PHYSICAL REVIEW C **75**, 044902 (2007)

J/ψ production in Au+Au and Cu+Cu collisions at $\sqrt{s}_{NN} = 200$ GeV and the threshold model

A. K. Chaudhuri*
Variable Energy Cyclotron Centre, 1/AF, Bidhan Nagar, Kolkata 700 064, India
(Received 4 October 2006; published 12 April 2007)

Using the quark gluon plasma (QGP) motivated threshold model, where all the J/ψ's are suppressed above a threshold density, we have analyzed the recent PHENIX data on the participant number dependence of the nuclear modification factor for J/ψ's, in Au+Au collisions, at RHIC energy, $\sqrt{s}_{NN} = 200$ GeV. Centrality dependence of midrapidity J/ψ suppression in Au+Au collisions are well explained in the model for threshold density $n_c \approx 3.6 \ \text{fm}^{-2}$. PHENIX data on J/ψ suppression at forward rapidity data are not explained in the model. The analysis strongly supports deconfined matter formation in central Au+Au collisions at midrapidity. We have also analyzed the preliminary PHENIX data on J/ψ suppression in Cu+Cu collisions. Cu+Cu data are not explained in the threshold model.

DOI: 10.1103/PhysRevC.75.044902 PACS number(s): 25.75.Dw, 12.38.Mh, 24.85.+p

I. INTRODUCTION

In relativistic heavy ion collisions J/ψ suppression has been recognized as an important tool to identify the possible phase transition to quark-gluon plasma. Because of the large mass of the charm quarks, $c\bar{c}$ pairs are produced on a short time scale. Their tight binding also makes them immune to final state interactions. Their evolution probes the state of matter in the early stage of the collisions. Matsui and Satz [1] predicted that in presence of quark-gluon plasma (QGP), binding of a $c\bar{c}$ pair into a J/ψ meson will be hindered, leading to the so-called J/ψ suppression in heavy ion collisions [1]. Over the years, several groups have measured the J/ψ yield in heavy ion collisions (for a review of the data prior to RHIC energy collisions, and the interpretations see Refs. [2,3]). In brief, experimental data do show suppression. However, this could be attributed to the conventional nuclear absorption, also present in pA collisions.

In recent Au+Au collisions at RHIC, one observe a dramatic suppression of hadrons with high momentum, transverse to beam direction (high p_T suppression) [4–7]. This has been interpreted as an evidence for the creation of high density, color opaque medium of deconfined quarks and gluons [8]. It is expected that a high density, color opaque medium will leave its imprint on J/ψ production. At RHIC energy, it has been argued that rather than suppression, charmonium production will be enhanced [9,10]. Due to large initial energy, a large number of $c\bar{c}$ pairs will be produced in initial hard scatterings. Recombination of $c\bar{c}$ can occur, enhancing the charmonium production. Recently, the PHENIX collaboration have published their measurement of the centrality dependence of J/ψ suppression in Au+Au collisions at RHIC energy [11]. Data are taken at midrapidity ($|y| < 0.35$) and at forward rapidity ($1.2 < |y| < 2.2$). In most central Au+Au collisions, J/ψ suppression factor is ~3 at midrapidity and ~6 at forward rapidity. J/ψ's are more suppressed at forward rapidity than at midrapidity. At midrapidity, centrality dependence of J/ψ suppression shows an indication of change in slope. At forward rapidity on the other hand, no such indication is obtained. The PHENIX collaboration have also measured the centrality dependence of J/ψ suppression in Cu+Cu collisions, at midrapidity and forward rapidity [12]. Analysis is not yet completed. Preliminary analysis indicate that, within the experimental errors, in most central Cu+Cu collisions, both at midrapidity and at forward rapidity, J/ψ's are suppressed by a similar factor of ~2, with a hint of more suppression in midrapidity data. Unlike in Au+Au collisions, in Cu+Cu collisions, J/ψ suppression does not show large dependence on rapidity. PHENIX data on J/ψ production in Au+Au/Cu+Cu collisions, are not consistent with models which predict J/ψ enhancement [9,10]. Various models, e.g., co-mover model [13], statistical coalescence model [14], or the kinetic model [15,16], also fail to explain the (preliminary) PHENIX data on the nuclear modification factor for J/ψ in Au+Au collisions. The data are also not explained in the Glauber model of normal nuclear absorption [17]. Recently, in a QCD based nuclear absorption model, we analyzed the preliminary PHENIX data on J/ψ suppression in Cu+Cu and in Au+Au collisions [18]. In the QCD based nuclear absorption model [19,20], a $c\bar{c}$ pair, during its passage through a nuclear medium, gain relative four-square momentum. Some of the pairs gain enough to cross the open charm threshold and are lost. The model explained the PHENIX data on the centrality dependence of J/ψ suppression in Cu+Cu collisions at RHIC but failed for Au+Au collisions. It was concluded that in Au+Au collisions, J/ψ are suppressed in a medium, unlike that produced in SPS energy nuclear collisions or at RHIC energy Cu+Cu collisions. Indeed, Cu+Cu data are explained in models that takes into account a suppression that depend on local densities [21,22].

