

$\Lambda_c(2910)$ and $\Lambda_c(2940)$ productions in π^-p scattering process

Quan-Yun Guo¹ and Dian-Yong Chen^{1,2,*}

¹*School of Physics, Southeast University, Nanjing 210094, People's Republic of China*

²*Lanzhou Center for Theoretical Physics, Lanzhou University, Lanzhou 730000, China*



(Received 9 February 2025; accepted 15 May 2025; published 16 June 2025)

In the present work, we propose to investigate the productions of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ in the $\pi^-p \rightarrow D^-D^0p$ processes by utilizing an effective Lagrangian approach, where $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are considered as D^*N molecular states with J^P quantum numbers to be $1/2^-$ and $3/2^-$, respectively. With the cutoff parameter determined by the upper limit of the cross sections for $\pi^-p \rightarrow D^*\Lambda_c(2286)$, the ratios of the cross sections for $\pi^-p \rightarrow D^*\Lambda_c(2286)$, $\pi^-p \rightarrow D^-\Lambda_c(2286)$, $\pi^-p \rightarrow D^-\Lambda_c(2910)$, and $\pi^-p \rightarrow D^-\Lambda_c(2940)$ are estimated to be 1:4.8:1.42:0.26 at $p_\pi = 30$ GeV. Considering that the $\Lambda_c(2910)$ and $\Lambda_c(2940)$ state can further decay into D^0p , we estimate the cross sections for $\pi^-p \rightarrow D^-D^0p$ process and the differential cross sections depending on the D^0p invariant mass spectrum. Our estimations indicate that the total cross sections are $(0.49^{+1.56}_{-0.38})$ nb when $p_\pi = 15$ GeV, where the uncertainties result from the variation of the Λ_c . By comparing the contributions of the s , u , and t -channels, we conclude that the t -channel plays the predominant role. Moreover, the present estimations suggest that the structure around 2.9 GeV in the D^0p invariant mass spectrum of the $\pi^-p \rightarrow D^-D^0p$ process should correspond to $\Lambda_c(2910)$ rather than $\Lambda_c(2940)$, which can be tested by further experimental measurements at J-PARC in the future.

DOI: [10.1103/prd-7r3c](https://doi.org/10.1103/prd-7r3c)

I. INTRODUCTION

In the last two decades, the exploration of multi-quark candidates has emerged as a significant area of interest. Numerous new hadron states, potential exotic state candidates, have been identified by experimental Collaborations including Belle, BelleII, BESIII, and LHCb (see Refs. [1–10] for representative examples). Of these exotic candidates, the possible pentaquark states, $P_c(4380)$ and $P_c(4450)$, were initially observed in the $J/\psi p$ invariant mass distributions of the $\Lambda_b^0 \rightarrow J/\psi K^- p$ process by the LHCb Collaboration in 2015 [6,11,12]. Subsequent analysis of the same process in 2019 suggested that the structure of $P_c(4380)$ could be described by a background effect, and a new narrow state, $P_c(4312)$, was observed for the first time, while $P_c(4450)$ appeared to split into two distinct states, $P_c(4440)$ and $P_c(4457)$ [13]. Following these observations, the LHCb Collaboration further observed strange counterparts of the P_c states, which are named the

P_{cs} states. The first P_{cs} state, $P_{cs}(4459)$, was observed in the $J/\psi\Lambda$ invariant mass distributions of the $\Xi_b^- \rightarrow K^- J/\psi\Lambda$ process in 2020 [14]. Two years later, another state, $P_{cs}(4338)$, was reported in the $J/\psi\Lambda$ invariant mass spectrum of the decay $B^- \rightarrow J/\psi\Lambda\bar{p}$ [15]. The masses of the observed P_c states are close to the thresholds of $D^{(*)}\Sigma_c$, while those of the P_{cs} states are close to the thresholds of $D^{(*)}\Xi_c$, which leads to the prosperity of the molecular interpretations of P_c and P_{cs} states [16–47].

Beyond the extensively studied P_c and P_{cs} states, the charmed baryons $\Lambda_c(2910)$ and $\Lambda_c(2940)$ have also been suggested as potential pentaquark state candidates. Experimentally, $\Lambda_c(2940)$ was first observed in the D^0p invariant mass distributions by the BABAR Collaboration using 287 fb^{-1} of the annihilation data collected by the BABAR detector at a center-of-mass energy of 10.58 GeV in 2006 [48]. Subsequently, the Belle Collaboration confirmed the observation of $\Lambda_c(2940)$ in the $\Sigma_c(2455)^{0,++}\pi^{+,-}$ invariant mass distributions, using a 553 fb^{-1} data sample recorded by the Belle detector at or 60 MeV below the $\Upsilon(4S)$ resonance in 2007 [49]. In 2022, the Belle Collaboration discovered a new structure, $\Lambda_c(2910)$, in the $\Sigma_c(2455)^{0,++}\pi^{+,-}$ invariant mass spectrum of $\bar{B}^0 \rightarrow \Sigma_c(2455)^{0,++}\pi^{+,-}\bar{p}$ processes with a significance of 4.2σ [50]. The measured resonance parameters of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are [51]

*Corresponding author: chendy@seu.edu.cn

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

$$\begin{aligned}
 \Lambda_c^+(2910): M &= (2914 \pm 7) \text{ MeV}, \\
 \Gamma &= (52 \pm 27) \text{ MeV}, \\
 \Lambda_c^+(2940): M &= (2939.6_{-1.5}^{+1.3}) \text{ MeV}, \\
 \Gamma &= (20_{-5}^{+6}) \text{ MeV},
 \end{aligned} \tag{1}$$

respectively.

Similarly to the case of P_c and P_{cs} states, the observed masses of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are close to the threshold of D^*N , which indicates that both $\Lambda_c(2910)$ and $\Lambda_c(2940)$ potentially are the D^*N pentaquark molecular states. In Ref. [52], the authors proposed that $\Lambda_c(2940)$ could be regarded as $D^{*0}p$ molecular state with $J^P = 1/2^-$. The estimations of the strong two-body decay channels D^0p , $\Sigma_c^{++}\pi^-$, $\Sigma_c^0\pi^+$ and three-body decay channels in Ref. [53,54] suggested that $\Lambda_c(2940)$ was consistent with the experimental data when $J^P = 1/2^+$, which indicated that $\Lambda_c(2940)$ should be a P -wave D^*N molecular state. Using the one-boson exchange model, the calculations of D^*N bound state in Ref. [55] indicated that $\Lambda_c(2940)$ could be explained as an isoscalar S -wave or an isoscalar P -wave state with $I(J^P) = 0(1/2^+ \text{ or } 0(3/2^-)$. QCD sum rules were also applied to investigate the properties of $\Lambda_c(2940)$ [56], and the results showed that $\Lambda_c(2940)$ could be regarded as the S -wave D^*N state with $J^P = 3/2^-$ although there may be some computational limitations. Considering the mass similarity of the mass splittings of $P_c(4440)/P_c(4457)$ and $\Lambda_c(2910)/\Lambda_c(2940)$, the authors in Ref. [57] investigated the decay properties of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ in the D^*N molecular frame by an effective Lagrangian approach, and the estimations suggested $\Lambda_c(2910)$ and $\Lambda_c(2940)$ could be assigned as D^*N molecular states with $J^P = 1/2^-$ and $3/2^-$, respectively. With the chiral effective field theory to the next-to-leading order, the estimations in Ref. [58] suggested that $\Lambda_c(2940)$ could be D^*N molecular state, and the observed signal of $\Lambda_c(2940)$ might contain the spin $-1/2$ and spin $-3/2$ structures. The QCD sum rule calculations by carrying out the operator product expansion up to the vacuum condensates of dimension 13 and taking full account of the light-flavor SU(3) breaking effects indicated that $\Lambda_c(2940)/\Lambda_c(2910)$ could be D^*N molecular state with the $3/2^-$ [59]. In the constituent quark model, the decay properties of $\Lambda_c(2940)$ were investigated in the D^*N molecular frame. By using the quark delocalization color screening model, the authors in Ref. [60] found that $\Lambda_c(2940)$ more likely to be a D^*N molecular state with $J^P = 3/2^-$, while $\Lambda_c(2910)$ could not be interpreted as a D^*N molecular state.

In addition to the mass spectrum and decay properties, researches on the productions of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ has also been performed. In Ref. [61], the cross sections of the $p\bar{p} \rightarrow \bar{\Lambda}_c\Lambda_c(2940)$ process were estimated, where the J^P quantum numbers of $\Lambda_c(2940)$ were considered to be $1/2^\pm$, $3/2^\pm$, or $5/2^\pm$, and the magnitudes of the estimated cross sections were between 10^0 nb and 10^5 nb. Similar

processes were investigated in Ref. [62], where $\Lambda_c(2940)$ was regarded as a $D^{*0}p$ molecular state with $J^P = 1/2^\pm$. In addition, Ref. [63] proposed that the production of $\Lambda_c(2940)$ could be studied in the $\gamma n \rightarrow D^-\Lambda_c(2940)$ process.

Recently, the J-PARC hadron facility [64] proposed that the expected pion energy will reach over 20 GeV in the laboratory frame, providing some new platform to investigate the productions of Λ_c states. In Ref. [65], the authors proposed that the $\pi^-p \rightarrow D^-D^0p$ reaction could be investigated by the t -channel D^{*0} meson exchange, s -channel nucleon pole, and u -channel Σ_c^{++} exchange, where $\Lambda_c(2940)$ was considered as a $D^{*0}p$ molecular state with $J^P = 1/2^+, 1/2^-$, respectively. The results indicated that in the above two cases, the t -channel provides the main contribution to the total cross section. After the observation of $\Lambda_c(2910)$ by Belle Collaboration in 2022, both $\Lambda_c(2910)$ and $\Lambda_c(2940)$ could be explained as S -wave ND^* molecular states. In addition, the estimations in Ref. [57] suggested that the J^P quantum numbers of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are preferred to be $1/2^-$ and $3/2^-$, respectively. Therefore, both $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are expected to contribute to the process $\pi^-p \rightarrow D^-D^0p$. It should be noted that the authors in Ref. [66] measured the cross sections for $\pi^-p \rightarrow D^{*-}\Lambda_c$ process at the AGS at Brookhaven National Laboratory, and the results showed that the upper limit of cross section is 7 nb when $P_\pi = 13$ GeV, which can be employed to determine the model parameters involved in the present estimations. Thus, in the present work, we first estimate the cross sections for $\pi^-p \rightarrow D^{*-}\Lambda_c$, with the experimental data in Ref. [66], the model parameter Λ_r can be determined. Then, with the same model parameter, the two body process $\pi^-p \rightarrow D^-\Lambda_c/\Lambda_c(2910)/\Lambda_c(2940)$ and the three-body process $\pi^-p \rightarrow D^-D^0p$ are investigated by considering $\Lambda_c(2910)$ and $\Lambda_c(2940)$ to be D^*N molecular states. In addition, we also estimate the D^0p invariant mass distributions of the process $\pi^-p \rightarrow D^-D^0p$ to further check the contributions of $\Lambda_c(2910)$ and $\Lambda_c(2940)$.

