J/ψ production and suppression in nuclear collisions

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In terms of a new QCD factorization formula for J/ψ production, we calculate the J/ψ suppression in nuclear collisions by including the multiple scattering between the pre-J/ψ partonic states and the nuclear medium. We find agreement with all data on J/ψ suppression in hadron-nucleus and nucleus-nucleus collisions, except a couple of points (the “second drop”) at the highest $E_T$ bins of the new NA50 data.

1. J/ψ Production

J/ψ suppression in relativistic heavy ion collisions was suggested as a potential signal of the quark-gluon plasma [1]. In order to study the J/ψ suppression quantitatively, we need to understand how the J/ψ mesons are produced, and the reliability of QCD calculations for J/ψ production.

In order to produce a J/ψ meson in hadronic collisions, the energy exchanges in the collisions have to be larger than the J/ψ mass ($M_{J/\psi}$) or the invariant mass of the produced quark pair ($m_{c\bar{c}} \geq 2M_c \sim 3$ GeV). The $c\bar{c}$ pairs should be produced at a distance scale $r_H \leq 1/2M_c \sim 1/15$ fm. Since this is much smaller than the size of a J/ψ and the energy exchanges are much larger than the nonperturbative momentum scales in the J/ψ wave functions, the J/ψ is unlikely to be formed at the collision point. Instead, the J/ψ meson should be formed after some resonance interactions (or coherent soft gluon interactions between the charm and anticharm quarks). Thus, the transformation from a pre-J/ψ $c\bar{c}$ pair to a physical J/ψ occurs over several Fermi [4]. During this transformation, the produced $c\bar{c}$ pairs can also radiate gluons and have interactions with spectators. Due to gluon radiation and the spectator interactions, it is possible for the $c\bar{c}$ states, even with different quantum numbers, to become a J/ψ meson.

However, because of the large energy exchange, the spectators’ roles in the hard collisions are suppressed by an extra factor $\rho_N L/[(2M_c)^2 + q_T^2]$ with the medium density $\rho_N$ and medium length $L$. If the transverse momentum $q_T$ is large enough, the spectator interactions are strongly suppressed, and the cross sections for hadronic J/ψ production can be factorized [5],

$$\frac{d^2\sigma_{AB \rightarrow J/\psi}}{dyd^2q_T} \approx \sum_{a,b} \int dx \phi_{a/A}(x) \int dx' \phi_{b/B}(x') \frac{d\hat{\sigma}_{ab \rightarrow J/\psi}}{dyd^2q_T}(x,x')$$

where $\Sigma_{ab}$ run over all parton flavors and the $\phi(x)$ are the normal parton distributions. The $\hat{\sigma}_{ab \rightarrow J/\psi}(x,x')$ represents the cross section for two partons to produce a J/ψ. Without the nuclear medium, $L$ is of the order of the hadron radius ($R \sim 1$ fm).
Because the production of the pre-J/ψ c¯c states and the transformation to the J/ψ take place at very different distance scales, quantum interference between these two stages is suppressed by the ratio of these two distance scales. Therefore, the partonic cross sections for the J/ψ production in Eq. (1) can be further factorized into two stages: (1) short-distance production of the pre-J/ψ partonic states, and (2) long-distance transition from the partonic states to the physical J/ψ mesons [3],

$$\frac{d\hat{\sigma}_{ab\rightarrow J/\psi}}{dyd^2q_T} \approx \sum_{[c\bar{c}]} \int \frac{dz}{z^2} \int dm_{c\bar{c}}^2 \left( \frac{d\hat{\sigma}_{ab\rightarrow [c\bar{c}]}^c}{dm_{c\bar{c}}^2dyd^2p_{c\bar{c}}^T} \right) D_{[c\bar{c}]\rightarrow J/\psi}(z;m_{c\bar{c}}^2)$$

where \(\sum_{[c\bar{c}]}\) sums over all \(c\bar{c}\) states, \(p_{c\bar{c}} = \vec{p}_{1/\psi}/z\) and \(m_{c\bar{c}}^2 \ll |\vec{p}_{c\bar{c}}|^2\). The \(D_{[c\bar{c}]}\) represent transition probabilities from pre-J/ψ \(c\bar{c}\) states to J/ψ mesons, and are defined by matrix elements of non-local operators [3]. The differences between our approach and other models of J/ψ production can be cast as differences in \(D_{[c\bar{c}]}\).

