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 c¯c pair, which is accurately calculable in QCD and (ii) formation of J/ψ meson from the c¯c pair, which can be conveniently parameterized. In a pA/AA collision, the as the c¯c pair pass through the nuclear medium, it gain relative square momentum at the rate of ε² per unit path length. As a result, some of the c¯c pairs can gain enough momentum to cross the threshold to become an open charm meson, leading to suppression in pA/AA collisions. 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 without any free parameter, give excellent description of NA50 data on E_T dependence of J/ψ to Drell-Yan ratio. The model was applied to predict the E_T dependence of J/ψ at RHIC energy. Much larger suppression of J/ψ, in agreement with other model calculations are predicted.

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¯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 c¯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 ε = 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 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]. Assumption that all the J/ψ mesons melt above a threshold density, implicitly assume that QGP like environment is produced in the collision. NA50 data could be explained in the conventional approach also, without invoking 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 adhoc factor ε can be justified in a model based on excited nucleons represented by strings [8].

Aim of the present paper is to show that while in 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 J/ψ meson is a two step process, (i) production of c¯c pairs with relative momentum square q^2,
and (ii) formation of $J/\psi$ mesons from the $c\bar{c}$ pairs. Step (i) can be accurately calculated in QCD. The second step, formation of $J/\psi$ mesons from initially compact $c\bar{c}$ pairs is non-perturbative. They used a parametric form for the step (ii), formation of $J/\psi$ from $c\bar{c}$ pairs. The $J/\psi$ cross section in $AB$ collisions, at center of mass energy $\sqrt{s}$ was then written as,

$$\sigma_{A+B \to J/\psi + X}(s) = K \sum_{a,b} \int d q^2 \left( \frac{\hat{\sigma}_{ab \to c\bar{c}}}{Q^2} \right) \int d x_F \phi_a/A(x_a, Q^2) \phi_b/B(x_b, Q^2) \frac{x_a x_b}{x_a + x_b} \times F_{c\bar{c} \to J/\psi}(q^2),$$  \hspace{1cm} (1)

where $\sum_{a,b}$ runs over all parton flavors, and $Q^2 = q^2 + 4m^2$. 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 sub processes for $c\bar{c}$ production. In the leading log, they are given by \[10\],

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

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

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

In a nucleon-nucleus/nucleus-nucleus collision, the produced $c\bar{c}$ pairs interact with 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 the threshold to become open charm mesons. Consequently, the cross sections for $J/\psi$ production are reduced in comparison with nucleon-nucleon collisions. If the $J/\psi$ meson travel a distance $L$, the transition probability $F_{c\bar{c}}(q^2)$ in eq\[E_{\rho}\] will be changed to

$$F_{c\bar{c} \to J/\psi}(q^2) \to F_{c\bar{c} \to J/\psi}(q^2 + \epsilon^2 L),$$  \hspace{1cm} (5)

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

$$F_{c\bar{c} \to J/\psi}(q^2) = N_{J/\psi} \theta(q^2)(1 - \frac{q^2}{4m^2 - 4m^2})^{\alpha_F},$$  \hspace{1cm} (6)

could describe the experimental $J/\psi$ data as a function of effective nuclear length \[9\]. For completeness purpose, we have redone the calculation of $J/\psi$ production as a function of effective nuclear length. We have used the CTEQ5 parton distribution functions \[11\]. In Fig.1, NA50 data \[12\] on $J/\psi$ cross section for proton-nucleon, proton-nucleus and nucleus-nucleus collisions as a function of the effective nuclear medium length $L(A,B)$ is shown. The solid line is a fit obtained in the model. The parameter values, $KN_{J/\psi}=.458$, $\epsilon^2=.225$ 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 $J/\psi$ to Drell-Yan ratio.

### III. $E_T$ Dependence of $J/\psi$ in Pb+Pb Collisions

NA50 collaboration presented transverse energy dependence of $J/\psi$ to Drell-Yan ratio in Pb+Pb collisions \[9\]. As mentioned in the beginning, the data shows 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 $J/\psi$ 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 $b$ as a function of $E_T$ can be written as,
\[ \frac{d^2 \sigma^{DY}}{dE_T d^2 b} = \sigma^{DY}_{NN} \int d^2 s T_A(s)T_B(s - b)P(b, E_T), \] (7)

where \( \sigma^{DY}_{NN} \) is the Drell-Yan cross section in \( NN \) collisions. All the nuclear information is contained in the nuclear thickness function, \( T_{A,B}(s) = \int dz \rho_{A,B}(s, z) \). Presently we have used the following parametric form for \( \rho_{A}(r) \) \[ \rho_A(r) = \frac{\rho_0}{1 + \exp \left( -\frac{r - a}{r_0} \right)} \] (8)

with \( a = 0.53 \text{fm}, \ r_0 = 1.14^{1/3} \). The central density is obtained from \( \int \rho_A(r)d^3r = A \). In Eq. 8, \( P(b, E_T) \) is the probability to obtain \( E_T \) at an impact parameter \( b \). Geometric model has been quite successful in explaining the transverse energy as well as multiplicity distributions in AA collisions \([4,5]\). Transverse energy distribution in Pb+Pb collisions also could be described in this model \([3]\). In this model, \( E_T \) distribution is written in terms of \( E_T \) distribution in \( NN \) collisions. One also assume that the Gama distribution, with parameters \( \alpha \) and \( \beta \) 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 \( \beta = 0.379 \pm 0.021 \) \([3]\).

