Strong decay of $\Lambda_c(2940)$ as a $2P$ state in the $\Lambda_c$ family

Qi-Fang Lü,1,2 Li-Ye Xiao,3,4 Zuo-Yun Wang,1,2 and Xian-Hui Zhong1,2,*

1Department of Physics, Hunan Normal University, and Key Laboratory of Low-Dimensional Quantum Structures and Quantum Control of Ministry of Education, Changsha 410081, China
2Synergetic Innovation Center for Quantum Effects and Applications (SICQEA), Hunan Normal University, Changsha 410081, China
3School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
4Center of High Energy Physics, Peking University, Beijing 100871, China

Electronic address: lqifang@hunnu.edu.cn
Electronic address: lxyiao@pku.edu.cn
Electronic address: zhongxh@hunnu.edu.cn

Considering the mass, parity and $D^0 p$ decay mode, we tentatively assign the $\Lambda_c(2940)$ as the $P$-wave states with one radial excitation. Then, via studying the strong decay behavior of the $\Lambda_c(2940)$ within the $3P_0$ model, we obtain that the total decay widths of the $\Lambda_c(\frac{3}{2}^+, 2P)$ and $\Lambda_c(\frac{1}{2}^+, 2P)$ states are 16.27 MeV and 25.39 MeV, respectively. Compared with the experimental total width $27.7_{-6.0}^{+5.2} \pm 0.9_{-0.4}^{+0.4}$ MeV measured by LHCb Collaboration, both assignments are allowed, and the $J^P = \frac{1}{2}^-$ assignment is more favorable. Other $\lambda$-mode $\Sigma_c(2P)$ states are also investigated, which are most likely to be narrow states and have good potential to be observed in future experiments.

PACS numbers: 13.60.Lt
Keywords: $\Lambda_c(2940)$; $3P_0$ model; Singly heavy baryons

I. INTRODUCTION

The singly charmed baryons are composed of one charm quark and two light quarks. Constraints on the nonstrange light quarks, they can be further categorized into the $\Lambda_c$ and $\Sigma_c$ families, which belong to the antisymmetric flavor structure $3_F$ and symmetric flavor structure $6_F$, respectively. Establishing the spectrum of these charmed baryons has attracted lots of theoretical and experimental attentions. From the Particle Data Group book, there exist nine $\Lambda_c$ and $\Sigma_c$ baryons, $\Lambda_c(2286)$, $\Lambda_c(2593)$, $\Lambda_c(2625)$, $\Lambda_c(2765)$, $\Lambda_c(2880)$, $\Lambda_c(2940)$, $\Sigma_c(2455)$, $\Sigma_c(2520)$, and $\Sigma_c(2800)$ [37]. $\Lambda_c(2286)$, $\Sigma_c(2455)$, and $\Sigma_c(2520)$ are the $S$-wave ground states, and $\Lambda_c(2593)$ and $\Lambda_c(2625)$ can be well understood as the $P$-wave $\Lambda_c$ states in the conventional quark model. In the $cqg$ configuration, $\Lambda_c(2765)$ and $\Lambda_c(2880)$ might be classified into the $2S$ and $1D \Lambda_c$ states, respectively, while $\Sigma_c(2800)$ is possibly a $1P \Sigma_c$ state. Other conventional or exotic interpretations are also suggested for the $\Lambda_c(2765)$, $\Lambda_c(2880)$, and $\Sigma_c(2800)$ states. Detailed discussions of various assignments and properties can be found in Refs. [32,34].

In 2017, the LHCb Collaboration performed an amplitude analysis of the $\Lambda^+_c(1520) \rightarrow D^{*+} p\pi^-$ decay process in the $D^0 p$ channel, and observed three $\Lambda_c$ resonances, $\Lambda_c(2860)$, $\Lambda_c(2880)$, and $\Lambda_c(2940)$ [35]. Their masses and decay widths were measured as follows,

$$m[\Lambda_c(2860)^+] = 2856.1_{-1.7}^{+2.0} \pm 0.5_{-5.6}^{+1.1} \text{ MeV},$$

$$\Gamma[\Lambda_c(2860)^+] = 67.6_{-8.1}^{+10.1} \pm 1.4_{-20.0}^{+5.9} \text{ MeV},$$

$$m[\Lambda_c(2880)^+] = 2881.75 \pm 0.29 \pm 0.07_{-0.20}^{+0.14} \text{ MeV},$$

The quantum numbers of $\Lambda_c(2860)$ and $\Lambda_c(2880)$ were determined to be $J^P = \frac{3}{2}^+$ and $J^P = \frac{5}{2}^+$, respectively. The measured information indicates that they may be good candidates of the $1D$-wave $\Lambda_c$ resonances. The spin and parity of the $\Lambda_c(2940)$ state were constrained. The most likely spin-parity quantum numbers of $\Lambda_c(2940)$ are $J^P = \frac{5}{2}^+$, while other possibilities cannot be excluded completely [38]. With the favorable $J^P = \frac{3}{2}^-$ assignment, the $\Lambda_c(2940)$ may correspond to a conventional $2P$-wave $\Lambda_c$ resonance in the quark model.

