J/ψ Suppression in Nucleus-Nucleus Collisions

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We propose a model for calculating J/ψ suppression in high-energy hadron-nucleus and nucleus-nucleus collisions. We factorized the process into a production of the $c\bar{c}$ pairs convoluted with a transition probability into the observed J/ψ mesons. As the produced $c\bar{c}$ pairs exit the nuclear matter, multiple scattering increases the square of the relative momentum between the c and $\bar{c}$ such that some pairs are transmuted into open charm states. With only one parameter, the energy gained by the produced $c\bar{c}$ pair per unit length in the nuclear medium, our model can fit all observed J/ψ suppression data in hadron-nucleus and nucleus-nucleus collisions.

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The suppression of J/ψ production in high-energy nucleus-nucleus collisions has been suggested as a potential signal for the quark-gluon plasma [1]. In recent years, strong J/ψ suppression has been observed [2–4], and various theoretical explanations have been proposed [5]. Recently, the NA50 Collaboration at CERN observed a much stronger J/ψ suppression in Pb-Pb collisions at SPS energies [6,7]. It has been argued that a "conventional" approach cannot explain these new data, and there are controversies on the origin of this suppression [5]. In this Letter, using the same mechanism proposed in Ref. [8] for the J/ψ suppression in hadron-nucleus collision, we explain the observed strong J/ψ suppression in high-energy Pb-Pb collisions.

The production of J/ψ mesons in high-energy hadronic collisions is believed to have two factorizable stages: the production of $c\bar{c}$ pairs and the subsequent formation of J/ψ mesons. Because of the large mass of the charm quark, the production should be a short-distance process calculable with perturbative methods. On the other hand, the formation of J/ψ mesons from the initially compact $c\bar{c}$ pairs takes a relatively long time and is nonperturbative [9]. The main debate on the mechanism of J/ψ production has focused on the second stage. Two approaches are commonly used for calculating the cross sections of J/ψ production: the color evaporation model (CEM) [10] and the nonrelativistic QCD (NRQCD) approach [11], which covers both the color-singlet model [12] and the so-called color-octet model [11,13]. However, recent data on J/ψ polarization from the CDF Collaboration at the Fermilab Tevatron seem to be inconsistent with the predictions from both approaches [14]. The disagreement may be caused by the radiation of semihard gluons from the $c\bar{c}$ pair prior to J/ψ formation [15]. We propose a model that is general enough to cover the effect of semihard gluon radiation as well as the physics addressed by these two approaches.

For the collisions between hadrons (or nuclei) A and B, $A(p_A) + B(p_B) \rightarrow J/\psi(P_{J/\psi}) + X$, the total J/ψ cross section can be factorized as follows [15,16]:

$$\sigma_{AB\rightarrow J/\psi X} = \sum_{[c\bar{c}]} \int dq^2 \int d^4Q \left(\frac{d\sigma_{AB\rightarrow[c\bar{c}]X}}{d^4Q} \right) \times \delta[q^2 + (k_c - k_{\bar{c}})^2] F_{[c\bar{c}]\rightarrow J/\psi}(q^2), \quad (1)$$

where $\sum_{[c\bar{c}]}$ sums singlet and octet color states, and $Q^\mu = k_c^\mu + k_{\bar{c}}^\mu$ is the total momentum of the produced $c\bar{c}$ pair. In Eq. (1), $q^2 = (2\vec{k}_c)^2$, the square of the relative momentum between the c and $\bar{c}$ in their rest frame. If the c and $\bar{c}$ can be approximated as on their mass shell, $k_c^2 = k_{\bar{c}}^2 = m_c^2$, $(k_c - k_{\bar{c}})^2 = Q^2 - 4m_c^2$. $F_{[c\bar{c}]\rightarrow J/\psi}(q^2)$ is the transition probability for a $[c\bar{c}]$ state of the relative momentum square q^2 to evolve into a physical J/ψ meson in hadronic collisions, which may be different from that in lepton-hadron collisions [15,16]. The aforementioned approaches correspond to different choices of $F_{[c\bar{c}]\rightarrow J/\psi}(q^2)$.