If in Au+Au collisions, J/ψ's are suppressed in a deconfined matter, PHENIX data should be explained in a QGP motivated model, like the threshold model [23,24]. Blaizot *et al.* [23,24], proposed the threshold model to explain the NA50 data on anomalous J/ψ suppression in 158A GeV Pb+Pb collisions at SPS energy [25]. To mimic the onset of deconfining phase transition above a critical energy density and subsequent melting of J/ψ's, J/ψ suppression was linked with the local energy density. If the energy density at the point

*Email address: akc@veccal.ernet.in

where J/ψ is formed, exceeds a critical value (ε_c), J/ψ's disappear.

In the present paper, in the threshold model, we have analyzed the recent PHENIX data [11] on the centrality dependence of J/ψ suppression in Au+Au collisions. Like the Glauber model of nuclear absorption, the threshold model is also designed for J/ψ suppression at midrapidity. In these models, J/ψ suppression does not depend on the rapidity variable. Rapidity dependence of J/ψ suppression, as observed in PHENIX Au+Au or in Cu+Cu collisions cannot be explained in the threshold model. Such dependence can only be accommodated in the model if the parameters of the model, (i) J/ψ-nucleon absorption cross section and (ii) the threshold density, depend on rapidity. As it will be shown below, the centrality dependence of J/ψ suppression in Au+Au collisions, at midrapidity, is well explained in the model. The model however fails to explain the centrality dependence of J/ψ suppression at forward rapidity. We have also analyzed the preliminary PHENIX data [12] on the centrality dependence of J/ψ suppression in Cu+Cu collisions. The Glauber model of nuclear absorption fails to describe the centrality dependence of mid/forward rapidity J/ψ suppression in Cu+Cu collisions. The threshold model on the other hand requires very small threshold density (<2.63 fm^{-2}) and even with small threshold density, the model fails to describe either the midrapidity or forward rapidity data. The PHENIX collaboration has also published the centrality dependence of p_T broadening of J/ψ in Au+Au and in Cu+Cu collisions [26,27]. We also analyze the p_T broadening data. Here again, the quality of data is poor and no definitive conclusions can be obtained from the p_T broadening data.

The plan of the paper is as follows. In Sec. II, we briefly describe the threshold model. The PHENIX data on the centrality dependence of J/ψ suppression are analyzed in Sec. III. In Sec. IV, we analyze the PHENIX data on the p_T broadening of J/ψ. Summary and conclusions are drawn in Sec. V.

II. THRESHOLD MODEL

The details of the threshold model could be found in [23,24]. It is assumed that the fate of J/ψ depends on the local energy density, which is proportional to participant density. If the energy density or equivalently, the participant density, exceeds a critical or threshold value, deconfined matter is formed and all the J/ψ's are completely destroyed (anomalous suppression). This anomalous suppression is in addition to the "conventional nuclear absorption". The transverse expansion of the system is neglected. It is implicitly assumed that J/ψ's are absorbed before the transverse expansion sets in.

In the threshold model, the number of J/ψ mesons, produced in a AA collision, at impact parameter $\mathbf{b}$ can be written as

$$\sigma_{AA}^{J/\psi}(\mathbf{b}) = \sigma_{NN}^{J/\psi} \int d^2\mathbf{s} T_A^{\rm eff}(\mathbf{s}) T_B^{\rm eff}(\mathbf{b}-\mathbf{s}) \times S_{\rm anom}(\mathbf{b},\mathbf{s}), \quad (1)$$

where $T^{\rm eff}(b)$ is the effective nuclear thickness,

$$T^{\rm eff}(\mathbf{b}) = \int_{-\infty}^{\infty} dz \rho(\mathbf{b},z) \exp\left(-\sigma_{\rm abs} \int_z^{\infty} dz' \rho(\mathbf{b},z')\right), \quad (2)$$

$\sigma_{\rm abs}$ being the J/ψ-nucleon absorption cross section. $S_{\rm anom}(\mathbf{b},\mathbf{s})$ in Eq. (1) is the anomalous suppression factor introduced by Blaizot *et al.* [23,24]. Assuming that all the J/ψ's get suppressed above a threshold density (n_c), the anomalous suppression can be written as

$$S_{\rm anom}(\mathbf{b},\mathbf{s}) = \Theta(n(\mathbf{b},\mathbf{s}) - n_c), \quad (3)$$

where n_c is the critical or the threshold density. $n(\mathbf{b},\mathbf{s})$ is the local transverse density. At impact parameter $\mathbf{b}$ and at the transverse position $\mathbf{s}$, local transverse density can be obtained as

$$n(\mathbf{b},\mathbf{s}) = T_A(\mathbf{s})[1-\exp(-\sigma_{NN} T_B(\mathbf{s}-\mathbf{b}))] + T_B(\mathbf{b}-\mathbf{s})[1-\exp(-\sigma_{NN} T_A(\mathbf{s}))]. \quad (4)$$

Blaizot *et al.* [23,24] fitted the NA50 data [25] on the transverse energy dependence of J/ψ suppression in 158A GeV Pb+Pb collisions and obtain the threshold density n_c. With J/ψ-nucleon absorption cross section $\sigma_{J/\psi N} = 6.4$ mb, NA50 data are well explained in the model with $n_c = 3.7$ fm^{-2}. A better fit to the data is obtained if the theta function [Eq. (3)] is smeared, at the expense of an additional parameter. Later experiments [28] indicate that J/ψ-nucleon absorption cross section is ~ 4 mb, rather than 6.4 mb. The NA50 collaboration also revised their data [29]. The revised NA50 data were also analyzed in the threshold model [30]. With $\sigma_{\rm abs} \sim 4$ mb, large smearing of the threshold density is required. Large smearing of threshold density, effectively excludes the formation of deconfined matter at SPS energy.

