GLUON SHADOWING AND CHARMONIUM/BOTTONIUM PRODUCTION ON NUCLEAR TARGETS

Sourendu Gupta and Helmut Satz*

Theory Division, CERN, CH-1211, Geneva 23, Switzerland.

ABSTRACT

We examine the suppression of J/ψ , ψ' and Υ production on nuclear targets, as observed for proton and pion beams of energies from 200 to 800 GeV. We find that this suppression leads to a universal scaling curve, which indicates that it is due to nuclear modifications of the gluon density ("shadowing"). A parametrisation of the nuclear effect on the gluon density is extracted from the data and used to obtain quantitative estimates for corresponding effects in high-energy heavy-ion collisions.

* On leave from the University of Bielefeld, Germany.

The production of heavy-flavour vector mesons (charmonium and bottonium) on nuclear targets is found to increase less than linearly [1–3] with nuclear mass number A . Hence the ratio of the normalised hadroproduction cross sections on nuclear targets, compared with that on protons, $\sigma_{hA}/A\sigma_{hp}$, is less than unity. This “suppression” has attracted much attention and led to a variety of models describing its different features [4]. We show here that the suppression is a manifestation of gluon shadowing in nuclei [5].

Data taken over the last two decades up to Tevatron energies strongly indicate that the production of heavy-flavour resonances in hadron-hadron collisions can be described through perturbative QCD. An immediate question that arises is whether hadron-nucleus collisions can be treated in a similar manner, and what nuclear effects this leads to. A first attempt to answer this was made in [6]. The advent of new data at higher energies [2,3] now makes it possible to undertake a more extensive investigation, which we shall do in this letter.

A description of heavy-flavour resonance production in QCD involves three sets of inputs— the distribution of quarks and gluons in the initial hadrons or nuclei, the cross section for these to produce heavy-flavour quarks, and a model for the binding of the produced quarks and antiquarks to charmonium or bottonium states. Denoting these three elements symbolically by F , $d\hat{\sigma}$ and H , respectively, the hadroproduction cross section is given by the convolution

$$d\sigma(s, M, x_F) = \left(\sum_{ij} F_i(x_1) F_j(x_2) d\hat{\sigma}_{ij} \right) H(Q) d\Gamma(Q). \quad (1)$$

Here the variables x_1 and x_2 denote the fractional momenta carried by partons from the beam and the target, respectively. The heavy flavour pair has 4-momentum Q , which we take also to be the momentum of the observed state, since the resonance is produced by a soft process. The Lorentz invariant phase space volume is denoted by $d\Gamma$; $\sqrt{s}$ is the CMS energy of the colliding hadrons, M the mass of the resonance and x_F its scaled longitudinal momentum.

We now consider $d\hat{\sigma}$ expanded in powers of the renormalised coupling α_s and retain only terms in the lowest order (α_s^2). Then we can use the kinematical identities (with $Q_T = 0$)

$$x_1 = \frac{1}{2} \left(\sqrt{4\tau + x_F^2} + x_F \right), \quad x_2 = \frac{1}{2} \left(\sqrt{4\tau + x_F^2} - x_F \right), \quad \tau = M^2/s. \quad (2)$$

To this order, the sum over parton species ij in Eq. (1) includes only the combinations where both are gluons (gluon fusion) or both are light quark-antiquark pairs of the same flavour (annihilation).

The subprocess cross sections $d\hat{\sigma}$ contain no nuclear effects. We know that the quark distributions do [7] and suspect this of the gluon distributions as well. To study such nuclear modifications of the gluon structure functions, we make the assumption that there is no nuclear effect on the resonance binding H . It is not *a priori* clear to what extent this assumption is correct; in general, it is probably not tenable. Present data, however, are taken in an x_F range in which the formation of the resonance occurs well outside the target nucleus [8]. In this case, the assumption thus seems not unreasonable; let us see what predictions it leads to. The ratio of cross sections (e.g., for J/ψ production) in collisions of a hadron (h) of fixed energy with a nucleus (A) and with a proton (p) is given by

$$R_{A/p}(\tau, x_F) = \frac{\sum F_i^h(x_1) F_j^A(x_2) d\hat{\sigma}_{ij}}{\sum F_i^h(x_1) F_j^p(x_2) d\hat{\sigma}_{ij}}. \quad (3)$$