In the past years, from the point view of the mass spectrum the properties of $\Lambda_c(2940)$ were attempted to be understood within various quark models. For example, some people studied the $\Lambda_c$ spectrum in the consistent quark model, and found $\Lambda_c(2940)$ could be an excited $\Lambda_c$ state with $J^P = 3/2^+$ [39]. Within the diquark picture, $\Lambda_c(2940)$ can be interpreted as the $2P$-wave $\Lambda_c$ resonance with $J^P = 1/2^-$ or the $2S$-wave state with $J^P = 3/2^+$ in the relativistic quark model [4]. The $2P$-wave $\Lambda_c$ resonance with $J^P = 1/2^-$ in the relativized quark model [40], and the $J^P = 5/2^+$ $1D$-wave state or the $2P$ -wave $\Lambda_c$ resonances in flux tube model [5,30]. Meanwhile, the $D^* N$ molecular state interpretations were suggested in some works [4,10], where with the $S$-wave $1/2^-$ or $3/2^-$ assignment, the near threshold behavior of $\Lambda_c(2940)$ can be naturally explained.

Besides the mass spectrum, the $\Lambda_c(2940)$ resonance was also investigated via its decay and production processes. For example, the strong decays of $\Lambda_c(2940)$ were studied within the chiral perturbation theory, one found that the spin-parity numbers might be $3/2^+$ or $5/2^{-}[1]$. Within the quark model, the strong decays indicated $\Lambda_c(2940)$ can be described as the $D$-wave $\Lambda_c$ state with spin-parity numbers $5/2^+$ [12] or $7/2^+$ [16]. Meanwhile, the decay behaviors of the $J^P =$

\begin{align*}
\Gamma[\Lambda_c(2880)^+] &= 5.43_{-0.71}^{+0.77} \pm 0.29_{-0.04}^{+0.05} \text{ MeV}, \\
m[\Lambda_c(2880)^+] &= 2944.8_{-2.5}^{+3.5} \pm 0.4_{-0.4}^{+0.4} \text{ MeV}, \\
\Gamma[\Lambda_c(2940)^+] &= 27.7_{-6.0}^{+8.2} \pm 0.9_{-10.4}^{+5.2} \text{ MeV}. 
\end{align*}
$1/2^-$, $3/2^-$, $1/2^+$ $D'N$ molecule states were investigated [6–8, 17], and no definitive conclusion was obtained. Furthermore, the productions of $\Lambda_c(2940)$ in the $p\bar{p}$, $\pi^+ p$, $\gamma n$, and $K^- p$ processes were studied within effective Lagrangian approaches [43, 45], which provide helpful references for future PANDA and COMPASS experiments.

It is shown that the theoretical works perform lots of interpretations on $\Lambda_c(2940)$, while the quantum numbers $J^P = \frac{3}{2}^-$ determined by LHCb Collaboration favor the conventional $2P$ $\Lambda_c$ resonance or the exotic $D'N$ molecule description. Although there are many discussions of $\Lambda_c(2940)$ in the literature as mentioned before, less discussions of the decay behaviors as the conventional $2P$ $\Lambda_c$ states can be found. Hence, in this work, we study the strong decays of the $2P$ charmed baryons within the $3P_0$ quark pair creation model. Our results indicate that $\Lambda_c(2940)$ as the $L$-mode $\Lambda_c(1/2^-, 2P)$ and $\Lambda_c(3/2^-, 2P)$ states are both allowed, and the $J^P = 3/2^-$ state $\Lambda_c(1/2^-, 2P)$ is more favorable.

This paper is organized as follows. The $3P_0$ model is briefly introduced in Sec. III. The strong decays of the $2P$ $\Lambda_c$ and $\Sigma_c$ charmed baryons are estimated in Sec. III. A short summary is presented in the last section.

