A possible interpretation of the newly observed $\Omega(2012)$ state

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Inspired by the newly observed $\Omega(2012)$ state at Belle II, we investigate the two-body strong decays of $\Omega$ baryons up to $N = 2$ shell within the chiral quark model. Our results indicate that: (i) the newly observed $\Omega(2012)$ state could be assigned to the spin-parity $J^P = 3/2^-$ state $[70,^2 10, 1, 1, \frac{3}{2}^-]$ and the experimental data can be reasonably described. However, the spin-parity $J^P = 1/2^-$ state $[70,^2 10, 1, 1, \frac{1}{2}^-]$ and spin-parity $J^P = 3/2^+$ state $[56,^4 10, 2, 0, \frac{3}{2}^-]$ can’t be completely excluded. (ii) The $D$-wave states in the $N = 2$ shell are most likely to be narrow states with a width of dozens of MeV and have a good potential to be observed in the $\Xi K$ and/or $\Xi(1530)K$ channels in future experiments. The $\Omega(2250)$ resonance listed in PDG may be a good candidate of the $J^P = 5/2^+ 1D$ wave state $[56,^4 10, 2, 2, 5/2^+]$.

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I. INTRODUCTION

Searching for the missing baryon resonances and understanding the baryon spectrum are important topics in hadron physics. In the past years, for the limitations of experimental conditions, our knowledge about $\Omega$ spectrum is still scarce. There are only a few data on the $\Omega$ resonances. In the review of the Particle Data Group (PDG) [1], only four $\Omega$ baryon states are listed: $\Omega(1672)$, $\Omega(2250)$, $\Omega(2380)$, and $\Omega(2470)$. Except the ground state $\Omega(1672)$ being well established with four-star ratings, the nature of the other three excited states are still rather uncertain with three- or two-star ratings. Fortunately, the Belle II experiments offer a great opportunity for our study of the $\Omega$ spectrum.

Very recently, Belle II Collaboration reported a new excited hyperon, an $\Omega^-$ candidate (denoted by $\Omega(2012)$ here), in the $\Xi^0 K^-$ and $\Xi^- K^0$ mass distributions very recently [22]. Its mass and decay width are measured to be

$$M = 2012.4 \pm 0.7 \text{ (stat)} \pm 0.6 \text{ (syst)} \text{ MeV}$$

and

$$\Gamma = 6.4^{+2.5}_{-2.0} \text{ (stat)} \pm 0.6 \text{ (syst)} \text{ MeV},$$

respectively. In various models and methods, such as the Skyrme model [2], quark model [3,4], lattice gauge theory [13,14] and so on [15,19], the masses of the first orbital excitations of $\Omega(1672)$ are predicted to be $\sim 2.0$ GeV. Thus, the newly observed $\Omega(2012)$ may be a good candidate of the first orbital $(1P)$ excitations of $\Omega(1672)$. In Ref. [9], the mass of $2S$ state (the first radially excitation of $\Omega(1672)$) with $J^P = 3/2^-$ was predicted to be 2065 MeV, which is also close to the mass of $\Omega(2012)$. To further determine the spin-parity quantum numbers and inner structure of $\Omega(2012)$, besides its mass one should study its other properties, such as magnetic moments, radiative and strong decays properties, as well. In the early literature, limited discussions exist on the magnetic moments [20], radiative decays [21] of the $\Omega$ resonances. In present work we will attempt to understand the inner structure of this newly observed state $\Omega(2012)$ by analyzing the strong decay properties of its possible candidates within a chiral quark model, so that our theoretical widths can be compared with the measured width directly.

