Production of the $D_{s0}(2317)$ and $D_{s1}(2460)$ by kaon-induced reactions on a proton target

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We investigate the possibility of studying the charmed-strange mesons $D_{s0}(2317)$ and $D_{s1}(2460)$ by kaon-induced reactions on a proton target in an effective Lagrangian approach. The production process is described by the t-channel D^0 and D^{*0} exchanges, respectively. Our theoretical approach is based on the chiral unitary theory where the $D_{s0}(2317)$ and $D_{s1}(2460)$ resonances are dynamically generated. Within the coupling constants of the $D_{s0}(2317)$ to KD and $D_{s1}(2460)$ to KD^* channels obtained from chiral unitary theory, the total and differential cross sections of the $K^-p \to \Lambda_c D_{s0}(2317)$ and $K^-p \to \Lambda_c D_{s1}(2460)$ are evaluated. The $\bar{K}p$ initial state interaction mediated by Pomeron and Reggeon exchanges, which reduces the production cross sections of the $D_{s0}(2317)$ and $D_{s1}(2460)$, is also included. If measured in future experiments, the predicted total cross sections and specific features of the angular distributions can be used to test the (molecular) nature of the $D_{s0}(2317)$ and $D_{s1}(2460)$.

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I. INTRODUCTION

In recent years, many charmed-strange mesons have been observed [1]. Among them, the $D_{s0}(2317)$ and $D_{s1}(2460)$ are two peculiar states (we abbreviate them as D_{s0}^* and D_{s1}^* hereafter) since their masses are about 160 and 70 MeV, respectively, below the quark model predicted values [2]. The charmed-strange meson D_{s0}^* was first observed by the *BABAR* Collaboration as a narrow peak in the $D_s\pi$ invariant mass distribution [3]. The state was shortly thereafter confirmed by the CLEO [4] and Belle [5,6] collaborations. Now it has been well established by the PDG [1] with quantum numbers $I(J^P) = 0(0^+)$. The D_{s1}^* was also observed in the CLEO experiment [4] in the $D_s^*\pi$ channel, and *BABAR* [7–9] also found a signal in that region. Now it has also been well established by the PDG [1] with quantum numbers $I(J^P) = 0(1^+)$. The mass and width of the D_{s0}^* and D_{s1}^* states reported by the above collaborations [3–9] are consistent with each other, i.e.,

$$\begin{aligned} D_{s0}(2317)^\pm:\ & \mathrm{M} = 2317.7 \pm 1.3\ \mathrm{MeV}, \\ & \Gamma < 3.8\ \mathrm{MeV}, \\ D_{s1}(2460)^\pm:\ & \mathrm{M} = 2459.5 \pm 0.6\ \mathrm{MeV}, \\ & \Gamma < 3.8\ \mathrm{MeV}. \end{aligned}$$

The large disagreement between the quark model expectations [2] and the experimental measurements [3–9] have made it difficult to designate these two states as conventional charmed-strange mesons. Since the masses of the D_{s0}^* and D_{s1}^* are about 40 MeV below the DK and D^*K thresholds, respectively, many studies have proposed that the D_{s0}^* and D_{s1}^* are S-wave DK and D^*K molecular states. The studies in the Bethe-Salpeter approach [10] and potential model [11] showed indeed that the D_{s0}^* could be a DK hadronic molecule. In Ref. [12], the D_{s0}^* and D_{s1}^* were considered kaonic molecules bound by strong short-range attraction. Assuming that the D_{s0}^* and D_{s1}^* are DK and D^*K molecular states, the strong and radiative decays of the D_{s0}^* and D_{s1}^* were studied by several groups [13–16]. The production of the D_{s0}^* and D_{s1}^* from the nonleptonic B decay were calculated in Ref. [17], in which the D_{s0}^* and D_{s1}^* were also considered hadronic molecules of DK and D^*K, respectively. In the chiral unitary approach [18–23], the D_{s0}^* and D_{s1}^* can be dynamically generated from the DK/D^*K and coupled channel interactions.