This work is organized as follows. After introduction, we present our estimation of the cross sections for $\pi^-p \rightarrow D^{*-}\Lambda_c$, $\pi^-p \rightarrow D^-\Lambda_c/\Lambda_c(2910)/\Lambda_c(2940)$ and $\pi^-p \rightarrow D^-D^0p$ processes. In Sec. III, the numerical results and related discussions of the cross sections are presented, and the last section is devoted to a short summary.

II. $\Lambda_c(2286)/\Lambda_c(2910)/\Lambda_c(2940)$ PRODUCTIONS IN THE π^-p SCATTERING PROCESS

A. Cross sections for $\pi^-p \rightarrow D^{*-}\Lambda_c$ and $\pi^-p \rightarrow D^-\Lambda_c/\Lambda_c(2910)/\Lambda_c(2940)$

As discussed in the introduction, the experimental measurement for the cross sections for $\pi^-p \rightarrow D^{*-}\Lambda_c$ provide us a reference process to determine the model parameter involved in the present estimations. The diagrams contributing to $\pi^-p \rightarrow D^{*-}\Lambda_c$ are listed in Fig. 1,

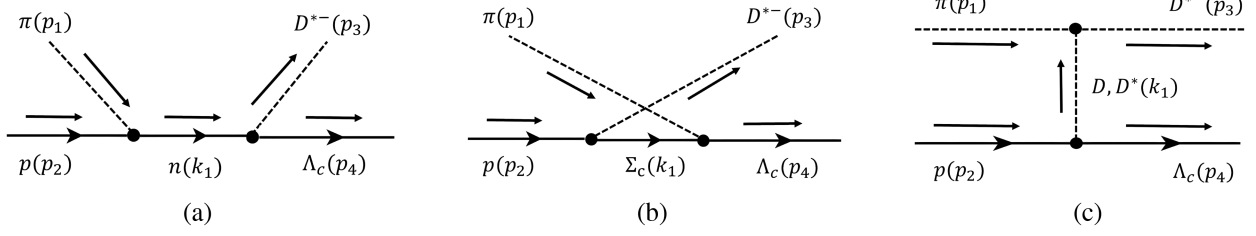


FIG. 1. Diagrams contributing to the process of $\pi^- p \rightarrow D^{*-} \Lambda_c$. Diagrams (a), (b), and (c) correspond to the s , u , and t -channels contributions, respectively. Here Λ_c refers to $\Lambda_c(2286)$.

where the s – channel nucleon exchange [diagrams (a)], u – channel Σ_c^{++} exchange [diagrams (b)] and t – channel D, D^* meson exchange [diagrams (c)] are considered, respectively.

In the present calculation, we employ the effective Lagrangian approach to depict the relevant hadron interaction vertices. The effective Lagrangians for πNN , $D^* D \pi$, $D^* D^* \pi$, $DN\Sigma_c$, $D^* N\Sigma_c$, $\Lambda_c ND$, $\Lambda_c \pi\Sigma_c$, $\Lambda_c ND^*$, $\Lambda_{c1}^* ND$, $\Lambda_{c1}^* \pi\Sigma_c$, $\Lambda_{c2}^* ND$, $\Lambda_{c2}^* \pi\Sigma_c$, can be written as [54,61,62,65,67–73]

$$\begin{aligned} \mathcal{L}_{\pi NN} &= -ig_{\pi NN} \bar{N} \gamma_5 \vec{\tau} \cdot \vec{\pi} N, \\ \mathcal{L}_{D^* D \pi} &= g_{D^* D \pi} D_\mu^* \vec{\tau} \cdot (D^\mu \vec{\pi} - \partial^\mu D \vec{\pi}), \\ \mathcal{L}_{D^* D^* \pi} &= -g_{D^* D^* \pi} \epsilon^{\mu\nu\alpha\beta} \partial_\mu D_\nu^* \pi \partial_\alpha \bar{D}_\beta^*, \\ \mathcal{L}_{DN\Sigma_c} &= -ig_{DN\Sigma_c} \bar{N} \gamma_5 D \Sigma_c + \text{H.c.}, \\ \mathcal{L}_{D^* N\Sigma_c} &= g_{D^* N\Sigma_c} \bar{N} \gamma_5 D^* \Sigma_c + \text{H.c.}, \\ \mathcal{L}_{Y_{1/2^\pm} ND} &= ig_{YND} \bar{Y} \left\{ \begin{matrix} \gamma_5 \\ 1 \end{matrix} \right\} ND + \text{H.c.}, \\ \mathcal{L}_{Y_{1/2^\pm} ND^*} &= g_{YND^*} \bar{Y} \gamma^\mu \left\{ \begin{matrix} \gamma_5 \\ 1 \end{matrix} \right\} ND_\mu^* + \text{H.c.}, \\ \mathcal{L}_{Y_{1/2^\pm} \pi\Sigma_c} &= ig_{Y\pi\Sigma_c} \bar{Y} \left\{ \begin{matrix} \gamma_5 \\ 1 \end{matrix} \right\} \vec{\pi} \cdot \vec{\Sigma}_c + \text{H.c.}, \\ \mathcal{L}_{Y_{3/2^\pm} ND} &= \frac{g_{YND}}{m_\pi} \bar{N} \left\{ \begin{matrix} \gamma_5 \\ 1 \end{matrix} \right\} Y^\mu \partial^\mu D + \text{H.c.}, \\ \mathcal{L}_{Y_{3/2^\pm} \pi\Sigma_c} &= \frac{g_{Y\pi\Sigma_c}}{m_\pi} \bar{\Sigma}_c \left\{ \begin{matrix} \gamma_5 \\ 1 \end{matrix} \right\} Y^\mu \partial^\mu \pi + \text{H.c.}, \end{aligned} \quad (2)$$

with the upper and lower symbols in the curly bracket to be the positive and negative parity of Λ_c states, respectively. The

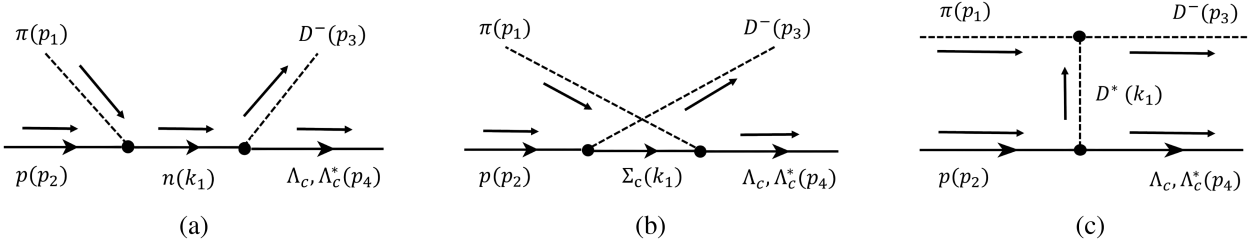


FIG. 2. Diagrams contributing to the process of $\pi^- p \rightarrow D^- \Lambda_c / \Lambda_c(2910) / \Lambda_c(2940)$. Diagrams (a), (b), and (c) correspond to the s , u , and t -channels contributions, respectively. Here Λ_c and Λ_c^* refer to $\Lambda_c(2286)$ and $\Lambda_c(2910) / \Lambda_c(2940)$, respectively.

symbol Y_{JP} refers to the $\Lambda_c(2286) / \Lambda_c(2910) / \Lambda_c(2940)$ states with spin J and parity P .

For the vertices $\Lambda_c(2910)ND^*$ and $\Lambda_c(2940)ND^*$, we consider that the $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are both ND^* molecular states, and the effective Lagrangians of the molecular states coupling to their components are [57]

$$\begin{aligned} \mathcal{L}_{\Lambda_{c1}^* ND^*} &= g_{\Lambda_{c1}^* ND^*} \bar{\Lambda}_{c1}^* \gamma^\mu \gamma_5 D_\mu^* N + \text{H.c.}, \\ \mathcal{L}_{\Lambda_{c2}^* ND^*} &= g_{\Lambda_{c2}^* ND^*} \bar{\Lambda}_{c2}^* D_\mu^* N + \text{H.c.} \end{aligned} \quad (3)$$

Hereafter Λ_{c1}^* and Λ_{c2}^* refer to $\Lambda_c(2910)$ and $\Lambda_c(2940)$, respectively. With the above effective Lagrangians, one can obtain the amplitudes of the $\pi^- p \rightarrow D^{*-} \Lambda_c$ process, which are

$$\begin{aligned} \mathcal{M}_n^s &= \bar{u}(p_4) (g_{\Lambda_c ND^*} \gamma^\mu) \mathcal{S}^{1/2}(k_1, m_n, \Gamma_n) (-ig_{\pi NN} \gamma_5) \\ &\quad \times u(p_2) \epsilon^\mu(p_3) [F(k_1, m_n, \Lambda_r)]^2, \\ \mathcal{M}_{\Sigma_c}^u &= \bar{u}(p_4) (ig_{\Lambda_c \pi \Sigma_c} \gamma_5) \mathcal{S}^{1/2}(k_1, m_{\Sigma_c}, \Gamma_{\Sigma_c}) (g_{D^* N \Sigma_c} \gamma_\mu) \\ &\quad \times u(p_2) \epsilon^\mu(p_3) [F(k_1, m_{\Sigma_c}, \Lambda_r)]^2, \\ \mathcal{M}_D^t &= \bar{u}(p_4) (ig_{\Lambda_c ND} \gamma_5) u(p_2) \mathcal{S}^0(k_1, m_D, \Gamma_D) \epsilon^\mu(p_3) \\ &\quad \times [g_{D^* D \pi} (-ip_1^\mu)] [F(k_1, m_D, \Lambda_r)]^2, \\ \mathcal{M}_{D^*}^t &= \bar{u}(p_4) (g_{\Lambda_c ND^*} \gamma_\nu) u(p_2) \mathcal{S}_{\nu\alpha}^1(k_1, m_{D^*}, \Gamma_{D^*}) \epsilon^\mu(p_3) \\ &\quad \times [-g_{D^* D^* \pi} \epsilon^{\mu\theta\alpha\beta} (p_3^\theta k_1^\beta)] [F(k_1, m_{D^*}, \Lambda_r)]^2, \end{aligned} \quad (4)$$

where the superscripts s , u , and t correspond to s , u , and t -channel, respectively, and the subscripts n , Σ_c , D , and D^* correspond to the propagators in the processes.

