# Charm meson production from meson-nucleon scattering

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## Abstract

Using an effective hadronic Lagrangian with physical hadron masses and coupling constants determined either empirically or from SU(4) flavor symmetry, we study the production cross sections of charm mesons from pion and rho meson interactions with nucleons. With a cutoff parameter of 1 GeV at interaction vertices as usually used in studying the cross sections for  $J/\psi$ absorption and charm meson scattering by hadrons, we find that the cross sections for charm meson production have values of a few tenth of mb and are dominated by the *s* channel nucleon pole diagram. Relevance of these reactions to charm meson production in relativistic heavy ion collisions is discussed.

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## I. INTRODUCTION

Because of their large masses, open charm mesons are expected to be mostly produced in the initial preequilibrium stage of relativistic heavy ion collisions. They have thus been suggested as possible probes of the initial dynamics in these collisions. Previous studies have been concentrated on the production of charm quarks from the preequilibrium partonic matter [1,2]. In these studies, it has been found that charm quark production is sensitive to not only the rapidity and space correlations of initial minipations but also their energy loss in the dense partonic matter. For charm meson production from nonpartonic matter, the only study is the one [3] based on the Hadron-String Dynamics (HSD) [4] using hadronic cross sections obtained from the Quark-Gluon String Model (QGSM) [5]. Allowing scatterings between the leading quark and diquark in a baryonic string with the quark and antiquark in a mesonic string and taking their cross sections to be the same as in meson-baryon scatterings, this study shows that charm production is appreciable even with a small cross section of a few  $\mu b$  as predicted by the QGSM. The factor of two enhancement obtained in this study for charm mesons over that produced from the primary nucleon-nucleon collisions offers a possible explanation for the observed enhancement of intermediate mass dileptons seen in heavy ion collisions at SPS [6].

The QGSM model treats charm meson production from pion-nucleon scattering as a process involving the exchange of the vector charm meson Regge trajectory in t-channel. Contributions from the s and u channels are neglected. Although the u channel is expected to be small as it involves nonplanar diagrams, which are known to be negligible in the large

 $N_c$  limit, the s channel contribution may not be small because of the planarity of associated diagrams. To study the relative importance of the s, t, and u channel contributions to charm meson production in pion-nucleon scattering, we use an effective hadronic Lagrangian based on the flavor SU(4) symmetry but with empirical hadron masses. This Lagrangian has recently been used to study the cross sections for both  $J/\psi$  absorption [7–11] and charm meson scattering [12] by hadrons. We find that the magnitude of the cross section for charm meson production from pion-nucleon scattering depends sensitively on the value of the cutoff parameter at interaction vertices. Using a cutoff parameter of 1 GeV as used previously in studying  $J/\psi$  absorption and charm meson scattering, we find that the t channel process involving vector charm meson exchange indeed gives a small cross section as in QGSM and the u channel contribution is negligible. The contribution from the s channel is, however, appreciable, leading to a few tenth of mb for the production cross section of charm meson from pion-nucleon scattering. Furthermore, the model allows us to study the cross section for charm production from the interaction of nucleons with rho mesons, which are abundant in the initial stage of the hadronic matter in heavy ion collisions and also have a lower threshold for charm meson production.

This paper is organized as follows. In Section II, we introduce the effective interaction Lagrangians needed for studying charm meson production from pion-nucleon and rho-nucleon scattering. Cross sections for theses processes are then derived in Section III and evaluated in Section IV. Finally, a summary is given in Section V.

## **II. INTERACTION LAGRANGIANS**

Possible processes for charm meson production from meson-nucleon scattering are  $\pi N \to \bar{D}\Lambda_c$  and  $\rho N \to \bar{D}\Lambda_c$  as shown by the diagrams in Fig. 1. For both pion-nucleon and rho-nucleon reactions, there are t channel charm meson exchange diagrams, s channel nucleon pole diagrams, and u channel charm baryon pole diagrams. Cross sections for these processes can be evaluated using the same Lagrangian introduced in Ref. [12] for studying charm meson scattering by hadrons. This Lagrangian is based on the gauged SU(4) flavor symmetry but with empirical masses. The coupling constants are taken, if possible, from empirical information. Otherwise, the SU(4) relations are used to relate the unknown coupling constants to the known ones.