In addition to the interpretation of the D_{s0}^* and D_{s1}^* as DK and D^*K molecules, the possibility of assigning them as a

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conventional open charmed meson was also discussed in many different approaches, such as the relativistic quark model [24], the chiral perturbation theory [25], the quark pair-creation model [26,27], and the QCD sum rules [28–32]. On the other hand, the large-N_c expansion indicated that the D_{s0}^* could be a tetraquark meson [33]. The tetraquark interpretation was also proposed to understand the mass and decay behavior of the D_{s0}^* [34]. We note that the QCD sum rules also supported the idea that the D_{s0}^* does not seem to be a standard quark-antiquark meson [35].

The present knowledge about the D_{s0}^* and D_{s1}^* was obtained from the e^+e^- collision [3–9]. Thus, it will be helpful to understand the nature of the D_{s0}^* and D_{s1}^* if we can observe them in other production processes. High-energy kaon beams are available at OKA@U-70 [36] and SPS@CERN [37], which provide another alternative to studying D_{s0}^* and D_{s1}^*. The kaon beam at J-PARC can also be upgraded to the energy region required in charmed-strange meson productions [38]. Therefore, it is interesting to study the D_{s0}^* and D_{s1}^* productions in the $K^-p \to \Lambda_c D_{s0}^*$ and $K^-p \to \Lambda_c D_{s1}^*$ reactions. Since there exists plenty of experimental information about the Kp elastic interaction in the energy region relevant to the D_{s0}^* and D_{s1}^* production [3–9], the effect from the Kp initial state interaction (ISI) can be taken into account in order to make a more reliable prediction.

This paper is organized as follows. In Sec. II, we will present the theoretical formalism. In Sec. III, the numerical result of the kaon-induced D_{s0}^* and D_{s1}^* production on a proton target will be given, followed by discussions and conclusions in Sec. IV.

II. THEORETICAL FORMALISM

The tree level Feynman diagrams for the $K^-p \to \Lambda_c D_{s0}^*$ and $K^-p \to \Lambda_c D_{s1}^*$ reactions are depicted in Fig. 1, where the t-channel D and D^* exchanges are considered. In this work, the contributions from the s- and u-channels are ignored because the s- and u-channels, which involve the creation of an additional $c\bar{c}$ quark pair creation in the kaon-induced production, are usually strongly suppressed. Hence, the $K^-p \to \Lambda_c D_{s0}^*$ and $K^-p \to \Lambda_c D_{s1}^*$ reactions should be dominated by the Born terms through the

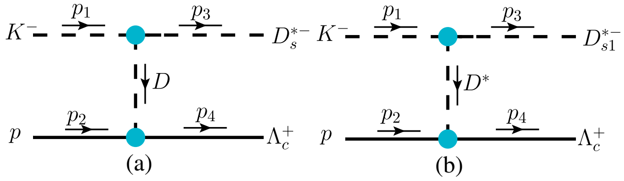

FIG. 1. Feynman diagram for the mechanism of the D_{s0}^* and D_{s1}^* production in the $K^-p \to D_{s0}^{*-}\Lambda_c$ and $K^-p \to D_{s1}^{*-}\Lambda_c$ reaction. We also show the definition of the kinematics (p_1, p_2, p_3, and $p4$) used in the calculation.

t-channel D and D^* exchanges, which makes the background very small.

A. Lagrangians

To compute the diagrams shown in Fig. 1, we need the effective Lagrangian densities for the relevant interaction vertices. For the $\Lambda_c pD$ and $\Lambda_c pD^*$ vertices, we adopt the commonly employed Lagrangian densities as follows [39]:

$$\mathcal{L}_{\Lambda_c pD} = ig_{\Lambda_c pD}\bar{\Lambda}_c\gamma_5 pD^0 + \text{H.c.}, \tag{1}$$

$$\mathcal{L}_{\Lambda_c pD^*} = g_{\Lambda_c pD^*}\bar{\Lambda}_c\gamma^\mu pD_\mu^{*0} + \text{H.c.} \tag{2}$$

The coupling constants $g_{\Lambda_c pD} = -13.98$ and $g_{\Lambda_c pD^*} = -5.20$ are determined from the SU(4) invariant Lagrangians [40] in terms of $g_{\pi NN} = 13.45$ and $g_{\rho NN} = 6.0$.

