Role of the $\Lambda_c^+(2940)$ in the $\pi^- p \to D^- D^0 p$ reaction close to threshold

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We report on a theoretical study of the $\pi^- p \to D^- D^0 p$ reaction near threshold within an effective Lagrangian approach. The production process is described by t-channel D^{*0} meson exchange, s-channel nucleon pole, and u-channel Σ_c^{++} exchange. In our work, the final $D^0 p$ results from the ground $\Lambda_c^+(2286)$ state and also dominantly from the excited $\Lambda_c^+(2940)$ state which is assumed as a $D^{*0} p$ molecular state with spin parity $J^P = \frac{1}{2}^+$ or $\frac{1}{2}^-$. We calculate the total cross section of the $\pi^- p \to D^- D^0 p$ reaction. It is shown that the spin-parity assignment of $\frac{1}{2}^-$ for $\Lambda_c^+(2940)$ gives a sizable enhancement for the total cross section in comparison with a choice of $J^p = \frac{1}{2}^+$. However, our theoretical result of the total cross section is sensitive to the value of the cutoff parameter involved in the form factor of the exchanged off-shell particles. Moreover, we also calculate the second order differential cross section and find it can be used to determine the parity of the $\Lambda_c^+(2940)$. It is expected that our model calculations can be tested by future experiments at J-PARC in Japan.

I. INTRODUCTION

The charmed baryon $\Lambda_c^+(2940)$ was first observed by *BABAR* Collaboration [1] and later confirmed by the Belle Collaboration [2] in 2007. Since its mass ($M_{\Lambda_c^+(2940)} = 2939.3^{+1.4}_{-1.5}$ MeV) is close to the threshold of $D^{*0} p$ (2945.2 MeV), and its width is rather narrow ($\Gamma_{\Lambda_c^+(2940)} = 17.5 \pm 5.2 \pm 5.9$ MeV [1]) the $\Lambda_c^+(2940)$ is explained as a $D^{*0} p$ hadronic molecular state [3]. It was first found that the molecular structure of the $\Lambda_c^+(2940)$ can explain the experimental data and that if the $\Lambda_c^+(2940)$ is a $D^{*0} p$ molecular state it is likely a spin-parity $J^P = \frac{1}{2}^-$ state [3]. In Ref. [4], it was pointed out that the $D^* N$ systems may behave as $J^P = \frac{1}{2}^\pm$ and $\frac{3}{2}^\pm$ baryon states with a systematical study of the interaction between D^* and the nucleon. On the other hand, the strong two-body decays of the $\Lambda_c^+(2940)$ have been calculated within the hadronic molecular approach in Ref. [5] and it was concluded that the $J^P = \frac{1}{2}^+$ assignment for $\Lambda_c^+(2940)$ is favored. This *ansatz* for the $\Lambda_c^+(2940)$ has been proved to be also reasonable for the observed three-body decay modes and radiative decays [6,7].

Theoretical studies on the production of the $\Lambda_c^+(2940)$ in the annihilation process $p\bar{p} \to p D^0 \bar{\Lambda}_c(2286)$ have been carried out in Refs. [8,9], where the total and differential cross sections of the $p\bar{p} \to p D^0 \bar{\Lambda}_c(2286)$ reaction were studied. In Ref. [8], different assignments ($J^P = \frac{1}{2}^\pm$, $J^P = \frac{3}{2}^\pm$, and $J^P = \frac{5}{2}^\pm$) for the $\Lambda_c^+(2940)$ were employed and the first calculations for the production rates of $\Lambda_c^+(2940)$ in the $p\bar{p} \to p D^0 \bar{\Lambda}_c(2286)$ and of $p\bar{p} \to \Sigma_c^{0,++} \pi^{+,-} \bar{\Lambda}_c(2286)$ processes were performed, however, the initial state interaction (ISI) and the contribution of D^* meson exchange are not included. While in Ref. [9], the $\Lambda_c^+(2940)$ was treated as a $J^P = \frac{1}{2}^+$ or as a $\frac{1}{2}^-$ molecular $D^{*0} p$ state, meanwhile, the ISI as well as the D and D^* mesons exchange are included. Those predictions of Refs. [8,9] could be tested by future experiments at $\bar{P}$ANDA.