In the threshold model, the fate of a J/ψ is determined by the local (transverse) density. If the local (transverse) density exceeds the threshold density, the J/ψ's are completely destroyed. In Fig. 1, for a number of impact parameters, the transverse density, $n(\mathbf{b},\mathbf{s})$ in Cu+Cu and in Au+Au collisions

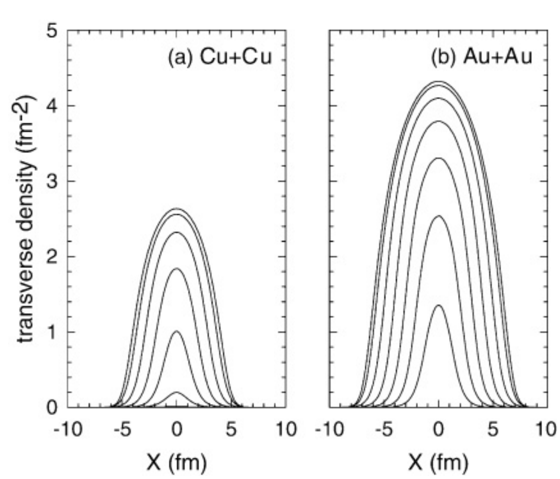

FIG. 1. Transverse density in Cu+Cu (left panel) and in Au+Au (right panel) collisions, for various values of the impact parameter, $b = 0, 2, 4 \ldots$ (from top to bottom). The origin is at a distance, $d = b/(1 + R_A/R_B)$ from the center of the nucleus A.

is shown. We have used the Woods-Saxon form for the density,

$$\rho(r) = \frac{\rho_0}{1+\exp((r-R)/a)}, \quad \int d^3r\rho(r) = A \qquad (5)$$

with $R = 4.456\,(5.415)$ fm and $a = 0.54\,(0.535)$ fm, for Cu (Au) nuclei.

For central collisions, the maximum transverse density in Cu+Cu collisions is $\sim$2.63 fm^{-2}, while that for Au+Au collisions is $\sim$4.32 fm^{-2}. Then if the J/ψ's are anomalously suppressed, say, above a threshold density, n_c = 3.7 fm^{-2}, J/ψ suppression in Cu+Cu collisions will not be affected as the transverse density never exceeds the threshold density. In Au+Au collisions, on the other hand, the J/ψ's will be anomalously suppressed. In Au+Au collisions also, only in collisions where local density $n(\mathbf{b},\mathbf{s})$ exceeds the threshold density, the J/ψ's will be anomalously suppressed. In all other collisions, the J/ψ's will be absorbed only due to the J/ψ-nucleon interaction. Then if the J/ψ suppression is measured as a function of impact parameter or equivalently, as a function of the centrality of collisions, a sudden change of slope will be observed.

III. J/ψ SUPPRESSION AT RHIC AND THE THRESHOLD MODEL

A. Au+Au collisions

In Fig. 2, we show the PHENIX data on the nuclear modification factor (R_{AA}) for J/ψ in Au+Au collisions, as a function of the number of participants. As mentioned earlier, the PHENIX collaboration took data at two rapidity intervals, (i) at midrapidity $|y| < 0.35$, and (ii) at forward rapidity $1.2 < |y| < 2.2$. Both data are shown in Fig. 2. We have also shown the PHENIX measurements for R_{AA} in d+Au collisions. d+Au collisions measure the effect of cold nuclear matter on J/ψ suppression at RHIC energy. J/ψ suppression in d+Au collisions is consistent with the Glauber model of nuclear absorption with J/ψ-nucleon absorption cross section $\sigma_{\rm abs}$ = 1–3 mb [17]. Several points are important to note. R_{AA} in very peripheral Au+Au collisions is not consistent with the PHENIX measurements in d+Au collisions. Even in very peripheral Au+Au collisions, J/ψ's are more suppressed than in d+Au collisions. As mentioned earlier, in midcentral/central Au+Au collisions, J/ψ's are more suppressed at forward rapidity than at midrapidity. In peripheral collisions on the other hand, both at midrapidity and forward rapidity, the J/ψ's are suppressed similarly. At forward rapidity centrality the dependence of J/ψ suppression does not show any indication of change of slope, but at midrapidity the slope change around $N_{\rm part} \approx 150$ is evident.