The notation implies the ratio of cross sections differential in x_F . We note that $R_{A/p}$ depends only on two dimensionless variables (τ and x_F , or, equivalently, x_1 and x_2), i.e., it scales. In view of the dominance of gluon fusion, to be shown later, we shall henceforth neglect the difference between proton and deuterium targets in the denominator.

We shall now first give our analysis in qualitative form, and then return to specific points in more detail. Over the range of $\sqrt{\tau}$ and x_F that we analyse, the cross section in Eq. (1) is strongly dominated by gluon fusion, whether we consider proton, pion or antiproton beams; shortly, we shall show that corrections amount to less than 10%. Hence we obtain the relation

$$R_{A/p}(\tau, x_F) = R_{A/p}(x_2) = \frac{g_A(x_2)}{g_p(x_2)}, \quad (4)$$

so that the measured ratio of resonance cross sections is the ratio of the gluon structure functions. Thus, in the region of phase space where the production process is dominated by gluon fusion, $R_{A/p}$ is expected to be a function of x_2 only. If it varies with x_2 in the same way as the ratio of quark structure functions does (see Fig. 1), then we can immediately predict the following pattern of behaviour:

- 1) At $x_F = 0$ (i.e., with $x_2 = \sqrt{\tau}$), an increase of $\sqrt{s}$ beyond about 20 GeV moves us deeper into the shadowing region; hence the production of J/ψ and ψ' will become more suppressed.
- 2) Up to $\sqrt{s} \approx 100$ GeV, Υ production will not change much with increasing $\sqrt{s}$. Beyond this energy, the Υ also enters the shadowing region, and hence its production will decrease.
- 3) For a given resonance, a parametrisation of the A -dependence in the form $R_{A/p} \sim A^{\alpha-1}$ will thus necessarily lead to an α which varies with $\sqrt{s}$.

- 4) For J/ψ and ψ' production at fixed $\sqrt{s} \geq 20$ GeV, x_2 already lies in the shadowing region for $x_F = 0$ and decreases with increasing x_F ; hence the corresponding ratios must also decrease with x_F . As x_F becomes negative, J/ψ and ψ' production will increase, since we move out of the shadowing region.
- 5) The suppression of J/ψ and ψ' must be nearly equal, with only a slight x_2 shift due the difference in masses.

Note that in particular the behaviour obtained in the last two predictions is often referred to as a “puzzle” in the literature.

We now proceed in three steps. We first show that gluon fusion is indeed the dominant term, not only for pA , but also for πA collisions. Next, we note that the J/ψ data for $R_{A/p}$ from the NA3 experiment [1] scale when the beam energy exceeds 200 GeV, and we show that the data from the E772 experiment for J/ψ , ψ' [2] and Υ [3] fall on this scaling curve. The same is true, within rather large errors, for recent NMC data for J/ψ production in deep inelastic muon scattering on nuclei [9]. Finally, we combine all available data to obtain a parametrisation of the ratio (Eq. (3)) of gluon structure functions in nuclei and in protons. This is then used to determine quantitatively the role of structure-function effects in nucleus-nucleus collisions.

Gluon dominance is easy to demonstrate when x_F is zero. Then the two combinations of densities

$$\begin{aligned} F_{qq} &= \sum_{f=u,d,s} f_h(x_1) \bar{f}_p(x_2) + \bar{f}_h(x_1) f_p(x_2), \\ F_{gg} &= g_h(x_1) g_p(x_2), \end{aligned} \tag{5}$$