In the present work, we try to study this charmed baryon in the pion-induced reaction related to the experiments at J-PARC where the expected pion energy will reach over 20 GeV in the laboratory frame [10], and therefore, it is sufficient to reproduce this charmed baryon at J-PARC. It is expected that the J-PARC in Japan is one of efficient facilities to study this charmed baryon. Based on the previous work of Ref. [9], and within the assumption that the $\Lambda_c^+(2940)$ is a $D^* p$ hadronic molecular state, we investigate the role of $\Lambda_c^+(2940)$ and $\Lambda_c^+(2286)$ in the $\pi^- p \to D^- D^0 p$ reaction with the energy closed to threshold and with a framework of an effective Lagrangian approach. Initial interaction between incoming π^- and proton is modeled by an effective Lagrangian which is based on the exchange of the D^{*0} meson. The $D^0 p$ production proceeds via the $\Lambda_c^+(2286)$ and $\Lambda_c^+(2940)$ intermediate states. The total and differential cross sections
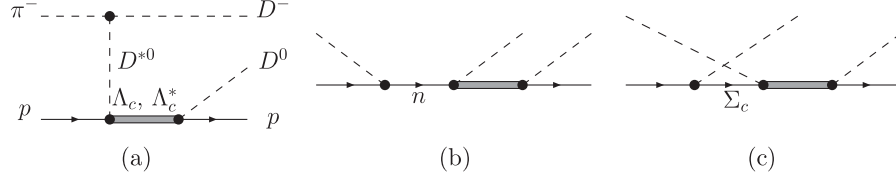
FIG. 1. Feynman diagrams for the $\pi^- p \to D^- D^0 p$ reaction. The contributions from t channel D^{*0} exchange (a), s channel nucleon pole (b), and u channel Σ_c^{++} exchange (c) are considered.

of the $\pi^- p \to D^- D^0 p$ reaction are calculated with different assignments $J^P = \frac{1}{2}^+$ and $\frac{1}{2}^-$ for the $\Lambda_c^+(2940)$ resonance for a comparison.

This paper is organized as follows. In Sec. II, we will present the formalism and ingredients necessary for our calculations. Then numerical results for the total and differential cross sections of the $\pi^- p \to D^- D^0 p$ reaction and discussions are given in Sec. III. A short summary is given in the last section.

II. FORMALISM AND INGREDIENTS

We study the $\pi^- p \to D^- D^0 p$ reaction within an effective Lagrangian approach, which has been extensively applied to the study of scattering processes [11–23] for the production of light baryon states. The basic tree level Feynman diagrams for the $\pi^- p \to D^- D^0 p$ reaction are depicted in Fig. 1. It is assumed that the $D^0 p$ final states are produced by the decay of the intermediate $\Lambda_c^+(2286)$ ($\equiv \Lambda_c$) and $\Lambda_c^+(2940)$ ($\equiv \Lambda_c^*$) states as the result of the D^{*0} meson exchanges [Fig. 1(a)]. Moreover, the contributions including the s-channel nucleon pole [Fig. 1(b)], and u-channel Σ_c^{++} [Fig. 1(c)] are also considered.

To compute the amplitudes of these diagrams shown in Fig. 1, the effective Lagrangian densities for the relevant interaction vertexes are needed. We use the commonly employed Lagrangian densities for $D^* D \pi$, πNN, $DN\Sigma_c$, $\Lambda_c p D$, $\Lambda_c p D^*$, and $\Lambda_c \pi \Sigma_c$ as follows [6,7,9,24–26]:

$$\mathcal{L}_{D^* D \pi} = g_{D^* D \pi} D_\mu^* \vec{\tau} \cdot (D \partial^\mu \vec{\pi} - \partial^\mu D \vec{\pi}), \tag{1}$$

$$\mathcal{L}_{\pi NN} = -i g_{\pi NN} \bar{N} \gamma_5 \vec{\tau} \cdot \vec{\pi} N, \tag{2}$$

$$\mathcal{L}_{DN\Sigma_c} = -i g_{DN\Sigma_c} \bar{N} \gamma_5 D \Sigma_c + \text{H.c.}, \tag{3}$$

$$\mathcal{L}_{\Lambda_c p D} = i g_{\Lambda_c p D} \bar{\Lambda}_c \gamma_5 p D^0 + \text{H.c.}, \tag{4}$$

$$\mathcal{L}_{\Lambda_c p D^*} = g_{\Lambda_c p D^*} \bar{\Lambda}_c \gamma^\mu p D_\mu^{*0} + \text{H.c.}, \tag{5}$$

$$\mathcal{L}_{\Lambda_c \pi \Sigma_c} = i g_{\Lambda_c \pi \Sigma_c} \bar{\Lambda}_c \gamma_5 \vec{\pi} \cdot \vec{\Sigma}_c + \text{H.c.} \tag{6}$$