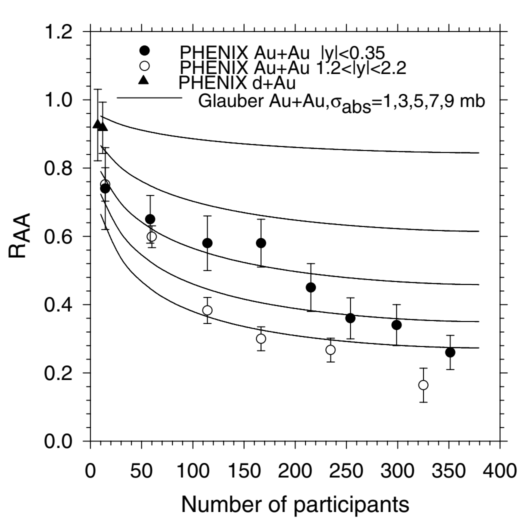

FIG. 2. PHENIX data on the participant number dependence of nuclear modification factor (R_{AA}) for J/ψ, in Au+Au collisions. R_{AA} for J/ψ in d+Au collisions are also shown. The solid lines (top to bottom) are Glauber model predictions for R_{AA} with $\sigma_{\rm abs}$ = 1, 3, 5, 7, and 9 mb.

In Fig. 2, we have shown Glauber model predictions for R_{AA} for J/ψ's in Au+Au collisions, for the J/ψ-nucleon absorption cross section $\sigma_{\rm abs}$ = 1, 3, 5, 7, and 9 mb. As mentioned earlier, the J/ψ suppression in d+Au collisions are explained in the Glauber model with $\sigma_{\rm abs}$ = 1–3 mb. However, the Glauber model of nuclear absorption, with $\sigma_{\rm abs}$ = 1–3 mb, cannot explain the PHENIX data even in peripheral Au+Au collisions, either at midrapidity or at forward rapidity. Rather the data indicate a slightly larger value for J/ψ-nucleon absorption cross section, $\sigma_{\rm abs} \approx$ 4–5 mb. With $\sigma_{\rm abs} \approx$ 4–5 mb, the Glauber model can explain a large part of the centrality dependence at midrapidity data, up to $N_{\rm part} \approx 150$. Beyond $N_{\rm part} = 150$, the Glauber model prediction underpredicts the nuclear modification factor R_{AA}. At forward rapidity on the other hand, Glauber model with $\sigma_{\rm abs} \approx$ 4–5 mb could explain data only in very peripheral collisions, $N_{\rm part} < 50$. It is apparent that the centrality dependence of J/ψ in Au+Au collisions, at midrapidity or at forward rapidity, is not explained in the Glauber model of nuclear absorption.

Additional suppression required in midrapidity data in very central Au+Au collisions, could be provided for in the threshold model. In Fig. 3 we show the threshold model predictions for the nuclear modification factor in Au+Au collisions, for various values of threshold density, n_c = 2.8, 3.0, 3.2, 3.4, 3.6, 3.8, and 4.0 fm^{-2}. We have used $\sigma_{\rm abs}$ = 4 mb. The Glauber model calculation for R_{AA} with $\sigma_{\rm abs}$ = 4 mb is shown in the figure as the dotted line. The Glauber model of nuclear absorption alone can explain the data up to $N_{\rm part} \sim 150$. In more central collisions, the J/ψ's are more suppressed than the Glauber model predictions. With anomalous suppression, the J/ψ's are strongly suppressed in central collisions and it is evident that for threshold density $n_c \sim 3.6$ fm^{-2}, the threshold model describes the PHENIX midrapidity data adequately well. In Fig. 3, we have also shown the forward rapidity data. The threshold model is not warranted by the forward rapidity data (no change in slope) and we find that the model, even with small threshold density, cannot explain the data at forward rapidity.

In the threshold model, it is implicitly assumed that the J/ψ's are absorbed in a deconfined matter. The critical energy density for deconfined matter formation is proportional to the threshold density. The melting of J/ψ due to color screening is mimicked by the sudden onset of suppression. A successful description of centrality dependence of J/ψ suppression in midrapidity Au+Au collisions then strongly

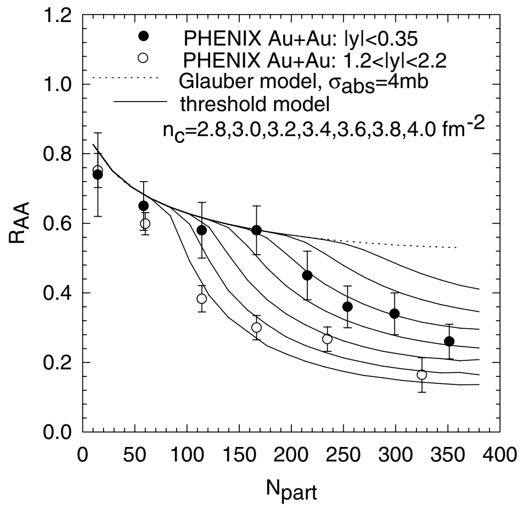

FIG. 3. PHENIX data on the centrality dependence of nuclear modification factor (R_{AA}) for J/ψ in Au+Au collisions. The dotted line is the prediction in the Glauber model with $\sigma_{\rm abs} = 4$ mb. The solid lines are threshold model predictions with threshold density $n_c = 2.8$, 3.0, 3.2, 3.4, 3.6, 3.8, and 4.0 fm^2 (bottom to top).

