Diffusion of Λ_c in hot hadronic medium and its impact on Λ_c/D ratio

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The drag and diffusion coefficients of the Λ_c(2286 MeV) have been evaluated in the hadronic medium which is expected to be formed in the later stages of the evolving fireball produced in heavy ion collisions at RHIC and LHC energies. The interactions between the Λ_c and the hadrons in the medium have been derived from an effective hadronic Lagrangian, as well as from the scattering lengths obtained in the framework of heavy baryon chiral perturbation theory (HBχPT). In both the approaches, the magnitude of the transport coefficients turn out to be significant. A larger value is obtained in the former approach with respect to the latter. Significant values of the coefficients indicate a substantial amount of interaction of the Λ_c with the hadronic thermal bath. Furthermore, the transport coefficients of the Λ_c are found to be different from the transport coefficients of the D meson. The present study indicates that the hadronic medium has a significant impact on the Λ_c/D ratio in heavy ion collisions.

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I. INTRODUCTION

One of the primary aims of the ongoing nuclear collision programs at the Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) energies is to create a new state of matter known as quark gluon plasma (QGP), the bulk properties of which are governed by the light quarks and gluons. Heavy quarks (HQs $\equiv$ charm and beauty) play crucial roles in understanding the properties of QGP [1], because they can witness the entire space-time evolution of the system as they are produced in the initial hard collision and remain extant during the evolution. Heavy flavor as a probe of the medium has generated significant interest in the recent past due to the suppression of its momentum distribution at large momentum in the thermal medium, denoted by $R_{AA}(p_T)$ [2–5] and its elliptic flow (v_2) [4]. Several attempts have been made to study these factors within the framework of the Fokker-Plank equation [1,6–18] and Boltzmann equation [19–22]. However, the roles of hadronic phase have been ignored in these works.

In heavy ion collision (HIC) at ultrarelativistic energies, the appearance of the hadronic phase is inevitable. To make reliable characterization of the QGP, the role of the hadronic phase should be assessed and its contribution must be subtracted out from the data. Recently the diffusion coefficients of the D and B mesons have been evaluated in the hadronic phase [23–30] and their effects on $R_{AA}(p_T)$ at large transverse momentum (p_T) [31] and elliptic flow (v_2) [32,33] have been studied and found to be significant. Apart from the heavy mesons (D and B) the heavy baryon (Λ_c) is also significant as its enhancement [34,35] due to quark coalescence would affect the $R_{AA}(p_T)$ of nonphotonic electrons. Furthermore, the baryon-to-meson ratio, (Λ_c/D), is fundamental for the understanding of in-medium hadronization [36] with respect to the light quark sector [37]. Enhancement of the heavy baryon-to-meson ratio (Λ_c/D) in Au + Au collisions compared to p + p collisions affects the nonphotonic electron spectrum (R_{AA}) [38–41]. The branching ratio for the process $\Lambda_c \to e + X(4.5\% \pm 1.7\%)$ is smaller than $D \to e + X(17.2\% \pm 1.9\%)$, resulting in fewer electrons from decays of Λ_c than D. Hence, enhancement of the Λ_c/D ratio in Au + Au collision will reduce the observed nonphotonic electrons. We notice that the p_T dependence of the Λ_c/D ratio may get modified further in the hadronic medium as the interactions of Λ_c and D with hadrons are non-negligible. Keeping this in mind, we attempt to study the transport coefficients (drag and diffusion coefficients) of Λ_c in hadronic phase.

The paper is organized as follows. In the next section we discuss the formalism used to evaluate the drag and diffusion coefficients of the heavy flavored baryon in a hot hadronic matter. Section III is devoted to presenting the results. Section IV contains summary and discussions.

II. FORMALISM

The drag and diffusion coefficients of the charmed baryon Λ_c, propagating through a hot hadronic medium have been evaluated using the scattering length obtained in Ref. [42], where Liu *et al.* have estimated next-to-next-to-leading order (NNLO) amplitudes in the framework of heavy baryon chiral perturbation theory (HBχPT). We consider the elastic interaction of Λ_c with thermal pions,

TABLE I. Table showing the extracted values of the T matrix from the scattering length, a, which were obtained by Liu et al. [42].

