Abstract Possible assignments of highly excited \( \Lambda_c(2860)^+ \), \( \Lambda_c(2880)^+ \) and \( \Lambda_c(2940)^+ \) are explored in a \( ^3P_0 \) strong decay model. Decay widths, branching fraction ratios \( \Gamma(\Sigma_c^+2520)/\Gamma(\Sigma_c^+2455) \) and the branching fractions of \( DN \) channels of these assignments are computed. \( B^0p \) channel is a very important channel to provide information on the inner excitation and structure of these highly excited \( \Lambda_c \). In our analysis, \( \Lambda_c(2860)^+ \) may be a 1\( D \)-wave excited \( \Lambda_c \) with \( J^P = \frac{3}{2}^- \), which has dominant \( DN \) decay channels with a branching fraction \( B(\Lambda_c(2860)^+ \to DN) = 75\% \) and a branching ratio \( R = \Gamma(\Sigma_c^+2520)/\Gamma(\Sigma_c^+2455) = 0.12 \). \( \Lambda_c(2880)^+ \) is very possibly a 1\( F \)-wave excited \( \Lambda_c \) with \( J^P = \frac{5}{2}^- \); In this assignment, the predicted total decay width (\( \Gamma \approx 4.49 \) MeV) is comparable to the measured \( \Gamma = 5.6^{+0.8}_{-0.6} \) MeV, and the predicted \( R = \Gamma(\Sigma_c^+2520)/\Gamma(\Sigma_c^+2455) = 0.12 \) is consistent with the measured \( R = 0.225 \pm 0.062 \pm 0.025 \). The \( DN \) channels are its dominant strong decay channels with a branching fraction \( B(\Lambda_c(2880)^+ \to DN) = 94\% \). \( \Lambda_c(2880)^+ \) seems impossibly a 1\( D \)-wave excited \( \Lambda_c \) with \( J^P = \frac{3}{2}^- \) once the presently measured \( R = \Gamma(\Sigma_c^+2520)/\Gamma(\Sigma_c^+2455) \) is confirmed. \( \Lambda_c(2940)^+ \) may be a 2\( P \)-wave excited \( \Lambda_c \) with \( J^P = \frac{1}{2}^- \), but nothing is known about its mass. \( \Lambda_c(2940)^+ \) is very possibly \( \frac{5}{2}^- \); In this assignment, the predicted total decay width (\( \Gamma \approx 8 \) MeV) is comparable to the measured \( \Gamma = 8.3^{+0.7}_{-0.6} \) MeV, and the predicted \( R = \Gamma(\Sigma_c^+2520)/\Gamma(\Sigma_c^+2455) = 0.89 \) is consistent with the measured \( R = 0.825 \pm 0.062 \pm 0.025 \). The \( DN \) channels are its dominant strong decay channels with a branching fraction \( B(\Lambda_c(2940)^+ \to DN) = 43\% \). In order to understand the inner excitation and structure of these highly excited \( \Lambda_c \), measurements of those predicted quantities are required in the future.

1 Introduction

Charmed baryons with single charmed quark provide ideal windows to study the baryon structure and quark dynamics. The heavy-quark symmetry works approximately in singly-charged baryons, and the quarks inside may correlate and exhibit their structure through their strong decays. There are now 36 established singly-charmed baryons \cite{1}, but their \( J^P \) numbers have seldom been measured in experiments.

\( \Lambda_c \) baryons are composed of one \( u \) quark, one \( d \) quark and one charmed quark. \( \Lambda_c(2286)^+ \) is believed the ground state with \( J^P = \frac{1}{2}^+ \), \( \Lambda_c(2593)^+ \) and \( \Lambda_c(2625)^+ \) are the \( P \)-wave excited states with \( J^P = \frac{1}{2}^- \) and \( J^P = \frac{3}{2}^- \), respectively. \( \Lambda_c(2765)^+ \) or \( \Sigma_c(2765)^+ \) [2] was seen in \( \Lambda^+_c\pi^+\pi^- \) with mass difference \( m(\Lambda_c(2765)^+) - m(\Lambda_c) \approx 480.1 \pm 2.4 \) MeV, but nothing is known about its \( J^P \) and isospin quantum numbers as indicated in PDG2020 (This state was reported as a \( \Lambda_c \) with zero isospin in HADRON 2019 \cite{3}).

\( \Lambda_c(2880)^+ \) was first observed by CLEO collaboration \cite{4}, and its quantum numbers have been constrained by Belle and LHCb collaborations \cite{5,6} with \( J^P = \frac{5}{2}^+ \). The spin hypothesis \( J = \frac{5}{2} \) is favored from an angular analysis in the experiment \cite{4} and the positive parity is assumed through the predictions of the heavy quark symmetry \cite{4,6–8}. \( \Lambda_c(2940) \) was first observed by BaBar collaboration \cite{9} and \( \Lambda_c(2880)^+ \) was first observed by LHCb collaboration \cite{5}, the quantum numbers \( J^P \) of \( \Lambda_c(2860)^+ \) and \( \Lambda_c(2940)^+ \) have not been measured. The masses, decay modes and decay widths of \( \Lambda_c(2860)^+ \), \( \Lambda_c(2880)^+ \) and \( \Lambda_c(2940)^+ \) were reported in these experiments.

