J/ψ Suppression in Nucleus-Nucleus Collisions

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Abstract

We propose a model for the production and suppression of J/ψ mesons in high-energy hadronic collisions. We factorized the process into a production of the $c\bar{c}$ pairs of relative momentum $k = k_c - k_{\bar{c}}$ convoluted with a transition probability from the produced $c\bar{c}$ pairs into the observed J/ψ mesons. As the produced $c\bar{c}$ pairs exit the nuclear matter, the multiple scattering between the colored $c$ and $\bar{c}$ and the nuclear medium increases the square of the relative momentum between the $c$ and $\bar{c}$, $q^2 = -k^2$, such that some of the $c\bar{c}$ pairs gain enough invariant mass to transmute into open charm states. With only one parameter, the amount of 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 including recent NA50 data from Pb-Pb 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 existence of the quark-gluon plasma [8]. In recent years, strong J/ψ suppression has been observed in high energy hadron-nucleus and nucleus-nucleus collisions by a number of experiments [9,10]; and various theoretical explanations of the observed J/ψ suppression have been proposed [11]. Recently, the NA50 Collaboration at CERN observed a much stronger J/ψ suppression in Pb-Pb collisions at SPS energies [12]. It has been argued that a “conventional” approach cannot explain this new data, and debates and controversies on the theorized origin of the suppression have reached a new level [13]. In this letter, using the same mechanism proposed in Ref. [14] for the J/ψ suppression in hadron-nucleus collision, we explain the newly 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 ¯c pairs, and the formation of J/ψ mesons from the produced c ¯c pairs. Due to the large mass of the charm quark, the c ¯c pair production should be a short-distance process in nature, and therefore calculable with perturbative methods. On the other hand, the formation of J/ψ mesons from the initially compact c ¯c pairs takes a relatively long time and is nonperturbative [15]. Throughout the years, the main debate on the mechanism of J/ψ production has focused on the second stage. Three models are commonly used in the literature for calculating the cross sections of J/ψ production: the Color Evaporation Model (CEM) [9], the Color-Singlet Model (CSM) [10], and the Color-Octet Model (COM) [11]. Since the data on J/ψ suppression in nucleus-nucleus collisions are presented in terms of total cross sections [16,17], we will focus the remainder of our discussions on the total production rate of J/ψ mesons in hadronic collisions at fixed target energies. For calculating the total J/ψ production rate, we propose a simple model which is general enough to admit any of the three possible formation mechanisms mentioned above.

For the collisions between hadrons (or nuclei) A and B, A(p_A) + B(p_B) → J/ψ(P_{J/ψ}) + X, the total J/ψ cross section can be factorized as follows,

$$
\sigma_{A+B→J/ψ+X}(S) = \int dq^2 \int d^4Q \left( \frac{d\sigma_{A+B→c\bar{c}+X}}{d^4Q} \right)
\times \delta \left( q^2 + (k_c - k_{\bar{c}})^2 \right) F_{c\bar{c}→J/ψ}(q^2), \quad (1)
$$

where the four-vector $Q^\mu = k_c^\mu + k_{\bar{c}}^\mu$ is the total momentum of the produced c ¯c pair. In Eq. (1), the variable $q^2$ is equal to the square of the relative momentum between the c and ¯c in their rest frame, $q^2 = (2k_c)^2$. If the c and ¯c can be approximated as on their mass-shell, $k_c^2 = k_{\bar{c}}^2 = m_c^2$, and we have $q^2 = Q^2 - 4m_c^2$. Without trying to separate contributions from different color channels, we define the $F_{c\bar{c}→J/ψ}(q^2)$ in Eq. (1) to be a transition probability for a color-averaged c ¯c pair of the relative momentum square $q^2$ to evolve into a physical J/ψ meson. We propose three alternatives for parameterizing the transition probability,

$$
F_{c\bar{c}→J/ψ}^{(C)}(q^2) = N_{J/ψ} \theta(q^2) \theta(4m_c^2 - 4m_{c\bar{c}}^2 - q^2), \quad (2a)
$$

$$
F_{c\bar{c}→J/ψ}^{(G)}(q^2) = N_{J/ψ} \theta(q^2) \exp \left[ -q^2/(2\alpha_F^2) \right], \quad (2b)
$$

$$
F_{c\bar{c}→J/ψ}^{(P)}(q^2) = N_{J/ψ} \theta(q^2) \theta(4m_c^2 - 4m_{c\bar{c}}^2 - q^2)
\times \left( 1 - q^2/(4m_c^2 - 4m_{c\bar{c}}^2) \right)^{\alpha_F}, \quad (2c)
$$
where \( m' \) is the mass scale for the open charm threshold. In Eq. (4), \( N_{1/\psi} \) and \( \alpha_F \) are to be fixed by fitting the existing total production cross section data from hadron-hadron collisions.