The chiral quark model [23] is developed and successfully used to study the Okubo-Zweig-Iizuka (OZI) allowed two-body strong decays of the heavy-light mesons [24,27] and baryons [28,55]. In this framework, the spatial wave functions of heavy baryons are described by harmonic oscillators, and an effective chiral Lagrangian is then introduced to account for the quark-meson coupling at the baryon-meson interaction vertex. The light pseudoscalar mesons, i.e., $\pi$, $K$, and $\eta$, are treated as Goldstone bosons. Since the quark-meson coupling is invariant under the chiral transformation, some of the low-energy properties of QCD are retained [23,36–38]. Within the chiral quark model, the OZI allowed two-body strong decays of $\Omega$ baryons up to $N = 2$ shell are analyzed in present work. The quark model classification for the $\Omega$ baryons and their theoretical masses are listed in Table 1. According to our calculations, we obtain that (i) the newly observed $\Omega(2012)$ resonance could be assigned to the spin-parity $J^P = 3/2^-$ state $[70,^2 10, 1, 1, \frac{3}{2}^-]$ and the experimental data can be reasonably described. However, the spin-parity $J^P = 1/2^-$ state $[70,^2 10, 1, 1, \frac{1}{2}^-]$ and spin-parity $J^P = 3/2^+$ state $[56,^4 10, 2, 0, \frac{3}{2}^-]$ can’t be completely excluded. (ii) The $D$-wave states in the $N = 2$ shell are most likely to be narrow states with a width of dozens of MeV and have a good potential to be observed in their corresponding dominant decay channels. The $\Omega(2250)$ resonance listed in PDG may be a good candidate of the $J^P = 5/2^+ 1D$ wave state $[56,^4 10, 2, 2, 5/2^+]$. This paper is organized as follows. In Sec. II we give a brief introduction of the chiral quark model. We present our
TABLE I: The theoretical masses (MeV) and spin-flavor-space wavefunctions of baryons, denoted by \([N^e, \frac{25}{3}+1, N_s, L, J^P]\) [30]. The Clebsch-Gordan series for the spin and angular-momentum addition \([J, J_z] = \sum_{l^e_s, s, l, L, S} J^e_s \langle J | J_z \rangle W_{J^e_s, L, S} \). The \([J, J_z] = \sum_{l^e_s, s, l, L, S} J^e_s \langle J | J_z \rangle W_{J^e_s, L, S} \) has been omitted.

| State | Wavefunction | Experiment \([1]\) | Theory \([4]\) | \([5]\) | \([6]\) | \([7]\) |
|-------|-------------|----------------|--------|--------|--------|--------|
| \([56,^4, 10, \bar{0}, 0, \frac{1}{2}^-]\) | \([56,^4, 10]^\Psi^m_{100}\) | 1672.45 | 1678 | 1635 | 1694 | 1675 |
| \([70^2, 10, 1, 1, \frac{1}{2}^-]\) | \([70^2, 10]^\Psi^m_{111L}\) | \([70^2, 10]^\Psi^m_{111L}\) | 1941 | 1950 | 1837 | 2020 |
| \([70^2, 10, 1, 1, \frac{1}{2}^-]\) | \([70^2, 10]^\Psi^m_{111L}\) | \([70^2, 10]^\Psi^m_{111L}\) | 2038 | 2000 | 1978 | 2020 |
| \([70^2, 10, 2, 0, \frac{1}{2}^-]\) | \([70^2, 10]^\Psi^m_{200}\) | \([70^2, 10]^\Psi^m_{200}\) | 2301 | 2220 | 2140 | 2190 |
| \([56,^4, 10, 2, 2, \frac{1}{2}^-]\) | \([56,^4, 10]^\Psi^m_{22L}\) | \([56,^4, 10]^\Psi^m_{22L}\) | 2255 | 2210 |
| \([56,^4, 10, 2, 0, \frac{1}{2}^-]\) | \([56,^4, 10]^\Psi^m_{200}\) | \([56,^4, 10]^\Psi^m_{200}\) | 2173/2304 | 2280 | 2282 | 2215 |
| \([70^2, 10, 2, 2, \frac{1}{2}^-]\) | \([70^2, 10]^\Psi^m_{22L}\) | \([70^2, 10]^\Psi^m_{22L}\) | 2345 | 2265 |
| \([56,^4, 10, 2, 2, \frac{1}{2}^-]\) | \([56,^4, 10]^\Psi^m_{22L}\) | \([56,^4, 10]^\Psi^m_{22L}\) | 2401 | 2280 | \([56,^4, 10]^\Psi^m_{22L}\) | 2225 |
| \([70^2, 10, 2, 2, \frac{1}{2}^-]\) | \([70^2, 10]^\Psi^m_{22L}\) | \([70^2, 10]^\Psi^m_{22L}\) | 2345 | \([56,^4, 10]^\Psi^m_{22L}\) | 2265 |
| \([56,^4, 10, 2, 2, \frac{1}{2}^-]\) | \([56,^4, 10]^\Psi^m_{22L}\) | \([56,^4, 10]^\Psi^m_{22L}\) | 2332 | 2295 | \([56,^4, 10]^\Psi^m_{22L}\) | 2210 |

