

$\Lambda_c(2910)$ and $\Lambda_c(2940)$ productions in $p\bar{p}$ annihilation

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In this work, we investigate the productions of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ in the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process by utilizing an effective Lagrangian approach, where both $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are considered as D^*N molecular states with $J^P = 1/2^-$ and $3/2^-$, respectively. In addition to the t -channel D and D^* exchanges, the contribution from light-meson exchange is also considered. At $\sqrt{s} = 10$ GeV, our estimations indicate that the total cross sections for $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ are $(130.7^{+397.1}_{-103.9})$ nb, where the central value is estimated with $\Lambda_r = 1.1$ GeV, and the uncertainties are resulted from the variation of parameter Λ_r from 1.0 to 1.2 GeV. Our results indicate that the light-meson exchange diagrams are very important, which provide a very large, smooth background. Moreover, the estimations of the $D^0 p$ invariant mass spectrum reveal that the peak structure between 2.9 and 3.0 GeV primarily originates from $\Lambda_c(2910)$, while the signal of $\Lambda_c(2940)$ is about 1 order smaller than that of $\Lambda_c(2910)$. Furthermore, the resulting Dalitz plot is estimated with $\sqrt{s} = 8$ GeV. It is expected that our estimations in the present work can be tested by future experiments at PANDA.

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I. INTRODUCTION

Since the observation of $X(3872)$ by the Belle Collaboration in 2003 [1], some potential exotic state candidates have been observed and identified by experimental collaborations including Belle/Belle II, BESIII, and LHCb (see Refs. [2–12] for examples). Among the possible pentaquark states, $P_c(4380)$ and $P_c(4450)$ were first observed in the $J/\psi p$ invariant mass distributions of the $\Lambda_b \rightarrow J/\psi K^- p$ process by the LHCb Collaboration in 2015 [13,14]. Later, the same process was analyzed with the dataset collected by the LHCb Collaboration in Run I and Run II in 2019 [15]. Their results indicated that $P_c(4380)$ could be described by the background and a new narrow state $P_c(4312)$ with a statistical significance of 7.3σ . Moreover, $P_c(4450)$ split into two narrow states $P_c(4440)$ and $P_c(4457)$. In addition to the above observations, the strange counterparts of the P_c states, P_{cs} , were further observed by the LHCb Collaboration, which included $P_{cs}(4459)$ [16] and $P_{cs}(4338)$ [17]. Because of the fact that the masses of P_c and P_{cs} states are close to the thresholds of $D^{(*)}\Sigma_c$ and $D^{(*)}\Xi_c$, respectively, the

properties of these states have been comprehensively investigated in the molecular frame [18–43].

In addition to the P_c and P_{cs} states, another two pentaquark candidates, $\Lambda_c(2910)$ and $\Lambda_c(2940)$, have also been discovered experimentally. In 2006, $\Lambda_c(2940)$ was observed in the $D^0 p$ invariant mass spectra by the BABAR Collaboration [44]. Then, the Belle Collaboration confirmed the existence of $\Lambda_c(2940)$ in the $\Sigma_c(2455)^{0,++}\pi^{+,-}$ invariant mass distributions, using a 533 fb^{-1} data sample recorded by the Belle detector at or 60 MeV below the $\Upsilon(4S)$ resonance [45]. In 2022, based on $772 \times 10^6 B\bar{B}$ events collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider, the Belle Collaboration observed a new structure, $\Lambda_c(2910)$, in the $\Sigma_c(2455)^{0,++}\pi^{+,-}$ invariant mass spectrum of the $\bar{B}^0 \rightarrow \Sigma_c(2455)^{0,++}\pi^{+,-}\bar{p}$ processes [46]. The Particle Data Group average of masses and widths of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are [47]

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

respectively.

Similar to the case of P_c states, the observed masses of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are close to the threshold of D^*N , indicating that these two states can be regarded as the D^*N

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pentaquark molecular states. In Ref. [48], the author investigated the properties of $\Lambda_c(2940)$ by using the QCD sum rules, indicating that $\Lambda_c(2940)$ could be regarded as the S -wave D^*N bound state with $J^P = 3/2^-$. Moreover, the authors in Ref. [49] proposed that $\Lambda_c(2910)/\Lambda_c(2940)$ could be regarded as a D^*N molecular state with $J^P = 3/2^-$ by using the QCD sum rules. Using the quark delocalization color screening model, the authors in Ref. [50] proposed that $\Lambda_c(2940)$ is likely to be interpreted as a D^*N molecular state with $J^P = 3/2^-$. By considering $\Lambda_c(2940)$ as a D^*N molecular state with $J^P = 1/2^\pm$ and $3/2^-$, respectively, the authors in Refs. [51–53] estimated the two-body decay channels $D^0 p$, $\Sigma_c^{++}\pi^-$, and $\Sigma_c^0\pi^+$ and three-body decay channels $\Lambda_c(2286)^+\pi^+\pi^-$ and $\Lambda_c(2286)^+\pi^0\pi^0$. In Ref. [54], the authors studied the decay properties of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ by using an effective Lagrangian approach, and the results suggested that $\Lambda_c(2910)$ and $\Lambda_c(2940)$ could be assigned as D^*N molecular states with $J^P = 1/2^-$ and $J^P = 3/2^-$, respectively, while the branching fractions for ND , $\Sigma_c\pi$, and $\Sigma_c^*\pi$ channels of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ were estimated. More recently, the authors in Ref. [55] investigated the DN - D^*N coupled-channel interactions using both heavy quark effective theory and a flavor-symmetry-constrained effective Lagrangian approach. Their estimations indicated that the mass spectrum of S -wave D^*N systems can be matched to three Λ_c exotic states. Among them, the masses of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ align with those of D^*N bound states with $J^P = 1/2^-$ and $J^P = 3/2^-$, respectively. In conclusion, both the spectrum estimations and the decay property investigations support that $\Lambda_c(2910)$ and $\Lambda_c(2940)$ can be identified as D^*N bound states with $J^P = 1/2^-$ and $J^P = 3/2^-$, respectively.

In addition to the mass spectrum and decay properties, we also notice some theoretical research on the productions of $\Lambda_c(2910)$ and $\Lambda_c(2940)$. The authors in Ref. [56] investigated the production of $\Lambda_c(2940)$ in the $\gamma n \rightarrow D^-\Lambda_c(2940)$ process, where $\Lambda_c(2940)$ was regarded as a $D^{*0}p$ molecular state with $J^P = 1/2^\pm$, and the estimations showed that the dominant contributions come from the t -channel with D^* exchange. Then, by considering $\Lambda_c(2940)$ as a $D^{*0}p$ molecular state with $J^P = 1/2^\pm$, the authors in Ref. [57] investigated the production of $\Lambda_c(2940)$ in the $\pi^- p \rightarrow D^- D^0 p$ process by including the s , u , and t channels, indicating that the total cross sections are of orders of $10 \mu\text{b}$ at $P_\pi = 15 \text{ GeV}$. Moreover, the authors in Ref. [58] studied the productions of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ in the process $\pi p \rightarrow D^- D^0 p$, where both $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are considered as D^*N molecular states, and the estimations indicated that the dominant contributions to the cross sections come from the intermediate state $\Lambda_c(2910)$.

