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Heavy flavor suppression: Role of hadronic matter

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The role of hadronic matter in the suppression of open heavy-flavored mesons is studied. The heavy-quark suppression factors are calculated and contrasted with the experimental data obtained from nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) and LHC experiments. It is found that the suppression in the hadronic phase at RHIC energy is around 20%–25% whereas at the LHC it is around 10%–12% for the D meson. In the case of B mesons the hadronic suppression is around 10%–12% and 5%–6% at RHIC and LHC energies, respectively. The present study suggests that the suppression of heavy flavor in the hadronic phase is significant at the RHIC. However, the effect of hadronic suppression at the LHC is marginal; this makes the characterization of quark-gluon plasma at the LHC less complicated.

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One of the primary aims of the ongoing heavy-ion collision experiments at the Relativistic Heavy Ion Collider (RHIC) and LHC energies is to create and study the properties of quark-gluon plasma (QGP). The heavy flavors (HFs) play a vital role in this purpose [1–11]. In particular, the depletion of high-transverse-momentum (p_T) hadrons (D and B) produced in nucleus + nucleus collisions relative to those produced in proton + proton ($p + p$) collisions has been considered as an indicator of QGP formation. The STAR [12], PHENIX [13], and ALICE [14] collaborations have measured this high-p_T depletion. To make the characterization of the QGP reliable the role of the hadronic matter should be taken into consideration and its contribution must be disentangled from the experimental observables. In this paper an attempt is made to estimate the effect of the hadronic phase on the nuclear suppressions of HFs.

We study the evolution of the HFs in the following scenario. We assume that the light quarks, antiquarks, and gluons form a thermalized matter and the nonequilibrated heavy quarks (HQs) are moving through the expanding QGP background. While the evolution of the expanding QGP is described by relativistic hydrodynamics with the initial temperature and thermalization time constrained by the measured charged-particle multiplicity, the motion of the nonequilibrated HQ is described by the Fokker-Planck equation (FP) with drag and diffusion coefficients arising due to the interaction of HQs with the expanding QGP background. The initial conditions for the distributions of HQs have been taken from the next-to-leading-order pQCD results obtained for pp collisions by using the Mangano-Nason-Ridolf code [15].

The expanding QGP converts to a hadronic system when it cools down to the transition temperature, T_c. The solution of the FP equation for the charm and bottom quarks at the transition point is folded with the Peterson fragmentation function [16] to obtain the momentum distributions of the heavy-flavored mesons containing the effects of the interaction of the expanding QGP background. The hadronic matter evolves in space and time described by relativistic hydrodynamics until the matter gets dilute enough to freeze-out kinematically. The motion of the nonequilibrated HF mesons (D and B) in the expanding hadronic system is again described by the FP equations with drag and diffusion coefficients evaluated due to their interactions with hadronic matter. The solution of the FP equation for the D and B mesons at the freeze-out point encompassing the effects of drag of both the QGP and the hadronic phases has been used to determine the suppression in the high-p_T domain.

The FP equation describing the motion of the non-equilibrated degrees of freedom (dof) in the bath of the equilibrated dof is [17,18]

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial p_i}\left[A_i(p)f + \frac{\partial}{\partial p_j}[B_{ij}(p)f]\right], \tag{1}$$

where f is the momentum distribution of the nonequilibrated dof, and A_i and B_{ij} are related to the drag and diffusion coefficients. The interaction between the probe and the medium enter through the drag and diffusion coefficients.

During their propagation through the QGP the HQs dissipate energy predominantly by two processes [7,8,19]: (i) collisional processes, e.g., $gQ \to gQ$, $qQ \to qQ$, and $\bar{q}Q \to \bar{q}Q$, and (ii) radiative processes, i.e., $Q + q \to Q + q + g$ and $Q + g \to Q + g + g$. The dead-cone and Landau-Pomeranchuk-Migdal effects on the radiative energy loss of heavy quarks have been considered. Both radiative and collisional processes of energy loss are included in the effective drag and diffusion coefficients [7,8]. The solutions of the FP equation have been convoluted with the Peterson fragmentation functions to obtain the D- and B-meson spectra at $T_c \sim 170$ MeV. We omit the detailed description here, as it is available in Refs. [7,8].

The motion of the out-of-equilibrium HF mesons (D and B) in the expanding hadronic matter (HM) is studied by using the FP equations. The drag and diffusion coefficients of the D and B mesons have been calculated in Refs. [20,21] for their interactions with pions, kaons, nucleons, and eta (see also Refs. [22–24]). The p_T distribution of the HF mesons obtained by convoluting the Peterson fragmentation function with the solution of the FP equation at the end of the QGP phase has been used as (initial) input for solving the FP equation in the hadronic phase. The solution of the FP equation for the D and B mesons in the expanding HM at the freeze-out is employed to determine the nuclear suppression. The expansion of the background medium (either QGP or HM) is described by relativistic hydrodynamics [25] with an equation of state that leads to the velocity of sound, $c_s = 1/\sqrt{4}$.

