Fading out of $J/\psi$ color transparency in high energy heavy ion peripheral collisions

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ABSTRACT

We provide predictions for the $J/\psi$ coherent production in the peripheral heavy ion collisions at LHC and RHIC using the leading twist model of nuclear shadowing based on the QCD factorization theorem for diffraction and the HERA hard diffraction data. We demonstrate that for LHC kinematics this model leads to a bump-shape distribution in rapidity which is suppressed overall as compared to the expectations of the color transparency regime by a factor $\sim 6$. This is a significantly larger suppression than that expected within the impact parameter eikonal model. Thus we show that the interaction of spatially small wave package for which the total cross section of interaction with nucleons is small is still strongly shadowed by nuclear medium in high energy processes.

1 Introduction

Interaction of small size color singlet objects with hadrons is one of the most actively studied issues in high-energy QCD. In perturbative QCD (similar to QED) the total cross section of the interaction of such systems with hadrons is proportional to the area occupied by color within projectile hadron \[ \frac{A}{r} \] leading to the expectation of a color transparency phenomenon for various hard processes with nuclei. In the case of incoherent processes cross sections are expected to be proportional to the number of nucleons in the nuclei while in the case of coherent processes the amplitude is proportional to number of nucleons times the nuclear form factor. Possibility to approximate projectile heavy quarkonium as colorless dipole of heavy quarks can be formally derived from QCD within the limit when mass of heavy quark $m_Q \to \infty$ but $x_{Bj} = 4m_Q^2/\nu$ is fixed and not extremely small \[ 2 \]. In this kinematics the size of heavy quarkonium is sufficiently small to justify applicability of PQCD.

Recently the color transparency (CT) phenomenon was observed at FNAL by E791 experiment\[ 3 \] which studied the coherent process of dissociation of a 500 GeV pion into...
two jets off the nuclei. The measurement has confirmed a number of predictions of \cite{4} including the A-dependence, and the transverse and longitudinal momentum distributions of the jets. Previously the color transparency type behaviour of the cross section was observed also in the coherent $J/\psi$ photoproduction at $\langle E_\gamma \rangle = 120 GeV$ \cite{5}.

A natural question is whether the color transparency will hold for arbitrary high energies? Two phenomena are expected to work against CT at high energies leading to onset of a new regime which we refer to as the color opacity regime. One is the leading twist gluon shadowing. Indeed the QCD factorization for hard exclusive coherent processes with nuclei like $\gamma_L^* + A \to "\text{Vector meson}" + A$ implies that the cross sections are proportional to the square of the gluon parton density $G_A(x,Q^2)$ at small $x$ which is screened in nuclei as compared to the nucleon: $G_A(x,Q^2)/AG_N(x,Q^2) < 1$. This obviously should lead to a gradual disappearance of color transparency \cite{4,6}. Another mechanism for violation of CT at high energies is the increase of the small dipole-nucleon cross section with energy $\propto G_N(x,Q^2)$. For sufficiently large energies this cross section becomes comparable to the meson-nucleon cross sections and hence one may expect a significant suppression of the hard exclusive diffractive processes like DIS diffractive production of vector meson and photoproduction of heavy quarkonium states as compared to the CT scenario. However it seems that this phenomenon is beyond the kinematics achievable for the photoproduction of $J/\psi$ mesons at RHIC ($x \approx 2 \cdot 10^{-2}, Q^2 \approx 10 GeV^2$) and probably even at LHC.

It was suggested in \cite{2,7} to look for color opacity phenomenon using $J/\psi$ (photo) electroproduction. This however requires energies much larger than those available at the fixed target facilities and would require use of electron-nucleus colliders. At the same time estimates of the counting rates performed within the framework of the FELIX study \cite{8} have demonstrated that the effective photon luminosities generated in peripheral heavy ion collisions at LHC would lead to significant rates of coherent photoproduction of vector mesons including $\Upsilon$ in reaction

$$A + A \to A + A + V.$$  

As a result it would be possible to study at LHC photoproduction of vector mesons in Pb-Pb and Ca-Ca collisions at energies much higher than the range $W_{\gamma p} \leq 17.3 GeV$ covered at the fixed target experiment at FNAL \cite{5}. Note that even current experiments at RHIC ($W_{\gamma p} \leq 25 GeV$) should also exceed this limit.

