NUCLEAR EFFECTS IN CHARMONIUM PRODUCTION IN QCD

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Abstract

It is shown that the nuclear shadowing of charmonium due to the modification of the nuclear parton distribution is similar in the factorization approach based on non relativistic QCD and in the color evaporation model. In the first model, a separate study of the color octet and color singlet contributions to the yields of the various charmonium states as well as the contributions of these states to the total $J/\Psi$ production is performed. It is found a clear $x_F$ dependence of these contributions which can reproduce experimental data for moderate $x_F$.

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1 INTRODUCTION

Since the observation of a possible anomalous suppression in lead on lead collisions by the NA50 collaboration [1, 2] a lot of theoretical work has been done trying to explain the data. Some papers use conventional physics [3]-[5] but most of the explanations are based on QGP formation [6]-[10], the new state that has been predicted to be formed at high enough temperatures and densities of hadronic matter and from which $J/\Psi$ suppression has been proposed as a signature long ago [11]. Although there are some consensus in the possibility of this state to be reached in 158 AGeV/c lead on lead collisions, a lot of uncertainties remain to be solved on the production and suppression of the $J/\Psi$. A deep study of the absorption mechanisms seems necessary in order to assert the anomaly on the observed suppression.

Charmonium production in hadron-hadron collisions is now quite accurately described by a factorization approach (FA) based on non-relativistic QCD (NRQCD) [12], although the so called color evaporation model (CEM) has also a remarkable success in describing integrated as well as differential cross sections [13] [14]. The main difference between them is the treatment of color, being the CEM quite radical in this sense: it simply forgets about color. In the calculations of this paper both models will be used, turning out to give almost identical results.

In parton model, the production mechanism is described by the fusion of a parton coming from the projectile with longitudinal momentum fraction $x_1$ and a parton from the target with longitudinal momentum fraction $x_2$. For a fixed $x_F > 0$ ($x_F \equiv x_1 - x_2$), this momentum fraction are $x_1 \simeq x_F$ and $x_2 \simeq M^2/x_1 s$.

For collisions involving nuclei the situation is much more complex. Multiple scattering of the initial partons as well as of the produced pre-resonant states with nucleons from the nucleus and even of the produced resonances with other produced particles (co-movers) must be taken into account. It is very common to call initial state interactions to multiple interactions of the initial partons (mostly gluons in the case of $J/\Psi$ and $\Psi'$) and final state interactions to the rescattering of the pre-resonant state. These names are senseless at high energies, where time ordering is lost. It is possible, however, to factorize the multiple scattering of light partons from that of the heavy pre-resonance. The former can be described by modifying the nucleon structure function inside nuclei (EMC effect). For the latter a probabilistic formula for the heavy system to interact is usually employed. This formula can also be derived in a field theoretical approach. All these features are discussed in [15]. In this way the situation is different in open charm as well as in Drell-Yan (DY) production, where there is no absorption of the produced heavy system (at least at moderate energy) but the effect of nuclear modifications on structure functions is almost the same as in the case of charmonium [10]. A combined

\footnote{Sometimes it is called Color Octet Model, although it seems now more frequent FA. The name COM is not very correct because it is not a model, but the solution of an effective theory and not only color octet states are taken into account.}
study of the different reactions should help to distinguish the contributions of each effect to the suppression.

In this paper we are only interested in studying the effect of the modification of the nucleon structure functions inside nuclei (EMC effect). As we will see, this modification has a big influence on the absorption of charmonium at large $x_F$, a problem that remains unsolved [17]. Although this effect is negligible in the integrated cross section at present energies, it will be important at higher ones. A better understanding of the different suppression mechanisms in pA and AB collisions could shed some light on what is happening in PbPb, and, for that, the $x_F$ dependence of absorption will be very helpful.

Concerning suppression, large $x_F$ is related with higher energies in two senses: first, from the point of view of suppression by EMC effect, as the momentum fraction of the target parton that takes part in the collision is $x_2 \simeq M^2/sx_F$, larger $x_F$ as well as $s$ imply smaller $x_2$ (the region of shadowing corrections). Second, from the point of view of rescattering of produced pre-resonances by nuclear matter (not studied here), again larger $x_F$ or $s$ means faster produced particles, that could lead to a bigger absorption cross section [18, 19]. This is discussed in detail in reference [15].

Further uncertainties come from the treatment of color in absorption of pre-resonant state by nuclear matter. It is usually assumed that a pre-resonant color octet state is absorbed by rescattering with other nucleons inside nuclei. But, as it is well known by FA, $J/\Psi$ is not fully formed in color octet state and, as we will see, the fraction of the different color contributions to the production cross section is affected by the EMC effect, being the color singlet states less shadowed than the color octet ones. Then, although the correction by EMC effect itself is not very big, it will have some effect in the amount of absorption by nuclear rescattering if different absorption cross section are used to color octet and color singlet states as done, for example, in reference [4].