In normal baryon interpretations, the quantum numbers and possible internal excitation of \( \Lambda_c(2860)^+ \), \( \Lambda_c(2880)^+ \) and \( \Lambda_c(2940)^+ \) have been studied in many models. The measured mass of \( \Lambda_c(2860)^+ \) is consistent with the theoretical predictions of the orbital \( 1D \)-wave \( \Lambda_c \) excitation with quantum numbers \( \frac{1}{2}^+ \) \cite{10,11}, so \( \Lambda_c(2860)^+ \) is supposed with the quantum numbers \( J^P = \frac{3}{2}^+ \). \( \Lambda_c(2880)^+ \) was supposed with quantum numbers \( J^P = \frac{5}{2}^+ \) in a framework of heavy hadron chiral perturbation theory \cite{7,8}, a constituent quark model \cite{12,13}, a relativistic flux tube model \cite{10}, and a \( ^3P_0 \) strong decay model \cite{14,15}, etc. \( \Lambda_c(2880)^+ \) was also assumed with

---

*e-mail: zhangal@shu.edu.cn* (corresponding author)
quantum numbers $J^P = \frac{3}{2}^+$ in a chiral quark model [16].

The assignments of $\Lambda_c(2940)^+$ is much more contradictory. $\Lambda_c(2940)^+$ was assumed with quantum numbers $J^P = \frac{1}{2}^-$, $J^P = \frac{3}{2}^+$, $J^P = \frac{5}{2}^+$, or $J^P = \frac{5}{2}^-$ in different models [7,8,12–16]. Obviously, the quantum numbers of $\Lambda_c(2860)^+, \Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ have not been fixed, their internal structures are not clear either.

The quarks in baryons may make complex structures and have complex excitations. In order to study the internal structures and excitations, the three-quark baryons are usually described by Jacobi coordinates: a relative coordinate $\rho$ between any two quarks, and a relative coordinate $\lambda$ between the center of mass of the two quarks and the other quark. As known, a diquark may be an important correlation and cluster in hadrons with more than two quarks, and the diquark has been introduced to interpret the light scalar mesons, the missing nucleons, the charmonium-like $X$, $Y$, $Z$, and so on. The diquark has also been employed to describe singly-charmed baryons in many models [10,12,13,17–21]. However, there is no evidence for the existence of diquark in baryons. In this paper, the strong decay properties of $\Lambda_c$ baryons with different $\rho$ or $\lambda$ mode excitations will be studied, and the relation between the excitations and the diquark correlation is explored.

In Ref. [15], all the observed $\Lambda_c$ states except for the ground $\Lambda_c(2286)^+$ were systematically examined as the $1P^-$-wave, $1D$-wave, or $2S$-wave $\Lambda_c$ baryons from their strong decay properties in the $3P_0$ model, and their possible assignments were suggested. In this paper, we continue the examination of $\Lambda_c(2860)^+, \Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ with the highly excited $1D$, $1F$ and $2P$ orbital or radial excitations assignments in detail.

The paper is organized as follows. A simple introduction of $3P_0$ strong decay model and analyses of the strong decay properties of $\Lambda_c(2860)^+, \Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ are given in Sect. 2. Conclusions and discussions are reserved in Sect. 3.

2 1D-wave, 1F-wave and 2P-wave possibilities of $\Lambda_c(2860)^+, \Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$

In order to fix the quantum numbers and to understand the internal structure of $\Lambda_c(2860)^+, \Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$, the $3P_0$ strong decay model is employed. As well known, the $3P_0$ model is usually known as the quark pair creation model. It was proposed by Micu [22] and developed by Le Yaouanc et al. [23–28]. This model has been employed to compute the Okubo-Zweig-Iizuka-allowed (OZI) strong decays widths with two final states and obtained good agreements with experiments.

Following Refs. [15,29–33], the strong decay width for an initial baryon $A$ decaying into two final hadrons $B$ and $C$ in the $3P_0$ model is

$$\Gamma = \frac{\pi^2 |\mathbf{p}|}{m_A^2} \frac{1}{2J_A + 1} \sum |\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}|^2$$

where $\mathcal{M}^{M_{J_A} M_{J_B} M_{J_C}}$ is the helicity amplitude. The explicit expression of the helicity amplitude, the flavor matrix, the space integral and some relevant notations could be found in detail in Ref. [15].

As indicated in Ref. [15], $\rho$ is the relative coordinate between the two light quarks (quarks 1 and 2), and $\lambda$ is the relative coordinate between the center of mass of the two light quarks and the charmed quark. In a constituent quark model, the internal structure of a baryon is also described by a set of quantum numbers $n_{\rho}, n_{\lambda}, L_{\rho}, L_{\lambda}$ and $S_{\rho}$. $n_{\rho}$ and $n_{\lambda}$ denote the nodal quantum numbers of the $\rho$ and $\lambda$ coordinates, respectively. $L_{\rho}$ and $L_{\lambda}$ denote the orbital angular momentum between the two light quarks and the orbital angular momentum between the charm quark and the two-light-quark system. $S_{\rho}$ denotes the total spin of the two light quarks. The total orbital angular momentum $L = L_{\rho} + L_{\lambda}$ and the total angular momentum of the baryons $J = J_1 + \frac{1}{2}$ with $J_1 = L + S_{\rho}$.

Therefore, in the constituent quark model with the heavy-quark symmetry [15,34], there are one $1S$-wave, seven $1P$-wave, seventeen $1D$-wave, and thirty-one $1F$-wave $\Lambda_c$ baryons. For the first radial excitations, the corresponding states are doublet. That is to say, there are two $2S$-wave, fourteen $2P$-wave, thirty-four $2D$-wave, and sixty-two $2F$-wave $\Lambda_c$ baryons. Internal quantum numbers of the $1D$-wave excited $\Lambda_c$ were given in Ref. [15], quantum numbers of the $1F$-wave and $2P$-wave excited $\Lambda_c$ are given in the appendix.