The coupling constants $g_{DN\Sigma_c} = -2.69$, $g_{\Lambda_c p D} = -13.98$, $g_{\Lambda_c p D^*} = -5.20$, and $g_{\Lambda_c \pi \Sigma_c} = 9.32$ are determined from $SU(4)$ invariant Lagrangians [6,26,27] in terms of $g_{\pi NN} = 13.45$ and $g_{\rho NN} = 6$. Besides, the coupling constant $g_{D^* D \pi}$ can be evaluated from the partial decay width of $D^* \to D\pi$,

$$\Gamma[D^{*0} \to D^0 \pi^0] = \frac{g_{D^* D \pi}^2}{24\pi} \frac{|\vec{p}_\pi|^3}{M_{D^{*0}}^2}, \tag{7}$$

with $\vec{p}_\pi$ the three-momentum of π^0 in the D^{*0} rest frame. Unfortunately, only an upper bound for this decay rate is known at present [28]. Here, we take $\Gamma_{D^{*0}}$ as the same as the total decay width of D^{*+}, which is $\Gamma_{D^{*0}} = \Gamma_{D^{*+}} = 83.4$ keV [28]. With a value of 0.62 (different from 2/3 due to the breaking of isospin symmetry) for the $D^{*0} \to D^0 \pi^0$ branching ratio, we get $g_{D^* D \pi} = 14.1$.[1]

For the $\Lambda_c^+(2940) pD$ and $\Lambda_c^+(2940) pD^*$ couplings, we take the interaction Lagrangian densities as used in Ref. [9],

$$\mathcal{L}_{\Lambda_c^* p D}^{\frac{1}{2}^+} = i g_{\Lambda_c^* p D} \bar{\Lambda}_c^* \gamma_5 p D^0 + \text{H.c.}, \tag{8}$$

$$\mathcal{L}_{\Lambda_c^* p D^*}^{\frac{1}{2}^+} = g_{\Lambda_c^* p D^*} \bar{\Lambda}_c^* \gamma^\mu p D_\mu^{*0} + \text{H.c.}, \tag{9}$$

for the assignment $J^P = \frac{1}{2}^+$ for $\Lambda_c^+(2940)$, and

$$\mathcal{L}_{\Lambda_c^* p D}^{\frac{1}{2}^-} = f_{\Lambda_c^* p D} \bar{\Lambda}_c^* p D^0 + \text{H.c.}, \tag{10}$$

$$\mathcal{L}_{\Lambda_c^* p D^*}^{\frac{1}{2}^-} = -f_{\Lambda_c^* p D^*} \bar{\Lambda}_c^* \gamma_5 \gamma^\mu p D_\mu^{*0} + \text{H.c.}, \tag{11}$$

for the assignment $J^P = \frac{1}{2}^-$ for $\Lambda_c^+(2940)$.

The couplings $g_{\Lambda_c^* p D^*}$, $g_{\Lambda_c^* p D}$ and $f_{\Lambda_c^* p D^*}$, $f_{\Lambda_c^* p D}$ in the above Lagrangians have been evaluated in Refs. [5,6] using the hadronic molecular approach with $g_{\Lambda_c^* p D^*} = 6.64$, $g_{\Lambda_c^* p D} = -0.54$, $f_{\Lambda_c^* p D^*} = 3.75$, and $f_{\Lambda_c^* p D} = -0.97$. In Ref. [9], these values are also employed in the calculation of the annihilation process of $\bar{p}p \to pD^0 \bar{\Lambda}_c(2940)$.