We propose two parametrizations for the transition probability,

$$F^{(G)}_{c\bar{c}\rightarrow J/\psi}(q^2) = N_{J/\psi}\theta(q^2)\exp[-q^2/(2\alpha_F^2)], \quad (2a)$$

$$F^{(P)}_{c\bar{c}\rightarrow J/\psi}(q^2) = N_{J/\psi}\theta(q^2)\theta(4m'^2 - 4m_c^2 - q^2) \times [1 - q^2/(4m'^2 - 4m_c^2)]^{\alpha_F}, \quad (2b)$$

where m' is the mass scale for the open charm threshold. In Eq. (2), we average over color states and let $N_{J/\psi}$ and α_F to be fixed by the existing total production cross section data from hadron-hadron collisions.

The F's in Eq. (2) represent a wide range of gluon radiation treatments in the J/ψ formation stage. The $F^{(G)}(q^2)$ corresponds to assuming the transition amplitude $\langle c\bar{c}|J/\psi\rangle$ does not involve any radiation or interaction with the medium, and it is then proportional to the J/ψ wave function square, parametrized as a Gaussian (G). Because of the narrow width of the J/ψ wave function, the production of $c\bar{c}$ pairs in Eq. (1) can be approximated at $q^2 = 0$, and

$$\sigma^{(G)}_{AB\to J/\psi X} \approx \int d^4Q\left(\frac{d\sigma_{AB\to c\bar{c}X}}{d^4Q}\right)\delta(Q^2 - 4m_c^2) \times \int dq^2\, F^{(G)}_{c\bar{c}\to J/\psi}(q^2) + O\left(\frac{\langle q^2\rangle}{Q^2}\right), \quad (3)$$

where $\langle q^2\rangle$ is an effective width of the transition distribution. The moments of the transition distribution, $\int dq^2\, F^{(G)}_{c\bar{c}\to J/\psi}(q^2)$, correspond to local matrix elements. Equation (1) with $F^{(G)}$ represents the leading contributions from the NRQCD approach. In this approach, probabilities for $c\bar{c}$ pairs with large invariant mass to form a J/ψ are strongly suppressed.

On the other hand, since the phase space between the thresholds of producing a $c\bar{c}$ pair and open charm mesons is not small, $4m'^2 - 4m_c^2 \sim 5\ \mathrm{GeV}^2$, semihard gluons can be radiated during the formation of $c\bar{c}$ pairs of large invariant mass. Although the semihard gluon radiation is suppressed by the heavy quark mass, the radiation reduces the pair's invariant mass, and strongly enhances the probability for the pair to form a J/ψ. It is then natural to assume that the q^2 dependence of the transition probability is associated with that radiation, and to choose a power-law (P) distribution, $F^{(P)}(q^2)$ in Eq. (2b), for the transition probability. The CEM is a special case of this form with $\alpha_F = 0$.

To evaluate the J/ψ total cross section in Eq. (1), we evaluate the $c\bar{c}$ production rate at invariant mass Q^2. As argued in Ref. [17], the production rate can be factorized into a convolution of two parton distributions from the two incoming hadrons and a short-distance part, $d\hat{\sigma}_{ab\to c\bar{c}X}/dQ^2$, which represents the perturbatively calculable hard parts for the parton a and b to produce the $c\bar{c}$ pairs with mass Q^2. Similar to the total Drell-Yan cross section, the *one-scale* cross section $d\hat{\sigma}/dQ^2$ for $c\bar{c}$ production at fixed target energies should be well represented by the leading order results in α_s, and the high order corrections given by a K factor. The total J/ψ cross section in Eq. (1) can then be written as [8]

$$\sigma_{AB\to J/\psi X} = K_{J/\psi}\sum_{a,b}\int dq^2\left(\frac{\hat{\sigma}_{ab\to c\bar{c}}(Q^2)}{Q^2}\right) \times \int dx_F\, \phi_{a/A}(x_a)\phi_{b/B}(x_b) \times \frac{x_a x_b}{x_a + x_b}\, F_{c\bar{c}\to J/\psi}(q^2), \quad (4)$$

where $\sum_{a,b}$ runs over all parton flavors, and $Q^2 = q^2 + 4m_c^2$. Because of the two-parton final state at the leading order, the incoming parton momentum fractions are fixed by the kinematics, and given by $x_a = (\sqrt{x_F^2 + 4Q^2/S} + x_F)/2$ and $x_b = (\sqrt{x_F^2 + 4Q^2/S} - x_F)/2$, respectively. At the leading order in α_s, the partonic production of the $c\bar{c}$ pairs come from two subprocesses: $q\bar{q} \to c\bar{c}$ and $gg \to c\bar{c}$. The short-distance hard parts in Eq. (4), $\hat{\sigma}_{q\bar{q}\to c\bar{c}}(Q^2)$ and $\hat{\sigma}_{gg\to c\bar{c}}(Q^2)$, are given in Refs. [8,10]. In Eq. (4), the integration limits of x_F are consistent with the data, and the limits of q^2 are specified by $F_{c\bar{c}\to J/\psi}(q^2)$ in Eq. (2).