## 2 QUARKONIUM PRODUCTION CROSS SECTION

The production cross section for a quarkonium state $H$ according to the process

$$P + T \rightarrow H + X$$

can be described in framework of parton model by the integral

$$\sigma_H = \int dx_1 dx_2 \sum_{i,j} f_i^P(x_1)f_j^T(x_2)\hat{\sigma}(i,j \rightarrow H),$$

(1)

where $f_i^{P(T)}(x_1)$ is the $i$-parton distribution function in the projectile (target).

The FA based on NRQCD gives the partonic elementary cross section,

$$\hat{\sigma}(i,j \rightarrow H) = \sum_n C_{Q\bar{Q}[n]}^{ij} < O_n^H >,$$

(2)
in terms of short distance parts \( C_{QQ(n)}^{ij} \), describing the partonic process to obtain a \( Q\bar{Q} \) pair in a state \([n]\) and long distance coefficients \( <\mathcal{O}_n^H> \) which describe the hadronization of this state into a physical particle \( H \). The short distance parts can be calculated in series of \( \alpha_s(2m_Q) \). However, the long distance ones are non-perturbative quantities, so they are not exactly calculable at present. They can be taken as parameters to be fixed by experimental data or lattice calculations. The matrix elements for the production of charmonium and bottomium states were computed in [21]-[22].

One of the quantum numbers which describe the state \([n]\) is the color of the \( c\bar{c} \) pair. Then, in this approach, contributions coming from different color states of the pre-resonant \( c\bar{c} \) pair are separately taken into account.

An alternative model for quarkonia production is the CEM [13, 14]. In this model it is assumed that the different quarkonia states come from the \( Q\bar{Q} \) pairs created below the threshold for open charm production (i.e. \( \hat{s} \equiv x_1x_2s = 4m_D^2 \)). In this case the cross section for the production of a given particle \( H \) is assumed to be a constant fraction \( F_H^p \) of the hidden cross section \( \tilde{\sigma}_{QQ} \) defined as: [13]

\[
\tilde{\sigma}_{QQ}(\hat{s}) = \int_{4m_D^2}^{4m_Q^2} d\hat{s} \int dx_1 dx_2 f_i^P(x_1)f_j^{T}(x_2)\hat{\sigma}(\hat{s})\delta(\hat{s} - x_1x_2s), \tag{3}
\]

so that

\[
\sigma_{pN \rightarrow H}(s) = F_H^p \tilde{\sigma}_{QQ}(s), \tag{4}
\]

being \( F_H^p \) the parameter for each particle \( H \). This parameter is free and independent of the process. \( \hat{\sigma}(\hat{s}) \) in equation (3) is the partonic cross section to produce a pair \( c\bar{c} \) with and invariant mass \( \hat{s} \) calculated in pQCD [23].

For \( J/\Psi \) production, contributions coming from the different decays must be taken into account. At fixed target energies the main contributions are the decays of the various \( \chi_{cJ} \) states and that of the \( \Psi' \). Other contributions, like the decay of \( B \) states are negligible [20]. Thus,

\[
\sigma_{J/\Psi} = \sigma_{J/\Psi}^{dir} + B(\Psi' \rightarrow J/\Psi)\sigma_{\Psi'} + \sum_{J=0,1,2} B(\chi_{cJ} \rightarrow J/\Psi)\sigma_{\chi_{cJ}}, \tag{5}
\]

being \( \sigma_{J/\Psi}^{dir} \) the direct \( J/\Psi \) production, i.e. not coming from decays, and \( B(H \rightarrow J/\Psi) \) the branching ratios for particle \( H \) to decay into a \( J/\Psi \). Experimentally it is found that the direct \( J/\Psi \) contribution is about 60% of the total \( J/\Psi \) cross section, \( \Psi' \) decay is less than 10% and all \( \chi_{cJ} \) contribute with more than 30%.

Decays into \( \Psi' \) are not important, and then \( \Psi' \) production is dominated by direct production.

In CEM it is not necessary to make this distinction, because the decays are implicitly taken into account in the parameters \( F_H^p \). The FA on the contrary offers the possibility
to study these different contributions in a separate way, calculations in [20]-[22] give an accurate description of these ratios.