In terms of experimental conditions, the PANDA Collaboration proposed to search for the charmed baryons

in the $p\bar{p}$ scattering process with the momentum range of $P_{\bar{p}} = [1.5, 15] \text{ GeV}$ [59]. Based on the high-energy beam and the potential higher-energy configurations with the future upgrades, one can investigate the productions of $\Lambda_c(2910)/\Lambda_c(2940)$ in the $p\bar{p}$ scattering process. It is worth noting that the estimations in Refs. [54,55] suggested that both $\Lambda_c(2910)$ and $\Lambda_c(2940)$ could be considered as D^*N molecular states with the J^P quantum numbers to be $1/2^-$ and $3/2^-$, respectively. Thus, we propose to investigate the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process with the contributions from both $\Lambda_c(2910)$ and $\Lambda_c(2940)$, while the light-meson exchange is also considered in the present work. Specifically, we first estimate the cross sections for the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process. Then, the $D^0 p$ invariant mass distributions and Dalitz plot are estimated to check the individual contributions of $\Lambda_c(2910)$ and $\Lambda_c(2940)$.

This work is organized as follows. After the Introduction, we present our estimations of the cross sections for $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$. In Sec. III, the numerical results and relevant discussions of the cross sections and differential cross sections are presented. The last section is devoted to a short summary.

II. $\Lambda_c(2910)$ AND $\Lambda_c(2940)$ PRODUCTIONS IN THE $p\bar{p}$ SCATTERING PROCESS

In the present estimations, we consider that both $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are D^*N molecular states with the J^P quantum numbers to be $1/2^-$ and $3/2^-$, respectively. In Fig. 1, we present the Feynman diagrams for the $p\bar{p}$ scattering process, where Figs. 1(a) and 1(b) correspond to the t -channel light-meson and D/D^* exchanges, respectively. In the present calculations, we employ the effective Lagrangian approach to depict the relevant hadron interaction vertices. The effective Lagrangians for $NN\pi$, $NN\eta$, $NN\sigma$, $NN\rho$, $NN\omega$, $\Lambda_c ND$, $\Lambda_c ND^*$, $\Lambda_{c1}^* ND$, and $\Lambda_{c2}^* ND$ can be written as [51–53,56–58,60–69]

$$\begin{aligned}
\mathcal{L}_{NN\pi} &= -ig_{NN\pi}\bar{N}\gamma_5\vec{\tau}\cdot\vec{\pi}N, \\
\mathcal{L}_{NN\eta} &= -ig_{NN\eta}\bar{N}\gamma_5\eta N, \\
\mathcal{L}_{NN\sigma} &= -g_{NN\sigma}\bar{N}N\sigma, \\
\mathcal{L}_{NN\rho} &= -g_{NN\rho}\bar{N}\left[\gamma_\mu - \frac{\kappa_{NN\rho}}{2m_N}\sigma^{\mu\nu}\partial_\nu\right]\vec{\tau}\cdot\vec{\rho}_\mu N, \\
\mathcal{L}_{NN\omega} &= -g_{NN\omega}\bar{N}\left[\gamma_\mu - \frac{\kappa_{NN\omega}}{2m_N}\sigma^{\mu\nu}\partial_\nu\right]\omega_\mu N, \\
\mathcal{L}_{\Lambda_c ND} &= ig_{\Lambda_c ND}\bar{\Lambda}_c\gamma_5 ND + \text{H.c.}, \\
\mathcal{L}_{\Lambda_c ND^*} &= g_{\Lambda_c ND^*}\bar{\Lambda}_c\gamma^\mu ND_\mu^* + \text{H.c.}, \\
\mathcal{L}_{\Lambda_{c1}^* ND} &= ig_{\Lambda_{c1}^* ND}\bar{\Lambda}_{c1}^* ND + \text{H.c.}, \\
\mathcal{L}_{\Lambda_{c2}^* ND} &= \frac{g_{\Lambda_{c2}^* ND}}{m_\pi}\bar{\Lambda}_{c2}^*\gamma^\mu N\partial_\mu D + \text{H.c.}
\end{aligned} \tag{2}$$

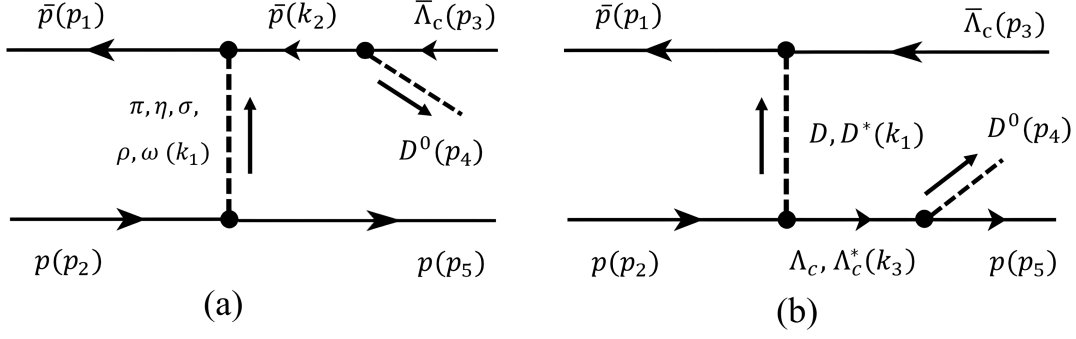


FIG. 1. Diagrams contributing to the production of $\Lambda_c(2910)/\Lambda_c(2940)$ in the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process. (a), (b) The t -channel light-meson and D and D^* exchanges, respectively. Here Λ_c and Λ_c^* refer to $\Lambda_c(2286)$ and $\Lambda_c(2910)/\Lambda_c(2940)$ states, respectively.