In Fig. 1, we plot the total J/ψ cross sections using Eq. (4) along with the data in hadronic collisions [18]. We used CTEQ4L parton distributions, and noticed that the EMC effect gives a very small modification to the total cross sections because of the integration of x_F and q^2 [8]. In addition, we set $m_c = 1.50$ GeV and $m' = 1.869$ GeV. Choosing different values for the m_c and m' changes the fitting parameters slightly without changing the quality of the fit. Combining the K factor with an overall normalization $N_{J/\psi}$, we have two parameters for each form of the transition probability α_F and $f_{J/\psi} = K_{J/\psi}N_{J/\psi}$. Following the same fitting approach used in Ref. [18], we fix $(\alpha_F, f_{J/\psi})$ to be (1.15 GeV, 0.470) for the Gaussian case (dashed line). For the power-law case, we fix $(\alpha_F, f_{J/\psi})$ to be (0.0, 0.250) for the solid line and (1.0, 0.485) for the dotted line. Both parametrizations in Eq. (2) provide a good fit to the total J/ψ cross sections from proton-nucleon collisions at fixed target energies. The small difference between the solid and dotted lines in Fig. 1 illustrates the insensitivity of the total cross section to the model details.

Observed anomalous nuclear enhancement of the momentum imbalance in dijet production tells us that a colored parton (quark or gluon) experiences multiple scatterings when it passes through the nuclear medium, and the square of the relative transverse momentum between two jets increases in proportion to the size of the nucleus [19,20]. If we let the c and $\bar{c}$ be the parent quarks of two jets, the q^2 becomes the square of the relative momentum between the two jets in their c.m. frame. Therefore, as the c and $\bar{c}$ pass through nuclear matter, just like a dijet system, the square of the relative momentum q^2 increases. As a result, some of the $c\bar{c}$ pairs gain enough relative momentum square q^2 to be pushed over the threshold to become open charm mesons, and consequently, the cross

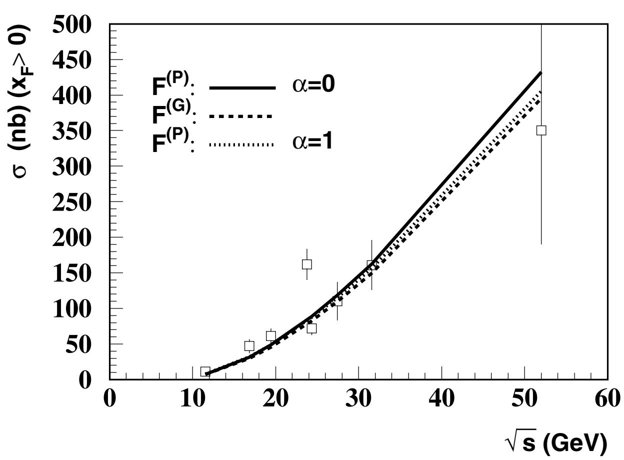

FIG. 1. Comparison of our model with data [7] on total J/ψ cross sections in nucleon-nucleon collisions as a function of collision energy $\sqrt{S}$.

sections for J/ψ production are reduced in comparison with nucleon-nucleon collisions.

If the formation length for the J/ψ, which depends on the momenta of the parent $c\bar{c}$ pair, is longer than the nuclear medium, it is reasonable to assume that the transition probability $F_{c\bar{c}\to J/\psi}(q^2)$, defined in Eq. (2), can be factorized from the multiple scattering. Then, as far as the total cross section is concerned, the net effect of the multiple scattering of the $c\bar{c}$ pairs can be represented by a shift of q^2 in the transition probability,

$$q^2 \to \bar{q}^2 = q^2 + \varepsilon^2 L(A,B). \tag{5}$$

In Eq. (5), $L(A,B)$ is the effective path length of nuclear medium for the $c\bar{c}$ pair in the (A,B) collisions, and it depends on the nuclear density distributions [21]. The ε^2 represents the square of the relative momentum received by the $c\bar{c}$ pairs per unit path length of the nuclear medium. Based on the observed nuclear enhancement in the momentum imbalance of two jets in hadron-nucleus collisions [20], we estimate $\epsilon^2 \sim 0.2\text{–}0.5\ \mathrm{GeV}^2$.

