# Soft Open Charm Production in Heavy-Ion Collisions

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The effects of strong longitudinal color electric fields on the open charm production in nucleus-nucleus ($A + A$) collisions at 200$A$ GeV are investigated within the framework of the HIJING/$B\bar{B}$ v2.0 model. A threefold increase of the effective string tension due to in-medium effects in $A + A$ collisions results in a sizable (≈60%–70%) enhancement of the total charm production cross sections ($\sigma_{c\bar{c}}^{NN}$). The nuclear modification factor shows a suppression at moderate transverse momentum ($p_T$) consistent with BNL Relativistic Heavy Ion Collider data. At Large Hadron Collider energies the model predicts an increase of $\sigma_{c\bar{c}}^{NN}$ by approximately an order of magnitude.

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The phase transition from hadronic degrees of freedom to partonic degrees of freedom in ultrarelativistic nuclear collisions is a central focus of experiments at the BNL Relativistic Heavy Ion Collider (RHIC). Heavy-flavor quarks are an ideal probe to study early dynamics in these nuclear collisions. Several theoretical studies predict [1–3] a substantial enhancement of open charm production associated to plasma formation of the deconfined parton matter relative to the case of a purely hadronic scenario without plasma formation. Therefore, these quarks are key observables in the study of thermalization of the initially created hot nuclear matter [4,5].

A review of heavy-flavor production in heavy-ion collisions has been recently published [6]. Direct reconstructed $D^0$ mesons via the hadronic channel ($D^0 \rightarrow K\pi$) in $d$ + Au [7], Cu + Cu [8], and Au + Au [9] collisions have been measured. Because of the difficulty to reconstruct $D$-meson hadronic decay vertex, both STAR and PHENIX have studied open charm indirectly via semileptonic decay to nonphotonic electrons (NPE) or muons [7,9–15]. Theory predicts that charm quarks are produced by initial gluon fusion [16] and their production rates are expected to be well described by perturbative quantum chromodynamics (pQCD) at fixed order plus next to-leading logarithms (FONLL) [17]. Total charm cross sections reported by both experiments are, however, only compatible with the upper limit of the FONLL predictions. In addition, the data indicate a suppression as large as that of light quarks [10,15], while, due to their large mass and to the dead cone effect, charm quarks are predicted to lose less energy than light quarks by gluon radiation in the medium [18].

Recent model calculations based on in-medium charm resonances or diffusion or collisional dissociation [19–21], radiative energy loss via few hard scatterings [22], or radiative energy loss via multiple soft collisions [23] have been applied to describe the NPE spectra. They all predict less suppression than that observed in experiments. On the other hand, a good description of the nuclear modification factor (NMF), $R_{AA}^{\rm NPE}(p_T)$, was obtained in nonperturbative time-dependent heavy-quark diffusion in the quark-gluon plasma [24].

In previous papers [25,26] we have shown that the dynamics of strangeness production deviates considerably from calculations based on Schwinger-like estimates for homogeneous and constant color fields [27] and point to the contribution of fluctuations of transient strong color fields (SCF). These fields are similar to those which could appear in a "glasma" [28] at initial stage of the collisions. In a scenario with quark-gluon plasma phase transitions the typical field strength of SCF at RHIC energies was predicted to be about 5–12 GeV/fm [29]. Recently Schwinger mechanism has been revisited [30] and pair production in time-dependent electric fields has been studied [31]. 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 ($\Delta\tau \approx 10 t_c$, where the Compton time $t_c = 1/m_c$) the Schwinger formula strongly underestimates the reachable particle number density.

In this Letter we extend our study in the framework of HIJING/$B\bar{B}$ v2.0 model [26] to open charm production. We explore dynamical effects associated with long-range coherent fields (i.e., SCF), including baryon junctions and loops [25], 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 200$A$ GeV energy.