Hereafter, Λ_{c1}^* and Λ_{c2}^* refer to $\Lambda_c(2910)$ and $\Lambda_c(2940)$, respectively. Then, because the $\Lambda_c(2910)$ and $\Lambda_c(2940)$ states are both considered as D^*N molecular states, the effective Lagrangians of the molecular states coupling to their components are [54]

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

With the above effective Lagrangians, one can obtain the amplitudes corresponding to the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process, which are

$$\begin{aligned}\mathcal{M}_{\pi,p} &= [\bar{u}(p_5)(-ig_{NN\pi}\gamma_5)u(p_2)]S^0(k_1, m_\pi, \Gamma_\pi)[\bar{v}(p_1)(-ig_{NN\pi}\gamma_5)S^{1/2}(k_2, m_p, \Gamma_p)(ig_{\Lambda_c ND}\gamma_5)v(p_3)] \\ &\quad \times F(k_2, m_p, \Lambda_r)[F(k_1, m_\pi, \Lambda_r)]^2, \\ \mathcal{M}_{\eta,p} &= [\bar{u}(p_5)(-ig_{NN\eta}\gamma_5)u(p_2)]S^0(k_1, m_\eta, \Gamma_\eta)[\bar{v}(p_1)(-ig_{NN\eta}\gamma_5)S^{1/2}(k_2, m_p, \Gamma_p)(ig_{\Lambda_c ND}\gamma_5)v(p_3)] \\ &\quad \times F(k_2, m_p, \Lambda_r)[F(k_1, m_\eta, \Lambda_r)]^2, \\ \mathcal{M}_{\sigma,p} &= [\bar{u}(p_5)(-g_{NN\sigma})u(p_2)]S^0(k_1, m_\sigma, \Gamma_\sigma)[\bar{v}(p_1)(-g_{NN\sigma})S^{1/2}(k_2, m_p, \Gamma_p)(ig_{\Lambda_c ND}\gamma_5)v(p_3)] \\ &\quad \times F(k_2, m_p, \Lambda_r)[F(k_1, m_\sigma, \Lambda_r)]^2, \\ \mathcal{M}_{\rho,p} &= \left[\bar{u}(p_5) \left(-g_{NN\rho} \left[\gamma_\mu - \frac{\kappa_{NN\rho}}{2m_N} \sigma^{\mu\nu} (ik_1^\nu) \right] \right) u(p_2) \right] S_{\mu\alpha}^1(k_1, m_\rho, \Gamma_\rho) \left[\bar{v}(p_1) \left(-g_{NN\rho} \left[\gamma_\alpha - \frac{\kappa_{NN\rho}}{2m_N} \sigma^{\alpha\beta} (ik_1^\beta) \right] \right) \right] \\ &\quad \times S^{1/2}(k_2, m_p, \Gamma_p)(ig_{\Lambda_c ND}\gamma_5)v(p_3) \times F(k_2, m_p, \Lambda_r)[F(k_1, m_\rho, \Lambda_r)]^2, \\ \mathcal{M}_{\omega,p} &= \left[\bar{u}(p_5) \left(-g_{NN\omega} \left[\gamma_\mu - \frac{\kappa_{NN\omega}}{2m_N} \sigma^{\mu\nu} (ik_1^\nu) \right] \right) u(p_2) \right] S_{\mu\alpha}^1(k_1, m_\omega, \Gamma_\omega) \left[\bar{v}(p_1) \left(-g_{NN\omega} \left[\gamma_\alpha - \frac{\kappa_{NN\omega}}{2m_N} \sigma^{\alpha\beta} (ik_1^\beta) \right] \right) \right] \\ &\quad \times S^{1/2}(k_2, m_p, \Gamma_p)(ig_{\Lambda_c ND}\gamma_5)v(p_3) \times F(k_2, m_p, \Lambda_r)[F(k_1, m_\omega, \Lambda_r)]^2, \\ \mathcal{M}_{D,\Lambda_c} &= [\bar{u}(p_5)(ig_{\Lambda_c ND}\gamma_5)S^{1/2}(k_3, m_{\Lambda_c}, \Gamma_{\Lambda_c})(ig_{\Lambda_c ND}\gamma_5)u(p_2)]S^0(k_1, m_D, \Gamma_D)[\bar{v}(p_1)(ig_{\Lambda_c ND}\gamma_5)v(p_3)] \\ &\quad \times F(k_3, m_{\Lambda_c}, \Lambda_r)[F(k_1, m_D, \Lambda_r)]^2, \\ \mathcal{M}_{D^*,\Lambda_c} &= [\bar{u}(p_5)(ig_{\Lambda_c ND}\gamma_5)S^{1/2}(k_3, m_{\Lambda_c}, \Gamma_{\Lambda_c})(g_{\Lambda_c ND^*}\gamma_\mu)u(p_2)]S_{\mu\nu}^1(k_1, m_{D^*}, \Gamma_{D^*})[\bar{v}(p_1)(g_{\Lambda_c ND^*}\gamma_\nu)v(p_3)] \\ &\quad \times F(k_3, m_{\Lambda_c}, \Lambda_r)[F(k_1, m_{D^*}, \Lambda_r)]^2,\end{aligned}$$

$$\begin{aligned}
 \mathcal{M}_{D,\Lambda_{c1}^*} &= [\bar{u}(p_5)(ig_{\Lambda_{c1}^*ND})S^{1/2}(k_3, m_{\Lambda_{c1}^*}, \Gamma_{\Lambda_{c1}^*})(ig_{\Lambda_{c1}^*ND})u(p_2)]S^0(k_1, m_D, \Gamma_D)[\bar{v}(p_1)(ig_{\Lambda_{c1}ND}\gamma_5)v(p_3)] \\
 &\quad \times F(k_3, m_{\Lambda_{c1}^*}, \Lambda_r)[F(k_1, m_D, \Lambda_r)]^2, \\
 \mathcal{M}_{D^*,\Lambda_{c1}^*} &= [\bar{u}(p_5)(ig_{\Lambda_{c1}^*ND})S^{1/2}(k_3, m_{\Lambda_{c1}^*}, \Gamma_{\Lambda_{c1}^*})(g_{\Lambda_{c1}^*ND^*}\gamma_\mu\gamma_5)u(p_2)]S_{\mu\nu}^1(k_1, m_{D^*}, \Gamma_{D^*})[\bar{v}(p_1)(g_{\Lambda_{c1}ND^*}\gamma_\nu)v(p_3)] \\
 &\quad \times F(k_3, m_{\Lambda_{c1}^*}, \Lambda_r)[F(k_1, m_{D^*}, \Lambda_r)]^2, \\
 \mathcal{M}_{D,\Lambda_{c2}^*} &= \left[\bar{u}(p_5)\left(\frac{g_{\Lambda_{c2}^*ND}}{m_\pi}\gamma_5(-ip_4^\mu)\right)S_{\mu\nu}^{3/2}(k_3, m_{\Lambda_{c2}^*}, \Gamma_{\Lambda_{c2}^*})\left(\frac{g_{\Lambda_{c2}^*ND}}{m_\pi}\gamma_5(ik_1^\nu)\right)u(p_2)\right]S^0(k_1, m_D, \Gamma_D)[\bar{v}(p_1)(ig_{\Lambda_{c2}ND}\gamma_5)v(p_3)] \\
 &\quad \times F(k_3, m_{\Lambda_{c2}^*}, \Lambda_r)[F(k_1, m_D, \Lambda_r)]^2, \\
 \mathcal{M}_{D^*,\Lambda_{c2}^*} &= \left[\bar{u}(p_5)\left(\frac{g_{\Lambda_{c2}^*ND}}{m_\pi}\gamma_5(-ip_4^\mu)\right)S_{\mu\nu}^{3/2}(k_3, m_{\Lambda_{c2}^*}, \Gamma_{\Lambda_{c2}^*})(g_{\Lambda_{c2}^*ND^*})u(p_2)\right]S_{\nu\theta}^1(k_1, m_{D^*}, \Gamma_{D^*})[\bar{v}(p_1)(g_{\Lambda_{c2}ND^*}\gamma_\theta)v(p_3)] \\
 &\quad \times F(k_3, m_{\Lambda_{c2}^*}, \Lambda_r)[F(k_1, m_{D^*}, \Lambda_r)]^2,
 \end{aligned} \tag{4}$$