$\Lambda_c M$	a (fm)	T
$\Lambda_c \pi$	0.06	9.28
$\Lambda_c K$	-0.032 ± 0.038	-12.42 to 1.06
$\Lambda_c \bar{K}$	$(0.79 + 0.27\mathrm{i}) \pm 0.044$	$(72.75 + 47.9\mathrm{i})$ to $(207.6 + 47.9\mathrm{i})$
$\Lambda_c \eta$	$(0.35 + 0.19\mathrm{i}) \pm 0.044$	$(55.27 + 34.32\mathrm{i})$ to $(71.17 + 34.32\mathrm{i})$

kaons, and η mesons. The temperature of the bath can vary from $T_c(\sim 170)$ to $T_F(\sim 120$ MeV), relevant for heavy ion collisions at RHIC and LHC energies. Here T_c is the transition temperature at which the QGP formed in HIC makes a transition to hadrons and T_F is the freeze-out temperature at which the hadrons cease to interact. In this temperature range the abundance of Λ_c and D is small and their thermal production and annihilation can be ignored. Hence, in evaluating the drag and diffusion coefficients of the Λ_c only elastic processes will be considered.

For the elastic scattering of Λ_c of momentum p_1 with a thermal hadron, H of momentum p_2, i.e., for the process $\Lambda_c(p_1) + H(p_2) \to \Lambda_c(p_3) + H(p_4)$, the drag coefficient γ can be expressed as [43] (see also [44,45])

$$\gamma = p_i A_i / p^2 \tag{1}$$

where A_i takes the form

$$\begin{aligned} A_i = & \frac{1}{2E_{p_1}} \int \frac{d^3 p_2}{(2\pi)^3 E_{p_2}} \int \frac{d^3 p_3}{(2\pi)^3 E_{p_3}} \int \frac{d^3 p_4}{(2\pi)^3 E_{p_4}} \\ & \times \frac{1}{g_{\Lambda_c}} \sum \overline{|\mathcal{M}|^2} (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) \\ & \times f(p_2)\{1 \pm f(p_4)\} \equiv \langle\langle (p_1 - p_3) \rangle\rangle, \end{aligned} \tag{2}$$

where g_{Λ_c} denotes the statistical degeneracy of Λ_c, and $f(p_2)$ is the Bose-Einstein (BE) or Fermi-Dirac (FD) distribution function depending upon the spin of H in the initial channel. Similarly, the factor $1 \pm f(p_4)$ represents Bose enhanced or Pauli suppressed probability of the corresponding H in the final channel. $\overline{|\mathcal{M}|^2}$ represents the modulus square of the spin averaged matrix element for the $\Lambda_c + H$ elastic scattering process. Equation (2) illustrates that the drag coefficient is the measure of the thermal average of the momentum transfer, $p_1 - p_3$, weighted by the interaction through $\overline{|\mathcal{M}|^2}$.

Similarly the diffusion coefficient B can be expressed as

$$B = \frac{1}{4}\left[\langle\langle p_3^2 \rangle\rangle - \frac{\langle\langle (p_1 \cdot p_3)^2 \rangle\rangle}{p_1^2}\right]. \tag{3}$$

With an appropriate choice of $T(p_3)$, both the drag and diffusion coefficients can be expressed in a single equation as follows:

$$\begin{aligned} \ll T(p_1) \gg = & \frac{1}{512\pi^4} \frac{1}{E_{p_1}} \int_0^\infty \frac{p_2^2 dp_2 d(cos\chi)}{E_{p_2}} \\ & \times \hat{f}(p_2)\{1 \pm f(p_4)\} \frac{\lambda^{\frac{1}{2}}(s, m_{p_1}^2, m_{p_2}^2)}{\sqrt{s}} \\ & \times \int_1^{-1} d(cos\theta_{\mathrm{c.m.}}) \frac{1}{g} \sum \overline{|\mathcal{M}|^2} \int_0^{2\pi} d\phi_{\mathrm{c.m.}} T(p_3), \end{aligned} \tag{4}$$

where $\lambda(s, m_{p_1}^2, m_{p_2}^2) = \{s - (m_{p_1} + m_{p_2})^2\}\{s - (m_{p_1} - m_{p_2})^2\}$ is the triangular function.

