Recall a prediction on $J/\psi$ nuclear modification factor for STAR measurements

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Abstract

STAR collaboration has offered eminent nuclear modification factor of $J/\psi$ at high $p_T$ and midrapidity produced in Cu-Cu collisions at $\sqrt{s_{NN}} = 200$ GeV. Recalling a prediction we can understand that the feature of high-$p_T$ nuclear modification factor is related to $c\bar{c}$ produced by $2 \rightarrow 1$ and $2 \rightarrow 2$ partonic processes in deconfined matter particularly in the prethermal stage and to the recombination of $c$ and $\bar{c}$. The nuclear modification factor at high $p_T$ is sensitive to the earliest form of deconfined matter that does not have a temperature.

Keywords: $J/\psi$ nuclear modification factor; the prethermal stage; recombination mechanism.
Recently, STAR collaboration has measured the midrapidity ratio $R_{AA}$ of $J/\psi$ produced in Cu-Cu collisions to $p-p$ collisions at $\sqrt{s_{NN}} = 200$ GeV [1]. The ratio is a function of the transverse momentum $p_T$. The ratio increases with increasing $p_T$ and arrives at 0.9±0.2 at $p_T > 5$ GeV/c. Error bars at $p_T > 5$ GeV/c are large. If $J/\psi$, $\chi_c$ and $\psi'$ undergo only dissociation processes due to the interaction with gluons of quark-gluon plasma [2], the ratio must be smaller than 1 [3]. On the other hand, the transverse momentum larger than 5 GeV/c is very much higher than the average momentum of quarks and gluons of quark-gluon plasma in thermal equilibrium. If the $J/\psi$ nuclear modification factor $R_{AA}$ at $p_T > 5$ GeV/c is taken to be larger than 1, how can we understand the measured $p_T$ dependence? This is can be understood from my prediction [4] as follows.

The prediction in Ref. [4] is about the ratio of momentum distribution of $J/\psi$ produced in central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV to nucleon-nucleon collisions. The predicted ratio is shown by the solid curve in Fig. 1. The $J/\psi$ production includes the contributions of direct $J/\psi$, the radiative feeddown from direct $\chi_{cJ}$ and the decay of direct $\psi'$. The theoretical ratio is larger than 1 at the transverse momentum between 2.5 and 7 GeV at rapidity $y = 0$. This enhancement as stated below is caused by $c\bar{c}$ yielded through $2 \rightarrow 1$ and $2 \rightarrow 2$ partonic processes in deconfined matter particularly in the prethermal stage [4] and by the recombination of charm quark and charm antiquark [5–12].

The history of a Au-Au nuclear collision at RHIC energies can be divided into four stages: (a) the initial nucleus-nucleus collision where quark-gluon matter is produced; (b) the prethermal stage where quark-gluon matter thermalizes and a temperature is eventually established; (c) the thermal stage where quark-gluon plasma evolves and is defined as quark-gluon matter with a temperature; (d) evolution of hadronic matter until kinetic freeze-out. Longitudinal expansion of deconfined matter and hadronic matter is assumed in Ref. [4]. I stress that quark-gluon matter in the prethermal stage does not have a temperature and is the earliest form of deconfined matter.

A $c\bar{c}$ pair is produced in the initial nuclear collision, in the prethermal stage and in the thermal stage. The produced $c\bar{c}$ pair is a pointlike color singlet or a color octet pair from $2 \rightarrow 1$ processes $a + b \rightarrow c\bar{c}$ and $2 \rightarrow 2$ processes $a + b \rightarrow c\bar{c} + x$ where $a$, $b$ and $x$ denote partons. The pointlike $c\bar{c}$ pair expands and may get into free states when it travels through the deconfined matter.

