J/ψ Suppression in Pb + Pb Collisions: A Conventional Description

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We have analyzed the latest NA50 data on J/ψ suppression in Pb + Pb collisions. J/ψ production is assumed to be a two-step process: (i) formation of a $c\bar{c}$ pair, which is accurately calculable in QCD, and (ii) formation of a J/ψ meson from the $c\bar{c}$ pair, which can be conveniently parametrized. The parameters of the model were fixed from experimental data on the total J/ψ cross section as a function of effective nuclear length. The model gives an excellent description of NA50 data on the E_T dependence of the J/ψ–to–Drell-Yan ratio. It was applied to the E_T dependence of J/ψ at RHIC energies, and predicts a much larger suppression of J/ψ, in agreement with other model calculations.

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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 the presence of quark-gluon plasma (QGP), binding of $c\bar{c}$ pairs 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 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.

The latest data obtained by the NA50 Collaboration [4] on J/ψ production in Pb + Pb collisions at 158 A GeV is the first indication of the anomalous mechanism of charmonium suppression, which goes beyond the conventional suppression in a nuclear environment. The ratio of J/ψ yield to that of Drell-Yan pairs decreases faster with E_T in the most central collisions than in the less central ones. It has been suggested that the resulting pattern can be understood in a deconfinement scenario in terms of successive melting of charmonium bound states [4]. In a recent paper, Blaizot *et al.* [5] have shown that the data can be understood as an effect of transverse energy fluctuations in central heavy ion collisions. Introducing a factor $\varepsilon = E_T/E_T(b)$, assuming that the suppression is 100% above a threshold density (a parameter in the model), and smearing the threshold density (at the expense of another parameter), the best fit to the data was obtained. Extending the Blaizot's model to include fluctuations in the number of NN collisions at a fixed impact parameter, NA50 data could be fitted with a single parameter, the threshold density, above which all the J/ψ mesons melt [6]. The assumption that all the J/ψ mesons melt above a threshold density implicitly assumes that a QGP-like environment is produced in the collision. NA50 data could be explained in the conventional approach also, without invoking a QGP-like scenario. Capella *et al.* [7] analyzed the data in the comover approach. There also the comover density has to be modified by the factor ε. Introduction of this *ad hoc* factor ε can be justified in a model based on excited nucleons represented by strings [8].

The aim of the present paper is to show that while in a conventional approach, nuclear suppression is not sufficient to explain NA50 data; the data are very well described in a model of Qiu, Vary, and Zhang [9], where the suppression due to nuclear environment is treated in an unconventional manner.

II. Model.—Recently, Qiu, Vary, and Zhang [9] proposed a model to describe the J/ψ suppression in nucleon-nucleus/nucleus-nucleus collisions. For the sake of completeness, we will briefly describe the model. Qiu, Vary, and Zhang assumed that the production of the J/ψ meson is a two-step process: (i) production of $c\bar{c}$ pairs with relative momentum square q^2, and (ii) formation of J/ψ mesons from the $c\bar{c}$ pairs. Step (i) can be accurately calculated in QCD. The second step, formation of J/ψ mesons from initially compact $c\bar{c}$ pairs, is nonperturbative. They used a parametric form for the step (ii), formation of J/ψ from $c\bar{c}$ pairs. The J/ψ cross section in AB collisions, at center of mass energy $\sqrt{s}$ was then written as

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

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. The incoming parton momentum fractions are fixed by kinematics and are $x_a = (\sqrt{x_F^2 + 4Q^2/s} + x_F)/2$ and $x_b = (\sqrt{x_F^2 + 4Q^2/s} - x_F)/2$. Quark annihilation and gluon fusion are the major subprocesses for $c\bar{c}$ production. In the leading log, they are given by [10]

