Estimation of coupling constants for D-meson, charmed, and light baryons in effective Lagrangian approach and quark model

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Abstract We estimate coupling constants for effective Lagrangians of $D$-meson, charmed, and light baryons from charmed baryon decay processes. First, we calculate decay widths for the processes $\Lambda_c \to D^* N$, $\Lambda_c \to D N$, $\Sigma_c \to DN$, $\Sigma_c \to D \Delta$, and $\Sigma_c \to D^* \Delta$ in effective Lagrangian method and quark model picture with $3\, P_0$ model. By employing the coupling constants for $D^* \Lambda_c N$ interaction from several literatures, the strength parameter $\lambda$ for $3\, P_0$ quark model is fixed in the decay process $\Lambda_c \to D^* N$. Then, the coupling constants for the effective Lagrangians of $D \Lambda_c N$, $D \Sigma_c N$, $D \Sigma_c \Delta$, and $D^* \Sigma_c \Delta$ interactions are estimated in the decay channels $\Lambda_c \to DN$, $\Sigma_c \to DN$, $\Sigma_c \to D \Delta$, and $\Sigma_c \to D^* \Delta$, respectively. Then, the coupling constants for $D \Sigma_c N$, $D^* \Sigma_c N$, and $D^* \Sigma_c \Delta$ interactions are calculated from heavy-quark and large-$N_c$ sum rules. The coupling constants from this study will be useful for further studies of charm hadrons.

1 Introduction

Physics of charm hadrons has been one of the main subjects in hadron physics since the first observations of $J/\psi$ meson in 1974 [1,2] and of charmed baryons ($\Lambda_c$, $\Sigma_c$) in 1975 [3]. Ever since, experimental observations for various exotic hadrons have been reported by Belle, BABAR, BESIII, and LHCb Collaborations [4–14], and theoretical studies have been carried out in a variety of models [15–35] (see Refs. [36,37] for reviews). While charmed mesons have been extensively investigated, the properties of charmed baryons are less known since they have not yet been explored in the same detail. Proposals for charmed baryons study have been planned at future experiments at PANDA [38] and J-PARC [39] and the facilities are now under preparation. Thus, theoretical study of their production is important. The production rate of charmed baryons will be crucial to guide and assess these experimental plans. Moreover, their production mechanism provides not only the information of their internal structure and non-perturbative QCD dynamics, but also the role of chiral and heavy quark symmetries in heavy-light quark systems.

One of the most important ingredients for calculation of charmed baryon production rate is the coupling constants. So far, it is not possible to determine the coupling constants for the effective Lagrangians of $D$-meson, charmed, and light baryons directly from the existing data. Therefore, several methods have been used to extract the coupling constants for various charmed baryon interaction vertices. In Refs. [40], coupling constants for strange hadrons derived from Nijmegen potential are employed to study charmed productions from pion-proton collisions. The coupling constants in these studies are of the same order as those in Ref. [41], where they are determined from the $SU(3)$ symmetry relations and from the fit with the observed data for strangeness productions. In Ref. [42], coupling constants derived from QCD light-cone sum rules are employed to predict charmed hadron production cross sections at PANDA. On the other hand, the coupling constants from the $SU(4)$ symmetry are utilized to study the production of charmed baryons from...
proton-antiproton collisions in Refs. [43–47]. The coupling constants for various charmed and bottom baryons are calculated in the context of QCD sum rules [48–51]. From the previous studies, different sets of coupling constants result in discrepancies in the predicted charm production rates.

In this study, we estimate the coupling constants for the effective Lagrangians of $D$-meson, charmed, and light baryons from the decay widths of $\Lambda_c$ and $\Sigma$ baryons. Firstly, the decay widths for the processes $\Lambda_c \rightarrow D^* N$, $\Lambda_c \rightarrow D N$, $\Sigma_c \rightarrow D N$, $\Sigma_c \rightarrow D \Delta$, and $\Sigma_c \rightarrow D^* \Delta$ are computed in effective Lagrangian method and quark model picture with $^3P_0$ model. Then, the strength parameter $\lambda$ of the $^3P_0$ quark model is fixed from the decay channel $\Lambda_c \rightarrow D^* N$, where the coupling constants for $D^* \Lambda_c N$ vertex from several literatures are used as inputs. The coupling constants for the vertices $D \Lambda_c N$, $D \Sigma_c N$, $D \Sigma_c \Delta$, and $D^* \Sigma_c \Delta$ are consequently estimated in the corresponding decay channels. Then, the coupling constants for $D \Sigma_c N$, $D^* \Sigma_c N$, and $D^* \Sigma_c \Delta$ interactions are calculated from heavy-quark and large-$N_c$ sum rules [60]. In this work, five sets of the coupling constants are presented.