With the observation of $\Lambda_c(2910)$ and $\Lambda_c(2940)$, we can investigate their production properties. The diagrams contributing to $\pi^- p \rightarrow D^- \Lambda_c / \Lambda_c(2910) / \Lambda_c(2940)$ are listed in Fig. 2. Similarly, we also consider the relevant s , u , and t -channel, respectively. It should be noted that only the

D^* meson exchange is valid in the t -channel. With the effective Lagrangians in Eqs. (2) and (3), one can obtain the amplitudes of the $\pi^- p \rightarrow D^- \Lambda_c / \Lambda_c(2910) / \Lambda_c(2940)$ process, which are

$$\begin{aligned}
 \mathcal{M}_{\Lambda_c}^s &= \bar{u}(p_4)(ig_{\Lambda_c ND}\gamma_5)\mathcal{S}^{1/2}(k_1, m_n, \Gamma_n)(-ig_{\pi NN}\gamma_5)u(p_2)[F(k_1, m_n, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_{c1}^*}^s &= \bar{u}(p_4)(g_{\Lambda_{c1}^* ND})\mathcal{S}^{1/2}(k_1, m_n, \Gamma_n)(-ig_{\pi NN}\gamma_5)u(p_2)[F(k_1, m_n, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_{c2}^*}^s &= \bar{u}^\mu(p_4)\left(\frac{g_{\Lambda_{c2}^* ND}}{m_\pi}\gamma_5(-ip_3^\mu)\right)\mathcal{S}^{1/2}(k_1, m_n, \Gamma_n)(-ig_{\pi NN}\gamma_5)u(p_2)[F(k_1, m_n, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_c}^u &= \bar{u}(p_4)(ig_{\Lambda_c \pi \Sigma_c}\gamma_5)\mathcal{S}^{1/2}(k_1, m_{\Sigma_c}, \Gamma_{\Sigma_c})(-ig_{DN\Sigma_c}\gamma_5)u(p_2)[F(k_1, m_{\Sigma_c}, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_{c1}^*}^u &= \bar{u}(p_4)(ig_{\Lambda_{c1}^* \pi \Sigma_c})\mathcal{S}^{1/2}(k_1, m_{\Sigma_c}, \Gamma_{\Sigma_c})(-ig_{DN\Sigma_c}\gamma_5)u(p_2)[F(k_1, m_{\Sigma_c}, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_{c2}^*}^u &= \bar{u}^\mu(p_4)\left(\frac{g_{\Lambda_{c2}^* \pi \Sigma_c}}{m_\pi}\gamma_5(-ip_1^\mu)\right)\mathcal{S}^{1/2}(k_1, m_{\Sigma_c}, \Gamma_{\Sigma_c})(-ig_{DN\Sigma_c}\gamma_5)u(p_2)[F(k_1, m_{\Sigma_c}, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_c}^t &= \bar{u}(p_4)(g_{\Lambda_c ND^*}\gamma_\mu)u(p_2)\mathcal{S}_{\mu\nu}^1(k_1, m_{D^*}, \Gamma_{D^*})(g_{D^* D\pi}(-ip_1^\nu))[F(k_1, m_{D^*}, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_{c1}^*}^t &= \bar{u}(p_4)(g_{\Lambda_{c1}^* ND^*}\gamma_5\gamma_\mu)u(p_2)\mathcal{S}_{\mu\nu}^1(k_1, m_{D^*}, \Gamma_{D^*})(g_{D^* D\pi}(-ip_1^\nu))[F(k_1, m_{D^*}, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_{c2}^*}^t &= \bar{u}^\mu(p_4)(g_{\Lambda_{c2}^* ND^*})u(p_2)\mathcal{S}_{\mu\nu}^1(k_1, m_{D^*}, \Gamma_{D^*})(g_{D^* D\pi}(-ip_1^\nu))[F(k_1, m_{D^*}, \Lambda_r)]^2,
 \end{aligned} \tag{5}$$

where the superscripts s , u , and t correspond to s , u , and t -channel, respectively, while the subscripts Λ_c , Λ_{c1}^* , and Λ_{c2}^* refer to the final states of the process, respectively.

In the above amplitudes, $\mathcal{S}^0(k_i, m_i, \Gamma_i)$ and $\mathcal{S}_{\mu\nu}^1(k_i, m_i, \Gamma_i)$ are the propagators of scalar and vector meson with four momentum k_i , mass m_i and width Γ_i , respectively, and the concrete expressions are

$$\begin{aligned}
 \mathcal{S}^0(k_i, m_i, \Gamma_i) &= \frac{i}{k_i^2 - m_i^2 + im_i\Gamma_i}, \\
 \mathcal{S}_{\mu\nu}^1(k_i, m_i, \Gamma_i) &= \frac{-g^{\mu\nu} + (k_i^\mu k_i^\nu / m_i^2)}{k_i^2 - m_i^2 + im_i\Gamma_i},
 \end{aligned} \tag{6}$$

Then, $\mathcal{S}^{1/2}(k_i, m_i, \Gamma_i)$ is the propagator of n , $\Lambda_c(2286)$, $\Lambda_c(2910)$, and Σ_c^{++} , whose spin of $1/2$. While $\mathcal{S}_{\mu\nu}^{3/2}(k_i, m_i, \Gamma_i)$ is the propagator of $\Lambda_c(2940)$. The detailed expressions of $\mathcal{S}^{1/2}(k_i, m_i, \Gamma_i)$ and $\mathcal{S}_{\mu\nu}^{3/2}(k_i, m_i, \Gamma_i)$ read,

$$\begin{aligned}
 \mathcal{S}^{1/2}(k_i, m_i, \Gamma_i) &= \frac{k_i + m_i}{k_i^2 - m_i^2 + im_i\Gamma_i}, \\
 \mathcal{S}_{\mu\nu}^{3/2}(k_i, m_i, \Gamma_i) &= \frac{k_i + m_i}{k_i^2 - m_i^2 + im_i\Gamma_i} \\
 &\quad \times \left(-g^{\mu\nu} + \frac{\gamma^\mu \gamma^\nu}{3} + \frac{2k^\mu k^\nu}{3m_i^2} + \frac{\gamma^\mu k^\nu - k^\mu \gamma^\nu}{3m_i} \right).
 \end{aligned} \tag{7}$$

In addition, the form factor $F(k_i, m_i, \Lambda_r)$ is introduced to depict the inner structure of the involved hadrons in each vertex, its specific expression is

$$F(k_i, m_i, \Lambda_r) = \frac{\Lambda_r^4}{\Lambda_r^4 + (k_i^2 - m_i^2)^2}, \tag{8}$$

where k_i and m_i are the four momentum and the mass of the exchanged hadron, respectively. Λ_r is a phenomenological

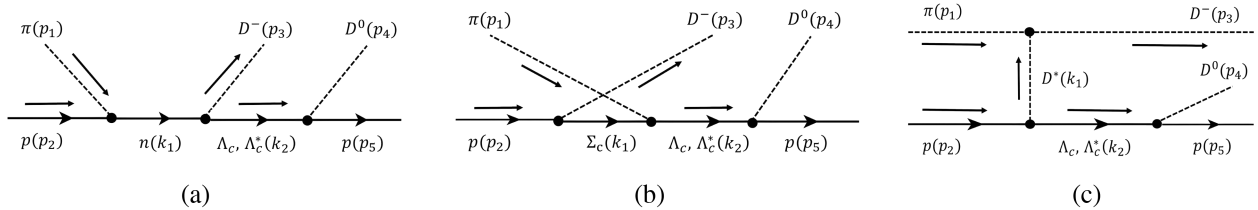


FIG. 3. Diagrams contributing to the process of $\pi^- p \rightarrow D^- D^0 p$. Diagrams (a), (b), and (c) correspond to the s , u , and t -channels contributions, respectively. Here Λ_c and Λ_c^* refer to $\Lambda_c(2286)$ and $\Lambda_c(2910)/\Lambda_c(2940)$, respectively.

model parameter and the specific value will be discussed in Sec. III.

B. Cross sections for $\pi^- p \rightarrow D^- D^0 p$

Since $\Lambda_c(2910)$ and $\Lambda_c(2940)$ can decay into $D^0 p$ final states, then we can investigate $\Lambda_c(2910)$ and $\Lambda_c(2940)$ in

the $\pi^- p \rightarrow D^- D^0 p$ process. The diagrams contributing to $\pi^- p \rightarrow D^- D^0 p$ are listed in Fig. 3. It should be noted that $\Lambda_c(2286)$ could play the role of background since $\Lambda_c(2286)$ is below the threshold of $D^0 p$ in this process. With the above effective Lagrangians in Eqs. (2) and (3), one can also obtain the amplitudes corresponding to the $\pi^- p \rightarrow D^- D^0 p$ processes, which are