where the subscripts correspond to the propagators involved in the relevant processes. In addition, $S^0(k_i, m_i, \Gamma_i)$ and $S_{\mu\nu}^1(k_i, m_i, \Gamma_i)$ are the propagators of scalar and vector mesons with four momentum k_i , mass m_i , and width Γ_i , respectively, and the concrete forms are

$$\begin{aligned}
 S^0(k_i, m_i, \Gamma_i) &= \frac{i}{k_i^2 - m_i^2 + im_i\Gamma_i}, \\
 S_{\mu\nu}^1(k_i, m_i, \Gamma_i) &= \frac{-g^{\mu\nu} + k_i^\mu k_i^\nu / m_i^2}{k_i^2 - m_i^2 + im_i\Gamma_i}.
 \end{aligned} \tag{5}$$

In addition, $S^{1/2}(k_i, m_i, \Gamma_i)$ and $S_{\mu\nu}^{3/2}(k_i, m_i, \Gamma_i)$ are the propagators of $\Lambda_c(2910)$ and $\Lambda_c(2940)$, respectively, which read

$$\begin{aligned}
 S^{1/2}(k_i, m_i, \Gamma_i) &= \frac{k_i + m_i}{k_i^2 - m_i^2 + im_i\Gamma_i}, \\
 S_{\mu\nu}^{3/2}(k_i, m_i, \Gamma_i) &= \frac{k_i + m_i}{k_i^2 - m_i^2 + im_i\Gamma_i} \\
 &\quad \times \left(-g^{\mu\nu} + \frac{\gamma^\mu\gamma^\nu}{3} + \frac{2k_i^\mu k_i^\nu}{3m_i^2} + \frac{\gamma^\mu k_i^\nu - k_i^\mu \gamma^\nu}{3m_i}\right).
 \end{aligned} \tag{6}$$

In the above amplitudes, the form factor $F(k_i, m_i, \Lambda_r)$ is introduced to depict the inner structure of the involved hadrons and the off-shell effects, and its specific expression is

$$F(k_i, m_i, \Lambda_r) = \frac{\Lambda_r^4}{\Lambda_r^4 + (k_i^2 - m_i^2)^2}, \tag{7}$$

where k_i and m_i are the four momentum and the mass of the exchanged state, respectively. It should be noted that the above form factor is typically applied to s -channel

processes. In Refs. [70–72], such kinds of form factors have been extended to apply to u and t channels, which play the role that smoothly suppresses the contributions from large momentum transfers while maintaining the physical behavior of the low-energy region. In the above form factor, a model parameter Λ_r is introduced, and its specific value should be determined by comparing the theoretical estimations with the corresponding experimental measurements. However, no experimental measurement for the considered process is available at present. In our previous work, when we evaluated the cross sections for the $\pi^- p \rightarrow D^{*-}\Lambda_c$ in the effective Lagrangian approach, we found that the cross sections at $P_\pi = 13$ GeV are estimated to be $2.59_{-2.00}^{+7.15}$ nb when taking $\Lambda_r = 1.0$ – 1.2 GeV [58], which is consistent with the upper limit of the experimental data reported by the AGS Collaboration at Brookhaven National Laboratory [73]. Thus, in the present work, we take the same parameter range as that employed in the estimations of the processes $\pi^- p \rightarrow D^- D^0 p$ to estimate the cross sections for the $p\bar{p} \rightarrow \Lambda_c D^0 p$ process.

III. NUMERICAL RESULTS AND DISCUSSIONS

A. Coupling constants

Before the estimations of the cross sections for the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process, the values of relevant coupling constants should be clarified. In the present estimations, both $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are considered as D^*N molecular states. Therefore, the coupling constants relevant to $\Lambda_c(2910)/\Lambda_c(2940)$ and their components D^*N could be determined by the compositeness condition [74–76], which is

$$g_{\Lambda_c^*ND^*}^2 = \frac{4\pi}{4M_{\Lambda_c^*}m_N} \frac{(m_{D^*} + m_N)^{5/2}}{(m_{D^*}m_N)^{1/2}} \sqrt{32\epsilon}, \tag{8}$$

TABLE I. The coupling constants involved in the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process.

Coupling constant	Value	Coupling constant	Value
$g_{\Lambda_c ND}$	-13.98	$g_{\Lambda_c ND^*}$	-5.20
$g_{\Lambda_c^* ND}$	0.99	$g_{\Lambda_c^* ND^*}$	3.55
$g_{\Lambda_c^* ND}$	0.84	$g_{\Lambda_c^* ND^*}$	2.34
$g_{KDD_s^*}$	5.0	$g_{KD_s^* D^*}$	7.0
$g_{KD_s D^*}$	5.0	$g_{NN\pi}$	13.46
$g_{NN\eta}$	4.76	$g_{NN\sigma}$	9.42
$g_{NN\rho}$	3.25	$\kappa_{NN\rho}$	6.10
$g_{NN\omega}$	11.76	$\kappa_{NN\omega}$	0

where $\epsilon = m_N + m_{D^*} - m_{\Lambda_c^*}$ stands for the binding energy of Λ_c^* , and we take $\epsilon = 32$ and 6.2 MeV for $\Lambda_c(2910)$ and $\Lambda_c(2940)$, respectively. In addition, the factor $1/(4M_{\Lambda_c^*}m_N)$ is introduced for the normalization of two involved fermion fields. The specific values of $g_{\Lambda_c^* ND^*}$ and $g_{\Lambda_c^* ND}$ estimated with the above relation are presented in Table I.

For the coupling constants $g_{\Lambda_c^* ND}$ and $g_{\Lambda_c^* ND^*}$, using the effective Lagrangians in Eq. (2), one can obtain the corresponding two-body amplitudes $\mathcal{M}_{\Lambda_c^* \rightarrow ND}$. Then, the decay widths of the $\Lambda_c^* \rightarrow ND$ processes can be written as

$$\Gamma_{\Lambda_c^* \rightarrow ND} = \frac{1}{(2J+1)8\pi} \frac{|\vec{k}_f|}{M^2} |\overline{\mathcal{M}_{\Lambda_c^* \rightarrow ND}}|^2, \quad (9)$$

where M and J are the mass and angular momentum of the initial Λ_c^* states. $\vec{k}_f$ is the three momentum of the final states in the initial rest frame. It is worth noting that the decay properties of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ have been investigated in Ref. [54], and the branching fractions of the ND channel for $\Lambda_c(2910)/\Lambda_c(2940)$ are estimated to be

$$\begin{aligned} \mathcal{B}(\Lambda_c(2910) \rightarrow ND) &\simeq 40\%, \\ \mathcal{B}(\Lambda_c(2940) \rightarrow ND) &\simeq 11\%. \end{aligned} \quad (10)$$

With the above branching fractions and the central values of the widths of $\Lambda_c(2940)$ and $\Lambda_c(2910)$ in Eq. (1), one can obtain the coupling constants $g_{\Lambda_c^* ND}$ and $g_{\Lambda_c^* ND^*}$, which are listed in Table I.