The content of this paper is organised as follows. In Sect. 2, we compute the decay widths of charmed baryons in effective Lagrangian method. In Sect. 3, the calculations of the same decay processes from Sect. 2 are performed in quark model with $^3P_0$ model. Then, the estimation of the coupling constants from the two models is presented in Sect. 4. Finally, the summary of this study is given in Sect. 5.

2 Effective Lagrangian method

In this section, we calculate decay widths of charmed baryons in effective Lagrangian method. The decay of an initial charmed baryon $B_c$ into an outgoing light baryon $B$ and a charmed meson $\phi_c$ is displayed by the diagram in Fig. 1. Here, the momentum of the initial charmed baryon ($\Lambda_c(2286)$ or $\Sigma_c(2455)$) is denoted by $p$, while $k$ and $q$ are those of the outgoing light baryon ($N(939)$ or $\Delta(1232)$) and charmed meson ($D(1868)$ or $D^*(2009)$) respectively.

The effective Lagrangians for $DB_cB$ interaction vertices are given by

$$\mathcal{L}_{D\Lambda_cN}^{(A)} = -\frac{g_{0}}{m_{D}} \bar{N} \gamma^\mu \gamma_5 \Lambda_c \partial_\mu D,$$

$$\mathcal{L}_{D\Lambda_cN}^{(P)} = g_{1} \bar{N} i \gamma_5 \Lambda_c D,$$

$$\mathcal{L}_{D\Sigma_c\Delta} = \frac{g_{2}}{m_{D}} \bar{\Lambda}_c \gamma_5 \Sigma_c \cdot T \partial_\mu D,$$

$$\mathcal{L}_{D\Sigma_c\Delta}^{(P)} = g_{3} \bar{N} i \gamma_5 \Sigma_c D.$$  

For $D^* B_c B$ interaction vertices, we introduce the following Lagrangians

$$\mathcal{L}_{D^*\Lambda_cN} = f_{0} \bar{D} \gamma^\mu \Lambda_c D_{\mu} + \frac{h_0}{m_{D}} \bar{\Lambda}_c \sigma^{\mu \nu} \partial_{\mu} D_{\nu},$$

$$\mathcal{L}_{D^*\Lambda_cN}^{(P)} = f_{1} \bar{D} \gamma_5 \Lambda_c D,$$

where $m_{D}$ corresponds to the approximate mass of the pseudoscalar $D$-meson and $T = (T_1, T_2, T_3)$ represents the isospin transition matrices operating on the isospin states of $\Delta$ and $D$ (or $D^*$).

By employing the Lagrangians in Eqs. (1)–(6), Feynman amplitudes for the decay processes $\Lambda_c \rightarrow D N, \Lambda_c \rightarrow D^* N$, $\Sigma_c \rightarrow D \Delta, \Sigma_c \rightarrow D N$, and $\Sigma_c \rightarrow D^* \Delta$ are written as

$$\mathcal{M}_{\Lambda_c \rightarrow D N}^{(A)} = \frac{g_{0}}{m_{D}} \bar{N} \gamma^\mu \gamma_5 \Lambda_c \left( p, s \right),$$

$$\mathcal{M}_{\Lambda_c \rightarrow D N}^{(P)} = g_{1} \bar{N} \left( p, s \right),$$

$$\mathcal{M}_{\Lambda_c \rightarrow D^* N} = i f_{0} \bar{u}_N \left( k, s' \right) \Gamma_{\mu} \Lambda_c \left( p, s \right) \epsilon_{\mu}^* \left( q, s'' \right),$$

$$\mathcal{M}_{\Sigma_c \rightarrow D \Delta} = -\frac{g_{2}}{m_{D}} \bar{q}_\mu \Lambda_c \left( k, s' \right) u_{\Sigma_c} \left( p, s \right),$$

$$\mathcal{M}_{\Sigma_c \rightarrow D^* N} = -g_{3} \bar{u}_N \left( k, s' \right) \gamma_5 \gamma_5 u_{\Sigma_c} \left( p, s \right),$$

where

$$\Gamma_{\mu} = \left[ \gamma^\mu + \frac{i}{m_{D}} \left( \frac{h_0}{f_0} \right) \sigma^{\mu \nu} q_{\nu} \right].$$