must be examined at $x_1 = x_2 = \sqrt{\tau}$. We use the parametrisation of [10] for the densities in a proton and the measurements of [11] for the densities in a pion. The resulting ratio F_{qq}/F_{gg} is shown in Fig. 2a. It is clear that the “luminosity” for the gluon-gluon process is strongly dominant already at rather small energies. Thus an effective gluon dominance could break down only if the subprocess cross sections [12] $d\hat{\sigma}_{q\bar{q}}$ would be much larger than $d\hat{\sigma}_{gg}$. This is not the case, since the diagram for the s-channel $q\bar{q}$ annihilation as well as the t-channel gluon fusion diagram are regularised by the heavy quark mass. As a result, the subprocess cross sections differ only by colour factors. For $x_F \leq 0.4$ the behaviour is similar, as shown in Fig. 2b; however, for larger x_F gluon fusion is no longer dominant.

High statistics data on J/ψ production was first obtained in the NA3 experiment at CERN [1], with pion beams at 150, 200 and 280 GeV and proton beams at 200 GeV, incident on hydrogen and platinum targets. Since then, the E772 experiment at Fermilab has provided further high-precision data. They use proton beams at an energy of 800 GeV incident on carbon, calcium, iron, and tungsten targets, and study nuclear

effects in J/ψ , ψ' [2] and Υ [3] production. Both experiments cover a considerable range in x_F . At very large x_F , however, diffractive production begins to dominate [1], and the cross section cannot be described by the form of Eq. (1). To eliminate the diffractive component, we thus restrict our considerations to the range $0 < x_F < 0.55$ in both NA3 and E772.

Let us first consider the pion beam data. It is found to scale for beam energies of 200 and 280 GeV: all points from the two sets of data for different x_F fall on one curve. The lowest energy data (150 GeV), however, have not quite reached this scaling curve [13]. We therefore restrict our considerations to energies of 200 GeV or more. Since the nuclear masses for tungsten and platinum are not too different, we can compare the ratios obtained in the two experiments as functions of x_2 for proton beams of 200 and 800 GeV, pion beams of 200 and 280 GeV, and for J/ψ , ψ' and Υ production. The result is shown in Fig. 3; all the different sets of data fall on one curve.

The nuclear dependence of J/ψ production has recently also been studied by the NMC collaboration at CERN [9] in deep inelastic scattering with muons of energies 200 and 280 GeV. They obtain the ratio of gluon distributions for carbon and tin targets,

$$R_{sn/c} = \frac{g_{sn}(x_2)}{g_c(x_2)}. \quad (6)$$

In Fig. 4 we show this ratio together with the ratios $R_{Fe/c}$ for J/ψ , ψ' and Υ production; iron is the heaviest intermediate target that can be reconstructed from the E772 data. The two sets of data are quite consistent. The comparison could be improved by extending the phase-space coverage of the deep inelastic scattering data towards smaller x_2 , and by a similar extension to measurements at negative x_F for J/ψ and ψ' or larger positive x_F for Υ . The importance of improving statistics is also evident from the data.

Let us now consider how the pattern seen in Fig. 3 changes with A . Since the effect decreases with decreasing A , we show in Fig. 5 the data on iron as the next heaviest target. The decrease with x_2 is now indeed weaker, but the qualitative pattern is similar to that of Fig. 3, i.e., there is a linear rise in $\ln x_2$. From the quark density behaviour (see Fig. 1), we expect a linear rise of $R_{A/p}(x_2)$ in $\ln A$ and in $\ln x_2$. Hence we can parametrise the data for $R_{A/p}$ in the form

$$R_{A/p}(x_2) = 1 + a \ln x_2 \ln A. \quad (7)$$

Fitting all the available data, with the cuts mentioned earlier, we get

$$a = 0.021 \pm 0.001 \quad \text{with} \quad \chi^2/\text{d.o.f} = 1.6. \quad (8)$$

Note that when a is small, we can consider Eq. (7) as the first terms of the Taylor expansion of

$$R_{A/p} = A^{(a \ln x_2 - 1)}, \quad (9)$$

with the relation

$$\alpha_{\text{eff}}(\sqrt{s}, x_F) = 1 + a \ln \left[\frac{1}{2}(\sqrt{4\tau + x_F^2} - x_F) \right], \quad (10)$$

which for $x_F = 0$ gives $\alpha_{\text{eff}} \sim \ln(\sqrt{s})$. In Table 1 we show the resulting α_{eff} obtained from Eq. (10) for average values $\bar{x}_F$; they are in good agreement with the NA3 and E772 data.