Another important point is the contribution of the different color states to the production of these particles, i.e. the color content of the pre-resonant state. In fact, the FA gives that direct $J/\Psi$ production is almost completely produced in color octet state, $\Psi'$ is also predominantly (about 90% or more) produced in color octet, and the main contribution of the $\chi_{cJ}$ states to $J/\Psi$ are given by color singlet matrix elements. Then, a separate study of the EMC effect in different particles and color states is possible in this approach. As we will see, the color octet and color singlet contributions to the production of charmonium have different suppression by EMC effect.

To introduce nuclear corrections by the EMC effect, we use the results of [24]. In this reference a parametrization of experimental data for the ratio

$$R_i^A(x, Q^2) = \frac{f_i^A(x, Q^2)}{Af_i^N(x, Q^2)}$$

is evolved by means of DGLAP equations. For this parametrization only DIS and DY experimental data has been taken into account. In this formula, $A$ is the atomic number, $f_i^A(x, Q^2)$ is the i-parton distribution function for nucleons inside nucleus $A$ and $f_i^N(x, Q^2)$ is the corresponding one in a free nucleon. Thus, the structure functions of equation (1) must be substituted by the corresponding ones for nucleons inside nuclei: $Af_i^N(x, Q^2)R_i^A(x, Q^2)$.

These ratios have a shadowing region for $x \lesssim 0.1$, in which the parton distribution function inside nucleus is depleted ($R_i^A < 1$) in comparison with that of free nucleon, an antishadowing region for $0.1 \lesssim x \lesssim 0.3$ in which this ratio is bigger than 1, a second shadowing region for large $x$ and a second antishadowing region (usually atributed to Fermi Motion of nucleons) for $x \gtrsim 0.85$.

3 NUMERICAL CALCULATIONS

The cross sections in the FA have been calculated using CTEQ-LO [25] parton distribution functions, $m_c = 1.5$ GeV and $\mu = 2m_Q$, i.e. the same parameters as in [20] in order to use the same values for the matrix elements $< O_n^H >$ fitted by them. In the case of CEM we use GRV-HO [26] parton distribution functions and the same values for the $c$ quark mass and renormalization scale.

The results are presented in the usual parametrization

$$\sigma^{pA(AA)} = A^\alpha \sigma^{pp}.$$  

\(^2\)It is worth noting that this common parameter $\alpha$ is in fact dependent on $A$ and then, although useful, it must be taken with caution.
It is clear that CEM will give the same results for all the different charmonium states, because the factors $F_{HP}$ are canceled when the ratio is done. It is not so in the case of FA, where every particle has different contributions coming from the different matrix elements and in the case of $J/\Psi$ also from the decays of the other charmonium states.

In Fig.1 it is shown the $\alpha$ parameters for the production of total $J/\Psi$, direct $J/\Psi$, $\Psi'$ and the contribution of the various $\chi_{CJ}$ states to the $J/\Psi$ in proton-gold collisions. Different color contributions are presented in separate curves, being each curve the result of \( \frac{\sigma_{singlet}^{pA}}{\sigma_{singlet}^{pp}} \), \( \frac{\sigma_{octet}^{pA}}{\sigma_{octet}^{pp}} \) and \( \frac{\sigma_{total}^{pA}}{\sigma_{total}^{pp}} \). We can see here the general features of the nuclear effects in charmonium production. First of all, the results for the CEM and for the FA are not so different, and difference is much smaller than the absorption produced by other mechanisms, like nuclear absorption of pre-resonant states by nuclear matter or co-movers. Second, shadowing corrections are more important at higher energies, as it is expected, because predominant contribution to the cross sections comes from partons in the target with $x_2 \simeq M^2/s$, so as energy raises, we are going to lower and lower values of $x$, the region of larger shadowing. Finally, color singlet states are less shadowed than color octet ones (color singlet curves are always above color octet ones). Moreover, more than 90% of direct $J/\Psi$ is produced in color octet, while, when different charmonium decays into this particle are taken into account, this ratio is less than 70%. This gives direct $J/\Psi$ production more suppressed than total one. In Fig.2 we present our results for gold on gold collisions. The same general trends as in proton-gold are present in this case. We can observe that effects now are comparatively less important than in the proton-gold case.