**II. THE CHIRAL QUARK MODEL**

In the chiral quark model, the effective low energy quark-pseudoscalar-meson coupling in the SU(3) flavor basis at tree level is given by [28]

\[
H_m = \sum_{j} \frac{1}{f_{m}} \bar{\psi}_j \gamma^{\mu} \gamma_5 \psi_j \phi^\mu_m, \tag{3}
\]

where \(f_m\) stands for the pseudoscalar meson decay constant. \(\psi_j\) corresponds to the \(j\)th quark field in a baryon and \(\phi_m\) denotes the pseudoscalar meson octet

\[
\phi_m = \begin{pmatrix}
\nu_\mu \eta^\nu + \nu^\nu \eta \\
\pi^+ \\
\pi^- - \nu_\mu \eta + \nu^\nu \eta \\
K^+ \\
\bar{K}^0 \\
K^0 - \nu_\mu \eta + \nu^\nu \eta
\end{pmatrix}. \tag{4}
\]

To match the nonrelativistic harmonic oscillator spatial wave function \(\Psi_{NLL}\), in the calculations, we adopt a nonrelativistic form of Eq. (3) and get [34][35]

\[
H_m^{nr} = \sum_{j} \left( \frac{\omega_m}{E_j + M_f} \sigma_j \cdot P_f + \frac{\omega_m}{E_i + M_i} \sigma_j \cdot P_i \right) - \sigma_j \cdot \mathbf{q} + \frac{\omega_m}{2 \mu_q} \sigma_j \cdot \mathbf{p}_j, \tag{5}
\]

where \((E_i, \mathbf{p}_i), (E_f, \mathbf{p}_f)\) and \((\omega_m, \mathbf{q})\) stand for the energy and three-vector momentum of the initial baryon, final baryon and meson, respectively. \(\sigma_j\) is the Pauli spin vector on the \(j\)th quark, and \(\mu_q\) is a reduced mass expressed as \(1/\mu_q = 1/m_j + 1/m_f\). \(P_j = \mathbf{p}_j - (m_j/M) \mathbf{p}_{c.m.}\) is the internal momentum of the \(j\)th quark in the baryon rest frame. \(\varphi_m = e^{-i q \cdot r}\) and \(e^{i q \cdot r}\) for emitting and absorbing a meson, respectively. The isospin operator \(I_j\) associated with the pseudoscalar meson is given by

\[
I_j = \begin{pmatrix}
\alpha_j^u(u) \alpha_j(s) \\
\alpha_j^d(d) \alpha_j(s) \\
\frac{1}{\sqrt{2}} \{ \alpha_j^u(u) \alpha_j(u) + \alpha_j^d(d) \alpha_j(d) \} \cos \theta \\
\alpha_j^u(s) \alpha_j(s) \sin \theta
\end{pmatrix}, \tag{6}
\]

for \(K^-\), \(K^0\), and \(\eta\). Here, \(\alpha_j^u(u, d, s)\) and \(\alpha_j(u, d, s)\) are the creation and annihilation operator for the \(u, d, s\) quarks on the \(j\)th quark. \(\theta\) is the mixing angle of the \(\eta\) meson in the flavor basis [1].

