Sizing up the Nuclear Glue in 
$J/\psi$-production

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Nuclear gluon densities are of great importance to the physics of relativistic heavy ion collisions, in particular, in assessing the origin of $J/\psi$-suppression. We describe our attempts to distinguish various models of the gluonic EMC-effect, using the existing $J/\psi$-production data in proton-nucleus collisions. We find that no model is capable of explaining all the features of the high precision E772 data although the overall trend suggests this to be more a matter of fine-tuning the models than the presence of new physical effects.

Talk presented at
‘Quark Matter ’93’, Borlänge, Sweden
June 20-24, 1993

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1. INTRODUCTION

Theoretical investigations of several aspects of the heavy-ion collisions at high energies depend crucially on the precise knowledge of the gluon distributions of the colliding nuclei. A well-known prime example is the $J/\psi$-suppression signal\cite{1,2} of quark-gluon plasma (QGP). It has been shown\cite{3,4} that this signal and its transverse momentum dependence can be mimicked by the nuclear structure function effects. The nuclear glue can thus be a potentially serious source of background which has to be subtracted off to see QGP. Another important reason to size up the nuclear glue is the EMC-effect observed in the ratio of quark structure functions, $\rho = F_2^A(x)/AF_2(x)$. There are a variety of diverse theoretical ideas which “explain” the data on $\rho$. Since most of these result in a prediction for the corresponding gluon ratio, $\rho_g$, any attempt to obtain experimental information on $\rho_g$ is likely to assist in distinguishing between the various models and in pinning down the likely cause of this effect.

Extraction of gluon densities from the data is known to be a difficult exercise although there are various known methods such as the direct photon production or the $J/\psi$-production. The problem is that in most cases the quark distributions also contribute and one has to invent clever tricks or resort to some approximations to separate the gluon densities. Recently, Drees and Kim advocated\cite{5} the study of associated production of $J/\psi$ and a photon at large $p_T$ as a clean probe of the gluon density in $pp$ and $ep$ collisions. We extended\cite{6} their considerations to $pA$ and $AA$ collisions for the fixed target experiments at FNAL and the collider experiments at RHIC. We found that the rates for these processes at both FNAL and RHIC are substantial and a large range of $x$ is covered by combining them, thus enabling a cleaner and better determination of $\rho_g$. For more details, including a technique to improve the statistics, we refer the reader to Ref.\cite{6}.

2. $J/\psi$-PRODUCTION

While the associated production of $J/\psi$ and photon at large $p_T$ could serve as a good probe of $\rho_g$ in future, one naturally asks the question whether the existing data can in some way be used for this purpose. In particular, the recent high statistics $J/\psi$ and $\Upsilon$-production data from the E772 experiment\cite{7}, combined with the older data\cite{8} have been exploited by Gupta and Satz\cite{9} to obtain $\rho_g$. We argue that their assumptions are not valid and one therefore needs to take a less ambitious approach of checking whether the data can be explained by the existing models for $\rho_g$. Before we do so, let us recall briefly the theoretical formalism.

2.1. Theoretical Models

The basic perturbative QCD-subprocesses which contribute to the production of $J/\psi$ are

$$gg \rightarrow c\bar{c}; \quad q\bar{q} \rightarrow c\bar{c} \quad \text{and} \quad gg \rightarrow c\bar{c}g; \quad q\bar{q} \rightarrow c\bar{c}g; \quad qg \rightarrow c\bar{c}q; \quad \bar{q}g \rightarrow c\bar{c}q$$

(1)

The first two of these contribute at $O(\alpha_s^2)$ while the rest do so at $O(\alpha_s^3)$. Furthermore, since the $c\bar{c}$ pair will hadronize to $J/\psi$, it is also clear that the former will result in $J/\psi$ at low ($\sim 0$) $p_T$ while the latter will yield large $p_T$ for $J/\psi$. Two popular\cite{10} models for
hadronization of the $c\bar{c}$ pair to $J/\psi$ are 1) semilocal duality and 2) colour singlet model. The former simply consists of computing the $c\bar{c}$ pair cross section with the appropriate perturbative QCD cross sections and the chosen quark and gluon densities and multiplying them by a constant if the pair mass lies in the range between $M_{J/\psi}$ and $M_D$. Hadronization in the latter model, on the other hand, is governed by the quarkonium wavefunction (or its derivative) at the origin. An interesting feature to note is that the charmonium is produced at the basic QCD vertex in this model and the kinematics is very different. Thus, e.g., the $J/\psi$ at large $p_T$ is produced in a basic $2 \rightarrow 2$ process in contrast to the semilocal duality model above.