II. $3P_0$ Model

In this work, we adopt the $3P_0$ model to calculate the Okubo-Zweig-Iizuka-allowed two-body strong decays of the $2P$ $\Lambda_c$ and $\Sigma_c$ states. The $3P_0$ model, also known as the quark pair creation model, has been extensively employed to study the strong decays with considerable successes [2, 18, 46–63]. In this model, the hadrons decay occurs through a quark-antiquark pair with the vacuum quantum number $J^P = 0^{++}$ [53]. Here we perform a brief review of the $3P_0$ model. In the nonrelativistic limit, the transition operator $T$ of the decay $A \rightarrow BC$ in the $3P_0$ model can be assumed as [2, 58]

$$T = -3\gamma \sum_m (1m1−m00) \int d^3p_4 d^3p_5 \delta^3(p_4 + p_5) \times Y_{1m}^m(p_4 - p_5) \chi_{1m}^{45} \phi_0^{45} \omega_0^{45} b_{4l}^1(p_4) d_{5l}^0(p_5),$$

(7)

where $\gamma$ is a dimensionless $q_4\bar{q}_5$ pair-production strength, and $p_4$ and $p_5$ are the momenta of the created quark $q_4$ and antiquark $q_5$, respectively. The $i$ and $j$ are the color indices of the created quark and antiquark. $\phi_0^{45} = (i\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$, $\omega_0^{45} = \delta_{ij}$, and $\chi_{1m}^{45}$ are the flavor singlet, color singlet, and spin triplet wave functions of the $q_4\bar{q}_5$, respectively. The solid harmonic polynomial $Y_{lm}^m(\theta, \phi, p) = |p| Y_{lm}^m(\theta, \phi)$ reflects the $P$-wave momentum-space distribution of the $q_4\bar{q}_5$ quark pair.

For the initial baryon $A$, we adopt the definition of the mock states [64]

$$|A_{\alpha A}^{25, +1} L_{J A}, M_j, \lambda \rangle (p A) = \sqrt{2 E_A} \sum_{M_{\lambda A}, M_{\phi A}} \langle L_{\lambda A} M_{\lambda A} S_{\lambda A} M_{\phi A} | J A, M_j \rangle \int d^3p_1 d^3p_2 d^3p_3 \times \delta^3(p_1 + p_2 + p_3 − p A) |\phi_{\alpha A}^{123} \omega_1^{123} | q_1(p_1) q_2(p_2) q_3(p_3) \rangle,$$

(8)

which satisfies the normalization condition

$$\langle A(p A)|A(\rangle^A) = 2 E_A \delta^3(p A − p A).$$

(9)

The $p_1$, $p_2$, and $p_3$ are the momenta of the quarks $q_1$, $q_2$, and $q_3$, respectively. $p A$ denotes the momentum of the initial state $A$, $\chi_{\lambda A}, \phi_1^{123}, \omega_1^{123}$, $\psi_{\alpha A}, \lambda A$, $(p_1, p_2, p_3)$ are the spin, flavor, color, and space wave functions of the baryon $A$ composed of $q_1q_2q_3$ with total energy $E_A$, respectively. The definitions of the mock states $B$ and $C$ are similar to that of initial state $A$, and can be find in Ref. [2].

For the decay of the charmed baryon $A$, three possible rearrangements exist,

$$A(q_1, q_2, c_3) + P(q_4, \bar{q}_3) \rightarrow B(q_2, q_4, c_3) + C(q_1, q_3),$$

(10)

$$A(q_1, q_2, c_1) + P(q_4, \bar{q}_3) \rightarrow B(q_1, q_4, c_3) + C(q_2, q_3),$$

(11)

$$A(q_1, q_2, c_3) + P(q_4, \bar{q}_3) \rightarrow B(q_1, q_2, q_4) + C(c_3, q_3).$$

(12)

where the $q_i$ and $c_j$ denote the light quark and charm quark, respectively. These three ways of recouplings are also shown in Figure 1.

![FIG. 1: The baryon decay process $A \rightarrow B + C$ in the $3P_0$ model.](image)

The $S$ matrix can be defined as

$$\langle f|S|i\rangle = I − i\sqrt{2} \pi \delta(E_f − E_i) M_{M_{\lambda A}, M_{\phi A}} M_{M_{\lambda B}, M_{\phi B}} =$$

(13)

where the $M_{M_{\lambda A}, M_{\phi A}}$ is the helicity amplitude of the decay process $A \rightarrow B + C$. The transition process $A(q_1, q_2, c_3) + P(q_4, \bar{q}_3) \rightarrow B(q_1, q_4, c_3) + C(q_2, \bar{q}_3)$ shown in Fig. 1(b) as an example, the helicity amplitude $M_{M_{\lambda A}, M_{\phi A}}$ reads [2, 55, 56],

$$\delta^3(p_B + p_C − p_A) M_{M_{\lambda A}, M_{\phi A}} =$$

(14)
functions. With the relativistic phase space, the decay width is given by the relativistic phase space, and the simple harmonic oscillator wave function.

\[ \Gamma_{\text{relativistic}} = \frac{\gamma}{\beta c} \]

and

\[ \gamma = \frac{\pi^2 p}{M_A^2} + \frac{3}{2} \sum_{M_A, M_B, M_C} |M_{M_A, M_B, M_C}|^2, \]

where \( p = |p| = \sqrt{\sum_{M_A, M_B, M_C} |M_{M_A, M_B, M_C}|^2} \), and \( M_A, M_B, \) and \( M_C \) are the masses of the hadrons \( A, B, \) and \( C \), respectively. \( s = 1/(1 + \delta_{MC}) \) is a statistical factor which is needed if \( B \) and \( C \) are identical particles. Due to \( B \) and \( C \) correspond to the baryon and meson, respectively, the \( s \) always equals to one in this work.