The suppression of high-p_T D or B mesons in the QGP phase, R_{AA}^Q, is given by $R_{AA}^Q = \frac{f_Q}{f_i}$, where f_Q is given by the convolution of the solution of the FP equation at the end of the QGP phase with the HQ fragmentation to a D or B meson and f_i is the function obtained from the convolution of the initial heavy-quark momentum distribution with the HQ fragmentation function to D and B mesons. Similarly, the suppression factor in the hadronic phase alone can be written as $R_{AA}^H = \frac{f_H}{f_Q}$, where f_H is the solution of the FP equation describing the evolution in the hadronic phase at the freeze-out. The net suppression of the HFs during the entire evolution process—from the beginning of the QGP phase to the end of the hadronic phase—is given by $R_{AA} = R_{AA}^Q \times R_{AA}^H$.

The results for the D meson at RHIC energy is depicted in Fig. 1. We have taken the initial temperature $T_i = 0.4$ GeV and thermalization time $\tau_i = 0.2$ fm/c. These values are constrained by the measured hadronic multiplicity, $dN/dy = 1100$. We observe that the D-meson suppression in the hadronic phase is around 20%–25% for $p_T = 3$–10 GeV at RHIC energy. This suggests that the effects of the hadronic medium on the charmed-meson suppression is non-negligible. Therefore, these effects should be excluded from the experimental data to estimate the suppression in QGP and make the characterization of QGP definitive. The results for B mesons are displayed in Fig. 2 at RHIC energies. In the hadronic phase the B-meson suppression is around 10%–12%, indicating a greater suppression of D than B. However, the overall suppression of B is also less than D, because the drag of b quarks (B mesons) in QGP (HM) is smaller than that for c quarks (D mesons).

In Figs. 1 and 2 the R_{AA} have been plotted for D and B mesons individually for RHIC collision conditions. However, the data for D and B mesons are not available separately from RHIC experiments. The PHENIX and STAR collaborations [12,13] have measured the $R_{AA}(p_T)$ of nonphotonic single electrons originating from the decays of mesons containing both open charm and bottom quarks, i.e., the experimental data contains the suppression of both the charm and bottom through the measured $R_{AA}(p_T)$. Theoretically, p_T spectra of nonphotonic electrons originating from the decays of D and B mesons ($D \rightarrow Xe\nu$ and $B \rightarrow Xe\nu$) produced in heavy-ion collisions have been obtained by following the procedure discussed in Ref. [7]. The p_T spectra of single electrons originating from pp collisions are obtained by using the HQs' distributions obtained from the Mangano-Nason-Ridolf code. The ratio of electron spectra from heavy-ion to pp collisions gives R_{AA}^Q. A similar exercise has been performed for the hadronic phase to obtain R_{AA}^H.

The theoretical results for QGP and the hadronic phases along with the total suppression is contrasted with the experimental data from RHIC experiments in Fig. 3. The results reveal that with the inclusion of the hadronic contributions the description of experimental results improves. For the LHC, the experimental results on the D suppression

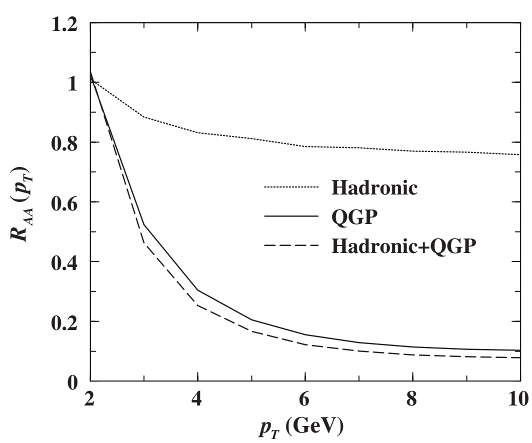

FIG. 1. Variation of D-meson suppression at RHIC energy for the QGP, hadronic, and hadronic + QGP phases.

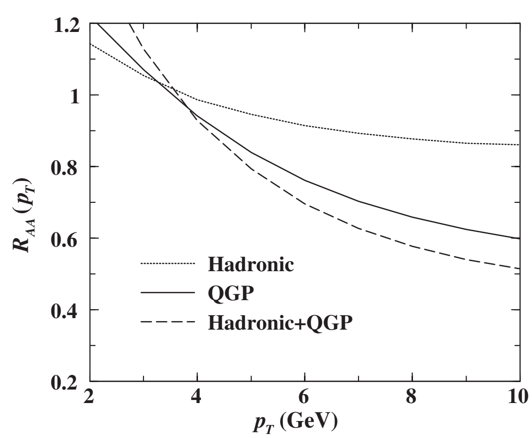

FIG. 2. Variation of B-meson suppression at RHIC energy for the QGP, hadronic, and hadronic + QGP phases.