In addition to the $\Lambda_c pD$ and $\Lambda_c pD^*$ vertices, we also need the information on the KDD_s^* and $KD^*D_{s1}^*$ vertices. As mentioned in the chiral unitary approach of Refs. [18–23], the D_s^* and D_{s1}^* resonances are identified as s-wave meson-meson molecules that include big $\bar{K}D$ and $\bar{K}D^*$ components, respectively. We can write down the KDD_s^* and $KD^*D_{s1}^*$ vertices of Fig. 1 as

$$\mathcal{L}_{KDD_{s0}^*} = g_{KDD_{s0}^*}\bar{K}DD_{s0}^*, \tag{3}$$

$$\mathcal{L}_{KD^*D_{s1}^*} = g_{KD^*D_{s1}^*}\bar{K}D^{*\mu}D_{s1,\mu}^*, \tag{4}$$

where the coupling of the D_{s0}^* to D^0K^-, $g_{KDD_{s0}^*}$, is obtained from the coupling constant of the D_{s0}^* to the DK channel in isospin $I=0$, found to be $g_{KDD_s^*} = 10.21$ in Ref. [18], multiplied by the appropriate Clebsch-Gordan coefficient—namely, $g_{K^-D^0D_s^{*-}} = g_{KDD_s^*}/\sqrt{2}$. As in Ref. [18], we rely on the chiral unitary approach [19] to obtain the coupling constant $g_{K^-D^{*0}D_{s1}^{*-}} = 9.82/\sqrt{2}$.

When evaluating the scattering amplitudes of the $K^-p \to \Lambda_c D_s^*$ and $K^-p \to \Lambda_c D_{s1}^*$ reactions, we need to include form factors because hadrons are not pointlike particles. We adopt here a common scheme used in many previous works [41,42],

$$F_{D^{(*)}}(q_{D^{(*)}}^2, M_{ex}) = \frac{\Lambda_{D^*}^2 - M_{D^*}^2}{\Lambda_{D^*}^2 - q_{D^*}^2}, \tag{5}$$

for the t-channel $D^{(*)}$ meson exchange. Here the $q_{D^{(*)}}$ and $M_{D^{(*)}}$ are the four-momentum and the mass of the exchanged $D^{(*)}$ meson, respectively. In this model, the $\Lambda_{D^{(*)}}$ is the hard cutoff, and it can be directly related to the hadron size. Empirically, the cutoff parameter $\Lambda_{D^{(*)}}$ should be at least a few hundred MeV larger than the $D^{(*)}$ mass. Hence, we chose $\Lambda_{D^{(*)}} = M_{D^{(*)}} + \alpha\Lambda_{\text{QCD}}$ with $\Lambda_{\text{QCD}} = 0.22$ GeV, as used in previous works [43–45] for other reactions. The parameter α reflects the nonperturbative property of QCD

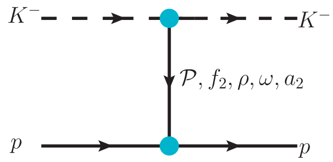

FIG. 2. Feynman diagram for the mechanism of the initial state interaction of the K^-p system.

at the low-energy scale, which will be taken as a parameter and discussed later.

B. ISI

Following Ref. [46], the initial state interaction for the $K^-p \to K^-p$ reaction at high energies will be taken into account, and the relevant Feynman diagram for the ISI is shown in Fig. 2. The amplitude $\mathcal{T}_{K^-p\to K^-p}$ is written in terms of the Pomeron and Reggeon exchanges [46]

$$\mathcal{T}_{K^-p\to K^-p} = A_{IP} + A_{f_2} + A_{a_2} + A_{\omega} + A_{\rho}. \tag{6}$$