Currently the theory of photoinduced processes in AA collisions is well developed, for the recent review see \cite{9}. Hence we can combine it with our previous studies of the coherent photo(electro)production of vector mesons to make predictions for production of $J/\psi$ in the process \cite{1}. Typical transverse momenta which are exchanged between two nuclei in the peripheral collisions which leave nuclei intact are much smaller than the typical transverse momenta in the coherent photoproduction of vector mesons. As a result for the cross section integrated over the momentum of the nucleus which emits the quasireal photons we can use the standard Weizsacker-Williams approximation.

Hence the cross section of the vector meson production integrated over the transverse momenta of the nucleus which emitted a photon can be written in the convoluted form:

$$\frac{d\sigma(AA \to J/\psi AA)}{dk} = 2 \int d^2b T_{AA}(\vec{b}) \frac{n(k,\vec{b})}{k} \sigma_{\gamma A \to J/\psi A}(k).$$  

(2)
Here $k = \gamma k_3$ is the photon momentum in the colliding frame ($k_3$ - momentum of photon in the rest system of emitting nucleus and $\gamma$ - Lorentz factor).

For the quantity $n(k, \vec{b})$ presenting the flux of photons with momentum $k$ in the collider frame we used the simplest approximated form:\[11\]:

$$n(k, \vec{b}) = \frac{Z^2 \alpha}{\pi^2} \frac{1}{b^2} X^2 \left[ K_0^2(X) + \frac{1}{\gamma} K_1^2(X) \right],$$

where $K_0(X)$ and $K_1(X)$ are modified Bessel functions with argument $X = \frac{\gamma k}{m}$ and $\vec{b}$ is the impact parameter distance between centres of colliding nuclei. The factor $T_{AA}(\vec{b})$ accounts for inelastic interactions of the nuclei at impact parameters $b \leq 2R_A$. It can be approximately calculated as

$$T_{AA}(\vec{b}) = \int d\vec{b}_1 T_{A}(\vec{b}_1) T_{A}(\vec{b} - \vec{b}_1),$$

where $T_{A}(\vec{b}) = \int_{-\infty}^{\infty} dz \rho_A(z, \vec{b})$ is the usual profile function of the nucleus. In our calculations we use the nuclear matter density $\rho_A(z, \vec{b})$ obtained from the mean field Hartree-Fock-Skyrme (HFS) model, which describes many global properties of nuclei as well as the intermediate and high energy elastic proton-nucleus scattering and nucleus electromagnetic form factors. This indicates that the HFS model provides a good description of both proton and neutron distribution in nuclei and takes into account a small difference between the matter distribution and the charge distribution.

The main subject of our interest in this paper is estimating the cross section of the process $\gamma A \rightarrow J/\psi A$

$$\sigma_{\gamma A \rightarrow J/\psi A}(k) = \int dt \frac{d\sigma(\gamma A \rightarrow VA)(\bar{s}, t)}{dt},$$

where

$$\bar{s} = 4E_Nk = 4\gamma km_N$$

is invariant energy for $\gamma - N$ scattering ($E_N = \gamma m_N$ is the energy per nucleon in the c.m. of the nucleus-nucleus collisions), $t = -|p_t^A|^2$ is square of the vector meson transverse momentum.

