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J/ψ production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and the nuclear absorption

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It is shown that a quantum chromodynamics-based nuclear absorption model, with few parameters fixed to reproduce experimental J/ψ yield in 200 GeV proton-proton/proton-nucleon and 450 GeV proton-nucleon collisions, can explain the preliminary PHENIX data on the centrality dependence of J/ψ suppression in Cu+Cu collisions at Relativistic Heavy Ion Collider (RHIC) energy, $\sqrt{s_{NN}} = 200$ GeV. However, the model does not give a satisfactory description for the preliminary PHENIX data on the centrality dependence of J/ψ suppression in Au+Au collisions. The analysis suggests that in Au+Au collisions, J/ψ are suppressed in a medium unlike the medium produced in CERN Super Proton Synchrotron energy nuclear collisions or in RHIC energy Cu+Cu collisions.

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I. INTRODUCTION

Lattice quantum chromodynamics (QCD) predicts that under certain conditions (sufficiently high energy density and temperature), ordinary hadronic matter (where quarks and gluons are confined) can undergo a phase transition to a deconfined matter, commonly known as quark gluon plasma (QGP). Nuclear physicists are trying to produce and detect this new phase of matter at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL). J/ψ suppression is recognized as one of the promising signals of the deconfinement phase transition. Due to screening of the color force, binding of a $c\bar{c}$ pair into a J/ψ meson is hindered, leading to the so-called J/ψ suppression in heavy-ion collisions [1]. However, J/ψ's are also absorbed in nuclear collisions and prior to the NA50 158A GeV Pb+Pb collisions [2], all the experimental data on J/ψ suppression are explained solely in terms of nuclear absorption. The NA50 collaboration measured centrality dependence of J/ψ suppression in 158A GeV Pb+Pb collisions. Data gave the first indication of the "anomalous" mechanism of charmonium suppression that goes beyond the conventional nuclear absorption. The data generated alot of excitement as it was believed to give the first indication of QGP formation. Later, the data were explained in a variety of models, with or without the assumption of QGP [3–13]. More recently, the NA60 collaboration measured the centrality dependence of charmonium suppression in 158A GeV In+In collisions [14–16]. In In+In collisions also, one observes anomalous suppression that is beyond the conventional nuclear absorption.

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) [17–20]. This has been interpreted as evidence for the creation of a high-density, opaque medium of deconfined quarks and gluons [21]. It is expected that a high-density, opaque medium will leave its imprint on J/ψ production. At the RHIC energy, it has been argued that, rather than suppression, charmoniums will be enhanced [22,23]. Due to a large initial energy, 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. The PHENIX collaboration have measured the centrality dependence of the J/ψ invariant yield in Au+Au collisions at RHIC energy, $\sqrt{s_{NN}} = 200$ GeV [24,25]. More recently, with improved statistics, they have measured J/ψ's in Cu+Cu and in Au+Au collisions. Preliminary results for the centrality dependence of nuclear modification factor (R_{AA}) and mean-square transverse momentum for J/ψ suppression in Cu+Cu and in Au+Au collisions are available [26,27]. PHENIX data on J/ψ production in Au+Au/Cu+Cu collisions are not consistent with models that predict J/ψ enhancement [22,23]. It was also seen that various models, e.g., the comover model [3], statistical coalescence model [4], or the kinetic model [5], fail to explain the PHENIX (preliminary) data on the nuclear modification factor for J/ψ in Cu+Cu and Au+Au collisions. The data are also not explained in the normal nuclear absorption model [28].