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$$\hat{\sigma}_{q\bar{q}\to c\bar{c}}(Q^2) = \frac{2}{9}\frac{4\pi\alpha_s}{3Q^2}\left(1 + \frac{\gamma}{2}\right)\sqrt{1-\gamma}, \quad (2)$$

$$\hat{\sigma}_{gg\to c\bar{c}}(Q^2) = \frac{\pi\alpha_s}{3Q^2}\left(1 + \frac{\gamma}{2} + \frac{\gamma^2}{16}\right)\log\left(\frac{1+\sqrt{1-\gamma}}{1-\sqrt{1-\gamma}}\right) - \left(\frac{7}{4} + \frac{31}{16}\gamma\right)\sqrt{1-\gamma}, \quad (3)$$

where α_s is the QCD running coupling constant and $\gamma = 4m_c^2/Q^2$. In Eq. (1) $F_{c\bar{c}\to J/\psi}(q^2)$ is the transition probability that a $c\bar{c}$ pair with relative momentum square q^2 evolves into a physical J/ψ meson. Qiu, Vary, and Zhang [9] considered three different parametric forms (representing different physical processes) for the transition probability. All three forms could describe the experimental energy dependence of total J/ψ cross section in hadronic collisions [9].

In a nucleon-nucleus/nucleus-nucleus collision, the produced $c\bar{c}$ pairs interact with the nuclear medium before they exit. Observed anomalous nuclear enhancement of the momentum imbalance in dijet production led Qiu, Vary, and Zhang [9] to argue that the interaction of a $c\bar{c}$ pair with nuclear environment increases the square of the relative momentum between the $c\bar{c}$ pair. As a result some of the $c\bar{c}$ pairs might gain enough relative momentum squared q^2 to be pushed over the threshold to become open charm mesons. Consequently, the cross sections for J/ψ production are reduced in comparison with nucleon-nucleon collisions. If the J/ψ meson travel a distance L, the transition probability $F_{c\bar{c}}(q^2)$ in Eq. (1) will be changed to

$$F_{c\bar{c}\to J/\psi}(q^2) \to F_{c\bar{c}\to J/\psi}(q^2 + \varepsilon^2 L), \quad (4)$$

with ε^2 being the square of relative momentum gained by the $c\bar{c}$ pair per unit length of the nuclear medium. Of the three different parametric forms of the transition probability, all of which fitted the energy dependence of the J/ψ cross section in hadron-nucleus collisions, only the following form,

$$F_{c\bar{c}\to J/\psi}(q^2) = N_{J/\psi}\theta(q^2)\theta(4m'^2 - 4m_c^2 - q^2) \times \left(1 - \frac{q^2}{4m'^2 - 4m_c^2}\right)^{\alpha_F}, \quad (5)$$

could describe the experimental J/ψ data as a function of effective nuclear length [9]. For completeness purpose, we have redone the calculation of J/ψ production as a function of effective nuclear length. We have used the CTEQ5 parton distribution functions [11]. In Fig. 1, NA50 data [12] on the J/ψ cross section for proton-nucleon, proton-nucleus, and nucleus-nucleus collisions as a function of the effective nuclear medium length $L(A,B)$ are shown. The solid line is a fit obtained in the model. The parameter values, $KN_{J/\psi} = 0.458$, $\varepsilon^2 = 0.225$ GeV^2/fm, and $\alpha_F = 1$, are very close to the values obtained in Ref. [9]. In the next section, we will use these parameters to analyze the NA50 data on the transverse energy dependence of J/ψ to the Drell-Yan ratio.

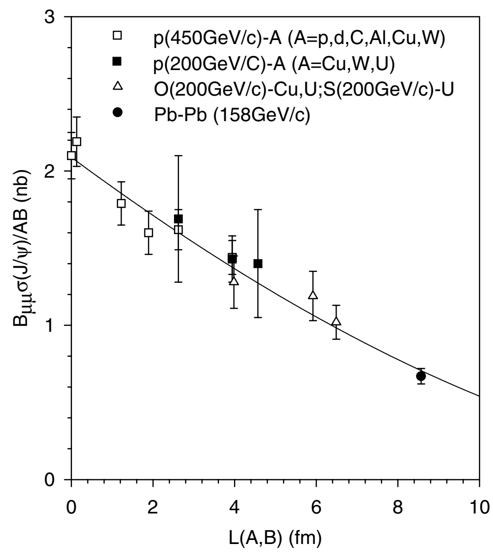

FIG. 1. Total J/ψ cross sections with the branching ratio to $\mu^+\mu^-$ in proton-nucleus, proton-nucleus, and nucleus-nucleus collisions, as a function of the effective nuclear length $L(A,B)$.