The drag and diffusion coefficients of Λ_c can be evaluated in hadronic matter by using $\overline{|T|^2}$ [27] in place of $\overline{|\mathcal{M}|^2}$ in Eq. (4), where the momentum independent T-matrix elements simply estimate the strength of the Λ_c interactions with the thermal hadrons.

The scattering lengths of Λ_c with light pseudoscalar mesons $M = \pi, K, \bar{K}$, and η have recently been obtained by Liu et al. [42] in the framework of HBχPT. From the scattering lengths, a (say) of Λ_c interacting with M, we can extract the T-matrix element by using the relation

$$T = 4\pi(m_{\Lambda_c} + m_M)a, \tag{5}$$

where m_{Λ_c} and m_M are the masses of Λ_c and mesons (M), respectively. From the scattering lengths (a in fm), the extracted values of T are given in Table I.

In Ref. [42] Liu et al. have fixed the low energy constants (LECs) with the help of relations based on quark model symmetry, heavy quark spin symmetry, $SU(4)$ flavor symmetry, and some empirical relations. However, a dimensionless constant α' remains unknown, which is taken in the natural range $[-1, 1]$ [42,46]. Therefore, the table shows a band of numerical values of T matrices, which are corrected up to the third order $[\mathcal{O}(\epsilon^3)]$ with the explicit power counting in HBχPT. Using the T matrices from Table I and corresponding BE distributions for $H = M = \pi$, K, η in Eq. (4), we can get an estimate of drag and diffusion coefficients of Λ_c in hadronic matter.

Besides the scattering length approach, we have also investigated the contributions of the drag and diffusion coefficients, resulting from the Born-like scattering: $\Lambda_c \pi \to \Sigma_c \to \Lambda_c \pi$. Using the effective hadronic Lagrangian [47],

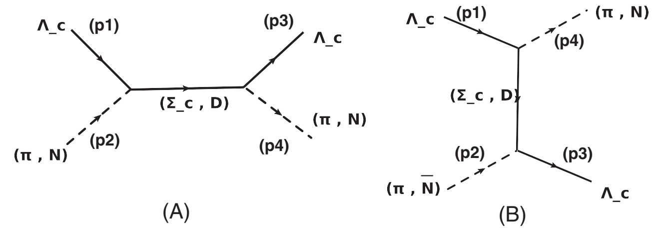

FIG. 1. Feynman diagrams for the scattering of Λ_c with the pion, nucleon, and antinucleon in the medium.

$$\mathcal{L}_{\Lambda_c\Sigma_c\pi} = \frac{g}{m_\pi}\overline{\Lambda_c}\gamma^5\gamma^\mu \mathrm{Tr}(\vec{\tau}\cdot\vec{\Sigma}_c\vec{\tau}\cdot\vec{\pi}) + \mathrm{H.c.}, \tag{6}$$

we can calculate the matrix elements for $\Lambda_c\pi$ scattering diagrams via Σ_c. The Lagrangian is based on the gauged $SU(4)$ flavor symmetry but with empirical masses. The coupling constant $g = 0.37$ is taken from Ref. [47], where $SU(4)$ relations are used to fix it.

The possible s and u channel diagrams for $\Lambda_c + \pi \to \Sigma_c \to \Lambda_c + \pi$ processes are shown in the panels (a) and (b) of Fig. 1. The matrix elements for the two channels are, respectively, given by

$$M_s^{\Lambda_c\pi} = -\left(\frac{2g}{m_\pi}\right)^2\left[\bar{u}(p_3)\gamma^5\not{p}_4\frac{(\not{p}_1+\not{p}_2+m_{\Sigma_c})}{(s-m_{\Sigma_c}^2)}\gamma^5\not{p}_2 u(p_1)\right] \tag{7}$$

and

$$M_u^{\Lambda_c\pi} = -\left(\frac{2g}{m_\pi}\right)^2\left[\bar{u}(p_3)\gamma^5\not{p}_2\frac{(\not{p}_1-\not{p}_4+m_{\Sigma_c})}{(u-m_{\Sigma_c}^2)}\gamma^5\not{p}_4 u(p_1)\right]. \tag{8}$$

