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Abstract
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Gluon Saturation Effects on J/ψ Production in Heavy Ion Collisions

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We consider a novel mechanism for J/ψ production in nuclear collisions arising due to the high density of gluons. The resulting J/ψ production cross section is evaluated as a function of rapidity and centrality. We compute the nuclear modification factor and show that the rapidity distribution of the produced J/ψ's is significantly more narrow in AA collisions due to the gluon saturation effects. Our results indicate that gluon saturation in the colliding nuclei is a significant source of J/ψ suppression and can explain the experimentally observed rapidity and centrality dependencies of the effect.

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Introduction.—The mechanism of J/ψ production in high-energy nuclear collisions can be expected to differ from that in hadron-hadron collisions. Consider first the J/ψ production in hadron-hadron collisions. The leading contribution is given by the two-gluon fusion (i) $G + G \to J/\psi$ + soft gluon; see Fig. 1(a). This process is of the order $O(\alpha_s^5)$. The three-gluon fusion (ii) $G + G + G \to J/\psi$ [see Fig. 1(b)] is parametrically suppressed as it is proportional to $O(\alpha_s^6)$. However, in hadron-nucleus collisions, an additional gluon can be attached to the nucleus. This brings in an additional enhancement by a factor $\sim A^{1/3}$. If the collision energy is high enough, the coherence length becomes much larger than the size of the interaction region. In this case, all A nucleons interact coherently as a quasiclassical field [1–4]. In the quasiclassical approximation, $\alpha_s^2 A^{1/3} \sim 1$. Therefore, the three-gluon fusion is actually *enhanced* by $1/\alpha_s$ as compared to the two-gluon fusion process. A similar conclusion holds for heavy-ion collisions (we do not consider any final state processes leading to a possible formation of the quark-gluon plasma).

In this Letter, we calculate the rapidity and centrality dependence of J/ψ production in AA collisions taking into account the gluon saturation effects [5,6]. The case of J/ψ production in dAu collisions was considered by two of us some time ago [7], where exactly the same mechanism was discussed, though the nuclear geometry was oversimplified. We note a reasonable agreement of this earlier approach with the dA data; a more definite conclusion can be reached once the higher statistics data become available in the near future. Our goal is to understand to what extent the cold nuclear matter effects are responsible for the J/ψ suppression in AA collisions. In our calculation, we use the dipole model [8] and take into account realistic nuclear geometry. In Ref. [7], detailed arguments were given which justify the application of the dipole model to the calculation of J/ψ production at the Relativistic Heavy Ion Collider (RHIC). We argued the following. (i) The coherence length for the production of the $c\bar{c}$ pair is sufficiently larger than the longitudinal extent of the interaction region. This means that the development of the light-cone "wave function" happens a long time before the collision. (ii) The formation of J/ψ is characterized by a time scale on the order of the inverse binding energy. This time is certainly much larger than the $c\bar{c}$ production coherence length (by a factor of $\sim 1/\alpha_s^2$), implying that the formation process takes place far away from the nucleus. Therefore, in the following, we concentrate on the dynamics of $c\bar{c}$ pair interactions with the nucleus.

New mechanism of J/ψ production.—A particularly helpful insight into the nature of the new production mechanism, depicted in Fig. 1(b), is obtained if we note that the three-gluon contribution is suppressed as compared to the two-gluon fusion mechanism [Fig. 1(a)] by an additional factor r^2, where r is $c\bar{c}$ transverse separation such that $(2m_c)^{-1} \lesssim r \lesssim (2m_c\alpha_s)^{-1}$. This factor arises since we need to have three gluons in the area of the order of r^2. In other words, it means that this reaction is originated from the next-twist contribution. However, in the hadron-nucleus interactions, the next-twist contribution appears always in the dimensionless combination $r^2 Q_s^2$ with the saturation scale Q_s. The saturation scale is proportional to $A^{1/3}$ which compensates for the smallness of r. The dominance of the higher twist process is the main idea of Ref. [7], and we develop it in this Letter in the case of heavy-ion collisions.