The coupling constants $g_{NN\pi}$, $g_{NN\eta}$, $g_{NN\sigma}$, $g_{NN\rho}$, $\kappa_{NN\rho}$, $g_{NN\omega}$, and $\kappa_{NN\omega}$ are obtained from Refs. [61–63,68,69]. The specific values of the coupling constants mentioned above are also listed in Table I.

B. Cross sections for the $p\bar{p}$ scattering process

After clarifying the amplitudes and relevant coupling constants, the cross sections for the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process can be estimated, and the total amplitude is

$$\begin{aligned} \mathcal{M}_{\text{Tot}} = & \mathcal{M}_{\pi,p} + \mathcal{M}_{\eta,p} + \mathcal{M}_{\sigma,p} + \mathcal{M}_{\rho,p} + \mathcal{M}_{\omega,p} \\ & + \mathcal{M}_{D,\Lambda_c} + \mathcal{M}_{D^*,\Lambda_c} + \mathcal{M}_{D,\Lambda_c^*} + \mathcal{M}_{D^*,\Lambda_c^*} \\ & + \mathcal{M}_{D,\Lambda_c^*} + \mathcal{M}_{D^*,\Lambda_c^*}. \end{aligned} \quad (11)$$

With the above total amplitude, one can obtain the differential cross sections of the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process, which is

$$d\sigma = \frac{1}{8(2\pi)^4} \frac{1}{\Phi} |\overline{\mathcal{M}_{\text{Tot}}}|^2 dp_3^0 dp_5^0 d\cos\theta d\eta, \quad (12)$$

where the flux factor $\Phi = 4|\vec{p}_1| |\sqrt{s}|$, $\vec{p}_1$ represents the three momentum of the initial antiproton. $\sqrt{s}$ is the center-of-mass energy. p_3^0 and p_5^0 refer to the energy of the outgoing $\bar{\Lambda}_c$ and proton, respectively.

With the above preparations, the cross sections for $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ depending on the center-of-mass energy $\sqrt{s}$ are presented in Fig. 2. Among them, Fig. 2(a) corresponds to the cross section for $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ estimated with $\Lambda_r = 1.1$ GeV, where the cyan dotted, red dashed, blue dash-dotted, and black dotted curves stand for the individual contributions from $\Lambda_c(2286)$, $\Lambda_c(2910)$, $\Lambda_c(2940)$, and light meson, respectively, while the black solid curve refers to the total cross sections for the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process. From this figure, one can find that the contributions from $\Lambda_c(2286)$ are not shown when $\sqrt{s} < 6$ GeV because its cross sections in this range are less than 1 pb. In addition, the cross section of $\Lambda_c(2910)$ is about 2 nb at $\sqrt{s} = 10$ GeV, which is about 250 times and 15 times of that from $\Lambda_c(2286)$ and $\Lambda_c(2940)$, respectively. Moreover, our estimations indicate that the cross section resulted from the light-meson intermediate process is predominant, which enhances the total cross section by more than 1 order of magnitude. In Fig. 2(b), we present the total cross sections for the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process, where the black solid curve is obtained with $\Lambda_r = 1.1$ GeV, while the cyan band represents the uncertainties resulted from the varying of Λ_r from 1.0 to 1.2 GeV. Our results show that the cross sections increase rapidly near the threshold and then increase rather slowly with the increasing of $\sqrt{s}$. In particular, the total cross sections are estimated to be $(130.7^{+397.1}_{-103.9})$ nb at $\sqrt{s} = 10$ GeV.

In addition to the cross sections, we present the Dalitz plot for the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process at $\sqrt{s} = 8$ GeV with $\Lambda_r = 1.1$ GeV depending on $m_{D^0 p}$ and $m_{\bar{\Lambda}_c D^0}$ [Fig. 3(b)] and the projections depending on $m_{D^0 p}$ [Fig. 3(c)] and $m_{\bar{\Lambda}_c D^0}$ [Fig. 3(a)]. From the Dalitz plot, one can find clear enhancement near the $D^0 p$ threshold. In the $\bar{\Lambda}_c D^0$ and $D^0 p$ invariant mass distributions, the cyan dotted, red dashed, blue dash-dotted, and black dotted curves correspond to the individual contributions from $\Lambda_c(2286)$, $\Lambda_c(2910)$, $\Lambda_c(2940)$, and light meson, respectively, while the black solid curve refers to the summation of the individual contributions as well as their interferences. In Fig. 3(a),

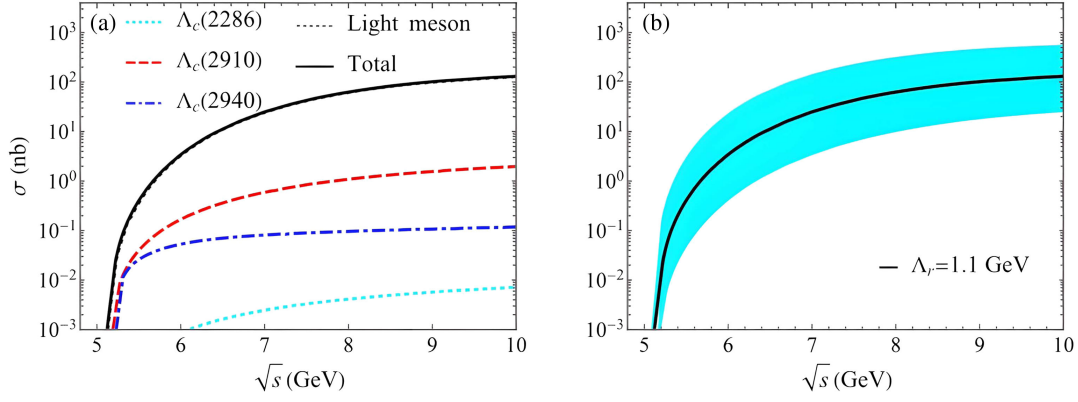


FIG. 2. The cross sections for the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process depending on the center-of-mass energy $\sqrt{s}$. (a) The individual contributions from light-meson and $\Lambda_c^{(*)}$ states. (b) The total cross sections with the uncertainty resulted from the model parameter Λ_r , where the black solid curve is obtained with $\Lambda_r = 1.1$ GeV, and the cyan band represents the uncertainties resulted from the variation of Λ_r from 1.0 to 1.2 GeV.

