Diffusion of $\Lambda_c$ in hot hadronic medium and its impact on $\Lambda_c/D$ ratio

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The drag and diffusion coefficients of the $\Lambda_c$ (2286 MeV) have been evaluated in the hadronic medium which is expected to be formed in the later stages of the evolving fire ball produced in heavy ion collisions at RHIC and LHC energies. The interactions between the $\Lambda_c$ 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 (HB$\chi$PT). In both the approaches, the magnitude of the transport coefficients are 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 substantial amount of interaction of the $\Lambda_c$ with the hadronic thermal bath. Furthermore, the transport coefficients of the $\Lambda_c$ is found to be different from the transport coefficients of $D$ meson. Present study indicates that the hadronic medium has a significant impact on the $\Lambda_c/D$ ratio in heavy ion collisions.

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I. INTRODUCTION

One of the primary aims of the ongoing nuclear collision programmes 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 to understand the properties of QGP \cite{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 $R_{AA}(p_T)$ \cite{2, 3} and its elliptic flow ($v_2$) \cite{4}. Several attempts have been made to study these factors within the framework of Fokker Plank equation \cite{5, 6, 7} and Boltzmann equation \cite{8, 9}. However, the roles of hadronic phase have been ignored in these works.

In heavy ion collision (HIC) at ultra-relativistic 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 coefficient of the $D$ and $B$ mesons have been evaluated in the hadronic phase \cite{10, 11, 12} and their effects on $R_{AA}(p_T)$ at large transverse momentum ($p_T$) \cite{3} and elliptic flow ($v_2$) \cite{5, 13} has been studied and found to be significant. Apart from the heavy mesons ($D$ and $B$) the heavy baryon ($\Lambda_c$) is also significant as its enhancement \cite{14, 15} due to quark coalescence would affect the $R_{AA}(p_T)$ of non photonic electrons. Furthermore the baryon-to-meson ratio, ($\Lambda_c/D$), is fundamental for the understanding of in medium hadronisation \cite{16} with respect to the light quark sector \cite{17}. Enhancement of heavy baryon-to-meson ratio ($\Lambda_c/D$) in Au+Au collisions compared to p+p collisions affects the non-photonic electron spectrum ($R_{AA}$) \cite{18, 19}. The branching ratio for the process $\Lambda_c \rightarrow e+X (4.5\% \pm 1.7\%)$ is smaller than $D \rightarrow e+X (17.2\% \pm 1.9\%)$, resulting in less electrons from decays of $\Lambda_c$ than $D$. Hence, enhancement of $\Lambda_c/D$ ratio in Au+Au collision will reduce the observed non-photonic electrons. We notice that the $p_T$ dependence of the $\Lambda_c/D$ ratio may get modified further in the hadronic medium as their interactions with hadrons are non-negligible. Keeping this in mind we attempt to study the transport coefficients (drag and diffusion coefficients) of $\Lambda_c$ 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 present the results. Section IV contains summary and discussions.

II. FORMALISM

The drag and diffusion coefficients of the charmed baryon $\Lambda_c$, propagating through a hot hadronic medium have been evaluated using the scattering length obtained in Ref. \cite{22}, where Liu et. al have estimated Next-to-Next-to-Leading order (NNLO) amplitudes in the framework of Heavy Baryon Chiral Perturbation Theory (HB$\chi$PT). We consider the elastic interaction of $\Lambda_c$ with thermal pions, kaons and $\eta$ mesons. The temperature of the bath can vary from $T_\epsilon$ ($\sim 170$) to $T_F$ ($\sim 120$ MeV), relevant for heavy ion collisions at RHIC and LHC energies. Here $T_\epsilon$ 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 $\Lambda_c$ and $D$ is small and their thermal production and annihilation can be ignored. Hence, in evaluating the drag and diffusion coefficients of the $\Lambda_c$ only elastic processes will be considered.

