Nuclear modification factor for J/ψ production in nucleus-nucleus collisions*

XU Xiao-Ming(许晓明)[1)] ZHOU Jie(周杰)

Department of Physics, Shanghai University, Shanghai 200444, China

Abstract: The STAR Collaboration has offered an eminent nuclear modification factor of J/ψ 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 $2\to1$ and $2\to2$ 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.

Key words: nuclear modification factor, prethermal stage, recombination mechanism

PACS: 12.38.Mh, 24.85.+p, 25.75.Dw **DOI:** 10.1088/1674-1137/35/5/011

1 Introduction

Recently, the STAR Collaboration has measured the midrapidity ratio R_{AA} of J/ψ produced in Cu-Cu collisions to p-p collisions at $\sqrt{s_{NN}}=200$ GeV [1, 2]. The ratio increases with increasing transverse momentum 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/ψ, χ_c and ψ′ undergo only dissociation processes due to the interaction with gluons of quark-gluon plasma [3], the ratio must be smaller than 1 [4]. 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/ψ nuclear modification factor R_{AA} at $p_T>5$ GeV/c is taken to be larger than 1 within the error bars, how can we understand the measured p_T dependence? In this paper, we show that this can be understood from the prediction in Ref. [5]. As stated in the next section, the eminent measured p_T dependence owes itself to the existence of deconfined matter and the recombination of charm quarks and charm antiquarks in matter [6].

2 J/ψ enhancement

The prediction in Ref. [5] is about the ratio of momentum distribution of J/ψ 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/ψ production includes the contributions of direct J/ψ, the radiative feeddown from direct χ_{cJ} and the decay of direct ψ′. 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 $2\to1$ and $2\to2$ partonic processes in deconfined matter, particularly in the prethermal stage [5], and by the recombination of the charm quark and the charm antiquark [6–13].

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; and (d) evolution of hadronic matter until kinetic freeze-out. Longitudinal expansion of deconfined matter and hadronic matter is assumed in Ref. [5]. We stress that quark-gluon matter in the prethermal stage does not have a temperature and is the earliest form of deconfined matter.

Received 12 August 2010

* Supported by National Natural Science Foundation of China (10675079)

1) E-mail: xmxu@mail.shu.edu.cn

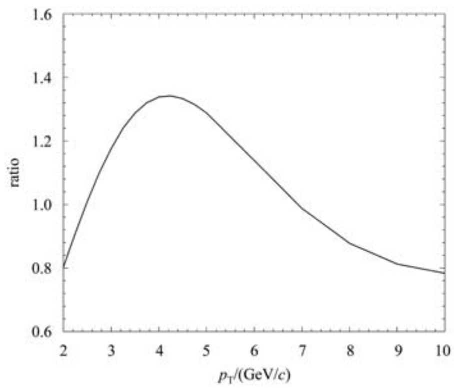

Fig. 1. Ratio versus transverse momentum at rapidity $y=0$ for prompt J/ψ production in central Au-Au collisions at $\sqrt{s_{\rm NN}}=200$ GeV.

A $\mathrm{c\bar{c}}$ pair is produced in the initial nuclear collision, in the prethermal stage and in the thermal stage. The $\mathrm{c\bar{c}}$ pair produced from $2\rightarrow1$ processes $\mathrm{a+b\rightarrow c\bar{c}}$ and $2\rightarrow2$ processes $\mathrm{a+b\rightarrow c\bar{c}+x}$ where a, b and x denote partons is a pointlike color singlet or a color octet pair. The pointlike $\mathrm{c\bar{c}}$ pair expands and gets into a physical bound state or 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 recombination probability in Ref. [6] is proportional to the nonperturbative matrix elements in nonrelativistic QCD [14],

$$\langle\mathcal{O}_8^{\rm H}(^3S_1)\rangle,\ \ \langle\mathcal{O}_8^{\rm H}(^1S_0)\rangle,\ \ \langle\mathcal{O}_8^{\rm H}(^3P_0)\rangle$$