Figure 1(b) represents the contribution of the order $(\alpha_s^2 A^{1/3})^2$. In general, there must be an odd number of gluons connected to the charm fermion line because the quantum numbers of J/ψ and of gluon are 1^{--}. Therefore, each inelastic interaction of the $c\bar{c}$ pair must involve two nucleons and hence is of the order $(\alpha_s^2 A^{1/3})^{2n}$, where

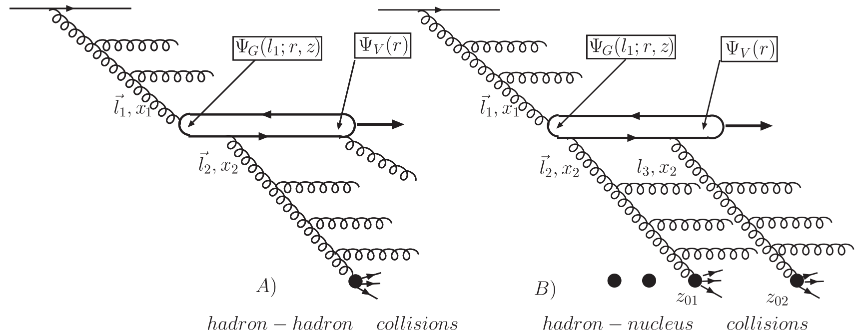

FIG. 1. The process of inclusive J/ψ production in hadron-hadron (a) and in hadron-nucleus collisions (b).

$n = 1, 2, \ldots, A/2$ is the number of nucleon pairs. To take this into account, we write the cross section as the sum over all inelastic processes (labeled by the index n). This sum involves only an even number of interactions. For a heavy nucleus $A \gg 1$, we have

$$\frac{d\sigma_{\rm in}(pA)}{dYd^2b} = C_F x_1 G(x_1, m_c^2) \int_0^{2R_A} \rho \hat{\sigma}_{\rm in}(x_2, r, r')dz_0 \int d^2 r \psi_G(l_1, r, z = 1/2)\psi_V(r) \otimes \int d^2 r' \psi_G(l_1, r', z = 1/2)$$
$$\times \psi_V(r')\bigg(e^{-[\sigma(x_2,r^2)+\sigma(x_2,r'^2)]\rho 2R_A} \sum_{n=0}^{\infty} \int_{z_0}^{2R_A} dz_1 \int_{z_1}^{2R_A} dz_2 \ldots \int_{z_{2n}}^{2R_A} dz_{2n+1} \rho^{2n+1} \hat{\sigma}_{\rm in}^{2n+1}(x_2, r, r')\bigg), \tag{1}$$

where $\psi_G \otimes \psi_V$ is the projection of the J/ψ light-cone wave function onto the virtual gluon one [7,9], z_i's are the nucleon longitudinal coordinates in the nucleus, and

$$\hat{\sigma}_{\rm in}(x_2, r, r') \equiv \sigma(x_2, r^2) + \sigma(x_2, r'^2) - \sigma[x_2, (\underline{r} - \underline{r}')^2]. \tag{2}$$

After integration over z_i's and summation over n, we obtain the following formula:

$$\frac{d\sigma_{\rm in}(pA)}{dYd^2b} = C_F x_1 G(x_1, m_c^2) \int d^2 r \psi_G(l_1, r, z = 1/2)\psi_V(r) \otimes \int d^2 r' \psi_G(l_1, r', z = 1/2)\psi_V(r')$$
$$\times \frac{1}{2}\big(\exp\{-\sigma[x_2, (\underline{r} - \underline{r}')^2]\rho 2R_A\} + \exp\{-[\sigma(x_2, r) + \sigma(x_2, r')$$
$$+ \hat{\sigma}_{\rm in}(x_2, r, r')]\rho 2R_A\} - 2\exp\{-[\sigma(x_2, r) + \sigma(x_2, r')]\rho 2R_A\}\big). \tag{3}$$

The color factor in (1) and (3) is calculated in the $N_c \gg 1$ limit.

In the quasiclassical approximation, the gluon saturation is given by [8] $Q_{s,A}^2(x) = 4\pi^2\alpha_s^2\rho T(\underline{b})$, where ρ is the nucleon density in a nucleus, N_c is the number of colors, $\underline{b}$ is the impact parameter, and $T(b)$ is the optical width of the nucleus. $Q_{s,A}$ determines the scale of the typical transverse momenta for inclusive gluon production [10]. Its value was extracted from the fit of the multiplicities of nuclear reactions at the RHIC [11,12] and from fits of the F_2 structure function in deep inelastic scattering [13–16].