The interaction Lagrangian densities that are relevant to the present study are given as follows:

$$\mathcal{L}_{\pi NN} = -\frac{f_{\pi NN}}{m_{\pi}} \bar{N} \gamma_5 \gamma^{\mu} \vec{\tau} N \cdot \partial_{\mu} \vec{\pi}, \qquad (1)$$

$$\mathcal{L}_{\rho NN} = g_{\rho NN} \bar{N} (\gamma^{\mu} \vec{\tau} \cdot \vec{\rho}_{\mu} + \frac{\kappa_{\rho}}{2m_{N}} \sigma_{\mu\nu} \vec{\tau} \cdot \partial_{\mu} \vec{\rho}_{\nu}) N, \qquad (2)$$

$$\mathcal{L}_{\pi DD^*} = i g_{\pi DD^*} D^{*\mu} \vec{\tau} \cdot (\bar{D} \partial_\mu \vec{\pi} - \partial_\mu \bar{D} \vec{\pi}) + \text{H.c.}, \qquad (3)$$

$$\mathcal{L}_{\rho DD} = i g_{\rho DD} (D \vec{\tau} \partial_{\mu} \bar{D} - \partial_{\mu} D \vec{\tau} \bar{D}) \cdot \vec{\rho}^{\mu}, \tag{4}$$

$$\mathcal{L}_{DN\Lambda_c} = \frac{J_{DN\Lambda_c}}{m_D} (\bar{N}\gamma_5 \gamma^{\mu} \Lambda_c \partial_{\mu} D + \partial_{\mu} \bar{D} \bar{\Lambda}_c \gamma_5 \gamma^{\mu} N), \tag{5}$$

$$\mathcal{L}_{D^*N\Lambda_c} = -g_{D^*N\Lambda_c}(\bar{N}\gamma_{\mu}\Lambda_c D^{*\mu} + \bar{D}^{*\mu}\bar{\Lambda}_c\gamma_{\mu}N), \tag{6}$$



FIG. 1. Charm meson production from meson-nucleon scattering.

$$\mathcal{L}_{\pi\Sigma_c\Lambda_c} = \frac{f_{\pi\Sigma_c\Lambda_c}}{m_{\pi}} [\bar{\Lambda}_c \gamma^5 \gamma^{\mu} \mathrm{tr}(\vec{\tau} \cdot \vec{\Sigma}_c \vec{\tau} \cdot \partial_{\mu} \vec{\pi}) + \mathrm{tr}(\vec{\tau} \cdot \bar{\vec{\Sigma}}_c \vec{\tau} \cdot \partial_{\mu} \vec{\pi}) \gamma^5 \gamma^{\mu} \Lambda_c], \tag{7}$$

$$\mathcal{L}_{\rho\Sigma_c\Lambda_c} = g_{\rho\Sigma_c\Lambda_c} [\bar{\Lambda}_c \gamma^{\mu} \mathrm{tr}(\vec{\tau} \cdot \vec{\Sigma}_c \vec{\tau} \cdot \vec{\rho}_{\mu}) + \mathrm{tr}(\vec{\tau} \cdot \bar{\vec{\Sigma}_c} \vec{\tau} \cdot \vec{\rho}_{\mu}) \gamma^{\mu} \Lambda_c], \tag{8}$$

$$\mathcal{L}_{DN\Sigma_c} = \frac{f_{DN\Sigma_c}}{m_D} (\bar{N}\gamma_5 \gamma^{\mu} \vec{\tau} \cdot \vec{\Sigma_c} \partial_{\mu} \bar{D} + \vec{\tau} \cdot \bar{\vec{\Sigma_c}} \gamma_5 \gamma^{\mu} N \partial_{\mu} D).$$
(9)

In the above,  $\vec{\tau}$  are Pauli matrices for isospin, and  $\vec{\pi}$  and  $\vec{\rho}$  denote the pion and rho meson isospin triplet, respectively, while  $D = (D^0, D^+)$  and  $D^* = (D^{*0}, D^{*+})$  denote the pseudoscalar and vector charm meson doublets, respectively.

