about a
factor of 6) than into the $\Xi_K^-$ channel. The calculated partial decay widths in this assignment are also listed in Table IV. The measurement of the partial decay widths into these two channels should allow a determination of the quantum number and structure of the $\Omega_c(3119)$.

F. $\Omega_c(2770)$

As a byproduct, we also study the radiative decay process $\Omega_c(2770) \to \Omega_c(2695)\gamma$ as a test of our simple model. Our predicted partial width is

$$\Gamma(\Omega_c(2770) \to \Omega_c(2695)\gamma) \approx 0.89 \text{ keV},$$

which is in good agreement with other predictions in Refs. [63,66]. Interestingly, one notices that the lattice QCD simulation yields a rather small value for this quantity at nearly physical pion mass [67], which is about an order of magnitude smaller than phenomenological model calculations. Finally, it should be mentioned that the decay widths of the low-lying $S$ and $P$-wave charmed baryons, such as $\Sigma_c(2455, 2520)$, $\Lambda_c(2593, 2625)$ and $\Xi_c(2645, 2815)$, predicted within our nonrelativistic constituent quark model [39,40] are in good agreement with the relativistic quark model predictions [68,69] and the experimental data [6], which indicates that the relativistic effects are relatively small for these processes.

IV. SUMMARY

In this work we have studied the strong and radiative decay properties of the newly observed $\Omega_c$ states, i.e. $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$, $\Omega_c(3090)$ and $\Omega_c(3119)$, by LHCb Collaboration in a constituent chiral quark model. It shows that these low-lying states can be accommodated into the quark model with the consideration of proper internal excitations. In particular, the excitations of the $\lambda$ mode in the Jacobi coordinate (Fig. 1) will give rise to the main configurations of these observed states.

It is also found that for these low-lying states with masses close to each other, their relative magnitudes of partial decay widths are a more selective observable for the determination of their quantum numbers. In contrast, the mass ordering pattern, which are determined by more detailed dynamics, may not be an ideal quantity for classifying their quantum numbers at the present stage.

As a conclusion of this investigation, the following assignments seem to be favored in the quark model: (i) The $\Omega_c(3000)$ has $J^P = 1/2^−$ and corresponds to the narrow $1P$ mixed state $|1P_1/2⟩_1$. Its partner $|1P_3/2⟩_2$ should be a broad state, which is worthy looking for in the future experiments. The lineshape distortion under the peak of $\Omega_c(3000)$ may be a signal for its presence. (ii) Both $\Omega_c(3050)$ and $\Omega_c(3066)$ have $J^P = 3/2^−$ and correspond to the $1P$ states $|1P_1⟩_1^+\gamma$ and $|1P_3⟩_2^+\gamma$, respectively. The $\Omega_c(3050)$ is expected to have large radiative decay rates into the $\Omega_c(2770)\gamma$ channel, while $\Omega_c(3066)$ has large radiative decay rates into the $\Omega_c(2695)\gamma$ channel. (iii) The $\Omega_c(3090)$ should correspond to the $J^P = 5/2^−$ state $|1P_3⟩_2^+\gamma$. The radiative decay rate of $\Omega_c(3050) \to \Omega_c(2770)\gamma$ is expected to be large as well. (iv) The $\Omega_c(3119)$ may correspond to one of the first radially excited $2S$ states, i.e. either $|2S_1⟩_1^+\gamma$ or $|2S_1⟩_2^+\gamma$. The relative partial decay width fraction $\Gamma(\Xi_cK) / \Gamma(\Xi_cK)$ can distinguish these two different assignments with either $J^P = 1/2^+$ or $3/2^+$.

Finally, we emphasize that the EM transitions appear to be useful for determining the quantum numbers of these $\Omega_c$ states in this analysis. Future experiments measuring their radiative decay widths are strongly recommended.

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TABLE III: The decay properties of the $P$-wave states compared with the observations. $\Gamma_{\text{total}}^{\text{exp}}$ stands for the total width obtained from the LHCb experiments. The unit of mass and width is MeV in the table.

| state | Mass (MeV) | $\Gamma(\Xi_c^+ \Lambda)$ | $\Gamma(\Xi_c^+ \Xi^0)$ | $\Gamma(\Omega_c(2695)\gamma)$ | $\Gamma(\Omega_c(2770)\gamma)$ | $\Gamma_{\text{total}}^{\text{exp}}$ | $\Gamma_{\text{total}}^{\text{exp}}$ Possible assignment |
|-------|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|------------------------------|
| $|P_{1/2}^+(1)$ | 3000 | 4.0 | | 0.36 | 0.20 | 0.02/0.08 | 4.38/4.28 | 4.5 ± 0.9 | $\Omega_c(3000)$ |
| $|P_{3/2}^+(1)$ | 3050 | 0.61 | | 1.12 × 10^{-3} | | 0.33 | 0.94 | 0.8 ± 0.3 | $\Omega_c(3050)$ |
| $|P_{1/2}^+(2)$ | 3066 | 4.61 | | 0.35 | 5.68 × 10^{-4} | | 4.96 | 3.5 ± 0.4 | $\Omega_c(3066)$ |
| $|P_{3/2}^+(2)$ | 3090 | 9.32 | 0.03 | 1.00 × 10^{-4} | | 0.18 | 9.53 | 8.7 ± 1.8 | $\Omega_c(3090)$ |

TABLE IV: The decay properties of $\Omega_c(3119)$ as the $2S$ states. $\Gamma_{\text{total}}^{\text{exp}}$ stands for the total width obtained from the LHCb experiments, while $\Gamma_{\text{total}}^{\text{exp}}$ stands for the total width obtained from the LHCb experiments. The unit of mass and width is MeV in the table.

| state | Mass (MeV) | $\Gamma(\Xi_c^+ \Lambda)$ | $\Gamma(\Xi_c^+ \Xi^0)$ | $\Gamma(\Omega_c(2695)\gamma)$ | $\Gamma(\Omega_c(2770)\gamma)$ | $\Gamma_{\text{total}}^{\text{exp}}$ | $\Gamma_{\text{total}}^{\text{exp}}$ |
|-------|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $|S_{1/2}^+(2)$ | 3119 | 0.60 | 0.45 | 2.9 × 10^{-3} | 6.4 × 10^{-4} | 1.15 | 1.1 ± 0.8 ± 0.4 |
| $|S_{1/2}^+(3)$ | 3119 | 0.60 | 0.11 | 1.0 × 10^{-3} | 8.1 × 10^{-4} | 0.73 | 1.1 ± 0.8 ± 0.4 |

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