## 2 Coherent photoproduction of $J/\psi$ off nuclei

Let us discuss the photoproduction amplitude $\gamma + A \rightarrow J/\psi + A$ in more details. We are interested here in the $W_{\gamma p}$ range which can be probed at RHIC and LHC. In this situation interaction of $c\bar{c}$ which in the final state forms $J/\psi$ is still rather far from the black body limit in which cross section can be calculated in the model independent way [10]. Several mechanism of coherent interaction with several nucleons were suggested for this process. We focus here on the **leading twist mechanism of shadowing**. There exist qualitative difference between the mechanism of interaction of a small dipole with several nucleons and the case of a similar interaction of an ordinary hadron. Let us for example consider interaction with two nucleons. The leading twist contribution is described by the diagrams where two gluons are attached to the dipole. To ensure that nucleus remains intact in such a
process we need to attach colorless lines to both nucleons. These diagrams are closely related to the diagrams corresponding to the gluon diffractive parton densities which are measured at HERA (see Fig. 1) and hence to the similar diagrams for the gluon nuclear shadowing [7].

As a result it was possible to express the quark and gluon nuclear shadowing for the interaction with two nucleons in a model independent way through the corresponding diffractive parton densities using the Gribov theory of inelastic shadowing[11] and the QCD factorization theorem for the hard diffraction [12]. An important discovery of HERA is that hard diffraction is indeed dominated by the leading twist contribution and gluons play a very important role in the diffraction(this is loosely referred to as gluon dominance of the Pomeron). Analysis of the DESY diffractive data indicates that in the gluon induced processes probability of the diffraction is much larger than in the quark induced processes [7].

The recent H1 data on diffractive dijet production [13] provide an additional confirmation of this observation. Large probability of diffraction in the gluon induced hard processes could be understood in the s-channel language as formation of color octet dipoles of rather large size which can elastically scatter with a rather large cross section. The strength of this interaction can be quantified using optical theorem and introducing

$$\sigma_{eff}^g = 16\pi \frac{d\sigma_{diff}(x,Q^2)/dt(t = 0)}{\sigma_{tot}(x,Q^2)}$$

for the hard process of scattering of a virtual photon off the gluon field of the nucleon. An important feature of this mechanism of coherent interaction is that it is practically absent for $x \geq 0.02 \div 0.03$ and may rather quickly become important with decrease of $x$. The gluon virtuality scale which is relevant for the $J/\psi$ photoproduction is 3-4 GeV$^2$ with a significant fraction of the amplitude due to smaller virtualities [2, 14]. Hence we will take the gluon shadowing in the leading twist at $Q^2 = 4 GeV^2$. Taking a smaller value of $Q^2$ would result in even larger shadowing effect. We present numerical values of $\sigma_{eff}^g(Q^2 = 4 GeV^2)$
for two current models of the diffractive gluon densities (Fig. 2) which practically cover the range of parameterizations available in the literature. The H1 parameterization leads to a more gradual onset of the contribution of the double interactions because in this model diffraction into masses with $M^2/Q^2 \leq 1$ is smaller. The dijet data of H1 prefer this scenario though it seems that further measurements will be necessary to clarify the issue. So we keep both models for the further analysis. For a more detailed discussion of the current models of diffraction and of the resulting values of $\sigma_{eff}$ see [15]. The effective cross section $\sigma_{eff}$ can be used to estimate relative importance of the interactions with $N \geq 3$ [7], which corresponds to account of diagrams of Fig. 3 in the quasieikonal approximation. As a result the $t$-dependence of the photoproduction turns out about the same as for the case of Glauber scattering of a projectile with cross section of interaction with a nucleon equal to $\sigma_{eff}$. The ratio of the photoproduction cross sections off nucleus and nucleon is expressed in the leading twist through the ratio of the skewed gluon parton densities. In the case of $J/\psi$ photoproduction Fermi motion effects lead to $x_2/x \sim 0.3 - 0.5$ and hence to $x_{eff} \approx x$.

In principle the multiple eikonal type rescatterings (at fixed transverse separations) due to multiple gluon exchanges - see Fig. 4 (the impact parameter eikonal rescattering model) could also result in suppression of the vector meson production. Though validity of this approximation is hard to justify in QCD the model calculations suggest that this effect is not small numerically [2]. However, it is still significantly smaller than the leading twist shadowing (at least for $x \leq 0.001$) which we find in our calculations. Note in passing that if one would consider the gluon shadowing using phenomenological models [6, 7] whereshadowing for gluons was assumed to be equal to that for quarks at low normalization scale one would find comparable suppressions due to the leading twist gluon shadowing and the eikonal rescatterings. This would make extraction of the gluon shadowing from measurements of photoproduction of $J/\psi$ highly problematic.

