Soft Open Charm Production in Heavy-Ion Collisions.

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Effects of strong longitudinal color electric fields (SCF) on the open charm production in nucleus-nucleus \((A + A)\) collisions at 200A GeV are investigated within the framework of the HIJING/BB v2.0 model. A three fold increase of the effective string tension due to in medium effects in \(A + A\) collisions, results in a sizeable \((\approx 60-70\%)\) enhancement of the total charm production cross sections \(\sigma_{c\bar{c}}^{pN}\). The nuclear modification factors show a suppression at moderate transverse momentum \(p_T\) consistent with RHIC data. At Large Hadron Collider energies the model predicts an increase of \(\sigma_{c\bar{c}}^{pN}\) by approximately an order of magnitude.

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The phase transition from hadronic degrees of freedom to partonic degrees of freedom in ultra-relativistic nuclear collisions is a central focus of experiments at the Relativistic Heavy Ion Collider (RHIC). Heavy-flavor quarks are an ideal probe to study early dynamics in these nuclear collisions. Several theoretical studies predict a substantial enhancement of open charm production associated to plasma formation of the de-confined parton matter relative to the case of a purely hadronic scenario without plasma formation. A recent analysis shows that the dynamics of heavy-quarks at RHIC are dominated by partonic or “pre-hadronic” interactions in the strongly coupled plasma (sQGP) stage and can neither be modeled by “hadronic interactions” nor described appropriately by color screening alone. Therefore, these quarks are key observables in the study of thermalization of the initially created hot nuclear matter.

A review of heavy-flavor production in heavy-ion collisions has been recently published. Direct reconstructed \(D^0\) mesons via hadronic channel \((D^0 \rightarrow K\pi)\) in \(d + Au\), \(Cu + Cu\) and \(Au + Au\) collisions have been measured. Due to the difficulty to reconstruct \(D\)-mesons hadronic decay vertex, both STAR and PHENIX have studied open charm indirectly via semileptonic decay to non-photonic electrons (NPE) or muons or radiative energy loss via multiple soft collisions. They all predict less suppression than that observed in experiments. On the other hand, a good description of the nuclear modification factor (NMF), \(R_{AA}^{p\bar{p}}(p_T)\), was obtained in non-perturbative time-dependent heavy-quark diffusion in the Quark-Gluon Plasma (QGP).

In previous papers we have shown that the dynamics of strangeness production deviates considerably from calculations based on Schwinger-like estimates for homogeneous and constant color fields and point to the contribution of fluctuations of transient strong color fields (SCF). These fields are similar with those which could appear in a “glasma” at initial stage of the collisions. In a scenario with QGP phase transition the typical field strength of SCF at RHIC energies was predicted to be about 5-12 GeV/fm. Recently Schwinger mechanism has been revisited and pair production in time-dependent electric fields has been studied. It is concluded that particles with large momentum are likely to have been created earlier than particles with small momentum and for very short temporal widths \((\Delta t \approx 10t_c, \text{ where the Compton time } t_c = 1/m_c)\) the Schwinger formula strongly underestimates the reachable particle number density.

In this paper we extend our study in the framework of HIJING/BB v2.0 model to open charm productions. We explore dynamical effects associated with long range coherent fields (i.e strong color fields, SCF), including baryon junctions and loops, with emphasis on the novel open charm observables measured at RHIC in \(p+p\) and heavy-ion collisions. Using this model we analyze the enhancement of total charm production at 200A GeV energy.

For a uniform chromoelectric flux tube with field \((E)\) the pair production rate \(\eta/p\) per unit volume for...
where for $Q = c$ or $b$, $m_Q = 1.27$, or 4.16 GeV (with $\pm 1\%$ uncertainty \[54\]). Note that $\kappa = |eE|_{\text{eff}} = \sqrt{C_2(A)/C_2(F)} \kappa_0$ is the effective string tension in terms of the vacuum string tension $\kappa_0 \approx 1$ GeV/fm and $C_2(A)$, $C_2(F)$ are the second order Casimir operators (see Ref. \[33\]). In a nuclear collisions, the local longitudinal field strength increases with the square root of the number of color exchanges proportional to the number of binary collisions per unit area ($\kappa(x_\perp,b) \propto \sqrt{T_A A(x_\perp,b)}$), where for a given impact parameter $b$ and transverse coordinate $x_\perp$, $T_A A \propto A^{2/3}$ is the Glauber $A+A$ binary collision distribution. Therefore, the effective string tension $\kappa \propto A^{1/3}$.