We have also calculated the $x_F$ dependence of nuclear effects for these processes. Figs. 3 and 4 are the $\alpha$’s for proton-gold and gold-gold collisions for $\sqrt{s} = 39 GeV$. We find that shadowing corrections are much more important as $x_F$ is getting larger, as expected (see above). This fact is found experimentally. Direct comparison of our results with experimental data is not possible because rescattering of produced pre-resonances is the main contribution to absorption. However, we are allowed to compare how much of the experimentally found bigger absorption at large $x_F$ is due to shadowing in the structure functions. To do this, we consider rescattering corrections to be independent on $x_F$. If both effects are taking into account in separate exponents

$$\sigma^{pA} = A^{\alpha(x_F)} A^{\beta-1} \sigma^{pp},$$

where $\alpha(x_F)$ are our results and $\beta$ is a new absorption parameter independent on $x_F$ and parametrizing other effects different from EMC, we can compare our results with experimental data by normalizing our curves in this way to one of the less shadowed experimental points. This has been done in Figure 5 where experimental points are from reference [27]. This normalization corresponds to $\sigma^{abs} \sim 6 mb$ in the probabilistic

\[3\text{In this reference different targets were used and a parametrization in the form \((7)\) is given taken}\]
formula for nuclear absorption, which is smaller than $\sigma_{abs} \sim 7\text{mb}$, used for instance in \cite{3} and \cite{10}. A different shape is found for large enough $x_F$ (not reached for $\Psi'$), being the experimental data more absorbed. Then EMC effect alone can not be responsible for this suppression, the additional depletion coming from other effects like an increase of rescattering absorption at large $x_F$, intrinsic charm, etc. The study of the EMC effect in charmonium production has been done previously in references \cite{28, 29, 30}. In this references, scaling in $x_2$ of the ratios $\sigma^{pA}/\sigma^{pp}$ is found for some energies. This scaling is ruled out in reference \cite{27}. In our approach this scaling violation should be due a different final state absorption depending on $x_F$ and $s$. Reference \cite{28} restrict their study to the $0 < x_F < 0.55$ region. In this sense, our results are in agreement with theirs. The main differences between the present work and the previous ones are the use of charmonium production cross section taken from hadron-hadron collisions and parametrization of EMC effect from DIS and DY experimental data. In particular, in \cite{29} the parametrization for the ratio (1) is much more shadowed than the one used by us for low $x$ and the $\sigma_{abs}$ used there to reproduce experimental data is quite small ($\sigma_{abs} = 2.6\text{ mb}$).

4 CONCLUSIONS

Effects of the modification of nucleon parton distribution functions inside nucleus on the production of different charmonium states have been studied. Energy as well as $x_F$ dependence of this effects have been calculated for proton-gold and gold-gold collisions. We have found a depletion on the ratio between the $pA(AA)$ to $pp$ cross sections for higher energies and larger $x_F$. This effect is, at present energies, much less important that the other absorption mechanisms of charmonium production, like pre-resonant absorption by rescattering with other nucleons in the nucleus or by co-movers. However, these processes superimpose to the production mechanism, so they are affected by the corrections due to EMC effect.

When FA is used, a separate study of the contributions of different color states and particle decays to the production mechanism is possible. Our result is that color octet states are more shadowed than color singlet ones, and that a slight difference is obtained for $J/\Psi$ production when decays of other charmonium states are taken into account.

We have also found a slightly different absorption for $J/\Psi$ and $\Psi'$ states, in the case of FA. This difference is not present in experimental data, being too small to be seen over the other absorption mechanisms. We can say then that nuclear corrections for $J/\Psi$ and $\Psi'$ production due to EMC effect are almost the same. In the CEM, as we have already said, they are exactly the same. We also obtain that CEM and FA give almost the same into account all the different nuclei. As we have said, this parameter is in fact A-dependent, then for comparison with our calculations only data for W target is used (we suppose that nuclear corrections to PDF in Au and in W are almost the same).
results in all our calculations.

Finally, we obtain a different shape for experimental and theoretical curves in $x_F$, being the suppression in experimental data bigger than that in our calculations for large $x_F$. Although our curves almost fit the experimental points (within errors) for the $x_F$ dependence of nuclear suppression, data seems to prefer a bigger absorption for large $x_F$. So we can conclude that modification of the nuclear parton distribution functions can account for the $x_F$ dependence of $J/\Psi$ suppression for moderate $x_F$ and that other mechanisms apart from EMC effect is needed at large $x_F$ in order to reproduce experimental data.

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Figure captions

**Fig.1.** Center of mass energy dependence of $\alpha$ for p-Au collisions. Different lines are: FA total contribution (solid), singlet contribution (dotted), octet contribution (dashed) and CEM (dotted-dashed).

**Fig.2.** Same as Fig.1 but for Au-Au collisions.

**Fig.3** $x_F$ dependence of $\alpha$ for $\sqrt{s} = 39$ GeV p-Au collisions with the same conventions for lines as in Fig.1.

**Fig.4.** Same as Fig.3 but for Au-Au collisions.

**Fig.5.** Comparison of $x_F$ dependence of nuclear corrections by EMC effect with experimental data of 800 GeV/c protons incident on tungsten target from reference [27]. Theoretical calculations have been normalized to one of the less shadowed experimental points (see text). Lines follow the same convention as Fig.1.
