Probing Parton Thermalization Time with Charm Production

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Preequilibrium parton scattering is shown to make an important contribution to the charm production in relativistic heavy ion collisions. In contrast to the gluon shadowing effect in the initial parton scattering, the enhancement of the final total open charm in the central region due to preequilibrium production could be used as a measure of the thermalization time of the dense partonic system.

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Hard or semihard parton scatterings with $p_T \gtrsim 2$ GeV/c are expected to dominate the interaction mechanism [1,2] in relativistic heavy ion collisions at $\sqrt{s} \gtrsim 100A$ GeV. Those scattered partons, usually referred to as minijets, have been estimated to contribute a large fraction of transverse energy deposited in the central region of heavy ion collisions at Brookhaven National Laboratory Relativistic Heavy Ion Collider (RHIC) and CERN Large Hadron Collider (LHC) energies. Because of their high density, the initially produced partons, mainly gluons, are expected to rescatter from each other leading to the suppression of high-p_T jets [3] as well as to partial thermal and chemical equilibration in the dense partonic system [4].

The thermalization time of the dense matter due to parton cascading and bremsstrahlung is usually longer [4,5] than what has been otherwise estimated [6]. Unless there are some yet unknown nonperturbative mechanisms which drive the system more quickly into equilibrium, the dense partonic matter could hadronize before being thermalized. Therefore, it is of interest to have some observables whose values can be related to the thermalization time. In this paper, we present arguments indicating that the total charmed quark production may be used for this purpose.

In general, we can divide the charm production into three stages: (1) initial production similar to minijets, (2) preequilibrium production from secondary parton cascade, and (3) thermal production. For a reasonable range of temperatures ($T \sim 200$–400 MeV), the thermal production is far below the initial one [7] due to the heavy quark mass $M_c \approx 1.5$ GeV/c^2. The charm production from the interaction between comovers in the hadronic phase should be even more suppressed for the same reason. On the other hand, secondary parton scatterings in the initially produced dense, though not thermalized, partonic system could lead to significant charmed quark production.

The dominant process in this preequilibrium stage is through gluon fusion. Because of the small interaction rate for $gg \to c\bar{c}$ relative to elastic gluon scattering $gg \to gg$, the chemical equilibrium time for the charmed quarks is much longer than the parton thermalization time. Therefore, the total number of charmed quarks produced in the preequilibrium stage should be approximately proportional to the thermalization time of the whole partonic system. When this preequilibrium charm production becomes comparable to, if not larger than, the initial production, the total charm can be used as a measure of the thermalization time scale. Another reason why the enhancement of hadrons with open charm is unique is that it is little influenced by final-state interactions. Since we are only interested in the central region, the nucleon intrinsic charm contribution [8] is negligible.

Minijet and initial charm production.—The number of hard or semihard parton scatterings in $A+B$ collisions can be given via perturbative QCD as

$$\frac{dN_{\rm jet}(b)}{dp_T^2\,dy_1\,dy_2} = K\int d^2r \sum_{a,b} x_1 f_{a/A}(x_1,p_T^2,\mathbf{r})\, x_2 f_{b/B}(x_2,p_T^2,\mathbf{b}-\mathbf{r})\frac{d\sigma_{ab}}{d\hat{t}}\,, \tag{1}$$

where $d\sigma_{ab}$ is the cross section for parton-parton scatterings, y_1 and y_2 are the rapidities of the scattered partons, x_1 and x_2 are the light-cone momentum fractions carried by the initial partons, and the summation runs over all parton species. The factor $K \approx 2$ accounts for next-to-leading-order effects. The parton structure density of a nucleus by our definition is

$$f_{a/A}(x,Q^2,\mathbf{r}) = t_A(\mathbf{r}) S_{a/A}(x,\mathbf{r}) f_{a/N}(x,Q^2)\,, \tag{2}$$