Since the hadrons are not pointlike particles, the form factors are also needed. For the exchanged D^{*0} meson, we adopt the monopole form factor following that used in Refs. [8,9,30,31],

$$F_{D^*}(q_{ex}^2, M_{ex}) = \frac{\Lambda_{D^*}^2 - M_{D^*}^2}{\Lambda_{D^*}^2 - q_{D^*}^2}, \tag{12}$$

and for the exchanged baryons, we take the form factor employed in Refs. [32,33],

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[1]The value we obtained here is in agreement with the value 12.5 ± 1.0 that was obtained with QCD sum rules in Ref. [29].

$$F_B(q_{ex}^2, M_{ex}) = \frac{\Lambda_B^4}{\Lambda_B^4 + (q_{ex}^2 - M_{ex}^2)^2}. \quad (13)$$

Here the q_{ex} and M_{ex} are the four-momentum and the mass of the exchanged hadron, respectively. In our present calculation, we use the cutoff parameters $\Lambda = \Lambda_{D^*} = \Lambda_N = \Lambda_{\Sigma_c} = \Lambda_{\Lambda_c^*} = 3$ GeV^2 for minimizing the free parameters.

The propagator for the exchanged D^{*0} meson used in our calculation is

$$G_{D^*}^{\mu\nu}(q_{D^*}) = \frac{-i(g^{\mu\nu} - q_{D^*}^\mu q_{D^*}^\nu / M_{D^*}^2)}{q_{D^*}^2 - M_{D^*}^2}. \quad (14)$$

For the propagator of the spin-1/2 baryon, we use

$$G_{\frac{1}{2}}(q) = \frac{i(\not{q} + M)}{q^2 - M^2 + iM\Gamma}, \quad (15)$$

where q and M stand for the four-momentum and the mass of the intermediate nucleon pole, Σ_c baryon, $\Lambda_c(2286)$ state, and $\Lambda_c(2940)$ resonance, respectively. Since $q^2 < 0$ for u-channel Σ_c exchange, we take $\Gamma = 0$ for Σ_c and also for the nucleon pole and $\Lambda_c(2286)$ state, while for the $\Lambda_c(2940)$ resonance, we take $\Gamma = 17$ MeV [28].

From the above effective Lagrangian densities, the scattering amplitudes for the $\pi^- p \to D^- D^0 p$ reaction can be obtained straightforwardly. For example, the amplitudes due to the D^{*0} exchange can be written as

$$\mathcal{M}_a^{\frac{1}{2}\pm} = \frac{i g_a^{\frac{1}{2}\pm}}{(q^2 - M_{\Lambda_c'}^2 + iM_{\Lambda_c'}\Gamma_{\Lambda_c'})(t - M_{D^*}^2)}$$
$$\times \bar{u}(p_5, s_f)(\not{q} \mp M_{\Lambda_c'})\left(\not{p}_1 - \frac{p_1 \cdot k_t k_t}{M_{D^*}^2}\right)$$
$$\times \gamma_5 u(p_2, s_i), \quad (16)$$

for Fig. 1(a), and

$$\mathcal{M}_b^{\frac{1}{2}\pm} = \frac{\sqrt{2} g_b^{\frac{1}{2}\pm}}{(q^2 - M_{\Lambda_c'}^2 + iM_{\Lambda_c'}\Gamma_{\Lambda_c'})(s - m_n^2)}$$
$$\times \bar{u}(p_5, s_f)(\not{q} \mp M_{\Lambda_c'})(\not{k}_s + m_n)\gamma_5 u(p_2, s_i), \quad (17)$$

$$\mathcal{M}_c^{\frac{1}{2}\pm} = \frac{g_c^{\frac{1}{2}\pm}}{(q^2 - M_{\Lambda_c'}^2 + iM_{\Lambda_c'}\Gamma_{\Lambda_c'})(u - M_{\Sigma_c}^2)}$$
$$\times \bar{u}(p_5, s_f)(\not{q} \mp M_{\Lambda_c'})(\not{k}_u + M_{\Sigma_c})\gamma_5 u(p_2, s_i), \quad (18)$$

for Figs. 1(b) and 1(c), respectively. Here p_1, p_2, p_3, p_4, and p_5 are the four-momenta of the π^-, initial proton, D^-,

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[2] Actually, the values of the cutoff parameters can be directly related to the hadron size. Since the question of hadron size is still very open, we have to adjust those cutoff parameters to fit the related experimental data. When choosing $\Lambda = 3$ GeV, we follow the argument given in Refs. [9,31], where such a value was employed.