A charm quark and a charm antiquark can recombine into a bound state with a probability. The probability is proportional to the nonperturbative matrix elements in nonrelativistic QCD [13],

$$< \mathcal{O}_8^H (3S_1) >, \quad < \mathcal{O}_8^H (1S_0) >, \quad < \mathcal{O}_8^H (3P_0) >$$
where \( \mathcal{O}_s^H(3S_1) = \chi^+ \sigma T^a \psi \cdot (a^+_H a_H) \psi^+ \sigma T^a \chi \), \( \mathcal{O}_s^H(1S_0) = \chi^+ T^a \psi (a^+_H a_H) \psi^+ T^a \chi \), and \( \mathcal{O}_s^H(3P_0) = \frac{1}{2} \chi^+ (-\frac{i}{2} \vec{D} \cdot \vec{\sigma}) T^a \psi (a^+_H a_H) \psi^+ (-\frac{i}{2} \vec{D} \cdot \vec{\sigma}) T^a \chi \) with \( \psi \) as the Pauli spinor field that annihilates a heavy quark, \( \chi \) as the Pauli spinor field that creates a heavy antiquark and \( a^+_H \) as the operator that creates a bound state is a constant. In the recombination mechanism proposed in Ref. [5], the probability for \( c\bar{c} \) to form a bound state is a constant.

When \( c\bar{c} \) penetrates through deconfined matter, it is broken into a free charm quark and a free charm antiquark by reactions

\[
g + c\bar{c}[n^{2S+1}L^{(1)}_j] \rightarrow c + \bar{c}, \quad g + c\bar{c}[n^{2S+1}L^{(8)}_j] \rightarrow c + \bar{c}
\]

where \( n^{2S+1}L^{(1,8)}_j \) is the spectroscopic notation for quantum numbers and for singlet or octet by the superscript. Cross sections for the reactions were obtained [4] with a formula in Ref. [2, 14]. In hadronic matter charmonia are dissociated by mesons into charmed mesons via the reactions

\[
q\bar{q} + c\bar{c}[n^{2S+1}L^{(1)}_j] \rightarrow q\bar{c} + c\bar{q}
\]

Cross sections for the reactions were calculated [4] with a formula of Ref. [15]. Based on these cross sections \( c\bar{c} \) survival probability can be obtained.

Momentum distribution of direct charmonium consists of five terms

\[
\frac{dN_{\text{direct}}}{dyd^2p_T} = \frac{dN^{2-2}_{\text{ini}}}{dyd^2p_T}(S_{a/A} \neq 1) + \frac{dN^{2-1}_{\text{pre}}}{dyd^2p_T} + \frac{dN^{2-2}_{\text{pre}}}{dyd^2p_T} + \frac{dN^{2-1}_{\text{the}}}{dyd^2p_T} + \frac{dN^{2-2}_{\text{the}}}{dyd^2p_T}
\]  

(1)

where the five terms result from \( c\bar{c} \) pairs produced in the initial nuclear collision via the \( 2 \rightarrow 2 \) processes, in the prethermal stage via the \( 2 \rightarrow 1 \) and \( 2 \rightarrow 2 \) processes and in the thermal stage via the \( 2 \rightarrow 1 \) and \( 2 \rightarrow 2 \) processes, respectively. Every term is the product of two parton distribution functions convoluted with the product of the short-distance production part, recombination probability and survival probability. The momentum distribution of prompt \( J/\psi \), \( \frac{dN^{J/\psi}_{\text{prompt}}}{dyd^2p_T} \), includes the contributions of direct \( J/\psi \), the radiative feeddown from direct \( \chi_{cJ} \) and the decay of direct \( \psi' \). Let \( \frac{dN^{J/\psi}_0}{dyd^2p_T} = \frac{dN^{2-2}_{\text{the}}}{dyd^2p_T}(S_{a/A} = 1) \) be the momentum distribution of prompt \( J/\psi \) while the cross sections for charmonia dissociated by gluons and hadrons are set as zero. The nuclear modification factor is

\[
R_{AA} = \frac{\frac{dN^{J/\psi}_{\text{prompt}}}{dyd^2p_T}}{\frac{dN^{J/\psi}_0}{dyd^2p_T}}
\]  

(2)

The \( R_{AA} \) has been shown in Fig. 1.

\( R_{AA} < 1 \) if \( S_{a/A} \neq 1 \), \( \frac{dN^{2-1}_{\text{pre}}}{dyd^2p_T} = \frac{dN^{2-2}_{\text{pre}}}{dyd^2p_T} = \frac{dN^{2-1}_{\text{the}}}{dyd^2p_T} = \frac{dN^{2-2}_{\text{the}}}{dyd^2p_T} = 0 \), and the charmonium dissociation cross sections are taken into account. Therefore, \( R_{AA} > 1 \) corresponding to
\[
\frac{dN_{2\to 1}}{dyd^2p_T} \neq 0, \quad \frac{dN_{2\to 2}}{dyd^2p_T} \neq 0, \quad \frac{dN_{\text{th}}}{dyd^2p_T} \neq 0 \quad \text{and} \quad \frac{dN_{\text{th}}}{dyd^2p_T} \neq 0
\]

indicates that charmonia yielded in the prethermal stage and in the thermal stage overcome the loss of charmonia due to the dissociation of charmonia in collisions with gluons and hadrons. Now the question left is why the ratio \( R_{AA} > 1 \) can take place at large \( p_T \)?