Some parameters are chosen as those in Refs. [15,32,35]. The dimensionless pair-creation $\gamma = 13.4$. The $\beta_{\lambda,\rho} = 600$ MeV in $1S$-wave baryon wave function, $\beta = 400$ MeV in the wave function of $\pi$ and $K$ mesons, $\beta = 600$ MeV for the $D$ meson [15,35]. $\beta_{\rho,\lambda} = 400$ MeV is for the excited $\Lambda_c(2860)^+, \Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$. The masses of relevant hadrons are chosen from Particle Data Group [1].

$D^0 p$ mode is an important channel for $\Lambda_c$ baryons in the $3P_0$ model. In this channel, the heavy charmed quark in initial baryon enters the final $D$ meson and other two light quarks enter the final $p$ baryon. Therefore, this channel may provide some information on the inner excitation and structure of $\Lambda_c$.

In theory, the helicity amplitudes of many high-lying $\Lambda_c$ decaying into $D^0 p$ channel vanish. Therefore, many possible assignments of $\Lambda_c(2860)^+, \Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ can be excluded through the observed $D^0 p$ final states. So does the $D^+ n$ channel. Possible high-lying $\Lambda_c$ which can decay into $D^0 p$ channel are given in Table 1. In these $\Lambda_c$ excita-
tions, $A_{1^c,1^c}(1^-, 2P)$ and $A_{1^c,1^c}(3^-, 2P)$ have radial $\rho$ mode excitation, while others have only $\lambda$ mode excitation.

2.1 1D-wave excitations

Among the seventeen 1D-wave $A_c$ states, there are only two $\lambda$ mode excited states $A_{2^c,0^c}(3^+, 1D)$ and $A_{2^c,0^c}(5^+, 1D)$ with $D^0\rho$ decay channel. The masses of $A_c(2860)^+$ and $A_c(2880)^+$ are comparable to the predicted spectrum of 1D-wave excited $A_c$ [10,11], and they could be the 1D-wave excitations. These two 1D-wave excitations are examined through their strong decay properties in this section.

In the framework of $^3P_0$ model, the decay widths of possible assignments of $A_c(2860)^+$, $A_c(2880)^+$ and $A_c(2940)^+$ are computed. The numerical results of $A_c(2860)^+$, $A_c(2880)^+$ and $A_c(2940)^+$ are presented in Tables 2, 3 and 4, respectively. Their total strong decay widths are also given. The results in these three tables are similar except for a new $\Sigma_c(2800)\pi$ channel for $A_c(2940)^+$. In our computation, $\Sigma_c(2800)$ is regarded as a 1P-wave $\Sigma_c$ with $J^P = \frac{3}{2}^-$ [36].

In each table, the main differences for the assignments of $A_{2^c,0^c}(3^+, 1D)$ and $A_{2^c,0^c}(5^+, 1D)$ are the total decay widths, branching fraction of $DN$ channels and the branching fraction ratios $R = \frac{\Gamma(\Sigma_c(2520)\pi)}{\Gamma(\Sigma_c(2455)\pi)}$. $A_c(2860)^+$ or $A_c(2880)^+$ in the $A_{2^c,0^c}(3^+, 1D)$ assignment has a larger total width, a smaller $R$ and a dominant $DN$ channel in comparison with the $A_{2^c,0^c}(5^+, 1D)$ assignment.

In experiments, $A_c(2880)^+$ has a small total decay width ($\Gamma = 5.6^{+0.8}_{-0.8}$ MeV) and a branching ratio $R = 0.225 \pm 0.062 \pm 0.025$ [1], which was doubted by an influence from its nearby state $A_c(2860)^+$ in Ref. [37]. $A_c(2860)^+$ and $A_c(2940)^+$ have total decay widths $\Gamma = 67.6^{+10.1}_{-8.1} \pm 1.4_{-0.0}^{+0.9}$ MeV and $\Gamma = 20.5 \pm 6$ MeV, respectively, but no branching fraction has been measured.

From the total strong decay width, $A_c(2860)^+$ is very possibly the 1D-wave excitation $A_{2^c,0^c}(3^+, 1D)$ while impossibly the 1D-wave excitation $A_{2^c,0^c}(5^+, 1D)$. In this assignment, $DN$ are the main two body strong decay channels with branching fraction $B(A_c(2860)^+ \rightarrow DN) = 75\%$, and the ratio $R = \frac{\Gamma(\Sigma_c(2520)\pi)}{\Gamma(\Sigma_c(2455)\pi)} = 0.12$. Their measurement in the future will provide more information on $A_c(2860)^+$.

From the total strong decay width, $A_c(2880)^+$ is impossible the the 1D-wave excitation $A_{2^c,0^c}(3^+, 1D)$, but may be a 1D-wave excitation $A_{2^c,0^c}(5^+, 1D)$. In the $A_{2^c,0^c}(5^+, 1D)$ assignment, $\Sigma_c(2520)\pi$ are the dominant two body strong decay channels with branching fraction $B(A_c(2880)^+ \rightarrow \Sigma_c(2520)\pi) = 94\%$. $DN$ channels have branching fraction $B(A_c(2880)^+ \rightarrow DN) = 3\%$. However, the predicted branching ratio $R = \frac{\Gamma(\Sigma_c(2520)\pi)}{\Gamma(\Sigma_c(2455)\pi)} = 44.29$ is much larger than the observed $R = 0.225 \pm 0.062 \pm 0.025$. Similarly large $R$ was predicted in Refs. [37,38]. Even though the theoretical