We have developed a QCD-based nuclear absorption model to explain the anomalous J/ψ suppression in 158A GeV Pb+Pb collisions [9,13]. Unlike in the conventional nuclear absorption model, in the QCD-based nuclear absorption model, the $c\bar{c}$ pair interact with the medium and gain relative four-square momentum. Some of the pairs can gain enough four-square momentum to cross the threshold for open charm meson, reducing the J/ψ yield. The parameters of the model were fixed to reproduce J/ψ yield in proton-proton (pp) and proton-nucleon (pA) collisions. The model give consistent description of the centrality dependence of the J/ψ suppression and p_T broadening in 158A GeV Pb+Pb collisions and in 200A GeV S+U collisions [11]. In the present article we have tested the model against the preliminary PHENIX data on J/ψ suppression in Cu+Cu and Au+Au collisions at RHIC energy, $\sqrt{s_{NN}} = 200$ GeV. Centrality dependence of J/ψ suppression, in Cu+Cu collisions, is well explained in the model, but the model fails to explain the suppression in Au+Au

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collisions. The analysis suggests that in Au+Au collisions at RHIC, J/ψ's are suppressed in a medium unlike the medium produced in S+U/Pb+Pb collisions at CERN Super Proton Synchrotron (SPS) energy or in Cu+Cu collisions at RHIC energy. We also apply the model to explain the preliminary PHENIX data on centrality dependence of p_T broadening for J/ψ's. Within errors, p_T broadening at RHIC seems to be consistent with that at SPS energy.

This article is organized as follows: in Sec. II, we briefly describe the QCD-based nuclear absorption model. In Sec. III, PHENIX data on the centrality dependence of J/ψ suppression in Cu+Cu and in Au+Au collisions are analyzed. Centrality dependence of p_T broadening of J/ψ's are analyzed in Sec. III. Summary and conclusions are drawn in Sec. IV.

II. QCD-BASED NUCLEAR ABSORPTION MODEL

In the QCD-based nuclear absorption model [9–13], J/ψ production is assumed to be a two-step process: (a) formation of a $c\bar{c}$ pair, which is accurately calculable in QCD, and (b) formation of a J/ψ meson from the $c\bar{c}$ pair, a nonperturbative process that is conveniently parametrized. The J/ψ cross section in pp collisions, at center-of-mass energy $\sqrt{s}$ is written as,

$$\sigma_{NN}^{J/\psi}(s) = K \sum_{a,b} \int dq^2 \left(\frac{\hat{\sigma}_{ab\to cc}}{Q^2}\right) \int dx_F \phi_{a/A}(x_a, Q^2) \times \phi_{b/B}(x_b, Q^2) \frac{x_a x_b}{x_a + x_b} \times F_{c\bar{c}\to J/\psi}(q^2), \tag{1}$$

where $\sum_{a,b}$ runs over all parton flavors and $Q^2 = q^2 + 4m_c^2$. The K factor takes into account the higher-order corrections. We have used the CTEQ5L parton distribution function for $\phi(x, Q^2)$ [29]. The incoming parton momentum fractions are fixed by kinematics and are $x_a = (\sqrt{x_F^2+4Q^2/s}+x_F)/2$ and $x_b = (\sqrt{x_F^2+4Q^2/s}-x_F)/2$. $\hat{\sigma}_{ab\to c\bar{c}}$ are the sub process cross sections and are given in Ref. [30]. $F_{c\bar{c}\to J/\psi}(q^2)$ is the transition probability that a $c\bar{c}$ pair with relative momentum square q^2 evolve into a physical J/ψ meson. It is parametrized as,

$$F_{c\bar{c}\to J/\psi}(q^2) = N_{J/\psi}\theta(q^2)\theta\left(4m'^2 - 4m_c^2 - q^2\right) \times \left(1 - \frac{q^2}{4m'^2 - 4m_c^2}\right). \tag{2}$$

All the energy dependence of J/ψ production is contained in Eq. (1). As shown in Fig. 1, with $KN_{J/\psi}$ as a overall normalization, over a wide range of energy, including the RHIC energy, the model correctly reproduces the experimental J/ψ cross sections in pp collisions.