For the decay processes, we select the initial-baryon-rest system in the calculations. Then, \(p_i = 0\) and \(p_f = -q\). The Eq. (5) can be further simplified and the partial decay amplitudes for \(B \to B' M\) can be calculated by

\[
M[B \to B'M] = 3 \left\langle B' \bigg| (G \sigma_3 \cdot \mathbf{q} + D \sigma_3 \cdot \mathbf{p}_3) I_5 e^{-i q \cdot R} \bigg| B \right\rangle. \tag{7}
\]

with

\[
h \equiv \frac{\omega_m}{2 \mu_q}, \quad G \equiv \left( \frac{\omega_m}{E_f + M_f} + 1 \right), \tag{8}
\]

where \(B'\) and \(B\) stand for the final and initial baryon wave functions listed in Table I.

With the derived decay amplitudes, the partial decay width for the emission of a light pseudoscalar meson is calculated by

\[
\Gamma = \left( \frac{5}{2m} \right)^2 \left( \frac{E_f + M_f}{4 \pi M_f} \right) \frac{1}{2 J_f + 1} \sum_{J_{c.f.}} |M_{J_{c.f.}}|^2, \tag{9}
\]

where \(J_{c.f.}\) and \(J_f\) represent the third components of the to-
predicted masses in various quark models for these two $1P$ wave states are about 2000 MeV, which are close to the mass of the newly observed $\Omega^{-}$ candidate [22]. As the possible assignments of the newly observed $\Omega(2012)$ state, it is crucial to study the decay properties of the two states.

Considering the $\Omega(2012)$ state as candidates of both the $J^P = 1/2^-$ and $J^P = 3/2^-$ states, we calculate their strong decay properties, our results are shown in Table III. As a candidate of the $J^P = 3/2^-$ state $[70^2, 10, 1, 1/2^-]$, the predicted width

$$\Gamma_{\text{total}}^{\Omega(2012)} = 6.6 \text{ MeV},$$

and branching fraction ratio

$$\mathcal{R} = \frac{\mathcal{B}[\Omega(2012) \to \Xi^0 K^-]}{\mathcal{B}[\Omega(2012) \to \Xi^- \bar{K}^0]} \approx 1.12,$$

are highly consistent with the measured width $\Gamma_{\exp} = 6.4^{+2.5}_{-2.0} \pm 0.6 \text{ MeV}$ and ratio $\mathcal{R}_{\exp} = 1.2 \pm 0.3$ of the newly observed $\Omega(2012)$ state.

Meanwhile, as candidate of the $J^P = 1/2^-$ state $[70^2, 10, 1, 1/2^-]$, the predicted width for $\Omega(2012)$ is

$$\Gamma_{\text{total}}^{\Omega(2012)} = 15.2 \text{ MeV},$$

and the branching fraction ratio is predicted to be

$$\mathcal{R} = \frac{\mathcal{B}[\Omega(2012) \to \Xi^0 K^-]}{\mathcal{B}[\Omega(2012) \to \Xi^- \bar{K}^0]} \approx 0.95,$$

The predicted total decay width of is about 2.5 times larger than the measured width of $\Omega(2012)$. Considering the model uncertainties, the possibility as the assignment of $J^P = 1/2^-$ state $[70^2, 10, 1, 1/2^-]$ can’t be excluded.

| States                  | $\Gamma[\Xi^0 K^-]$ | $\Gamma[\Xi^- \bar{K}^0]$ | $\Gamma_{\text{total}}^{\Omega}$ |
|-------------------------|---------------------|-----------------------------|----------------------------------|
| $[70^2, 10, 1, 1/2^-]$  | 7.43                | 7.82                        | 15.2                             |
| $[70^2, 10, 1, 1, 3/2^-]$ | 3.51               | 3.12                        | 6.64                             |