From this we see that the usual A^α fits, with one constant α , become meaningless for data at different energies and x_F . In particular, we note that the increase of the suppression with increasing $\sqrt{s}$ will provide in p - A collisions at RHIC energies ($\sqrt{s} = 200$ GeV) as much suppression for the Υ as seen for the J/ψ in the E772 experiment.

We thus conclude: the non-diffractive nuclear effects observed so far in charmonium and bottonium production by hadron-nucleus as well as by deep inelastic muon-nucleus scattering appear to be due to a modification of the gluon density profile in nuclei, with respect to that in nucleons. This provides very naturally an increase in suppression with increasing x_F as well as nearly equal suppression for J/ψ and ψ' . In contrast to descriptions invoking either absorption inside the nucleus or comover interactions, our picture is thus fully in accord with the idea of colour transparency, since the initial-state partons and not the final state $c\bar{c}/b\bar{b}$ pairs are affected by the nuclear medium.

However, the very consistency of our results provides a means of determining other effects. If measurements are made for values of x_F lying in the target fragmentation region, so that the resonance is fully formed inside the target, then the resonance could be broken up through interactions with nucleons. A breakdown of scaling in x_2 would thus signal the onset of absorption*. One direct test of this would be to look for differences in the suppression of J/ψ and ψ' at the same x_F and $\sqrt{s}$. Another test would be to compare J/ψ suppression in the backward x_F region with Υ suppression in the forward region, both at the same value of x_2 . For example, in the E772 experiment, if J/ψ suppression for $x_F \leq -0.2$ is found to be different from Υ suppression at the present $\bar{x}_F = 0.2$, then this would imply a new mechanism, such as absorption.

Absorption will, however, make it difficult for us to test if gluon densities contain the equivalent of the EMC effect, *i.e.*, a decrease with x_2 in the region above $x_2 \simeq 0.2$ – 0.3 . Consider the E772 experiment: $c\bar{c}$ pairs formed in the centre of the nucleus with $x_F = -0.2$ and vanishing transverse momentum will reach J/ψ size just at the surface of a lead nucleus. For $x_F = -0.2$, however, we have $x_2 = 0.23$; as seen from figures 1 and 5, this is not yet in the EMC region. If at all, this region can be reached only with the Υ or in high Q_T studies of charmonium production.

* Such a breakdown has also been used to argue in favour of intrinsic charm [4] or higher twist effects [13].

We have considered here nuclear modifications of the parton density for the case of gluons, and the resulting effect on charmonium/bottonium production. The corresponding modification of the quark density in nuclei should lead to observable effects in Drell-Yan dilepton production [14]. Since the ratio of the quark structure functions is not much different from unity in most of the x_2 region accessible in present experiments, little or no A dependence should be observed. For sufficiently large x_F in E772, however, we do get into the shadowing region, and here there are indeed signs for a suppression [15].

We now want to extend our considerations to high-energy heavy-ion experiments. What effect should be expected for the ^{32}S - ^{238}U interactions presently being studied by the NA38 collaboration at CERN [16]? Comparing J/ψ production in S - U collisions to that in p - p collisions, we get

$$R_{(SU)/(pp)} = \frac{g_S(x_1)g_U(x_2)}{g_p(x_1)g_p(x_2)} = R_{S/p}(x_1)R_{U/p}(x_2) \quad (11)$$

for the relative suppression of the rate in nuclear collisions, if gluon shadowing is the only suppression mechanism. In the NA38 experiment we have $\sqrt{s} = 20$ GeV and an average x_F close to zero; because of the latter, we can approximately set $x_1 = x_2 = \sqrt{\tau}$. For the J/ψ , we are then in the region of applicability of Eq.(7); this gives us

$$R_{(SU)/(pp)} \simeq 0.86 \times 0.79 \simeq 0.68. \quad (12)$$

Shadowing thus reduces the J/ψ production in SU collisions at $\sqrt{s} = 20$ GeV by about 30%, in comparison to pp collisions. Comparing the J/ψ cross section values of NA38 [17] with those measured by NA3 [1], we get $R_{(SU)/(pp)} = 0.58 \pm 0.12$. Although the measured suppression is larger than that expected from shadowing alone, it is, within errors, compatible with Eq.(12).