where

$$\mathcal{O}_8^{\rm H}(^3S_1)\ =\ \chi^+\vec{\sigma}T^a\psi\cdot(a_{\rm H}^+a_{\rm H})\psi^+\vec{\sigma}T^a\chi,$$

$$\mathcal{O}_8^{\rm H}(^1S_0)\ =\ \chi^+T^a\psi(a_{\rm H}^+a_{\rm H})\psi^+T^a\chi,$$

and

$$\mathcal{O}_8^{\rm H}(^3P_0)\ =\ \frac{1}{3}\chi^+\left(-\frac{\rm i}{2}\overleftrightarrow{D}\cdot\vec{\sigma}\right)T^a\psi(a_{\rm H}^+a_{\rm H})\psi^+ \times\left(-\frac{\rm i}{2}\overleftrightarrow{D}\cdot\vec{\sigma}\right)T^a\chi$$

with ψ as the Pauli spinor field that annihilates a heavy quark, χ as the Pauli spinor field that creates a heavy antiquark and $a_{\rm H}^+$ as the operator that creates the quarkonium H in the out state. The nonperturbative matrix elements are constants. In the recombination mechanism proposed in Ref. [6], the recombination probability is also proportional to a medium modification factor that depends on temperature and is related to cross sections for reactions $\mathrm{g+c\bar{c}}[^{2S+1}L_J^{(8)}]\rightarrow\mathrm{c+\bar{c}}$ where in addition to the spectroscopic notation $n^{2S+1}L_J$ the superscript 8 means octet.

When a singlet $\mathrm{c\bar{c}}$ penetrates through the deconfined matter, it is broken into a free charm quark and a free charm antiquark by reactions

$$\mathrm{g+c\bar{c}}[n^{2S+1}L_J^{(1)}]\rightarrow\mathrm{c+\bar{c}},$$

where the singlet is indicated by the superscript 1. The cross sections for the reactions were obtained [5] with a formula in Refs. [3, 15]. In hadronic matter, charmonia dissociated by mesons yield charmed mesons via the reaction

$$\mathrm{q\bar{q}+c\bar{c}}[n^{2S+1}L_J^{(1)}]\rightarrow\mathrm{q\bar{c}+c\bar{q}}.$$

The cross sections for the reaction were calculated [5] with a formula of Ref. [16]. Based on these cross sections for charmonia dissociated by gluons and hadrons, $\mathrm{c\bar{c}}$ survival probability can be obtained.

The momentum distribution of direct charmonium consists of five terms,

$$\frac{{\rm d}N_{\rm direct}}{{\rm d}y{\rm d}^2p_{\rm T}}\ =\ \frac{{\rm d}N_{\rm ini}^{2\rightarrow2}}{{\rm d}y{\rm d}^2p_{\rm T}}(S_{a/A}\neq1)+\frac{{\rm d}N_{\rm pre}^{2\rightarrow1}}{{\rm d}y{\rm d}^2p_{\rm T}} +\frac{{\rm d}N_{\rm pre}^{2\rightarrow2}}{{\rm d}y{\rm d}^2p_{\rm T}}+\frac{{\rm d}N_{\rm the}^{2\rightarrow1}}{{\rm d}y{\rm d}^2p_{\rm T}}+\frac{{\rm d}N_{\rm the}^{2\rightarrow2}}{{\rm d}y{\rm d}^2p_{\rm T}},\quad(1)$$

where the five terms result from $\mathrm{c\bar{c}}$ pairs produced in the initial nuclear collision via the $2\rightarrow2$ processes, in the prethermal stage via the $2\rightarrow1$ and $2\rightarrow2$ processes and in the thermal stage via the $2\rightarrow1$ and $2\rightarrow2$ processes, respectively. Every term is the product of two parton distribution functions convoluted with the product of the short-distance production part, the recombination probability and the survival probability. The momentum distribution of prompt J/ψ,