where $t_A(\mathbf{r})$ is the thickness of the nucleus which is normalized to $\int d^2r\, t_A(\mathbf{r}) = A$, $f_{a/N}(x,Q^2)$ is the parton structure function of a nucleon [9], and $S_{a/A}(x,\mathbf{r})$ accounts for parton shadowing. From deep inelastic scatterings [10], it is well known that the quark structure functions with small $x \lesssim 0.1$ are depleted in a nucleus relative to a free nucleon. This depletion, usually referred to as parton shadowing, is also expected for gluons. Although the present data on charm production in $p+A$ collisions can shed some light on this [11], we simply assume here that quarks and gluons are shadowed by the same amount. Motivated by geometrical consideration [12] and constrained by European Muon Collaboration data [10], we parametrize the shadowing factor

$S_{a/A}(x,\mathbf{r})$ for all parton structure functions in a nucleus as

$$S_{a/A}(x,\mathbf{r})=1-a(x)(A^{1/3}-1)\tfrac{4}{3}(1-r^2/R_A^2)^{1/2}, \quad (3)$$

where R_A is the nuclear radius and $a(x)\approx 0.1\times\exp(-x^2/0.01)$ describes the behavior of parton depletion at small $x\lesssim 0.1$ (see [2] for the complete form at moderate and high x).

If we neglect parton shadowing for a moment, the total number of parton scatterings with $p_T>p_0$ in nuclear collisions can be estimated as $N_{\text{jet}}=T_{AB}(b)\sigma_{\text{jet}}(p_0)$, where $\sigma_{\text{jet}}(p_0)$ is the inclusive minijet cross section and $T_{AB}(b)$ is the nuclear overlap function with $T_{AA}(0)\approx A^2/\pi R_A^2$. For $\sqrt{s}=200$ (6000) GeV, $\sigma_{\text{jet}}(p_0=2\text{ GeV}/c)\approx 10$ (100) mb (see [2]). Since each scattering produces at least two partons, we expect $\gtrsim 600$ (6000) partons with $p_T\gtrsim 2$ GeV/c in central Au+Au collisions at RHIC (LHC) energy. By the uncertainty principle, minijets are produced on a time scale $\tau_i\sim 1/p_0\sim 0.1$ fm/c. The corresponding initial parton density in a volume $V\sim\tau_i\pi R_A^2$ is then ~ 40 (400) fm^{-3}. Though parton shadowing could reduce this number by a half [3] (two-thirds for $\sqrt{s}=6000$ GeV), this is still a dense partonic system which is yet not thermalized.

Similarly, Eq. (1) can be used to calculate charm production in the initial parton scatterings. The change we have to make is to substitute $d\sigma_{ab}$ with $d\sigma_{ab\to c\bar{c}}$ and restrict the summation only to $gg\to c\bar{c}$ and $q\bar{q}\to c\bar{c}$. Taking into account parton shadowing, we estimate the total number of charmed quark pairs in a central Au+Au collision to be about 2 (34) at $\sqrt{s}=200$ (6000) GeV. The A dependence of charm production per central event from Eq. (1) is $N_c\propto A^{4/3}$, neglecting parton shadowing. We will only consider central $A+A$ collisions in the following.

Preequilibrium charm production.—Since the density of initially produced partons, mainly gluons, is very high, they will inevitably rescatter from each other leading to partial thermalization as well as charm production. Given the phase-space density of the initially produced gluons $f(k)$, the differential production rate is then

$$E\frac{d^3A}{d^3p}=\frac{1}{16(2\pi)^8}\int\frac{d^3k_1}{\omega_1}\frac{d^3k_2}{\omega_2}f(k_1)f(k_2)\delta^{(4)}(k_1+k_2-p-p_2)\tfrac{1}{2}g_G^2|\overline{\mathcal{M}}_{gg\to c\bar{c}}|^2\frac{d^3p_2}{E_2}, \quad (4)$$