Our main interest here is to test the model against the preliminary PHENIX data on the centrality dependence of J/ψ suppression in Cu+Cu and Au+Au collisions at RHIC energy [26,27]. In AA collisions, at impact parameter $\mathbf{b}$, number of J/ψ mesons produced is calculated as,

$$N_{AA}^{J/\psi}(\mathbf{b}) = \sigma_{NN}^{J/\psi} \int d^2s T_A(\mathbf{s}) T_B(\mathbf{b}-\mathbf{s}) S[L(\mathbf{b},\mathbf{s})], \tag{3}$$

where $T_{A,B}$ are the nuclear thickness function,

$$T_A(\mathbf{b}) = \int dz \rho_A(\mathbf{b}, z), \tag{4}$$

For the density we use the Woods-Saxon form,

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

with $R = 6.38(4.45)$ fm and $a = 0.535(0.54)$ fm for the Au (Cu) nucleus [31].

In Eq. (3), $S(L)$ is the suppression factor due to passage of J/ψ through a length L in nuclear environment. As mentioned earlier, in the QCD-based nuclear absorption model, J/ψ's are suppressed due to gain in relative four-square momentum of a $c\bar{c}$ pair. In a nucleon-nucleus/nucleus-nucleus collision, the produced $c\bar{c}$ pairs interact with the nuclear medium before they exit. Interaction of a $c\bar{c}$ pair with the nuclear environment increases the square of the relative momentum between the pair. As a result, some of the $c\bar{c}$ pairs can gain enough relative square momentum to cross the threshold to become an open charm meson. Consequently, the cross section for J/ψ production is reduced in comparison with nucleon-nucleon cross section. If the J/ψ meson travel a distance L, q^2 in the transition probability is replaced to,

$$q^2 \to q^2 + \varepsilon^2 L, \tag{6}$$

ε^2 being the relative square momentum gain per unit length. The length $L(\mathbf{b},\mathbf{s})$ that the J/ψ meson will traverse is obtained as,

$$L(\mathbf{b},\mathbf{s}) = n(\mathbf{b},\mathbf{s})/2\rho_0, \tag{7}$$

where $n(\mathbf{b},\mathbf{s})$ is the transverse density,

$$n(\mathbf{b},\mathbf{s}) = T_A(\mathbf{s})[1 - e^{-\sigma_{NN}T_B(\mathbf{b}-\mathbf{s})}] + [A \leftrightarrow B]. \tag{8}$$

J/ψ suppression in the model is governed by the parameter ε^2 and L [see Eq. (6)]. The length L is a geometric term. It has weak energy dependence from the energy dependence of σ_{NN}, the inelastic NN cross section. Energy dependence of J/ψ suppression will affect mostly ε^2. NA50 data on J/ψ production in 450 GeV pp/pA collisions and in 200 GeV pA collisions are well fitted with a common square momentum gain factor, $\varepsilon^2 = 0.187$ GeV^2/fm [10]. The model then explains the centrality dependence of S+U and Pb+Pb collisions at SPS energy. As the model parameters are fixed to reproduce J/ψ production in pA collisions, where deconfined matter formation is unlikely, it was concluded that at SPS energy S+U/Pb+Pb collisions, J/ψ's are absorbed in a nuclear medium [9,10].

If at RHIC energy J/ψ's are suppressed in a medium denser than the medium produced in SPS energy nuclear collisions, ε^2 will increase. In a denser medium, the $c\bar{c}$ pair will interact more with the medium and per unit length will gain more square momentum. The parametric value of ε^2 at RHIC energy can then indicate whether a dense medium is produced. We note that due to enhanced energy charmonium production increases at RHIC, but as shown in Fig. 1, that energy dependence is included in the model.

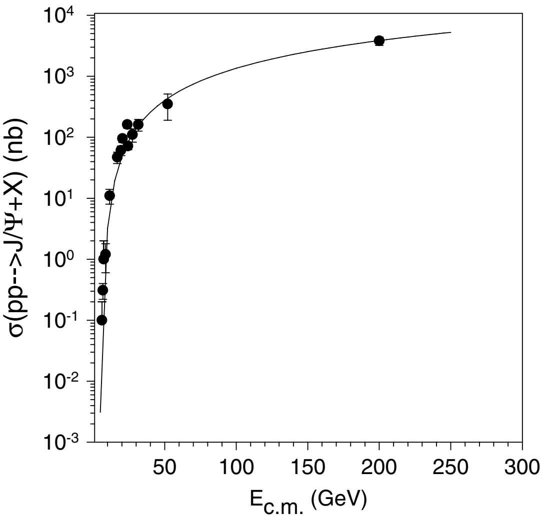

FIG. 1. Energy dependence of total J/ψ cross section in *pp* collisions. The solid line is the fit obtained to the data with Eq. (1).

