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

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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.

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

where \(\sum_{a,b}\) 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 \(10\). This is the leading order formula in \(\alpha_s\) and the phenomenological constant \(K_{J/\psi}\) corrects the higher order effects. \(F_{c\bar{c} \rightarrow J/\psi}(q^2)\) describes the transition probability for the \(c\bar{c}\) state to evolve into a physical J/ψ meson. For this transition probability they propose a parametrization of

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

which includes the effect of the open charm threshold at \(4m^2\) and simulates the gluon radiation effect with the parameter \(\alpha_F > 0\) with 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

\[
F_{c\bar{c} \rightarrow J/\psi}(q^2) = F_{c\bar{c} \rightarrow J/\psi}(q^2 + \varepsilon^2 L), \tag{3}
\]

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 \(q^2 > 4m^2 - 4m_c^2\) the transition probability essentially vanishes due to the existence of the open charm threshold (2). This apparently gives rise to a much

24.85.+p, 12.38.-t, 25.75.-q, 14.40.-n
We would like to describe now the momentum diffusion effect by modifying the transition probability $F_{c\bar{c} \rightarrow J/\psi}$ 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 $J/\psi$ with the probability $F_{c\bar{c} \rightarrow J/\psi}(q'')$. 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

$$F_{c\bar{c} \rightarrow J/\psi}(q'') \approx \frac{1}{(2\pi\varepsilon^2 L)^{3/2}} \int d^3q' e^{-\frac{(q'-q'')^2}{\varepsilon^2 L}} F_{c\bar{c} \rightarrow J/\psi}(q'').$$  

(4)

Note that the transition probability $F_{c\bar{c} \rightarrow J/\psi}(q'')$ 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

$$F_{c\bar{c} \rightarrow J/\psi}(q'') \approx \frac{1}{(2\pi\varepsilon^2 L)^{3/2}} \int d^3q' F_{c\bar{c} \rightarrow J/\psi}(q').$$  

(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 $J/\psi$ 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 $\int_{J/\psi} \equiv K_{J/\psi} N_{J/\psi} = 0.485$ for the transition probability (2). The multiple scattering is included as smearing with $\varepsilon^2 = 0.185$ GeV$/\text{fm}$. Our model reasonably fits the data in the pA and AB collisions taken from [2] except the Pb-Pb point. The curve bends upward in the semi-log 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$/\text{fm}$ (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 lies far below the curve calculated by our model. The concavity of the suppression curve in the semi-log 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.

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 $\alpha_s$ 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 $J/\psi$ 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 $J/\psi$ yield observed in Pb-Pb collisions at SPS energy, which is therefore left anomalous in this treatment.

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