$$\begin{aligned}
 \mathcal{M}_{\Lambda_c}^s &= \bar{u}(p_5)(ig_{\Lambda_c ND}\gamma_5)\mathcal{S}^{1/2}(k_2, m_{\Lambda_c}, \Gamma_{\Lambda_c})(ig_{\Lambda_c ND}\gamma_5)\mathcal{S}^{1/2}(k_1, m_n, \Gamma_n)(-ig_{\pi NN}\gamma_5)u(p_2) \\
 &\quad \times F(k_2, m_{\Lambda_c}, \Lambda_r)[F(k_1, m_n, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_{c1}^*}^s &= \bar{u}(p_5)(g_{\Lambda_{c1}^* ND})\mathcal{S}^{1/2}(k_2, m_{\Lambda_{c1}^*}, \Gamma_{\Lambda_{c1}^*})(g_{\Lambda_{c1}^* ND})\mathcal{S}^{1/2}(k_1, m_n, \Gamma_n)(-ig_{\pi NN}\gamma_5)u(p_2) \\
 &\quad \times F(k_2, m_{\Lambda_{c1}^*}, \Lambda_r)[F(k_1, m_n, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_{c2}^*}^s &= \bar{u}(p_5)\left[\frac{g_{\Lambda_{c2}^* ND}}{m_\pi}\gamma_5(-ip_4^\mu)\right]\mathcal{S}_{\mu\nu}^{3/2}(k_2, m_{\Lambda_{c2}^*}, \Gamma_{\Lambda_{c2}^*})\left[\frac{g_{\Lambda_{c2}^* ND}}{m_\pi}\gamma_5(-ip_3^\nu)\right]\mathcal{S}^{1/2}(k_1, m_n, \Gamma_n)(-ig_{\pi NN}\gamma_5)u(p_2) \\
 &\quad \times F(k_2, m_{\Lambda_{c2}^*}, \Lambda_r)[F(k_1, m_n, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_c}^{tu} &= \bar{u}(p_5)(ig_{\Lambda_c ND}\gamma_5)\mathcal{S}^{1/2}(k_2, m_{\Lambda_c}, \Gamma_{\Lambda_c})(ig_{\Lambda_c \pi \Sigma_c}\gamma_5)\mathcal{S}^{1/2}(k_1, m_{\Sigma_c}, \Gamma_{\Sigma_c})(-ig_{DN\Sigma_c}\gamma_5)u(p_2) \\
 &\quad \times F(k_2, m_{\Lambda_c}, \Lambda_r)[F(k_1, m_{\Sigma_c}, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_{c1}^*}^{tu} &= \bar{u}(p_5)(g_{\Lambda_{c1}^* ND})\mathcal{S}^{1/2}(k_2, m_{\Lambda_{c1}^*}, \Gamma_{\Lambda_{c1}^*})(ig_{\Lambda_{c1}^* \pi \Sigma_c})\mathcal{S}^{1/2}(k_1, m_{\Sigma_c}, \Gamma_{\Sigma_c})(-ig_{DN\Sigma_c}\gamma_5)u(p_2) \\
 &\quad \times F(k_2, m_{\Lambda_{c1}^*}, \Lambda_r)[F(k_1, m_{\Sigma_c}, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_{c2}^*}^{tu} &= \bar{u}(p_5)\left[\frac{g_{\Lambda_{c2}^* ND}}{m_\pi}\gamma_5(-ip_4^\mu)\right]\mathcal{S}_{\mu\nu}^{3/2}(k_2, m_{\Lambda_{c2}^*}, \Gamma_{\Lambda_{c2}^*})\left[\frac{g_{\Lambda_{c2}^* \pi \Sigma_c}}{m_\pi}\gamma_5(-ip_1^\nu)\right]\mathcal{S}^{1/2}(k_1, m_{\Sigma_c}, \Gamma_{\Sigma_c})(-ig_{DN\Sigma_c}\gamma_5)u(p_2) \\
 &\quad \times F(k_2, m_{\Lambda_{c2}^*}, \Lambda_r)[F(k_1, m_{\Sigma_c}, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_c}^t &= \bar{u}(p_5)(ig_{\Lambda_c ND}\gamma_5)\mathcal{S}^{1/2}(k_2, m_{\Lambda_c}, \Gamma_{\Lambda_c})(g_{\Lambda_c ND^*}\gamma^\mu)\mathcal{S}_{\mu\nu}^1(k_1, m_{D^*}, \Gamma_{D^*})[g_{D^* D\pi}(-ip_1^\nu)]u(p_2) \\
 &\quad \times F(k_2, m_{\Lambda_c}, \Lambda_r)[F(k_1, m_{D^*}, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_{c1}^*}^t &= \bar{u}(p_5)(g_{\Lambda_{c1}^* ND})\mathcal{S}^{1/2}(k_2, m_{\Lambda_{c1}^*}, \Gamma_{\Lambda_{c1}^*})(g_{\Lambda_{c1}^* ND^*}\gamma_5\gamma^\mu)\mathcal{S}_{\mu\nu}^1(k_1, m_{D^*}, \Gamma_{D^*})[g_{D^* D\pi}(-ip_1^\nu)]u(p_2) \\
 &\quad \times F(k_2, m_{\Lambda_{c1}^*}, \Lambda_r)[F(k_1, m_{D^*}, \Lambda_r)]^2, \\
 \mathcal{M}_{\Lambda_{c2}^*}^t &= \bar{u}(p_5)\left[\frac{g_{\Lambda_{c2}^* ND}}{m_\pi}\gamma_5(-ip_4^\mu)\right]\mathcal{S}_{\mu\nu}^{3/2}(k_2, m_{\Lambda_{c2}^*}, \Gamma_{\Lambda_{c2}^*})(g_{\Lambda_{c2}^* ND^*})\mathcal{S}_{\nu\rho}^1(k_1, m_{D^*}, \Gamma_{D^*})[g_{D^* D\pi}(-ip_1^\rho)]u(p_2) \\
 &\quad \times F(k_2, m_{\Lambda_{c2}^*}, \Lambda_r)[F(k_1, m_{D^*}, \Lambda_r)]^2,
 \end{aligned} \tag{9}$$

where the superscripts s , u , and t correspond to the s , u , and t -channel, respectively. In the above amplitudes, the form of propagators and form factor are consistent with those in Eqs. (6)–(8).

III. NUMERICAL RESULTS AND DISCUSSIONS

A. Coupling constants

Before the estimations of the cross sections, the values of coupling constants should be clarified. The coupling constants $g_{\pi NN}$, $g_{\Lambda_c ND}$, $g_{\Lambda_c \pi \Sigma_c}$, $g_{DN\Sigma_c}$, $g_{D^* N\Sigma_c}$, and $g_{\Lambda_c ND^*}$ can be determined by SU(4) symmetry [54,61,62,65,67,69–71], and the specific values are collected in Table I. It should be noted that the large mass differences between the charmed quark and the light quarks significantly break SU(4) flavor

symmetry. Despite this limitation, theorists often invoke this symmetry to estimate coupling constants, particularly those involving charmed baryons, due to the lack of alternative systematic methods. The coupling constant $g_{D^* D^* \pi}$ can be determined by the heavy quark spin symmetry and the value is 9.08 [73]. In addition, the coupling constants $g_{\Lambda_{c1}^* ND}$, $g_{\Lambda_{c1}^* \pi \Sigma_c}$, $g_{\Lambda_{c2}^* ND}$, $g_{\Lambda_{c2}^* \pi \Sigma_c}$, and $g_{D^* D\pi}$ can be determined by combining the related effective Lagrangians and the corresponding decay widths of the corresponding decay processes. Based on the effective Lagrangians, one can obtain the

TABLE I. The coupling constants involved in the $\pi^- p \rightarrow D^- D^0 p$ process.

Coupling constant	Value	Coupling constant	Value
$g_{\pi NN}$	13.45	$g_{\Lambda_c^* ND}$	0.99
$g_{\Lambda_c ND}$	-13.98	$g_{\Lambda_c^* ND}$	0.84
$g_{\Lambda_c \pi \Sigma_c}$	9.32	$g_{\Lambda_c^* \pi \Sigma_c}$	2.22
$g_{DN \Sigma_c}$	-2.69	$g_{\Lambda_c^* \pi \Sigma_c}$	1.35
$g_{D^* N \Sigma_c}$	3.75	$g_{D^* D^* \pi}$	9.08
$g_{\Lambda_c ND^*}$	-5.20	$g_{\Lambda_c^* ND^*}$	3.55
$g_{D^* D \pi}$	14.1	$g_{\Lambda_c^* ND^*}$	2.34

corresponding amplitude $\mathcal{M}_{A \rightarrow BC}$. Then, the decay width of the decay process $A \rightarrow BC$ can be written as

$$\Gamma_{A \rightarrow BC} = \frac{1}{(2J+1)8\pi M^2} |\vec{k}_f| |\overline{\mathcal{M}_{A \rightarrow BC}}|^2, \quad (10)$$

where M and J are the mass and angular momentum of the initial states. $\vec{k}_f$ is the three momentum of the final states in the initial rest frame. In addition, in Ref. [57], the decay properties of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ were investigated, and the estimations indicated that the branching fractions of ND and $\pi \Sigma_c$ channels for $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are about,

$$\begin{aligned} \text{Br}(\Lambda_c(2910) \rightarrow ND) &= 40\%, \\ \text{Br}(\Lambda_c(2910) \rightarrow \pi \Sigma) &= 60\%, \\ \text{Br}(\Lambda_c((2940)) \rightarrow ND) &= 11\%, \\ \text{Br}(\Lambda_c(2940) \rightarrow \pi \Sigma) &= 12.5\%. \end{aligned} \quad (11)$$

With the above branching fractions, the central values of the widths of $\Lambda_c(2940)$ and $\Lambda_c(2910)$ and the formula in Eq. (10), one can obtain the coupling constants $g_{\Lambda_c^* ND}$, $g_{\Lambda_c^* \Sigma_c \pi}$, $g_{\Lambda_c^* ND}$, and $g_{\Lambda_c^* \Sigma_c \pi}$, which are listed in Table I. As for the coupling constant $g_{D^* D \pi}$, we take the same value as the one in Ref. [65], which is $g_{D^* D \pi} = 14.1$.

In addition to the above coupling constants, the coupling constants relevant to $\Lambda_c(2910)/\Lambda_c(2940)$ and their components $D^* N$ could be determined by the compositeness condition with nonrelativistic limit [74,75], which is

$$g_{\Lambda_c^* ND^*}^2 = \frac{4\pi}{4M_{\Lambda_c^*} m_N} \frac{(m_{D^*} + m_N)^{5/2}}{(m_{D^*} m_N)^{1/2}} \sqrt{32\epsilon}, \quad (12)$$

with $\epsilon = m_N + m_{D^*} - m_{\Lambda_c^*}$ to be the binding energy of $\Lambda_c(2910)/\Lambda_c(2940)$. Here, we take $\epsilon = 32$ MeV for $\Lambda_c(2910)$ and $\epsilon = 6.2$ MeV for $\Lambda_c(2940)$. The concrete values of $g_{\Lambda_c^* ND^*}$ are also presented in Table I.

B. Cross sections for $\pi^- p \rightarrow D^{*-} \Lambda_c$ and $\pi^- p \rightarrow D^- \Lambda_c/\Lambda_c(2910)/\Lambda_c(2940)$

After determining the coupling parameters, we need determine the model parameter Λ_r introduced by the form factor $F(k_i, m_i, \Lambda_r)$. As discussed in the above sections, $\pi^- p \rightarrow D^{*-} \Lambda_c$ could perform as a reference channel, since the upper limit of the cross sections have been measured at $P_\pi = 13$ GeV. Thus, we estimate the cross sections for $\pi^- p \rightarrow D^{*-} \Lambda_c$ with the amplitudes in Eq. (4). The total amplitude of the $\pi^- p \rightarrow D^{*-} \Lambda_c$ can be expressed as

$$\mathcal{M}_{\text{Tot}} = \mathcal{M}_n^s + \mathcal{M}_{\Sigma_c}^u + \mathcal{M}_D^t + \mathcal{M}_{D^*}^t, \quad (13)$$

and with this total amplitude, the differential cross sections depending on $\cos \theta$ for $\pi^- p \rightarrow D^{*-} \Lambda_c$ can be obtained by

$$\frac{d\sigma}{d\cos \theta} = \frac{1}{32\pi s} \frac{|\vec{p}_f|}{|\vec{p}_i|} \left(\frac{1}{2} |\overline{\mathcal{M}_{\text{Tot}}}|^2 \right), \quad (14)$$

where s and θ refer to the square of the center-of-mass energy and the scattering angle, which is the angle of outgoing D^{*-} and the pion beam direction in the center direction. The $\vec{p}_f$ and $\vec{p}_i$ stand for three momenta of the final D^{*-} meson and the initial pion beam in the center of mass system, respectively.