While Drell-Yan pairs do not suffer interactions with nuclear matter, the \( J/\psi \) mesons do. In the model of Qiu, Vary and Zhang \([8]\), suppression factor depend on the length traversed by the \( c \bar{c} \) mesons in nuclear medium. Consequently, we write the \( J/\psi \) cross section at an impact parameter \( b \) as,

\[ \frac{d^2 \sigma^{J/\psi}}{dE_T d^2 b} = \sigma^{J/\psi}_{NN} \int d^2 s T_A(s)T_B(s - b)S(L(b, s))P(b, E_T), \] (9)

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

\[ n(b, s) = T_A(s)[1 - e^{-\sigma_{NN}T_B(b-s)}] + T_B(b-s)[1 - e^{-\sigma_{NN}T_A(s)}], \] (10)

and the length \( L(b, s) \) that the \( J/\psi \) meson will traverse can be obtained as,

\[ L(b, s) = n(b, s)/2\rho_0 \] (11)

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

\[ \epsilon^2(E_T) = \epsilon_0^2 \frac{L(E_T)}{dE_T L(E_T)}, \] (12)

where \( \epsilon_0^2 \) 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 \( J/\psi \) meson with transverse energy \( E_T \) will travel. The length \( L(E_T) \) can be calculated \([8]\),

\[ L(E_T) = \frac{\int d^2 b d^2 s T_A(s)T_B(b-s)[T_A(s) + T_B(b-s)]P(b, E_T)}{2\sigma_{NN} \rho_0 \int d^2 b d^2 s T_A(s)T_B(b-s)P(b, E_T)} \] (13)

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 2nd drop in the data is due to the fluctuations in \( E_T \). In order to account for the fluctuations, following Capella et al. \([6]\), we calculate,

\[ F(E_T) = E_T/E_{TNF}^N(E_T), \] (14)

where,

\[ E_{TNF}^N(E_T) = \frac{\int d^2 b E_{TNF}^{NF}(b)P(b, E_T)}{\int d^2 b P(b, E_T)} \] (15)

The function \( F(E_T) \) is unity up to the knee of the distribution, and increases thereafter, precisely, where fluctuations dominates. The replacement,
\[ L(b, s) \rightarrow L(b, s)F(E_T), \]  

then properly accounts for the fluctuations in the \( E_T \) distributions.

In Fig.2, we have compared the \( E_T \) distribution of \( J/\psi \) to Drell-Yan ratio, obtained in the model with the experimental data obtained by NA50 collaboration. In the calculation, we have used \( \sigma_{NN} =32 \text{ mb and } \sigma_{NN}^{J/\psi}/\sigma_{NN}^{DY} =53.5 \) \[2\]. We obtain excellent agreement with data. The second drop at \( E_T=100 \text{ GeV} \) 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 the fitting the total \( J/\psi \) cross section in pA and AA collisions. Excellent agreement with data indicate that the NA50 data is fully explained in terms of suppression in nuclear environment.

### IV. PREDICTION FOR RHIC ENERGY

Present model can be used to predict \( E_T \) dependence of \( J/\psi \) to Drell-Yan ratio at RHIC energy. 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 \( \left( \sigma_{NN} \right) \) 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 number of binary collisions appear. Model dependent calculations indicate that the hard component grows from 22% to 37% as the energy changes from \( \sqrt{s}=56 \) GeV to 130 GeV \[18\]. \( J/\psi \) suppression will strongly depend on the hard component, as it effectively increases the density of the nuclear medium. For \( f \) fraction of hard scattering, transverse density \( n(b, s) \) in Eq\[14\] is modified to \[17\].

\[ n_{mod}(b, s) \rightarrow (1-f)n(b, s) + fn_{hard}(b, s), \]  

with \( n_{hard}(b, s) = \sigma_{NN}T_A(s)T_B(b-s) \). With 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 \( J/\psi \) to Drell-Yan ratio at RHIC energy, for Au+Au collisions, obtained with 37% hard scattering component in the density. Very large suppression is obtained. 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 Blaizot \textit{et al.} \[17\] in model where all the \( J/\psi \) mesons melts above a threshold density, essentially in a deconfined scenario. Very close agreement between the predictions obtained in a nuclear environment and 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 \( J/\psi \) data. Recently several authors have proposed that at RHIC energy, in a deconfined scenario, recombination of \( \bar{c}c \) pairs will lead to enhancement of \( J/\psi \)'s, rather than its suppression \[16\]. Inclusion of recombination effects may mask the large suppression obtained by Blaizot \textit{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 \( J/\psi \) data.

### V. SUMMARY

To summarize, we have analyzed the NA50 data on transverse energy distribution of \( J/\psi \) to Drell-Yan ratio in Pb+Pb collisions. The data were analyzed in a model, where suppression of \( J/\psi \) is due to gain in relative square momentum of \( \bar{c}c \) pairs as it travels through the nuclear environment. Some of the \( \bar{c}c \) 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 \( J/\psi \) 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 \( J/\psi \) to Drell-Yan ratio at RHIC energy. At RHIC 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 \( \bar{c}c \) in a deconfined scenario may lead to enhancement, rather than suppression of \( J/\psi \) at RHIC energy. Recombination effect will not affect the nuclear suppression. Observation of enhanced production \( J/\psi \) at RHIC energy will then confirm deconfinement phase transition.
FIG. 1. Total $J/\psi$ 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 $L(A,B)$. 

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FIG. 2. Open and closed circles are the $J/\psi$ to Drell-Yan ratio in a Pb+Pb collision obtained by 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 Blaizot et al. [17] for Au+Au collisions at RHIC energy, in a model where all the $J/\psi$ mesons melts above a threshold density.