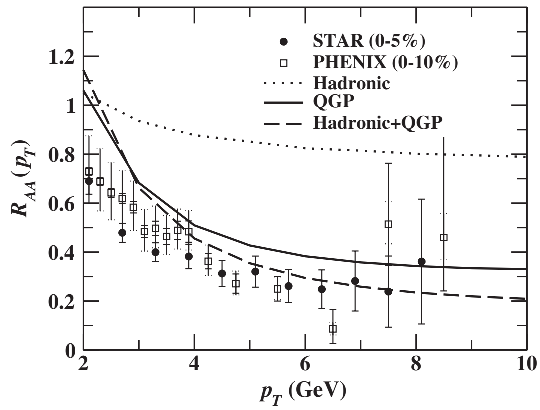

FIG. 3. R_{AA} of heavy-flavored mesons measured through their semileptonic decays as a function of p_T at the RHIC (see text). Experimental data is taken from Refs. [12,13].

are available directly [14]. We have taken the value of $T_i = 550$ MeV and $\tau_i = 0.1$ fm/c for $\sqrt{s_{NN}} = 2.76$ TeV. It is found that the D-meson suppression in the hadronic phase at LHC energy is around 10%–12% for $p_T =$ 3–10 GeV. The comparison of theoretical and experimental results (Fig. 4) indicate that the hadronic phase plays a less dominant role at the LHC than at the RHIC. It will be interesting to compare the experimental data on B with the theoretical results and check whether both D and B spectra are reproduced simultaneously with the same initial conditions.

It is to be noted that the theoretical descriptions overestimate the experimental data for $p_T \leq 3$ GeV at the RHIC and for $p_T \leq 4$ GeV at the LHC. The spectra of D and B mesons are obtained here from the fragmentation of high-energy charm and bottom quarks. Such mechanisms of hadronization may not be valid for the low-p_T hadrons. The low-p_T hadrons may be produced from the coalescence of thermal partons [26]. The D- and B-meson spectra at lower p_T may be reproduced by using coalescence-model calculations [27].

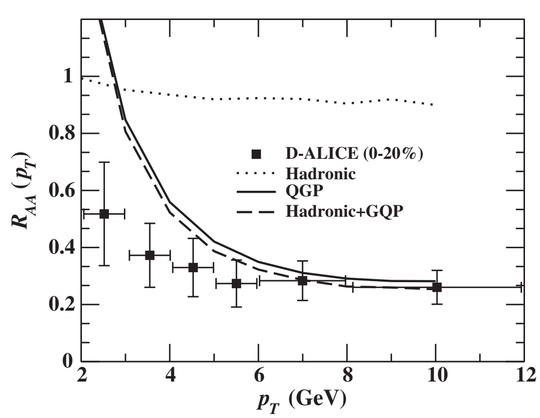

FIG. 4. R_{AA} of D mesons as a function of p_T at LHC. Experimental data is taken from Ref. [14].

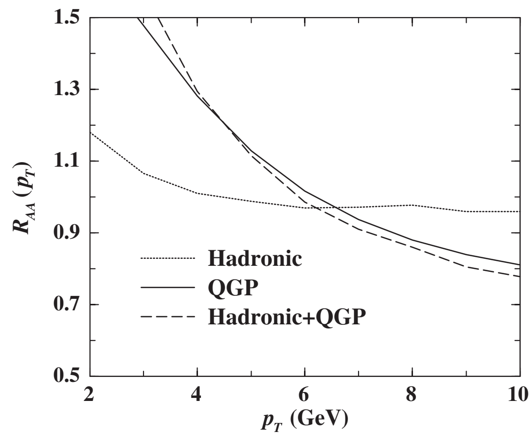

FIG. 5. Variation of B-meson suppression at LHC energy for the QGP, hadronic, and hadronic + QGP phases.

Figure 5 displays the depletion of B mesons at the LHC. The effects of the hadronic phase are found to be negligibly small, indicating the fact that the response of the hadronic medium is less pronounced at the LHC than at the RHIC. Therefore, the role of the hadronic medium in characterizing the QGP by using heavy flavors can be ignored, making the task of QGP detection less complex at the LHC.

The differences in the magnitude of R_{AA}^H at the RHIC and LHC can be understood from the corresponding results plotted in Figs. 6 and 7. The temperature of the hadronic system for both the RHIC and LHC varies from T_c to T_f (170 to 120 MeV), and therefore the values of the drag coefficients remain same. However, the input distribution to the hadronic matter is harder at the LHC than at the RHIC, resulting in less suppression at the LHC.

