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Exploring the melting of heavy-flavor hadrons and diffusion of charm quarks

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Charm quarks, due to their significant mass, serve as an excellent tool for investigating the deconfined medium composed of quarks and gluons. These charm quarks interact with this medium and carry crucial information about it before they undergo hadronization to form heavy flavor hadrons. In this study, we employ the color string percolation model (CSPM) and the van der Waals Hadron Resonance Gas (VDWHRG) model to study the diffusion of charm quarks and the D^0 meson in both the deconfined and hadronic phases, respectively. CSPM, a QCD-inspired model, proposes that the colored strings are stretched between the partons of the colliding nuclei. As a well-established theoretical framework, it has been used to compute a range of thermodynamic and transport properties of the matter formed in ultra-relativistic hadronic and heavy-ion collisions. Conversely, the VDWHRG model is a modified hadron resonance gas model. It considers both attractive and repulsive interactions among the hadrons. This model is successful in explaining various lattice QCD thermodynamic results up to a temperature of 180 MeV. We estimate the drag coefficient (γ) and diffusion coefficients in both momentum (B_0) and coordinate space (D_s) using the formalism of the CSPM model for the deconfined phase and the VDWHRG model for the hadronic phase. Our findings indicate the existence of a minima for the spatial diffusion coefficient near the deconfinement temperature. This minima suggests a phase transition.

Furthermore, we delve into the phenomenon of melting of charmed hadrons. This is achieved by computing the charm susceptibilities using the VDWHRG model. Our findings indicate a smooth transition in the vicinity of the deconfinement region at a vanishing chemical potential, suggesting a crossover transition. The net charm fluctuations can be deduced experimentally by considering the net number fluctuation of the $D^{\pm}$ meson. This has not been executed in experiments so far. Nevertheless, with ALICE Run-3 progressing towards increased luminosity and improved detection capabilities, this study can be conducted experimentally. This study provides pivotal insights into the characteristics of charm quarks and open charm hadrons, thereby broadening the understanding of the interaction of heavy flavors within a thermalized medium.

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1. Introduction

The Ultra-relativistic heavy-ion collisions at RHIC (Relativistic Heavy-Ion Collider) and the LHC (Large Hadron Collider) provide an opportunity to understand the primordial matter and the microsecond old universe. Such collisions produce a hot and dense deconfined medium of quarks and gluons called Quark-Gluon Plasma (QGP). This medium expands with time, and the temperature of the system decreases sharply. Eventually, the quarks and gluons hadronize to form a hadronic medium. We detect only the final state hadrons, which undergo many complex processes in the hadronic phase, as well as their constituent quarks, which undergo such processes in the QGP medium.

To understand these microscopic processes, one needs to look for a probe that can provide information about both the partonic and hadronic media. One such probe is the Heavy quarks (HQs), which serve as an excellent probe for studying the QGP medium. The charm and bottom quarks are produced relatively early in the system, and their masses are much larger than that of the thermalized lighter quarks. The energy loss mechanism for the heavy quarks in the QGP medium is different from that of the lighter quarks. While lighter quarks primarily lose energy through gluon radiation, heavy quarks predominantly lose energy through collisions with lighter quarks. [1, 2]. As a result, they undergo Brownian motion in the deconfined medium of lighter quarks. These heavy quarks traverse the deconfined medium, and around the hadronization temperature, they hadronize to form heavy flavor hadrons. One can look into the diffusion of heavy quarks by employing the Fokker-Planck equation in the QCD medium. In doing so, we can estimate the drag and diffusion coefficients of the charm and bottom quarks. Furthermore, for the hadronic medium, we use D^0 ($c\bar{u}$) meson as a probe, which is the lightest open-charmed meson. Due to its heavier mass, as compared to the lighter abundant hadrons such as pion, kaon, and protons, the D^0 meson undergoes Brownian motion in the hadronic medium, which makes it a suitable probe to explore the transport properties in a hadronic medium.