D^0, and final proton, respectively; s_i and s_f are the spin projections of the initial and final protons, respectively; $k_t = p_1 - p_3$, $k_s = p_1 + p_2$, and $k_u = p_2 - p_3$ are the four-momenta for the exchanged D^{*0} meson in t channel, nucleon pole in s channel, and Σ_c in u channel, respectively. In the above equations, $s = k_s^2$, $t = k_t^2$, and $u = k_u^2$ indicate the Mandelstam variables. The couplings $g_{a,b,c}^{\frac{1}{2}\pm}$ are defined as[3]

$$g_a^{\frac{1}{2}+} = g_{D^*D\pi} g_{\Lambda_c^* pD^*} g_{\Lambda_c^* pD}, \quad (19)$$

$$g_a^{\frac{1}{2}-} = g_{D^*D\pi} f_{\Lambda_c^* pD^*} f_{\Lambda_c^* pD}, \quad (20)$$

$$g_b^{\frac{1}{2}+} = -g_{\pi NN} g_{\Lambda_c^* pD}^2, \quad (21)$$

$$g_b^{\frac{1}{2}-} = g_{\pi NN} f_{\Lambda_c^* pD}^2, \quad (22)$$

$$g_c^{\frac{1}{2}+} = -g_{DN\Sigma_c} g_{\Lambda_c^* \pi \Sigma_c} g_{\Lambda_c^* pD}, \quad (23)$$

$$g_c^{\frac{1}{2}-} = -g_{DN\Sigma_c} f_{\Lambda_c^* \pi \Sigma_c} f_{\Lambda_c^* pD}. \quad (24)$$

Then the calculations of the differential and total cross sections for the $\pi^- p \to D^- D^0 p$ reaction are

$$d\sigma(\pi^- p \to D^- D^0 p)$$
$$= \frac{m_p}{2\sqrt{(p_1 \cdot p_2)^2 - m_\pi^2 m_p^2}} \sum_{s_i, s_f} |\mathcal{M}|^2$$
$$\times \frac{d^3 p_3}{2E_3} \frac{d^3 p_4}{2E_4} \frac{m_p d^3 p_5}{E_5} \delta^4(p_1 + p_2 - p_3 - p_4 - p_5), \quad (25)$$

where E_3, E_4, and E_5 stand for the energy of the D^-, D^0, and final proton, respectively.

III. NUMERICAL RESULTS AND DISCUSSIONS

In this section we show our theoretical numerical results for the total and differential cross sections of the $\pi^- p \to D^- D^0 p$ reaction near the reaction threshold.

A. Total cross sections

With the formalism and ingredients given above, the total cross section versus the beam momentum p_{π^-} for the $\pi^- p \to D^- D^0 p$ reaction is calculated by using a Monte Carlo multiparticle phase space integration program. The theoretical numerical results obtained with cutoff $\Lambda = 3$ GeV for the total cross section for $J^P = \frac{1}{2}^+$ of the $\Lambda_c^+(2940)$ are

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[3] Since the spin parity of $\Lambda_c(2286)$ is $J^P = 1/2^+$, we replace $g_i^{\frac{1}{2}+}$ ($i = a, b, c$) by g_i ($g_a = g_{D^*D\pi} g_{\Lambda_c pD^*} g_{\Lambda_c pD}$, $g_b = -g_{\pi NN} g_{\Lambda_c pD}^2$, and $g_c = -g_{DN\Sigma_c} g_{\Lambda_c \pi \Sigma_c} g_{\Lambda_c pD}$) then we can get the scattering amplitude for the case of the $\Lambda_c(2286)$ state.
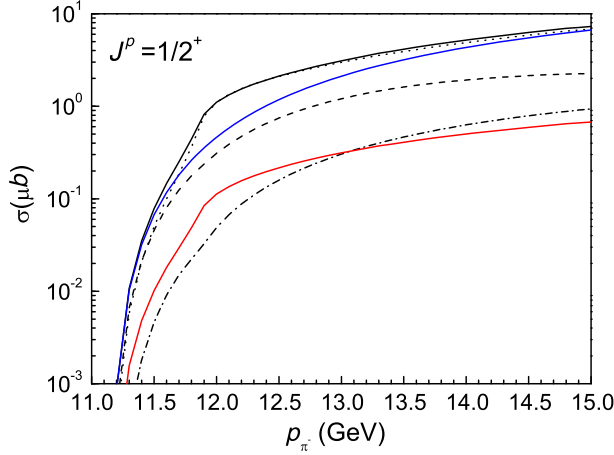
FIG. 2 (color online). Total cross sections for the $\pi^- p \to D^- D^0 p$ reaction as a function of the beam momentum p_{π^-} for $J^P = \frac{1}{2}^+$ of the $\Lambda_c^+(2940)$. The dashed, dotted, and dash-dotted curves stand for the contributions from the s channel, t channel, and u channel, respectively. Their total contribution is shown by the solid line. The blue line stands for the contributions from the ground $\Lambda_c^+(2286)$ state.