For the elastic scattering of $\Lambda_c$ of momentum $p_1$ with a thermal hadron, $H$ of momentum $p_2 \ i.e. \ for \ the \ process, \ \Lambda_c(p_1) + H(p_2) \rightarrow \Lambda_c(p_3) + H(p_4)$, the drag coefficient, $\gamma$ can be expressed as \( \gamma \) (see also \[13\] ) :

\[
\gamma = p_i A_i / p^2
\]

where \( A_i \) takes the form

\[
A_i = \frac{1}{2E_{p_3}} \int \frac{d^3p_2}{(2\pi)^3E_{p_2}} \int \frac{d^3p_3}{(2\pi)^3E_{p_3}} \int \frac{d^3p_4}{(2\pi)^3E_{p_4}} \frac{1}{g_{\Lambda_c}} \sum |\mathcal{M}|^2 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4) f(p_2) \{1 \pm f(p_4)\} \langle p_1 - p_3 \rangle \equiv \langle \langle p_1 - p_3 \rangle \rangle
\]

(2)

where \( g_{\Lambda_c} \) denotes the statistical degeneracy of $\Lambda_c$, \( f(p_2) \) 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. \( |\mathcal{M}|^2 \) represents the modulus square of the spin averaged matrix element for $\Lambda_c + H$ elastic scattering process. Eq. (2) illustrate that the drag coefficient is the measure of the thermal average of the momentum transfer, \( p_1 - p_3 \) weighted by the interaction through \( |\mathcal{M}|^2 \).

Similarly the diffusion coefficient $B$ can be expressed as:

\[
B = \frac{1}{4} \left( \langle p^2_3 \rangle - \frac{\langle \langle p_1 - p_3 \rangle^2 \rangle}{p_i^2} \right)
\]

(3)

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

\[
\ll T(p_1) \gg = \frac{1}{512\pi^4 E_{p_1}} \int_0^{\infty} \frac{p^2_2 dp^2_2 d(\cos\chi)}{E_{p_2}} \int_0^{2\pi} \frac{d(\cos\phi_{c.m.})}{2\pi} \lambda^2 (s, m_{p_1}^2, m_{p_2}^2) \int_1^\infty d(\cos\theta_{c.m.})
\]

(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 $\Lambda_c$ can be evaluated in hadronic matter by using $\langle T^2 \rangle$ \[23\] in place of $|\mathcal{M}|^2$ in Eq. (4), where the momentum dependent $T$-matrix elements simply estimate the strength of the $\Lambda_c$ interactions with the thermal hadrons.

The scattering lengths of $\Lambda_c$ with light pseudoscalar mesons $M = \pi, K, K^*$ and $\eta$ have recently been obtained by Liu et. al \[12\] in the framework of HB$\chi$PT. From the scattering lengths, $a$ (say) of $\Lambda_c$ interacting with $M$, we can extract the $T$-matrix element by using the relation

\[
T = 4\pi (m_{\Lambda_c} + m_M)a.
\]

(5)

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

| $\Lambda_cM$ | $a$(fm) | $T$ |
|-----------|--------|---|
| $\Lambda_c\pi$ | 0.06 | 9.28 |
| $\Lambda_cK$ | -0.032±0.038 | -12.42 to 1.06 |
| $\Lambda_cK^*$ | (0.79±0.27)±0.044 | (72.75±47.91) to (207.6±47.91) |
| $\Lambda_c\eta$ | (0.35+0.19)+0.044 | (55.27±34.32i) to (71.17+34.32i) |

TABLE I: Table showing the extracted values of $T$-matrix from the scattering length, $a$, which are obtained by Liu et. al \[12\].