Thus, we make an attempt to understand the system formed in ultrarelativistic heavy-ion collision with heavy flavor as a probe. In the partonic medium, we estimate the relaxation time, drag, and diffusion coefficients of charm quarks using Color String Percolation Model (CSPM) formalism. For the hadronic phase, we estimate the drag and diffusion coefficient of the D^0 meson by employing the van der Waals Hadronic Resonance Gas (VDWHRG) model. Moreover, we make an attempt to approximate the melting temperature of the charmed hadrons and compare our results with lQCD results.

2. Formulation

2.1 Color String Percolation Model

In the color string percolation model, particle production is a consequence of the color strings stretching between the partons in the target and projectile. The number of strings increases with higher collision energies and parton numbers, leading to overlap and eventually to the formation of clusters. When the string density reaches a critical value (ξ_c), occupying more than 50% of the transverse space, a percolation phase transition occurs. According to Schwinger's mechanism, the strings break into quark-antiquark pairs, which hadronize into final state particles [3]. Assuming the transverse nuclear overlap area S and string density ρ, the dimensionless percolation density parameter ξ is defined as [3]:

$$\xi = \rho S_1 = \frac{N_s S_1}{S}, \tag{1}$$

In the thermodynamic limit, where the number of strings $N_s \to \infty$ and ξ is fixed, the distribution of the overlap of n strings follows a Poisson distribution with a mean of ξ. Thus, the color suppression factor is given as [3],

$$F(\xi) = \sqrt{\frac{1 - e^{-\xi}}{\xi}}. \tag{2}$$

Finally, the initial temperature of the percolation cluster is expressed in terms of $F(\xi)$ as [3],

$$T(\xi) = \sqrt{\frac{\langle p_T^2 \rangle_1}{2F(\xi)}}, \tag{3}$$

By taking $T_c = 167.7 \pm 2.8$ MeV and $\xi_c \sim 1.2$ [3], the single string squared average transverse momentum, $\sqrt{\langle p_T^2 \rangle_1} = 207.2 \pm 3.3$ MeV. A detailed formulation can be found in [4].

2.2 van der Waals Hadron Resonance Gas Model

The ideal Hadron Resonance Gas (HRG) model is a statistical framework that assumes thermal and chemical equilibrium with non-interacting, point-like hadrons. The van der Waals HRG model (VDWHRG), on the other hand, assumes both attractive and repulsive interactions among the hadrons through the parameters a and b, respectively [5]. The equation of state in the VDWHRG formalism is given as,

$$\left(P + a\left(\frac{N}{V}\right)^2\right)(V - bN) = NT. \tag{4}$$

Here, P, N, V, and T represent the system's pressure, particle number, volume, and temperature, respectively. The van der Waals parameters a and b account for interactions, with $b = \frac{16}{3}\pi r^3$, where r is the hadron's hardcore radius. In the GCE, we can express pressure as [6],

$$P(T, \mu) = P^{id}(T, \mu^*) - an^2, \tag{5}$$

where n is the number density estimated in the VDWHRG model and μ^* is the effective chemical potential. Moreover, we compute different orders of susceptibilities by taking the derivative of pressure with the respective chemical potential. A detailed discussion on VDWHRG formalism can be found in Ref. [7].

2.3 Drag and diffusion coefficients

To study the interaction of charm quark and D^0 meson with the thermalized medium of lighter quarks and hadrons, respectively, we take advantage of the Fokker-Planck transport equation, which can be written as

$$\frac{\partial f(t, p)}{\partial t} = \frac{\partial}{\partial p^i}\left[(A^i f(t, p)) + \frac{\partial}{\partial p^j}(B^{ij} f(t, p))\right]. \tag{6}$$

