Effects of a $N_{cc}^*$ resonance with hidden charm in the $\pi^- p \to D^- \Sigma_c^+$ reaction near threshold

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We study the effect of a hidden charm nuclear excited state $N_{cc}^*$ in the $\pi^- p \to D^- \Sigma_c^+$ reaction near threshold using an effective Lagrangian approach. We calculate the background contribution of the $t$ and $u$ channels by the $D^{*0}$ vector meson exchange and $\Sigma_c^{*+}$ intermediate state, respectively. We show that the consideration of a $N_{cc}^*$ resonance provides an enhancement of the total cross section close to the reaction threshold. We also evaluate the differential cross section for different energies and we study the angle dependence. It is expected that our model calculations will be tested in future experiments.

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I. INTRODUCTION

The study of the hidden charm sector has been a very active field lately with many studies involving interactions of meson-baryon or meson-meson\textsuperscript{14}. In particular, the $N_{cc}^*(4261)$ resonance is predicted in many models including the meson-baryon interaction\textsuperscript{8,9} or heavy quark spin symmetries\textsuperscript{10}. The role of those states in the production of charmed hadrons is a new field that requires an exhaustive study because new facilities will have enough energy to generate those particles. One example is the pion beam experiments at J-PARC where the energy of the pion is expected to be over 20 GeV\textsuperscript{11}, and therefore, it is sufficient to produce those hidden charmed baryons at J-PARC. In the near future the J-PARC in Japan will be one of the efficient facilities in which to study the predicted baryon states dynamically generated from the meson-baryon interaction with hidden charm.

The effective Lagrangian approach has been successfully used in Ref.\textsuperscript{12} where three $N^*$ resonances are included to reproduce the $\pi^- p \to K^0\Lambda$ reaction near the threshold and also in Ref.\textsuperscript{13} which is a study about the role of the $\Lambda_c^+(2940)$ state in the $\pi^- p \to D^- D^0 p$. In Refs.\textsuperscript{8,14}, it was found that the $N_{cc}^*(4261)$ couples mostly to $D\Sigma_c$, and it could be considered a $D\Sigma_c$ bound state that, however, decays into the opened channels $\eta_c N$ and $J/\psi N$. In Ref.\textsuperscript{15}, the production cross sections of the $N_{cc}^*(4261)$ resonance in the $pp \to pp\eta_c$ and $pp \to ppJ/\Psi$ reactions were estimated. In Ref.\textsuperscript{16}, the $N_{cc}^*(4261)$ resonance is considered in the $\pi^- p \to \eta_c n$ reaction, where a clear signal is expected in the total cross section of the $\pi^- p \to \eta_c n$ reaction. Huang et al.\textsuperscript{15}, studied the photo-production of this $N_{cc}^*(4261)$ resonance and they found that it is difficult to search for the $N_{cc}^*(4261)$ resonance in photo-production because of the very large background.

It has been found in previous works\textsuperscript{16,18} that states below the threshold of a process can generate bumps close to the threshold, leading to claims of resonance above the threshold of the reaction studied; hence, we expect that if the $N_{cc}^*(4261)$ state is created in the $\pi^- p$ scattering, a strong signal in the $D^- \Sigma_c^+$ production should be visible close to the reaction threshold.

In this work, we study the role of the hidden charm nuclear excited state $N_{cc}^*(4261)$ ($\equiv N_{cc}^*$) in the $\pi^- p \to D^- \Sigma_c^+$ reaction close to the threshold using the effective Lagrangian approach. In addition to the contribution from the $s$ channel hidden charm $N_{cc}^*$ resonance, the background contributions from the $t$ channel $D^{*0}$ exchange and the $u$ channel $\Sigma_c^{*+}$ exchange are also considered. We calculate the total and differential cross sections of the $\pi^- p \to D^- \Sigma_c^+$ reaction near the threshold.

This article is organized as follows. In Sec. II we present the formalism and the procedure in our calculations. We give the results and some discussion in Sec. III. Finally in Sec. IV we give some conclusions.

