GLUON DEPLETION AND $J/\psi$ SUPPRESSION IN $pA$ COLLISIONS

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The gluon distribution of a nucleon propagating through a nucleus can change depending on how far the penetration depth is. It is a nonperturbative process that we describe by an evolution equation. The kernel of the integral equation is to be determined by a phenomenological study of $J/\psi$ suppression in $pA$ collision, treated as a perturbative process. The data of E866 on $\alpha(x_F)$ shows significant dependence on $x_F$ at large $x_F$. It presents a feature that has not been explained by any dynamical model. We show that gluon depletion is a simple mechanism that can account for it. The result has far-reaching implications on the role of partons in nuclear collisions.

The conventional reason for studying $J/\psi$ suppression in heavy-ion collisions is that it might reveal evidences for the existence of quark-gluon plasma which enhances the deconfinement of the charmonium states. Thus the theoretical attention is usually focused on the effect of the medium on the $c\bar{c}$ states that are created by gluons. Most experimental work that reveal the suppression mechanism in nucleus-nucleus (AB) collisions have been done at CERN-SPS, where the measurement is limited to the central rapidity region. Indeed, impressive results have stimulated a great deal of excitement.

The emphases in this paper are unconventional. First, we consider $pA$ collisions for which we know that quark-gluon plasma is not likely to form. Second, we examine the $J/\psi$ at all positive $x_F$, not just around $x_F \approx 0$. Third, we focus on the possibility that the gluon distribution is significantly modified as the projectile traverses the target nucleus. Note that we use the word “projectile” instead of “proton” because what goes the nucleus can be so distorted from the incident proton that a realistic description of the “projectile” may well be just a flux of partons. Indeed, the significance of this work is in sowing the seeds of suspicion that the conventional notions of wounded nucleon and participating nucleons may be outmoded.

The stimulus for this line of investigation is the FNAL-E866 data on $J/\psi$ suppression in $pA$ collisions at large $x_F$. The cross section for $J/\psi$ production is found to depend on $A$ and $x_F$ as

$$\sigma_{pA\rightarrow J/\psi}(x_F) = \sigma_{pp\rightarrow J/\psi}(x_F)A^{\alpha(x_F)}.$$  \hspace{1cm} (1)

In Ref. 5 the values of $\alpha(x_F)$ are tabulated; moreover, a fit of $\alpha(x_F)$ by an
analytic formula is given:

\[ \alpha(x_F) = 0.96 \left( 1 - 0.0519 x_F - 0.338 x_F^2 \right). \]  

(2)

Evidently, there is a sizable amount of suppression at large \( x_F \). The issue is how this enhanced suppression can be understood theoretically.

The conventional approach, as stated in the beginning, is to study the effects of the medium on the produced \( c\bar{c} \) state. That has been carried out by at least three groups of investigators. The consensus is that if the \( c\bar{c} \) state is to break up quickly at high \( x_F \), the time involved is too short (\( \sim 0.02 \text{fm}/c \)) to be feasible in the usual nuclear medium. The conclusion is that there is no mechanism in hadronic absorption of the final state capable of explaining the \( x_F \) dependence. If we use \( H(A) \) to denote that hadronic absorption effect, it is reasonably safe at this stage to assume that it is insensitive to \( x_F \). The canonical description of \( H(A) \) is the exponential form:

\[ H(A) = \exp \left[ -\rho \sigma z(A) \right], \]  

(3)

where \( \rho \) is the average nuclear density, \( \sigma \) the absorption cross section, and \( z(A) \) is the average path length in \( A \) that the \( c\bar{c} \) state traverses.

If the final state dynamics cannot account for the \( x_F \) dependence, then the only alternative is in the initial state. The subprocess of \( g + g \to c + \bar{c} \) is cancelled in the ratio \( R = \sigma_{pA\to J/\psi}/A\sigma_{pp\to J/\psi} \). There are two types of effects on the initial state, both having to do with the gluon flux that leads to the subprocess \( g(x_1) + g(x_2) \to c\bar{c}(x_F) \). Here \( g(x_1) \) is the gluon with momentum fraction \( x_1 \) of the initial proton, \( g(x_2) \) is the gluon with momentum fraction \( x_2 \) of some nucleon in the target nucleus, and \( x_F = x_1 - x_2 \). The two effects are gluon depletion associated with \( g(x_1) \), and nuclear shadowing associated with \( g(x_2) \). Denoting the two by \( G(x_1, A) \) and \( N(x_2, A) \), respectively, we can write the ratio \( R \), defined earlier, by

\[ R(x_F, A) = G(x_1(x_F), A) N(x_2(x_F), A) H(A). \]  