For a uniform chromoelectric flux tube with field ($E$) the pair production rate [30,32,33] per unit volume for a heavy quark is given by

$$\Gamma = \frac{\kappa^2}{4\pi^3} \exp\left(-\frac{\pi m_Q^2}{\kappa}\right), \qquad (1)$$

where for $Q = c$ or $b$, $m_Q = 1.27$ or 4.16 GeV (with ±1% uncertainty [34]) Note that $\kappa = |eE|_{\rm eff} = \sqrt{C_2(A)/C_2(F)}\kappa_0$ is the effective string tension in terms of the vacuum string

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tension $\kappa_0 \approx 1$ GeV/fm and $C_2(A)$, $C_2(F)$ are the second-order Casimir operators (see Ref. [33]).

A measurable rate for spontaneous pair production requires "strong chromoelectric 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

$$\gamma_{Q\bar{Q}} = \frac{\Gamma_{Q\bar{Q}}}{\Gamma_{q\bar{q}}} = \exp\left(-\frac{\pi(m_Q^2 - m_q^2)}{\kappa_0}\right) \ll 1 \qquad (2)$$

for $Q = c$ and $q = u, d$. For a color rope, on the other hand, if the average string tension value ($\langle\kappa\rangle$) increases from 1.0 GeV/fm to 3.0 GeV/fm, the rate $\Gamma$ for charm pairs to tunnel through the longitudinal field increases from $\approx 1.4 \times 10^{-12}$ to $\approx 3.5 \times 10^{-4}$ fm$^{-4}$, 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/$B\bar{B}$ 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. Here we do not investigate in detail 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 1 shows the measured total charm production cross sections at midrapidity $d\sigma_{c\bar{c}}^{NN}/dy$ (left-hand panel) and in all phase space $\sigma_{c\bar{c}}^{NN}$ (right-hand panel). The data from both experiments seem to indicate a scaling with number of binary collisions ($N_{\rm bin}$), 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 2 between STAR and PHENIX data. The predictions of HIJING/$B\bar{B}$ 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 midrapidity are strongly overestimated [35]. The main parameters used in the calculations are given in Table II of Ref. [26] and correspond to strengths of strong color (electric) field dependent on collision system ($\kappa = 1.5, 2.0, 3.0$ GeV/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 ($D^0, \bar{D}^0, D^{0*}, \bar{D}^{0*}, D^+, \bar{D}^+, D^{+*}, \bar{D}^{+*}, D_s, \bar{D}_s, D_s^*, \bar{D}_s^*$) and the hyperons $\Lambda_c$ and $\bar{\Lambda}_c$. The contribution of higher mass charm hyperons is negligible. For calculations which take into consideration SCF effects (filled squares)

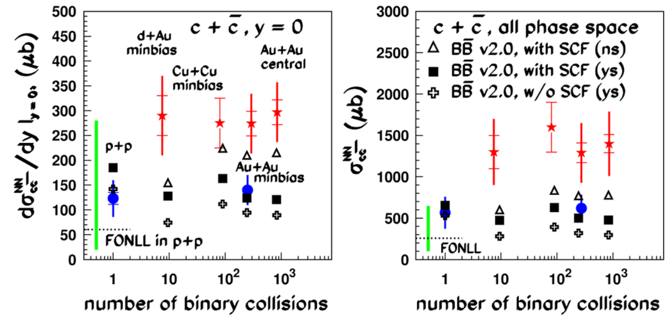


FIG. 1 (color online). Comparison of HIJING/$B\bar{B}$ v2.0 predictions for midrapidity (left-hand panel) and all phase space (right-hand panel) charm cross sections per nucleon-nucleon collision as a function of $N_{\rm bin}$ in $(d)A + A$ collisions. The symbols are the results with (filled squares) and without (open crosses) SCF effects. Both include quenching and shadowing (ys) effects. The open triangles are the results with SCF and quenching effects, but no shadowing (ns). The values of FONLL predictions are shown as a dotted line. The bands at the left indicate the FONLL uncertainties [11,17]. The data are from STAR (stars) [7–9,11] and PHENIX (solid circles) [12,14]. Statistical and systematical error bars are shown.

