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J/ψ suppression in heavy ion collisions by quark momentum diffusion

H. Fujii
Institute of Physics, University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan
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The momentum diffusion effect of the quark pair due to the multiple scattering in a nuclear medium is studied to explain the observed J/ψ yields in SPS experiments. The resulting suppression is found to be insufficient to reproduce the J/ψ yield in Pb-Pb collisions at SPS energy.

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The suppression of the J/ψ cross section in ultrarelativistic nucleus-nucleus collisions has drawn much attention since its proposal as a possible signal of the quark-gluon plasma (QGP) [1], and the interest is even more increased after the anomalous suppression observed in Pb-Pb interactions at SPS energy [2]. There have been so many works done for explaining this anomalous suppression in the conventional manner or in the QGP-presuming way [3,4].

Qiu, Vary, and Zhang (QVZ) recently proposed a model [5] for calculating the J/ψ suppression caused by the nuclear effect in high-energy proton-nucleus (pA) and nucleus-nucleus (AB) collisions. Their model is based on the QCD factorization of the inclusive processes. The nuclear medium effect is taken into account as a modification of the transition probability of the $c\bar{c}$ pair due to the multiple scattering in the nuclear environment. The multiple scattering effects have been observed as the momentum imbalance of two jets in hadron-nucleus collisions [6,7]. For the J/ψ production in heavy ion collisions, the multiple scattering will increase the relative momentum of the pair and accordingly push the invariant mass toward the open charm threshold as it traverses the nuclear medium. QVZ model successfully explains the observed suppression from pA to AB collisions including the Pb-Pb data as nuclear effect [5,8].

In QVZ model, the net effect of the multiple scattering is expressed as a shift of the relative momentum of the quark pair in the transition probability function [see Eq. (3)]. This shift operator may be obtained by summing up all twist contributions at the leading order in the strong coupling constant α_s and the nuclear size, in the perturbative QCD calculation [9,10]. This is quite different from the result of the classical multiple scattering process; after independent multiple collisions with random momentum transfers, the distribution of the relative momentum q of the pair diffuses, while the mean q^2 increases. The only aim of this paper is to examine to what extent the J/ψ yield in heavy ion collisions is explained as the influence of the momentum diffusion, treating the multiple scattering of the quark pair as random walk. We show that the resulting suppression is insufficient to explain the Pb-Pb data and looks rather similar to the Glauber model result.

Let us first review QVZ model [5]. The inclusive cross section of the J/ψ production in the collision of the hadrons A and B is written in a factorized form:

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

where $\Sigma_{a,b}$ runs over all parton flavors, $Q^2=q^2+4m_c^2$, $\phi_{a/A}(x_a)$ is the distribution function of parton a in hadron A, and $x_F=x_a-x_b$ and $x_a x_b=Q^2/s$. The parton cross section $\hat{\sigma}$ is given in Ref. [10]. This is the leading order formula in α_s and the phenomenological constant $K_{J/\psi}$ corrects the higher order effects. $F_{c\bar{c}\to J/\psi}(q^2)$ describes the transition probability for the $c\bar{c}$ state of the relative momentum q^2 to evolve into a physical J/ψ meson. For this transition probability they propose a parametrization of

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

which includes the effect of the open charm threshold at $4m'^2$ and simulates the gluon radiation effect by the parameter $\alpha_F>0$ by putting the larger weight to the smaller q^2. The constant probability ($\alpha_F=0$) corresponds to the color-evaporation (CE) model.

For the J/ψ production in the pA and AB collisions QVZ model additionally assumes the separation of the multiple scattering which affects the pair state and the formation of the J/ψ resonance in the high-energy interactions. The multiple scattering of the pair in the nuclear medium would increase the relative momentum q^2 of the pair. The effect of coherent multiple scattering in the perturbative QCD calculation may be represented by shifting of the relative momentum in the transition probability [5] as

$$F_{c\bar{c}\to J/\psi}(\overline{q^2})=F_{c\bar{c}\to J/\psi}(q^2+\varepsilon^2 L), \tag{3}$$

where L is the effective length of the nuclear medium in the AB collisions. We note here that for a large enough L such that $\overline{q^2}>4m'^2-4m_c^2$ the transition probability essentially vanishes due to the existence of the open charm threshold

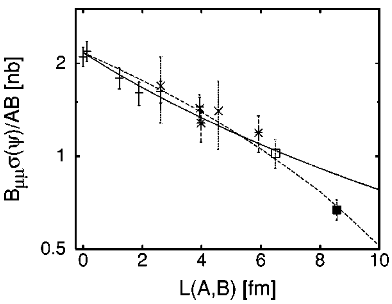

FIG. 1. J/ψ cross section to $\mu^+\mu^-$ pair [2] compared with the models using the smeared transition probability Eq. (4) (solid line) and the transition probability with the shifted momentum Eq. (3) (dashed line).

in Eq. (2). This apparently gives rise to a much stronger suppression than the exponential one following from the Glauber model.