In Fig. 2, we plot the J/ψ total cross sections in proton-proton, proton-nucleus, and nucleus-nucleus collisions. The data in Fig. 2 are from Ref. [6], in which all data were rescaled to $P_{\mathrm{beam}} = 200$ GeV. The effective length $L(A,B)$ is taken from Ref. [6]. Two theory curves correspond to two parametrizations defined in Eq. (2). For the Gaussian form $F^{(G)}(q^2)$ in Eq. (2a), a shift of q^2 to $\bar{q}^2$ in Eq. (5) for the J/ψ suppression in nucleus-nucleus collisions yields

$$\sigma_{AB\to J/\psi} = \exp\left[-\frac{\varepsilon^2}{2\alpha_F^2} L(A,B)\right]\sigma_{NN\to J/\psi}. \tag{6}$$

This relation is effectively the same as that predicted by the Glauber theory with the suppression factor $\exp[-\sigma_{\mathrm{abs}}\rho L(A,B)]$, and ρ being the nuclear density. Using the same parameters for corresponding curve in Fig. 1, we need an effective absorption cross section, $\sigma_{\mathrm{abs}} \sim 6.3$ mb, for the Gaussian form (dashed line) to fit the data. Like the Glauber theory, the parametrization of $F^{(G)}(q^2)$ does not generate enough suppression for heavy (A,B) collisions.

On the other hand, due to the threshold effect, we expect the power-law form to generate a much stronger suppression for collisions with large nuclei. Since α_F of the power-law distribution was not well determined by the total cross section data in Fig. 1, we adjust it to fit the data in Fig. 2 to obtain $\alpha_F = 0.4$ and corresponding $\varepsilon^2 = 0.335\ \mathrm{GeV}^2$ per unit $L(A,B)$ (solid line). We find that all values of $\alpha_F \in (0.0, 1.0)$ can provide a reasonable fit to the data in Fig. 2 by adjusting the ε^2. That is, for a given ε^2, which is determined by the multiple scattering between the $c\bar{c}$ pair and the medium, J/ψ suppression is very sensitive to the functional form of the transition distribution $F_{c\bar{c}\to J/\psi}(q^2)$—the details of the formation process. Since gluon radiation is essential for the color neutralization of the octet channel and for mass adjustment from the $c\bar{c}$ pairs to the final J/ψ eigenstate [15], we believe that the power-law shape is a better description of the J/ψ formation. Figure 2 shows that the power-law form is consistent with all data on suppression of J/ψ total cross sections.

Recently, the NA50 Collaboration published the transverse energy E_T distribution for J/ψ suppression [7]. In order to evaluate the dependence on E_T within our model we need a relationship between E_T and the in-medium path length, $L(A,B)$. To establish this relation we first take the relationship between E_T and impact parameter from NA50 [7]. We then calculate the relation between impact parameter and in-medium length from geometrical overlaps using Saxon-Woods forms dictated by the rms radii of the heavy ions. We substitute this relationship between E_T and $L(A,B)$ back into Eq. (4) to obtain the E_T distribution of J/ψ suppression which is then plotted in Fig. 3 along with the new NA50 data [7]. Both curves in Fig. 3 have the same parameters as the corresponding curves in Fig. 2 [22].

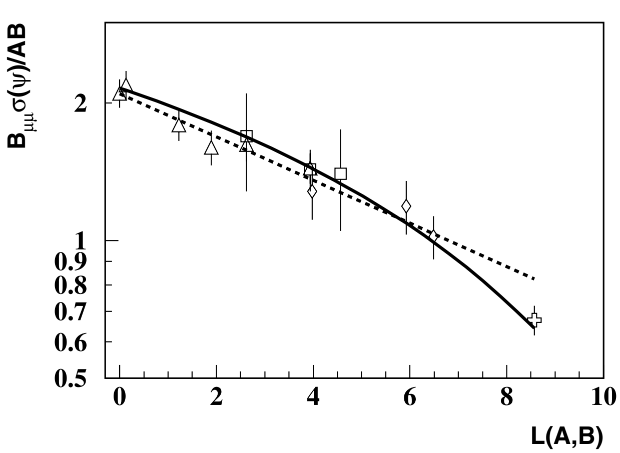

FIG. 2. Comparison of data on total J/ψ cross sections with the branching ratio to $\mu^+\mu^-$ in hadronic collisions [6] with our calculation with Gaussian distribution (dashed) and power-law distribution (solid).