II. FORMALISM

We study the $\pi^- p \to D^- \Sigma_c^+$ reaction using an effective Lagrangian approach as in Ref.\textsuperscript{13} and in many other works\textsuperscript{19,22}. We want to study the effect of the

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hidden charm $N_{cc}^*(4261)$ resonance in the cross section of the $\pi^- p \rightarrow D^- \Sigma^+_c$ reaction. To see the effect of this resonance on the total cross section, we consider the background of the reaction. As shown in Fig. 4 we are going to include (a) the t-channel mediated by a $D^{*0}$ vector meson exchange and (b) the u-channel considering a $\Sigma_{cc}^+$ state as an intermediate state. We include the s-channel assuming the creation of a $N_{cc}^*$ state in the process, as shown in Fig. 4(c).

To evaluate the diagrams shown in Fig. 1 we use the effective Lagrangian densities of the interaction vertices. We use the Lagrangian densities of $D^* D \pi$, $N_{cc}^* \Sigma_{cc} \bar{D}$, $D N \Sigma_c$, and $\pi \Sigma_c \Sigma_c$ as follows,

$$\mathcal{L}_{D^* D \pi} = g_{D^* D \pi} (D \partial_\mu \pi - \pi \partial_\mu D),$$

$$\mathcal{L}_{\Sigma_{cc} D \Sigma_c} = g_{\Sigma_{cc} D \Sigma_c} (\Sigma_\mu \Sigma_c \bar{D} + h.c.),$$

$$\mathcal{L}_{N_{cc} \Sigma_{cc}} = -g_{N_{cc} \Sigma_{cc}} \Sigma_{cc} \bar{N} \Sigma_{cc} + h.c.,$$

$$\mathcal{L}_{\pi \Sigma_{cc}} = -i g_{\pi \Sigma_{cc}} \Sigma_{cc} \bar{D} \Sigma_c + h.c.,$$

From Ref. [9] we have a prediction for the partial decay width of the $N_{cc}^*(4261)$ resonance to the $\pi N$ channel, $\Gamma (N_{cc}^* \rightarrow \pi N) = 3.8$ MeV. We can get the coupling constant, $g_{N_{cc} \Sigma_{cc}}$, from the formula of the partial decay width of the $N_{cc}^*(4261)$ resonance to this channel,

$$\Gamma (N^* \rightarrow \pi N) = \frac{3g^2_{NN^* \Sigma_{cc}}} {4\pi} \frac {E_N + m_N |\vec{p}_N|} {M_{N^*}}.$$

where $\vec{p}_N$ being the three-momentum of final proton in the rest frame of the $N_{cc}^*(4261)$ resonance. Using the value $M_{N^*} = 4261.87$ MeV for the mass of the $N_{cc}^*(4261)$ resonance, we get a coupling of $g_{N_{cc} \Sigma_{cc}} = 0.1$. In Ref. [10] there is a calculation for the coupling of the $N_{cc}^*(4261)$ resonance to the $D \Sigma_c$ being $g_{N_{cc} \Sigma_{cc}} = 2.13$. In the case of $g_{D^* D \pi}$, as done in Ref. [11], we assume the same partial decay width as for $D^{*0} \rightarrow D^0 \pi^0$, with a coupling of $g_{D^* D \pi} = 14.1$.

Furthermore, the coupling constants $g_{\Sigma_{cc} N D^{*0}} = -7.8$, $g_{D N \Sigma_c} = 2.69$, and $g_{\Sigma_{cc} \Sigma_c} = 10.76$ are determined from the SU(4) invariant Lagrangians and SU(3) flavor symmetry in terms of $g_{\rho N N} = 13.45$ and $g_{\rho N N} = 6$. We list in Table I also the mass and spin-parity of the other related states in our calculation.

The evaluation of the diagrams of Fig. 1 using the Lagrangian densities shown above, leads us to the following amplitudes for the $t$, $u$, and $s$ channels,

$$\mathcal{M}_t = \frac {g_{D^* D \pi} g_{\Sigma_{cc} N D^{*0}}} {q_t^2 - M_{D^{*0}}^2} \times \bar{u}_{\Sigma_c^+} (p_f) \frac {q_t \cdot p_f g_\Sigma D} {M_{D^{*0}}^2} u_p (p_i),$$

$$\mathcal{M}_u = \frac {g_{D N \Sigma_c} g_{\Sigma_{cc} \Sigma_c}} {q_u - m_{\Sigma_{cc}^+}} \times \bar{u}_{\Sigma_{cc}^+} (p_f) \frac {q_u + m_{\Sigma_{cc}^+}} {u_p (p_i)},$$