(4)

From (1) we know empirically

\[ R(x_F, A) = (x_F)^{\alpha(x_F)} A^{\alpha(x_F)}. \]  

(5)

Since there is some independent information on \( N(x_2, A) \), to be discussed shortly, it is clear from (3)-(5) that the behavior of \( G(x_1, A) \) is highly constrained by what is already known phenomenologically. Our goal is to determine \( G(x_1, A) \) on the basis of a sensible evolution equation for the gluon distribution.
On nuclear shadowing there exists now extensive quantification of the quark and gluon distribution functions in nuclei\textsuperscript{10,11}. They are determined by analyzing the deep inelastic scattering and dilepton production data of nuclear targets at high $Q^2$ on the basis of DGLAP evolution\textsuperscript{12}. The results are given in terms of numerical parameterizations (called EKS98\textsuperscript{11}) of the ratio \( N_i^A (x, Q^2) = f_{i/A} (x, Q^2) / f_i (x, Q^2) \), where \( f_i \) is the parton distribution of flavor \( i \) in the free proton and \( f_{i/A} \) is that in a proton in a nucleus \( A \). We shall be interested in the ratio for the gluon distribution only at \( Q^2 = 10 \text{GeV}^2 \), which corresponds to producing $c\bar{c}$ near the threshold. We denote that ratio of the gluon distributions by \( N(x_2, A) \), which is what appears in (4). A simple formula was found that can provide a good fit of the EKS98 results; the details of which will appear in Ref.13. Here, we simply state the formula, used already in Ref.4.

\[
N(x_2, A) = A^{\beta(x_2)} ,
\]

where

\[
\beta (\xi (x_2)) = \xi \left( 0.0284 + 0.0008\xi - 0.0041\xi^2 \right) ,
\]

and

\[
\xi = 3.912 + \ell \ln x_2 .
\]

For \( \xi > 0 \), corresponding to \( x_2 > 0.02 \), \( \beta \) is positive and the region is usually referred to as anti-shadowing. The region of \( x_2 \) that is relevant to our study of $J/\psi$ suppression at all positive values of \( x_F \) turns out to straddle \( x_2 = 0.02 \) and thus includes both shadowing and anti-shadowing. Using (5) and (6) in (4) we have

\[
G(x_1 (x_F), A) H(A) = A^{\alpha(x_F) - \beta(x_2 (x_F)) - 1} ,
\]

whose RHS is now regarded as known.

\( G(x_1, A) \) is the ratio of the gluon distribution of a proton penetrating a nucleus, \( g(x_1, A) \), to that in a free proton, \( g(x_1, 0) \). To be more precise, \( g(x_1, A) \) should be labeled as \( g(x_1, z(A)) \), where \( z(A) \) is the average distance that a proton propagates in the nucleus \( A \) before its gluon at \( x_1 \) interacts with a gluon in the target at \( x_2 \) to produce the $c\bar{c}$ pair. The modified distribution \( g(x_1, z(A)) \) is, of course, independent of what hard subprocess takes place at \( x_1 \); the label \( z(A) \) merely denotes how far the gluons have penetrated the nucleus \( A \) when that subprocess does occur. Let us then write explicitly

\[
G(x_1, A) = g(x_1, A) / g(x_1, 0) .
\]
Using this in (9), it is convenient to consider another function $J(x_1, A)$, defined by

$$J(x_1, A) = g(x_1, A) H(A) = g(x_1, 0) A^{\alpha - \beta - 1}.$$  \hfill (11)

For the gluon distribution in a free proton, it is sufficient for us to use the canonical form

$$g(x_1, 0) = g_0 (1 - x_1)^5,$$  \hfill (12)

since it is only the deviation from that form that is of interest; even the coefficient $g_0$ is unimportant for it will be cancelled out in the ratio (10). The significance of $J(x_1, A)$ is that it is completely known by virtue of the RHS of (11). Thus, in principle $g(x_1, A)$ is known phenomenologically. However, we need some theoretical input to give $g(x_1, A)$ a suitable analytical form.