### Table 1 Possible $A_c$ decaying into $DN$ final states

| $A_{L^c, J^P}^{L^c, J^P}$ | $n_\rho$ | $n_\lambda$ | $L_\rho$ | $L_\lambda$ | $S_\rho$ | $J_L$ | $J^P$ |
|-------------------------|---------|---------|--------|--------|--------|------|------|
| $A_{2^c,0^c}^{2^c,0^c}(3^+, 1D)$ | 0 | 0 | 2 | 2 | 0 | 2 | $\frac{3}{2}^+$ |
| $A_{2^c,0^c}^{2^c,0^c}(5^+, 1D)$ | 0 | 0 | 2 | 2 | 0 | 2 | $\frac{5}{2}^+$ |
| $A_{3^c,0^c}^{3^c,0^c}(3^-, 1F)$ | 0 | 0 | 3 | 3 | 0 | 3 | $\frac{5}{2}^-$ |
| $A_{3^c,0^c}^{3^c,0^c}(7^-, 1F)$ | 0 | 0 | 3 | 3 | 0 | 3 | $\frac{7}{2}^-$ |
| $A_{1^c,1^c}^{1^c,1^c}(1^-, 2P)$ | 1 | 0 | 1 | 1 | 0 | 1 | $\frac{1}{2}^-$ |
| $A_{1^c,1^c}^{1^c,1^c}(3^-, 2P)$ | 1 | 0 | 1 | 1 | 0 | 1 | $\frac{3}{2}^-$ |

### Table 2 Possible decay widths (MeV), branching fraction of $DN$ channels and $R = \frac{\Gamma(\Sigma_c(2520)\pi)}{\Gamma(\Sigma_c(2455)\pi)}$ of $A_c(2860)^+$ as $A_{2^c,0^c}^{2^c,0^c}(3^+, 1D)$ and $A_{2^c,0^c}^{2^c,0^c}(5^+, 1D)$

| channel | $A_{2^c,0^c}^{2^c,0^c}(3^+, 1D)$ | $A_{2^c,0^c}^{2^c,0^c}(5^+, 1D)$ |
|---------|-----------------|-----------------|
| $\Sigma_c^{++}\pi^-$ | 4.03 | 0.05 |
| $\Sigma_c^{+}\pi^0$ | 4.10 | 0.05 |
| $\Sigma_c^{0}\pi^+$ | 4.04 | 0.05 |
| $\Sigma_c^{++}(2520)\pi^-$ | 0.47 | 2.72 |
| $\Sigma_c^{+}(2520)\pi^0$ | 0.48 | 2.79 |
| $\Sigma_c^{0}(2520)\pi^+$ | 0.47 | 2.72 |
| $D^0\rho$ | 22.33 | 0.06 |
| $D^+n$ | 19.19 | 0.04 |
| Total width | 55.11 | 8.48 |
| $R$ | 0.12 | 54.87 |
| $B(A_c(2860)^+ \rightarrow DN)$ | 75% | 1% |
uncertainties in the $3P_0$ model have been taken into account, it is difficult to assign the $\Lambda_c(2880)^+$ with the 1D-wave excitation $\Lambda_{c,2.0}^{2.0}(5^+,1D)$ through its strong decay properties.

Through the strong decay widths only, $\Lambda_c(2940)^+$ could be the 1D-wave excitation $\Lambda_{c,2.0}^{2.0}(5^+,1D)$ and is impossibly the 1D-wave excitation $\Lambda_{c,2.0}^{2.0}(3^+,1D)$. Taking into account the fact that $\Lambda_c(2940)^+$ has a higher mass than the predicted 1D-wave excited $\Lambda_c$, it can not be the 1D-wave excitation.

2.2 1F-wave excitations

Among the thirty-one 1F-wave $\Lambda_c$ states, there are also only two $\lambda$ mode excited states $\Lambda_{c,3.0}(5^-,1F)$ and $\Lambda_{c,3.0}(7^-,1F)$ with $D^0\rho$ decay channel. As a 1F-wave excitation candidate, $\Lambda_c(2940)^+$ has numerical results similar to $\Lambda_c(2860)^+$ and $\Lambda_c(2880)^+$ except for the $\Sigma_c(2800)\pi$ channel. The decay widths of $\Lambda_c(2860)^+$, $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ are computed. To avoid tedious duplicate tables, only the results of $\Lambda_c(2880)^+$ are presented in Table 5.

Obviously, as a $\Lambda_{c,3.0}^{3.0}(5^-,1F)$, the predicted total decay widths $\Gamma = 4.49$ MeV and the branching ratio $R = \Gamma(\Sigma_c(2520)\pi)/\Gamma(\Sigma_c(2520)\pi)$ = 0.12 of $\Lambda_c(2880)^+$ are consistent with the observed total decay width $\Gamma = 5.6^{+0.8}_{-0.6}$ MeV and branching ratio $R = 0.225\pm0.062\pm0.025$. $\Lambda_c(2880)^+$ is very possibly the 1F-wave excitation $\Lambda_{c,3.0}^{3.0}(5^-,1F)$. In this assignment, the channels $DN$ are the dominant two-body decay channels with branching fraction $B(\Lambda_c(2880)^+ \rightarrow DN) = 94\%$.

$\Lambda_c(2860)^+$ seems impossibly $\Lambda_{c,3.0}^{3.0}(5^-,1F)$ for its much larger decay width in comparison to the predicted one. Since no branching ratio has been measured, it is difficult to assign $\Lambda_c(2940)^+$ with the $\Lambda_{c,3.0}^{3.0}(5^-,1F)$ only from its total decay width.

