PHYSICAL REVIEW C **66**, 021902(R) (2002)

Nuclear absorption and J/ψ suppression in Pb+Pb collisions

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(Received 19 March 2002; published 26 August 2002)

We have analyzed the NA58 data on J/ψ suppression in Pb+Pb collisions. J/ψ production is assumed to be a two step process, (i) formation of $c\bar{c}$ pair, which is accurately calculable in QCD and (ii) formation of J/ψ meson from the $c\bar{c}$ pair, which can be conveniently parametrized. In a pA/AA collision, a $c\bar{c}$ pair gains relative square momentum as it passes through the nuclear medium and some of the $c\bar{c}$ pairs can gain enough momentum to cross the threshold to become an open charm meson, leading to suppression in pA/AA collisions. A new prescription is proposed for the gain in momentum square, consistent with Krammer process. The model could explain the E_T dependence of J/ψ over Drell-Yan ratio.

DOI: 10.1103/PhysRevC.66.021902 PACS number(s): 25.75.Dw

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 $c\bar{c}$ 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, which 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 158A 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]. Essentially in a QGP-like scenario, assuming all the J/ψ melts above a threshold density, NA50 data could be explained as an effect of transverse energy fluctuations [5–7]. The data could be also be explained in the comover approach without invoking QGP-like scenario [8]. Recently we have shown [9] that the NA50 data could be well explained extending the model of Qiu *et al.* [10]. In this model suppression is due to gain in relative square momentum of $c\bar{c}$ pair, as it pass through the nuclear medium. Some of the $c\bar{c}$ pair might gain enough momentum to cross the open charm threshold.

In the present Rapid Communication, we further analyze the problem and alter the prescription used by Qiu *et al.* [10] to calculate the gain in the relative square momentum of the $c\bar{c}$ pair to be consistent with theoretical understanding. We argue that square of relative momentum gained by $c\bar{c}$ pair for traversing a length L in nuclear medium goes as L^2 rather than L, as was proposed by Qiu *et al.* [10].

We briefly describe the model of Qiu *et al.* [10]. Production of J/ψ meson is assumed to be 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 [10,11]. The second step, formation of J/ψ mesons from initially compact $c\bar{c}$ pairs is nonperturbative. They used a parametric form for 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

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

where $\Sigma_{a,b}$ 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 $x_b=(\sqrt{x_F^2+4Q^2/s}-x_F)/2$. $F_{c\bar{c}\to J/\psi}(q^2)$ is the transistion probability to form a J/ψ meson from the initially compact $c\bar{c}$ pair. Subprocess cross sections can be found in [11].

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 [10] 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. They prescribed that if the pair traverses a length L in nuclear medium, then the relative square momentum q^2 in the transition probability $F_{c\bar{c}\to J/\psi}(q^2)$ should be changed to

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$$q^2 \rightarrow q^2 + \varepsilon^2 L \quad (2)$$

with ε^2 being the square of relative momentum gained by the pair per unit length of nuclear medium. In Refs. [10,9] it was shown that with appropriate transition probability, Eq. 2 can describe the total J/ψ cross section as pA/AA collisions. However, the NA50 data on transverse energy dependence of the ratio J/ψ over Drell-Yan require ε^2 to be scaled by a factor $L/\langle L \rangle$ [9]. The square of the relative momentum gain, for traversing a length L of nuclear medium goes as L^2 rather than L. The dependence is consistent with Brownian motion of the realtive square momentum of the $c\bar{c}$ pair. Kramers equation is a special Fokker-Plank equation for the distribution function in position and momentum space [12]. For harmonically bound particles, the steady state variances can be written as [13]

$$\langle (x-\bar{x})^2 \rangle = v_{th}^2/\omega_0^2, \quad (3)$$

$$\langle (v-\bar{v})^2 \rangle = v_{th}^2, \quad (4)$$

where $v_{th} = \sqrt{T/m}$ is the thermal velocity of a particle with mass m. In an external force free condition, above eqautions lead to

$$\langle (p_f - p_i)^2 \rangle \propto \langle (x_f - x_i)^2 \rangle. \quad (5)$$