The spin projections of the initial charmed baryon, outgoing light baryon and $D^*$-meson are respectively denoted by $s, s'$, and $\Delta$. The decay width of the initial charmed baryon $B_c$ is then computed from

$$\Gamma_{\text{EFT}} = \frac{1}{32\pi^2 m_{B_c}} \int \langle |M|^2 \rangle d\Omega,$$

where

$$\langle |M|^2 \rangle = \begin{cases} \frac{1}{2} \sum_{s'} |M|^2 & \text{if } \phi_c = D, \\ \frac{1}{2} \sum_{s', \Delta} |M|^2 & \text{if } \phi_c = D^*. \end{cases}$$
The mass of the initial charmed baryon and the magnitude of outgoing 3-momentum in the center of mass frame of the initial charmed baryon are denoted by $m_{B_c}$ and $|\mathbf{q}|$.

By expanding the decay width with respect to the outgoing 3-momentum $q$ near the threshold, the following expressions for the decay widths are obtained

\[
\Gamma^{(A)}_{\Lambda_c \rightarrow D N} = \frac{g_0^2 (m_D + 2m_N)^2}{8\pi m_D^2 m_N m_{\Lambda_c}} q^3, \tag{16}
\]

\[
\Gamma^{(P)}_{\Lambda_c \rightarrow D N} = \frac{g_1^2}{8\pi m_N m_{\Lambda_c}} q^3, \tag{17}
\]

\[
\Gamma_{\Lambda_c \rightarrow D^+ N} = \frac{g_2^2}{8\pi m_D^2 m_{D^+} m_N m_{\Lambda_c}} q^3, \tag{18}
\]

\[
\Gamma_{\Sigma^+_c \rightarrow D \Lambda} = \frac{g_3^2 (m_D + m_{\Lambda})^2}{3\pi m_D^2 m_{\Lambda} m_{\Sigma^+_c}} q^3, \tag{19}
\]

\[
\Gamma^{(P)}_{\Sigma^+_c \rightarrow D N} = \frac{g_4^2}{8\pi m_N m_{\Sigma^+_c}} q^3, \tag{20}
\]

\[
\Gamma_{\Sigma^-_c \rightarrow D^+ \Lambda} = \frac{f_1^2}{4\pi m_D m_{\Sigma^-} q^3}, \tag{21}
\]

where

\[
A = f_0^2 \left(3m_D^2 + m_D m_N - 2m_D^2 + m_N m_D\right)
- 6f_0 h_0 \left(m_D^2 + m_D m_N - 2m_D^2 + m_N m_D\right)
+ h_0^2 \left(3m_D^4 + m_N^2 - 8m_D^2 m_N + 8m_D^2 m_N^2\right). \tag{22}
\]

We note that the decay widths in Eqs. (16)–(21) hold for real and imaginary outgoing momenta.

### 3 $^3P_0$ quark model

In this section, decay widths of the same decay processes as in Sect. 2 are calculated in a quark model picture with the $^3P_0$ model. The corresponding diagram is displayed in Fig. 2. Here, the decay process $B_c \rightarrow B \phi_c$ may arise from the $qq$ and $c$ of the initial state $B_c$ which are directly dressed by two additional quark-antiquark pair pumped out of the vacuum to form $B$ and $\phi_c$ in the final state.

The transition amplitude derived in the $^3P_0$ model is written as

\[
T = \langle B \phi_c | V_{qq} | B_c \rangle, \tag{23}
\]

where $V_{qq}$ corresponds to the effective quark-antiquark vertex. The $^3P_0$ model defines the quantum states of quark-antiquark pair that are destroyed into or created from vacuum ($^3P_0$, isospin $I = 0$, and color singlet). The effective quark-antiquark vertex in the $^3P_0$ model is defined according to Refs. [52,53]:

\[
\gamma_{ij}^{qq} = \lambda \sigma_{ij} \cdot (\mathbf{p}_i - \mathbf{p}_j) \hat{F}_{ij} \hat{c}_{ij} \delta(\mathbf{p}_i + \mathbf{p}_j)
= \lambda \sum_{\mu} \frac{4\pi}{3} (-1)^{\mu} \sigma_{ij}^{\mu} Y_{1\mu}(\mathbf{p}_i - \mathbf{p}_j) \hat{F}_{ij} \hat{c}_{ij} \delta(\mathbf{p}_i + \mathbf{p}_j) \tag{24}
\]

where the parameter $\lambda$ denotes the effective coupling strength of the $^3P_0$ vertex. The spin operator that creates (or annihilates) the spin-1 $qq$ pair is denoted by $\sigma_{ij}^{\mu}$ and $Y_{1\mu}(\mathbf{p})$ corresponds to the spherical harmonics in the momentum space. The flavor and color unit operators are denoted by $\hat{F}_{ij}$ and $\hat{c}_{ij}$.