Considering the uncertainties of the predicted masses, we plot the variation of the decay properties of the two states as functions of the masses in Fig. I. The total decay width of $[70^2, 10, 1, 1/2^-]$ is about $\Gamma \sim (12 - 18) \text{ MeV}$ with the mass varied in the range of (1900-2100) MeV and insensitive to its mass within the considered range. For the state $[70^2, 10, 1, 3/2^-]$, if it lies below the threshold of $\Xi(1530)K$, its dominant decay mode is $ZK$ with a fairly narrow width $\Gamma < 8 \text{ MeV}$. However, if its mass is above the threshold of $\Xi(1530)K$, it mainly decays into $\Xi(1530)K$ channel and its total decay width may reach up to $\Gamma \sim 90 \text{ MeV}$ with the mass $M = 2100 \text{ MeV}$.  

![Graph](image.png)
TABLE III: The predicted partial and total decay widths of the $S$- and $D$-wave states in the $N = 2$ shell. $\Gamma_{\text{total}}^{\text{th}}$ stands for the total decay width and $\mathcal{B}$ represents the ratio of the branching fraction $\Gamma(\Xi K)/\Gamma(\Xi(1530)K)$. The unit of widths and masses is MeV.

| States       | Mass [7] | $\Gamma(\Xi K)$ | $\Gamma(\Xi(1530)K)$ | $\Gamma(\Omega K)$ | $\Gamma_{\text{total}}^{\text{th}}$ | $\mathcal{B}$ |
|--------------|----------|-----------------|----------------------|---------------------|--------------------------------------|--------------|
| $2S$ wave    | $[70,2,10,2,0,1/2^+)]$ | 2190             | 0.06                 | 2.43                | $\cdots$                             | 2.49         | 0.02         |
|              | $[56,4,10,2,0,3/2^+)]$ | 2065             | 0.96                 | $\cdots$            | 2.00                                 | 1.07         |
| $1D$ wave    | $[56,4,10,2,2,1/2^+)]$ | 2210             | 51.8                 | 4.53                | $\cdots$                             | 56.3         | 11.4         |
|              | $[56,4,10,2,2,3/2^+)]$ | 2215             | 25.8                 | 15.7                | $\cdots$                             | 41.5         | 1.64         |
|              | $[56,4,10,2,2,5/2^+)]$ | 2225             | 6.58                 | 22.6                | 0.11                                 | 29.2         | 0.29         |
|              | $[56,4,10,2,2,7/2^+)]$ | 2210             | 26.2                 | 1.51                | $\cdots$                             | 27.7         | 17.4         |
|              | $[70,2,10,2,2,3/2^+)]$ | 2265             | 7.40                 | 11.9                | 1.60                                 | 20.9         | 0.62         |
|              | $[70,2,10,2,2,5/2^+)]$ | 2265             | 0.99                 | 11.6                | 0.83                                 | 13.4         | 0.08         |

B. 2S wave states in the $N = 2$ shell

In the quark model, there are two $2S$ wave states with $J^P = 1/2^+$ and $J^P = 3/2^+$. Their masses were predicted to be about 2.19 GeV and 2.06 GeV, respectively. Using these predicted masses, we calculate their partial and total strong decay widths. Our results have been listed in Table III. It is found that both $[70,2,10,2,0,1/2^+]$ and $[56,4,10,2,0,3/2^+]$ are most likely to be the relatively narrow states with a width of $\Gamma \approx 2.0$ MeV.

The dominant decay mode of $[70,2,10,2,0,1/2^+]$ is $\Xi K$. The decay width of $[70,2,10,2,0,1/2^+]$ and $[56,4,10,2,0,3/2^+]$ are $\Xi(1530)K$, and the predicted branching fraction ratio is

$$\frac{\mathcal{B}[56,4,10,2,0,3/2^+ \rightarrow \Xi K]}{\mathcal{B}[56,4,10,2,0,3/2^+ \rightarrow \Xi(1530)K]} \approx 1.07.$$  (14)

From the point of view of the mass and decay width, we can't excluded the first radially excited $\Omega$ state $[56,4,10,2,0,3/2^+]$ as a assignment of the newly observed $\Omega(2012)$ state.