For coupling constants, we use the empirical values for  $f_{\pi NN}/m_{\pi} = 7.18 \text{ GeV}^{-1}$  [13],  $g_{\rho NN} = 3.25$ , and  $\kappa_{\rho} = 6.1$  [14]. From the recently measured width  $\Gamma_D^* \sim 96 \text{ keV}$  of  $D^*$  [15], we obtain the coupling constant  $g_{\pi DD^*} = 5.56$ , which is slightly larger than the one used in Refs. [7–11] based on a smaller width of  $D^*$ . The coupling constant  $g_{\rho DD}$  is taken to be  $g_{\rho DD} = 2.52$ , which is determined in Refs. [7,9] based on the vector meson dominance model. The values for both  $g_{\pi DD^*}$  and  $g_{\rho DD}$  are comparable to those obtained from the QCD sum rules [16,17].

Other coupling constants, which are not known empirically, are obtained using SU(4) relations [11,12], i.e.,

$$\frac{f_{DN\Lambda_c}}{m_D} = \frac{3 - 2\alpha_D}{\sqrt{3}} \frac{f_{\pi NN}}{m_\pi} \simeq \frac{f_{\pi NN}}{m_\pi} = 7.18 \text{ GeV}^{-1},$$
(10)

$$g_{D^*N\Lambda_c} = \sqrt{3}g_{\rho NN} = 5.58,$$
(11)

$$\frac{f_{\pi\Sigma_c\Lambda_c}}{m_{\pi}} = \frac{\alpha_D}{\sqrt{3}} \frac{f_{DN\Lambda_c}}{m_D} \simeq 2.66 \text{ GeV}^{-1},$$
(12)

$$\frac{f_{DN\Sigma_c}}{m_D} = (2\alpha_D - 1)\frac{f_{DN\Lambda_c}}{m_D} = 2.01 \text{ GeV}^{-1}.$$
(13)

where  $\alpha_D = D/(D+F) \simeq 0.64$  [18] with D and F being the coefficients for the usual D-type and F-type couplings.

## **III. CROSS SECTIONS**

The amplitudes for the two processes in Fig. 1 can be written as

$$\mathcal{M}_1 = \mathcal{M}_{1a} + \mathcal{M}_{1b} + \mathcal{M}_{1c},\tag{14}$$

$$\mathcal{M}_2 = (\mathcal{M}_{2a}^{\mu} + \mathcal{M}_{2b}^{\mu} + \mathcal{M}_{2c}^{\mu})\varepsilon_{\mu}, \tag{15}$$

where  $\varepsilon_{\mu}$  is the polarization vector of rho meson. The amplitudes  $\mathcal{M}_{1a}, \mathcal{M}_{1b}$  and  $\mathcal{M}_{1c}$  are for the top three diagrams in Fig. 1 and are given by

$$\mathcal{M}_{1a} = -g_{\pi DD^*} g_{D^* N\Lambda_c} (\tau^i)_{\alpha\beta} (p_1 + p_3)^{\mu} \times \frac{1}{t - m_{D^*}^2} [g_{\mu\nu} - \frac{(p_1 - p_3)_{\mu} (p_1 - p_3)_{\nu}}{m_{D^*}^2}] \times \bar{\Lambda}_c (p_4) \gamma^{\nu} N(p_2),$$
(16)

$$\mathcal{M}_{1b} = \frac{f_{\pi NN} f_{DN\lambda_c}}{m_D m_\pi} (\tau^i)_{\alpha\beta} \bar{\Lambda}_c(p_4) \not p_3 \times \frac{m_N - \not q_s}{s - m_N^2} \not p_1 N(p_2), \tag{17}$$

$$\mathcal{M}_{1c} = \frac{f_{\pi \Sigma_c \Lambda_c} f_{DN\Lambda_c}}{m_\pi m_D} (2\delta_{ij} \tau^j)_{\alpha\beta} \bar{\Lambda}_c \not p_1 \times \frac{m_{\Sigma_c} - \not q_u}{u - m_{\lambda_c}^2} \not p_3 N, \tag{18}$$