A measurable rate for spontaneous pair production requires “strong chromo electric fields”, such that $\kappa/m_Q^2 > 1$ at least some of the time. On the average, longitudinal electric field “string” models predict for heavier flavor a very suppressed production rate per unit volume $\gamma_Q$ via the well known Schwinger formula \[27\], since

$$\gamma_Q = \frac{\Gamma_{QQ}}{\Gamma_{q\bar{q}}} = \exp \left( -\frac{\pi (m_Q^2 - m_q^2)}{\kappa_0} \right) \ll 1 \quad (2)$$

for $Q = c$ and $q = u, d$. For a color rope on the other hand, if the average string tension value ($< \kappa >$) increases from 1.0 GeV/fm to 3.0 GeV/fm, the rate $\Gamma$ for charm pairs to tunnel through the longitudinal field in-creases from 1.0 GeV/fm to 3.0 GeV/fm, the rate $\Gamma$ for charm pairs to tunnel through the longitudinal field increases from $1.4 \cdot 10^{-12}$ to $3.5 \cdot 10^{-4}$ fm$^{-2}$, and this can lead to a net “soft” tunneling production comparable to the initial “hard” FONLL pQCD production.

The conventional hard pQCD mechanism, mainly gluon fusion \[1\], is calculated via the PYTHIA subroutines in HIJING/BB v2.0. The advantage of HIJING over PYTHIA is the ability to include novel SCF color rope effects that arise from longitudinal fields amplified by the random walk in color space of the high $x$ valence partons in $A+A$ collisions. This random walk could induce a very broad fluctuation spectrum of the effective string tension. Thus, if the average or mean $< \kappa >$ is equal to $n \kappa_0$, then the typical fluctuation is of order $1/\sqrt{n}$ which is large because $n \approx 6$ for Au nuclei. A Poisson fluctuation of effective $\kappa$ about the mean, gives a strong bias toward less probable but larger than the average value $< \kappa >$. This is amplified for heavy quarks. Here we do not investigate in details such fluctuations, but we will estimate the effects of a larger effective value $\kappa > 3$ GeV/fm on the enhancement of $\sigma_{c\bar{c}}^{NN}$.

Both STAR and PHENIX experiments have measured charm production cross sections in several collision systems. Figure \[4\] shows the measured total charm production cross sections at mid-rapidity, $d\sigma_{c\bar{c}}^{NN}/dy$ (left panel) and in all phase space, $\sigma_{c\bar{c}}^{NN}$ (right panel). The data from both experiments seems to indicate a scaling with number of binary collisions ($N_{\text{bin}}$), as expected because of the high mass of charm pairs produced in initial nucleon-nucleon collisions \[16\]. However, there is still an unresolved discrepancy of the order of a factor of two between STAR and PHENIX data.

The predictions of HIJING/BB v2.0 model without SCF (open crosses) and including SCF effects (filled squares) are shown in the figure. For completeness the results with SCF but no gluon shadowing effects (open triangles) are also included. However, in this scenario multiplicities at mid-rapidity are strongly overestimated \[35\]. The main parameters used in the calculations are given in Table II of reference \[20\], and corresponds to strengths of strong color (electric) field dependent on collision system ($\kappa = 1.5$; 2.0; 3.0 GV/fm for $p + p$, $d + Au$, and $A + A$ collisions respectively). In our calculations we estimate the total open charm production ($c + \bar{c}$) cross section considering the 12 lightest $D$-mesons ($D^0$, $\bar{D}^0$, $D^{*+}$, $D^{*0}$, $D^+$, $D^-$, $D^{++}$, $D^{*-}$, $D_s$, $D_s^*$, $D_s^*$), and the hyperons $\Lambda_c$ and $\Lambda_b$. The contribution of higher mass charm hyperons is negligible. For calculations which take into consideration SCF effects (filled squares) we obtain an increase of $60 - 70\%$ in comparison with a scenario without SCF effects (open crosses). These results describe well the PHENIX data within statistical and systematical errors and are close to the upper limit of uncertainty band of the pQCD FONLL predictions \[17\]. Our calculations also show that the scaling with $N_{\text{bin}}$ is only approximately satisfied, the reason being an interplay between the mass

\[\text{FIG. 1: (Color online) Comparison of HIJING/B ¯B v2.0 predictions for mid-rapidity (left panel) and all phase space (right panel) charm cross sections per nucleon-nucleon collisions as a function of $N_{\text{bin}}$ in (d)+A collisions. The symbols are the results with (filled squares) and without (open crosses) SCF effects. Both include quenching and shadowing (ys) effects. The open triangles are the results with SCF effects but no shadowing (xs). The values of FONLL predictions are shown as a dotted line. The band at the left mark the FONLL uncertainties \[17\]. The data are from STAR (stars) \[3, 8, 11\] and PHENIX (solid circles) \[12, 14\]. Statistical and systematical error bars are shown.} \]
dependent SCF and shadowing effects, which act in opposite directions. In fact, we calculate that only 60% of total open charm production ($c + \bar{c}$) comes from partons embedded within the target and projectile.