When the center-of-mass energy $\sqrt{s}$ is large, the elastic K^-p scattering amplitude is a sum of the following terms,

$$A_i(s,t) = \eta_i s C_i^{KN} \left(\frac{s}{s_0}\right)^{\alpha_i(t)-1} \exp\left(\frac{B_{KN}^i}{2} t\right), \tag{7}$$

where $i = I\!P$ for Pomeron and f_2, a_2, ω, and ρ Reggeons. The energy scale is $s_0 = 1\ \mathrm{GeV}^2$. The coupling constants C_i^{KN}, the parameters of the Regge linear trajectories $[\alpha_i(t) = \alpha_i(0) + \alpha_i' t]$, the signature factors (η_i), and the B_{KN}^i used in Ref. [46] provide a rather good description of the experimental data. The parameters determined in Ref. [46] are listed in Table I.

III. KAON-INDUCED $D_s^*(2317)$ AND $D_{s1}^*(2460)$ PRODUCTION ON PROTON TARGET

First, we calculate the total cross section of the $K^-p \to \Lambda_c^+ D_s^{*-}$ and $K^-p \to \Lambda_c^+ D_{s1}^{*-}$ reactions. The corresponding unpolarized differential cross section reads

TABLE I. Parameters of Pomeron and Reggeon exchanges determined from elastic and total cross sections in Ref. [46].

i	η_i	$\alpha_i(t)$	C_i^{KN} (mb)	B_i^{KN} (GeV^{-2})
$I\!P$	i	$1.081 + (0.25\ \mathrm{GeV}^{-2})$t	11.82	2.5
f_2	$-0.861 + i$	$0.548 + (0.93\ \mathrm{GeV}^{-2})$t	15.67	2.0
ρ	$-1.162 - i$	$0.548 + (0.93\ \mathrm{GeV}^{-2})$t	2.05	2.0
ω	$-1.162 - i$	$0.548 + (0.93\ \mathrm{GeV}^{-2})$t	7.055	2.0
a_2	$-0.861 + i$	$0.548 + (0.93\ \mathrm{GeV}^{-2})$t	1.585	2.0

$$\frac{d\sigma}{d\cos\theta} = \frac{m_p m_{\Lambda_c}}{8\pi s} \frac{|\vec{p}_{3\mathrm{cm}}|}{|\vec{p}_{1\mathrm{cm}}|} \left(\frac{1}{2}\sum_{s_c,s_2} |\mathcal{M}^{1/2^\pm}|^2\right), \tag{8}$$

where $s = (p_1 + p_2)^2$, θ is the scattering angle of the outgoing meson relative to the beam direction, and $\vec{p}_{1\mathrm{cm}}$ and $\vec{p}_{3\mathrm{cm}}$ are the K^- and $D_s^{*-}(D_{s1}^{*-})$ three-momenta in the center-of-mass frame,

$$|\vec{p}_1| = \frac{\lambda^{1/2}(s, m_{K^-}^2, m_p^2)}{2\sqrt{s}}, \tag{9}$$

$$|\vec{p}_3| = \frac{\lambda^{1/2}(s, m_{D_{s/s1}^{-*}}^2, m_{\Lambda_c^+}^2)}{2\sqrt{s}}, \tag{10}$$

where $\lambda(x,y,z)$ is the Källen function with $\lambda(x,y,z) = (x-y-z)^2 - 4yz$. m_{K^-}, m_p, and m_{Λ_c} are the masses of the K^- meson, proton, and Λ_c, respectively. Here we take $m_{K^-} = 493.68$ MeV, $m_p = 938.27$ MeV, and $m_{\Lambda_c} = 2286.46$ MeV.

Taking the ISI of the K^-p system into account, the full amplitude for the process $K^-p \to \Lambda_c^+ D_{s0/s1}^{*-}$ is a sum of the Born and ISI amplitudes. With the Lagrangians given in the previous section, the Born amplitude of the $K^-(p_1)p(p_2) \to \Lambda_c^+(p_4) D_{s0/s1}^{*-}(p_3)$ reaction can be obtained as

$$\mathcal{M}_B^{D_{s0}^*} = -g_{\Lambda_c p D_{s0}^*} \bar{u}(p_4, s_c)\gamma_5 u(p_2, s_2) \frac{1}{(p_3 - p_1)^2 - m_D^2} \times g_{K D_{s0}^* D} F_D^2((p_3 - p_1)^2, m_D), \tag{11}$$