3 Numerical results and discussion.

Having build the quasieikonal model for the amplitudes of the interaction of $c\bar{c}$ pair with several nucleons we can now calculate the amplitude of scattering off nuclei. We have demonstrated in [7] that the amplitude in this approximation has the same structure of the rescattering terms as the Glauber model with $\sigma_{tot}$ substituted by $\sigma_{eff}$. Hence we can use the optical limit of the Glauber model [8] to calculate the cross section of $J/\psi$ photoproduction

$$\frac{d\sigma_{\gamma A \rightarrow V A}(s, t)}{dt} = \frac{d\sigma_{\gamma N \rightarrow VN}(s, t = 0)}{dt} \left| \int d^2 b d z e^{i q \cdot \vec{b}} \rho(\vec{b}, z) e^{i q \cdot \vec{z}} \cdot e^{-i z \cdot \rho(\vec{b}, z')} dz' \right|^2. \quad (8)$$

Here the exponential factor with $q_\ell = m_{\psi}^2/2k$ accounts for finite longitudinal distances in the transition $\gamma \rightarrow V$ (finite longitudinal momentum transfer). The forward elementary cross section for photoproduction of $J/\psi$ meson on nucleon was taken using the fit to experimental
Figure 2: The quantity $\sigma_{\text{eff}}^g$ for $Q^2 = 4GeV^2$ as a function of the Bjorken x for H1 (solid line) and Alvero et al [20] (dashed line) parameterizations of the gluon diffractive density.
Figure 3: Leading twist diagrams for the production of $J/\psi$ off two and three nucleons.

Figure 4: Typical diagrams for the higher twist eikonal interactions of a small dipole with two nucleons.
data presented in [19] (this is preferable to using the theoretical calculations which for photoproduction of $J/\psi$ have theoretical uncertainty of the order of two).

We focus here on the distributions over rapidity:

$$y = \frac{1}{2} \ln \frac{E_V - p_3^V}{E_V + p_3^V} = \ln \frac{2k}{m_V}. \quad (9)$$

In Figs. 5, 6, and Fig. 7 we present the differential cross sections both including effects of gluon shadowing and without gluon shadowing (impulse approximation) for lead-lead peripheral collisions at LHC and gold-gold collisions at RHIC.

One can see that on the top of the overall suppression of the cross section the gluon nuclear shadowing leads to a significant modification of the shape of the rapidity distribution as compared to the impulse approximation. Bumps near the edges of rapidity distribution are due to a sharp increase of the effective cross section found in the calculation based on the Alvero et. al. model of the gluon diffractive density in the region of Bjorken $x$ close to $x \approx 10^{-2}$. A bump in the center region of $y$ arises due to the drop of the photon flux as can be seen from Fig. 4. These effects are weakened for the H1 parameterization which leads to a more gradual increase of $\sigma_{eff}$ and they disappear in the impulse approximation. It is also of interest that in the LHC kinematics we are sensitive to the cross section of photoproduction at $W_{\gamma p}$ up to a factor of three larger than $W_{\gamma p}$ corresponding to production at $y = 0$. Hence the measurements will actually probe the $J/\psi$ photoproduction at the energies beyond those reachable at HERA in electron-nucleus mode.

In the RHIC kinematics we find even more nice picture in the case of gold-gold collision. The decrease of cross section as a function of rapidity due to the shadowing is combined with drop of the photon flux in the same region of rapidities. This results in a narrow dip at $y = 0$ which is very sensitive to pattern of onset of the gluon shadowing. The test of this prediction will be feasible at RHIC since the rates of $J/\psi$ production are pretty high [21].