### III. STRONG DECAY

#### A. Notations and parameters

In our calculation, we adopt the same notations of \( \Lambda_c, \Sigma_c, \) and \( \Xi_c \) baryons as those in Ref. [32]. For the spatial \( 2P \) excited states, the symbol \( 2P \) are added. In Table I, The \( n_{i}, \) and \( L_{i} \) stand the nodal and orbital angular momentum between the two light quarks, while \( n_{j} \) and \( L_{j} \) denote the nodal and angular momentum between the two light quark system and the charm quark. \( L \) is the total orbital angular momentum, \( S_{ij} \) is the total spin of the two light quarks, \( J_{i} \) is total angular momentum of \( L \) and \( S_{ij} \), and \( J \) is the total angular momentum.

For the masses of the two \( \Lambda_{c1}(2P) \) states, we adopt the mass of \( \Lambda(2940) \) from LHCb experimental data. Masses of the other \( 2P \) states are taken from theoretical predictions. For the final ground states, their masses are adopted from the Particle Data Group [37]. For the harmonic oscillator parameters of mesons, we use the effective values obtained by relativized quark model, i.e., \( R = 2.5 \text{ GeV}^{-1} \) for \( \pi/\rho/\omega/K/\eta \) meson, \( R = 1.67 \text{ GeV}^{-1} \) for \( D \) meson, \( R = 1.94 \text{ GeV}^{-1} \) for \( D^{*} \) meson, and \( R = 1.54 \text{ GeV}^{-1} \) for \( D_{s} \) meson [62]. For the baryon parameters, we use \( \alpha_{Q} = 400 \text{ MeV} \) and

\[ \alpha_{Q} = \left( \frac{3m_{Q}}{2m_{Q} + m_{Q}} \right)^{\frac{1}{2}} \alpha_{Q}, \]

where \( m_{Q} \) and \( m_{Q} \) are the heavy and light quark masses, respectively [12]. The \( m_{u/d} = 220 \text{ MeV}, m_{s} = 419 \text{ MeV}, \) and \( m_{c} = 1628 \text{ MeV} \) are introduced to explicitly break the SU(4) symmetry [62, 63, 68]. There is an overall parameter \( \lambda \), which is determined by the well determined width of the \( \Sigma_c(2520)^{++} \rightarrow \Lambda_c \pi^{+} \) process. The \( \lambda = 9.83 \) is obtained by reproducing the width, \( \Gamma[\Sigma_c(2520)^{++} \rightarrow \Lambda_c \pi^{+}] = 14.78 \text{ MeV} \) [37].

#### B. \( \Lambda_c(2940) \)

The strong decays of \( \Lambda_c(2940) \) as the \( \Lambda_c(1^{+}, 2P) \) and \( \Lambda_c(3^{+}, 2P) \) assignments are calculated. The results are listed in Table I. It is shown that the total decay widths of the \( \Lambda_c(1^{+}, 2P) \) and \( \Lambda_c(3^{+}, 2P) \) states are 16.27 MeV and 25.39 MeV, respectively. Compared with the experimental total width \( 27.7_{-6.5}^{+8.0} \pm 9.2 \text{ MeV} \) measured by LHCb Collaboration, both assignments are allowed. However, the \( J^{P} = \frac{1}{2}^{+} \) assignment is more favorable. The main decay mode is the \( DN \) channel, and the partial decay widths of the \( \Sigma_c \pi \) and \( \Xi_c \pi \) channels are rather small, which is consistent with the fact...
The partial decay width ratios of the $J^P = \frac{1}{2}^-$ state are predicted to be
\[
\Gamma[\Sigma,\pi] : \Gamma[\Sigma^*,\pi] : \Gamma[DN] = 1 : 0.52 : 6.91, \tag{18}
\]
and the partial decay width ratios of the $J^P = \frac{3}{2}^-$ state are predicted to be
\[
\Gamma[\Sigma,\pi] : \Gamma[\Sigma^*,\pi] : \Gamma[DN] = 1 : 3.22 : 22.03. \tag{19}
\]
These ratios are independent with the overall parameter $\gamma$ in the $3P_0$ model, and the divergence of these two set of quantum number assignments can be tested in future experimental data.