Table 3 Possible decay widths (MeV), branching fraction of $DN$ channels and $R = \Gamma(\Sigma_c(2520)\pi)/\Gamma(\Sigma_c(2520)\pi)$ of $\Lambda_c(2880)^+$ as $\Lambda_{c,2.0}^{2.0}(5^+,1D)$ and $\Lambda_{c,2.0}^{2.0}(3^+,1D)$

| Channel | $\lambda_{c,2.0}^{2.0}(5^+,1D)$ | $\lambda_{c,2.0}^{2.0}(3^+,1D)$ |
|---------|-------------------------------|-------------------------------|
| $\Sigma_c^{++}\pi^-$ | 4.85 | 0.08 |
| $\Sigma_c^{+}\pi^0$ | 4.92 | 0.08 |
| $\Sigma_c^0\pi^+$ | 4.86 | 0.08 |
| $\Sigma_c^0(2520)\pi^-$ | 0.62 | 3.52 |
| $\Sigma_c^+(2520)\pi^0$ | 0.64 | 3.59 |
| $\Sigma_c^+(2520)\pi^+$ | 0.62 | 3.52 |
| $D^0\rho$ | 35.75 | 0.22 |
| $D^+n$ | 32.71 | 0.17 |
| Total width | 84.97 | 11.26 |
| $R$ | 0.13 | 44.29 |
| $B(\Lambda_c(2880)^+ \rightarrow DN)$ | 81% | 3% |

As a $\Lambda_{c,3.0}^{3.0}(5^-,1F)$, the predicted total decay widths of $\Lambda_c(2860)^+$, $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ are much smaller than the observed ones, so $\Lambda_c(2860)^+$, $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ are impossibly the 1F-wave excitation $\Lambda_{c,3.0}^{3.0}(5^-,1F)$.

2.3 2P-wave excitations

There are fourteen 2P-wave excited $\Lambda_c$, among which there are four excitations with $D^0\rho$ decay channels. As indicated in Table 1, these excitations are $\Lambda_{c,1.0}^{1.0}(7^-,1P)$, $\Lambda_{c,1.0}^{1.0}(3^-,2P)$, $\Lambda_{c,1.1}^{1.0}(7^-,1P)$ and $\Lambda_{c,1.1}^{1.0}(3^-,2P)$. From the appendix, $\Lambda_{c,1.0}^{1.0}(7^-,1P)$ and $\Lambda_{c,1.0}^{1.0}(3^-,2P)$ are $\lambda$ mode.

| Channel | $\lambda_{c,2.0}^{2.0}(5^+,1D)$ | $\lambda_{c,2.0}^{2.0}(3^+,1D)$ |
|---------|-------------------------------|-------------------------------|
| $\Sigma_c^{++}\pi^-$ | 6.85 | 0.21 |
| $\Sigma_c^{+}\pi^0$ | 6.91 | 0.22 |
| $\Sigma_c^0\pi^+$ | 6.85 | 0.21 |
| $\Sigma_c^0(2520)\pi^-$ | 1.07 | 5.67 |
| $\Sigma_c^+(2520)\pi^0$ | 1.09 | 5.76 |
| $\Sigma_c^+(2520)\pi^+$ | 1.07 | 5.67 |
| $\Sigma_c^+(2800)\pi^0$ | 8.71 | 6.38 $\times 10^{-5}$ |
| $D^0\rho$ | 61.62 | 1.36 |
| $D^+n$ | 59.52 | 1.19 |
| Total width | 153.69 | 20.29 |
| $R$ | 0.16 | 26.72 |
| $B(\Lambda_c(2880)^+ \rightarrow DN)$ | 79% | 13% |

| Channel | $\lambda_{c,3.0}^{3.0}(5^-,1F)$ | $\lambda_{c,3.0}^{3.0}(7^-,1F)$ |
|---------|-------------------------------|-------------------------------|
| $\Sigma_c^{++}\pi^-$ | 8.54 $\times 10^{-2}$ | 6.96 $\times 10^{-4}$ |
| $\Sigma_c^{+}\pi^0$ | 8.78 $\times 10^{-2}$ | 7.37 $\times 10^{-4}$ |
| $\Sigma_c^0\pi^+$ | 8.56 $\times 10^{-2}$ | 7.00 $\times 10^{-4}$ |
| $\Sigma_c^0(2520)\pi^-$ | 1.03 $\times 10^{-2}$ | 4.55 $\times 10^{-2}$ |
| $\Sigma_c^+(2520)\pi^0$ | 1.07 $\times 10^{-2}$ | 4.73 $\times 10^{-2}$ |
| $\Sigma_c^+(2520)\pi^+$ | 1.03 $\times 10^{-2}$ | 4.55 $\times 10^{-2}$ |
| $D^0\rho$ | 2.28 | 7.02 $\times 10^{-3}$ |
| $D^+n$ | 1.92 | 4.98 $\times 10^{-3}$ |
| Total width | 4.49 | 0.15 |
| $R$ | 0.12 | 64.84 |
| $B(\Lambda_c(2880)^+ \rightarrow DN)$ | 94% | 8% |
The observed ones of $\Lambda$ decay width, and high-lying radial excitations, and $A_{c1,1} (\frac{1}{2}^-, 2P)$ and $A_{c1,1} (\frac{3}{2}^-, 2P)$ are $\rho$ mode radial excitations.

The decay widths of possible assignments of $A_c (2940)^+$ are computed when it is regarded as $A_{c1,0} (\frac{1}{2}^-, 2P)$, $A_{c1,0} (\frac{3}{2}^-, 2P)$, $A_{c1,1} (\frac{1}{2}^-, 2P)$ or $A_{c1,1} (\frac{3}{2}^-, 2P)$. The numerical results are given in Table 6. $A_c (2860)^+$ and $A_c (2880)^+$ have similar numerical results which have not been presented explicitly.