III. E_T dependence of J/ψ in Pb + Pb collisions.— The NA50 Collaboration presented transverse energy dependence of J/ψ to Drell-Yan ratio in Pb + Pb collisions [4]. As mentioned in the beginning, the data show anomalous suppression, which goes beyond the conventional nuclear suppression. In the present section, it will be shown that the data are fully explained in the model of Qiu, Vary, and Zhang, which treat J/ψ suppression in nuclear environment in an unconventional manner.

The Drell-Yan pairs do not suffer final state interactions, and the cross section at an impact parameter $\mathbf{b}$ as a function of E_T can be written as

$$d^2\sigma^{DY}/dE_T\, d^2b = \sigma_{NN}^{DY}\int d^2s\, T_A(\mathbf{s})T_B(\mathbf{s}-\mathbf{b})P(b,E_T), \quad (6)$$

where σ_{NN}^{DY} is the Drell-Yan cross section in NN collisions. All the nuclear information is contained in the nuclear thickness function, $T_{A,B}(\mathbf{s})[= \int dz\, \rho_{A,B}(\mathbf{s},z)]$. Presently we have used the following parametric form for $\rho_A(r)$ [5]:

$$\rho_A(r) = \frac{\rho_0}{1 + \exp(\frac{r-r_0}{a})} \quad (7)$$

with $a = 0.53$ fm, $r_0 = 1.1A^{1/3}$. The central density is obtained from $\int \rho_A(r)\, d^3r = A$. In Eq. (6), $P(b,E_T)$ is the probability to obtain E_T at an impact parameter b. The geometric model has been quite successful in explaining the transverse energy as well as multiplicity distributions in AA collisions [13,14]. Transverse energy distribution in Pb + Pb collisions also could be described in this model [6]. In this model, E_T distribution is written in terms of E_T distribution in NN collisions. One also assumes that the Gamma distribution, with parameters α and β describe the E_T distributions in NN collisions. Pb + Pb data on E_T distribution could be fitted with $\alpha = 3.46 \pm 0.19$ and $\beta = 0.379 \pm 0.021$ [6].

While Drell-Yan pairs do not suffer interactions with nuclear matter, the J/ψ mesons do. In the model of Qiu, Vary, and Zhang [9], the suppression factor depends on the length traversed by the $c\bar{c}$ mesons in the nuclear medium. Consequently, we write the J/ψ cross section at an impact parameter $\mathbf{b}$ as

$$d^2\sigma^{J/\psi}/dE_T d^2b = \sigma_{NN}^{J/\psi} \int d^2s\, T_A(\mathbf{s}) \times T_B(\mathbf{s} - \mathbf{b}) S(L(\mathbf{b},\mathbf{s})) P(b, E_T), \tag{8}$$

where $\sigma_{NN}^{J/\psi}$ is the J/ψ cross section in NN collisions and $S(L(\mathbf{b},\mathbf{s}))$ is the suppression factor due to passage through a length L in nuclear environment. At an impact parameter $\mathbf{b}$ and at point $\mathbf{s}$, the transverse density can be calculated as

$$n(\mathbf{b},\mathbf{s}) = T_A(\mathbf{s})[1 - e^{-\sigma_{NN} T_B(\mathbf{b}-\mathbf{s})}] + T_B(\mathbf{b} - \mathbf{s})[1 - e^{-\sigma_{NN} T_A(\mathbf{s})}], \tag{9}$$

and the length $L(\mathbf{b},\mathbf{s})$ that the J/ψ meson will traverse can be obtained as

$$L(\mathbf{b},\mathbf{s}) = n(\mathbf{b},\mathbf{s})/2\rho_0. \tag{10}$$

Suppression factor $S(L(\mathbf{b},\mathbf{s}))$ can be calculated using Eq. (1), noting that $c\bar{c}$ pairs gain ε^2 momentum per unit length L. Parametric value of ε^2, as shown before was obtained by fitting nucleon-nucleus and nucleus-nucleus J/ψ cross section data containing all E_T. However, Eq. (8) corresponds to a particular E_T. Accordingly, momentum gain factor ε^2 needs to be modified. We modify the momentum gain factor ϵ^2 to take into account the E_T dependence as