Similarly from the Lagrangian density [47],

$$\mathcal{L}_{\Lambda_c ND} = \frac{f}{m_D}\bar{N}\gamma^5\gamma^\mu\Lambda_c\partial_\mu D + \partial_\mu\bar{D}\,\overline{\Lambda_c}\,\gamma^5\gamma^\mu N, \tag{9}$$

one can obtain the matrix elements for the processes $\Lambda_c N \to D \to \Lambda_c N$ and $\Lambda_c\bar{N} \to D \to \Lambda_c\bar{N}$ (see Fig. 1). The modulus square of the spin averaged total amplitudes $|\mathcal{M}|^2$ for all processes are given in the Appendix. Using those $|\mathcal{M}|^2$ from the effective hadronic model as well as the corresponding BE and FD distributions for $H = \pi$ and N in Eq. (4), we can get alternative estimates of the drag and diffusion coefficients of Λ_c in the hadronic medium. We have included form factors in each of the interaction vertices to take into account the finite size of the hadrons. For the u and s channel diagrams the form factors are taken as [47] $F_u = \Lambda^2/(\Lambda^2 + \vec{q}^2)$ and $F_s = \Lambda^2/(\Lambda^2 + \vec{p_i}^2)$, respectively, where $\vec{q}$ is the three-momentum transfer, p_i is the initial momentum of the pions, and $\Lambda = 1$ GeV.

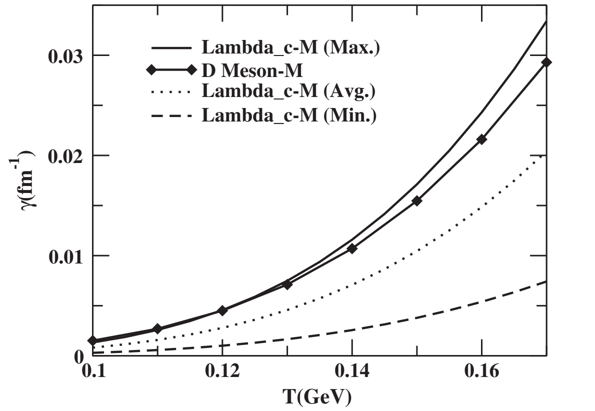

FIG. 2. Variation of the drag coefficient with temperature for the Λ_c and D meson [27] in a mesonic medium, where their interaction strengths are governed from their scattering lengths (SL) [42].

III. RESULTS AND DISCUSSION

Let us first discuss the results of the drag coefficients obtained from the T-matrix elements of $\Lambda_c M$ scattering, given in Table I. The variation of the drag coefficient of Λ_c with temperature is depicted in Fig. 2 and compared with the drag coefficient of the D mesons [27] while propagating through the same thermal medium consisting of pions, kaons, and eta. The magnitude of the drag coefficients is quite significant, indicating a substantial interaction of Λ_c with the thermal hadrons. The maximum and minimum values of the drag coefficient for Λ_c correspond to the band associated with the T-matrix element presented in Table I. The average value of the drag of Λ_c is found to be smaller than that of D.

The single electron spectrum originating from the decays of Λ_c and D measured in HIC is sensitive to the following two mechanisms: (i) the production of Λ_c in HIC is enhanced compared to that in pp because of the direct interaction of c with $[ud]$ bound states available in the QGP [34], (ii) the Λ_c has a smaller branching ratio to semileptonic decay than D. These two mechanisms lead to a deficiency of electrons at intermediate p_T $[2 < p_T\ (\mathrm{GeV}) < 5]$ [38]. If the drag of Λ_c is more (less) than D, then that will further reduce (enhance) the electrons in this domain of p_T. We find here that the value of the drag of Λ_c has a band of uncertainties as shown in Fig. 2; therefore, it is not possible to draw a conclusion regarding which way the drag of Λ_c will contribute to the electron spectra originating from the decays of charm mesons and baryons. However, measurements of D meson spectra via hadronic and semileptonic channels in the same collision conditions will help in estimating the electron spectra from Λ_c and hence its drag coefficients.