In Figure 2, we plot the variation of the decay widths as a function of the initial baryon mass. It is seen that the partial width of the $DN$ channel decreases for the $1/2^-$ state, while increases for the $3/2^-$ state. The $\Sigma,\pi$ and $\Sigma^*,\pi$ decay modes are small enough in this mass region. When the mass lies above the $D^*N$ threshold, the $D^*N$ channel also performs significant contributions to the total decay widths in both cases. Since the mass splitting of $\Lambda_c(1P)$ is
\[
m[\Lambda_c(2625)] - m[\Lambda_c(2595)] = 36 \text{ MeV}, \tag{20}
\]
the mass splitting of the two $\Lambda_c(2P)$ states is smaller than $36 \text{ MeV}$. Considering $\Lambda_c(2940)$ as the $\Lambda_c(1\frac{3}{2}^-,2P)$ state, the

Table II: Decay widths of the $\Lambda_c(2940)$ as the $\Lambda_c(1\frac{3}{2}^-,2P)$ and $\Lambda_c(1\frac{5}{2}^-,2P)$ in MeV.

| Mode               | $\Lambda_c(2940)$ | $\Lambda_c(1\frac{3}{2}^-,2P)$ | $\Lambda_c(1\frac{5}{2}^-,2P)$ |
|--------------------|-------------------|-------------------------------|-------------------------------|
| $\Sigma^+_\pi^-$   | 0.65              | 0.32                          |
| $\Sigma^0\pi^0$    | 0.64              | 0.33                          |
| $\Sigma^0\pi^+$    | 0.65              | 0.32                          |
| $\Sigma^+\pi^-    $ | 0.33              | 1.04                          |
| $\Sigma^0\pi^0$    | 0.34              | 1.03                          |
| $\Sigma^+\pi^-$    | 0.33              | 1.04                          |
| $D^*n$             | 7.21              | 10.26                         |
| $D^0p$             | 6.13              | 11.05                         |
| Total width        | 16.27             | 25.39                         |
| Experiment         | $27.7^{+8.2}_{-6.0} \pm 0.9^{+5.2}_{-10.4}$ |
TABLE III: Predicted masses for the $\lambda$-mode $\Sigma_c(2P)$ states in the literature. The units are in MeV.

| State | RQM [66] | RQM [67] | RQM [68] | HCQM [66] | NRQM [18] |
|-------|----------|----------|----------|------------|------------|
| $\Sigma_{c0}(1/2^+, 2P)$ | 3185 | 3186 | 3172 | 3245 | 2971 |
| $\Sigma_{c1}(3/2^-, 2P)$ | 3195 | 3176 | 3125 | 3256 | 3018 |
| $\Sigma_{c2}(5/2^-, 2P)$ | 3195 | 3180 | 3172 | 3223 | 3036 |
| $\Sigma_{c3}(7/2^-, 2P)$ | 3210 | 3147 | 3151 | 3233 | 3044 |
| $\Sigma_{c4}(9/2^-, 2P)$ | 3220 | 3167 | 3161 | 3203 | 3040 |

TABLE IV: The strong decay behaviors of the five $\lambda$-mode $\Sigma_c(2P)$ states. The masses of the initial baryons are taken from Ref. [66]. The units are in MeV.

| Mode | $\Sigma_{c0}(1/2^+, 2P)$ | $\Sigma_{c1}(3/2^-, 2P)$ | $\Sigma_{c2}(5/2^-, 2P)$ | $\Sigma_{c3}(7/2^-, 2P)$ | $\Sigma_{c4}(9/2^-, 2P)$ |
|------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| $\Lambda_c\pi^*$ | 1.04 | -- | -- | 2.20 | 2.20 |
| $\Lambda_c\rho^*$ | -- | 3.09 | 3.09 | 0.92 | 1.05 |
| $\Sigma_c^0\pi^+$ | 0.01 | 0.69 | 1.29 | 0.59 |
| $\Sigma_c^0\pi^0$ | 0.01 | 0.69 | 1.29 | 0.59 |
| $\Sigma_c^0\pi^-$ | 1.09 | 0.60 | 1.05 | 1.69 |
| $\Sigma_c^0\eta$ | -- | 0.86 | 0.12 | 0.26 | 0.13 |
| $\Sigma_c^0\eta$ | -- | 0.10 | 1.51 | 0.12 | 0.21 |
| $\Sigma_c^0\pi^0$ | -- | 1.96 | 1.04 |
| $\Sigma_c^0\pi^+$ | -- | 5.13 | 0.08 | 0.19 | 0.10 |
| $\Sigma_c^0\pi^-$ | -- | 0.02 | 5.01 | 0.03 | 0.08 |
| $\Xi_c^0 K^*$ | 4.93 | -- | -- | 9.71 |
| $\Xi_c^0 K^+$ | -- | 8.98 | 3.21 | 0.62 |
| $\Xi_c^0 K^-$ | -- | 9.18 | 8.63 | 34.46 | 21.77 |
| $D^* p$ | 4.17 | 8.98 | 3.21 | 0.62 | 9.71 |
| $D^* p$ | 1.08 | 11.63 | 8.63 | 34.46 | 21.77 |
| $D^* +\Delta^{++}$ | 9.44 | 5.82 | 16.16 | 18.16 | 12.33 |
| $D^* +\Delta^{-}$ | 2.83 | 1.77 | 5.22 | 6.70 | 3.85 |
| $D^* +\Sigma_c$ | 4.56 | 8.92 | 0.07 | 0.03 | 0.70 |
| Total | 28.06 | 48.52 | 45.68 | 69.32 | 57.73 |