Here, $f(t, p)$ is the time evolution phase-space distribution of charm quarks. $A^i(\mathbf{p})$ and $B^{ij}(\mathbf{p})$ are the collision kernel. For the partonic medium, we use the CSPM formalism to estimate the drag and diffusion coefficients of the charm quark traveling the QCD medium. For the charm quarks, the relaxation time can be expressed by [4, 9],

$$\tau_c = \frac{m_c}{T}\tau_q = \frac{m_c}{T}\frac{L}{(1-e^{-\xi})}, \tag{7}$$

where m_c is the mass of the charm quark, $m_c \simeq 1.275$ GeV, L is the longitudinal extension of a string ($\sim$ 1 fm) and τ_q is the relaxation time of the lighter quarks. However, for D^0 meson, in an interacting hadron gas, we estimate the relaxation time as,

$$\tau_D^{-1} = \sum_j n_j \langle \sigma_j v_j \rangle, \tag{8}$$

where n_j is the number density of j^{th} hadronic species. σ_j and v_j are the cross-section and relative velocities between j^{th} hadronic species and D^0 meson. The drag coefficient or drag force (γ) is inversely related to the thermal relaxation time of the particle, $\gamma = \frac{1}{\tau_D}$.

From the Einstein's relation, the transverse momentum diffusion coefficient is related to the drag coefficient as [10],

$$B_0 = \gamma T m \tag{9}$$

Finally, we estimate the spatial diffusion coefficient, D_s, under the static limit, it can be expressed as,

$$D_s = \frac{T}{m\gamma}. \tag{10}$$

3. Result and Discussion

We plot the drag coefficient (γ), which incorporates average momentum change, and the transverse momentum diffusion coefficient (B_0), which accounts for the broadening of the final momentum distribution, with temperature in Fig. 1. With increasing temperature, we observe an increasing trend for both γ and B_0. This is due to the increase in the number density of the system, which increases the rate of interaction of the heavy particles. We compare our results with other phenomenological models, and our results seem to agree well with various models. However, due to the nature of interaction taken for D^0 meson in VDWHRG as compared to the charm quarks within the CSPM formalism, we observe a sharp increase in both γ and B_0 for the D^0 meson.

In Fig. 2 (left panel), we plot the spatial diffusion coefficient as a function of temperature. Here, we multiply D_s with the factor $2\pi T$, which allows us to express this quantity in the units of thermal wavelength. We observe that the diffusion coefficient decreases with increasing temperature until it approaches the hadronization temperature. However, we observe a rising trend beyond the hadronization temperature (T_c). As the system nears T_c, the D^0 meson diffusion drops sharply, becoming almost comparable to that of charm quark diffusion at the critical temperature, indicating a smooth transition from the hadronic to the partonic phase. At lower temperatures, in the hadronic phase, the interactions are weaker, which leads to a higher spatial diffusion coefficient. As the temperature increases toward T_c, interactions become stronger, leading to a decrease of $2\pi T D_s$. At $T = T_c$, due to the onset of the deconfined medium, the interaction strength is maximum, which results in a minimum value for $2\pi T D_s$. Beyond this temperature, the spatial diffusion coefficient

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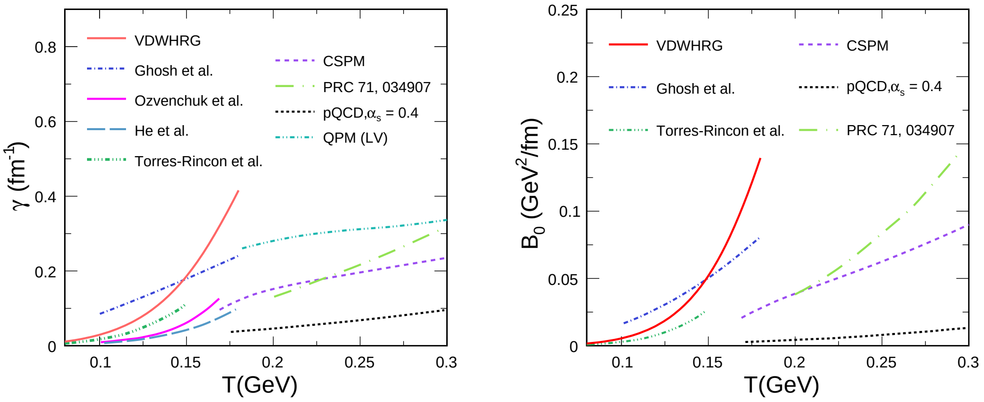

Figure 1: Drag coefficient (left panel) and Transverse momentum diffusion coefficient (right panel) of D^0 meson and charm quarks as a function of temperature [4, 7].