For a hadronic system of lifetime, $\Delta\tau$, and drag γ, the momentum suppression is approximately given by $R_{AA} \sim e^{-\Delta\tau\gamma}$ [24]. Picking up a value of γ of D at $T = 170$ MeV

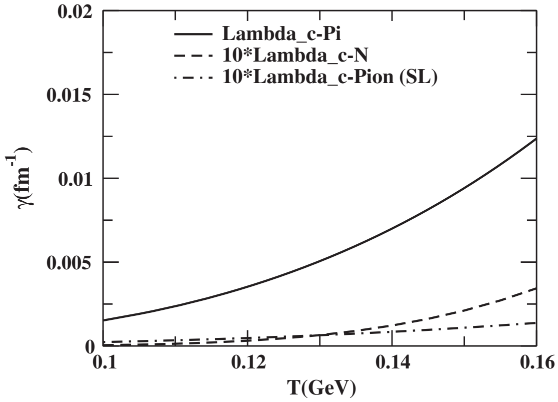

FIG. 3. Variation of the drag coefficient with temperature for Λ_c in a pionic medium, using the dynamics of effective Lagrangian (EL) and scattering length (SL). The contribution of the drag coefficient for $\Lambda_c N$ scattering in the EL dynamics is also presented.

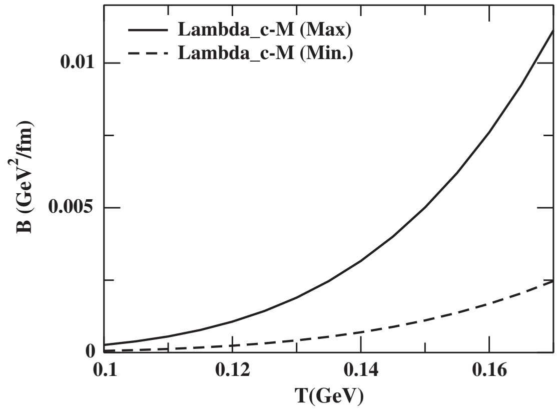

FIG. 4. Variation of the diffusion coefficient with temperature, when Λ_c interacts with all the light pseudoscalar mesons M (in SL dynamics).

from the results displayed in Fig. 2, we get $R_{AA} \sim 14\%$ for $\Delta\tau = 5$ fm/c. The values of R_{AA} for Λ_c at the same temperature and $\Delta\tau$ are about 16% and 4%, respectively, for maximum and minimum values of γ shown in Fig. 2. Similarly the Λ_c/D ratio at the same temperature and $\Delta\tau$ is approximately given by $\Lambda_c/D \sim e^{\Delta\tau(\gamma_D - \gamma_{\Lambda_c})}$, where γ_D and γ_{Λ_c} are the drag coefficients of the D meson and Λ_c, respectively. The Λ_c/D ratio can vary up to 12% depending on the minimum to maximum value of the drag coefficients of Λ_c.

The temperature variation of the drag coefficient of Λ_c in a pionic medium has been depicted in Fig. 3. Here EL corresponds to the matrix element obtained from the effective hadronic Lagrangian [47] and SL corresponds to the scattering length or the T-matrix element obtained from the HBχPT. We found that the drag of Λ_c in pionic medium for EL is much larger than that for SL.

The corresponding SL results for the momentum diffusion coefficient as a function of temperature are depicted in Fig. 4. The difference between the maximum and minimum values of both coefficients gets larger at higher temperature as displayed in Figs. 2 and 4.

The variation of the ratio of Λ_c to D is shown in Fig. 5 as a function of p_T. The Fokker-Planck (FP) equation has been used to study the time evolution of the D and Λ_c in the hadronic bath of the equilibrated degrees of freedom. This is given by [31,43]

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial p_i}\left[A_i(p)f + \frac{\partial}{\partial p_j}[B_{ij}(p)f]\right], \qquad (10)$$

where f is the momentum distribution of the nonequilibrated degrees of freedom, and $A_i(p)$ and $B_{ij}(p)$ are related to the drag and diffusion coefficients. The interaction between the probe and the thermal bath enter through the drag and diffusion coefficients. The initial distributions of the D meson and Λ_c are obtained (at the end of QGP phase) by using the fragmentation and coalescence techniques of [36] and results of [8]. Their ratio (at the end of the QGP phase) has been shown in the solid line of Fig. 5. In the present calculation of Λ_c spectra, resonances are not taken into account at variance with Ref. [35].