III. J/ψ SUPPRESSION IN CU+CU/AU+AU COLLISIONS AT RHIC

PHENIX collaboration has measured the centrality dependence of J/ψ suppression, in Cu+Cu and in Au+Au collisions, in two ranges of rapidity intervals: (i) $-0.35 \leqslant y \leqslant 0.35$ and (ii) $1.2 \leqslant y \leqslant 2.2$, [26,27]. In Fig. 2, preliminary PHENIX data on the centrality dependence of nuclear modification factor (R_{AA}) for J/ψ, in Cu+Cu collisions are shown. Two rapidity ranges of data are not distinguished. We note that the present model is designed for central rapidity only. However, presently we ignore this limitation of the model. As is evident from Fig. 2, rapidity dependence of J/ψ suppression is not large in Cu+Cu collisions. Using the CERN minimization program MINUIT, with ε^2 as a parameter of the QCD-based absorption model, we fit the data. The best fit is obtained with $\varepsilon^2 = 0.173 \pm 0.007$ GeV^2/fm. The fit is shown in Fig. 2 (the solid line). With the exception of very peripheral collisions, PHENIX data on the centrality dependence of R_{AA}, for J/ψ in Cu+Cu collisions, are well explained by the QCD-based nuclear absorption model. In very peripheral collisions, the model overpredicts the suppression. Indeed, in very peripheral collisions, PHENIX data indicate enhancement rather than suppression of J/ψ, presumably due to Cronin effect.

As discussed earlier, if at RHIC energy, J/ψ's are suppressed in a medium denser than the medium created in SPS energy nuclear collisions, ε^2 should increase. In Cu+Cu collisions, a contrary result is obtained. Compared to ε^2 at SPS energy, at RHIC Cu+Cu collisions, ε^2 decreases by a modest 7%. J/ψ's are less suppressed. The result is consistent with the PHENIX measurement of J/ψ suppression in d+Au collisions at RHIC [32]. At RHIC d+Au collisions, J/ψ-nucleon absorption cross section, $\sigma_{J/\psi N} \approx 1$–3 mb, is less than the J/ψ-nucleon absorption cross section at SPS energy, $\sigma_{J/\psi N} \approx 4$–5 mb [33]. Good fit to the centrality dependence of J/ψ suppression in Cu+Cu collisions, data, in the QCD-based nuclear absorption model, with ε^2 close to the value at SPS energy, indicate that in Cu+Cu collisions, J/ψ's are suppressed in a nuclear medium, much like the medium produced in nuclear collisions at SPS energy.

Next we fit the PHENIX data on J/ψ suppression in Au+Au collisions. Centrality dependence of the nuclear modification factor (R_{AA}) for J/ψ in the central rapidity region $-0.35 < y < 0.35$ is shown in Fig. 3. Data points are few and error bars are also large. The best fit to the data is obtained with $\varepsilon^2 = 0.146 \pm .014$ GeV^2/fm. It is shown as the solid line in Fig. 3. The fit to the data is not satisfactory. In very central collisions, the model overpredicts R_{AA} and in mid-central collisions the model underpredicts R_{AA}. The best fitted value