2.2. Results

In order to extract $\rho_g$, Ref. [9] assumed that the data can be described by $O(\alpha_s^2)$ partonic cross section and by further assuming that gluons dominate. Since the $p_T$-range of E772 goes up to 2.25 GeV, the first assumption implies rather high values for primordial $p_T$: $\langle p_T \rangle \sim 1-2$ GeV. Furthermore, as Fig. 1 shows, the assumption of gluon dominance is both $x_F$-dependent and structure function parametrization-dependent. What is plotted in the figure is the ratio of the product of quark structure functions to that of gluon structure functions which act respectively as the weights of the quark-antiquark and gluon-gluon terms in $pp$ collisions at $\tau = M_{J/\psi}/\sqrt{s} = 0.0775$. The various curves are for different popular parametrizations of the structure functions. The corresponding curves for $\Upsilon$ cast even more doubt on the validity of gluon dominance.

We therefore used the $O(\alpha_s^3)$ partonic subprocesses to compute the $p_T$-distribution of $J/\psi$ and $\Upsilon$ for the E772 acceptance for both the semilocal duality model and the colour singlet model. The details of our calculations can be found in Ref. [11]. Here we wish to make only some general comments. Since the E772 data is unfortunately not sufficiently differential, we had to extend our integration range over larger $x_F$ where our approach may be inadequate. Fortunately, the contribution from the large $x_F$ region is small and thus will not affect our conclusions. Since the $x_F$-spectrum of E772 also includes low $p_T$ data, we are unable to compute it at all in our approach. Figs. 2 and 3 exhibit our results along with the E772 data for their lightest and heaviest target for three different models of $\rho_g$. Again, more details about these models, including original references can be found in Ref. [11]. What is remarkable is that for Tungsten, none of the model agrees with the data, although for carbon, the so-called Gas model seems to perform well. For the other two targets of E772, situation is akin to that in Fig. 2.

Performing the same computation for the colour singlet model is computationally a lot easier since the final state is simpler. In order to highlight the independence of the above results on the hadronization models in a typical example, we display in Fig. 4 the ratio of the results for the two models discussed above as a function of $p_T$ for the Tungsten nucleus. The agreement is really remarkable, especially when one takes into account the differences in kinematics as well. We conclude from here that the data are really a reflection of the structure function effects alone, although the models of $\rho_g$ considered here need to be fine-tuned.

Essentially the same conclusion seems to emerge from our analysis of the E772 data on $\Upsilon$-production. Since only $\alpha(p_T)$ as a function of $p_T$ is available in this case, where $\alpha(p_T)$ is obtained by fitting the cross section at each value of $p_T$ for all nuclei to the form $A^\alpha$,
we followed the same E772 procedure and obtained $\alpha(p_T)$ in the range 1-4 GeV. As seen in Fig. 6, a very good agreement with the E772 data is obtained for both the Gas model and a 6-quark cluster model for $p_T$ up to 3 GeV. Surprisingly, the computations remain much flatter at even higher $p_T$ values whereas the data show a dramatic increase. Since the large $p_T$-domain is theoretically better suited for the description employed above, this discrepancy is even more striking and needs to be understood more carefully.

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Figure Captions

Figure 1. Test of gluon dominance as a function of $x_F$.

Figure 2. $R(p_T)$ vs. $p_T$: Carbon

Figure 3. $R(p_T)$ vs. $p_T$: Tungsten

Figure 4. Ratio of models: Tungsten

Figure 5. $\alpha(p_T)$ vs. $p_T$: $\Upsilon$