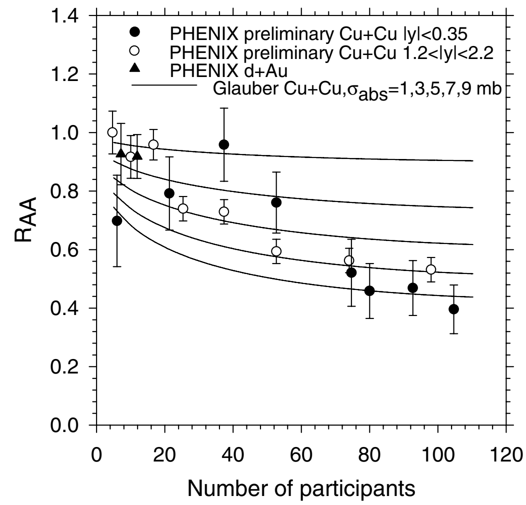

FIG. 4. PHENIX data on the participant number dependence of the nuclear modification factor (R_{AA}) for J/ψ, in Au+Au collisions. R_{AA} for J/ψ in d+Au collisions are also shown. The solid lines (top to bottom) are Glauber model predictions for R_{AA} with $\sigma_{\rm abs} = 1, 2, 3, 4,$ and 5 mb.

supports the formation of deconfined matter in central Au+Au collisions. However, we note that the model neglects some very important effects, e.g., (i) feedback from ψ' and χ states and (ii) transverse expansion. A considerable fraction ($\sim 40\%$) of J/ψ's is from the decay of ψ' and χ states [31]. That part is completely neglected here. Threshold density for anomalous suppression of higher states, ψ' and χ, should be less than that for J/ψ. Then the presently estimated threshold density n_c represents an upper limit of the threshold density. Additionally, at RHIC, model studies indicate that in the deconfined phase the system undergoes significant transverse expansion [32]. The local transverse density is a key ingredient to the threshold model. In an expanding system, the local transverse density will be diluted. The J/ψ's, which are anomalously suppressed in a static system, may survive in an expanding system due to dilution. Then, the presently estimated threshold density will again represent an upper limit of the threshold density.

B. Cu+Cu collisions

The PHENIX collaboration has not completed the analysis of J/ψ suppression in Cu+Cu collisions. Preliminary results for the nuclear modification factor (R_{AA}) for J/ψ in Cu+Cu collisions, as a function of the number of participants are shown in Fig. 4. Both the midrapidity and forward rapidity data are shown. We have also shown the PHENIX measurements for R_{AA} in d+Au collisions. The R_{AA} in peripheral Cu+Cu collisions at forward rapidity are consistent with d+Au measurements, but at midrapidity, the J/ψ's in peripheral Cu+Cu collisions are more suppressed than in d+Au collisions. It is also interesting to note that in central Cu+Cu collisions, within the experimental errors, the J/ψ's are suppressed similarly both at midrapidity and forward rapidity, with a slightly larger suppression at midrapidity. At forward rapidity J/ψ suppression in Cu+Cu collisions does not show any indication of change of slope with centrality. At midrapidity the suppression pattern indicates a broad peak-like structure around $N_{\rm part} = 40$. The quality of data needs to be improved. It is important to establish the peak-like structure in midrapidity Cu+Cu data. The Glauber model or the threshold model suppression increases with centrality and peak-like structure cannot be reproduced in either of the models.

In Fig. 4, we have shown the Glauber model prediction for R_{AA} for J/ψ's in Cu+Cu collisions, for the J/ψ-nucleon absorption cross section $\sigma_{\rm abs} = 1, 3, 5, 7,$ and 9 mb. The centrality dependence of J/ψ suppression in Cu+Cu collisions, at midrapidity or at forward rapidity, is not explained in the Glauber model. As indicated earlier, at forward rapidity, the J/ψ suppression in very peripheral Cu+Cu collisions is consistent with the Glauber model predictions with $\sigma_{\rm abs} =$ 1–3 mb, but in more central collisions, the suppression exceeds the model predictions. The midrapidity data are also not explained in the Glauber model. For the threshold model to be effective in Cu+Cu collisions, the threshold density needs to be less than $n \approx 2.63$ fm^{-2}, the maximum transverse density that can be reached in Cu+Cu collisions (see Fig. 1). As shown earlier, in Au+Au collisions, the threshold density is of the order of 3.6 fm^{-2}. The threshold density is directly related to the critical energy density for the deconfinement phase transition. It is not acceptable that the critical energy density for the confinement-deconfinement phase transition depends on the colliding system. We have not shown that even with a small threshold density, the centrality dependence of J/ψ suppression in Cu+Cu collisions, at midrapidity or at forward rapidity, is not explained in the threshold model. The forward rapidity data do not show any change in slope and the threshold model is not warranted. The broad peak-like structure in midrapidity data is also not reproducible in the threshold model.

IV. CENTRALITY DEPENDENCE OF p_T BROADENING IN Cu+Cu/Au+Au COLLISIONS

It is well known that in pA and AA collisions, the secondary hadrons generally show p_T broadening [33,34]. The p_T broadening of J/ψ in Cu+Cu and in Au+Au collisions at RHIC energy $\sqrt{s}_{NN} = 200$ GeV, has been measured by the PHENIX collaboration [26,27]. They measured the collision number dependence of the square of transverse momentum for J/ψ. It is interesting to compare the threshold model predictions with the PHENIX data.