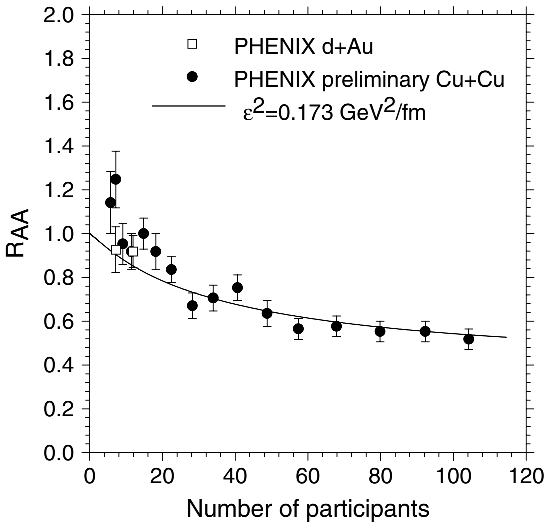

FIG. 2. Preliminary PHENIX data on the centrality dependence of nuclear modification factor for J/ψ in Cu+Cu collisions at RHIC. The solid lines is the best fit in the QCD-based nuclear absorption model with $\varepsilon^2 = 0.173$ GeV^2/fm.

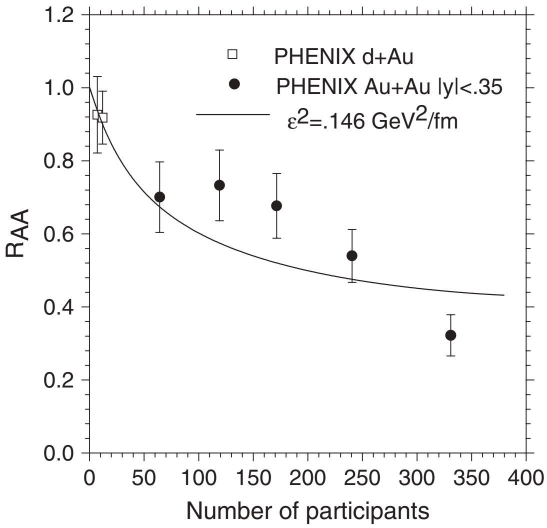

FIG. 3. Preliminary PHENIX data on the centrality dependence of nuclear modification factor for J/ψ in Au+Au collisions at RHIC. The solid line is the best fit in the QCD-based nuclear absorption model with $\varepsilon^2 = 0.146$ GeV^2/fm.

of $\varepsilon^2 = 0.146 \pm .014\,\mathrm{GeV}^2/\mathrm{fm}$ is ~15% lower than the value required to explain the PHENIX data on J/ψ suppression in Cu+Cu collisions. Apparently, in Au+Au collisions, J/ψ's are suppressed in a medium less dense than that produced in Cu+Cu collisions. This is inconsistent with other results at RHIC Au+Au collisions [17–20]. As mentioned earlier, in RHIC Au+Au collisions, deconfined matter can be formed. J/ψ's can be suppressed in the deconfined matter. QCD-based nuclear absorption models do not account for such a suppression. Unsatisfactory fit to the Au+Au data may be due to neglect of deconfined medium production in Au+Au collisions.

IV. p_T BROADENING OF J/ψ IN CU+CU AND AU+AU COLLISIONS

It is well known that in pA and AA collisions, the secondary hadrons generally show a p_T broadening [34,35]. p_T broadening of J/ψ's in S+U and Pb+Pb collisions are well explained in the QCD-based nuclear absorption model. Recently PHENIX collaboration has measured p_T broadening of J/ψ in Cu+Cu and Au+Au collisions [26,27]. It is interesting to compare the QCD-based nuclear absorption model predictions with the PHENIX data.

The natural basis for the p_T broadening is the initial state parton scatterings. For J/ψ's, 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

$$f(q_T) \sim \exp\left(-q_T^2/\langle q_T^2\rangle\right), \tag{9}$$

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

$$f_{NN}^{J/\psi}(p_T) \sim \exp\left(-p_T^2/\langle p_T^2\rangle_{NN}^{J/\psi}\right), \tag{10}$$

where $\langle p_T^2\rangle_{NN}^{J/\psi} = \langle q_T^2\rangle + \langle q_T^2\rangle$. In NN collisions at impact parameter $\mathbf{b}$, if before fusion, a gluon undergo random walk and suffer 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 subcollisions. Square momentum of J/ψ then easily obtained as,

$$\langle p_T^2\rangle_{AB}^{J/\psi}(b) = \langle p_T^2\rangle_{NN}^{J/\psi} + \delta_0 N_{AB}(\mathbf{b}), \tag{11}$$