![Graphs showing decay widths](image)

There are five $\lambda$-mode $\Sigma_c(2P)$ states, denoted as $\Sigma_{c0}(1/2^+, 2P)$, $\Sigma_{c1}(3/2^-, 2P)$, $\Sigma_{c2}(5/2^-, 2P)$, $\Sigma_{c3}(7/2^-, 2P)$, and $\Sigma_{c4}(9/2^-, 2P)$, respectively. Although no information exists for these states in the experiments, some theoretical works have investigated their masses [4, 18, 66, 68]. In Tab. [III] we collect the predicted masses of $\lambda$-mode $\Sigma_c(2P)$ states in the literature. Here, we employ the masses predicted by the relativized quark model [66] to calculate their strong decays, and the results are listed in Tab. [IV]. The total decay widths of these five states are about 28 ~ 69 MeV, which are relatively narrow. The main decay modes are light baryon plus heavy meson channels, while the heavy baryon plus light meson channels are rather small. The narrow total decay widths and large $D^{*+}N$ branching ratios suggest that these states have good potential to be observed in future experiments. Moreover, the decay widths as functions of their initial masses are plotted in Fig. [IV] for reference.

There are also $\rho$-mode excited $2P$ states, where a symbol “ $\sim$ ” are added to distinguish them from the $\lambda$-mode states in Tab. [III]. The theoretical predictions of these states are[

mass of the $\Lambda_c(1/2^-, 2P)$ state should lie in 2909 ~ 2945 MeV. From Fig. [II] the $\Lambda_c(1/2^-, 2P)$ state has a width of 16 ~ 33 MeV, which can be searched in the $DN$ final state in future experiments.

The dependence on the harmonic oscillator parameter $\alpha_p$ is also investigated in Fig. [III]. When the $\alpha_p$ increases, the total decay width also increases for the $1/2^-$ state. While, the total decay width of the $3/2^-$ state is almost unchanged with the $\alpha_p$ variation. Within this reasonable range of the parameter $\alpha_p$, our conclusions remain.
scarce. In the singly heavy baryon sector, exciting the $\lambda$-mode is much easier than the $\rho$-mode, hence, the $\rho$-mode excited 2$P$ states should be much higher than the $\lambda$-mode states. With the higher masses, more strong decay channels will be open. Due to the lack of mass information and the uncertainties of many decay channels, it seems untimely to study their properties in present work.

IV. SUMMARY

In this work, we study the strong decays of the $\Lambda_c(2940)$ baryon within the $^3P_0$ model. Considering the mass, parity and $D^0p$ decay mode, we tentatively assign $\Lambda_c(2940)$ as the $\lambda$-mode $\Lambda_c(2P)$ states. The main decay mode is $DN$ channel for both $1/2^-$ and $3/2^-$ states. The total decay width of the $\Lambda_c(1^{+}, 2P)$ and $\Lambda_c(2^{+}, 2P)$ states are 16.27 MeV and 25.39 MeV, respectively. Compared with the total width measured by LHCb Collaboration, both assignments are allowed, and the $J^P = \frac{3}{2}^-$ assignment is more favorable. Other $\lambda$-mode $\Sigma_c(2P)$ states are also investigated. The relatively narrow total decay widths and large $D^{\ast\ast}N$ branching ratios can be tested in future experimental searches.

ACKNOWLEDGEMENTS

We would like to thank Yu-Bing Dong, De-Min Li and Yin-Huang for valuable discussions. This project is supported by the National Natural Science Foundation of China under Grants No. 11705056 and No. 11775078. This work is also in part supported by China Postdoctoral Science Foundation under Grant No. 2017M620492.