The ratio estimated after evolving the D [31] and Λ_c in the hadronic medium through the Fokker-Planck equation is displayed in Fig. 5. In Fig. 5 QGP refers to the ratio at the end of the QGP phase and "QGP + hadronic" refers to the ratio at the end of the hadronic phase. Maximum and minimum of the ratio correspond to the maximum and minimum values of the drag and diffusion coefficients of Λ_c. The results indicate that the ratio gets enhanced for $2 \le p_T \le 7$ due to the interactions of the D and Λ_c while propagating through the hadronic medium. Such enhancement will have interesting consequences on the nuclear suppression of the charm quarks in QGP measured through the single electron spectra originating from the decays of charmed hadrons.

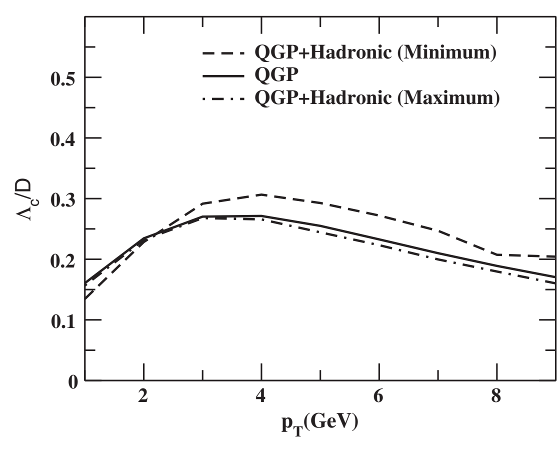

FIG. 5. Transverse momentum variation of the Λ_c to D ratio has been displayed for maximum and minimum values of the drag of Λ_c (see text).

IV. SUMMARY AND DISCUSSION

We have studied the diffusion of Λ_c in a hot hadronic medium. Using scattering amplitudes, obtained by Liu *et al.* [42] in the framework of HBχPT, we have evaluated the drag and diffusion coefficients of the Λ_c interacting with a hadronic background composed of pions, kaons, and eta. We have also calculated the drag coefficients of the Λ_c interacting with the pion and nucleon, using an effective hadronic Lagrangian. It is found that the coefficients in the pionic medium, obtained from the effective hadronic Lagrangian, are quite higher than those obtained from the dynamics of scattering length. However, the coefficients resulting from the $\Lambda_c N$ scattering obtained within an effective hadronic model approach are comparable to the coefficients estimated in the scattering length approach. The value obtained for the Λ_c has been compared with the drag coefficient of the D meson calculated within the framework of heavy meson chiral perturbation theory. It is found that the value of the drag coefficient of Λ_c is generally lower than that of D mesons. This result shows a significant effect on the p_T dependence of the Λ_c/D ratio and hence also on R_{AA} of single electrons originating from the decay of Λ_c.

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APPENDIX

The modulus square of the spin averaged total amplitude for the processes of $\Lambda_c + \pi \to \Sigma_c \to \Lambda_c + \pi$ is given by

$$\overline{|M^{\Lambda_c \pi}|^2} = \frac{3}{2}\left(\frac{2g}{m_\pi}\right)^4 \left[\frac{A_{ss}}{(s-m_{\Sigma_c}^2)^2} + \frac{A_{uu}}{(u-m_{\Sigma_c}^2)^2} + \frac{2A_{su}}{(s-m_{\Sigma_c}^2)(u-m_{\Sigma_c}^2)}\right], \tag{A1}$$

where

$$A_{ss} = [-2m_\pi^2 m_{\Lambda_c}(s-m_{\Lambda_c}^2)^2(m_{\Lambda_c}+2m_{\Sigma_c}) + m_\pi^4(s+m_{\Lambda_c}^2+2m_{\Lambda_c}m_{\Sigma_c})^2 - (s-m_{\Lambda_c}^2)^2(su-m_{\Lambda_c}^4+tm_{\Sigma_c}^2)], \tag{A2}$$

$$A_{uu} = [-2m_\pi^2 m_{\Lambda_c}(u-m_{\Lambda_c}^2)^2(m_{\Lambda_c}+2m_{\Sigma_c}) + m_\pi^4(u+m_{\Lambda_c}^2+2m_{\Lambda_c}m_{\Sigma_c})^2 - (u-m_{\Lambda_c}^2)^2(su-m_{\Lambda_c}^4+tm_{\Sigma_c}^2)], \tag{A3}$$