In other words, for a Krammer-like process, square of relative momentum gain goes as L^2 rather than L as in Eq. (2). Accordingly, we suggest that for traversing a length L in nuclear medium, the relative momentum q^2 in the transition probability $F_{c\bar{c}\rightarrow J/\psi}(q^2)$ should be changed to

$$q^2 \rightarrow q^2 + \varepsilon^2 L^2. \quad (6)$$

The parameter ε^2 was obtained by fitting NA50 data [15] on J/ψ production in pA and AA collisions. For the transition probability, we use the following form [10,9]:

$$F_{c\bar{c}\rightarrow J/\psi}(q^2) = N_{J/\psi}\theta(q^2)\,\theta(4m'^2 - 4m_c^2 - q^2) \times \left(1 - \frac{q^2}{4m'^2 - 4m_c^2}\right)^{\alpha_F}, \quad (7)$$

and we have used CTEQ5M parton distribution function [14] in the calculation. In Fig. 1, we have compared NA50 experimental data [15] with the best fitted curve. Except for the pd reaction, all the data points are correctly reproduced. The cross section for pd reaction is underpredicted. Indeed, we do not expect Eq. (5) to predict correctly the suppression in pd collisions. The equation was obtained assuming Brownian motion of charm and anticharm quarks in a nuclear medium (heat bath). The deuteron can provide hardly any nuclear medium. It is evident from the length of nuclear medium in pd collision, which is 0.13 fm only. Also, Eq. (5) ($\Delta p^2 \propto \Delta x^2$) corresponds to the steady state, i.e., for $t\rightarrow\infty$. In order to be valid, the size of the system must be larger than the relaxation time scale of the charm quarks. Relaxation time scale for charm quarks in a nuclear environment is not known. Thermalization time scale of charm quarks in a

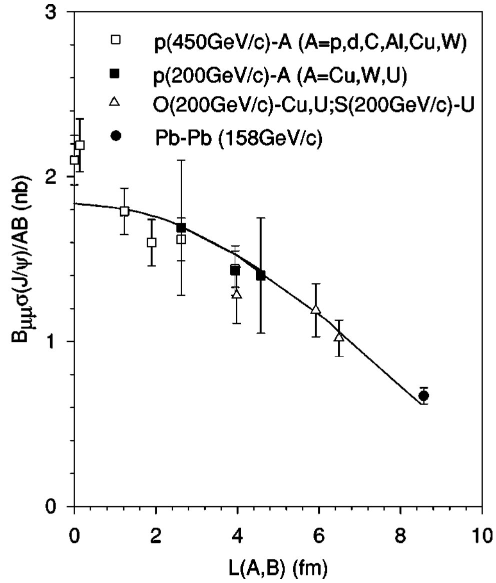

FIG. 1. Total J/ψ cross sections with the branching ratio to $\mu^+\mu^-$ in proton-nucleus, proton-nucleus, and nucleus-nucleus collisions, as a function of the effective nuclear length $L(A,B)$.

gluonic bath has been estimated in Ref. [16]. It is 0.89 fm at RHIC energy and 1.6 fm at LHC energy. It is difficult to say what its value will be at SPS energy, and in a nuclear medium, consisting of pions, nucleons, etc. However, we expect it to be much larger than 0.13 fm. If indeed, the relaxation time scale of charm quarks is much larger than 0.13 fm, then Eq. (5) will not be valid for pd collsions.

We now apply the model to obtain transverse energy dependence of the J/ψ over Drell-Yan ratio. 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

$$d^2\sigma^{DY}/dE_T d^2b = \sigma_{NN}^{DY} \int d^2s\, T_A(\mathbf{s}) T_B(\mathbf{s}-\mathbf{b}) P(b,E_T), \quad (8)$$

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]:

$$\rho_A(r) = \frac{\rho_0}{1 + \exp\left(\frac{r - r_0}{a}\right)} \quad (9)$$

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. (8), $P(b,E_T)$ 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 [17,18]. 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 assumed 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 α=3.46±0.19 and β=0.379±0.021 [6].