Since the NA3 data are taken at a somewhat different average x_F , it is desirable that this conclusion be confirmed within the same experiment. This is possible by looking at the relative suppression in S - U and p - U collisions, both measured in the same set-up of NA38. Shadowing here leads to

$$R_{(SU)/(pU)} = \frac{g_S(x_1)}{g_p(x_1)} = R_{S/p}(x_1) \simeq 0.86, \quad (13)$$

taking again $\bar{x}_F \simeq 0$. From the NA38 data [17] we get, for the ratio of the S - U rate to that in p - p interactions, integrated over the transverse energy E_T , the value $R_{(SU)/(pU)} = 0.73 \pm 0.21$. Again, the experimental value is lower, but, within errors, compatible with the prediction from shadowing.

On the other hand, nucleus-nucleus interactions lead to an increase of J/ψ suppression with increasing transverse hadron energy E_T , up to a value corresponding to $R_{(SU)/(pU)} = 0.5 \pm 0.1$ for the highest E_T bin in $S-U$ collisions [16]. A suppression of this magnitude and E_T dependence cannot be explained in terms of a nuclear gluon-density modification. Shadowing is an initial-state effect on the partons within a given nucleus, whereas the E_T dependence is due to the collision geometry and final state interactions. Note, however, that in any quantitative study of the mechanism responsible for the E_T dependence, the different degree of shadowing in $p-U$ and $S-U$ collisions has to be taken into account. An E_T dependence of shadowing could be obtained by introducing parton density modifications which depend on the position within a nucleus [18]. So far, however, there seems to be little justification for such an assumption, once we are away from the “edge” of the nucleus.

Our results thus raise serious doubts on the validity of any comparison of the overall suppression in present $p-A$ and nucleus-nucleus data [4]. A space-time analysis [8] has already shown that the formation of the J/ψ occurs within the stopped “debris” of beam and target participant nucleons, making absorption in hadronic matter possible here. In contrast, as already noted, the J/ψ is formed far out of the target in $p-A$ collisions, so that it does not have much hadronic environment for absorption. In accord with this, we find now that the whole nuclear suppression effect in $p-A$ and $\mu-A$ collisions can be understood as initial-state phenomena. Moreover, the observed transverse momentum broadening of charmonium and bottonium production on nuclear targets has been shown to be in accord with initial state parton scattering [19]. We thus conclude that *all* non-diffractive nuclear modifications at present observed in $p-A$ collisions can be understood as initial-state effects.