In addition, we also plot the decay widths of $[70,2,10,2,0,1/2^+]$ and $[56,4,10,2,0,3/2^+]$ as functions of the masses in the range of $M = (2000 - 2300)$ MeV in Fig. 2. The variation curves between the decay widths and the masses of the two states can be obtained from the figure.

C. 1D wave states in the $N = 2$ shell

There are six 1D wave states according to the quark model classification (see Table I). Their masses are estimated to be in the range of $2.2 - 2.3$ GeV in various quark models. With the predicted masses from Ref. [7], we further analyze the decay properties of the 1D wave states in the $N = 2$ shell, and collect their strong decay widths in Table III. The predicted masses of the 1D wave states our model have a large uncertainty, which may bring uncertainties to our theoretical predictions. To investigate this effect, we plot the total and partial decay widths of these states as functions of the masses in the range of $M = (2100 - 2400)$ MeV in Fig. 2 as well.

It is found that the total decay widths of the 1D wave states are not broad, they are about $\Gamma \approx (10 - 100)$ MeV. The strong decays of both $[56,4,10,2,2,1/2^+]$ and $[56,4,10,2,2,7/2^+]$ are governed by the $\Xi K$ mode. The strong decays of both $[56,4,10,2,2,5/2^+]$ and $[70,2,10,2,2,3/2^+]$ are governed by the $\Xi(1530)K$ mode. While the $[56,4,10,2,2,3/2^+]$ and $[70,2,10,2,2,5/2^+]$ states mainly decay into $\Xi K$ and $\Xi(1530)K$ channels.

It should be mentioned that the $\Omega(2250)$ resonance with a width of $\Gamma = 55 \pm 18$ MeV listed in PDG [11] may be a good candidate of $[56,4,10,2,2,5/2^+]$. The $\Omega(2250)$ was seen in the $\Xi(1530)K$ and $\Xi^-\pi K^-$ channels. The measured mass of $\Omega(2250)$ is consistent with the quark model predictions [3, 7]. Assigning it as $\Omega(2250)$, the total width is predicted to be

$$\Gamma_{\text{total}}^{\text{th}}(\Omega(2250)) = 36 \text{ MeV}.$$  (15)

Its strong decays are dominated by the $\Xi(1530)K$ mode, while the decay rate into the $\Xi K$ is sizeable. The partial width ratio between $\Xi(1530)K$ and $\Xi K$ is predicted to be

$$\frac{\mathcal{B}[\Omega(2250) \rightarrow \Xi(1530)K]}{\mathcal{B}[\Omega(2250) \rightarrow \Xi K]} \approx 3.2.$$  (16)

Both the decay width and decay mode are consistent with the observations.

As a whole, the 1D wave states are relatively narrow states with a typical width of 10s MeV. They mainly decay into $\Xi K$ and/or $\Xi(1530)K$ final states. To establish these missing 1D wave states, observations in the both $\Xi K$ and $\Xi(1530)K$ channels are expected to be carried out in future experiments.

IV. SUMMARY

In the present work, we carry out a systematic study of the OZI allowed two-body strong decays of $\Omega$ resonances up to the $N = 2$ shell within the chiral quark model. For the newly observed $\Omega(2012)$ state, we give a possible interpretation in theory. Meanwhile, we give the predictions for the decay properties of the 1D wave states, and hope to provide helpful information for searching these missing $\Omega$ states in the future.
be explained as the $1P$ wave state with $J^P = 3/2^-$, $[70,^2, 10, 1, 1, 3/2^-]$. Meanwhile, with the present information from experiments we can’t rule out the $\Omega(2112)$ as the assignments of the $1P$ wave state $[70,^2, 10, 1, 1, 1/2^-]$ with $J^P = 1/2^-$ and the $2S$ wave state $[56,^4, 10, 2, 0, 3/2^+]$ with $J^P = 3/2^+$ completely.