and

$$\begin{aligned} A_{su} = [&-4m_\pi^6 m_{\Lambda_c}^2 + (4s-2t+4u)m_{\Lambda_c}^6 - 2m_{\Lambda_c}^8 \\ &+ 2t(s^2-t^2-2su+u^2)m_{\Lambda_c}m_{\Sigma_c} + 8t^2 m_{\Lambda_c}^3 m_{\Sigma_c} \\ &+ m_{\Lambda_c}^4\{-3s^2+5t^2+2s(t-3u)+2tu-3u^2-2tm_{\Sigma_c}^2\} \\ &- (s^2-t^2+u^2)(su-tm_{\Sigma_c}^2) + m_{\Lambda_c}^2\{s^3+6t^2m_{\Sigma_c}^2 \\ &- (t-u)(t+u)^2 + s^2(t+3u) - s(t^2+4tu-3u^2)\} \\ &+ 2m_\pi^4\{su+3m_{\Lambda_c}^4 - 4tm_{\Lambda_c}m_{\Sigma_c} + 8m_{\Lambda_c}^3 m_{\Sigma_c} \\ &- 2tm_{\Sigma_c}^2 - m_{\Lambda_c}^2(t+4m_{\Sigma_c}^2)\} - 2m_\pi^2\{m_{\Lambda_c}m_{\Sigma_c}\{s^2 \\ &- 4t^2 + s(t-2u) + tu + u^2\} + 14tm_{\Lambda_c}^3 m_{\Sigma_c} \\ &+ 8m_{\Lambda_c}^4(t+m_{\Sigma_c}^2) + 2t(su-tm_{\Sigma_c}^2) + m_{\Lambda_c}^2\{s^2-2t^2 \\ &- tu + u^2 - s(t+2u) + (-4s+6t-4u)m_{\Sigma_c}^2\}\}]. \end{aligned} \tag{A4}$$

The modulus square of the spin averaged total amplitude for the processes of $\Lambda_c + N \to D \to \Lambda_c + N$ and $\Lambda_c + \bar{N} \to D \to \Lambda_c + \bar{N}$ are, respectively, given by

$$\begin{aligned} \overline{|M^{\Lambda_c N}|^2} = &\frac{1}{2}\left(\frac{f}{m_D}\right)^4 \frac{1}{(s-m_D^2)^2} \\ &\times \mathrm{Tr}[(\not{p}_3+m_{\Lambda_c})(\not{p}_1+\not{p}_2)(\not{p}_4-m_N)(\not{p}_1+\not{p}_2)] \\ &\times \mathrm{Tr}[(\not{p}_2-m_N)(\not{p}_1+\not{p}_2)(\not{p}_1+m_{\Lambda_c})(\not{p}_1+\not{p}_2)] \\ = &\frac{2(f/m_D)^4}{(s-m_D^2)^2}(m_{\Lambda_c}-m_N)^2\{s-(m_{\Lambda_c}+m_N)^2\} \\ &\times [3(m_{\Lambda_c}^4+m_N^4) + 10m_{\Lambda_c}^2 m_N^2 + (t+u)^2 - s^2 \\ &- 4(t+u)(m_{\Lambda_c}^2+m_N^2) + s(m_{\Lambda_c}-m_N)^2] \end{aligned} \tag{A5}$$

and

$$\begin{aligned} \overline{|M^{\Lambda_c \bar{N}}|^2} = &\frac{1}{2}\left(\frac{f}{m_D}\right)^4 \frac{1}{(u-m_D^2)^2} \\ &\times \mathrm{Tr}[(\not{p}_3+m_{\Lambda_c})(\not{p}_1-\not{p}_4)(\not{p}_2+m_N)(\not{p}_1-\not{p}_4)] \\ &\times \mathrm{Tr}[(\not{p}_1+m_{\Lambda_c})(\not{p}_1-\not{p}_4)(\not{p}_4+m_N)(\not{p}_1-\not{p}_4)] \\ = &\frac{2(f/m_D)^4}{(u-m_D^2)^2}(m_{\Lambda_c}-m_N)^2\{u-(m_{\Lambda_c}+m_N)^2\} \\ &\times [3(m_{\Lambda_c}^4+m_N^4) + 10m_{\Lambda_c}^2 m_N^2 + (t+s)^2 - u^2 \\ &- 4(t+s)(m_{\Lambda_c}^2+m_N^2) + u(m_{\Lambda_c}-m_N)^2]. \end{aligned} \tag{A6}$$

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