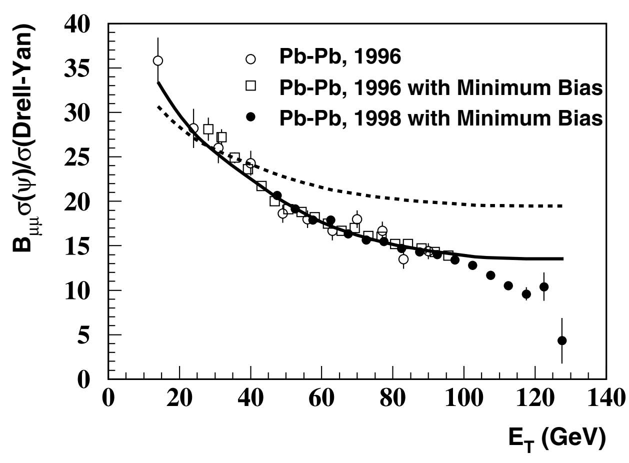

FIG. 3. Comparison of data on ratio of J/ψ cross section to inclusive Drell-Yan [7] with our calculation with Gaussian distribution (dashed) and power-law distribution (solid).

Our results in Figs. 2 and 3 depend on an additional assumption: the separation of the multiple scattering of the $c\bar{c}$ pairs and the formation of the J/ψ mesons. We believe that this is justified when the J/ψ formation length is larger than the effective medium length $L(A, B)$ [9]. Once the J/ψ meson is formed, the multiple scattering with the nuclear medium should be reduced due to the color singlet nature of the meson, and then, the Glauber formalism for the suppression should be more relevant. Therefore, if there is no phase transition to the quark-gluon plasma, we expect the following features for the J/ψ suppression in nucleus-nucleus collisions. As the size of colliding nuclei increases, the J/ψ suppression should follow the solid curve in Fig. 2; and when the $L(A, B)$ is comparable to the J/ψ formation length, there will be less suppression than what is predicted by the solid curve.

Our $F^{(P)}$ assumes that all $c\bar{c}$ pairs with invariant mass greater than the open charm threshold have zero probability to become the J/ψ meson. In quantum theory, the $c\bar{c}$ pairs with invariant mass more than the $4m'^2$ should have a small, but nonzero, probability to become the J/ψ. Hence, we relaxed this restriction with a Saxon-Woods tail on the transition probability extending above the $4m'^2$ threshold but found negligible changes. Our results with $F^{(P)}$ shown in Figs. 2 and 3 are consistent with all the data except the last few points in Fig. 3. As pointed out in Ref. [23], this "second drop" in the data trend of Fig. 3 is due to the fluctuation in transverse energy at the fixed impact parameter, and can be easily incorporated into our model [24].

The E772 Collaboration at Fermilab measured J/ψ suppression in pA collisions as a function of x_F [3]. It was found that the suppression at large x_F is stronger than in the central region ($x_F \sim 0$). Parton multiple scattering in our model increases invariant mass of the $c\bar{c}$ pairs. Some of the $c\bar{c}$ pairs are transmuted into open charm states, while the others lose their longitudinal momenta due to the induced gluon radiation ("energy loss"). That is, we expect a stronger J/ψ suppression at large x_F due to the dropoff in the x_F distribution.

Finally, we conclude that our simple model for the total cross sections of J/ψ production in (A, B) collisions, as defined in Eq. (4), can explain the existing data in hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions [16,22].

At collider energies, J/ψ cross sections are often measured as a function of transverse momentum Q_T and rapidity y. Because of enhanced fragmentation contributions to J/ψ production at high Q_T [13], J/ψ suppression could be mixed with the Cronin effect. A careful study of the nuclear dependence in $d\sigma_{AB\to J/\psi X}/dQ_T^2\, dy$ is important for understanding J/ψ production at RHIC and the LHC.

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