our estimations indicate that the $\bar{\Lambda}_c D^0$ invariant mass spectrum is smooth across the entire mass range and shows no sharp structure. In Fig. 3(c), our estimations show that the contribution from $\Lambda_c(2286)$ is relatively small, while the contribution from the light meson is rather large and smooth, which plays the role of background of the

observations of $\Lambda_c(2910)/\Lambda_c(2940)$. As for $\Lambda_c(2910)$ and $\Lambda_c(2940)$, our estimations suggested that the signal of $\Lambda_c(2910)$ is predominant, which is about 1 order larger than that of $\Lambda_c(2940)$. In addition, as shown in the inner figure of Fig. 3(c), a clear structure can be observed between 2.9 and 3.0 GeV in the $D^0 p$ invariant mass

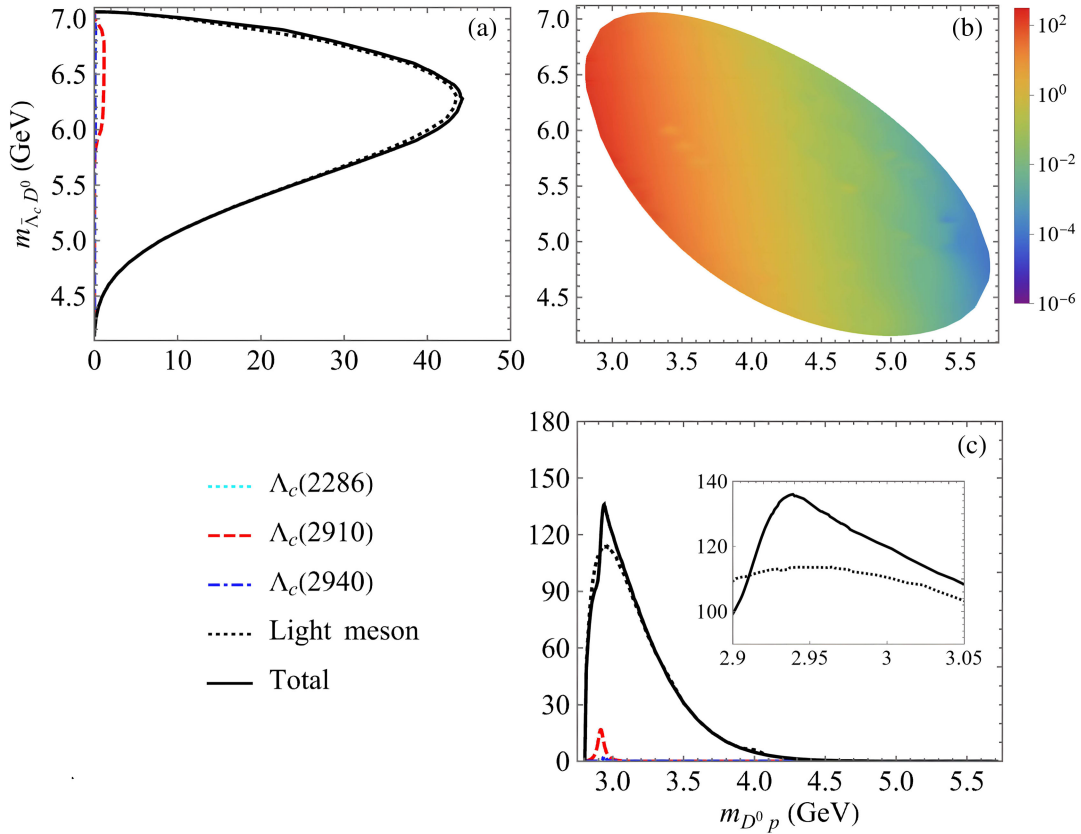


FIG. 3. (b) The Dalitz plot for $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process at $\sqrt{s} = 8$ GeV with $\Lambda_r = 1.1$ GeV depending on $m_{D^0 p}$ and $m_{\bar{\Lambda}_c D^0}$. (a), (c) The $\bar{\Lambda}_c D^0$ and $D^0 p$ invariant mass distributions, respectively.

spectra, which should correspond to $\Lambda_c(2910)$ rather than $\Lambda_c(2940)$.

IV. SUMMARY

The observed masses of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are close to the threshold of D^*N , and the mass splitting of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ is similar to the pentaquark candidates $P_c(4440)$ and $P_c(4457)$. These particular properties suggest that both $\Lambda_c(2910)$ and $\Lambda_c(2940)$ are good candidates of the D^*N pentaquark molecular states with different J^P quantum numbers. In addition to the decay behaviors, the production studies of $\Lambda_c(2910)$ and $\Lambda_c(2940)$ also provide useful information for the inner structures of these two Λ_c states. Experimentally, the PANDA Collaboration proposed to search for the charmed baryons in the $p\bar{p}$ scattering process with $P_{\bar{p}} = [1.5, 15]$ GeV. Therefore, we propose to investigate the $\Lambda_c(2910)$ and $\Lambda_c(2940)$ productions in the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process in the present work.

For the individual contributions, our results show that the cross section of $\Lambda_c(2910)$ is about 2 nb at $\sqrt{s} = 10$ GeV, which is about 250 times and 15 times that from $\Lambda_c(2286)$ and $\Lambda_c(2940)$, respectively. Moreover, our estimations indicate that the cross section resulted from the light-meson intermediate process plays a significant role, which enhances the total cross section by more than 1 order of magnitude. In particular, the total cross sections for $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ are estimated to be $(130.7^{+397.1}_{-103.9})$ nb at $\sqrt{s} = 10$ GeV, where the central value is estimated with

the parameter $\Lambda_r = 1.1$ GeV, and the uncertainties come from the variation of Λ_r from 1.0 to 1.2 GeV.