FIG. 3 (color online). As shown in Fig. 2 but for $J^P = \frac{1}{2}^-$ of the $\Lambda_c^+(2940)$.

shown in Fig. 2. The dashed, dotted, and dash-dotted curves stand for the contributions from the s channel, t channel, and u channel, respectively. Their total contribution is shown by the solid line. In Fig. 2, the blue line stands for the contributions from the ground $\Lambda_c^+(2286)$ state. One can see that the t-channel D^{*0} meson exchange plays a predominant role, while contributions from the s-channel nucleon pole and u-channel Σ_c exchange are small. The dominant D^{0*} exchange contribution can be easily understood since the $\Lambda_c^+(2940)$ resonance is assumed as a molecular state of $D^{*0} p$. In addition, the contribution from $\Lambda_c^+(2286)$ is also important especially for the very close to threshold region. Besides, there is no contributions from D meson exchange in the t channel. Hence, this reaction provides a good platform for studying the $\Lambda_c^+(2940)$ resonance with the assumption that it is a molecular $D^{*0} p$ state.

It is worth mentioning that the numerical results are sensitive to the value of the cutoff parameter Λ. To see how much it depends on the cutoff parameter, we also show by the red solid curve in Fig. 2 the theoretical result for the total contributions with $\Lambda = 2.5$ GeV for comparison. We see that the total cross section reduces by a factor of 10 when Λ decreases from 3 to 2.5 GeV.

The results for $J^P = \frac{1}{2}^-$ of the $\Lambda_c^+(2940)$ are shown in Fig. 3. We can see that the total cross sections are larger than the case of $J^P = \frac{1}{2}^+$, and the t-channel D^{*0} exchange is also predominant. In this case, the contribution from the ground $\Lambda_c^+(2286)$ state is less important than in the case of $J^P = \frac{1}{2}^+$ for $\Lambda_c^+(2940)$ resonance near the threshold region.

From Figs. 2 and 3, we see a clear sharp growing around $p_{\pi^-} = 12$ GeV which is because at that energy point, the invariant mass of the $D^0 p$ system will reach and pass by
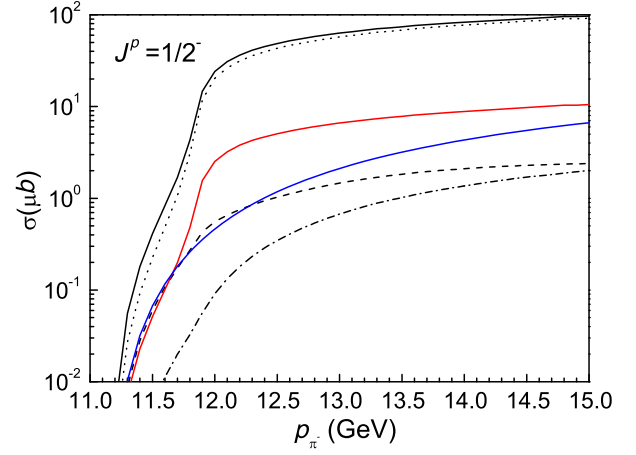
2.94 GeV[4] that is the mass of the $\Lambda_c^+(2940)$ resonance, the propagator $\frac{1}{q^2 - M^2 + iM\Gamma}$ of the $\Lambda_c^+(2940)$ resonance will give a large contribution because of its narrow total decay width. Furthermore, a change of the spin-parity assignment from $\frac{1}{2}^+$ to $\frac{1}{2}^-$ leads to an enhancement of the total cross section by a factor of more than 10, as found in Ref. [9]. However, as discussed before, our theoretical result on the total cross section of the $\pi^- p \to D^- D^0 p$ reaction is sensitive to the cutoff Λ. Thus we cannot adjust the parity of $\Lambda_c(2940)$ from the total cross section of the $\pi^- p \to D^- D^0 p$ reaction. We should study other observables to distinguish the two parity assignments.