$$\frac{{\rm d}N_{\rm prompt}^{\rm J/\psi}}{{\rm d}y{\rm d}^2p_{\rm T}},$$

includes the contributions of direct J/ψ, the radiative feeddown from direct $\chi_{\rm cJ}$ and the decay of direct ψ′. $S_{a/A}$ is the nuclear parton shadowing factor. Let

$$\frac{{\rm d}N_0^{\rm J/\psi}}{{\rm d}y{\rm d}^2p_{\rm T}}=\frac{{\rm d}N_{\rm ini}^{2\rightarrow2}}{{\rm d}y{\rm d}^2p_{\rm T}}(S_{a/A}=1)$$

be the momentum distribution of prompt J/ψ if the cross sections for charmonia dissociated by gluons and hadrons are set as zero and no recombination of charm quarks and charm antiquarks is allowed. The nuclear modification factor is

$$R_{\rm AA}=\frac{{\rm d}N_{\rm prompt}^{\rm J/\psi}}{{\rm d}y{\rm d}^2p_{\rm T}}\bigg/\frac{{\rm d}N_0^{\rm J/\psi}}{{\rm d}y{\rm d}^2p_{\rm T}}.\quad(2)$$

The ratio $R_{\rm AA}$ is shown in Fig. 1.

The inequality $R_{\rm AA}<1$ holds if $S_{a/A}\neq1$,

$$\frac{{\rm d}N_{\rm pre}^{2\rightarrow1}}{{\rm d}y{\rm d}^2p_{\rm T}}=\frac{{\rm d}N_{\rm pre}^{2\rightarrow2}}{{\rm d}y{\rm d}^2p_{\rm T}}=\frac{{\rm d}N_{\rm the}^{2\rightarrow1}}{{\rm d}y{\rm d}^2p_{\rm T}}=\frac{{\rm d}N_{\rm the}^{2\rightarrow2}}{{\rm d}y{\rm d}^2p_{\rm T}}=0,$$

and only the charmonium dissociation cross sections are taken into account. Therefore, $R_{\rm AA} > 1$ corresponds to the case of

$$\frac{{\rm d}N^{2\to 1}_{\rm pre}}{{\rm d}y{\rm d}^2p_{\rm T}} \neq 0,\ \frac{{\rm d}N^{2\to 2}_{\rm pre}}{{\rm d}y{\rm d}^2p_{\rm T}} \neq 0,\ \frac{{\rm d}N^{2\to 1}_{\rm the}}{{\rm d}y{\rm d}^2p_{\rm T}} \neq 0$$

and

$$\frac{{\rm d}N^{2\to 2}_{\rm the}}{{\rm d}y{\rm d}^2p_{\rm T}} \neq 0,$$

and this indicates that charmonia yielded in the prethermal stage and in the thermal stage as well as from the recombination processes 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 can become larger than 1 at large $p_{\rm T}$.

Momentum and space distributions of partons in the prethermal stage were studied in detail in Refs. [17–19]. Fig. 5 given by Eskola and Wang [17] showed the variation in transverse momentum distribution ${\rm d}N/{\rm d}^2p_{\rm T}$ with time. Before hard scattering partons are in Gaussian distribution due to the initial state radiation. However, the large momentum transfer in the hard scattering considerably increases the parton numbers at large $p_{\rm T}$ and an approximate exponential distribution comes with a larger $p_{\rm T}$ tail. The abundance of partons with transverse momenta greater than 5 GeV is exactly what we want for getting the enhancement of J/ψ production at large $p_{\rm T}$ as the $2 \to 1$ processes ${\rm a}+{\rm b} \to {\rm c\bar{c}}$ explicitly lead to large-$p_{\rm T}$ ${\rm c\bar{c}}$ pairs. The dashed, dot-dashed and dotted curves in Figs. 2–4 stand for the direct charmonia from the initial nuclear collision, the prethermal stage and the thermal stage, respectively. We found that the yield of charmonia resulting from ${\rm c\bar{c}}$ pairs