The transition probabilities in Eq. (4) represent a wide range of \( J/\psi \) formation mechanisms. The \( F^{(C)}(q^2) \) implies that all \( c\bar{c} \) pairs with invariant mass below the open charm threshold have the same constant (C) probability to become the physical \( J/\psi \) mesons, which is effectively the same as the Color Evaporation Model [9]. The \( F^{(G)}(q^2) \) corresponds to the following assumptions: the transition amplitude \( \langle c\bar{c}J/\psi \rangle \) does not involve any radiation and interaction with the medium, and it is then proportional to the \( J/\psi \) wave function parameterized as a Gaussian (G). If we neglect the \( q^2 \)-dependence in the production of the \( c\bar{c} \) pairs in Eq. (4), and require the \( c\bar{c} \) to be color-singlet, the total cross section with \( F^{(G)}(q^2) \) is effectively the same as that from the Color-Singlet Model [10].

If the \( J/\psi \) mesons are formed after a long-time expansion from the small size \( c\bar{c} \) pairs, and radiating soft gluons adjusts the color of the pairs, 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. (4), for the transition probability. If we expand the transition probability at \( q^2 \approx 0 \), the normalization of \( F^{(P)}(q^2) \) can be related to the combination of the matrix elements in the Color-Octet Model [11].

In principle, with a different functional form of \( F(q^2) \), our factorized formula in Eq. (4) can be generalized to calculate the total cross sections for producing other quarkonium states.

To evaluate the \( J/\psi \) total cross section in Eq. (4), we need to calculate the production rate for the \( c\bar{c} \) pairs at invariant mass \( Q^2 \). As argued in Ref. [12], the production rate can be factorized into a convolution of two parton distributions from the two incoming hadrons and a short-distance hard part, \( d\sigma_{a+b\to c\bar{c}+X}/dQ^2 \), 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 \( d\sigma/dQ^2 \) for producing the \( c\bar{c} \) pairs at the fixed target energies should be well-represented by the leading order calculations in \( \alpha_s \), and the high order corrections are given by a smooth K-factor. At the leading order in \( \alpha_s \), the partonic contributions come from two subprocesses: \( q\bar{q} \to c\bar{c} \) and \( gg \to c\bar{c} \). With the K-factor for effective high order contributions, the total \( J/\psi \) cross section in Eq. (4) can be written as [4]

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

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. In Eq. (3), the short-distance hard parts for producing the \( c\bar{c} \) pairs, \( \hat{\sigma}_{q\bar{q}\to c\bar{c}}(Q^2) \) and \( \hat{\sigma}_{gg\to c\bar{c}}(Q^2) \), are given in Refs. [4,13]. In Eq. (3), the integration limits of \( x_F \) are chosen to be consistent with the data, and the limits of \( q^2 \) are specified by the functional form of
$F_{c\bar{c} \rightarrow J/\psi}(q^2)$ in Eq. (2). Eq. (3) combining the transition probability defined in Eq. (2) is our model for calculating the total $J/\psi$ hadronic cross sections.

In Fig. 1, we plot the total $J/\psi$ cross sections using Eq. (3) in comparison with the data in hadronic collisions [14]. Following the same fitting approach used in Ref. [14], we fix all parameters in Eq. (2) and list them in Table I, in which $f_{J/\psi} = K_{J/\psi} N_{J/\psi}$ is defined as an overall normalization factor. To obtain the theory curves in Fig. 1, we used CTEQ4L parton distributions [15], and noticed that EMC effect gives a very small modification to the total cross sections because of the integration of $x_F$ and $q^2$ [7]. 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 in Table I slightly. But, it does not change the quality of the comparison in Fig. 1. All three parameterizations in Eq. (2) provide a good fit to the total $J/\psi$ cross sections from proton-nucleon collisions at fixed target energies.