$$\mathcal{M}_s = \frac {\sqrt{2} g_{\Sigma_{cc} \Sigma_{cc}^+}} {q_s^2 - M_{\Sigma_{cc}^+}^2} \times \bar{u}_{\Sigma_{cc}^+} (p_f) \frac {q_s - M_{\Sigma_{cc}^+}} {u_p (p_i)},$$

where $p_i$ and $p_f$ are four-momenta for the initial proton and final $\Sigma_{cc}^+$, respectively. In the above equations, $\mathcal{M}_t$ corresponds to Fig. 4(a), and $\mathcal{M}_u$ and $\mathcal{M}_s$ correspond to Figs. 4(b) and 4(c), respectively. In the equations above $q_i (i = t, u)$ represents the four momentum of the particle exchanged in each of the channels. In the $t$-channel $q_t$ is the four-momentum of the $D^{*0}$ which corresponds to $q_t^2 = (p_X - p_D)^2$, equivalent to the Mandelstam variable $t$, for the $u$-channel $q_u$ is the four-momentum of the $\Sigma_{cc}^+$ being $q_u^2 = (p_X - p_D)^2$ or $u$, and for the $s$-channel $q_s$ is the four-momentum of the $N_{cc}^*$ (4261), and $q_s^2 = (p_X + p_D)^2 = s$ is the invariant mass square of the $\pi^- p$ system.

Besides, we need to add form factors for the hadrons since they are not point-like particles. In the case of the $D^{*0}$ meson, we use the form factor used in Refs. [37] [40] as follows

$$F_D (q_t^2, M_{D^*}) = \frac {A_{D^0}^2 - M_{D^0}^2} {A_{D^*}^2 - q_t^2}$$

In the case of the baryons, we use another form factor as done in Refs. [41] [42]

$$F_B (q_{ext}^2, M) = \frac {A_B^4} {A_B^4 + (q_{ext}^2 - M^2)^2}$$

where $M$ is the mass of the exchanged baryon $m_{\Sigma_{cc}}$ and $M_{N_{cc}^*}$, and $q_{ext}$ is the exchanged four-momentum of each baryon. In our study we use all the cut off parameters $\Lambda = \Lambda_D = \Lambda_{\Sigma^+} = \Lambda_{N_{cc}^*} = 2.5$ GeV to minimize the free parameters.

The differential cross section in the center of mass (c.m.) frame for the $\pi^- p \rightarrow D^- \Sigma_{cc}^+$ reaction is calculated

| State | Mass (MeV) | Spin-parity $(J^P)$ |
|-------|------------|---------------------|
| $\pi$ | 139.57     | 0$^-$               |
| $p$   | 938.27     | 1$^+$               |
| $D^-$ | 1869.61    | 0$^-$               |
| $\Sigma^+_c$ | 2452.90   | 1$^+$               |
| $D^{*0}$ | 2006.96   | 1$^-$               |
using the following equation
\[
\frac{d\sigma}{d\Omega} = \frac{d\sigma}{2\pi d\cos\theta} = \frac{m_{\Sigma_c} m_p}{32 \pi^2 s} \left| \frac{\rho_{D}}{\rho_{c,m}} \right|^2 \sum |M_{\pi^- p \rightarrow D^- \Sigma_c^+}|^2,
\]
where \(M_{\pi^- p \rightarrow D^- \Sigma_c^+} = M_t + M_u + M_s\) is the total scattering amplitude of the \(\pi^- p \rightarrow D^- \Sigma_c^+\) reaction, and \(\theta\) is the scattering angle of the outgoing \(D^-\) meson relative to the beam direction, while \(\rho_{\pi,m}\) and \(\rho_{D,m}\) are the \(\pi^-\) and \(D^-\) three momenta in the c.m. frame, which are
\[
|\rho_{\pi,m}| = \frac{\lambda^{1/2}(s, m_{\pi}^2, m_p^2)}{2\sqrt{s}}, \quad (16)
\]
\[
|\rho_{D,m}| = \frac{\lambda^{1/2}(s, m_D^2, m_{\Sigma_c^+}^2)}{2\sqrt{s}}. \quad (17)
\]
where \(\lambda\) is the K"allen function with \(\lambda(x, y, z) = (x - y - z)^2 - 4yz\).