In Ref. \[12\] Liu et al., have fixed the LECs (low energy constants) with the help of relations based on quark model symmetry, heavy quark spin symmetry, SU(4) flavor symmetry as well as some empirical relations. However, a dimensionless constant $a'$ remains unknown, which is taken in the natural range \([-1, 1]\) \[12\]. Therefore, the table shows a band of numerical values of $T$-matrices, which are corrected up to the 3rd order ($O(\epsilon^3)$) with the explicit power counting in HB$\chi$PT. Using the $T$-matrices from Table I and corresponding BE distributions for $H = M = \pi, K, \eta$ in Eq. (4), we can get an estimate of drag and diffusion coefficients of $\Lambda_c$ 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 : $\Lambda_c + \pi \rightarrow \Sigma_c \rightarrow \Lambda_c + \pi$. Using the effective hadronic Lagrangian: \[47\]

\[
\mathcal{L}_{\Lambda_c, \Sigma_c} = \frac{g}{m_\pi} \sum_{\gamma} \bar{\psi}_c \gamma^\mu \text{Tr} (\bar{\tau} \cdot \Sigma_c \cdot \tau) + \text{h.c.},
\]

(6)

we can calculate the matrix elements for $\Lambda_c$ scattering diagrams via $\Sigma_c$. 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 $\Lambda_c + \pi \rightarrow \Sigma_c \rightarrow \Lambda_c + \pi$ processes are shown in the panels (A) and (B) of Fig 11 The matrix elements for the two channels...
are respectively given by,

\[ M_{s}^{\Lambda_c,\pi} = -\left(\frac{2g}{m_\pi}\right)^2 \left[ \frac{\bar{u}(p_1)\gamma_5\gamma_\mu p_1 (\mathcal{D}_1 + \mathcal{D}_2 + m_\Sigma) - \gamma_5 p_2 u(p_1)}{(s - m_\Sigma)} \right] \]

and

\[ M_{u}^{\Lambda_c,\pi} = -\left(\frac{2g}{m_\pi}\right)^2 \left[ \frac{\bar{u}(p_1)\gamma_5\gamma_\mu p_2 (\mathcal{D}_1 + \mathcal{D}_2 + m_\Sigma) - \gamma_5 p_2 u(p_1)}{(u - m_\Sigma)} \right] \]

Similarly from the Lagrangian density \[47\],

\[ \mathcal{L}_{\Lambda_c ND} = \int \frac{d^4x}{\mathcal{F}^{\Lambda_c,\pi} = \Lambda_5^{\Lambda_c,\pi} D_5} \partial_\mu \partial_\mu \Lambda_c \gamma_\mu \gamma_\tau N, \]

one can obtain the matrix elements for the processes \( \Lambda_c N \rightarrow D \rightarrow \Lambda_c N \) and \( \Lambda_c N \rightarrow D \rightarrow \Lambda_c N \), (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 effective hadronic model as well as the corresponding BE and FD distributions for \( H = \pi \) and \( N \) in Eq.4, we can get an alternative estimates of the drag and diffusion coefficients of \( \Lambda_c \) 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 \( F_s = \Lambda^2/(\Lambda^2 + \vec{q}^2) \) respectively, where \( \vec{q} \) is the three momentum transfer, \( p_i \) is the initial three momentum of the pions and \( \Lambda = 1 \) GeV.

III. RESULTS AND DISCUSSIONS

Let us first discuss the results of the drag coefficients obtained from the \( T \)-matrix elements of \( \Lambda_c M \) scattering, given in Table 1. The variation of the drag coefficient of \( \Lambda_c \) 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 \( \Lambda_c \) with the thermal hadrons. The maximum and minimum values of the drag coefficient for \( \Lambda_c \) correspond to the band associated with the \( T \) matrix element presented in Table 1. The average value of the drag of \( \Lambda_c \) is found to be smaller than that of \( D \).

The single electron spectra originating from the decays of \( \Lambda_c \) and \( D \) measured in HIC is sensitive to the following two mechanisms: (i) the production of \( \Lambda_c \) 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 \( \Lambda_c \) has smaller branching ratio to semileptonic decay than \( D \). These two mechanisms lead to a deficiency of electrons at intermediate \( p_T \) (\( 2 < p_T \text{ GeV} < 5 \)) \[55\]. If the drag of \( \Lambda_c \) 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 \( \Lambda_c \) 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 \( \Lambda_c \) will contribute to the electron spectra originating from the decays of charm mesons and baryons. However, measurements of \( D \) meson spectra via hadronic as well as semileptonic channels in the same collision conditions will help in estimating the electron spectra from \( \Lambda_c \) and hence its drag coefficients.