In this work, the baryon and meson spatial wave functions are approximated with the Gaussian form [54]. The flavor and color unit operators are denoted by $\hat{F}_{ij}$ and $\hat{c}_{ij}$.

\[
T = \lambda \sqrt{\frac{4\pi}{3}} C_i \ f e^{-Qq^2} C(S_1; 1; S_f, s_1 + \mu), \tag{25}
\]

with

\[
f = \frac{6\sqrt{3a^2 b^3/2 (2b^2 m_r + 2a^2 (1 + m_r))} |\mathbf{q}|}{(3a^2 + b^2)^{5/2}(1 + m_r)\pi^{3/4}},
\]

\[
Q = \frac{a^2(3a^2 (1 + m_r) + b^2 (2m_r + 2m_r^2))}{6(3a^2 + b^2)(1 + m_r)^2}.
\]

\[
C_i = \frac{2}{\sqrt{3}} \left( \frac{1}{\sqrt{2}} \right)^{3r - 1} \frac{\sqrt{2S^r + 2(2S^r + 1)(2S^r + 1)}}{\sqrt{2T^r + 2(2T^r + 1)(2T^r + 1)}}
\]
Table 1 The flavor-spin-color factors $C_i$ corresponding to the decay processes $B_c \rightarrow B \phi_c$

| Processes                      | $C_i$ | $S_f = 1/2$ | $S_f = 3/2$ |
|--------------------------------|------|-------------|-------------|
| $\Lambda_c(2286) \rightarrow ND$ | $\frac{1}{\sqrt{2}}$ |              |             |
| $\Lambda_c(2286) \rightarrow ND^*$ | $-\frac{1}{\sqrt{2}}$ | $\sqrt{3}$ |             |
| $\Sigma_c(2455) \rightarrow ND$ | $\frac{1}{\sqrt{6}}$ |              |             |
| $\Sigma_c(2455) \rightarrow \Delta D^*$ | $-\frac{1}{\sqrt{2}}$ | $\sqrt{3}$ |             |
| $\Sigma_c(2455) \rightarrow \Delta D$ | $\frac{4}{3}$ |              | $\frac{2}{\sqrt{10}}$ |

where $(S_i, T_i), (S', T'),$ and $(S'', T'')$ denote the spin-isospin of the states $B_c$, $B$, and $\phi_c$, respectively. The spin $S_f$ and isospin $T_f$ are defined by $S_f = S' \otimes S''$ and $T_f = T' \otimes T''$. The spin projections of the $q\bar{q}$ pair in the $3P_0$ model and the initial charmed baryon $B_c$ are denoted by $\mu$ and $s_i$. $C$ is the Clebsch-Gordan coefficient. The parameter $m_r = m_q/m_Q$ is the ratio between the light quark mass $m_q$ and heavy quark mass $m_Q$. The value of $m_r$ in this study is 300/1270. $\delta$ is the Kronecker delta and the brackets $\{ \}$ in $C_i$ are the 9-j symbols. The flavor-spin-color factors $C_i$ for the decay processes in this study are summarized in Table 1. The baryon and meson length parameters $a$ and $b$ are respectively 3.0 GeV$^{-1}$ and 2.28 GeV$^{-1}$ [55–59].

The decay width of the charmed baryon $B_c$ is calculated from

$$\Gamma_{QM} = \frac{2\pi E' E'' |q|}{m_Bc(2S_i + 1)} \sum_{S_i, \mu, S_f} |T|^2,$$

where $E'$ and $E''$ denote energies of the outgoing light baryon $B$ and charmed meson $\phi_c$ while $|q|$ and $m_Bc$ are similar to those in Eq. 14.