With the above preparations, the cross sections for $\pi^- p \rightarrow D^{*-} \Lambda_c$ depending on the momentum of the incident pion beam are presented in Fig. 4. Among them, Fig. 4(a) corresponds to the total cross sections for the $\pi^- p \rightarrow D^{*-} \Lambda_c$ process, the black solid curves represent the cross sections obtained with $\Lambda_r = 1.1$ GeV, while the cyan band are the uncertainties resulted from the varying of Λ_r from 1.0 GeV to 1.2 GeV. The center position of red pentagram corresponds to the upper limit of cross section $\sigma = 7$ nb at $P_\pi = 13$ GeV [66]. In particular, the cross section is estimated to be $(2.59_{-2.00}^{+7.15})$ nb at $P_\pi = 13$ GeV in the consider parameter range. In Fig. 4(b), the cyan dotted, red dashed, and blue dash-dotted curves stand for the individual contributions to cross sections from the s , u , and t -channel, respectively, where the parameter is set to be $\Lambda_r = 1.1$ GeV. Our results show that the contributions from s -channel are negligible, while the main contributions come from t -channel. In summary, our estimations show that the cross section for $\pi^- p \rightarrow D^{*-} \Lambda_c$ is 2.59 nb at $P_\pi = 13$ GeV with $\Lambda_r = 1.1$ GeV, which is safely under the experimental upper limit reported in Ref. [66]. Thus, in the following we will adopt $\Lambda_r = 1.1$ GeV to discuss other involved processes.

In addition to $\Lambda_c(2286)$, we also investigate the productions of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ in the $\pi^- p$ scattering processes, with the amplitudes in Eq. (5), one can estimate the cross sections for the $\pi^- p \rightarrow D^- \Lambda_c/\Lambda_c(2910)/\Lambda_c(2940)$ processes, the relevant total amplitudes can be expressed as

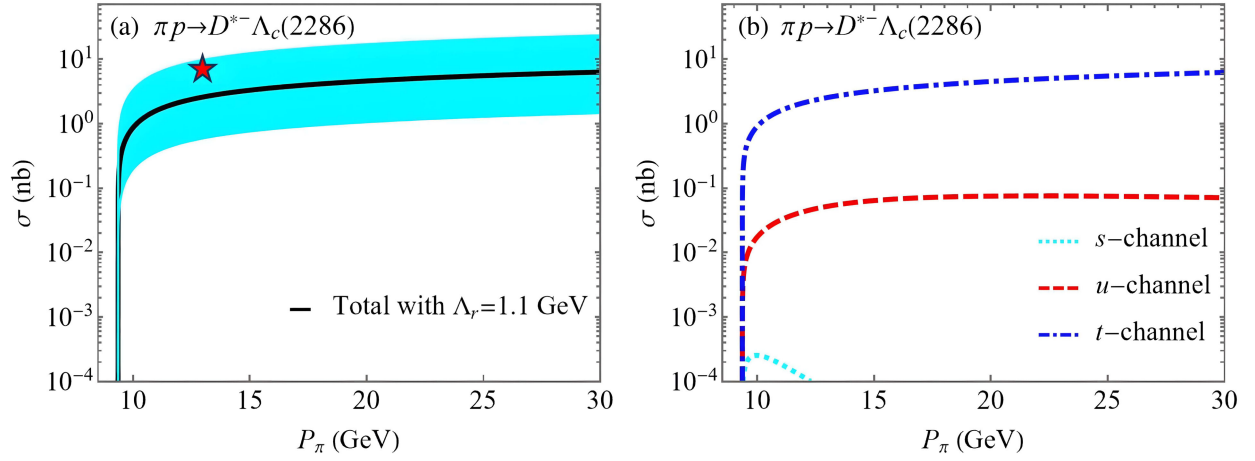


FIG. 4. The cross sections for the $\pi^- p \rightarrow D^{*-} \Lambda_c$ process depending on the momentum of the incident pion beam. Diagram (a) shows the total cross sections for $\pi^- p \rightarrow D^{*-} \Lambda_c$, the black solid curve are obtained with $\Lambda_r = 1.1$ GeV, while the cyan band are the uncertainties resulted from the varying of Λ_r from 1.0 GeV to 1.2 GeV. The red pentagram represents the upper limit of cross section $\sigma = 7$ nb at $P_\pi = 13$ GeV from Ref. [66]. Diagram (b) corresponds to the individual contributions from s , u and t -channels, respectively.

$$\begin{aligned}\mathcal{M}_{\text{Tot}-\Lambda_c} &= \mathcal{M}_{\Lambda_c}^s + \mathcal{M}_{\Lambda_c}^u + \mathcal{M}_{\Lambda_c}^t, \\ \mathcal{M}_{\text{Tot}-\Lambda_{c1}^*} &= \mathcal{M}_{\Lambda_{c1}^*}^s + \mathcal{M}_{\Lambda_{c1}^*}^u + \mathcal{M}_{\Lambda_{c1}^*}^t, \\ \mathcal{M}_{\text{Tot}-\Lambda_{c2}^*} &= \mathcal{M}_{\Lambda_{c2}^*}^s + \mathcal{M}_{\Lambda_{c2}^*}^u + \mathcal{M}_{\Lambda_{c2}^*}^t.\end{aligned}\quad (15)$$

The cross sections for $\pi^- p \rightarrow D^- \Lambda_c / \Lambda_c(2910) / \Lambda_c(2940)$ and $\pi^- p \rightarrow D^{*-} \Lambda_c$ processes depending on the momentum of the incident pion beam with $\Lambda_r = 1.1$ GeV are presented in Fig. 5, where the cyan dotted, red dashed, blue dash-dotted, and black solid curves correspond to the cross section for $D^- \Lambda_c(2286)$, $D^- \Lambda_c(2910)$, $D^- \Lambda_c(2940)$, and $D^{*-} \Lambda_c(2286)$ final states,

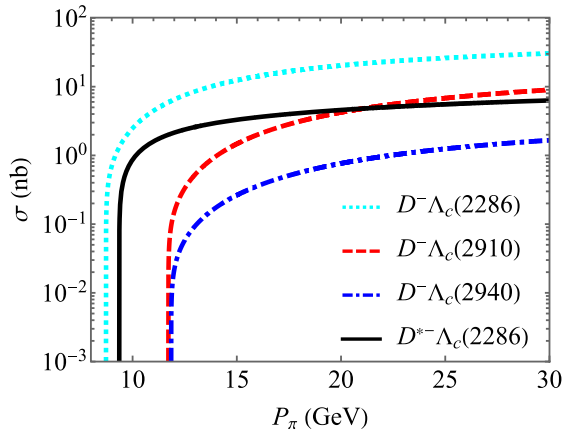


FIG. 5. The cross sections for the $\pi^- p \rightarrow D^- \Lambda_c / \Lambda_c(2910) / \Lambda_c(2940)$ and $\pi^- p \rightarrow D^{*-} \Lambda_c$ processes depending on the momentum of the incident pion beam with $\Lambda_r = 1.1$ GeV. The cyan dotted, red dashed, blue dash-dotted, and black solid curves correspond to the contributions from $D^- \Lambda_c(2286)$, $D^- \Lambda_c(2910)$, $D^- \Lambda_c(2940)$, and $D^{*-} \Lambda_c(2286)$ final states of the relevant processes, respectively.

respectively. From the figure, one can find that each cross section curve increases rapidly near the threshold and then becomes weakly dependent on the momentum of the incident pion beam. In addition, our results show that the cross sections for $D^- \Lambda_c(2286)$ final states are larger than that of $D^- \Lambda_c(2910)$ and $D^- \Lambda_c(2940)$, while the cross sections for $D^{*-} \Lambda_c(2286)$ final states are similar to that of $D^- \Lambda_c(2910)$. At $p_\pi = 30$ GeV, the ratios of the cross sections for $\pi^- p \rightarrow D^{*-} \Lambda_c(2286)$, $\pi^- p \rightarrow D^- \Lambda_c(2286)$, $\pi^- p \rightarrow D^- \Lambda_c(2910)$, and $\pi^- p \rightarrow D^- \Lambda_c(2940)$ are estimated to be 1:4.8:1.42:0.26.

C. Cross sections for $\pi^- p \rightarrow D^- D^0 p$

Since the $\Lambda_c(2910)$ and $\Lambda_c(2940)$ state can further decay into $D^0 p$, so one can estimate the cross sections for the $\pi^- p \rightarrow D^- D^0 p$ process. With the amplitudes in Eq. (9), the total amplitude of the $\pi^- p \rightarrow D^- D^0 p$ process can be expressed as

$$\begin{aligned}\mathcal{M}'_{\text{Tot}} &= \mathcal{M}'_{\Lambda_c}{}^s + \mathcal{M}'_{\Lambda_{c1}^*}{}^s + \mathcal{M}'_{\Lambda_{c2}^*}{}^s + \mathcal{M}'_{\Lambda_c}{}^u + \mathcal{M}'_{\Lambda_{c1}^*}{}^u \\ &\quad + \mathcal{M}'_{\Lambda_{c2}^*}{}^u + \mathcal{M}'_{\Lambda_c}{}^t + \mathcal{M}'_{\Lambda_{c1}^*}{}^t + \mathcal{M}'_{\Lambda_{c2}^*}{}^t.\end{aligned}\quad (16)$$

With the above total amplitude, one can obtain the differential cross sections of the $\pi^- p \rightarrow D^- D^0 p$ process,

$$d\sigma = \frac{1}{8(2\pi)^4} \frac{1}{\Phi} |\overline{\mathcal{M}'_{\text{Tot}}}|^2 dp_5^0 dp_3^0 d\cos\theta d\eta, \quad (17)$$

where the flux factor $\Phi = 4|\vec{p}_1| \sqrt{s}$, $\vec{p}_1$ and $\sqrt{s}$ represent the three momentum of the initial π^- particle and the center-of-mass energy, respectively. p_3^0 and p_5^0 are the energy of the outgoing D^- meson and p , respectively.