Since the effect of a nuclear target on the projectile gluon distribution is highly nonperturbative, there is no reliable analytical way to treat the problem of gluon depletion from first principles. Nevertheless, we propose an evolution equation in the spirit of DGLAP\footnote{DGLAP} except that we replace $\ell n Q^2$ by penetration length $z$ in a nucleus. For the change of $g(x, z)$, as the gluon traverses a distance $dz$, we write

$$\frac{d}{dz} g(x, z) = \int_x^1 \frac{dx'}{x'} g(x', z) Q \left( \frac{x}{x'} \right),$$  \hfill (13)

where $Q(x/x')$ describes the gain and loss of gluons in $dz$, but unlike the splitting function in pQCD, it cannot be calculated in perturbation theory. Eq. (13) represents an approximation that ignores the quark channel, which should be included in a more complete treatment. Since $Q(x/x')$ is unknown, we determine it phenomenologically from our knowledge of $J(x, A)$ through (11).

Eq. (13) can easily be solved if it is put in the form of its moments. Define

$$g_n(z) = \int_x^1 dx x^{n-2} g(x, z)$$  \hfill (14)

and similarly $Q_n$. Then from the convolution theorem follows

$$\frac{dg_n(z)}{dz} = g_n(z) Q_n,$$  \hfill (15)

which yields

$$g_n(z) = g_n(0) e^{z Q_n}.$$  \hfill (16)
If we also take the moments of the left half of (11), we have
\[ J_n(z) = g_n(z)H(z), \]
since \( H(A) \) is independent of \( x_1 \). Using (3) and (16), we obtain
\[ K_n(z) = \ell n \left[ J_n(z)/g_n(0) \right] = z \left( Q_n - \rho\sigma \right). \] (17)

Since the quantity in the middle above is known, we can determine \( Q_n \). It turns that there are some subtleties that render the determination less than straightforward. For details the reader is referred to Refs. 4 and 13.

Once \( Q_n \) is known, we can use (4) to calculate \( g_n(z) \), which in turn determines \( g(x_1, z) \). The result can best be exhibited by \( G(x_1, A) \). Using \( z \) to denote \( z(A) \), the average path length in \( A \) for the \( c\bar{c} \) state to be produced, we show the behaviors of \( G(x_1, A) \) for two representative values of \( A \) in Fig. 1. Evidently, there is an appreciable degree of suppression of the gluon distribution function at high \( x_1 \), and a small enhancement at low \( x_1 \). The implication is that a gluon with high momentum can, upon interaction with the nuclear target, split up into gluons with lower momenta.

The significance of our finding about the modification of the gluon distribution goes beyond the \( J/\psi \) suppression problem itself, since it would revise the conventional thinking concerning the role of partons in nuclear collisions. The usual procedure for calculating hard processes is to use the parton distribution in the free proton as input for the hard subprocess. That procedure is based on factorization, which is obviously invalid if significant depletion of gluons takes place in the nucleus. Furthermore, the redistribution of gluons as they propagate through the nucleus casts doubt on the plausibility of the notion that a penetrating nucleon can be identified as a recognizable entity, even if wounded. If so, the validity of the wounded-nucleon model that is conventionally used in nuclear collisions is now subject to serious reexamination. Perhaps even the meaningfulness of the discrete counting of the number of participants is questionable. All these issues need further investigation in light of our present finding.

A way to confirm gluon depletion is to measure the suppression of strangeness production, either open or closed \( s\bar{s} \) states, at large \( x_F \). The general strangeness enhancement can only partially be affected by the small gluon enhancement at small \( x_1 \), as can be seen in Fig. 1. That small enhancement does not lead to any significant increase in the \( c\bar{c} \) state either, so that the known \( J/\psi \) suppression in the central region of \( AB \) collisions should be unaffected. A rather intriguing question is the behavior of \( J/\psi \) suppression in \( pA \) collisions in the \( x_F < 0 \) region. Experimentally, that can be investigated in the inverse collision processes of nuclei on fixed proton target, or in colliding beams as at RHIC. Apart from the characteristics of parton redistribution in nuclei that will play a strong role in this problem, a new feature of gluon depletion can possibly
arise and be tested. In the proton rest from one has a row of nucleons moving
the same direction, but the gluons belonging to the rear part of the row may
be depleted due to their interactions with the slow gluons in the front part of
row that are set free by their interactions first with the target proton. This
type of effect, called nonlinear depletion, was first studied in Ref. 14, but could
not be independently tested. But in the $x_F < 0$ region of $pA$ collisions, that
would be be a unique opportunity to study such effects.

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Figure Captions

**Fig. 1** The ratio $G(x_1, A)$ of gluon distributions showing the effects of gluon depletion.