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

Average number of collisions $N_{AB}(\mathbf{b})$ can be obtained in a Glauber model [35]. 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,

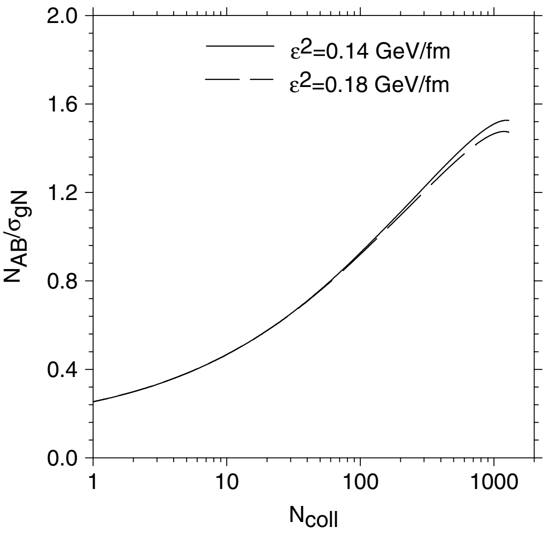

FIG. 4. Collision number dependence of the ratio of average number of gluon-nucleon collisions to the gluon-nucleon cross section in Au+Au collisions. The solid and dashed lines are obtained with $\varepsilon^2 = 0.14$ and $0.18\,\mathrm{GeV}^2/\mathrm{fm}$, respectively.

$$N(b, s, z, z') = \sigma_{gN}\int_{-\infty}^{z} dz_A\rho_A(s, z_A) + \sigma_{gN}\int_{-\infty}^{z'} dz_B\rho_B(b-s, z'), \tag{12}$$

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,

$$N_{AB}(b) = \int d^2s\int_{-\infty}^{\infty} dz\rho_A(s,z)\int_{-\infty}^{\infty} dz'\rho_B(b-s,z') \tag{13}$$

$$\times S(\mathbf{b},\mathbf{s})N(b,s,z,z')\Big/\int d^2s\int_{-\infty}^{\infty} dz\rho_A(s,z) \times \int_{-\infty}^{\infty} dz'\rho_B(b-s,z')S(b,s,z,z'). \tag{14}$$

In Fig. 4, the centrality dependence of the ratio N_{AB}/σ_{gN}, in Au+Au collisions are shown. The solid and dashed lines corresponds to $\varepsilon^2 = 0.14$ and 0.18 GeV/fm, respectively. N_{AB}/σ_{gN} do not show large dependence on ε^2. Even though ε^2 differ by 25%, N_{AB} differs by less than 3% in central collisions. In less central collisions, the difference is even less. p_T broadening of J/ψ will not depend much on the exact value of ε^2.

p_T broadening of J/ψs in AA collisions depends on two parameters: (i) $\langle p_T^2\rangle_{NN}^{J/\psi}$, the mean-square 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 a measured in RHIC energy $p+p$ collisions, $\langle p_T^2\rangle_{NN}^{J/\psi} = 4.2 \pm 0.7\,\mathrm{GeV}^2$. The other parameter, $\sigma_{gN}\delta_0$, is essentially nonmeasurable,