[1] H. Y. Cheng and C. K. Chua, Strong Decays of Charmed Baryons in Heavy Hadron Chiral Perturbation Theory, Phys. Rev. D 75, 014006 (2007).
[2] C. Chen, X. L. Chen, X. Liu, W. Z. Deng and S. L. Zhu, Strong decays of charmed baryons, Phys. Rev. D 75, 094017 (2007).
[3] A. Valcarce, H. Garcilazo and J. Vijande, Towards an understanding of heavy baryon spectroscopy, Eur. Phys. J. A 37, 217 (2008).
[4] D. Ebert, R. N. Faustov and V. O. Galkin, Spectroscopy and Regge trajectories of heavy baryons in the relativistic quark-diquark picture, Phys. Rev. D 84, 014025 (2011).
[5] B. Chen, K. W. Wei and A. Zhang, Assignments of $\Lambda_2$ and $\Xi_2$ baryons in the heavy quark-light diquark picture, Eur. Phys. J. A 51, 82 (2015).
[6] X. G. He, X. Q. Li, X. Liu and X. Q. Zeng, $\Lambda_3^*$ (2940): A Possible molecular state?, Eur. Phys. J. C 51, 883 (2007).
[7] P. G. Ortega, D. R. Entem and F. Fernandez, Quark model description of the $\Lambda_c(2940)^+$ as a molecular $DN$ state and the possible existence of the $\Lambda_c(6248)$, Phys. Lett. B 718, 1381 (2013).
[8] P. G. Ortega, D. R. Entem and F. Fernandez, Hadronics in the open charm and open bottom baryon spectrum, Phys. Rev. D 90, 114013 (2014).
[9] L. Zhao, H. Huang and J. Ping, $ND$ and $NB$ systems in quark delocalization color screening model, Eur. Phys. J. A 53, 28 (2017).
[10] D. Yang, J. Liu and D. Zhang, $ND^{(*)}$ and $NB^{(*)}$ interactions in a chiral quark model, arXiv:1508.03883.
[11] Z. Y. Wang, J. J. Qi, X. H. Guo and K. W. Wei, Study of molecular $ND$ bound states in the Bethe-Salpeter equation approach, Phys. Rev. D 97, 094025 (2018).
[12] X. H. Zhong and Q. Zhao, Charmed baryon strong decays in a chiral quark model, Phys. Rev. D 77, 074008 (2008).
[13] 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).
[14] 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).
[15] 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.
Phys. Rev. D 60, 094002 (1999).

[29] X. H. Guo, K. W. Wei and X. H. Wu, Strong decays of heavy baryons in Bethe-Salpeter formalism, Phys. Rev. D 77, 036003 (2008).

[30] B. Chen, D. X. Wang and A. Zhang, J′′ Assignments of Λc Baryons, Chin. Phys. C 33, 1327 (2009).

[31] Z. H. Guo and J. A. Oller, Resonance on top of thresholds: the Λc(2595)+ as an extremely fine-tuned state, Phys. Rev. D 93, 054014 (2016).

[32] H. X. Chen, W. Chen, X. Liu, Y. R. Liu and S. L. Zhu, A review of the open charm and open bottom systems, Rept. Prog. Phys. 80, 076201 (2017).

[33] V. Crede and W. Roberts, Progress towards understanding baryon resonances, Rept. Prog. Phys. 76, 076301 (2013).

[34] H. Y. Cheng, Charmed baryons circa 2015, Front. Phys. (Beijing) 10, 101406 (2015).

[35] J. M. Richard, The Nonrelativistic three-body problem for baryons, Phys. Rept. 212, 1 (1992).

[36] E. Klempt and J. M. Richard, Baryon spectroscopy, Rev. Mod. Phys. 82, 1095 (2010).

[37] C. Patrignani et al. [Particle Data Group], Review of Particle Physics, Chin. Phys. C 40, 100001 (2016).

[38] R. Aaij et al. [LHCb Collaboration], Study of the Δc+ p amplitude in Λc→Δc+p− decays, JHEP 1705, 030 (2017).

[39] H. Garcilazo, J. Vijande and A. Valcarce, Faddeev study of heavy baryon spectroscopy, J. Phys. G 34, 961 (2007).

[40] Q. F. Liu, Y. Dong, X. Liu and T. Matsuki, Puzzle of the Λc spectrum, Nucl. Phys. Rev. 35, 1 (2018).

[41] J. He, Z. Ouyang, X. Liu and X. Q. Li, Production of charmed baryon Λc(2940)+ at PANDA, Phys. Rev. D 84, 114010 (2011).