B. Differential cross sections

In addition to the total cross section, we studied also the invariant mass and angle distributions for the $\pi^- p \to D^- D^0 p$ reaction. Unfortunately, we cannot distinguish the two spin-parity assignments from those first order differential cross sections. This is because the $D^0 p$ angular distribution is determined solely by the spin of $\Lambda_c^+(2940)$ and not its parity [34]. Furthermore, the contributions from u channel and s channel are too small to affect the mass distributions of $D^0 p$ for the two spin-parity assignments, which means the mass distributions are almost the same for the two cases. In order to see the difference between the two assignments of the $\Lambda_c(2940)$ resonance, we further move to study the second order differential cross section of the $\pi^- p \to D^- D^0 p$ process.

The second order differential cross section for the process $\pi^- p \to D^- D^0 p$ is obtained through the expression

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[4]The maximal value of the invariant mass of the $D^0 p$ system is $\sqrt{s} - m_{D^-}$ with $s = m_{\pi^-}^2 + m_p^2 + 2m_p\sqrt{p_{\pi^-}^2 + m_{\pi^-}^2}$ the invariant mass square of the $\pi^- p$ system. It is easy to get $\sqrt{s} - m_{D^-} = 2.97$ GeV with $p_{\pi^-} = 12$ GeV.
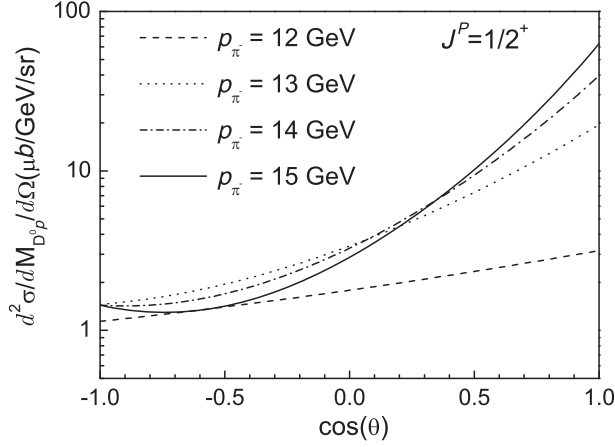
FIG. 4.   Differential cross sections for the $\pi^- p \to D^- D^0 p$ reaction as a function of the scattering angle (θ) of the outgoing D^- meson in the c.m. frame of $\pi^- p$ system for $J^P = \frac{1}{2}^+$ of the Λ_c^+(2940).

$$\frac{d^2\sigma}{dM_{D^0 p} d\Omega} = \frac{m_p^2}{2^9 \pi^5 \sqrt{s[(p_1 \cdot p_2)^2 - m_\pi^2 - m_p^2]}}$$
$$\times \int \sum_{s_i, s_f} |\mathcal{M}|^2 |\vec{p}_3| |\vec{p}_5^*| d\Omega^*, \qquad (26)$$

where $|\vec{p}_5^*|$ and Ω^* are the three-momentum and solid angle of the outing proton in the center-of-mass (c.m.) frame of the final $D^0 p$ system, while $|\vec{p}_3|$ and Ω (θ, ϕ) are the three-momentum and solid angle of the final D^- meson in the c.m. frame of the initial $\pi^- p$ system. In the above equation $M_{D^0 p}$ is the invariant mass of the final $D^0 p$ two-body system, and s is the invariant mass square of the $\pi^- p$ system.

The numerical results obtained with $\Lambda = 3$ GeV at $M_{D^0 p} = 2940$ MeV,[5] for the case of $J^P = \frac{1}{2}^+$ and $J^P = \frac{1}{2}^-$ for the Λ_c^+(2940), are shown in Figs. 4 and 5, respectively. In those figures, the dashed, dotted, dash-dotted, and solid curves stand for the results obtained at $p_{\pi^-} = 12$, 13, 14, and 15 GeV, respectively. We see that our theoretical numerical results of the differential cross sections for the two assignments are different and can be easily distinguished. Therefore, this observable can be employed, in the future experiments at J-PARC, to tell the intrinsic parity of the Λ_c(2940) resonance.