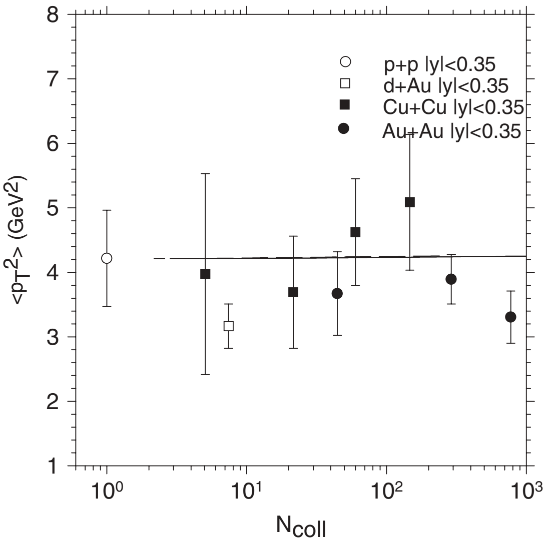

FIG. 5. J/ψ mean-square transverse momentum as a function of collision number, in $p + p$, d+Au, Cu+Cu and Au+Au collisions are shown. The solid and dashed lines are fit to the Au+Au and Cu+Cu data, respectively.

as gluons are not free. Its value can be obtained only from experimental data on p_T broadening of J/ψ. At SPS energy S+U/Pb+Pb collisions $\sigma_{gN}\delta_0$ is estimated to be 0.442 ± 0.056 GeV^2 [12]. PHENIX data on J/ψ p_T broadening can be used to estimate its value at RHIC energy.

In Fig. 5, PHENIX data on the centrality dependence of mean-square transverse momentum $\langle p_T^2 \rangle$ in Cu+Cu and in Au+Au collisions are shown. For comparison, $\langle p_T^2 \rangle$ in $p + p$ and in d+Au collisions are also shown. As data points are few, we do not fit the individual Cu+Cu or Au+Au data sets. Rather we fit the combined data sets. We fix $\langle p_T^2 \rangle_{NN}$ at the measured central value, $\langle p_T^2 \rangle_{NN} = 4.2\,\text{GeV}^2$, and vary $\sigma_{gN}\delta_0$. Best fit is obtained with $\sigma_{gN}\delta_0 = 0.03 \pm 0.51\,\text{GeV}^2$. RHIC data show no evidence of p_T broadening, as indicated by very small values of $\sigma_{gN}\delta_0$. In Fig. 5, model predictions with the central value, $\sigma_{gN}\delta_0 = 0.03\,\text{GeV}^2$ are shown. The solid and dashed lines are for Au+Au and Cu+Cu collisions, respectively. The predictions for Cu+Cu collisions closely match that for Au+Au collisions and cannot be distinguished.

V. SUMMARY AND CONCLUSIONS

To summarize, we analyzed the (preliminary) PHENIX data [24,25] on the centrality dependence of J/ψ suppression and p_T broadening in Cu+Cu and in Au+Au collisions at RHIC energy, $\sqrt{s} = 200$ GeV. The data are analyzed in the QCD-based nuclear absorption model [9–13]. In the model, J/ψ suppression is controlled by parameter ε^2. The larger the ε^2, the more the suppression. Centrality dependence of J/ψ suppression at SPS energy requires $\varepsilon^2_{\text{SPS}} = 0.187\,\text{GeV}^2/\text{fm}$. With ε^2 as a parameter, we have fitted the PHENIX data on the centrality dependence of J/ψ suppression in Cu+Cu and in Au+Au collisions. Cu+Cu data are well explained with $\varepsilon^2 = 0.173 \pm 0.007\,\text{GeV}^2/\text{fm}$, close to the SPS energy value. In Cu+Cu collisions, J/ψs are suppressed in a medium much like the medium created in SPS energy collisions. No exotic, high-density matter is created in Cu+Cu collisions.

Centrality dependence of J/ψ suppression, in Au+Au collisions, is not well explained in the model. The best fitted value, $\varepsilon^2 = 0.146 \pm 0.014\,\text{GeV}^2/\text{fm}$, overpredicts the suppression in mid-central collisions and underpredict the suppression in very central collisions. We conclude that in Au+Au collisions, J/ψs are suppressed in medium unlike the medium created in SPS energy nuclear collisions or in Cu+Cu collisions at RHIC energy. We also analyzed the PHENIX data on p_T broadening of J/ψ in Cu+Cu and Au+Au collisions. RHIC data on p_T broadening show no evidence of p_T broadening.