4 Estimation of coupling constants with charmed baryon

In this section, we estimate the coupling constants for the effective Lagrangians in Eqs. (1)–(6) from the decay widths calculated in Sects. 2 and 3. Considering that the decay width formulas in Eqs. (16)–(21) and Eq. (27) hold for both the real and imaginary values of the outgoing momentum $q$, one may estimate the coupling constants by applying the near threshold off-shell decay processes of $\Lambda_c$ and $\Sigma_c$ baryons under consideration. In the low $q$ region, one requires

$$\Gamma_{EFT} = \Gamma_{QM}.$$  

The coupling constants determined from Eq. (28) are those at $q^2 = 0$. For comparison, we employ as inputs five different sets of the coupling constants $f_{D^*\Lambda_c,N}$ and $h_{D^*\Lambda_c,N}$ from Refs. [40–43,49] for the decay process $\Lambda_c \rightarrow D^*N$. From Eq. (28), we fix the $3P_0$ strength parameter $\lambda$ in Eq. (25) for each input set and then use its value to estimate the coupling constants $g_{D\Lambda_c,N}^{(P)}$, $g_{D\Sigma_c,\Delta}^{(A)}$, $f_{D^*\Sigma_c,\Delta}$, and $g_{D\Sigma_c,\Delta}$ of the effective Lagrangians. Then, these results are used to determine the coupling constants $g_{D\Sigma_c,\Delta}^{(A)}$, $f_{D^*\Sigma_c,\Delta}$, and $h_{D^*\Sigma_c,\Delta}$ from heavy-quark and large-$N_c$ sum rules [60]. In our case, we assume that all coupling constants are positive and they are displayed in Table 2.

Here, we have used $g_{D\Delta_c,N}^{(P)} = g_1$, $g_{D\Sigma_c,\Delta}^{(A)} = g_2$, $g_{D\Sigma_c,\Delta}^{(P)} = g_3$, and $f_{D^*\Sigma_c,\Delta} = f_1$. The coupling constants $g_{D\Delta_c,N}^{(A)}$, $f_{D^*\Delta_c,N}$, and $h_{D^*\Delta_c,N}$ are obtained by rescaling the coupling constants $g_0$, $f_0$, and $h_0$ in Eqs. (1) and (5) to those in Refs. [40,41,43]. Note that the expressions for the coupling constants resulted from Eq. (28) are independent of the corresponding initial masses.

From our study, we have found that the magnitudes of the coupling constants are of the same orders as those in the cited literatures. As the original values of $g_{D\Sigma_c,\Delta}$, $f_{D^*\Sigma_c,\Delta}$, and $h_{D^*\Sigma_c,\Delta}$ are not presented anywhere, we only display the results from our estimation.

5 Summary and conclusion

In this study, we have estimated the coupling constants for the effective Lagrangians of D-meson, charmed, and light baryons from several decay processes of $\Lambda_c$ and $\Sigma_c$ baryons. We first calculated the decay widths for the processes $\Lambda_c \rightarrow D^*N$, $\Delta_c \rightarrow D N$, $\Sigma_c \rightarrow D N$, $\Sigma_c \rightarrow D \Delta$, and $\Sigma_c \rightarrow D^* \Delta$ from effective Lagrangian method and quark model picture with the $3P_0$ model, and then compared the decay widths from the two models to fix the strength parameter $\lambda$, where the coupling constants $f_{D^*\Delta_c,N}$ and $h_{D^*\Delta_c,N}$ from literatures are used as inputs. By utilizing the obtained value of $\lambda$, the coupling constants $g_{D\Delta_c,N}^{(P)}$, $g_{D\Delta_c,N}^{(A)}$, $g_{D\Sigma_c,\Delta}$, $f_{D^*\Sigma_c,\Delta}$, and $g_{D\Sigma_c,\Delta}$ are estimated from the decay widths of the processes $\Lambda_c \rightarrow D N$, $\Delta_c \rightarrow D N$, $\Sigma_c \rightarrow D \Delta$, and $\Sigma_c \rightarrow D^* \Delta$ near threshold. Then, the coupling constants $g_{D\Sigma_c,\Delta}^{(A)}$, $f_{D^*\Sigma_c,\Delta}$, and $h_{D^*\Sigma_c,\Delta}$ are obtained from heavy-quark and large-$N_c$ sum rules. It turns out that the expressions for the coupling constants are independent of the initial masses when one considers decay processes near threshold.

It is found that the coupling constants derived in this study are consistent with those in the cited literatures. These cou-
plunging constants are expected to be useful for further studies of charmed hadron production.

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