$$\mathcal{M}_B^{D_{s1}^*} = i g_{\Lambda_c p D_{s1}^*} \bar{u}(p_4, s_c)\gamma_\mu u(p_2, s_2) \frac{1}{(p_3 - p_1)^2 - m_{D^*}^2} \times \left(-g^{\mu\nu} + \frac{(p_3 - p_1)^\mu (p_3 - p_1)^\nu}{m_{D^*}^2}\right) \times g_{K D_{s1}^* D^*} F_D^2((p_3 - p_1)^2, m_{D^*}) \epsilon_\nu^*(p_3), \tag{12}$$

where $\bar{u}(p_4, s_c)$ and $u(p_2, s_2)$ are the Dirac spinors, with s_c (p_4) and s_2 (p_2) being the spins (the four-momenta) of the outgoing Λ_c and the initial proton, respectively. The $\epsilon_\nu^*(p_3)$ is the polarization vector of the D_{s1}^*.

Following the strategy of Ref. [46], the ISI amplitude can be written as

$$\mathcal{M}_{ISI}^{D_{s/s1}^*} = \frac{i}{16\pi^2 s} \int d^2\vec{k}_t \mathcal{T}_{K^-p\to K^-p}(s, k_t^2) \times \mathcal{M}_{D_{s/s1}^*}^{1/2^\pm}(-p_2 - k_t + p_4), \tag{13}$$

where k_t is the momentum transfer in the $K^-p \to K^-p$ reaction.

With the formalism and ingredients given above, the total cross section versus the beam momentum of the K^-p system for the $K^-p \to \Lambda_c^+ D_{s0}^{*-}$ and $K^-p \to \Lambda_c^+ D_{s1}^{*-}$

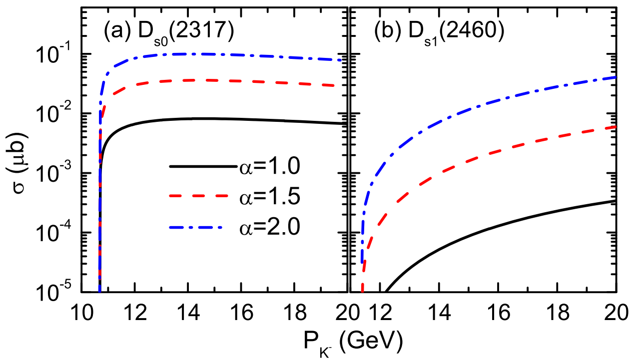

FIG. 3. The total cross section for the processes (a) $K^-p \to \Lambda_c^+ D_{s0}^{*-}$ and (b) $K^-p \to \Lambda_c^+ D_{s1}^{*-}$ with different α.

reactions can be evaluated. In Fig. 3, the total cross section of $K^-p \to \Lambda_c^+ D_{s0}^{*-}$ [Fig. 3(a)] and $K^-p \to \Lambda_c^+ D_{s1}^{*-}$ [Fig. 3(b)] reactions with different α is presented, where we restrict the α value within a reasonable range from 1.0 to 2.0. It is worth mentioning that the value of the cross section is very sensitive to the model parameter α. This is because the model parameters we selected are very close to the masses of the exchanged particles. To have a reliable prediction for the cross section for the reaction $K^-p \to \Lambda_c^+ D_s^{*-}$ and $K^-p \to \Lambda_c^+ D_{s1}^{*-}$ thus requires a good knowledge of the form factors. More accurate experimental data can also be used to constrain the value of the cutoff parameter.

Though the value of α could not be determined from first principles, it can be better determined from the experimental data. As the free parameter in our calculation, $\alpha = 1.5$ or 1.7 is fixed by fitting the experimental data of Refs. [47,48], whose procedures are just illustrated in Ref. [49]. In the following, we adopt parameter $\alpha = 1.5$ or 1.7 because this value is determined from the experimental data of Refs. [47,48] within the same D and D^* form factors adopted in the current work of Ref. [49]. The results for beam momentum P_{k^-} from the reaction threshold to 20.0 GeV are shown in Fig. 4. In the discussed cutoff range, the total cross section increases with α. Our numerical results show that the value of the cross section is not very sensitive to the model parameter α when varying the cutoff parameter α from 1.5 to 1.7.