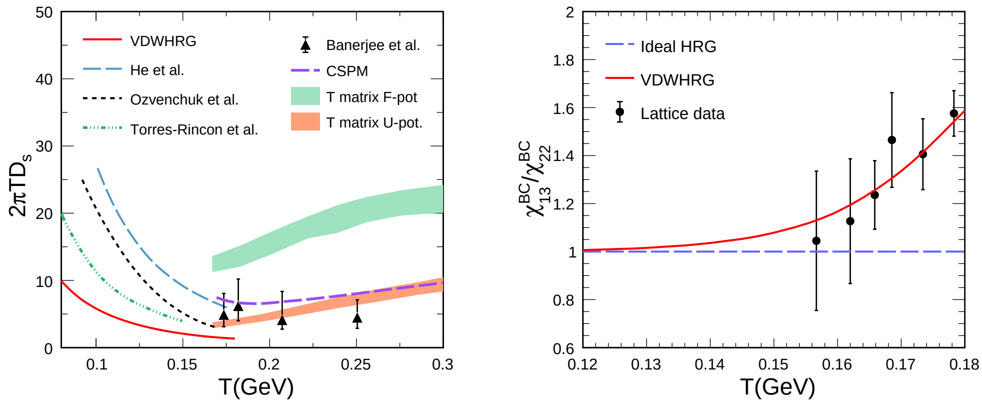

Figure 2: Left panel: Spatial diffusion coefficient of D^0 meson and charm quarks. Right panel: Ratio of fourth-order cumulants of charmed baryons [4, 7].

increases again with an increase in temperature as particles become asymptotically free, which reduces the interaction strength.

In the right panel of Fig. 2, we plot the ratio of the fourth-order cumulants, χ_{13}^{BC} and χ_{22}^{BC}. This can be understood as the ratio of charm number to baryon number. In the hadronic phase, where $|B| = |C| = 1$, the ratio is expected to be to be unity. However, in the partonic phase, with $|C| = 1$ and $|B| = 1/3$, the ratio increases to 3. We observe a rise in the ratio near the hadronization temperature, which increases towards 3 with increasing temperature. This shows that the open-charmed hadrons start to melt near 160 MeV; however, the slow rise in the ratio hints towards a mixed phase, where open-charmed hadrons and charm quarks exist simultaneously. Our results indicate that the ideal HRG model fails to explain this trend; however, the VDWHRG model provides better agreement to the lQCD data [11]. The VDWHRG model is able to explain the lQCD data up to temperatures of 180 MeV. This is because the van der Waals interactions between hadrons at higher temperatures appear to mimic the behavior of a deconfined medium up to a certain temperature.

The study of heavy-flavour dynamics allows us to understand the hot and dense matter produced in heavy-ion collisions. The D^0 meson can give us information about the medium by the estimation of its drag and diffusion coefficients. This information is embedded within the elliptic flow (v_2) and the nuclear suppression factor (R_{AA}) of D^0 meson, and these observables are measured in experiments. Additionally, the net D^+ and D^- meson fluctuations can be estimated to understand the net charm fluctuations, which could be a cleaner probe for locating the QCD critical point. In our recent work [12], we have further explored this idea by estimating the diffusion matrix coefficients for various conserved charges. We observe that at low center-of-mass energy, where one should ideally look for the QCD critical point, the diffusion of hadrons carrying charm conserved charges are much smaller than the diffusion of baryon, electric, and strange charges. Thus, it hints towards the idea that, net charm fluctuation can be a better probe than net-proton fluctuation.

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