We would like to describe now the momentum diffusion effect by modifying the transition probability $F_{c\bar{c}\to J/\psi}$ of QVZ model. The $c\bar{c}$ pair with relative momentum q produced in a hard parton collision, will change its momentum to q' after the random multiple scattering, and then transforms into the J/ψ with the probability $F_{c\bar{c}\to J/\psi}(q'^2)$. Here, we treat the exchanged soft momenta as independent and random in the multiple scatterings. After many scatterings, this classical, elementary diffusion process of the momentum results in the Gaussian distribution around the initial value q with the variance $\varepsilon^2 L$. The three-dimensional random walk is assumed here only for simplicity. The transition probability should be in effect replaced by the one smeared with this Gaussian weight as

$$\bar{F}_{c\bar{c}\to J/\psi}(q^2) \equiv \frac{1}{(2\pi\varepsilon^2 L)^{3/2}} \times \int d^3q' e^{-(q'-q)^2/2\varepsilon^2 L} F_{c\bar{c}\to J/\psi}(q'^2). \tag{4}$$

Note that the transition probability $\bar{F}_{c\bar{c}\to J/\psi}(q^2)$ never vanishes for any q although the average momentum of the pair increases as $\langle q'^2\rangle = q^2 + 3\varepsilon^2 L$ after the multiple scattering. We immediately find that the transition probability behaves for the asymptotically large L as

$$\bar{F}_{c\bar{c}\to J/\psi}(q^2) \sim \frac{1}{(2\pi\varepsilon^2 L)^{3/2}} \int d^3q' F_{c\bar{c}\to J/\psi}(q'^2). \tag{5}$$

This power suppression in L which stems from the depletion of the normalization factor is more moderate than the exponential one.

In Fig. 1, we show our result on the J/ψ suppression calculated using the formula (1) with the smeared probability (4). The parton distribution function of CTEQ5L [11] is used without any nuclear modification, and the parameters are fixed to the same as [5]: $\alpha_F = 1$ and $f_{J/\psi} \equiv K_{J/\psi} N_{J/\psi} = 0.485$ for the transition probability (2). The multiple scattering is included as smearing with $\varepsilon^2 = 0.185$ GeV^2/fm. Our model reasonably fits the data in the pA and AB collisions taken from Ref. [2] except the Pb-Pb point. The curve bends upward in the semilog plot as is expected from Eq. (5), but is almost consistent with the straight line within this interval of L. The original QVZ model (3) with $\varepsilon^2 = 0.25$ GeV^2/fm (dashed line) can explain all the data points in Fig. 1. The downward bending of QVZ model is the result of the existence of the open charm threshold in the transition probability (2) and the uniform shift of the momentum (3).

We performed the calculations using other forms for the transition probability, the Gaussian form and the CE form, besides Eq. (2) [5], and confirmed that the qualitative behavior of the suppression is unaltered; the Pb-Pb data alone lie far below the curve calculated by our model. The concavity of the suppression curve in the semilog plot is a robust consequence of the momentum diffusion Eq. (4) by the multiple scattering, irrespective of the detailed form of the transition probability. Therefore, the Pb-Pb data cannot be explained as the momentum diffusion effect of the quark pair due to the multiple scattering before forming a physical resonance.

We like to comment that in the high-energy collisions the transverse momentum diffusion in two dimensions might be more appropriate than the three-dimensional one, as in the Glauber approach. Then, the L dependence of the suppression would change from $L^{-3/2}$ to L^{-1}.

The absorption of a hadronic state by a power in L is similar to the result of the color transparency at high energies predicted in many theoretical studies [12,13]. In the model studied here, however, the color degrees of freedom of the pair states are not explicitly treated in the transition probability nor any interference effect. Hence, the relation to the color transparency effect is unclear within this model. At the collider energies like RHIC and LHC the coherence effect becomes more important and the quantum description of the resonance production at parton level should be more elaborated.

The uniform shift of the relative momentum is the result of the selective sum of higher twists at the leading order of α_s and the nuclear size [9]. From the view of our model, it may be worthwhile to investigate the smearing effect due to the correction terms in the perturbative QCD calculation.

In conclusion, the suppression of the J/ψ cross section in AB collisions except the Pb-Pb at SPS energy can be described by the momentum diffusion by the multiple scattering of the $c\bar{c}$ pair before the resonance formation. The suppression of the model is insufficient to explain the J/ψ yield observed in Pb-Pb collisions at SPS energy, which is therefore left anomalous in this treatment.

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