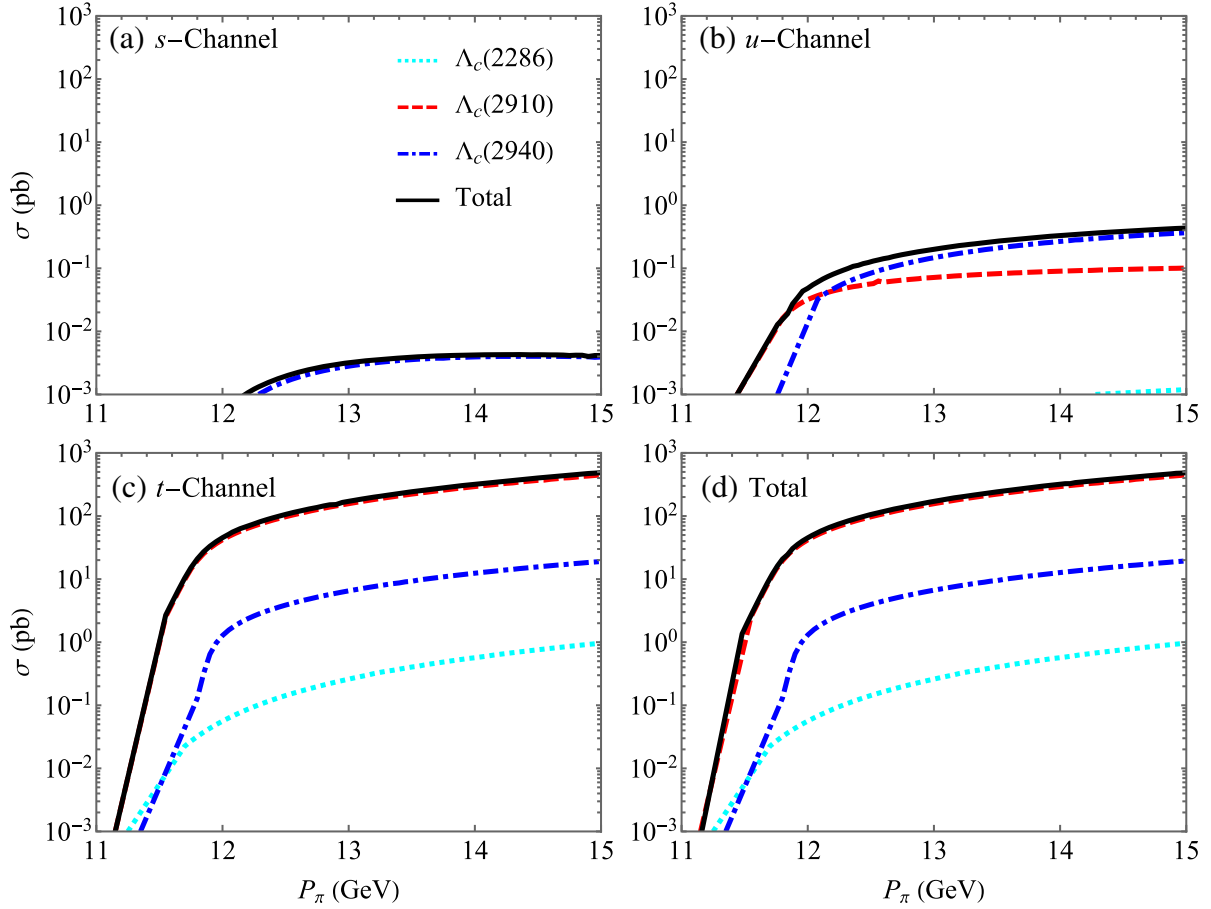


FIG. 6. The cross sections for the $\pi^- p \rightarrow D^- D^0 p$ process depending on the momentum of the incident pion beam. Diagram (a), (b), and (c) correspond to the individual contributions from s , u , and t -channels, respectively. While diagram (d) shows the individual contributions from $\Lambda_c(2286)$, $\Lambda_c(2910)$, and $\Lambda_c(2940)$.

The cross sections for $\pi^- p \rightarrow D^- D^0 p$ depending on the momentum of the incident pion beam with $\Lambda_r = 1.1$ GeV are presented in Fig. 6. Among them, Figs. 6(a)–6(c) correspond to the cross sections resulted from the s , u , and t -channel, respectively. In these three figures, the black solid curves represent the total contributions of each channels. The cyan dotted, red dashed, and blue dash-dotted curves stand for the contributions from the processes that include propagators $\Lambda_c(2286)$, $\Lambda_c(2910)$ and $\Lambda_c(2940)$, respectively. As indicated in diagram (a), the contributions from $\Lambda_c(2286)$ and $\Lambda_c(2940)$ are not shown in the diagram because their cross sections are less than 1 fb. As for the u -channel, $\Lambda_c(2940)$ intermediate process is dominant, while the cross section of $\Lambda_c(2910)$ is about 0.1 pb when $P_\pi = 15$ GeV, which is several times smaller than that of $\Lambda_c(2940)$. But for the t -channel, the cross section resulted from $\Lambda_c(2910)$ intermediate process is predominant, which is about 20 times of that from $\Lambda_c(2940)$, and about 450 times of that from $\Lambda_c(2286)$ when $P_\pi > 13$ GeV. By comparing Figs. 6(a)–6(c), one can find the cross sections resulted from s , u , and t -channels are of orders of 10^{-2} pb, 10^{-1} pb, and 10^2 pb,

respectively, which indicates that at high-energy scattering process, the t -channel contributions are dominant.

In Fig. 6(d), we present the individual contributions from $\Lambda_c(2286)$, $\Lambda_c(2910)$, and $\Lambda_c(2940)$, which correspond to cyan dotted, red dashed, and blue dash-dotted curves, while the solid curve refers to the total cross sections for the $\pi^- p \rightarrow D^- D^0 p$ process. From this diagram, one can find that the total cross sections increase rapidly near the threshold, and with P_π greater than 12.5 GeV, the cross sections increase rather slowly with the increasing of p_π . At $P_\pi = 15$ GeV, the cross section reaches up to 487 pb. In addition, the present estimations indicate that the dominant contributions to the cross sections for $\pi^- p \rightarrow D^- D^0 p$ come from the intermediate state $\Lambda_c(2910)$.

In addition to the cross sections, we also investigate the differential cross section for $\pi^- p \rightarrow D^- D^0 p$ depending on the invariant mass of $D^0 p$. The $D^0 p$ invariant mass distributions at $p_\pi = 14$ GeV are presented in Fig. 7. The cyan dotted, red dashed, and blue dash-dotted curves correspond to the individual contributions from $\Lambda_c(2286)$, $\Lambda_c(2910)$, and $\Lambda_c(2940)$, respectively, while the black solid curve refers to the summation of the individual

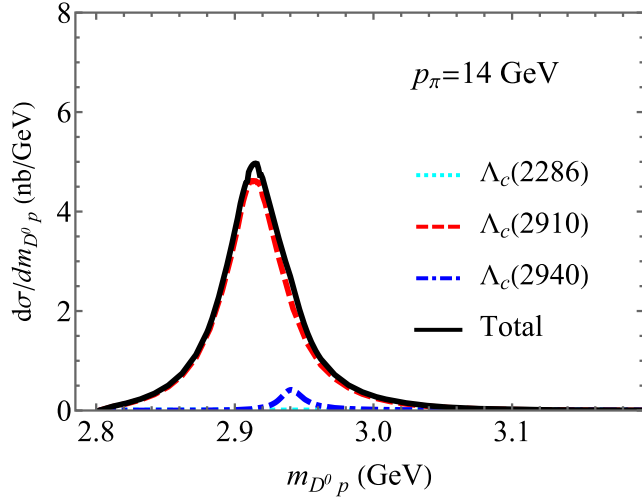


FIG. 7. The $D^0 p$ invariant mass distributions of the $\pi^- p \rightarrow D^- D^0 p$ process at $p_\pi = 14$ GeV.

contributions as well as their interferences. From this figure, one can find that the contributions from $\Lambda_c(2286)$ are rather smooth, which plays the role of the background. As for $\Lambda_c(2910)$ and $\Lambda_c(2940)$, our estimations suggested that the signal of $\Lambda_c(2910)$ is predominant, while the signal of $\Lambda_c(2940)$ is about one order smaller than that of $\Lambda_c(2910)$, which indicate the expected structure near 2.9 GeV in the $D^0 p$ invariant mass spectrum of $\pi^- p \rightarrow D^- D^0 p$ process should corresponds to $\Lambda_c(2910)$ rather than $\Lambda_c(2940)$.

It is worth noting that the cutoff parameter Λ_r cannot be well-determined experimentally at present. So in the present estimation, we vary Λ_r from 1.0 GeV to 1.2 GeV to further check the parameter dependence of the total cross sections for the $\pi^- p \rightarrow D^- D^0 p$ process. Our estimated cross sections are presented in Fig. 8, where the

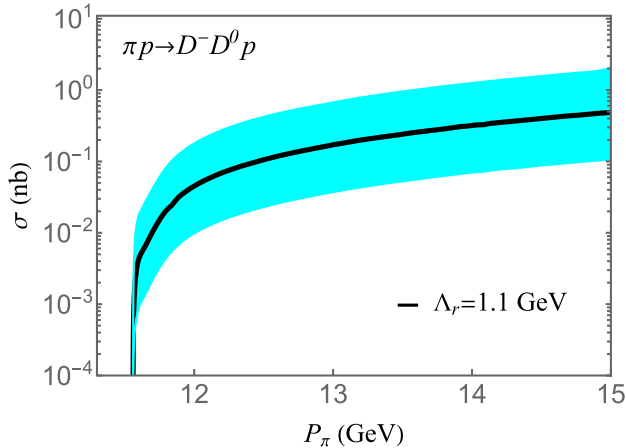


FIG. 8. The total cross sections for the $\pi^- p \rightarrow D^- D^0 p$ process depending on the momentum of the incident pion beam. The black solid curve are obtained with $\Lambda_r = 1.1$ GeV, while the cyan band are the uncertainties resulted from the varying of Λ_r from 1.0 to 1.2 GeV.

black curve is calculated with $\Lambda_r = 1.1$ GeV and the cyan band indicates the uncertainties resulting of the parameter Λ_r . In the considered model parameter range, the total cross section at $p_\pi = 15$ GeV is estimated to be $(0.49_{-0.38}^{+1.56})$ nb at $p_\pi = 15$ GeV, which means that the values of the total cross sections cross an order of magnitude when Λ_r ranges from 1.0 GeV to 1.2 GeV.