$$\varepsilon^2(E_T) = \varepsilon_0^2 \frac{L(E_T)}{\int dE_T\, L(E_T)}, \tag{11}$$

where ε_0^2 is the momentum gain factor for all E_T (which was obtained by fitting experimental data). $L(E_T)$ is the length through which a J/ψ meson with transverse energy E_T will travel. The length $L(E_T)$ can be calculated [2],

$$L(E_T) = \frac{\int d^2b\, d^2s\, T_A(\mathbf{s}) T_B(\mathbf{b} - \mathbf{s})[T_A(\mathbf{s}) + T_B(\mathbf{b} - \mathbf{s})] P(b, E_T)}{2\sigma_{NN}\rho_0 \int d^2b\, d^2s T_A(\mathbf{s}) T_B(\mathbf{b} - \mathbf{s}) P(b, E_T)}. \tag{12}$$

Fluctuations of transverse energy at a fixed impact parameter plays an important role in the explanation of the NA50 data. Above 100 GeV, i.e., approximately at the position of the knee, the second drop in the data is due to the fluctuations in E_T. In order to account for the fluctuations, following Capella *et al.* [7], we calculate

$$F(E_T) = E_T/E_T^{NF}(E_T), \tag{13}$$

where

$$E_T^{NF}(E_T) = \frac{\int d^2b\, E_T^{NF}(b) P(b, E_T)}{\int d^2b P(b, E_T)}. \tag{14}$$

The function $F(E_T)$ is unity up to the knee of the distribution, and increases thereafter, precisely where fluctuations dominate. The replacement,

$$L(\mathbf{b},\mathbf{s}) \to L(\mathbf{b},\mathbf{s}) F(E_T), \tag{15}$$

then properly accounts for the fluctuations in the E_T distributions.

In Fig. 2, we have compared the E_T distribution of J/ψ to the Drell-Yan ratio, obtained in the model with the experimental data obtained by the NA50 Collaboration. In the calculation, we have used $\sigma_{NN} = 32$ mb and $\sigma_{NN}^{J/\psi}/\sigma_{NN}^{DY} = 53.5$ [5]. We obtain excellent agreement with data. The second drop at $E_T = 100$ GeV is correctly reproduced. It may be emphasized that the present calculation is essentially a parameter-free calculation. The few parameters of the model were obtained previously from fitting the total J/ψ cross section in pA and AA collisions. Excellent agreement with data indicates that the NA50 data are fully explained in terms of suppression in nuclear environment.

IV. Prediction for RHIC energy.—The present model can be used to predict E_T dependence of J/ψ to the Drell-Yan ratio at RHIC energy. The recent PHOBOS experiment [15] showed that for central collisions, total multiplicity is larger by 70% at RHIC than at SPS. E_T can be assumed to be increased by the same factor. Accordingly, scaled the E_T distribution for Pb + Pb collisions at SPS energy can represent the experimental E_T distribution at RHIC energy for Au + Au collisions (small mass difference between Au and Pb can be neglected). We have fitted the rescaled E_T distribution in the geometric model to obtain the parameters, $\alpha = 3.09$ and $\beta = 0.495$ [16]. Nucleon-nucleon inelastic cross section (σ_{NN}) was assumed to be 41 mb at RHIC, instead of 32 mb at SPS [17].

At RHIC energy the so-called hard component which is proportional to the number of binary collisions appears. Model dependent calculations indicate that the hard component grows from 22% to 37% as the energy changes from $\sqrt{s} = 56$ to 130 GeV [16]. J/ψ suppression will strongly depend on the hard component, as it effectively increases the density of the nuclear medium. For the f fraction of hard scattering, transverse density $n(\mathbf{b},\mathbf{s})$ in Eq. (10) is modified to [17]

$$n_{\text{mod}}(\mathbf{b},\mathbf{s}) \to (1 - f) n(\mathbf{b},\mathbf{s}) + f n^{\text{hard}}(\mathbf{b},\mathbf{s}), \tag{16}$$

