Heavy flavor suppression: role of hadronic matter

Santosh K. Das\textsuperscript{a,b}, Sabyasachi Ghosh\textsuperscript{c}, Sourav Sarkar\textsuperscript{a} and Jan-e Alam\textsuperscript{a}

\textsuperscript{a} Variable Energy Cyclotron Centre, 1/AF, Bidhan Nagar, Kolkata - 700064
\textsuperscript{b} Department of Physics and Astronomy, University of Catania, Via S. Sofia 64, I-95125 Catania, Italy and
\textsuperscript{c} Centre for Astroparticle Physics and Space Bose Institute Block-EN, Sector-V, Salt Lake Bidhan Nagar, Kolkata - 700091 India

The role of hadronic matter in the suppression of open heavy flavored mesons has been studied. The heavy-quarks (HQs) suppression factors have been calculated and contrasted with the experimental data obtained from nuclear collisions at Relativistic Heavy Ion Collider (RHIC) and Large Hadronic Collider (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 case of B meson the hadronic suppression is around 10% – 12% and 5% – 6% at RHIC and LHC energies respectively. Present study suggests that the suppression of heavy flavor in the hadronic phase is significant at RHIC. However, the effect of hadronic suppression at LHC is marginal, this makes the characterization of QGP at LHC less complicated.

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One of the primary aims of the ongoing heavy-ion collision experiments at RHIC and LHC energies is to create and study the properties of Quark Gluon Plasma (QGP). The heavy flavours (HF) play a vital role to serve 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 the 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 work an attempt has been 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, anti-quarks and gluons form a thermalized matter and the non-equilibrated heavy quarks (HQs) are moving through the expanding QGP background. While the evolution of the expanding QGP is described by the relativistic hydrodynamics with initial temperature and the thermalization time constrained by the measured charged particle multiplicity, the motion of the non-equilibrated HQ is described by the Fokker-Planck equation (FP) with drag and diffusion co-efficient 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 NLO pQCD results obtained for pp collisions by using the MNR code [15].

The expanding QGP converts to 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 flavoured mesons containing the effects of the interaction of the expanding QGP background. The hadronic matter evolves in space and time described by relativistic hydrodynamics till the matter gets dilute enough to freeze-out kinematically. The motion of the non-equilibrated 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 reads as [17, 18]:

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

(1)

where $f$ is the momentum distribution of the non-equilibrated dof, $A_i$ 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 HOs dissipate energy predominantly by two processes [7, 8, 15]: (i) collisional, e.g. $gQ \rightarrow gQ$, $qQ \rightarrow qQ$ and $qQ \rightarrow gQ$ and (ii) radiative processes, i.e. $Q + g \rightarrow Q + q + g$ and $Q + g \rightarrow g + Q + g$. The dead cone and Landau-Pomeranchuk-Migdal (LPM) effects on 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 [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.
Hadronic mesons in the expanding HM at the freeze-out is emission of state (eos) which leads to the velocity of sound, described by relativistic hydrodynamics \cite{25} with equation of the background medium (either QGP or HM) is employed to determine the nuclear suppression. The expansion of the background medium (either QGP or HM) is described by relativistic hydrodynamics \cite{25} with equation of state (eos) which leads to the velocity of sound, \( c_s = 1/\sqrt{A} \).

The suppression of high \( p_T \) quark and \( b \) mesons in the QGP phase, \( R_{AA}^Q \), is given by: \( R_{AA}^Q = \frac{dN}{dy} \) 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 function to \( D \) and \( B \) mesons. Similarly, the suppression factor in the hadronic phase alone can be written as, \( R_{AA}^H = \frac{4\pi}{f_Q} f_H \) is the solution of the FP equation describing the evolution in the hadronic phase at the freeze-out. The net suppression of the HF mesons 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. \ref{fig1}. We have taken the initial temperature, \( T_i = 0.4 \text{ GeV} \) and thermalization time, \( \tau_i = 0.2 \text{ fm}/c. \) 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 \( p_T = 3–10 \text{ GeV} \) at RHIC. 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 \( B \) meson is displayed in Fig. \ref{fig2} at RHIC. In the hadronic phase the \( B \) meson suppression is around 10\%–12\%, indicating 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 (\( D \) meson).

In Figs. \ref{fig1} and \ref{fig2} 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 \cite{12,13} have measured the \( R_{AA}(p_T) \) of non-photonic single electrons originating from the decays of mesons containing both open charm and bottom quarks, \( i.e. \) the experimental data contains suppression of both the charm and bottom through the measured, \( R_{AA}(p_T) \).

Theoretically \( p_T \) spectra of non-photonic electrons originating from the decays of \( D \) and \( B \) mesons...
(D → Xeν and B → Xeν) produced in heavy ion collisions have been obtained by following the procedure discussed in [2]. The pt spectra of single electrons originating from the pp collisions is accomplished by using the HQs distributions obtained from the MNR code. The ratio of electron spectra from heavy ion to pp collisions gives $R_{Q\AA}^{pT}$. Similar exercise has been performed for the hadronic phase to obtain $R_{H\AA}^{pT}$. The theoretical results for QGP and 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 LHC the experimental results on the D suppression is 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 play less dominant role at LHC than 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 same initial condition.

It is to be noted that the theoretical descriptions over estimate the experimental data for $p_T \leq 3$ GeV at RHIC and for $p_T \leq 4$ GeV at 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. 5 displays the depletion of B mesons at LHC. The effects of the hadronic phase is found to be negli-
ingibly small. Indicating the fact that the response of the hadronic medium is less pronounced at LHC than RHIC. Therefore, the role of hadronic medium in characterizing the QGP by using heavy flavours can be ignored making the task of QGP detection less complex at LHC.

The differences in the magnitude of $R_{AA}$ in RHIC and LHC can be understood from the corresponding results plotted in Fig. 3 and Fig. 4. The temperature of the hadronic system for both RHIC and LHC varies from $T_c$ to $T_f$ (170 to 120 MeV) and therefore, the value of the drag coefficients remain same. However, the input distribution to the hadronic matter is harder at LHC than RHIC, resulting in less suppression at LHC.

Some comments on the sensitivity of $R_{AA}$ on the initial condition 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 $R_{AA}$ on 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 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. 5. For higher $T_i$ the the drag in the QGP phase is higher which results in more suppression. The net change (QGP+hadronic) also remains 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 $B$ in the hadronic medium because the hadrons drag the $D$ more than the $B$. The suppression at RHIC energy is significant and hence the hadronic contributions should be taken into account in analyzing the experimental data. It is also interesting to note that the role of hadronic medium in HFs (especially for $B$) suppressions at LHC is not substantial because $D$ and $B$ meson distributions are harder at LHC than RHIC. Since the role of hadrons in $B$ meson suppression is very minimal, therefore, $B$ may play a unique role in characterizing QGP. This has a great advantage compared to other signals of QGP, for example, in case of electromagnetic probes (see [28–30] for review) i.e. 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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\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig8.png}
\caption{(color on-line) The variation of $R_{AA}$ with $p_T$ for two sets of initial conditions.}
\end{figure}

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