Before the end of this work, it is worth mentioning that the cutoff employed in the present estimations is determined by the upper limit of the cross section for $\pi^- p \rightarrow D^{*-} \Lambda_c$ at $P_\pi = 13$ GeV. Physically, the cutoff is related to the size of the interacting particles. Compared to the traditional Λ_c baryon state, $\Lambda_c(2910)$ and $\Lambda_c(2940)$, as the ND^* molecular states, should exhibit a larger size. This suggests that the cutoff for the vertices involving $\Lambda_c(2910)/\Lambda_c(2940)$ should be smaller than 1 GeV, and leading to smaller cross sections.

IV. SUMMARY

With the observations of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ by the *BABAR* and *Belle* Collaborations, the investigations of these two states have become intriguing. The observed masses of both $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are close to the threshold of $D^* N$, this situation is similar to the well-known pentaquark candidates $P_c(4440)$ and $P_c(4457)$, and in addition, the mass splitting of $\Lambda_c(2940)$ and $\Lambda_c(2910)$ is very similar to that of $P_c(4440)$ and $P_c(4457)$. These particular spectrum properties inspire the ND^* molecular interpretations to the $\Lambda_c(2910)$ and $\Lambda_c(2940)$.

Besides the mass spectrum and decay behaviors, the production properties of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ can also shed light on the inner structure of these two states. In addition, the pion beam energy will reach over 20 GeV in the J-PARC hadron facility. Thus, in the present work, we propose to investigate the $\Lambda_c(2910)$ and $\Lambda_c(2940)$ productions in πp scattering process. For parameter Λ_r , the measurement in Ref. [66] indicated that the upper limit of cross section for $\pi^- p \rightarrow D^{*-} \Lambda_c$ was 7 nb at $P_\pi = 13$ GeV. Thus, we adopt $\Lambda_r = 1.1$ GeV in the present estimation by comparing our estimations with the experimental measurement. The $\pi^- p \rightarrow D^- \Lambda_c/\Lambda_c(2910)/\Lambda_c(2940)$ processes are also estimated, and our estimations indicate that at $p_\pi = 30$ GeV, the ratios of the cross sections for $\pi^- p \rightarrow D^{*-} \Lambda_c(2286)$, $\pi^- p \rightarrow D^- \Lambda_c(2286)$, $\pi^- p \rightarrow D^- \Lambda_c(2910)$, and $\pi^- p \rightarrow D^- \Lambda_c(2940)$ are 1:4.8:1.42:0.26.

Considering the fact that $\Lambda_c(2910)$ and $\Lambda_c(2940)$ can decay into $D^0 p$, we propose to investigate these two states in the $D^0 p$ invariant mass spectrum of $\pi^- p \rightarrow D^- D^0 p$ process. Our estimations indicate that the cross sections for $\pi^- p \rightarrow D^- D^0 p$ range from several hundreds pb to several nb with the varying of the model parameter Λ_r . Moreover, our estimations suggest that the dominant contributions come from $\Lambda_c(2910)$, and the expected structure around 2.9 GeV in the $D^0 p$ invariant mass spectrum of $\pi^- p \rightarrow D^- D^0 p$ process

should corresponds to $\Lambda_c(2910)$ rather than $\Lambda_c(2940)$, which could be tested by further experimental measurements at J-PARC in the future.

ACKNOWLEDGMENTS

The authors would like to thank Prof. Ju-Jun Xie for useful discussions. This work is partly supported by the National Natural Science Foundation of China under the Grants No. 12175037 and No. 12335001, as well as supported,

in part, by National Key Research and Development Program under Contract No. 2024YFA1610503.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

-
- [1] S. K. Choi *et al.*, Observation of a narrow charmonium-like state in exclusive $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ decays, *Phys. Rev. Lett.* **91**, 262001 (2003).
 - [2] S. K. Choi *et al.*, Observation of a resonance-like structure in the $\pi^\pm \psi'$ mass distribution in exclusive $B \rightarrow K \pi^\pm \psi'$ decays, *Phys. Rev. Lett.* **100**, 142001 (2008).
 - [3] S. Uehara *et al.*, Observation of a charmonium-like enhancement in the $\gamma\gamma \rightarrow \omega J/\psi$ process, *Phys. Rev. Lett.* **104**, 092001 (2010).
 - [4] M. Ablikim *et al.*, Observation of a charged charmonium-like structure in $e^+e^- \rightarrow \pi^+ \pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV, *Phys. Rev. Lett.* **110**, 252001 (2013).
 - [5] Z. Q. Liu *et al.*, Study of $e^+e^- \rightarrow \pi^+ \pi^- J/\psi$ and observation of a charged charmoniumlike state at Belle, *Phys. Rev. Lett.* **110**, 252002 (2013); *Phys. Rev. Lett.* **111**, 019901(E) (2013).
 - [6] Roel Aaij *et al.*, Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \rightarrow J/\psi K^- p$ decays, *Phys. Rev. Lett.* **115**, 072001 (2015).
 - [7] Roel Aaij *et al.*, Observation of $J/\psi \phi$ structures consistent with exotic states from amplitude analysis of $B^+ \rightarrow J/\psi \phi K^+$ decays, *Phys. Rev. Lett.* **118**, 022003 (2017).
 - [8] Medina Ablikim *et al.*, Precise measurement of the $e^+e^- \rightarrow \pi^+ \pi^- J/\psi$ cross section at center-of-mass energies from 3.77 to 4.60 GeV, *Phys. Rev. Lett.* **118**, 092001 (2017).
 - [9] Roel Aaij *et al.*, First observation of excited Ω_b^- states, *Phys. Rev. Lett.* **124**, 082002 (2020).
 - [10] Roel Aaij *et al.*, Observation of an exotic narrow doubly charmed tetraquark, *Nat. Phys.* **18**, 751 (2022).
 - [11] Roel Aaij *et al.*, Model-independent evidence for $J/\psi p$ contributions to $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays, *Phys. Rev. Lett.* **117**, 082002 (2016).
 - [12] Roel Aaij *et al.*, Evidence for exotic hadron contributions to $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ decays, *Phys. Rev. Lett.* **117**, 082003 (2016); *Phys. Rev. Lett.* **117**, 109902(A) (2016); **118**, 119901(A) (2017).
 - [13] Roel Aaij *et al.*, Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$, *Phys. Rev. Lett.* **122**, 222001 (2019).
 - [14] Roel Aaij *et al.*, Evidence of a $J/\psi \Lambda$ structure and observation of excited Ξ^- states in the $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ decay, *Sci. Bull.* **66**, 1278 (2021).
 - [15] R. Aaij *et al.*, Observation of a $J/\psi \Lambda$ resonance consistent with a strange pentaquark candidate in $B^- \rightarrow J/\psi \Lambda \bar{p}$ decays, *Phys. Rev. Lett.* **131**, 031901 (2023).
 - [16] Hua-Xing Chen, Wei Chen, and Shi-Lin Zhu, Possible interpretations of the $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$, *Phys. Rev. D* **100**, 051501 (2019).
 - [17] Rui Chen, Zhi-Feng Sun, Xiang Liu, and Shi-Lin Zhu, Strong LHCb evidence supporting the existence of the hidden-charm molecular pentaquarks, *Phys. Rev. D* **100**, 011502 (2019).
 - [18] Feng-Kun Guo, Hao-Jie Jing, Ulf-G Meißner, and Shuntaro Sakai, Isospin breaking decays as a diagnosis of the hadronic molecular structure of the $P_c(4457)$, *Phys. Rev. D* **99**, 091501 (2019).
 - [19] Ming-Zhu Liu, Ya-Wen Pan, Fang-Zheng Peng, Mario Sánchez Sánchez, Li-Sheng Geng, Atsushi Hosaka, and Manuel Pavon Valderrama, Emergence of a complete heavy-quark spin symmetry multiplet: Seven molecular pentaquarks in light of the latest LHCb analysis, *Phys. Rev. Lett.* **122**, 242001 (2019).
 - [20] Cheng-Jian Xiao, Yin Huang, Yu-Bing Dong, Li-Sheng Geng, and Dian-Yong Chen, Exploring the molecular scenario of $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$, *Phys. Rev. D* **100**, 014022 (2019).
 - [21] C. W. Xiao, J. Nieves, and E. Oset, Heavy quark spin symmetric molecular states from $\bar{D}^{(*)} \Sigma_c^{(*)}$ and other coupled channels in the light of the recent LHCb pentaquarks, *Phys. Rev. D* **100**, 014021 (2019).
 - [22] Jian-Rong Zhang, Exploring a $\Sigma_c \bar{D}$ state: With focus on $P_c(4312)^+$, *Eur. Phys. J. C* **79**, 1001 (2019).
 - [23] Zhi-Gang Wang and Xu Wang, Analysis of the strong decays of the $P_c(4312)$ as a pentaquark molecular state with QCD sum rules, *Chin. Phys. C* **44**, 103102 (2020).
 - [24] Yong-Jiang Xu, Chun-Yu Cui, Yong-Lu Liu, and Ming-Qiu Huang, Partial decay widths of $P_c(4312)$ as a $\bar{D} \Sigma_c$ molecular state, *Phys. Rev. D* **102**, 034028 (2020).
 - [25] T. J. Burns and E. S. Swanson, Molecular interpretation of the $P_c(4440)$ and $P_c(4457)$ states, *Phys. Rev. D* **100**, 114033 (2019).
 - [26] Yong-Hui Lin and Bing-Song Zou, Strong decays of the latest LHCb pentaquark candidates in hadronic molecule pictures, *Phys. Rev. D* **100**, 056005 (2019).