The natural basis for the p_T broadening is the initial state parton scatterings. For J/ψ's, the gluon fusion being the dominant mechanism for $c\bar{c}$ production, initial state scattering of the projectile/target gluons with the target/projectile nucleons causes the intrinsic momentum broadening of the gluons, which is reflected in the p_T distribution of the resulting J/ψ's. Parametrizing the intrinsic transverse momentum of a gluon, inside a nucleon as

$$f(q_T) \sim \exp\left(-q_T^2/\langle q_T^2\rangle\right), \tag{6}$$

the momentum distribution of the resulting J/ψ in NN collision is obtained by convoluting two such distributions,

$$f_{NN}^{J/\psi}(p_T) \sim \exp\left(-p_T^2/\langle p_T^2\rangle_{NN}^{J/\psi}\right), \tag{7}$$

where $\langle p_T^2\rangle_{NN}^{J/\psi} = \langle q_T^2\rangle + \langle q_T^2\rangle$. In nucleus-nucleus collisions at impact parameter $\mathbf{b}$, if before fusion, a gluon undergoes random walk and suffers N number of subcollisions, its square momentum will increase to $q_T^2 \rightarrow q_T^2 + N\delta_0$, δ_0 being the average broadening in each subcollision. The square momentum of J/ψ can then easily obtained as

$$\langle p_T^2\rangle_{AB}^{J/\psi}(b) = \langle p_T^2\rangle_{NN}^{J/\psi} + \delta_0 N_{AB}(\mathbf{b}), \tag{8}$$

where $N_{AB}(\mathbf{b})$ is the number of subcollisions suffered by the projectile and target gluons with the target and projectile nucleons, respectively.

The average number of collisions $N_{AB}(\mathbf{b})$ can be obtained in a Glauber model [34]. At impact parameter $\mathbf{b}$, the positions $(\mathbf{s}, z)$ and $(\mathbf{b} - \mathbf{s}, z')$ specify the formation point of $c\bar{c}$ in the two nuclei, with $\mathbf{s}$ in the transverse plane and z, z' along the beam axis. The number of collisions, prior to $c\bar{c}$ pair formation, can be written as

$$\begin{aligned} N(b, s, z, z') = {}& \sigma_{gN} \int_{-\infty}^{z} dz_A \rho_A(s, z_A) \\ & + \sigma_{gN} \int_{-\infty}^{z'} dz_B \rho_B(b - s, z'), \end{aligned} \tag{9}$$

where σ_{gN} is the gluon-nucleon cross section. The above expression should be averaged over all positions of $c\bar{c}$ formation with a weight given by the product of nuclear densities and survival probabilities S,

$$\begin{aligned} N_{AB}(b) = {}& \int d^2s \int_{-\infty}^{\infty} dz \rho_A(s, z) \int_{-\infty}^{\infty} dz' \rho_B(b - s, z') \\ & \times S(b, s, z, z') N(b, s, z, z') \Big/ \int d^2s \\ & \times \int_{-\infty}^{\infty} dz \rho_A(s, z) \int_{-\infty}^{\infty} dz' \rho_B(b - s, z') \\ & \times S(b, s, z, z'). \end{aligned} \tag{10}$$

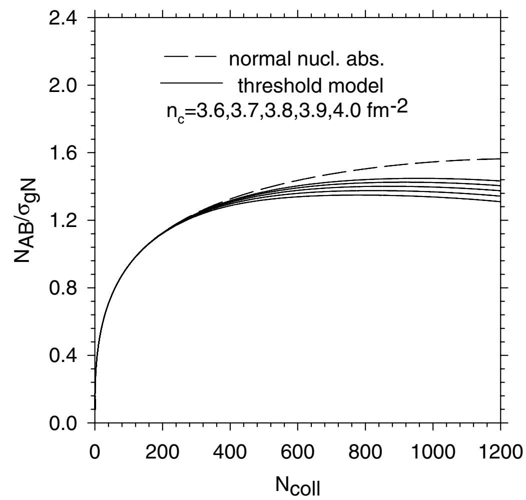

FIG. 5. Collision number dependence of the ratio N_{AB}/σ_{gN} in Au+Au collisions. The dashed line is the ratio in the normal nuclear absorption model, with $\sigma_{\rm abs} = 4$ mb. The solid lines are N_{AB}/σ_{gN} in the threshold model, with threshold density $n_c = 3.6, 3.7, 3.8, 3.9$, and 4.0 fm^{-2} (from bottom to top), respectively.

The centrality dependence of the ratio N_{AB}/σ_{gN}, in Au+Au collisions, for the threshold densities, $n_c = 3.6, 3.7, 3.8, 3.9$, and 4.0 fm^{-2}, are shown in Fig. 5, (the solid lines from bottom to top). We also show the ratio in the normal nuclear absorption model (the dashed line). N_{AB}/σ_{gN} increases with centrality, the more central the collisions, the more the gluons suffer a number of collisions. In a normal nuclear absorption model, N_{AB}/σ_{gn} continues to increase with centrality (or collision number). However, the rate of increase slows down at more central collisions. A different behavior is obtained in the threshold model. For a fixed threshold density n_c, N_{AB}/σ_{gn} exactly corresponds to a normal nuclear absorption model, until a collision number N_c. Beyond N_c, N_{AB}/σ_{gN} hardly changes. It is understood. Beyond N_c, transverse density exceeds the threshold density and J/ψ's are completely destroyed. As N_{AB} is weighted by the anomalous suppression, it hardly changes beyond that collision number.