To see clearly how different the differential cross sections for the two assignments, we define the ratio R as

FIG. 5.   As shown in Fig. 4 but for $J^P = \frac{1}{2}^-$ of the Λ_c^+(2940).

$$R = \frac{\frac{d^2\sigma}{dM_{D^0 p} d\Omega}\left(J^P = \frac{1}{2}^-\right)}{\frac{d^2\sigma}{dM_{D^0 p} d\Omega}\left(J^P = \frac{1}{2}^+\right)}, \qquad (27)$$

which will be not flat vs $\cos\theta$ if the shape of the differential cross sections for the two assignments are different. Furthermore, the ratio R is not sensitive to the value of the cutoff parameter Λ. We show the numerical results for R in Fig. 6 with $\Lambda = 3$ (black curves) and 2.5 GeV (red curves). We see clearly that R is not flat as a function of $\cos\theta$, it changes dramatically. This phenomenon tells that the shapes of the second order differential cross section $\frac{d^2\sigma}{dM_{D^0 p} d\Omega}$ for the two assignments $J^P = \frac{1}{2}^\pm$ for the Λ_c^+(2940) resonance are sizably different. We hope that this feature may be used to determine the parity of the Λ_c^+(2940) resonance.

FIG. 6 (color online).   Ratio of the differential cross sections for $J^P = \frac{1}{2}^-$ and $J^P = \frac{1}{2}^+$. The black and red curves are obtained with $\Lambda = 3$ and 2.5 GeV, respectively.

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[5]At this energy point, the contribution from ground Λ_c^+(2286) state will be very small compared to the Λ_c^+(2940) resonance because of the narrow total decay width of the Λ_c^+(2940) resonance.
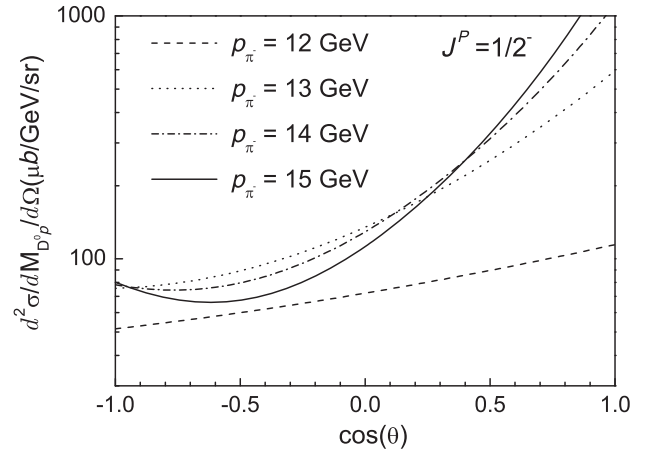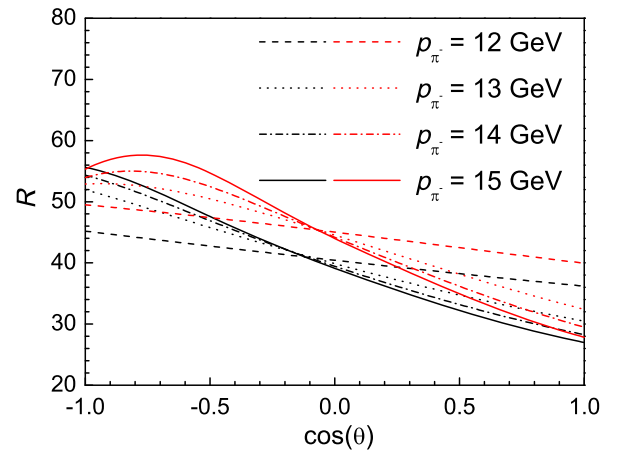
IV. SUMMARY

In this work, we have studied the $\pi^- p \to D^- D^0 p$ reaction near threshold within an effective Lagrangian approach. In addition to the s-channel nucleon pole, u-channel Σ_c exchange, the D^{*0} meson exchange in the t-channel is also investigated by the assumption that the $\Lambda_c^+(2940)$ is a molecular $D^{*0} p$ state. The total and differential cross sections are predicted. Our results show that the t-channel D^{*0} exchange is predominant, and also a change of the spin-parity assignment for the $\Lambda_c^+(2940)$ resonance from $\frac{1}{2}^+$ to $\frac{1}{2}^-$ leads to an enhancement of the total cross section by a factor of more than 10. Furthermore, it is found that the theoretical numerical results of the second order

differential cross sections, $d^2\sigma/dM_{D^0 p}/d\Omega$, of the two assignments are sizably different. This conclusion can be easily distinguished and may be tested by the future experiments at J-PARC.

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