For a hadronic system of life time, \( \Delta \tau \) and drag, \( \gamma \) the momentum suppression is approximately given by, \( R_{AA} \sim e^{-\Delta \tau \gamma} \) \[24\]. Picking up a value of \( \gamma \) of \( D \) at \( T = 170 \text{ MeV} \) from the results displayed in Fig.2 we get \( R_{AA} \sim 14\% \) for \( \Delta \tau = 5 \text{ fm/c} \). The values of \( R_{AA} \) for \( \Lambda_c \) at the same temperature and \( \Delta \tau \) are about 16\% and 4\% respectively for maximum and minimum values of \( \gamma \) shown in Fig.2. Similarly the \( \Lambda_c/D \) ratio at the same temperature and \( \Delta \tau \) is approximately given by, \( \Lambda_c/D \sim e^{\Delta \tau \gamma} \). Where \( \gamma_D \) and \( \gamma_{\Lambda_c} \) are the drag coefficients of the \( D \) meson and \( \Lambda_c \) respectively. The \( \Lambda_c/D \) ratio can vary up to 12\% depending on the minimum to maximum value of the drag coefficients of \( \Lambda_c \).

The temperature variation of the drag coefficient of \( \Lambda_c \) in a piconic medium has been depicted in Fig.3. Here EL corresponds to the matrix element obtained from the
FIG. 3: Variation of the drag coefficient with temperature for \( \Lambda_c \) in a pionic medium, using the dynamics of Effective Lagrangian (EL) and Scattering Length (SL). The contribution of drag coefficient for \( \Lambda_cN \) scattering in the EL dynamics is also presented.

FIG. 4: Variation of the diffusion coefficient with temperature, when \( \Lambda_c \) interact with all the light pseudo scalar mesons \( M \) (in SL dynamics).

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

IV. SUMMARY AND DISCUSSIONS

We have studied the diffusion of \( \Lambda_c \) in a hot hadronic medium. Using scattering amplitudes, obtained by Liu et al. [42] in the framework of HB\( \chi \)PT, we have evaluated the drag and diffusion coefficients of the \( \Lambda_c \) interacting with a hadronic background composed of pions, kaons and eta. We have also calculated the drag coefficients of the \( \Lambda_c \) 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 hadronized degrees of freedom, \( A_i(p) \) and \( B_{ij}(p) \) are related to the drag and diffusion coefficients. The interaction between the probe and the thermal bath enters through the drag and diffusion coefficients. The initial distribution of \( D \) meson and \( \Lambda_c \) 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 \( \Lambda_c \) spectra, resonances are not taken into account at variance with ref. [35].

The ratio estimated after evolving the \( D \) [30] and \( \Lambda_c \) 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 corresponds to the maximum and minimum values of the drag and diffusion coefficients of \( \Lambda_c \). The results indicate that the ratio gets enhanced for \( 2 \leq p_T \leq 7 \) due to the interactions of the \( D \) and \( \Lambda_c \) 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.
hadronic Lagrangian is quite higher than that 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 \(\Lambda_c\) has been compared with the drag coefficient of the \(D\) meson calculated within the framework of heavy meson chiral perturbation theory (HMChPT). It is found that the value of the drag coefficient of \(\Lambda_c\) is generally lower than that of \(D\) mesons. This result shows a significant effect on the \(p_T\) dependence of \(\Lambda_c/D\) ratio and hence also on \(R_{AA}\) of single electrons originating from the decay of \(\Lambda_c\).

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V. 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

\[
|M_{\Lambda_c \pi}|^2 = \frac{3}{2} \left( \frac{2g}{m_\pi} \right)^4 \left[ \frac{A_{ss}}{(s - m_{\Sigma_c}^2)^2} + \frac{A_{uu}}{(u - m_{\Sigma_c}^2)^2} \right]
\]

and

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

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

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

\[
|M_{\Lambda_c N}|^2 = \frac{1}{2} \left( \frac{f}{m_D} \right)^4 \left[ \frac{1}{(s - m_N^2)^2} \right]
\]

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

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