The p_T broadening of J/ψ's in AA collisions depends on two parameters, (i) $\langle p_T^2\rangle_{NN}^{J/\psi}$, the mean squared transverse momentum in NN collisions and (ii) the product of the gluon-nucleon cross section and the average parton momentum broadening per collision, $\sigma_{gN}\delta_0$. $\langle p_T^2\rangle_{NN}^{J/\psi}$ is measured in RHIC energy $p + p$ collisions, $\langle p_T^2\rangle_{NN}^{J/\psi} = 4.2 \pm 0.7$ GeV^2. As

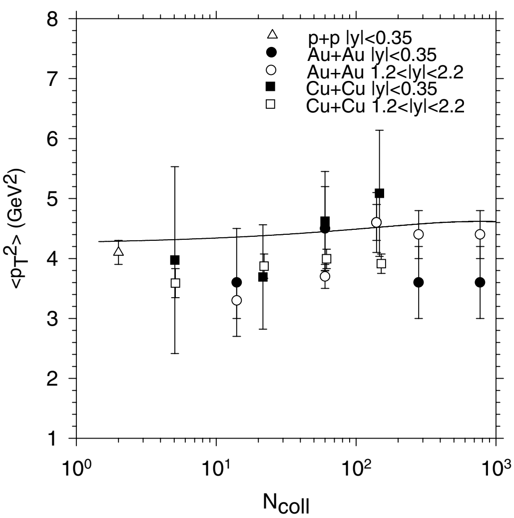

FIG. 6. J/ψ mean square transverse momentum as a function of collision number, in $p+p$, d+Au, Cu+Cu, and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, are shown. The solid line is the best fit, in the threshold model, to the combined Cu+Cu and Au+Au data.

gluons are not free, the other parameter, $\sigma_{gN}\delta_0$, is essentially nonmeasurable. Its value can be obtained from experimental data on p_T broadening of J/ψ. In SPS energy S+U/Pb+Pb collisions $\sigma_{gN}\delta_0$ is estimated as 0.442 ± 0.056 GeV^2 [35]. $\sigma_{gN}\delta_0$ at RHIC energy is of interest.

The PHENIX data on the centrality dependence of mean square transverse momentum $\langle p_T^2 \rangle$, in Cu+Cu and in Au+Au collisions is shown Fig. 6. $\langle p_T^2 \rangle$ in $p+p$ and in d+Au collisions is also shown. The quality of data is poor, with only a few data points with large error bars. Evidently, data do not show any evidence of p_T broadening. Within the errors, $\langle p_T^2 \rangle$ in Cu+Cu and in Au+Au collisions agree with those in NN collisions. The p_T broadening of J/ψ's is minimum at RHIC.

To find $\sigma_{gN}\delta_0$ at RHIC energy, we fit the combined Cu+Cu and Au+Au data set (individual Cu+Cu or Au+Au data points are few). We fix $\langle p_T^2 \rangle_{NN}$ at the measured central value, $\langle p_T^2 \rangle_{NN} = 4.2$ GeV^2, and vary $\sigma_{gN}\delta_0$. $\langle p_T^2 \rangle$ in Au+Au or in Cu+Cu show very little dependence on the threshold density. In Fig. 6, the best fit obtained with threshold density $n_c = 3.6, 3.7, 3.8, 3.9$, and 4.0 fm^{-2} is shown. They cannot be distinguished. The best fit is obtained with $\sigma_{gN}\delta_0 = 0.31 \pm 0.48$ GeV^2. Due to the poor quality of the data, the $\sigma_{gN}\delta_0$ is ill determined. The estimated error is larger than the central value. We conclude that the PHENIX data cannot determine the $\sigma_{gN}\delta_0$ at RHIC energy.

V. SUMMARY AND CONCLUSIONS

To conclude, in the QGP motivated threshold model, we have analyzed the PHENIX data on the centrality dependence of J/ψ suppression in Au+Au collisions. In the threshold model, in addition to the normal nuclear absorption, the J/ψ's are anomalously suppressed, such that, if the local transverse density exceeds a threshold density n_c, all the J/ψ's are absorbed. The model predicts a sudden change in slope in J/ψ suppression as a function of centrality. Midrapidity PHENIX data do indicate a sudden change in slope. Data up to $N_{\rm part} \approx 150$ are well explained in the Glauber model of nuclear absorption with the J/ψ-nucleon absorption cross section $\sigma_{\rm abs} = 4$ mb. Data beyond $N_{\rm part} \approx 150$ require anomalous suppression and are well explained in the threshold model, with threshold density $n_c \approx 3.6$ fm^{-2}. J/ψ suppression at forward rapidity does not show any sudden change of slope and is not explained in the threshold model. The analysis suggests that J/ψ suppression at forward rapidity is more complex than envisaged in the simple Glauber model or its extended version, the threshold model. More detailed models are necessary for J/ψ suppression at forward rapidity. We have also analyzed the preliminary PHENIX data on the centrality dependence of J/ψ suppression in Cu+Cu collisions. The quality of data is not good. Forward rapidity data again do not show any change in slope with centrality, the midrapidity data on the other hand show a broad peak-like structure around $N_{\rm part} \approx 40$. Both data are not explained in the Glauber model of nuclear absorption or in the threshold model. We have also analyzed the PHENIX data on p_T broadening. The quality of data is not good enough for a definitive conclusion. Apparently at RHIC energy, J/ψ's do not show any p_T broadening.