with $n^{\text{hard}}(\mathbf{b},\mathbf{s}) = \sigma_{NN} T_A(\mathbf{s}) T_B(\mathbf{b} - \mathbf{s})$. With a hard component, transverse density is increased; as a result, suppression will be increased at RHIC energy. In Fig. 2, the thick solid line is the prediction for J/ψ to the Drell-Yan ratio at RHIC energy, for Au + Au collisions, obtained with a 37% hard scattering component in the density. Very large suppression is obtained. The effect of $E_T$fluctuations is not visible anymore (very large suppression washes out E_T fluctuations). It is interesting to compare the present prediction with other model calculations. In Fig. 2, the thin dotted line is the prediction obtained by Dinh *et al.* [17] in a model where all the J/ψ mesons melt above a threshold density, essentially in a

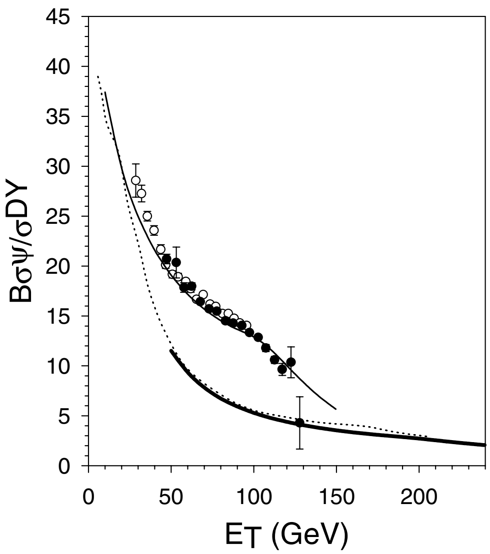

FIG. 2. Open and closed circles are the J/ψ to Drell-Yan ratio in a Pb + Pb collision obtained by the NA50 Collaboration in 1996 and 1998, respectively. The thin line is a fit to the data in the model described in the text. The thick solid line is the prediction obtained for Au + Au collisions at RHIC energy, with 37% hard scattering component (see text). The thin dotted line is the prediction obtained by Dinh *et al.* [17] for Au + Au collisions at RHIC energy, in a model where all the J/ψ mesons melt above a threshold density.

deconfined scenario. Very close agreement between the predictions obtained in a nuclear environment and those obtained in a deconfined scenario is interesting. It seems that it may not be possible to confirm the deconfinement phase transition, which is expected to occur at RHIC energy, from the J/ψ data. Recently several authors have proposed that at RHIC energy, in a deconfined scenario, recombination of $c\bar{c}$ pairs will lead to enhancement of J/ψ's, rather than its suppression [19]. Inclusion of recombination effects may mask the large suppression obtained by Dinh *et al.* [17]. However, nuclear suppression as calculated presently will remain unaltered. It may then be possible to distinguish the deconfinement phase transition from the J/ψ data.

V. Summary.—To summarize, we have analyzed the NA50 data on transverse energy distribution of J/ψ to the Drell-Yan ratio in Pb + Pb collisions. The data were analyzed in a model, where the suppression of J/ψ is due to gain in relative square momentum of $c\bar{c}$ pairs as it travels through the nuclear environment. Some of the $c\bar{c}$ pairs can gain enough momentum to cross the threshold to become open charm mesons. The model, without any free parameters, can well explain the NA50 data on J/ψ suppression. Present analysis clearly shows that it is not essential to assume a deconfined scenario to explain the NA50 data. The model was used to predict E_T distribution of J/ψ to the Drell-Yan ratio at RHIC energy. At RHIC the hard component of scattering may be important. Very large suppression is obtained if the hard component is included. Interestingly, the prediction obtained in the model with only nuclear suppression agrees closely with the prediction obtained in a deconfined scenario. However, as suggested by several authors, recombination of $c\bar{c}$ in a deconfinement scenario may lead to enhancement, rather than suppression of J/ψ at RHIC energy. Recombination effect will not affect the nuclear suppression. Observation of enhanced production J/ψ at RHIC energy will then confirm deconfinement phase transition.

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