The $\Omega(2250)$ resonance listed in PDG may be a good candidate of the $J^P = 5/2^+$ $1D$ wave state $[56,^4, 10, 2, 2, 5/2^+]$. Generally, the $1D$ wave states are relatively narrow states with a typical width of $10s$ MeV. They mainly decay into $\Xi K$ and/or $\Xi(1530)K$ final states. To establish these missing $1D$ wave states, observations in the both $\Xi K$ and $\Xi(1530)K$ channels are expected to be carried out in future experiments.

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[1] C. Patrignani et al. [Particle Data Group], Review of Particle Physics, Chin. Phys. C 40, 100001 (2016).
[2] Y. Oh, $\Xi$ and $\Omega$ baryons in the Skyrme model, Phys. Rev. D 75, 074002 (2007).
[3] S. Capstick and N. Isgur, Baryons in a Relativized Quark Model with Chromodynamics, Phys. Rev. D 34, 2809 (1986).
[4] R. N. Faustov and V. O. Galkin, Strange baryon spectroscopy in the relativistic quark model, Phys. Rev. D 92, 054005(2015).
[5] U. Loring, B. C. Metsch and H. R. Petry, The Light baryon spectrum in a relativistic quark model with instanton induced quark forces: The Strange baryon spectrum, Eur. Phys. J. A 10, 447 (2001).
[6] J. Liu, R. D. McKeown and M. J. Ramsey-Musolf, Global Analysis of Nucleon Strange Form Factors at Low $Q^2$, Phys. Rev. C 76, 025202 (2007).
[7] K. T. Chao, N. Isgur and G. Karl, Strangeness -2 and -3 Baryons in a Quark Model With Chromodynamics, Phys. Rev. D 23, 155 (1981).
[8] Y. Chen and B. Q. Ma, Light flavor baryon spectrum with higher order hyperfine interactions, Nucl. Phys. A 831, 1 (2009).
[9] C. S. An, B. C. Metsch and B. S. Zou, Mixing of the low-lying three- and five-quark $\Omega$ states with negative parity, Phys. Rev. C 87, 065207 (2013).
[10] C. S. Kalman, $P$ Wave Baryons in a Consistent Quark Model With Hyperfine Interactions, Phys. Rev. D 26, 2326 (1982).
[11] M. Pervin and W. Roberts, Strangeness -2 and -3 baryons in a constituent quark model, Phys. Rev. C 77, 025202 (2008).
[12] C. S. An and B. S. Zou, Low-lying $\Omega$ states with negative parity in an extended quark model with Nambu-Jona-Lasinio interaction, Phys. Rev. C 89, 055209 (2014).
[13] G. P. Engel et al. [BGR Collaboration], QCD with Two Light Dynamical Chirally Improved Quarks: Baryons, Phys. Rev. D 87, 074504 (2013).
[14] J. Liang et al. [CLQCD Collaboration], Spectrum and Bethe-Salpeter amplitudes of $\Omega$ baryons from lattice QCD, Chin. Phys. C 40, 041001 (2016).
[15] C. E. Carlson and C. D. Carone, Predictions for decays of radially excited baryons, Phys. Lett. B 484, 260 (2000).
[16] J. L. Goity, C. Schat and N. N. Scoccola, Analysis of the $[56,^2^+]$ baryon masses in the $1/N(c)$ expansion, Phys. Lett. B 564, 83 (2003).
[17] C. L. Schat, J. L. Goity and N. N. Scoccola, Masses of the 70-baryons in large $N(c)$ QCD, Phys. Rev. Lett. 88, 102002 (2002).
[18] N. Matagne and F. Stancu, Masses of $[70,^1^+]$ Baryons in the $1/N(c)$ Expansion, Phys. Rev. D 74, 034014 (2006).
[19] R. Bijker, F. Iachello and A. Leviatan, Algebraic models of

FIG. 2: The strong decay properties of the 2S - and 1D-wave states in the $N = 2$ shell.
hadron structure. 2. Strange baryons, Annals Phys. 284, 89 (2000).