To generalize (3) to the case of AA collisions, we use the approach suggested by Kovchegov [17] and replace the lowest order gluon field correlation function by the full MV formula as follows:

$$\frac{\alpha_s \pi^2}{3} x_1 G(x_1, m_c^2) \to \frac{d^2 b}{r^2}\bigg[1 - \exp\bigg(-\frac{r^2 Q_{s,A_1}^2}{8}\bigg)\bigg]. \tag{4}$$

Furthermore, noting that the dominant contribution to the integral over r' in (3) comes from the region $r \gg r'$ [7], we obtain

$$\frac{1}{S_A}\frac{d\sigma(AA)}{dYd^2b} \propto Q_{s,A_1}^2(x_1)Q_{s,A_2}^2(x_2)[Q_{s,A_1}^2(x_1) + Q_{s,A_2}^2(x_2)]$$
$$\times \int_0^{\infty} d\zeta \zeta^9 K_2(\zeta) e^{-[\zeta^2/(8m_c^2)][Q_{s,A_1}^2(x_1)+Q_{s,A_2}^2(x_2)]}. \tag{5}$$

Equation (5) is derived in the quasiclassical approximation which takes into account multiple scattering of the $c\bar{c}$ pair in the cold nuclear medium. At forward rapidities at the RHIC and at the LHC, the gluon distribution functions (4) evolve according to the evolution equations of the color glass condensate. Inclusion of this evolution in the case of J/ψ production presents a formidable technical challenge. Therefore we adopt a phenomenological approach of Ref. [12] in which the quantum evolution is encoded in the energy or rapidity dependence of the saturation scales.

In our numerical calculations, we take explicit account of the impact parameter dependence of the saturation scales of each nucleus. We employ the Glauber approximation and assume that the nucleons are small compared to the size of the nuclei. The number of J/ψ's inclusively produced in ion-ion collisions at given rapidity Y and centrality characterized by b reads

$$\frac{dN^{AA}(Y,b)}{dY} = C\frac{dN^{pp}(Y)}{dY}\int d^2 s T_{A_1}(\underline{s})T_{A_2}(\underline{b}-\underline{s}) \times [Q^2_{s,A_1}(x_1,\underline{s}) + Q^2_{s,A_2}(x_2,\underline{b}-\underline{s})]\frac{1}{m_c^2} \times \int_0^\infty d\zeta \zeta^9 K_2(\zeta)\exp\bigg(-\frac{\zeta^2}{8m_c^2}[Q^2_{s,A_1}(x_1,\underline{s}) + Q^2_{s,A_2}(x_2,\underline{b}-\underline{s})]\bigg), \tag{6}$$

where $x_{1/2} = (m_{J/\psi,t}/\sqrt{s})e^{\mp Y}$, with $m^2_{J/\psi,t} = m^2_{J/\psi} + p_t^2$, p_t being the transverse momentum J/ψ. The overall normalization constant C includes the color and the geometric factors $C_F^2/(4\pi^2\alpha_s S_p)$, where S_p is the interaction area in proton-proton collisions. C also includes the amplitude of quark-antiquark annihilation into J/ψ and a soft gluon in the case of pp collisions. This amplitude as well as the mechanism of Fig. 1(a) have a significant theoretical uncertainty. Therefore, we decided to parameterize these contributions by an overall normalization constant in (6).

The rapidity distribution of J/ψ's in pp collisions, the factor dN^{pp}/dY appearing in Eq. (6), is fitted to the experimental data given in Ref. [18] with a single Gaussian. In Fig. 2(a), the results provided by Eq. (6) are then compared to the experimental data from the PHENIX Collaboration [19] for Au-Au collisions at $\sqrt{s} = 200$ GeV. The global normalization factor C is found from the overall fit. There are no other free parameters. The agreement of the theoretical results with experimental data is reasonable. It is evident that the effect of the gluon saturation on the J/ψ rapidity distribution in nucleus-nucleus collisions is to make its width a decreasing function of centrality. The distribution in the most central bin is significantly more narrow than in the peripheral bin.

It is important that we describe well the data in the semiperipheral region. This ensures that our model gives a good description of the J/ψ production in dAu collisions. We also note that an earlier approach [7] in which the same model was employed (albeit with an oversimplified nuclear geometry) provided a reasonable description of the data. Still a more detailed investigation is required which takes into account the exact deuteron and gold nuclear distributions. This will allow a model-independent fixing of the overall normalization constant C. Such an analysis will be presented in the near future.

Previously, the initial-state effects on the nuclear suppression of J/ψ's have been estimated [20,21] through the product of nuclear modification factors measured in dAu collisions. This estimate holds as long as the collinear factorization holds for the process of J/ψ production (this would be true, for example, in the limit of small cc-bar dipole size). Here we find that the effects beyond the collinear factorization are strong and may account for a large part of the suppression measured in Au-Au, especially at forward rapidities (where the density of gluons in the initial state, inside one of the colliding nuclei, is the largest).