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[1] T. Matsui and H. Satz, Phys. Lett. **B178**, 416 (1986).
[2] M. C. Abreu *et al.* (NA50 Collaboration), Phys. Lett. **B477**, 28 (2000).
[3] A. Capella, E. G. Ferreiro, and A. B. Kaidalov, Phys. Rev. Lett. **85**, 2080 (2000).
[4] A. P. Kostyuk, M. I. Gorenstein, H. Stocker, and W. Greiner, Phys. Rev. C **68**, 041902(R) (2003).
[5] M. I. Gorenstein, A. P. Kostyuk, H. Stoecker, and W. Greiner, Phys. Lett. **B509**, 277 (2001).
[6] L. Grandchamp, R. Rapp, and G. E. Brown, Phys. Rev. Lett. **92**, 212301 (2004).
[7] J. P. Blaizot, P. M. Dinh, and J. Y. Ollitrault, Phys. Rev. Lett. **85**, 4012 (2000).
[8] A. K. Chaudhuri, Phys. Lett. **B527**, 80 (2002).
[9] A. K. Chaudhuri, Phys. Rev. Lett. **88**, 232302 (2002).
[10] A. K. Chaudhuri, Phys. Rev. C **68**, 014906 (2003).
[11] A. K. Chaudhuri, Phys. Rev. C **68**, 024906 (2003).
[12] A. K. Chaudhuri, J. Phys. G **32**, 229 (2006).
[13] J. Qiu, J. P. Vary, and X. Zhang, Phys. Rev. Lett. **88**, 232301 (2002).
[14] R. Shahoyan *et al.* (NA60 Collaboration), arXiv:hep-ex/0505049.
[15] K. Borer *et al.*, Nucl. Phys. **A749**, 251 (2005).
[16] R. Arnaldi *et al.* (NA60 Collaboration), Nucl. Phys. **A774**, 711 (2006).
[17] BRAHMS Collaboration, I. Arsene *et al.*, Nucl. Phys. **A757**, 1 (2005).
[18] B. B. Back *et al.* (PHOBOS Collaboration), Nucl. Phys. **A757**, 28 (2005).
[19] K. Adcox *et al.* (PHENIX Collaboration), Nucl. Phys. **A757**, 184 (2005).
[20] J. Adams *et al.* (STAR Collaboration), Nucl. Phys. **A757**, 102 (2005).
[21] 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.
[22] R. L. Thews, M. Schroedter, and J. Rafelski, Phys. Rev. C **63**, 054905 (2001) [arXiv:hep-ph/0007323].
[23] P. Braun-Munzinger and J. Stachel, Phys. Lett. **B490**, 196 (2000).

[24] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. C **69**, 014901 (2004).

[25] J. L. Nagle (PHENIX Collaboration), Nucl. Phys. **A715**, 252 (2003).

[26] J. L. Nagle (PHENIX Collaboration), arXiv:nucl-ex/0509024.

[27] H. Pereira Da Costa (PHENIX Collaboration), arXiv:nucl-ex/0510051.

[28] R. Vogt, arXiv:nucl-th/0507027.

[29] H. L. Lai, J. Botts, J. Huston, J. G. Morfin, J. F. Owens, J. W. Qiu, W. K. Tung, and H. Weerts, Phys. Rev. D **51**, 4763 (1995).

[30] C. J. Benesh, J. Qiu and J. P. Vary, Phys. Rev. C **50**, 1015 (1994).

[31] C. W. deJager, H. deVries, and C. deVries, At. Data Nucl. Data Tables, **14**, 479 (1974).

[32] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **96**, 012304 (2006).

[33] P. Cortese *et al.* (NA50 Collaboration), Nucl. Phys. **A715**, 679 (2003).

[34] 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); S. Gupta and H. Satz, *ibid.* **283**, 439 (1992).

[35] D. Kharzeev, M. Nardi, and H. Satz, Phys. Lett. **B405**, 14 (1997).