The results in Fig. 4 also show that the total cross section increases sharply near the $D_{s0/s1}^{*-}\Lambda_c$ threshold. At higher energies, the cross section increases continuously but relatively slowly compared with that near threshold. However, the total cross section decreases, but very slowly, for the D_{s0}^* production in the $K^-p \to \Lambda_c^+ D_{s1}^{*-}$ reaction when we change the beam energy P_{K^-} from 14.6 to 20.0 GeV. Comparing the cross section of the $K^-p \to \Lambda_c^+ D_{s0}^{*-}$ reaction with that of the $K^-p \to \Lambda_c^+ D_{s1}^{*-}$ reaction, we found that the line shapes of the cross section are very different. A possible explanation for this may be that the KD interaction to form the D_{s0}^* is stronger than the KD^* interaction to form D_{s1}^* due to the fact that the D^* meson decays completely to the final state containing the D meson [1].

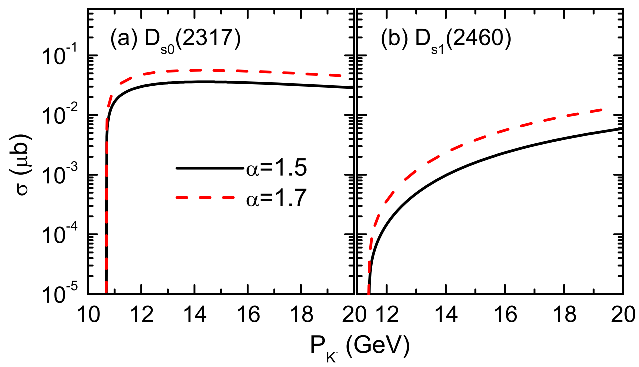

FIG. 4. Total cross section σ for (a) the $K^-p \to \Lambda_c^+ D_{s0}^{*-}$ and (b) $K^-p \to \Lambda_c^+ D_{s1}^{*-}$ reactions as a function of the beam momentum p_{K^-}.

The results show that the total cross section for D_{s0}^* production is bigger than that for D_{s1}^* production. At a beam momentum of about 14.6 GeV and a parameter $\alpha = 1.5$ ($\alpha = 1.7$), the cross section is of the order of 10 (25) nb, which is quite large for an experimentally observation of the D_{s0}^* at current and future facilities. Our results suggest that it will takes high energy, at least above 14.6 GeV, to observe the production of D_{s1}^* in the $K^-p \to \Lambda_c^+ D_{s1}^{*-}$ reaction.

To show the effect from the K^-p ISI, we compare the cross sections obtained with and without ISI for the cutoff of $\alpha = 1.7$ in Fig. 5, for the $K^-p \to \Lambda_c^+ D_{s0}^{*-}$ [Fig. 5(a)] and $K^-p \to \Lambda_c^+ D_{s1}^{*-}$ [Fig. 5(b)] reactions, respectively. In Fig. 5, the dashed red lines are the pure Born amplitude contribution, while the solid black lines are the full results. It shows that the role of the ISI is to reduce the cross section by approximately 20%, in agreement with the conclusions drawn from Refs. [39,50,51] that the ISI for pp or $p\bar{p}$ reactions reduces the cross section.