REFERENCES

- 1) J. Badier *et al.*, *Z. Phys.* C20 (1983) 101.
- 2) D. M. Alde *et al.*, *Phys. Rev. Lett.* 66 (1991) 133.
- 3) D. M. Alde *et al.*, *Phys. Rev. Lett.* 66 (1991) 2285.
- 4) See e.g., S. Brodsky, P. Hoyer and R. Vogt, *Nucl. Phys.* B360 (1991) 97,
and further literature cited there.
- 5) See e.g., A. H. Mueller and Jianwei Qiu, *Nucl. Phys.* B268 (1986) 427;
P. Castorina and A. Donnachie, *Z. Phys.* C45 (1989) 141;
N. N. Nikolaev and V. I. Zakharov, *Z. Phys.* C49 (1991) 607,
and further references cited there.
- 6) R. V. Gavai and S. Gupta, *Phys. Lett.* B216 (1989) 239;
R. V. Gavai, S. Gupta and K. Sridhar, *Phys. Lett.* B227 (1989) 161;
R. V. Gavai and S. Gupta, *Z. Phys.* C49 (1991) 663.
- 7) J. J. Aubert *et al.*, *Phys. Lett.* B123 (1983) 275;
A. C. Benvenuti *et al.*, *Phys. Lett.* B189 (1987) 483;
P. Amaudruz *et al.*, *Z. Phys.* C51 (1991) 387.
- 8) R. Vogt, "Charming Aspects of Heavy-Ion Collisions", Darmstadt Preprint GSI-
91-68, December 1991.
- 9) P. Amaudruz *et al.*, preprint CERN-PPE/91-198.
- 10) M. Diemoz *et al.*, *Z. Phys.* C39 (1988) 21.
- 11) J. Badier *et al.*, *Z. Phys.* C18 (1983) 281.
- 12) B. L. Combridge, *Nucl. Phys.* B151 (1979) 429.
- 13) P. Hoyer, M. Vanttinen and U. Sukhatme, *Phys. Lett.* B246 (1990) 217.
- 14) H. Satz, in *Proceedings of Quark Matter '84*, K. Kajantie (Ed.), Springer Lecture
Notes in Physics 221 (1985) 278.
- 15) D. M. Alde *et al.*, *Phys. Rev. Lett.* 64 (1991) 2479.
- 16) C. Baglin *et al.*, *Phys. Lett.* B220 (1989) 471; *Phys. Lett.* B251 (1990) 465; *Phys.*
Lett. B251 (1990) 472; *Phys. Lett.* B255 (1991) 459; and *Phys. Lett.* B262 (1991)
362.
- 17) C. Baglin *et al.*, *Phys. Lett.* B270 (1991) 105.
- 18) S. Kumano and F. Close, "Dependence of the EMC-effect on Nuclear Structure",
preprint IU/NTC-89-21, 1989.
- 19) C. Baglin *et al.*, *Phys. Lett.* B268 (1991) 453.

TABLE 1

A parametrisation of the A -dependence of gluon densities in the shadowing region. Shown are the values of α_{eff} for $J/\psi, \psi'$ and Υ production; at $\sqrt{s} = 20$ GeV, we have used $\bar{x}_F = 0.3$ for J/ψ and ψ' , while at $\sqrt{s} = 40$ GeV we have used $\bar{x}_F = 0.2$ for Υ and 0.27 for J/ψ and ψ' .

	$\sqrt{s} = 20$ GeV		$\sqrt{s} = 40$ GeV	
	prediction	experiment	prediction	experiment
J/ψ	0.943 ± 0.003	0.94 ± 0.03 (pA) 0.96 ± 0.01 (πA)	0.919 ± 0.004	0.920 ± 0.008
ψ'	0.947 ± 0.003		0.923 ± 0.004	0.920 ± 0.008
Υ			0.961 ± 0.002	0.962 ± 0.008

FIGURE CAPTIONS

- Fig. 1: a) The nuclear dependence of quark structure functions in deep inelastic lepton scattering on calcium and deuterium targets [7].
b) The A -dependence of the ratio of quark structure functions on targets of mass A compared to deuterium, at two fixed values of x_2 [7].
- Fig. 2: The ratio of $q\bar{q}$ and gg structure function factors (Eq. (5)) relevant to charmonium and bottomium production, shown as a function of $\sqrt{\tau}$ for (a) $x_F = 0$ and (b) $x_F = 0.5$.
- Fig. 3: Pion (200 and 280 GeV) and proton (200 and 800 GeV) beam data for the ratio of $J/\psi, \psi'$ and Υ production on platinum (NA3) and tungsten (E772) targets to that on hydrogen/deuterium.
- Fig. 4: Data from deep inelastic muon scattering on tin and carbon, with 200 and 280 GeV muon beams [9], compared to the ratio iron to carbon with 800 GeV proton beams [2,3].
- Fig. 5: Data for J/ψ and Υ production on iron and deuterium, with proton beams of 800 GeV [2,3].

Fig. 1a

Fig. 1b

Fig. 2a

Fig. 2b

Fig. 3

Fig. 4

Fig. 5