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 FNOLL predictions [17]. Our calculations also show that the scaling with $N_{\rm bin}$ is only approximately satisfied, the reason being an interplay between the mass 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 allows one 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 parametrization implemented also in our model seems to be too strong [36]. 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 [37]. 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-hand panel).

We study whether 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. Therefore, we study the effect of a further increase of mean value of the string tension from 3.0 to 5.0 GeV/fm on $c\bar{c}$ pair production. This results in only a modest increase of scaled cross sections, $\sigma_{c\bar{c}}^{sNN} = \sigma_{c\bar{c}}^{AA}/N_{\rm bin}$, by approximately 20% for central collisions. For values between 5–10 GeV/fm a saturation sets in, as an effect of energy and momentum conservation constraints. In our model the multiplicative factor that accounts for next-to-leading order corrections [38] in calculations of hard or semihard parton scattering processes via pQCD is set to $K = 2$. Increasing this factor to $K = 3.5$, as suggested in Ref. [38], results in an increase of $\sigma_{c\bar{c}}^{sNN}$ by approximately 70% in central Au + Au collisions, but also overpredicts by 40% the total charged particle production at midrapidity [$N_{\rm ch}$ $(y = 0)$]. Therefore, we conclude that the 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 [7–9]. 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 [11]. Note that within our phenomenology we cannot describe the large elliptic flow ($v_2$) as observed by PHENIX [15] in nonphotonic electrons.

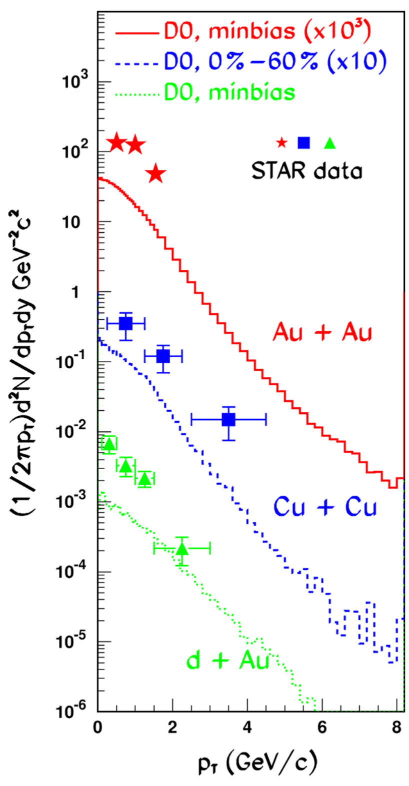


FIG. 2 (color online). Comparison of HIJING/$B\bar{B}$ v2.0 predictions for $p_T$ distribution of invariant yield for reconstructed $D^0$ in minimum-bias $(d)A + A$ collisions. For clarity the results for Cu + Cu (preliminary) and Au + Au are multiplied by 10 and $10^3$, respectively. The data are from STAR [7–9]. Only statistical error bars are shown.

However, in order to draw a more quantitative conclusion, data on reconstructed $D^0$-mesons spectra are required.

Figure 3 shows our predictions for the NMF $R_{AA}(p_T)$ for $D^0$ and $\pi^0$ mesons. Both include quenching and shadowing effects. For $D^0$ mesons the calculation without shadowing (not included here) results in a similar shape of NMF $R_{AA}(p_T)$, but shifted up by a factor of roughly 1.6. Note, that nonphotonic electrons include also electrons from bottom ($b$) production ($B \to lX$) and the yields of $D^0$ mesons could be affected by the decay ($B \to D$). For central (0%–10%) Au + Au collisions we calculate a scaled total cross section for bottom production with (without) SCF of $\sigma_{b\bar{b}}^{sNN} = 17.8$ $\mu$b ($\sigma_{b\bar{b}}^{sNN} = 0.86$ $\mu$b). These values are few orders of magnitude lower than $\sigma_{c\bar{c}}^{sNN}$ 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/$c$), nonperturbative 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 [25]. The yields of $D^0$ 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 [18,19,22,23,39]. Our model predicts a suppression consistent with the data. We can interpret this result as experimental evidence for "in-medium mass modification" of charm quark, due to possible induced chiral symmetry restoration [40]. An in-medium mass modification has also been predicted near the phase boundary (i.e., at lower energy) in [41]. In contrast, statistical hadronization model [42] predicts no medium effects at top RHIC energy.