In nucleus-nucleus collisions, the produced $c\bar{c}$ pairs are likely to interact with the nuclear medium before they exit. 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 [16]. 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 di-jet system, the square of the relative momentum $q^2$ increases. As a result, some of the $c\bar{c}$ pairs might gain enough relative momentum square $q^2$ to be pushed over the threshold to become open charm mesons, and consequently, the cross sections for $J/\psi$ production are reduced in comparison with nucleon-nucleon collisions.

If the formation length for the $J/\psi$ meson, which depends on the momenta of the $c\bar{c}$ pairs produced in the hard collision, is longer than the size of the nuclear medium, it is reasonable to assume that the transition probability $F_{c\bar{c} \rightarrow J/\psi}(q^2)$, 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,

$$q^2 \rightarrow q^2 = q^2 + \varepsilon^2 L(A,B).$$

In Eq. (4), $L(A,B)$ is the effective length of nuclear medium for the $c\bar{c}$ pair to pass through in the collisions of two nuclei of $A$ and $B$, and it depends on the details of the nuclear density distributions [18]. In Eq. (4), the $\varepsilon^2$ represents the square of the relative momentum received by the $c\bar{c}$ pairs per unit length of the nuclear medium. The value of the $\varepsilon^2$ can be estimated from the observed nuclear enhancement in the momentum imbalance of two-jets in hadron-nucleus collisions [13]. Using the data from pion-nucleus collisions [16], we estimate that $\varepsilon^2 \sim 0.2 - 0.5$ GeV$^2$ per unit length of nuclear medium [13,17].

In Fig. 2, we plot the predictions of $J/\psi$ total cross sections in proton-nucleon, proton-nucleus and nucleus-nucleus collisions. The data in Fig. 2 are from Ref. [19], in which all data were rescaled to $P_{\text{beam}} = 200$ GeV. The effective length $L(A,B)$ were chosen to be the same as those used in Ref. [19]. Three theory curves correspond to three parameterizations defined in Eq. (2). The values of the parameter $\varepsilon^2$ for different parameterizations are listed in Table I, which are consistent with our earlier estimates from the momentum imbalance of a
di-jet system. As in Fig. 1, we used the CTEQ4L parton distributions and set \( m_c = 1.50 \text{ GeV} \) and \( m' = 1.869 \text{ GeV} \) for plotting Fig. 2. Choosing different values for the \( m_c \) and \( m' \) changes the values of \( \varepsilon^2 \) slightly, but, it does not change the features of Figs. 1 and 2.

The three parameterizations of the transition probability in Eq. (2) represent the different \( J/\psi \) production mechanisms, and naturally, they predict different behavior of \( J/\psi \) suppression in Fig. 2. Therefore, understanding the suppression can also help us to distinguish the production mechanism.

For the parameterization \( F^{(G)}(q^2) \) in Eq. (2b), a shift of \( q^2 \) to \( \bar{q}^2 \) in Eq. (4) for the \( J/\psi \) suppression in nucleus-nucleus collisions gives following relation

\[
\sigma_{AB \rightarrow J/\psi}(S) = \exp \left[ -\frac{\varepsilon^2}{2\alpha^2_F} L(A, B) \right] \sigma_{NN \rightarrow J/\psi}(S). \tag{5}
\]

This relation is effectively the same as that predicted by the Glauber theory, if we let the suppression factor in the simple Glauber theory be \( \exp[-\sigma_{\text{abs}} \rho L(A, B)] \), with \( \rho \) being the nuclear density. With the parameters in Table 1, we have the effective absorption cross section \( \sigma_{\text{abs}} \sim 5.9 \text{ mb} \), which is the same as that obtained in Ref. [19]. In addition, our model interprets the \( \sigma_{\text{abs}} \) in Glauber theory is proportional to the energy absorbed by the colored \( c\bar{c} \) pairs. As expected [3], like the Glauber theory, the parameterization of \( F^{(G)}(q^2) \) does not generate enough suppression for heavy nucleus-nucleus collisions. As discussed earlier, the Gaussian parameterization corresponds to assuming that the formation process does not have radiation, and is then proportional to the square of the \( J/\psi \) wave-function. However, as we learned from the success of the Color-Octet Model [11], the formation of \( J/\psi \) should involve the expansion of the \( c\bar{c} \) pairs and the radiation of soft gluons. Therefore, we should prefer a power-law parameterization than a Gaussian parameterization, and consequently, we expect to have more suppression than that expected from the Glauber approach.