Once the strong decay widths are taken into account only, $A_c (2860)^+$ could be the $A_{c1,1} (\frac{1}{2}^-, 2P)$ under large uncertainty and can not be any other $2P$-wave excited $A_c$. Taking into account the fact that $A_c (2860)^+$ has a lower mass in comparison to theoretical predicition of $2P$-wave, $A_c (2860)^+$ can not be a $2P$-wave excited $A_c$.

When the predicted total decay widths are compared with the observed ones of $A_c (2880)^+$ and $A_c (2940)^+$, $A_c (2880)^+$ is impossibly a $2P$-wave excitation for its small total decay width, and $A_c (2940)^+$ is possibly the $A_{c1,0} (\frac{3}{2}^-, 2P)$.

As a $A_{c1,1} (\frac{3}{2}^-, 2P)$ excitation, the total decay width $\Gamma = 17.56$ MeV, the branching ratio $R = \frac{\Gamma (A_c (2520))}{\Gamma (A_c (2880))} = 0.89$ and the branching fraction $B(A_c (2940)^+ \rightarrow D N) = 43\%$ are predicted for $A_c (2940)^+$.

In comparison with the $D$-wave and $F$-wave excited $A_c$ with $\lambda$ mode excitation only, the $2P$-wave excited $A_c$ with $\rho$ mode excitation has a much lower branching fraction of $D N$ channels.

### Table 6: Possible decay widths (MeV), branching fraction of $D N$ channels and $R = \frac{\Gamma (A_c (2520)))}{\Gamma (A_c (2880))}$ as four $2P$-wave excitations

| Channel                  | $A_{c1,0} (\frac{1}{2}^-, 2P)$ | $A_{c1,0} (\frac{3}{2}^-, 2P)$ | $A_{c1,1} (\frac{1}{2}^-, 2P)$ | $A_{c1,1} (\frac{3}{2}^-, 2P)$ |
|--------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| $\Sigma^+ \pi^-$         | 2.91                            | 2.22                            | 0.06                            | 1.76                            |
| $\Sigma^+ \pi^0$         | 2.91                            | 2.28                            | 0.05                            | 1.79                            |
| $\Sigma^0 \pi^+$         | 2.91                            | 2.23                            | 0.06                            | 1.76                            |
| $\Sigma^+ (2520) \pi^-$  | 2.02                            | 28.27                           | 1.87                            | 1.58                            |
| $\Sigma^+ (2520) \pi^0$  | 2.08                            | 28.32                           | 1.92                            | 1.57                            |
| $\Sigma^0 (2520) \pi^+$  | 2.02                            | 28.26                           | 1.87                            | 1.58                            |
| $\Sigma^+ (2800) \pi^0$  | 0.02                            | $2.66 \times 10^{-3}$           | 0.11                            | 0.01                            |
| $D^0 p$                  | 49.18                           | $7.56 \times 10^{-3}$           | 51.83                           | 3.93                            |
| $D^+ n$                  | 47.84                           | $1.09 \times 10^{-2}$           | 52.99                           | 3.58                            |
| Total width              | 190.66                          | 91.60                           | 110.76                          | 17.56                           |
| $R$                      | 0.07                            | 12.61                           | 33.29                           | 0.89                            |
| $B(A_c (2940)^+ \rightarrow D N)$ | 51%                             | $\approx 0\%$                  | 95%                             | 43%                             |

3 Conclusions and discussions

The $1D$-wave, $1F$-wave and $2P$-wave assignments of the high-lying $A_c (2860)^+$, $A_c (2880)^+$ and $A_c (2940)^+$ are examined from their strong decay properties in the $^3P_0$ model.

Based on experimental results, some possible or favored assignments of these excited $A_c$ are suggested to them, and some impossible assignments are pointed out.

$A_c (2860)^+$ may be the $1D$-wave excited $A_{c2,0} (\frac{3}{2}^+, 1D)$, it is impossibly the $1D$-wave excited $A_{c2,0} (\frac{5}{2}^+, 1D)$, $1F$-wave excitation or $2P$-wave excited $A_c$. The $D^0 p$ mode is the dominant decay channel with branching fraction $B(A_c (2860)^+ \rightarrow D N) = 75\%$, and the branching ratio $R = \frac{\Gamma (A_c (2520) \pi)}{\Gamma (A_c (2880))} = 0.12$. In experiment, only the $D^0 p$ channel has been observed, the observation of other decay channels such as $\Sigma_c \pi$ or $\Sigma_c (2520) \pi$ and measurement of their branching fractions are required to understand its inner excitation and structure.

As reported in Ref. [4], an analysis of angular distribution in $A_c (2880)^+ \rightarrow \Sigma_c (2455)^{0+,+} \pi^+$ strongly favors the $A_c (2880)^+$ with spin $\frac{3}{2}^-$. In their analysis, the measured $R = \frac{\Gamma (\Sigma_c (2520) \pi)}{\Gamma (\Sigma_c (2880))} = 0.225 \pm 0.062 \pm 0.025$ is found around the prediction of heavy quark symmetry $R = 0.23 - 0.36$ for the $\frac{5}{2}^-$ state [6–8], so the positive parity was assumed to the $A_c (2880)^+$ [4]. In our analysis, the $A_c (2880)^+$ is very possibly the $1F$-wave excited $A_{c3,0} (\frac{3}{2}^-, 1F)$ with negative parity. As a $A_{c3,0} (\frac{3}{2}^-, 1F)$, our prediction of the total decay width and the branching ratio agrees well with experiments. Furthermore, the dominant decay channel $D^0 p$ with branching fraction $B(A_c (2880)^+ \rightarrow D N) = 94\%$ is also predicted. $A_c (2880)^+$ is impossibly the $1D$-wave excitation, the $1F$-wave excited $A_{c3,0} (\frac{7}{2}^-, 1F)$ or the $2P$-wave excitation. Accordingly, the $J, P$ quantum numbers of $A_c (2880)^+$ can not be $\frac{3}{2}^+$ or $\frac{5}{2}^-$. In experiment, the channels $\Sigma_c (2455) \pi$, $\Sigma_c (2520) \pi$, $A_c \pi \pi$ and $D^0 p$ have been observed, the mea-
measurement of all the branching fractions of these channels is very important for the understanding of this state.