We performed calculations at the much higher Large Hadron Collider (LHC) energy using parameters from Ref. [43], i.e., $\kappa = 2.0, 5.0$ GeV/fm for $p + p$ and central

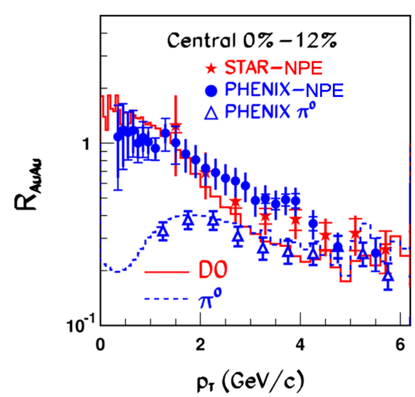


FIG. 3 (color online). Comparison of HIJING/$B\bar{B}$ v2.0 predictions of nuclear modification factor $R_{AA}(p_T)$ for $D^0$ and $\pi^0$ mesons in central (0%–12%) Au + Au collisions. Data from STAR (stars) [10] and PHENIX (circles) [15] are NMF for nonphotonic electrons, $R_{AA}^{\rm NPE}(p_T)$. The data for $\pi^0$ mesons are from PHENIX [44]. Error bars include the statistical and systematic uncertainties.

(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 $\sigma_{c\bar{c}}^{NN} = 6.4$ mb in $p + p$ collisions and a (scaled) cross section $\sigma_{c\bar{c}}^{sNN} = 2.8$ mb for central Pb + Pb collisions [$N_{\rm bin} = 960$ and $N_{\rm ch}\,(y = 0) = 2500$]. This indicates a clear violation of scaling with $N_{\rm bin}$ at the LHC. These values increase by a factor of 2–3 if the effects of shadowing are not included [$N_{\rm ch}\,(y = 0) \approx 5000$ and $\sigma_{c\bar{c}}^{sNN} \approx 8.4$ mb].

In summary, we studied the influence of possible strong homogeneous constant color fields in open charm production in heavy-ion collisions by varying the effective string tension that controls $Q\bar{Q}$ 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 $D$-meson enhanced production observed by the PHENIX experiment. Our model is based on the time-independent color field while in reality the production of $Q\bar{Q}$ pairs is a far-from-equilibrium, time-dependent phenomenon. Thus to achieve more quantitative conclusions, such mechanisms [31] should be considered in future generation 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 preequilibrium production from secondary parton cascades [1] or hot-glue scenario [2].