In QCD perturbation theory, the \(D_{[c\bar{c}]}\) include all soft resonance interactions and gluon radiations. Similar to the parton-to-hadron fragmentation functions, the \(D_{[c\bar{c}]}\) depend on nonperturbative physics. Thus, the predictive power of the factorized formula relies on the universality of these transition distributions [3].

The non-relativistic QCD (NRQCD) model [4] and the color evaporation (CE) model [5] correspond to two diverse assumptions for the \(D_{[c\bar{c}]}\). The NRQCD model assumes that the \(D_{[c\bar{c}]}\) are steeply falling functions of the invariant masses of the states, and sensitive to the pairs’ quantum numbers (such as color and spin). We can represent the leading contributions of this model by expanding the partonic cross section \(\hat{\sigma}_{ab\rightarrow [c\bar{c}]}\) in Eq. (2) at \(m_{c\bar{c}}^2 = 4M_c^2\) and \(z = 1\). In the NRQCD model, the produced \(c\bar{c}\) pairs with large \(m_{c\bar{c}}^2\) have very small probabilities to become J/ψ mesons. On the other hand, the CE model assumes that the \(D_{[c\bar{c}]}\) are independent of the pairs’ invariant masses (provided they are below the open charm threshold), and are not sensitive to the pairs’ quantum numbers. We can represent the CE model by taking \(D_{[c\bar{c}]} = f_{J/\psi}\delta(1-z)\theta(4M_c^2 - m_{c\bar{c}}^2)\) in Eq. (2) with a fitting constant \(f_{J/\psi}\) independent of the \(c\bar{c}\) pairs’ quantum numbers.

Since the NRQCD and the CE models are both consistent with the existing data on inclusive J/ψ production, the new QCD factorized formula should also be consistent with the data [3]. However, both models have difficulties explaining the recent CDF data from Fermilab on J/ψ polarization at large transverse momentum [6].

At large transverse momentum, J/ψ are produced mainly from the fragmentation contribution, as shown in Fig. 1, where a virtual gluon is produced and decays into a \(c\bar{c}\) pair.
which transmutes into a physical $J/\psi$. The polarization of the produced $J/\psi$ depends on the polarization of the $c\bar{c}$ pair and the details of the transition distributions $D_{[c\bar{c}]}$. In order to use the polarization measurements to discern between the production models, we need independent tests of the reliability of the QCD formalism for calculating the $c\bar{c}$ polarization at large transverse momentum. As illustrated in Fig. 1, the low mass Drell-Yan lepton-pair’s angular distributions at large transverse momentum have a lot in common with the $c\bar{c}$ polarization. If the QCD calculations are consistent with the virtual photon polarization in Drell-Yan massive lepton-pair production, we can conclude that the QCD formalism for calculating the polarization of the $c\bar{c}$ at large transverse momentum is reliable, and therefore, measurements of $J/\psi$ polarization provide decisive tests for models of $J/\psi$ production.

2. $J/\psi$ Suppression

In addition to polarization measurements, the nuclear medium dependence of $J/\psi$ production is sensitive to the $J/\psi$ formation process. If the $J/\psi$ mesons are formed immediately after the production of the $c\bar{c}$ pair, the medium dependence is dominated by the hadronic scattering between a color-singlet $J/\psi$ and the nuclear matter. On the other hand, if the $J/\psi$ mesons are formed much later, the observed medium dependence is a consequence of the dynamical interactions between the pre-$J/\psi$ $c\bar{c}$ states and the nuclear medium. Therefore, the nuclear dependence can help select the correct model for $J/\psi$ production.