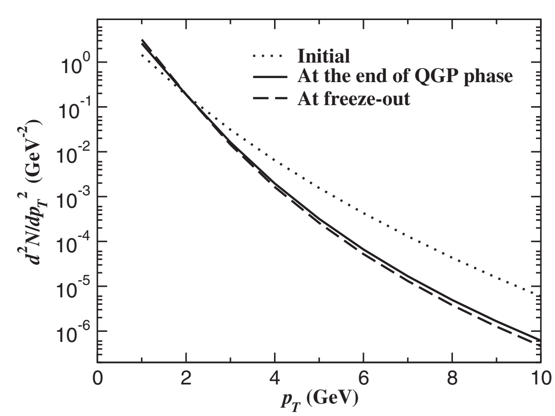

FIG. 6. The p_T spectra of the D mesons at the RHIC obtained by convoluting the charm quark to D meson fragmentation with (i) the initial charm-quark distribiuon (dotted line), (ii) the solution of the FP equation at the transition point (solid line), and (iii) the solution of the FP equation at the end of the hadronic phase (i.e., at freeze-out) which contains the effects of suppression in the QGP as well as in the hadronic phases (dashed line).

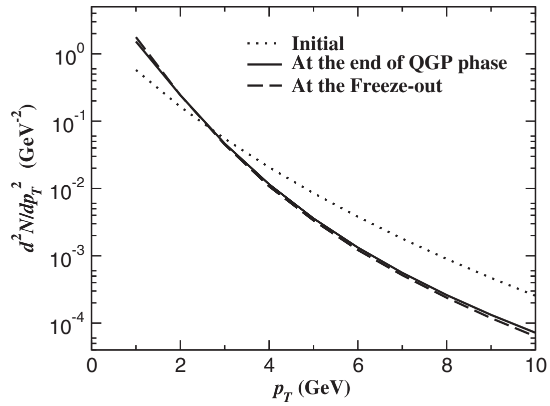

FIG. 7. Same as Fig. 5 for LHC conditions.

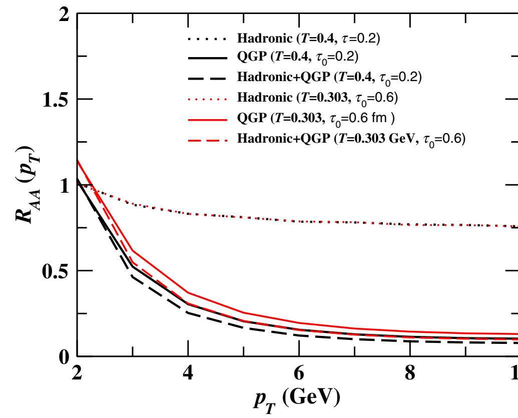

FIG. 8 (color online). The variation of R_{AA} with p_T for two sets of initial conditions.

Some comments on the sensitivity of R_{AA} on the initial conditions are in order here. The initial temperature and the thermalization time of the QGP is not uniquely known. Therefore, it may be interesting to study the sensitivity of R_{AA} to the initial conditions. In Fig. 8 we display the results for two sets of initial conditions, keeping other parameters like T_c and T_f unaltered. We observe that the suppression in the hadronic phase is negligible due to the change in the initial conditions, as is expected, because the maximum (T_c) and the minimum (T_f) temperature of this phase are kept unaltered. However, the suppression in the QGP phase changes by approximately 20% due to the change in the initial conditions, as indicated in Fig. 8. For higher T_i the drag in the QGP phase is higher, which results in more suppression. The net change (QGP + hadronic) also remains at about 20% as the change in the hadronic phase can be ignored.

In summary, we have evaluated the suppression of HFs due to their interactions with the QGP and HM. While the HF suppression in QGP is used as a signal of QGP, the hadronic suppression is treated as background. We observe that the suppression of D is more than that of B in the hadronic medium because the hadrons drag the D more than the B [21]. The suppression at RHIC energy is significant and hence the hadronic contributions should be taken into account when analyzing the experimental data. It is also interesting to note that the role of the hadronic medium in HF (especially for B) suppressions at the LHC is not substantial because D- and B-meson distributions are harder at the LHC than at the RHIC. Since the role of hadrons in B-meson suppression is very minimal, B may play a unique role in characterizing QGP. This has a great advantage compared to other signals of QGP, for example, in the case of electromagnetic probes (see Refs. [28–30] for review), i.e., for direct photons and lepton pairs the role of hadronic matter is significant, which makes the task of extracting QGP properties difficult after filtering out hadronic contributions.

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