In conclusion, the present analysis strongly supports deconfined matter formation in midrapidity central Au+Au collisions at RHIC energy $\sqrt{s_{NN}} = 200$ GeV.

[1] T. Matsui and H. Satz, Phys. Lett. **B178**, 416 (1986).
[2] R. Vogt, Phys. Rep. **310**, 197 (1999).
[3] C. Gerschel and J. Huefner, Annu. Rev. Nucl. Part. Sci. **49**, 255 (1999).
[4] BRAHMS Collaboration, I. Arsene *et al.*, Nucl. Phys. **A757**, 1 (2005).
[5] PHOBOS Collaboration, B. B. Back *et al.*, Nucl. Phys. **A757**, 28 (2005).
[6] PHENIX Collaboration, K. Adcox *et al.*, Nucl. Phys. **A757**, 184 (2005).
[7] STAR Collaboration, J. Adams *et al.*, Nucl. Phys. **A757**, 102 (2005).
[8] M. Gyulassy, I. Vitev, X.-N. Wang, and B.-W. Zhang, in *Quark-Gluon Plasma 3*, edited by R. C. Hwa and X.-N. Wang (World Scientific, Singapore, 2004), p. 123.
[9] R. L. Thews, M. Schroedter, and J. Rafelski, Phys. Rev. C **63**, 054905 (2001).
[10] P. Braun-Munzinger and J. Stachel, Phys. Lett. **B490**, 196 (2000).
[11] PHENIX Collaboration, A. Adare *et al.*, arXiv:nucl-ex/0611020.
[12] PHENIX Collaboration, V. Cianciolo *et al.*, arXiv:nucl-ex/0601012, AIP Conf. Proc. **842**, 41 (2006).
[13] A. Capella, E. G. Ferreiro, and A. B. Kaidalov, Phys. Rev. Lett. **85**, 2080 (2000).

[14] A. P. Kostyuk, M. I. Gorenstein, H. Stoecker, and W. Greiner, Phys. Rev. C **68**, 041902(R) (2003).
[15] M. I. Gorenstein, A. P. Kostyuk, H. Stoecker, and W. Greiner, Phys. Lett. **B509**, 277 (2001).
[16] L. Grandchamp, R. Rapp, and G. E. Brown, Phys. Rev. Lett. **92**, 212301 (2004).
[17] R. Vogt, Acta Phys. Hung. A **25**, 97 (2006).
[18] A. K. Chaudhuri, Phys. Rev. C **74**, 044907 (2006).
[19] J. Qiu, J. P. Vary, and X. Zhang, Phys. Rev. Lett. **88**, 232301 (2002).
[20] A. K. Chaudhuri, Phys. Rev. Lett. **88**, 232302 (2002).
[21] A. Capella and E. G. Ferreiro, Eur. Phys. J. C **42**, 419 (2005).
[22] A. Capella and E. G. Ferreiro, arXiv:hep-ph/0610313.
[23] J. P. Blaizot, M. Dinh, and J. Y. Ollitrault, Phys. Rev. Lett. **85**, 4012 (2000).
[24] J. P. Blaizot and J. Y. Ollitrault, Phys. Rev. Lett. **77**, 1703 (1996).
[25] NA50 Collaboration, M. C. Abreu *et al*., Phys. Lett. **B477**, 28 (2000).
[26] PHENIX Collaboration, J. L. Nagle *et al*., arXiv:nucl-ex/0509024.
[27] PHENIX Collaboration, H. Pereira Da Costa *et al*., Nucl. Phys. **A774**, 747 (2006).
[28] NA50 Collaboration, P. Cortese *et al*., Nucl. Phys. **A715**, 679 (2003).
[29] NA50 Collaboration, L. Ramello *et al*., Quark Matter 2002, Nantes, France, July 2002 (unpublished).
[30] A. K. Chaudhuri, Phys. Rev. C **68**, 037901 (2003).
[31] H. Satz, J. Phys. G **32**, R25 (2006).
[32] P. F. Kolb and U. W. Heinz, arXiv:nucl-th/0305084.
[33] A. Krzywicki, J. Engels, B. Petersson, and U. P. Sukhatme, Phys. Lett. **B85**, 407 (1979); S. Gavin and M. Gyulassy, *ibid.* **B214**, 241 (1988); J. P. Blaizot and J. Y. Ollitrault, *ibid.* **B217**, 392 (1989).
[34] D. Kharzeev, M. Nardi, and H. Satz, Phys. Lett. **B405**, 14 (1997).
[35] A. K. Chaudhuri, J. Phys. G **32**, 229 (2006).