In proton-nucleus or nucleus-nucleus collisions, the produced $c\bar{c}$ pairs are likely to interact with the nuclear medium before they exit. If we assume each interaction between the $c\bar{c}$ pair and the nuclear medium is about the same and can be treated independently, we naturally derive the Glauber formula: $\sigma_{AB} = \exp[-\rho_N\sigma_{abs}L(A,B)]$ with effective absorption cross section $\sigma_{abs}$ to change a $c\bar{c}$ pair to a pair of open charms, and effective length $L(A,B)$ of the medium in A+B collisions. The characteristic feature of the Glauber formula is a straight line on a semi-log plot of $\sigma_{AB}$ vs. $L(A,B)$, which is not consistent with the strong $J/\psi$ suppression observed in Pb-Pb collisions.

Our model of $J/\psi$ suppression is based on the following points: (1) it is the $c\bar{c}$ pair, not the $J/\psi$ meson, that interacts through most of the nuclear medium; (2) multiple interactions of the $c$ and/or $\bar{c}$ with soft gluons in the medium increase the relative momentum between the $c$ and $\bar{c}$; and (3) as the relative momentum increases, the phase space to form a $J/\psi$ meson decreases. Since multiple soft-scatterings lead to a larger relative momentum between the $c$ and $\bar{c}$, the effective $\sigma_{abs}$ of the pair increases as the $c\bar{c}$ passes through the medium leading to a stronger suppression than given by the simple Glauber formula which applies to single particle propagation.

Integrating over $J/\psi$'s momentum in Eq. (1), we obtain a factorized expression for the $J/\psi$ total cross section

$$\sigma_{AB\rightarrow J/\psi} \approx \sum_{a,b,[c\bar{c}]} \int dx \phi_a/A(x) \int dx' \phi_b/B(x') \int dm_{c\bar{c}}^2 \frac{d\sigma_{ab\rightarrow [c\bar{c}]}(m_{c\bar{c}}^2)}{dm_{c\bar{c}}^2} F_{[c\bar{c}]\rightarrow J/\psi}(m_{c\bar{c}}^2)$$

where $F_{[c\bar{c}]\rightarrow J/\psi}$ represents an inclusive transition probability for a $c\bar{c}$ pair of invariant mass $m_{c\bar{c}}^2$ to become a $J/\psi$ meson. Without the large transverse momentum, the cor-
rrections to Eq. (3) from the spectator interactions, which are suppressed by a factor \( \sim \rho_N L(A,B)/4M_c^2 \), become more important because of the large medium length \( L(A,B) \). Just like the random walk of two particles, the soft spectator interactions effectively increase the invariant masses of the \( c\bar{c} \) pairs, and therefore, reduce the phase space to form \( J/\psi \) mesons. We calculate the \( J/\psi \) suppression in the nuclear medium by including the multiple spectator interactions to the pre-\( J/\psi \) \( c\bar{c} \) pairs, and plot our results in Figs. 2 and 3. The data are from Ref. [9]. The dashed lines are predictions of the Glauber formula, and the solid lines are the results of our calculations. With only one parameter \( \varepsilon^2 \), which is defined as average gain of invariant mass per unit medium length and is fixed by the total suppression in Fig. 2, our calculations of the \( J/\psi \) suppression are consistent with all existing data, except a couple of points at the highest \( E_T \) bins of the New NA50 data [8].

We conclude that the NRQCD model and the CE model are closely connected to the new QCD factorization formula for \( J/\psi \) production. The measurements of \( J/\psi \) polarization could provide a decisive test of the production mechanism. Our model of \( J/\psi \) suppression is consistent with nearly all existing data on \( J/\psi \) total cross section.

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