Momentum and space distributions of partons in the prethermal stage were studied in detail in Refs. [16–18]. The Fig. 5 given by Eskola and Wang [16] showed the variation of transverse momentum distribution \( dN/d^2p_T \) with time. Before hard scatterings partons are in Gaussian distribution due to the initial state radiation. However, the large momentum transfer in the hard scatterings considerably increases the parton numbers at large \( p_T \) and an approximate exponential distribution comes with a larger \( p_T \) tail. The abundance of partons with transverse momenta greater than 5 GeV is exactly a requisite what we want for getting the enhancement of \( J/\psi \) production at large \( p_T \) as the \( 2 \to 1 \) processes \( a + b \to c \bar{c} \) explicitly lead to large-\( p_T \) \( c \bar{c} \) pairs. The dashed, dot-dashed and dotted curves in Figs. 2-3 stand for direct charmonia from the initial nuclear collision, the prethermal stage and the thermal stage, respectively. We found that the yield of charmonia resulting from \( c \bar{c} \) pairs produced in the prethermal stage can be larger than that in the initial nuclear collision and can be much larger than that in the thermal stage. Therefore, quark-gluon matter in the perthermal stage dominates the contributions to \( R > 1 \).

We have seen that \( R > 1 \) in the region \( 2.5 \text{ GeV} < p_T < 7 \text{ GeV} \) at \( y = 0 \) is a result of \( c \bar{c} \) yielded from the prethermal stage and by means of the recombination mechanism. In Cu-Cu collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) the thermal stage is shortened or disappeared and the number density of deconfined matter gets smaller. Hence, charmonium dissociation gets weaker and less \( c \bar{c} \) pairs are produced. But the two factors compete. Since quarks and gluons at high \( p_T \) in the prethermal stage are still abundant, we can expect \( R_{AA} \sim 0.9 \) or even larger than 1 as a result of deconfined matter in the prethermal stage as well as the recombination mechanism.

In summary, the enhancement of \( J/\psi \) at high \( p_T \) at midrapidity is related to the earliest form of deconfined matter, i.e., quark-gluon matter in the prethermal stage. The nuclear modification factor \( R_{AA} \sim 0.9 \) or even larger is due to \( c \bar{c} \) produced in deconfined matter in the prethermal stage and the recombination of \( c \) and \( \bar{c} \).

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Figure 1: Ratio versus transverse momentum at rapidity $y = 0$ for prompt $J/\psi$ production in central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV.
Figure 2: $J/\psi$ momentum distributions versus rapidity at $p_T = 4$ GeV in the left panel and transverse momentum at $y = 0$ in the right panel for central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The dashed, dot-dashed, dotted and lower solid curves correspond to $c\bar{c}$ productions in the initial collision, the prethermal stage, the thermal stage and the all three stages (direct $J/\psi$), respectively. The upper solid curves (prompt $J/\psi$) are the sum of all contributions including the radiative feeddown from direct $\chi_{cJ}$ and the decay of direct $\psi'$. 
Figure 3: Direct $\psi'$ momentum distributions versus rapidity at $p_T = 4$ GeV in the left panel and transverse momentum at $y = 0$ in the right panel for central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The dashed, dot-dashed, dotted and solid curves correspond to $c\bar{c}$ productions in the initial collision, the prethermal stage, the thermal stage and the all three stages (direct $\psi'$), respectively.
Figure 4: Direct $\chi_c$ momentum distributions versus rapidity at $p_T = 4$ GeV in the left panel and transverse momentum at $y = 0$ in the right panel for central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The dashed, dot-dashed, dotted and solid curves correspond to $c\bar{c}$ productions in the initial collision, the prethermal stage, the thermal stage and the all three stages (direct $\chi_c$), respectively.