In addition to the total cross section, we also compute the differential cross section for the $K^-p \to \Lambda_c^+ D_{s0}^{*-}$ and

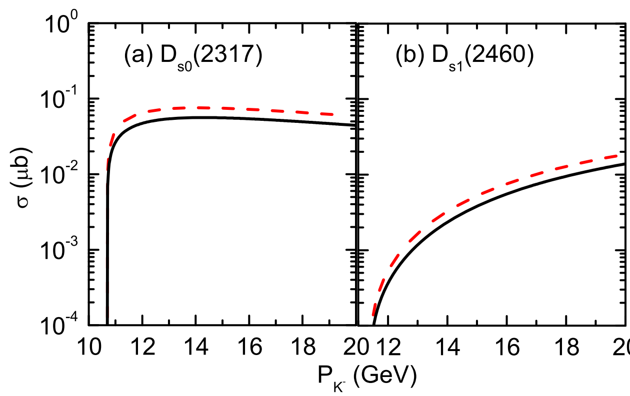

FIG. 5. Total cross section with or without ISI for the $K^-p \to D_{s0/s1}^{*-}\Lambda_c^*$ reaction as a function of the beam momentum p_{K^-} for (a) the D_{s0}^* case and (b) the D_{s1}^* case.

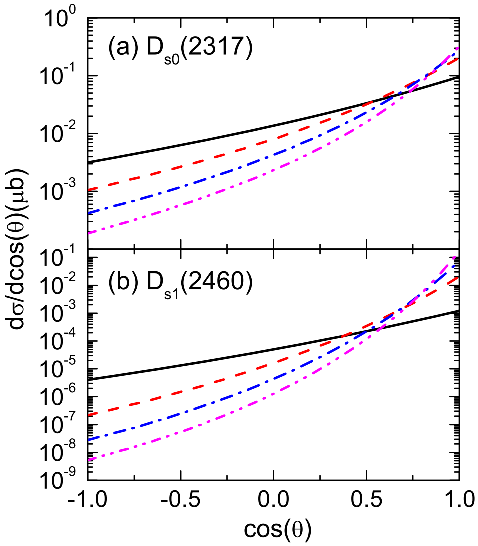

FIG. 6. (a) The $K^- p \to \Lambda_c^+ D_{s0}^{*-}$ and (b) $K^- p \to \Lambda_c^+ D_{s1}^{*-}$ differential cross sections at different energies with $\alpha = 1.7$. The black solid lines, red dashed lines, blue dashed-dotted lines, and straight dashed-dotted-dotted lines are obtained at beam energies $P_{K^-} = 12.0$, 14.0, 16.0, and 18.0 GeV, respectively.

$K^- p \to \Lambda_c^+ D_{s1}^{*-}$ reactions as a function of the scattering angle of the outgoing meson relative to the beam direction at different beam energies, i.e., $P_{K^-} = 12.0$, 14.0, 16.0, and 18.0 GeV. The theoretical results are shown in Fig. 6. We note that the differential cross section is the largest at the extreme forward angle and decreases with the increase of the scattering angle. This is because we have considered only the contributions from the t-channel D and D^* exchanges. It should be pointed out that, if there are contributions from the s- and u-channels, there will be a clear bump (or peak) in the total cross section which can be distinguished easily.

IV. SUMMARY

In this work, the production of the D_{s0}^{*-} and D_{s1}^{*-} resonances in the $K^- p \to \Lambda_c^+ D_{s0}^{*-}$ and $K^- p \to \Lambda_c^+ D_{s1}^{*-}$ reactions was studied in an effective Lagrangian approach. The production process is described by the t-channel D^0 and D^{*0} meson exchanges, respectively. The coupling constants of the D_{s0}^* to KD and D_{s1}^* to KD^* are obtained from chiral unitary theory [18,19], where the D_{s0}^{*-} and D_{s1}^{*-} resonances are dynamically generated. The $K^- p$ ISI was included by Pomeron and Reggeon exchanges [46], which was shown to reduce the cross section by about 20%. The total and differential cross sections computed can be used to test the molecular picture of the D_{s0}^* and D_{s1}^* mesons in facilities such as OKA@U-70, SPS@CERN, and the future J-PARC.

Finally, we would like to stress that, thanks to the absence of the s-channel, u-channel, and background contributions in the $K^- p \to \Lambda_c^+ D_s^{*-}$ and $K^- p \to \Lambda_c^+ D_{s1}^{*-}$ reactions, future experimental data for these two reactions can be used to improve our knowledge of D_{s0}^{*-} and D_{s1}^{*-} properties, which are at present poorly known.

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