where $g_G=16$ is the degeneracy factors for gluons and $|\overline{\mathcal{M}}_{gg\to c\bar{c}}|^2$ is the *averaged* matrix element for the $gg\to c\bar{c}$ process which is related to $d\sigma_{gg\to c\bar{c}}/d\hat{t}=|\overline{\mathcal{M}}_{gg\to c\bar{c}}|^2/16\pi\hat{s}^2$. Because of the small charm density, we can neglect the Pauli blocking of the final charm quarks. The initial phase-space density for gluons can be related to $dN_{\text{jet}}/dk_T\,dy$ as calculated from Eq. (1) by

$$f(k)=\frac{(2\pi)^2}{g_GV}\frac{1}{k_T|\mathbf{k}|}\frac{dN_{\text{jet}}}{dk_T\,dy}\equiv\frac{(2\pi)^2}{g_GV}g(k), \quad (5)$$

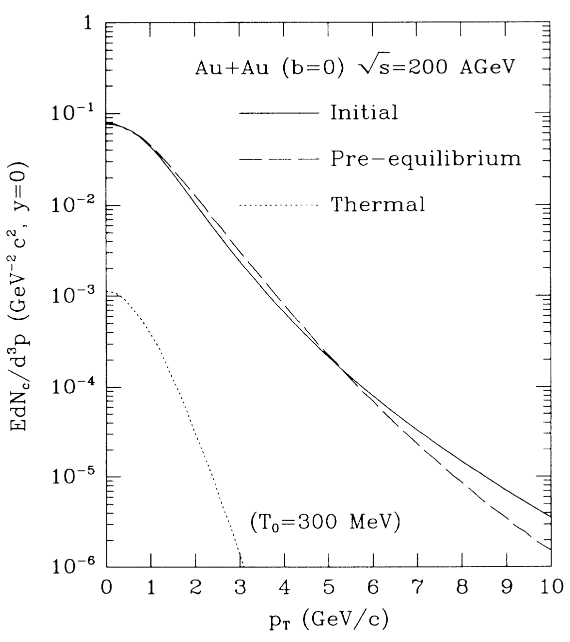

FIG. 1. The p_T distribution of initial (solid), preequilibrium with $\tau_0=1$ fm/c (dashed), and thermal (dotted) charm production in central Au+Au collisions at $\sqrt{s}=200$ GeV.

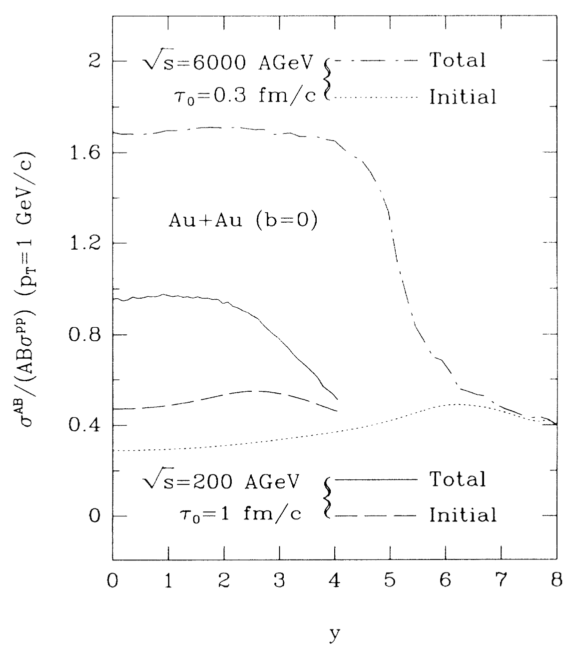

FIG. 2. The ratio $R_{AB}^{\text{charm}}=\sigma^{AB}/AB\sigma^{pp}$ for charm production at $p_T=1$ GeV/c as functions of rapidity in central Au+Au collisions at $\sqrt{s}=200$ (6000) GeV. The solid (dot-dashed) line is for the total charm with thermalization time $\tau_0=1$ (0.3) fm/c while the dashed (dotted) line is only for the initial production.