### III. NUMERICAL RESULTS

In this section, we show our theoretical results for the total and differential cross section of the \(\pi^- p \rightarrow D^- \Sigma_c^+\) reaction near the threshold. We have evaluated the diagrams of the \(\pi^- p \rightarrow D^- \Sigma_c^+\) reaction with a \(D^{*0}\) exchange in the \(t\) channel and with \(\Sigma_c^{++}\) as an intermediate state in the \(u\) channel. Those diagrams provide us the background of the reaction where we can see the effects of the \(N_{c*}(4261)\) resonance under the threshold, then we are able to compare the effect in the cross section. In Fig. 2 we show our numerical results for the total cross section as a function of the invariant mass \(W = \sqrt{s}\) of the \(\pi^- p\) system comparing the effect of including or not the \(N_{c*}(4261)\) resonance in the total scattering amplitude.

As we can see in Fig. 2, the dotted line shows the cross section of the background including the \(t\) channel mediated by the exchange of a \(D^{*0}\) meson and the \(u\) channel where \(\Sigma_c^{++}\) is considered an intermediate state. The dashed line includes only the contribution of the \(s\) channel process with the \(N_{c*}(4261)\) resonance; we can see the important contribution of this state to the total

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FIG. 1: Diagrams considered in the \(\pi^- p \rightarrow D^- \Sigma_c^+\) reaction.

FIG. 2: Comparison of the total cross section of the \(\pi^- p \rightarrow D^- \Sigma_c^+\) reaction: (solid line) total cross section including \(N_{c*}(4261)\), (dotted line) cross section of the background (\(t\) and \(u\) channels) and (dashed line) cross section for the \(s\) channel \([N_{c*}(4261)]\) only.
cross section of the $\pi^- p \rightarrow D^- \Sigma^+_c$ reaction close to the reaction threshold where there is a clear enhancement.

In addition to the total cross section, we present in Fig. 3 the differential cross section of this reaction depending on the scattering angle $\theta$ for different energies. We show the results for $W = 4.35$ GeV (solid line) because this energy point is close to the peak in the total cross section and should be dominated by the $s$ channel $N^*_c\bar{c}(4261)$ resonance. This is what occurs but we can see in Fig. 2 a small contribution of the background at this energy point. In the case of other energy points, with $W = 4.45$ GeV (dashed line) we have a mix of the background and the $s$ channel $N^*_c\bar{c}(4261)$ resonance and we can see this effect in Fig. 3 where the dependence on the angle starts to be relevant. Finally, with $W = 4.55$ GeV (dotted line), the background almost dominates the behavior and the dependence on the angle of the differential cross section becomes more important. This phenomenon with the clear threshold enhancement of the total cross section shown in Fig. 2 shows that the contributions of the $N^*_c\bar{c}(4261)$ resonance and the background are sizably different. We hope that this feature may be used to study the $N^*_c\bar{c}(4261)$ resonance in future experiments.

IV. CONCLUSIONS

We have studied the total and differential cross sections of the $\pi^- p \rightarrow D^- \Sigma^+_c$ reaction near the threshold and the effects of the presence of a $N^*_c\bar{c}$ resonance. The background of this reaction is taken into account by the exchange of a $D^{*0}$ meson and $\Sigma^+_c$ as an intermediate state while we consider the $s$ channel mediated by the $N^*_c\bar{c}(4261)$ resonance. We use an effective Lagrangian approach to calculate the interaction vertices for the considered diagrams and where the different couplings of the Lagrangians are determined using partial decay widths or $SU(4)$ Lagrangian relations. The evaluation of the $t$ and $u$ channels provides us a background to study the effects of the consideration of the $N^*_c\bar{c}(4261)$ state. The results of the total cross section show a clear enhancement close to the reaction threshold that could be observed in future experiments with pion beams. We also evaluate the differential cross sections for different energies and we predict a small dependence on the angle close to the threshold but the dependence starts to be important as the energy increases and the background contribution becomes dominant. We hope that this study helps us to understand the results of future experiments at J-PARC.

![Differential cross section of the $\pi^- p \rightarrow D^- \Sigma^+_c$ reaction at different energies in center of mass frame: $W = 4.35$ GeV (solid line), $W = 4.45$ GeV (dashed line) and $W = 4.55$ GeV (dotted line).](image)

**FIG. 3:** Differential cross section of the $\pi^- p \rightarrow D^- \Sigma^+_c$ reaction at different energies in center of mass frame: $W = 4.35$ GeV (solid line), $W = 4.45$ GeV (dashed line) and $W = 4.55$ GeV (dotted line).

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