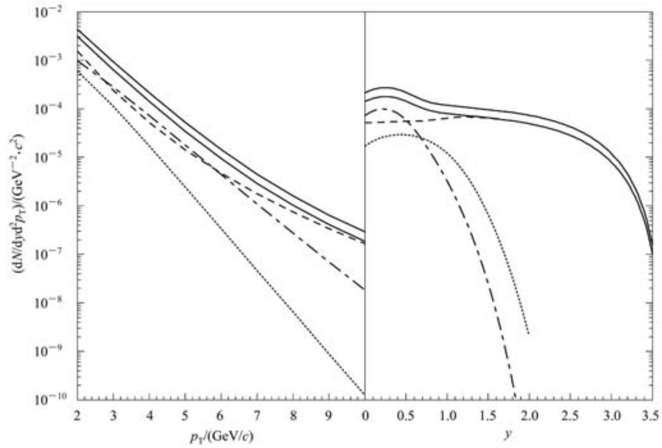

Fig. 2. J/ψ momentum distributions versus transverse momentum at $y = 0$ in the left panel and versus rapidity at $p_{\rm T} = 4$ GeV in the right panel for central Au-Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. The dashed, dot-dashed, dotted and lower solid curves correspond to ${\rm c\bar{c}}$ yields in the initial collision, the prethermal stage, the thermal stage and the all three stages (direct J/ψ), respectively. The upper solid curves (prompt J/ψ) are the sum of all contributions including the radiative feeddown from direct $\chi_{\rm cJ}$ and the decay of direct ψ′.

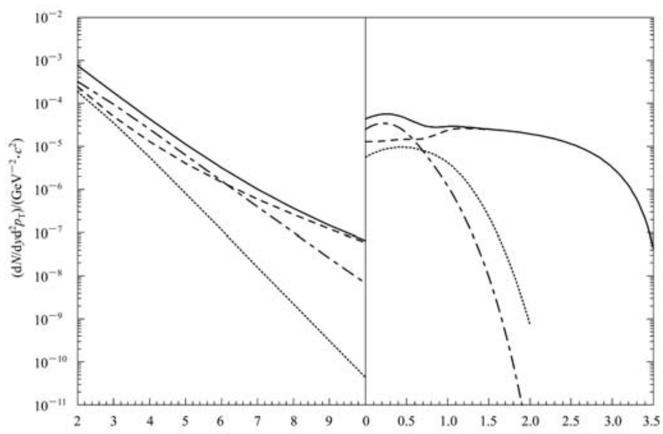

Fig. 3. Direct ψ′ momentum distributions versus transverse momentum at $y=0$ in the left panel and versus rapidity at $p_{\rm T} = 4$ GeV in the right panel for central Au-Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. The dashed, dot-dashed, dotted and solid curves correspond to ${\rm c\bar{c}}$ yields in the initial collision, the prethermal stage, the thermal stage and the all three stages (direct ψ′), respectively.

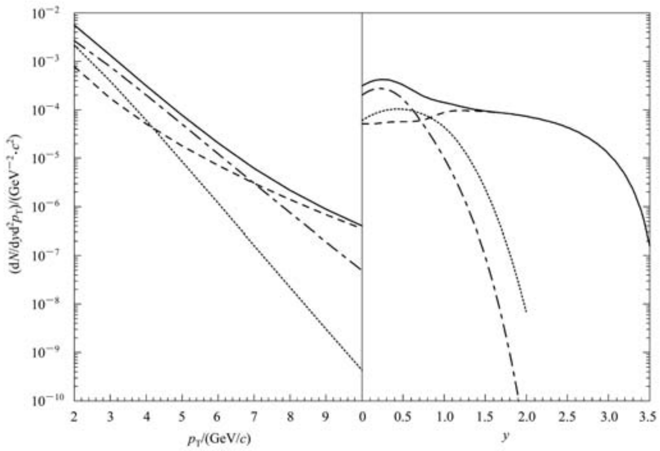

Fig. 4. Direct χ_c momentum distributions versus transverse momentum at $y=0$ in the left panel and versus rapidity at $p_T = 4$ GeV in the right panel for central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The dashed, dot-dashed, dotted and solid curves correspond to $c\bar{c}$ yields in the initial collision, the prethermal stage, the thermal stage and the all three stages (direct χ_c), respectively.

produced in the prethermal stage can be larger than those in the initial nuclear collision and can be much larger than those in the thermal stage. Therefore, quark-gluon matter in the prethermal stage can dominate the contributions to $R_{AA} > 1$.