To emphasize the nuclear dependence of the inclusive cross sections, it is convenient to introduce the nuclear modification factor

$$R_{AA}(y, N_{\text{part}}) = \frac{\frac{dN^{AA}}{dy}}{N_{\text{coll}}\frac{dN^{pp}}{dy}}. \tag{7}$$

It is normalized in such a way that no nuclear effect would correspond to $R_{AA} = 1$. In Fig. 2(b), we plot the result of

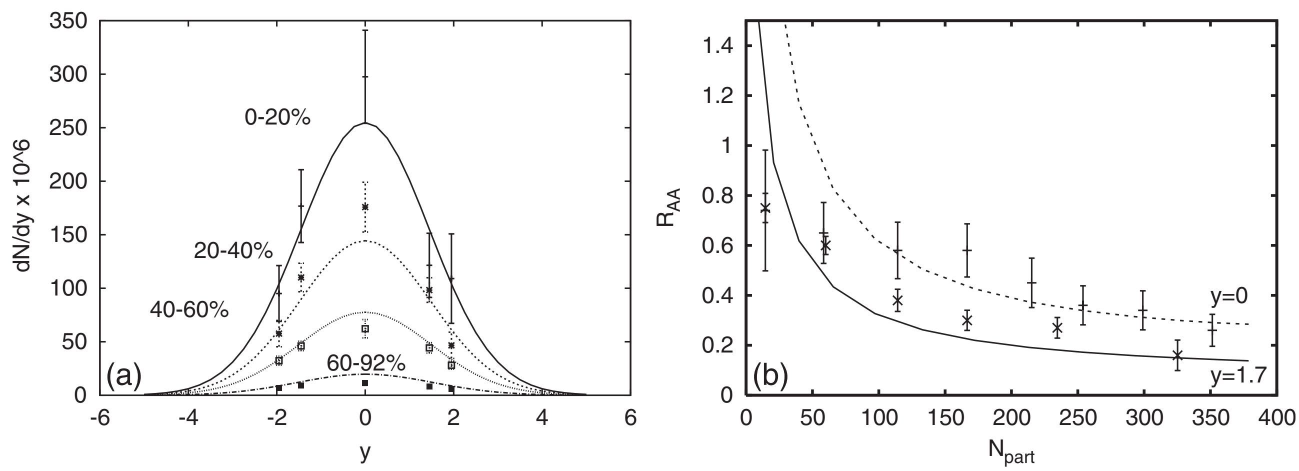

FIG. 2. (a) J/ψ rapidity distribution in Au-Au collisions for different centrality cuts. (b) Nuclear modification factor for J/ψ production in heavy-ion collisions for different rapidities. Experimental data from Ref. [19].

our calculation. The nuclear modification factor exhibits the following two important features: (i) Unlike the open charm production, J/ψ is suppressed even at $y = 0$; (ii) cold nuclear matter effects account for a significant part of the "anomalous" J/ψ suppression in heavy-ion collisions at both $y = 0$ and $y = 2$.

Conclusions.—The main results of this Letter are exhibited in Fig. 2. It is seen that the rapidity and centrality dependence of J/ψ production are reproduced with a reasonable accuracy even without taking into account any hot nuclear medium effects. This observation allows us to conclude that a fair amount (and perhaps most) of the J/ψ suppression in high-energy heavy-ion collisions arises from the cold nuclear matter effects. In other words, J/ψ is expected to be strongly suppressed even if there were no hot nuclear matter effect produced. In this sense, we can talk about the separation of the cold and hot nuclear medium effects as advertised in the introduction.

A certain fraction of J/ψ suppression in the forward direction can be attributed to suppression of the constituent c and $\bar{c}$ quarks [22–25] which would lead to suppression of D mesons [26]. However, D mesons are not predicted to be suppressed at central rapidities [26].

The reason for J/ψ suppression at midrapidities is that the multiple scattering of $c\bar{c}$ in the cold nuclear medium increases the relative momentum between the quark and antiquark, which makes the bound state formation less probable. It was proven in Ref. [27] that, unless quantum $\log(1/x)$ corrections become important, the inclusive gluon production satisfies the sum rule that requires the nuclear modification factor to be of order unity. A similar sum rule holds for heavy quark production but fails in the case of a bound states, such as J/ψ.

We realize that, although our calculation gives the parametrically leading result at high gluon density, other production channels involving the gluon radiation in the final state and the color octet mechanism of J/ψ production may give phenomenologically significant contributions. These are likely to become the leading mechanisms in the peripheral collisions where the strength of the gluon fields is significantly diminished. However, we believe that our main results are robust for central high-energy collisions of heavy ions. These results imply that the observed J/ψ suppression is a result of an interplay between the cold and hot nuclear matter effects.

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