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[1] B. Muller and X.-N. Wang, Phys. Rev. Lett. **68**, 2437 (1992).
[2] E. Shuryak, Phys. Rev. Lett. **68**, 3270 (1992).
[3] K. Geiger, Phys. Rev. D **48**, 4129 (1993).
[4] O. Linnyk, E. L. Bratkovskaya, and W. Cassing, Int. J. Mod. Phys. E **17**, 1367 (2008).
[5] X. Zhu, M. Bleicher, S. L. Huang, K. Schweda, H. Stocker, N. Xu, and P. Zhuang, Phys. Lett. B **647**, 366 (2007).
[6] A. D. Frawley, T. Ulrich, and R. Vogt, Phys. Rep. **462**, 125 (2008).
[7] J. Adams *et al.* (STAR Collaboration), Phys. Rev. Lett. **94**, 062301 (2005).
[8] S. L. Baumgart (STAR Collaboration), arXiv:0805.4228.
[9] B. I. Abelev *et al.* (STAR Collaboration), arXiv:0805.0364.
[10] B. I. Abelev *et al.* (STAR Collaboration), Phys. Rev. Lett. **98**, 192301 (2007).
[11] Y. Zhang, J. Phys. G **35**, 104022 (2008).
[12] A. Adare *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **94**, 082301 (2005).
[13] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **96**, 032301 (2006).
[14] A. Adare *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **97**, 252002 (2006).
[15] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **98**, 172301 (2007).
[16] Z. Lin and M. Gyulassy, Phys. Rev. C **51**, 2177 (1995).
[17] R. Vogt, Eur. Phys. J. Special Topics **155**, 213 (2008); M. Cacciari, P. Nason, and R. Vogt, Phys. Rev. Lett. **95**, 122001 (2005).
[18] Yu. L. Dokshitzer and D. E. Kharzeev, Phys. Lett. B **519**, 199 (2001).
[19] H. van Hees, V. Greco, and R. Rapp, Phys. Rev. C **73**, 034913 (2006).
[20] A. Adil and I. Vitev, Phys. Lett. B **649**, 139 (2007).
[21] G. D. Moore and D. Teaney, Phys. Rev. C **71**, 064904 (2005).
[22] M. Djordjevic, M. Gyulassy, R. Vogt, and S. Wicks, Phys. Lett. B **632**, 81 (2006).
[23] N. Armesto, M. Cacciari, A. Dainese, C. A. Salgado, and U. A. Wiedemann, Phys. Lett. B **637**, 362 (2006).
[24] H. van Hees, M. Mannarelli, V. Greco, and R. Rapp, Phys. Rev. Lett. **100**, 192301 (2008).
[25] V. Topor Pop, M. Gyulassy, J. Barrette, and C. Gale, Phys. Rev. C **72**, 054901 (2005).
[26] V. Topor Pop, M. Gyulassy, J. Barrette, C. Gale, S. Jeon, and R. Bellwied, Phys. Rev. C **75**, 014904 (2007).
[27] J. S. Schwinger, Phys. Rev. **82**, 664 (1951).
[28] L. McLerran, J. Phys. G **35**, 104001 (2008).
[29] V. K. Magas, L. P. Csernai, and D. Strotman, Nucl. Phys. **A712**, 167 (2002).
[30] T. D. Cohen and D. A. McGady, Phys. Rev. D **78**, 036008 (2008).
[31] F. Hebenstreit, R. Alkofer, and H. Gies, Phys. Rev. D **78**, 061701 (2008).
[32] T. S. Biro, H. B. Nielsen, and J. Knoll, Nucl. Phys. **B245**, 449 (1984).
[33] M. Gyulassy and A. Iwazaki, Phys. Lett. B. **165**, 157 (1985).
[34] M. Steinhauser, arXiv:0809.1925.
[35] V. Topor Pop *et al.*, Phys. Rev. C **68**, 054902 (2003).
[36] Shi-yuan Li and Xin.-N. Wang, Phys. Lett. B **527**, 85 (2002).
[37] D. d'Enteria *et al.* (CMS Collaboration), J. Phys. G **35**, 104039 (2008).
[38] K. J. Eskola and H. Honkanen, Nucl. Phys. **A713**, 167 (2003).
[39] S. Wicks, W. Horowitz, M. Djordjevic, and M. Gyulassy, Nucl. Phys. **A783**, 493 (2007).
[40] D. Kharzeev and K. Tuchin, Nucl. Phys. **A753**, 316 (2005).
[41] L. Tolos, J. Schaffner-Bielich, and H. Stocker, Phys. Lett. B **635**, 85 (2006).
[42] A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, J. Phys. G **35**, 104155 (2008).
[43] V. Topor Pop, J. Barrette, C. Gale, S. Jeon, and M. Gyulassy, J. Phys. G **35**, 054001 (2008).
[44] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **91**, 072301 (2003).