Since the \( F^{(C)}(q^2) \) is the same as the \( F^{(P)}(q^2) \) when \( \alpha_F = 0 \), we expect a maximum suppression from the Color-Evaporation Model, as seen in Fig. 2. The Color-Evaporation Model assumes that all \( c\bar{c} \) pairs with invariant mass less than the open charm threshold should have the same transition probability to become the \( J/\psi \) meson. However, the phase space cutoff for the \( c\bar{c} \) pairs to become the open charm in Eq. (3) appears classical. In quantum theory, the \( c\bar{c} \) pairs with invariant mass less than the \( 4m'^2 \) should have a small, but non-zero, probability to become open charm systems, and in general, the pairs just below the threshold should have a relatively larger probability for a transition to open charm than those far below the threshold. With these considerations, we believe that the power-law parameterization \( F^{(P)}(q^2) \) with \( \alpha > 0 \) represents the more accurate physics for the \( J/\psi \) production.

Our model of the \( J/\psi \) production relies on the factorization between the production of the \( c\bar{c} \) pairs and the formation of the \( J/\psi \) mesons, and accurate calculation for the production of the \( c\bar{c} \) pairs. For the total cross sections at fixed target energies, we believe that such factorization is justified, and the perturbative calculations are reliable. However, at collider energies, most \( J/\psi \) events are measured at large transverse momentum, \( Q_T \); and the \( \sqrt{S} \) as well as the \( Q_T \) are much larger than the invariant mass of the \( c\bar{c} \) pairs, \( Q \), in Eq. (3). Therefore, the perturbative calculations of \( d\sigma/dQ^2 \) and \( d\sigma/dQ^2 dQ_T^2 \) for the production of the \( c\bar{c} \) pairs become very nontrivial due to the large logarithms \( \log(1/x) \sim \log(S/Q^2) \) and \( \log(Q_T^2/Q^2) \). A resummation of such large logarithms to all order in \( \alpha_s \) is necessary in order
to have a reliable prediction. We defer our detailed discussions on $J/\psi$ production and suppression at the collider energies to another publication.

Our predictions of the $J/\psi$ suppression, as shown in Fig. 2, depend on an additional assumption: the separation of the multiple scattering of the $c\bar{c}$ pairs and the formation of the $J/\psi$ mesons. We believe that this additional assumption can only be justified when the $J/\psi$ formation length is larger than the effective medium length $L(A, B)$ in our Eq. (4). Once the $J/\psi$ meson is formed, the multiple scattering with 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 QCD phase transition to the quark-gluon plasma, we expect the following features for the $J/\psi$ suppression in nucleus-nucleus collisions. As the size of colliding nuclei increases, the $J/\psi$ suppression should follow the dotted curves in Fig. 2, and when the $L(A, B)$ is compatible to the $J/\psi$ formation length, the suppression will become smaller than what is predicted by the dotted curve. Finally, we conclude that our simple model for the total cross sections of $J/\psi$ production in nucleus-nucleus collisions, as defined in Eq. (3), can explain the existing data in hadron-hadron, hadron-nucleus and nucleus-nucleus collisions. Although our model is different in many aspects from what have been discussed in the literature, we believe that it has the key physical mechanisms for the $J/\psi$ production and suppression. Detailed comparison between our work and others in the literature are given in Ref. [13].

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FIG. 1. Total $J/\psi$ cross sections in proton-nucleon collisions as a function of the colliding energy $\sqrt{s}$.
FIG. 2. Total J/ψ cross sections with the branching ratio to μ⁺μ⁻ in proton-nucleon, hadron-nucleus and nucleus-nucleus collisions as a function of the effective nuclear medium length $L(A, B)$. 
TABLE I. Values of parameters used to produce the theory curves in Figs. 1 and 2.

| Parameter          | $F^{(C)}$ | $F^{(G)}$ | $F^{(P)}$ |
|--------------------|-----------|-----------|-----------|
| $f_{J/\psi}$       | 0.248     | 0.470     | 0.485     |
| $\alpha_F$         | 0         | 1.2 GeV   | 1.0       |
| $\varepsilon^2$ (GeV$^2$/fm) | 0.45     | 0.29      | 0.25      |