(19)

while the amplitudes  $\mathcal{M}_{2a}^{\mu}, \mathcal{M}_{2b}^{\mu}$ , and  $\mathcal{M}_{2b}^{\mu}$  are for the bottom three diagrams, and they are

$$\mathcal{M}_{2a}^{\mu} = \frac{-if_{DN\Lambda_c}g_{\rho DD}}{m_D} (\tau^i)_{\alpha\beta} (2p_3 - p_1)^{\mu} \times \bar{\Lambda}_c \gamma_5 \frac{\not{p}_1 - \not{q}_3}{t - m_D^2} N,$$
(20)

$$\mathcal{M}_{2b}^{\mu} = \frac{i f_{DN\Lambda_c} g_{\rho NN}}{m_D} (\tau^i)_{\alpha\beta} \bar{\Lambda}_c \gamma_5 \not p_3 \frac{\not q_s + m_N}{s - m_N^2} (\gamma^{\mu} + i \frac{k_{\rho}}{2m_N} \sigma^{\nu\mu} p_{1\nu}) N(p_2), \tag{21}$$

In the above,  $p_1, p_2, p_3$  and  $p_4$  denote the momenta of  $\pi(\rho)$ , N,  $\overline{D}$  and  $\Lambda_c$ , respectively;  $s = (p_1 + p_2)^2$ ,  $t = (p_1 - p_3)^2$ , and  $u = (p_1 - p_4)^2$  are the usual Mandelstam variables; and  $q_s = p_1 + p_2$  and  $q_u = p_2 - p_3$ .

The isospin- and spin-averaged differential cross sections for the two processes in Fig. 1 are then

$$\frac{d\sigma_{\pi N \to \bar{D}\Lambda_c}}{dt} = \frac{1}{768\pi s p_i^2} |\mathcal{M}_1|^2,\tag{23}$$

$$\frac{d\sigma_{\rho N \to \bar{D}\Lambda_c}}{dt} = \frac{1}{2304\pi s p_i^2} |\mathcal{M}_2|^2.$$
(24)

The squared invariant scattering amplitudes  $|\mathcal{M}_1|^2$  and  $|\mathcal{M}_2|^2$ , which include the summation over the spins and isospins of both initial and final particles, can be evaluated using the software package *FORM* [19]. In evaluating these cross sections, we have introduced form factors at the interaction vertices. For three-point vertices, i.e.,  $\pi DD^*$ ,  $\rho DD$ ,  $\rho NN$ ,  $\pi NN$ ,  $DN\Lambda_c$ ,  $D^*N\Lambda_c$ ,  $DN\Sigma_c$ , and  $\rho\Sigma_c\Lambda_c$ , they are taken to have the form [12,20]

$$f_1 = \frac{\Lambda^2}{\Lambda^2 + \mathbf{q}^2}, \qquad f_2 = \frac{\Lambda^2}{\Lambda^2 + \mathbf{p}_i^2}.$$
(25)

where  $f_1$  is for t and u channels and  $f_2$  for s channel with  $\mathbf{q}^2$  and  $\mathbf{p}_i^2$  being, respectively, the squared three momentum transfer and squared initial three momentum in the center-of-mass frame of the pion or rho meson and nucleon. In studying  $J/\psi$  absorption and charm meson scattering using the same interaction Lagrangians [8–10], values for the cutoff parameter  $\Lambda$  are usually taken to be 1 or 2 GeV. We use these values in the present study.