In [5], the most likely spin-parity assignment for \( \Lambda_c \) (2940)\(^+\) was suggested with \( J^P = \frac{3}{2}^- \). However, other solutions with spins \( \frac{1}{2} \) to \( \frac{7}{2} \) have not been excluded. In our analysis, \( \Lambda_c \) (2940)\(^+\) could be the 2\(P\)-wave excited \( \Lambda_{c1,1}^{1,0}(\frac{3}{2}^-, 2P) \). It is impossibly the 1\(D\)-wave excited \( \Lambda_c \), 1\(F\)-wave excited \( \Lambda_{c3,0}^{3,0}(2^-, 1F) \) or any other 2\(P\)-wave excitations. In the \( \Lambda_{c1,1}^{1,0}(\frac{3}{2}^-, 2P) \) assignment, \( \Lambda_c \) (2940)\(^+\) has a total decay width \( \Gamma = 17.56 \) MeV, the branching ratio \( R = \frac{\Gamma(\Sigma(2520)^0)}{\Gamma(\Sigma(2455)^0)} = 0.89 \) and the \( DN \) channels with branching fraction \( B(\Lambda_c(2940)^+ \to DN) = 43\% \).

So far, \( D^0 p \) channel has been observed in all highly excited \( \Lambda_c \) above their threshold, which may imply that the two light quarks in initial baryons enters the final baryon in the strong decay process. In the same time, the \( DN \) channels are dominant and the two internal light quarks in initial baryons coupling with a total spin \( S_p = 0 \) in all possible assignments of \( \Lambda_c \) (2860)\(^-\), \( \Lambda_c \) (2880)\(^+\) and \( \Lambda_c \) (2940)\(^+\), which may imply that the two light quarks in initial \( \Lambda_c \) make a good diquark. Furthermore, the 2\(P\)-wave excited \( \Lambda_c \) with \( \rho \) mode excitation has a much lower branching fraction of \( DN \) channel in comparison with the 1\(D\)-wave and 1\(F\)-wave excited \( \Lambda_c \) with \( \lambda \) mode excitation only. The existence and properties of diquark require more exploration.

In addition to the normal uncertainties, three-body decay cannot be computed in the \( 3P_0 \) model. In our analyses, the parameters \( \beta \) are chosen the same for \( \rho \) mode and \( \lambda \) mode for simplicity though the parameters \( \beta \) (represent the inverse root mean square radius) of \( \rho \) and \( \lambda \) mode excitation may be different. More highly excited possibilities to these \( \Lambda_c \) have not yet analyzed. In order to identify these highly-excited \( \Lambda_c \) baryons and to understand their inner structure and dynamics, measurements of the \( J, P \) quantum numbers and branching fractions of the main decay channels of these highly excited \( \Lambda_c \) are required, more theoretical analyses in different models are also required.

**Acknowledgements** This work is supported by National Natural Science Foundation of China under the Grant No. 11975146.

**Data Availability Statement** This manuscript has no associated data or the data will not be deposited. [Authors’ comment: The data can be reproduced without any difficulty through the formula in the paper.]

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. In all other cases, the \( \rho \) mode excitation may be

---

**Table 7  2\(P\)-wave excited \( \Lambda_c \)**

| \( \Lambda_{c,1,1}^{1,0}(\frac{3}{2}^-, 2P) \) | \( n_\rho \) | \( n_\lambda \) | \( L_\rho \) | \( L_\lambda \) | \( L \) | \( S_p \) | \( J_L \) | \( J^P \) |
|---|---|---|---|---|---|---|---|---|
| \( \Lambda_{c1,1}^{1,0}(\frac{3}{2}^-, 2P) \) | 0 | 1 | 0 | 1 | 1 | 0 | 1 | \( \frac{1}{2}^- \) |
| \( \Lambda_{c1,1}^{1,0}(\frac{3}{2}^-, 2P) \) | 0 | 1 | 0 | 1 | 1 | 0 | 1 | \( \frac{3}{2}^- \) |
| \( \Lambda_{c1,1}^{1,0}(\frac{3}{2}^-, 2P) \) | 0 | 1 | 1 | 0 | 1 | 1 | 0 | \( \frac{1}{2}^+ \) |
| \( \Lambda_{c1,1}^{1,0}(\frac{3}{2}^-, 2P) \) | 0 | 1 | 1 | 0 | 1 | 1 | 0 | \( \frac{1}{2}^- \) |
| \( \Lambda_{c1,1}^{1,0}(\frac{3}{2}^-, 2P) \) | 0 | 1 | 1 | 0 | 1 | 1 | 0 | \( \frac{1}{2}^- \) |
| \( \Lambda_{c2,1}^{1,0}(\frac{5}{2}^-, 2P) \) | 0 | 1 | 1 | 0 | 1 | 1 | 2 | \( \frac{3}{2}^- \) |
| \( \Lambda_{c2,1}^{1,0}(\frac{5}{2}^-, 2P) \) | 0 | 1 | 1 | 0 | 1 | 1 | 2 | \( \frac{3}{2}^- \) |
| \( \Lambda_{c2,1}^{1,0}(\frac{5}{2}^-, 2P) \) | 0 | 1 | 1 | 0 | 1 | 1 | 2 | \( \frac{3}{2}^- \) |
| \( \Lambda_{c2,1}^{1,0}(\frac{5}{2}^-, 2P) \) | 0 | 1 | 1 | 0 | 1 | 1 | 2 | \( \frac{3}{2}^- \) |
| \( \Lambda_{c2,1}^{1,0}(\frac{5}{2}^-, 2P) \) | 0 | 1 | 1 | 0 | 1 | 1 | 2 | \( \frac{3}{2}^- \) |
| \( \Lambda_{c2,1}^{1,0}(\frac{5}{2}^-, 2P) \) | 0 | 1 | 1 | 0 | 1 | 1 | 2 | \( \frac{3}{2}^- \) |