- [27] Jun He and Dian-Yong Chen, Molecular states from $\Sigma_c^{(*)}\bar{D}^{(*)} - \Lambda_c\bar{D}^{(*)}$ interaction, *Eur. Phys. J. C* **79**, 887 (2019).
- [28] Meng-Lin Du, Vadim Baru, Feng-Kun Guo, Christoph Hanhart, Ulf-G Meißner, José A. Oller, and Qian Wang, Interpretation of the LHCb P_c states as hadronic molecules and hints of a narrow $P_c(4380)$, *Phys. Rev. Lett.* **124**, 072001 (2020).
- [29] Guang-Juan Wang, Li-Ye Xiao, Rui Chen, Xiao-Hai Liu, Xiang Liu, and Shi-Lin Zhu, Probing hidden-charm decay properties of P_c states in a molecular scenario, *Phys. Rev. D* **102**, 036012 (2020).
- [30] Hao Xu, Qiang Li, Chao-Hsi Chang, and Guo-Li Wang, Recently observed P_c as molecular states and possible mixture of $P_c(4457)$, *Phys. Rev. D* **101**, 054037 (2020).
- [31] Yong-Jiang Xu, Yong-Lu Liu, and Ming-Qiu Huang, The magnetic moment of $P_c(4312)$ as a $\bar{D}\Sigma_c$ molecular state, *Eur. Phys. J. C* **81**, 421 (2021).
- [32] Xi-Zhe Ling, Jun-Xu Lu, Ming-Zhu Liu, and Li-Sheng Geng, $P_c(4457) \rightarrow P_c(4312) \pi/\gamma$ in the molecular picture, *Phys. Rev. D* **104**, 074022 (2021).
- [33] Kan Chen, Rui Chen, Lu Meng, Bo Wang, and Shi-Lin Zhu, Systematics of the heavy flavor hadronic molecules, *Eur. Phys. J. C* **82**, 581 (2022).
- [34] Meng-Lin Du, Zhi-Hui Guo, and J. A. Oller, Insights into the nature of the $P_{cs}(4459)$, *Phys. Rev. D* **104**, 114034 (2021).
- [35] Rui Chen and Xiang Liu, Mass behavior of hidden-charm open-strange pentaquarks inspired by the established P_c molecular states, *Phys. Rev. D* **105**, 014029 (2022).
- [36] Hong-Wei Ke, Fang Lu, Hai Pang, Xiao-Hai Liu, and Xue-Qian Li, Study on the possible molecular states composed of $\Lambda_c\bar{D}^*$, $\Sigma_c\bar{D}^*$, $\Xi_c\bar{D}^*$ and $\Xi'_c\bar{D}^*$ in the Bethe-Salpeter frame based on the pentaquark states $P_c(4440)$, $P_c(4457)$ and $P_{cs}(4459)$, *Eur. Phys. J. C* **83**, 1074 (2023).
- [37] Kai Xu, Kanokphon Phumphan, Wiriya Ruangyoo, Chia-Chu Chen, Ayut Limphirath, and Yupeng Yan, P_c states in the mixture of molecular and pentaquark pictures, *Phys. Rev. D* **109**, 036019 (2024).
- [38] Rui Chen, Can the newly reported $P_{cs}(4459)$ be a strange hidden-charm $\Xi_c\bar{D}^*$ molecular pentaquark?, *Phys. Rev. D* **103**, 054007 (2021).
- [39] Rui Chen, Strong decays of the newly $P_{cs}(4459)$ as a strange hidden-charm $\Xi_c\bar{D}^*$ molecule, *Eur. Phys. J. C* **81**, 122 (2021).
- [40] Jun-Tao Zhu, Lin-Qing Song, and Jun He, $P_{cs}(4459)$ and other possible molecular states from $\Xi_c^{(*)}\bar{D}^{(*)}$ and $\Xi'_c\bar{D}^{(*)}$ interactions, *Phys. Rev. D* **103**, 074007 (2021).
- [41] C. W. Xiao, J. J. Wu, and B. S. Zou, Molecular nature of $P_{cs}(4459)$ and its heavy quark spin partners, *Phys. Rev. D* **103**, 054016 (2021).
- [42] Jun-Xu Lu, Ming-Zhu Liu, Rui-Xiang Shi, and Li-Sheng Geng, Understanding $P_{cs}(4459)$ as a hadronic molecule in the $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ decay, *Phys. Rev. D* **104**, 034022 (2021).
- [43] Xiu-Wu Wang and Zhi-Gang Wang, Analysis of $P_{cs}(4338)$ and related pentaquark molecular states via QCD sum rules, *Chin. Phys. C* **47**, 013109 (2023).
- [44] Albert Feijoo, Wen-Fei Wang, Chu-Wen Xiao, Jia-Jun Wu, Eulogio Oset, Juan Nieves, and Bing-Song Zou, A new look at the P_{cs} states from a molecular perspective, *Phys. Lett. B* **839**, 137760 (2023).
- [45] Qi Wu and Dian-Yong Chen, Production of $P_{\psi s}^\Lambda(4338)$ from Ξ_b decay, *Phys. Rev. D* **109**, 094003 (2024).
- [46] Qi Wu and Dian-Yong Chen, Production of P_c states from Λ_b decay, *Phys. Rev. D* **100**, 114002 (2019).
- [47] Qi Wu, Dian-Yong Chen, and Ran Ji, Production of $P_{cs}(4459)$ from Ξ_b decay, *Chin. Phys. Lett.* **38**, 071301 (2021).
- [48] Bernard Aubert *et al.*, Observation of a charmed baryon decaying to $D^0 p$ at a mass near $2.94 - \text{GeV}/c^2$, *Phys. Rev. Lett.* **98**, 012001 (2007).
- [49] Kazuo Abe *et al.*, Experimental constraints on the possible J^P quantum numbers of the $\Lambda_c(2880)^+$, *Phys. Rev. Lett.* **98**, 262001 (2007).
- [50] Y. B. Li *et al.*, Evidence of a new excited charmed baryon decaying to $\Sigma_c(2455)^{0,++}\pi^\pm$, *Phys. Rev. Lett.* **130**, 031901 (2023).
- [51] S. Navas *et al.*, Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [52] Xiao-Gang He, Xue-Qian Li, Xiang Liu, and Xiao-Qiang Zeng, $\Lambda_c^+(2940)$: A possible molecular state?, *Eur. Phys. J. C* **51**, 883 (2007).
- [53] Yubing Dong, Amand Faessler, Thomas Gutsche, and Valery E. Lyubovitskij, Strong two-body decays of the $\Lambda_c(2940)^+$ in a hadronic molecule picture, *Phys. Rev. D* **81**, 014006 (2010).
- [54] Yubing Dong, Amand Faessler, Thomas Gutsche, S. Kumano, and Valery E. Lyubovitskij, Strong three-body decays of $\Lambda_c(2940)^+$, *Phys. Rev. D* **83**, 094005 (2011).
- [55] Jun He, Yuan-Tao Ye, Zhi-Feng Sun, and Xiang Liu, The observed charmed hadron $\Lambda_c(2940)^+$ and the D^*N interaction, *Phys. Rev. D* **82**, 114029 (2010).
- [56] Jian-Rong Zhang, S -wave $D^{(*)}N$ molecular states: $\Sigma_c(2800)$ and $\Lambda_c(2940)^{+?}$, *Phys. Rev. D* **89**, 096006 (2014).
- [57] Zi-Li Yue, Quan-Yun Guo, and Dian-Yong Chen, Strong decays of the $\Lambda_c(2910)$ and $\Lambda_c(2940)$ in the ND^* molecular frame, *Phys. Rev. D* **109**, 094049 (2024).
- [58] Bo Wang, Lu Meng, and Shi-Lin Zhu, $D^{(*)}N$ interaction and the structure of $\Sigma_c(2800)$ and $\Lambda_c(2940)$ in chiral effective field theory, *Phys. Rev. D* **101**, 094035 (2020).
- [59] Qi Xin, Xiao-Song Yang, and Zhi-Gang Wang, The singly charmed pentaquark molecular states via the QCD sum rules, *Int. J. Mod. Phys. A* **38**, 2350123 (2023).
- [60] Ye Yan, Xiaohuang Hu, Yuheng Wu, Hongxia Huang, Jialun Ping, and Youchang Yang, Pentaquark interpretation of Λ_c states in the quark model, *Eur. Phys. J. C* **83**, 524 (2023).
- [61] Jun He, Zhen Ouyang, Xiang Liu, and Xue-Qian Li, Production of charmed baryon $\Lambda_c(2940)^+$ at PANDA, *Phys. Rev. D* **84**, 114010 (2011).
- [62] Yubing Dong, Amand Faessler, Thomas Gutsche, and Valery E. Lyubovitskij, Role of the hadron molecule $\Lambda_c(2940)$ in the $p\bar{p}B D^0\bar{\Lambda}_c(2286)$ annihilation reaction, *Phys. Rev. D* **90**, 094001 (2014).
- [63] Xiao-Yun Wang, Alexey Guskov, and Xu-Rong Chen, $\Lambda_c^*(2940)^+$ photoproduction off the neutron, *Phys. Rev. D* **92**, 094032 (2015).
- [64] Kazuya Aoki *et al.*, Extension of the J-PARC hadron experimental facility: Third white paper, [arXiv:2110.04462](https://arxiv.org/abs/2110.04462).

- [65] Ju-Jun Xie, Yu-Bing Dong, and Xu Cao, Role of the $\Lambda_c^+(2940)$ in the $\pi^- p \rightarrow D^- D^0 p$ reaction close to threshold, *Phys. Rev. D* **92**, 034029 (2015).
- [66] J. H. Christenson, E. Hummel, G. A. Kreiter, J. Sculli, and P. Yamin, Limits on charm production in hadronic interactions near threshold, *Phys. Rev. Lett.* **55**, 154 (1985).
- [67] Yubing Dong, Amand Faessler, Thomas Gutsche, S. Kumano, and Valery E. Lyubovitskij, Radiative decay of $\Lambda_c(2940)^+$ in a hadronic molecule picture, *Phys. Rev. D* **82**, 034035 (2010).
- [68] Sang-Ho Kim, Atsushi Hosaka, Hyun-Chul Kim, and Hiroyuki Nouni, Production of strange and charmed baryons in pion induced reactions, *Phys. Rev. D* **92**, 094021 (2015).
- [69] Dian-Yong Chen and Xiang Liu, Predicted charged charmonium-like structures in the hidden-charm dipion decay of higher charmonia, *Phys. Rev. D* **84**, 034032 (2011).
- [70] W. Liu, C.M. Ko, and Z.W. Lin, Cross-section for charmonium absorption by nucleons, *Phys. Rev. C* **65**, 015203 (2002).
- [71] S. Okubo, SU(4), SU(8) mass formulas and weak interactions, *Phys. Rev. D* **11**, 3261 (1975).
- [72] Benjamin C. Jackson, Yongseok Oh, H. Haberzettl, and K. Nakayama, $\bar{K} + N \rightarrow K + \Xi$ reaction and $S = -1$ hyperon resonances, *Phys. Rev. C* **91**, 065208 (2015).
- [73] Yong-seok Oh, Taesoo Song, and Su Hounng Lee, J/ψ absorption by π and ρ mesons in meson exchange model with anomalous parity interactions, *Phys. Rev. C* **63**, 034901 (2001).
- [74] Steven Weinberg, Evidence that the deuteron is not an elementary particle, *Phys. Rev.* **137**, B672 (1965).
- [75] V. Baru, J. Haidenbauer, C. Hanhart, Yu. Kalashnikova, and Alexander Evgenyevich Kudryavtsev, Evidence that the $a_0(980)$ and $f_0(980)$ are not elementary particles, *Phys. Lett. B* **586**, 53 (2004).