The differential cross sections for the $p\bar{p} \rightarrow \bar{\Lambda}_c D^0 p$ process are also estimated with $\sqrt{s} = 8$ GeV in this work. For the $D^0 p$ invariant mass spectrum, the contributions from $\Lambda_c(2286)$ and the light meson play the role of the background. In addition, our estimations indicate that the dominant contributions to the structure between 2.9 and 3.0 GeV come from $\Lambda_c(2910)$, indicating that the expected structure in the $D^0 p$ invariant mass spectra should correspond to $\Lambda_c(2910)$ rather than $\Lambda_c(2940)$. It is expected that the estimations in the present work could be tested by further experimental measurements at PANDA in the future.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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- [1] S.K. Choi *et al.* (Belle Collaboration), 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] B. Aubert *et al.* (BABAR Collaboration), Observation of a broad structure in the $\pi^+ \pi^- J/\psi$ mass spectrum around 4.26 GeV/c², *Phys. Rev. Lett.* **95**, 142001 (2005).
 - [3] K. Abe *et al.* (Belle Collaboration), Observation of a new charmonium state in double charmonium production in $e^+ e^-$ annihilation at $\sqrt{s} \approx 10.6$ GeV, *Phys. Rev. Lett.* **98**, 082001 (2007).
 - [4] X.L. Wang *et al.* (Belle Collaboration), Observation of two resonant structures in $e^+ e^- \rightarrow \pi^+ \pi^- \psi(2S)$ via initial state radiation at Belle, *Phys. Rev. Lett.* **99**, 142002 (2007).
 - [5] M. Ablikim *et al.* (BESIII Collaboration), Observation of a charged charmoniumlike structure $Z_c(4020)$ and search for the $Z_c(3900)$ in $e^+ e^- \rightarrow \pi^+ \pi^- h_c$, *Phys. Rev. Lett.* **111**, 242001 (2013).
 - [6] M. Ablikim *et al.* (BESIII Collaboration), Observation of a charged $(D\bar{D}^*)^\pm$ mass peak in $e^+ e^- \rightarrow \pi D\bar{D}^*$ at $\sqrt{s} = 4.26$ GeV, *Phys. Rev. Lett.* **112**, 022001 (2014).
 - [7] R. Aaij *et al.* (LHCb Collaboration), 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] K. Chilikin *et al.* (Belle Collaboration), Observation of an alternative $\chi_{c0}(2P)$ candidate in $e^+ e^- \rightarrow J/\psi D\bar{D}$, *Phys. Rev. D* **95**, 112003 (2017).
 - [9] R. Aaij *et al.* (LHCb Collaboration), First observation of excited Ω_b^- states, *Phys. Rev. Lett.* **124**, 082002 (2020).
 - [10] R. Aaij *et al.* (LHCb Collaboration), Observation of an exotic narrow doubly charmed tetraquark, *Nat. Phys.* **18**, 751 (2022).
 - [11] Y. Dong, A. Faessler, and V. E. Lyubovitskij, Description of heavy exotic resonances as molecular states using phenomenological Lagrangians, *Prog. Part. Nucl. Phys.* **94**, 282 (2017).

- [12] Y. R. Liu, H. X. Chen, W. Chen, X. Liu, and S. L. Zhu, Pentaquark and Tetraquark states, *Prog. Part. Nucl. Phys.* **107**, 237 (2019).
- [13] R. Aaij *et al.* (LHCb Collaboration), 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).
- [14] R. Aaij *et al.* (LHCb Collaboration), Model-independent evidence for $J/\psi p$ contributions to $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays, *Phys. Rev. Lett.* **117**, 082002 (2016).
- [15] R. Aaij *et al.* (LHCb Collaboration), 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).
- [16] R. Aaij *et al.* (LHCb Collaboration), 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).
- [17] R. Aaij *et al.* (LHCb Collaboration), 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).
- [18] H. X. Chen, W. Chen, and S. L. Zhu, Possible interpretations of the $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$, *Phys. Rev. D* **100**, 051501 (2019).
- [19] R. Chen, Z. F. Sun, X. Liu, and S. L. Zhu, Strong LHCb evidence supporting the existence of the hidden-charm molecular pentaquarks, *Phys. Rev. D* **100**, 011502 (2019).
- [20] F. K. Guo, H. J. Jing, U. G. Meißner, and S. Sakai, Isospin breaking decays as a diagnosis of the hadronic molecular structure of the $P_c(4457)$, *Phys. Rev. D* **99**, 091501 (2019).
- [21] M. Z. Liu, Y. W. Pan, F. Z. Peng, M. Sánchez Sánchez, L. S. Geng, A. Hosaka, and M. 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).
- [22] C. J. Xiao, Y. Huang, Y. B. Dong, L. S. Geng, and D. Y. Chen, Exploring the molecular scenario of $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$, *Phys. Rev. D* **100**, 014022 (2019).
- [23] 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).
- [24] J. R. Zhang, Exploring a $\Sigma_c \bar{D}$ state: With focus on $P_c(4312)^+$, *Eur. Phys. J. C* **79**, 1001 (2019).
- [25] Z. G. Wang and X. 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).
- [26] Y. J. Xu, C. Y. Cui, Y. L. Liu, and M. Q. Huang, Partial decay widths of $P_c(4312)$ as a $\bar{D}\Sigma_c$ molecular state, *Phys. Rev. D* **102**, 034028 (2020).
- [27] 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).
- [28] Y. H. Lin and B. S. Zou, Strong decays of the latest LHCb pentaquark candidates in hadronic molecule pictures, *Phys. Rev. D* **100**, 056005 (2019).
- [29] J. He and D. Y. Chen, Molecular states from $\Sigma_c^{(*)}\bar{D}^{(*)} - \Lambda_c \bar{D}^{(*)}$ interaction, *Eur. Phys. J. C* **79**, 887 (2019).
- [30] M. L. Du, V. Baru, F. K. Guo, C. Hanhart, U. G. Meißner, J. A. Oller, and Q. 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).
- [31] G. J. Wang, L. Y. Xiao, R. Chen, X. H. Liu, X. Liu, and S. L. Zhu, Probing hidden-charm decay properties of P_c states in a molecular scenario, *Phys. Rev. D* **102**, 036012 (2020).
- [32] H. Xu, Q. Li, C. H. Chang, and G. L. Wang, Recently observed P_c as molecular states and possible mixture of $P_c(4457)$, *Phys. Rev. D* **101**, 054037 (2020).
- [33] Y. J. Xu, Y. L. Liu, and M. Q. Huang, The magnetic moment of $P_c(4312)$ as a $\bar{D}\Sigma_c$ molecular state, *Eur. Phys. J. C* **81**, 421 (2021).
- [34] X. Z. Ling, J. X. Lu, M. Z. Liu, and L. S. Geng, $P_c(4457) \rightarrow P_c(4312)\pi/\gamma$ in the molecular picture, *Phys. Rev. D* **104**, 074022 (2021).
- [35] K. Chen, R. Chen, L. Meng, B. Wang, and S. L. Zhu, Systematics of the heavy flavor hadronic molecules, *Eur. Phys. J. C* **82**, 581 (2022).
- [36] M. L. Du, Z. H. Guo, and J. A. Oller, Insights into the nature of the $P_{cs}(4459)$, *Phys. Rev. D* **104**, 114034 (2021).
- [37] R. Chen and X. Liu, Mass behavior of hidden-charm open-strange pentaquarks inspired by the established P_c molecular states, *Phys. Rev. D* **105**, 014029 (2022).
- [38] R. 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] J. T. Zhu, L. Q. Song, and J. 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).
- [40] 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).
- [41] Q. Wu and D. Y. Chen, Production of $P_{\psi s}^\Lambda(4338)$ from Ξ_b decay, *Phys. Rev. D* **109**, 094003 (2024).
- [42] Q. Wu and D. Y. Chen, Production of P_c states from Λ_b decay, *Phys. Rev. D* **100**, 114002 (2019).
- [43] Q. Wu, D. Y. Chen, and R. Ji, Production of $P_{cs}(4459)$ from Ξ_b decay, *Chin. Phys. Lett.* **38**, 071301 (2021).
- [44] B. Aubert *et al.* (BABAR Collaboration), Observation of a charmed baryon decaying to $D^0 p$ at a mass near 2.94 GeV/c², *Phys. Rev. Lett.* **98**, 012001 (2007).
- [45] K. Abe *et al.* (Belle Collaboration), Experimental constraints on the possible J^P quantum numbers of the $\Lambda_c(2880)^+$, *Phys. Rev. Lett.* **98**, 262001 (2007).
- [46] Y. B. Li *et al.* (Belle Collaboration), Evidence of a new excited charmed baryon decaying to $\Sigma_c(2455)^{0,++}\pi^\pm$, *Phys. Rev. Lett.* **130**, 031901 (2023).
- [47] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [48] J. R. Zhang, S -wave $D^{(*)}N$ molecular states: $\Sigma_c(2800)$ and $\Lambda_c(2940)^{+?}$, *Phys. Rev. D* **89**, 096006 (2014).
- [49] Q. Xin, X. S. Yang, and Z. G. Wang, The singly charmed pentaquark molecular states via the QCD sum rules, *Int. J. Mod. Phys. A* **38**, 2350123 (2023).
- [50] Y. Yan, X. Hu, Y. Wu, H. Huang, J. Ping, and Y. Yang, Pentaquark interpretation of Λ_c states in the quark model, *Eur. Phys. J. C* **83**, 524 (2023).
- [51] Y. Dong, A. Faessler, T. Gutsche, and V. E. Lyubovitskij, Strong two-body decays of the $\Lambda_c(2940)^+$ in a hadronic molecule picture, *Phys. Rev. D* **81**, 014006 (2010).
- [52] Y. Dong, A. Faessler, T. Gutsche, S. Kumano, and V. E. Lyubovitskij, Radiative decay of $\Lambda_c(2940)^+$ in a hadronic molecule picture, *Phys. Rev. D* **82**, 034035 (2010).