---

**Appendix**

In the constituent quark model with the heavy-quark symmetry, internal quantum numbers of 1\(F\)-wave and 2\(P\)-wave
excited $A_c$ and their name are given in the following two tables (Tables 7 and 8).

### References

1. P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

2. M. Artuso et al. (CLEO Collaboration), Phys. Rev. Lett. **86**, 4479 (2001)
3. K. Tanida et al. (Belle Collaboration), (2019). arXiv:1908.06235
4. K. Abe et al. (Belle Collaboration), Phys. Rev. Lett. **98**, 262001 (2007)
5. R. Aaij et al. (LHCb Collaboration), J. High Energy Phys. **05**, 030 (2017)
6. N. Isgur, M.B. Wise, Phys. Rev. Lett. **66**, 1130 (1991)
7. H.-Y. Cheng, C.-K. Chua, Phys. Rev. D **75**, 014006 (2007)
8. H.-Y. Cheng, C.-K. Chua, Phys. Rev. D **92**, 074014 (2015)
9. B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. 98, 012001 (2007)
10. B. Chen, K.-W. Wei, A. Zhang, Eur. Phys. J. A 51, 82 (2015)
11. H.-X. Chen, Q. Mao, A. Hosaka, X. Liu, S.-L. Zhu, Phys. Rev. D 94, 114016 (2016)
12. D. Ebert, R.N. Faustova, V.O. Galkin, Phys. Lett. B 659, 612 (2008)
13. D. Ebert, R.N. Faustova, V.O. Galkin, Phys. Rev. D 84, 014025 (2011)
14. L. Qi-Fang, L.-Y. Xiao, Z.-Y. Wang, X.-H. Zhong, Eur. Phys. J. C 78, 599 (2018)
15. J.-J. Guo, P. Yang, A. Zhang, Phys. Rev. D 100, 014001 (2019)
16. X.-H. Zhong, Q. Zhao, Phys. Rev. D 77, 074008 (2008)
17. X.-H. Guo, A. William Thomas, Phys. Rev. D 59, 116007 (1999)
18. A. Selem, F. Wilczek, (2020). arXiv: hep-ph/0602128
19. B. Chen, D.-X. Wang, A. Zhang, Chin. Phys. C 33, 1327 (2009)
20. D. Jido, M. Sakashita, Prog. Theor. Exp. Phys. 2016, 083D02 (2016)
21. Y. Kim, E. Hiyama, M. Oka, K. Suzuki, Phys. Rev. D 102, 014004 (2020)
22. L. Micu, Nucl. Phys. B 10, 521 (1969)
23. A. Le Yaouanc, L. Oliver, O. Pène, J.C. Raynal, Phys. Rev. D 8, 2223 (1973)
24. A. Le Yaouanc, L. Oliver, O. Pène, J.C. Raynal, Phys. Rev. D 9, 1415 (1974)
25. A. Le Yaouanc, L. Oliver, O. Pène, J.C. Raynal, Phys. Rev. D 11, 1272 (1975)
26. A. Le Yaouanc, L. Oliver, O. Pène, J.C. Raynal, Phys. Lett. 71B, 397 (1977)
27. A. Le Yaouanc, L. Oliver, O. Pène, J.C. Raynal, Phys. Lett. 72B, 57 (1977)
28. A. Le Yaouanc, L. Oliver, O. Pène, J.C. Raynal, Hadron Transitions in the Quark Model (Gordon and Breach Science Publishers, New York, 1987)
29. C. Chen, X.-L. Chen, X. Liu, W.-Z. Deng, S.-L. Zhu, Phys. Rev. D 75, 094017 (2007)
30. Z. Zhao, D.-D. Ye, A. Zhang, Phys. Rev. D 95, 114024 (2017)
31. D.-D. Ye, Z. Zhao, A. Zhang, Phys. Rev. D 96, 114003 (2017)
32. D.-D. Ye, Z. Zhao, A. Zhang, Phys. Rev. D 96, 114009 (2017)
33. P. Yang, J.-J. Guo, A. Zhang, Phys. Rev. D 99, 034018 (2019)
34. H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, S.-L. Zhu, Rep. Prog. Phys. 80, 076201 (2017)
35. L. Qi-Fang, X.-H. Zhong, Phys. Rev. D 101, 014017 (2020)
36. R. Mizuk et al. (Belle Collaboration), Phys. Rev. Lett. 94, 122002 (2005)
37. Y.-X. Yao, K.-L. Wang, X.-H. Zhong, Phys. Rev. D 98, 076015 (2018)
38. B. Chen, X. Liu, A. Zhang, Phys. Rev. D 95, 074022 (2017)