# $\begin{array}{c} 0.8 \\ 0.6 \\ 0.6 \\ 0.6 \\ 0.6 \\ 0.4 \\ 0.2 \\ 0.0 \\ 4 \\ 5 \\ s^{1/2} (GeV) \end{array}$

### **IV. RESULTS**

FIG. 2. Cross sections for charm meson production from meson-nucleon scattering as functions of center-of-mass energy for cutoff parameter of 1 GeV.

We first show the results obtained with a cutoff parameter  $\Lambda = 1$  GeV. In Fig. 2, the cross sections for charm meson production from meson-nucleon scattering are given as functions of center-of-mass energy. It is seen that the cross section for the reaction  $\pi N \to \bar{D}\Lambda_c$  (dotted curve) has a peak value of about 0.2 mb. Although, this value is much larger than that predicted by the QGSM model [3], it is mainly due to the *s* channel that involves a nucleon pole as shown by the dashed curve in Fig. 3, where the cross sections from individual amplitudes are shown. The contribution from the *t* channel charm vector meson exchange (solid curve) at low center-of-mass energy has a similar magnitude as found in QGSM, while the *u* channel contribution (dotted curve) is indeed negligible as assumed in Ref. [3].



FIG. 3. Contributions from t, s, and u channels to the charm meson production cross section from pion-nucleon scattering as functions of center-of-mass energies with cutoff parameter  $\Lambda = 1$ GeV.

The cross section for the reaction  $\rho N \to \overline{D}\Lambda_c$  from rho-nucleon scattering shown by the solid curve in Fig. 2 is about a factor of two larger than that from pion-nucleon scattering. The relative importance of the contributions from the *s*, *t*, and *u* channels in this case is shown in Fig. 4. Again, the dominant contribution is from *s* channel, while the *t* and *u* channel contributions are much smaller.

The magnitude of charm meson production cross sections depends strongly on the value of the cutoff parameter. If we use a larger value of  $\Lambda = 2$  GeV as suggested by the QCD sum rules [21], these cross sections are increased by an order of magnitude. On the other hand, their values are reduced by more than an order of magnitude if a smaller value of  $\Lambda = 0.5$ GeV is used. We note that to reproduce the empirical cross section for kaon production from pion-nucleon scattering, i.e.,  $\pi N \to K\Lambda$ , using the same SU(4) invariant Lagrangian at the Born approximation requires  $\Lambda \sim 0.4$  GeV. Because of the smaller sizes of charm hadrons, we expect, however, that the cutoff parameter at interaction vertices involving these particles should have a larger value than at those involving strange hadrons. Using  $\Lambda = 1$  GeV for charm meson production thus seems reasonable.

## V. SUMMARY

Using a SU(4) invariant meson-baryon effective Lagrangian, we have studied the cross section for charm meson production in pion-nucleon and rho-nucleon scattering. We find that the magnitude of these cross sections depends sensitively on the value of the cutoff parameter at interaction vertices. With a cutoff parameter of 1 GeV, the cross section for



FIG. 4. Same as Fig. 3 charm meson production cross section from rho-nucleon scattering.

 $\pi N \to \bar{D}\Lambda_c$  has a peak value of about 0.2 mb, while that for  $\rho N \to \bar{D}\Lambda_c$  is about a factor of two larger. The dominant contribution to these cross sections is from the *s* channel nucleon pole diagram. The contribution from the *t* channel charm meson exchange is less important and has a magnitude comparable to that given by the Quark-Gluon String Model. The *u* channel contribution is negligible for charm meson production from both pion-nucleon and rho-nucleon scattering. Since our cross sections for charm meson production are much larger than that given by the QGSM model, they would lead to too large an enhancement of charm meson production if used during the initial string stage of heavy ion collisions as in Ref. [3]. On the other hand, more reasonable results for charm production are expected if these cross sections are used only for collisions between mesons and baryons in the hadronic matter.

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