[20] I. M. Narodetskii and M. A. Trusov, Magnetic moments of negative parity baryons from effective hamiltonian approach to QCD, JETP Lett. 99, 57 (2014).

[21] E. Kaxiras, E. J. Moniz and M. Soyeur, Hyperon Radiative Decay, Phys. Rev. D 32, 695 (1985).

[22] J. Yelton et al. [Belle Collaboration], Observation of an excited $\Omega^-$ baryon, [arXiv:1805.09384 [hep-ex]].

[23] A. Manohar and H. Georgi, Chiral Quarks and the Nonrelativistic Quark Model, Nucl. Phys. B 234, 189 (1984).

[24] X. H. Zhong and Q. Zhao, Strong decays of heavy-light mesons in a chiral quark model, Phys. Rev. D 78, 014029 (2008).

[25] X. H. Zhong, Strong decays of the newly observed $D(2550)$, $D(2600)$, $D(2750)$, and $D(2760)$, Phys. Rev. D 82, 114014 (2010).

[26] X. H. Zhong and Q. Zhao, Strong decays of newly observed $D(sJ)$ states in a constituent quark model with effective Lagrangians, Phys. Rev. D 81, 014031 (2010).

[27] L. Y. Xiao and X. H. Zhong, Strong decays of higher excited heavy-light mesons in a chiral quark model, Phys. Rev. D 90, 074029 (2014).

[28] X. H. Zhong and Q. Zhao, Charmed baryon strong decays in a chiral quark model, Phys. Rev. D 77, 074008 (2008).

[29] L. H. Liu, L. Y. Xiao and X. H. Zhong, Charm-strange baryon strong decays in a chiral quark model, Phys. Rev. D 86, 034024 (2012).

[30] L. Y. Xiao and X. H. Zhong, $\Xi$ baryon strong decays in a chiral quark model, Phys. Rev. D 87, 094002 (2013).

[31] H. Nagahiro, S. Yasui, A. Hosaka, M. Oka and H. Noumi, Structure of charmed baryons studied by pionic decays, Phys. Rev. D 95, 014023 (2017).

[32] K. L. Wang, L. Y. Xiao, X. H. Zhong and Q. Zhao, Understanding the newly observed $\bar{\Omega}_c$ states through their decays, Phys. Rev. D 95, 116010 (2017).

[33] K. L. Wang, Y. X. Yao, X. H. Zhong and Q. Zhao, Strong and radiative decays of the low-lying $S$- and $P$-wave singly heavy baryons, Phys. Rev. D 96, 116016 (2017).

[34] L. Y. Xiao, K. L. Wang, Q. f. Lu, X. H. Zhong and S. L. Zhu, Strong and radiative decays of the doubly charmed baryons, Phys. Rev. D 96, 094005 (2017).

[35] Y. X. Yao, K. L. Wang and X. H. Zhong, Strong and radiative decays of the low-lying $D$-wave singly heavy baryons, [arXiv:1803.00364 [hep-ph]].

[36] Q. Zhao, J. S. Al-Khalili, Z. P. Li and R. L. Workman, Pion photoproduction on the nucleon in the quark model, Phys. Rev. C 65, 065204 (2002).

[37] Z. P. Li, The Threshold pion photoproduction of nucleons in the chiral quark model, Phys. Rev. D 50, 5639 (1994).

[38] Z. P. Li, H. X. Ye and M. H. Lu, An Unified approach to pseudoscalar meson photoproductions off nucleons in the quark model, Phys. Rev. C 56, 1099 (1997).