The study of open charm production in $d + Au$ collisions allow to separate “cold nuclear matter” effects. The initial production of $c \bar{c}$ pairs by gluon fusion might be suppressed due to gluon shadowing. We recall that shadowing is a depletion of the low-momentum parton distribution in a nucleon embedded in a nucleus compared to a free nucleon; this leads to a lowering in the (scaled) $c + \bar{c}$ production relative to $p + p$ collisions. The shadowing in the regular HIJING parameterization is implemented also in our model seems to be too strong. There is a considerable uncertainty (up to a factor of 3) in the amount of shadowing predicted at RHIC energies by the different models with HIJING predicting the strongest effect. This could explain why the results for scaled cross sections in $d + Au$ collisions are smaller than those obtained for $p + p$ collisions (see Fig. 1 left panel).

We study if we can find scenarios that would give larger enhancement of total cross sections for open charm production, than those reported in Fig. 1 (filled squares), and that would be consistent with the STAR data. The random walk in color space of heavy quark production cannot be explained within our phenomenology. The initial production of $c\bar{c}$ mesons is much smaller than the STAR data, consistent with large charm cross sections obtained by the STAR collaboration cannot be explained within our phenomenology.

The $D^0$-mesons spectra are sensitive to the dynamics of produced charm particles. In Fig. 2 we present the calculated $D^0$-mesons spectra for systems where data are available. In all cases, the calculated yield is much smaller than the STAR data, consistent with the results shown in Fig. 1. The calculated spectra show little shoulder at low $p_T$ indicating small radial flow of $D^0$-mesons consistent with the results of STAR.

Figure 3 shows our predictions for the Nuclear Modification factor (NMF), $R_{AA}(p_T)$ for $D^0$ and $\pi^0$ mesons. Data (filled symbols) are NMF for non photonic electrons, $R_{AA}^{\text{NPF}}(p_T)$ [10,11]. The data for $\pi^0$ meson (open symbols) are from reference [40]. Note, that non photonic electrons include also electrons from bottom (b) production (B $\rightarrow$ X) and the yields of $D^0$ mesons could be affected by the decay (B $\rightarrow$ D). For central (0-10%) $Au + Au$ collisions we calculate a scaled total cross section for bottom production with (without) SCF of $\sigma_{b b}^{NN} = 17.8 \mu b$ ($\sigma_{b b}^{NN} = 0.86 \mu b$). These values are few orders of magnitude lower than $\sigma_{c c}^{NN}$ and this contribution is estimated to be negligible for $p_T < 6.0$ GeV/c.

In our calculations for low $p_T$ ($0 < p_T < 2.5$ GeV/c), non-perturbative production mechanism via SCF results in a split between $D^0$ and $\pi^0$ mesons. The charged and $\pi^0$ mesons are suppressed due to conservation of energy. The yields of the $D^0$-mesons are enhanced due to an increase of $c \bar{c}$ pair production rate (see Eq. 1). In central (0-10%) $Au + Au$ collisions a suppression at moderate $p_T$ ($4 < p_T < 6$ GeV/c) as large...
as that of light quarks is observed in contrast to previous theoretical studies [18, 19, 22, 23, 41]. Our model predicts a suppression consistent with the data. We can interpret this results as experimental evidence for “in-medium mass modification” of charm quark, due to possible induced chiral symmetry restoration [22]. An in-medium mass modification has also been predicted near the phase boundary (i.e. at lower energy) in [42]. In contrast statistical hadronization model [44] predicts no medium effects at top RHIC energy.

We performed calculations at the much higher Large Hadrons Collider (LHC) energy using parameters from reference [45], i.e. $\kappa = 2.0$; 5.0 GeV/fm for $p + p$ and central (0-10 %) Pb + Pb collisions respectively. The predicted charm production cross section is approximately an order of magnitude larger than at RHIC energy. We obtain $\sigma^{NN}_{p+p} = 6.4$ mb in $p + p$ collisions and a (scaled) cross section $\sigma^{cNN}_{c} = 2.8$ mb for central Pb + Pb collisions ($N_{bin} = 960$ and $N_{ch} (y=0) = 2500$). This indicates a clear violation of scaling with $N_{bin}$ at the LHC. These values increase by a factor of 2 to 3 if the effects of shadowing are not included ( $N_{ch} (y=0) \approx 5000$ and $\sigma^{cNN}_{c} \approx 8.4$ mb).

In summary, we studied the influence of possible strong homogenous constant color fields in open charm production in heavy-ion collisions by varying the effective string tension that control Q\Q pair creation rates. This is equivalent with assuming an in-medium mass modification of charm quark. We show that this approach is an important dynamical mechanism that can explain the observed D-mesons enhancement production observed by the PHENIX experiments. Our model is based on the time-independent color field while in reality the production of Q\Q pairs is a far-from-equilibrium, time-dependent phenomenon. Thus to achieve more quantitative conclusions, such mechanisms [31] should be considered in future generation of Monte Carlo codes.

The large cross sections reported by the STAR collaboration remain unexplained within our study. Solving the discrepancy between the measurements is important, since confirmation of the STAR results may indicate the importance of other dynamical mechanisms such as pre-equilibrium production from secondary parton cascades [1], or hot-glue scenario [2].

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