where V is the volume of the partonic system. Notice that $g(k)$ has a scale of GeV^{-3}. In our actual calculation we will use the results of the HIJING Monte Carlo model [2] for $dN_{\rm jet}/dk_T dy$, in which initial- and final-state radiation is also included. To obtain an order-of-magnitude estimate, we neglect the time evolution of the distribution $g(k)$ and assume that it remains unchanged during the thermalization time τ_0. Then the total preequilibrium charm production is

$$E\frac{d^3N_c}{d^3p} \approx \frac{\tau_0/\tau_i}{\pi R_A^2 32(2\pi)^4}\int \frac{d^3k_1}{\omega_1}\frac{d^3k_2}{\omega_2} g(k_1)g(k_2)\delta^{(4)}(k_1+k_2-p-p_2)|\overline{\mathcal{M}}_{gg\to c\bar{c}}|^2\frac{d^3p_2}{E_2}\,. \tag{6}$$

If the complicated expansion of the partonic system during τ_0 is taken into account, the dependence of $E\,d^3N_c/d^3p$ on τ_0/τ_i will change and is model dependent, but the fact that it increases with τ_0/τ_i remains. Since $g(k)$ is proportional to $A^{4/3}$ from Eq. (1), we can see that the preequilibrium charm production grows like A^2 as compared to $A^{4/3}$ for the initial production. The energy dependence is also much stronger since $g(k_1)g(k_2)$ is proportional to $\sigma_{\rm jet}^2$.

Thermal charm production.—The thermal production of charmed quarks is completely analogous to that of strange quarks which has been studied extensively. We refer to Ref. [13] for details. In our calculation, we follow the idealized scaling hydrodynamic expansion of the quark-gluon plasma with phase transition temperature $T_c=160$ MeV.

Shown in Fig. 1 are the transverse momentum distributions of charm production in central Au+Au collisions at $\sqrt{s}=200A$ GeV. For the preequilibrium production (dashed line), we have assumed the initial parton production time $\tau_i=0.1$ fm/c and the thermalization time $\tau_0=1$ fm/c. It almost looks identical to the initial direct charm production (solid line), except that its spectrum at large p_T is softer, indicating the partial thermalization due to parton cascading. For the initial temperature $T_0=300$ MeV, thermal charm production (dotted line) is negligible as compared to initial and preequilibrium production. In our calculation of the minijet and initial charm production, we have assumed that gluons and quarks are shadowed by the same amount at small x. This shadowing essentially suppresses low-p_T minijet [3] and charm production. Therefore, the ratio $R_{AB}^{\rm charm}=\sigma^{AB}/AB\sigma^{pp}$ for the initial charm production at low p_T, $=1$ GeV/c as shown in Fig. 2 (dashed line), is only about 0.5 for central Au+Au collisions at $\sqrt{s}=200A$ GeV. However, if the preequilibrium contribution with $\tau_0=1$ fm/c is included (solid line), the ratio becomes about 1 in the central rapidity region. At $\sqrt{s}=6000A$ GeV, the shadowing suppresses the initial production by $\frac{2}{3}$ (dotted line) and the preequilibrium production is so abundant that it increases the ratio $R_{AB}^{\rm charm}$ to 1.7 even though we have chosen a short thermalization time of $\tau_0=0.3$ fm/c.

The preequilibrium enhancement over the initial charm production depends sensitively on the value of thermalization time τ_0. This demonstrates that the total charm production can be used as a measure of the thermalization time scale. If some nonperturbative mechanism could drastically reduce the thermalization time, we would see instead a ratio $R_{AB}^{\rm charm}$ very close to the value from the initial production. We also note that the preequilibrium enhancement is only relative to the suppression by gluon shadowing. Since gluon shadowing is also a fundamental issue in its own right, it is therefore essential to study the charm production systematically in $p+p$ and $p+A$ collisions at the same energy where the only nuclear effect comes from gluon shadowing. Unlike J/ψ, which can be absorbed by the nuclear matter, open charm production in $p+A$ is not influenced by final-state interactions. It is therefore unique and useful for determining gluon shadowing which in turn can be used to extract information on preequilibrium charm enhancement and jet quenching [3] in $A+A$ collisions.

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