- [53] Y. Dong, A. Faessler, T. Gutsche, S. Kumano, and V.E. Lyubovitskij, Strong three-body decays of $\Lambda_c(2940)^+$, *Phys. Rev. D* **83**, 094005 (2011).
- [54] Z. L. Yue, Q. Y. Guo, and D. Y. Chen, Strong decays of the $\Lambda_c(2910)$ and $\Lambda_c(2940)$ in the ND^* molecular frame, *Phys. Rev. D* **109**, 094049 (2024).
- [55] C. W. Shen, Y. H. Lin, and H. J. Jing, Towards the LHCb pentaquark modes in the single-charm sector, *arXiv:2511.15649*.
- [56] X. Y. Wang, A. Guskov, and X. R. Chen, $\Lambda_c^*(2940)^+$ photoproduction off the neutron, *Phys. Rev. D* **92**, 094032 (2015).
- [57] J. J. Xie, Y. B. Dong, and X. 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).
- [58] Q. Y. Guo and D. Y. Chen, $\Lambda_c(2910)$ and $\Lambda_c(2940)$ productions in $\pi^- p$ scattering process, *Phys. Rev. D* **111**, 114011 (2025).
- [59] M. F. M. Lutz *et al.* (PANDA Collaboration), Physics performance report for PANDA: Strong interaction studies with antiprotons, *arXiv:0903.3905*.
- [60] G. Janssen, K. Holinde, and J. Speth, $\pi\rho$ correlations in the NN potential, *Phys. Rev. C* **54**, 2218 (1996).
- [61] F. Q. Wu and B. S. Zou, Role of t -channel meson exchange in S -wave πN and KN scattering, *Chin. Phys. C* **32**, 629 (2008).
- [62] F. Huang, M. Doring, H. Haberzettl, J. Haidenbauer, C. Hanhart, S. Krewald, U. G. Meissner, and K. Nakayama, Pion photoproduction in a dynamical coupled-channels model, *Phys. Rev. C* **85**, 054003 (2012).
- [63] Y. Chen and J. He, Study of Λp and $\bar{\Lambda} p$ pscatterings via quasipotential Bethe-Salpeter equation, *Phys. Lett. B* **871**, 140004 (2025).
- [64] Y. Dong, A. Faessler, T. Gutsche, and V. E. Lyubovitskij, Role of the hadron molecule $\Lambda_c(2940)$ in the $p\bar{p} \rightarrow pD^0\bar{\Lambda}_c(2286)$ annihilation reaction, *Phys. Rev. D* **90**, 094001 (2014).
- [65] D. Y. Chen and X. Liu, Predicted charged charmonium-like structures in the hidden-charm dipion decay of higher charmonia, *Phys. Rev. D* **84**, 034032 (2011).
- [66] S. Okubo, SU(4), SU(8) mass formulas and weak interactions, *Phys. Rev. D* **11**, 3261 (1975).
- [67] B. C. Jackson, Y. Oh, H. Haberzettl, and K. Nakayama, $\bar{K} + N \rightarrow K + \Xi$ reaction and $S = -1$ hyperon resonances, *Phys. Rev. C* **91**, 065208 (2015).
- [68] R. Machleidt, K. Holinde, and C. Elster, The Bonn meson exchange model for the nucleon–nucleon interaction, *Phys. Rep.* **149**, 1 (1987).
- [69] C. Schutz, J. Haidenbauer, J. Speth, and J. W. Durso, Extended coupled channels model for πN scattering and the structure of $N^*(1440)$ and $N^*(1535)$, *Phys. Rev. C* **57**, 1464 (1998).
- [70] S. Janssen, J. Ryckebusch, D. Debruyne, and T. Van Cauteren, Kaon photoproduction: Background contributions, form factors and missing resonances, *Phys. Rev. C* **65**, 015201 (2002).
- [71] V. Shklyar, H. Lenske, and U. Mosel, A coupled-channel analysis of $K\Lambda$ production in the nucleon resonance region, *Phys. Rev. C* **72**, 015210 (2005).
- [72] J. J. Xie and B. C. Liu, Role of the $N^*(2080)$ in $pp \rightarrow pK^+\Lambda(1520)$ and $\pi^- p \rightarrow K^0\Lambda(1520)$ reactions, *Phys. Rev. C* **87**, 045210 (2013).
- [73] 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).
- [74] S. Weinberg, Evidence that the deuteron is not an elementary particle, *Phys. Rev.* **137**, B672 (1965).
- [75] V. Baru, J. Haidenbauer, C. Hanhart, Y. Kalashnikova, and A. E. Kudryavtsev, Evidence that the $a_0(980)$ and $f_0(980)$ are not elementary particles, *Phys. Lett. B* **586**, 53 (2004).
- [76] Y. H. Lin, C. W. Shen, F. K. Guo, and B. S. Zou, Decay behaviors of the P_c hadronic molecules, *Phys. Rev. D* **95**, 114017 (2017).