At LHC the total cross section calculated with accounting for the gluon shadowing effects is $\sigma(PbPb \rightarrow J/\psi + PbPb) \approx 14$ mb and the value $\sigma(PbPb \rightarrow J/\psi + PbPb) \approx 85$ mb was obtained in the impulse approximation. Hence, we have found a strong suppression of the $J/\psi$ yield for this case as it was predicted on the base of rough estimates in [7]. In kinematic of RHIC the effect of suppression due to the gluon shadowing is rather small and $\sigma(AuAu \rightarrow J/\psi + AuAu) \approx 0.320$ mb while in the impulse approximation $\sigma(AuAu \rightarrow J/\psi + AuAu) \approx 0.360$ mb.

Let us compare our results with two other calculations of the reaction (1). The first rather detailed calculation of the coherent process $AA \rightarrow A + V + A$ has been reported in Ref. [21]. To evaluate nuclear shadowing effects in the total $J/\psi A$ cross section the vector dominance model, classical mechanics formulae (accounting for the elastic rescatterings of vector meson only) have been used in [21]. On the contrary our calculation uses eikonal approximation where inelastic shadowing effects dominate. Really $\sigma_{eff}^0$ derived from the diffractive gluon densities includes both the elastic and inelastic shadowing. It is also assumed in Ref. [21] that the $t$-dependence of the cross section is $\propto |F_A(t)|^2$ (where $F_A(t)$ is the nuclear form factor) while account for the rescattering effects (eq. 8) leads to somewhat steeper $t$-dependence. For the RHIC energies whenever comparison is possible the results of Ref. [21] are pretty close to ours. This is because nuclear shadowing effects are a small correction for the photoproduction of $J/\psi$ in the kinematics of RHIC. For the LHC kinematics we obtained cross section for the
Figure 5: The rapidity distribution for the $J/\psi$ production in lead-lead peripheral collisions at LHC. Solid line - production by two-side beams, dashed - production by one-side beam only. Calculations were performed with $\sigma_{eff}^{J/\psi N}$ based on Alvero et.al. parameterization of the gluon diffractive density.
Figure 6: The rapidity distributions for the LHC lead-lead peripheral collision $J/\psi$ coherent production calculated with $\sigma_{J/\psi N}^{\text{eff}}$ based on H1 (solid line) and Alvero et al (dashed line) parameterizations of gluon density and in the impulse approximation (dot-dashed line)
Figure 7: The same as in Fig. 6 but for gold-gold collisions at RHIC.
coherent $J/\psi$ production significantly below the value of \cite{21} (a factor of two for lead-lead collisions). The difference is because approach used in \cite{21} significantly underestimates the strengths of multiple interaction of $c\bar{c}$ pair with the nucleus. Also rapidity distributions for lead-lead collisions for which we find an interesting shape were not considered in Ref.\cite{21}.

After this study was nearly completed a report has appeared \cite{22} where it has been suggested to use the coherent $J/\psi$ production in the peripheral ion-ion collisions to measure shadowing of gluon densities in nuclei. The analysis in \cite{22} is based on the factorization theorem of \cite{4, 6}, the $t$-dependence of the coherent $\gamma A \rightarrow J/\psi A$ cross section has been approximated as $F^2(t)$ and three sets of the gluon distributions has been used. Calculations with the GRV gluon distribution is effectively equivalent to the impulse approximation. Two others model accounts for the nuclear shadowing. The distribution of \cite{17} assumes the same shadowing for gluons as for quarks which is in variance with diffractive data from HERA. The second model \cite{23} attempts to account for nonlinear QCD evolution in the gluon density and in this case application of the factorization approximation is hardly justified. It would be reasonable to expect that at least for $J/\psi$ production in the kinematics at RHIC where the shadowing effects don't influence essentially the total cross sections our numerical results should be qualitatively similar. However we found gross differences - our absolute cross sections are considerably larger as compared to that in \cite{22} both for the kinematics at RHIC and at LHC.

To conclude, we have demonstrated that heavy ion collisions at RHIC are sensitive to the onset of gluon nuclear shadowing while the measurements at LHC will allow to establish disappearance of transparency of nuclear matter for spatially small $c\bar{c}$ dipole at high energies.

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