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

$$d^2\sigma^{J/\psi}/dE_T d^2b = \sigma_{NN}^{J/\psi}\int d^2s T_A(\mathbf{s})T_B(\mathbf{s}-\mathbf{b})S(L(\mathbf{b},\mathbf{s}))P(b,E_T), \tag{10}$$

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 **b** and at point **s**, the transverse density can be calculated as

$$n(\mathbf{b},\mathbf{s}) = T_A(\mathbf{s})[1-e^{-\sigma_{NN}T_B(\mathbf{b}-\mathbf{s})}] + T_B(\mathbf{b}-\mathbf{s})[1-e^{-\sigma_{NN}T_A(\mathbf{s})}], \tag{11}$$

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

$$L(\mathbf{b},\mathbf{s}) = n(\mathbf{b},\mathbf{s})/2\rho_0. \tag{12}$$

Suppression factor $S(L(\mathbf{b},\mathbf{s})$ is then easily calculated using Eq. (1).

Fluctuations of E_T, at a fixed impact parameter, play an important role in the explanation of NA50 data. Following Blaizot *et al.* [5], we take into account E_T fluctuations by the following replacement:

$$L(\mathbf{b},\mathbf{s}) \rightarrow L(\mathbf{b},\mathbf{s})E_T/E_T(b). \tag{13}$$

In Fig. 2, we have compared the model prediction with the NA50 experimental data on J/ψ over DY ratio. The solid line is the ratio obtained without any E_T fluctuations. The data are reproduced up to the knee of the E_T distribution. Beyond the knee of the E_T distribution, model prediction saturates, while the data show rapid fall of the ratio. The dashed line is the model prediction obtained including the E_T fluctuations. The model without any *free parameter* gives excellent description of the data, throughout the E_T range. The results clearly show that the rapid fall of the J/ψ over Drell-Yan ratio beyond the knee of the E_T distribution is due to E_T fluctuation only. The present calculation also establishes that it is not essential to assume a deconfined scenario to explain the NA50 data on J/ψ to Drell-Yan ratio. Nuclear absorption alone is capable of explaining it.

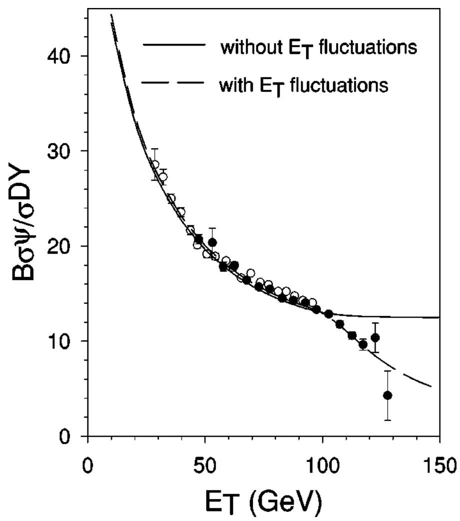

FIG. 2. Open and closed circles are the J/ψ to Drell-Yan ratio in a Pb+Pb collision obtained by NA50 Collaboration in 1996 and 1998, respectively. The solid line is the model prediction obtained without any E_T fluctuations and the dashed line is obtained including E_T fluctuations.

To summarize, we have analyzed the NA50 data on transverse energy distribution of J/ψ in Pb+Pb collisions at CERN SPS. In the model, $c\bar{c}$ pairs gain relative square momentum ε^2 as it travels a square of length L^2 through the nuclear environment. Suppression occurs as some of the pairs can gain enough momentum to cross the threshold to become an open charm meson. The parameters of the model were fixed by fitting experimental J/ψ cross section in pA and AA collisions. The model could very well describe the transverse energy dependence of J/ψ over Drell-Yan ratio upto the knee of the E_T distribution. It explains the data, throughout the E_T range if E_T fluctuations are included.

The author would like to thank the Lady Davis Fellowship trust for supporting his visit to Technion.

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