We have seen that $R_{AA} > 1$ in the region 2.5 GeV $< p_T <$ 7 GeV at $y = 0$ is a result of $c\bar{c}$ yielded mainly from the prethermal stage and by means of the recombination mechanism. In Cu-Cu collisions at $\sqrt{s_{NN}} = 200$ GeV, the thermal stage is shortened or disappears and the number density of deconfined matter gets smaller. Hence, charmonium dissociation gets weaker and fewer $c\bar{c}$ 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. The recently published PHENIX data on J/ψ nuclear modification factor at $p_T < 5$ GeV/c in Cu-Cu collisions [20] do not mean disagreement in comparison with the STAR data in the present statistics.

3 Conclusions

We have compared our prediction with the STAR data on the p_T dependence of J/ψ nuclear modification factor. The enhancement of J/ψ at high p_T at midrapidity is related to the recombination mechanism and 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 mainly due to $c\bar{c}$ produced in deconfined matter in the prethermal stage and the recombination of c and $\bar{c}$.

References

1 TANG Z (STAR collaboration). J. Phys. G, 2008, **35**: 104135
2 Abelev B I et al. (STAR collaboration). Phys. Rev. C, 2009, **80**: 041902
3 Kharzeev D, Satz H. Phys. Lett. B, 1994, **334**: 155
4 XU X M, Kharzeev D, Satz H, WANG X N. Phys. Rev. C, 1996, **53**: 3051
5 XU X M. Nucl. Phys. A, 2002, **697**: 825
6 XU X M. Nucl. Phys. A, 1999, **658**: 165
7 Braun-Munzinger P, Stachel J. Phys. Lett. B, 2000, **490**: 196
8 Thews R L, Schroedter M, Rafelski J. Phys. Rev. C, 2001, **63**: 054905
9 Grandchamp L, Rapp R. Phys. Lett. B, 2001, **523**: 60
10 Gorenstein M I, Kostyuk A P, Stöcker H, Greiner W. Phys. Lett. B, 2001, **509**: 277
11 LIN Z W, Molnar D. Phys. Rev. C, 2003, **68**: 044901
12 Greco V, Ko C M, Rapp R. Phys. Lett. B, 2004, **595**: 202
13 YAN L, ZHUANG P, XU N. Phys. Rev. Lett., 2006, **97**: 232301
14 Caswell W E, Lepage G P. Phys. Lett. B, 1986, **167**: 437; Lepage G P, Magnea L, Nakhleh C, Magnea U, Hornbostel K. Phys. Rev. D, 1992, **46**: 4052; Bodwin G T, Braaten E, Lepage G P. Phys. Rev. D, 1995, **51**: 1125
15 Peskin M E. Nucl. Phys. B, 1979, **156**: 365; Bhanot G, Peskin M E. Nucl. Phys. B, 1979, **156**: 391
16 Barnes T, Swanson E S. Phys. Rev. D, 1992, **46**: 131; Swanson E S. Ann. Phys. (N.Y.), 1992, **220**: 73
17 Eskola K J, WANG X N. Phys. Rev. D, 1994, **49**: 1284
18 Lévai P, Müller B, WANG X N. Phys. Rev. C, 1995, **51**: 3326
19 LIN Z, Gyulassy M. Phys. Rev. C, 1995, **51**: 2177
20 Adare A et al. (PHENIX collaboration). Phys. Rev. Lett., 2008, **101**: 122301