[42] Y. Dong, A. Faessler, T. Gutsche and V. E. Lyubovitskij, Role of the hadron molecule Λc(2940) in the p̅p→pΔc(2286) annihilation reaction, Phys. Rev. D 90, 094001 (2014).

[43] J. J. Xie, Y. B. Dong and X. Cao, Role of the Λc(2940) in the π+ p→Δc+D0 reaction close to threshold, Phys. Rev. D 92, 034029 (2015).

[44] X. Y. Wang, A. Guskov and X. R. Chen, Λc′(2940)+ photoproduction from the neutron, Phys. Rev. D 92, 094032 (2015).

[45] Y. Huang, J. He, J. J. Xie, X. Chen and H. F. Zhang, Production of charmed baryon Λc(2940) by kaon-induced reaction on a proton target, arXiv:1610.06994

[46] A. Yaouanc, L. Oliver, O. Pene, and J-C. Raynal, Hardon Transitions in the quark model (Gordon and Breach, New York, 1988).

[47] W. Roberts and B. Silverstr-Brac, General method of calculation of any hadronic decay in the 3P0 model, Few-Body Syst. 11, 171 (1992).

[48] H. G. Blundell, Meson properties in the quark model: A look at some outstanding problems, arXiv: hep-ph/9608473

[49] E. S. Ackleh, T. Barnes, and E. S. Swanson, On the mechanism of open flavor strong decays, Phys. Rev. D 54, 6811 (1996).

[50] T. Barnes, F. E. Close, P. R. Page, and E. S. Swanson, Higher quarkonia, Phys. Rev. D 55, 4157 (1997).

[51] T. Barnes, N. Black, and P. R. Page, Strong decays of strange quarkonia, Phys. Rev. D 68, 054014 (2003).

[52] A. Le Yaouanc, L. Oliver, O. Pene, and J. C. Raynal, Why is ψ(4.414) so narrow? Phys. Lett. B 72, 57 (1977).

[53] L. Micu, Decay rates of meson resonances in a quark model, Nucl. Phys. B 10, 521, (1969).

[54] Z. Zhao, D. D. Ye and A. Zhang, Nature of charmed strange baryons Ξ(3055) and Ξ(3080), Phys. Rev. D 94, 114020 (2016).

[55] D. D. Ye, Z. Zhao and A. Zhang, Study of P-wave excitations of observed charmed strange baryons, Phys. Rev. D 96, 114009 (2017).

[56] D. D. Ye, Z. Zhao and A. Zhang, Study of 2S- and 1D- excitations of observed charmed strange baryons, Phys. Rev. D 96, 114003 (2017).

[57] Z. Zhao, D. D. Ye and A. Zhang, Hadronic decay properties of newly observed Ωc baryons, Phys. Rev. D 95, 114024 (2017).

[58] B. Chen and X. Liu, New Ωc baryons discovered by LHCb as the members of 1P and 2S states, Phys. Rev. D 96, 094015 (2017).

[59] Q. F. Lü and D. M. Li, Understanding the charmed states recently observed by the LHCb and BaBar Collaborations in the quark model, Phys. Rev. D 90, 054024 (2014).

[60] Q. F. Lü, T. T. Pan, Y. Y. Wang, E. Wang and D. M. Li, Excited bottom and bottom-strange mesons in the quark model, Phys. Rev. D 94, 074012 (2016).

[61] J. Ferretti, G. Galata and E. Santopinto, Quark structure of the X(3872) and χc(3P) resonances, Phys. Rev. D 90, 054010 (2014).

[62] S. Godfrey and K. Moats, Properties of Excited Charm and Charm-Strange Mesons, Phys. Rev. D 93, 034035 (2016).

[63] J. Segovia, D. R. Entem and F. Fernandez, Scaling of the 3P0 Strength in Heavy Meson Strong Decays, Phys. Lett. B 715, 322 (2012).

[64] C. Hayne and N. Isgur, Beyond the Wave Function at the Origin: Some Momentum Dependent Effects in the Nonrelativistic Quark Model, Phys. Rev. D 25, 1944 (1982).

[65] S. Godfrey and N. Isgur, Mesons in a Relativized Quark Model with Chromodynamics, Phys. Rev. D 32, 189 (1985).

[66] S. Capstick and N. Isgur, Baryons in a Relativized Quark Model with Chromodynamics, Phys. Rev. D 34, 2809 (1986).

[67] D. Ebert, R. N. Faustov and V. O. Galkin, Masses of excited heavy baryons in the relativistic quark model, Phys. Lett. B 659, 612 (2008).

[68] Z. Shah, K. Thakkar, A. Kumar Rai and P. C. Vinodkumar, Excited State Mass spectra of Singly Charmed Baryons, Eur. Phys. J. A 52, 313 (2016).