Gluon shadowing and unitarity effects

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Abstract. New data from HERA experiment on deep inelastic scattering have been used to parametrize nucleon and Pomeron structure functions. Within the Gribov theory, the parameterizations were employed to calculate gluon shadowing for various heavy ions. The latter was compared with predictions from other models. Calculations of multiplicity reduction due to gluon shadowing for d+Au collisions at forward rapidities at \(\sqrt{s_{NN}}=200\) GeV are in good agreement with BRAHMS data on the nuclear modification factor.

Keywords: gluon nuclear shadowing, Gribov theory, unitarity effects

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1. Introduction

For low energies of the incoming beam in a hadron-nucleus collision, the successive elastic rescatterings of the initial hadron on the various nuclei of the nucleus are well described within the probabilistic Glauber model \([1]\). At higher energies, corresponding to \(E_{\text{crit}} \sim m_N \mu R_A\), the hadronic fluctuation length can become of the order of nuclear radius and there will be coherent interaction of constituents of the hadron with several nucleons of the nucleus. Within the Gribov approach \([2]\), this corresponds to summing up contributions of inelastic intermediate states, and leads to a reduction of the total cross section of the reaction, i. e. to nuclear shadowing.

We calculate the total amount of gluon shadowing for low values of the Bjorken variable \(x\) for heavy ions, ignoring for the time being the contribution from the quarks. The most recent data on diffractive structure functions are used and much stronger shadowing effects than previously expected are found. These effects will
lead to a strong multiplicity reduction in A+A collisions at RHIC and LHC energies.

2. The Model

The diffractive $\gamma^* N$ scatterings are described by Pomeron exchange. The scattering amplitude of an incoming photon with virtuality $Q^2$ on a nuclear target, consisting of A nucleons, can then be written as 

$$\sigma_A = A\sigma_N + \sigma_A^{(2)} + \ldots.$$  \hspace{1cm} (1)

The second term in (1) is negative and is related to diffractive DIS through the AGK cutting rules [4]. Higher order rescatterings in (1) are model dependent.

The Schwimmer unitarization [5] for the $\gamma^* A$ cross section is used to obtain the shadowing ratio

$$R_{A/N}^{Sch}(x) \equiv \frac{\sigma_{\gamma^*A}}{A\sigma_{\gamma^*N}} = \int d^2b \frac{T_A(b)}{1 + (A-1)f(x, Q^2)T_A(b)},$$  \hspace{1cm} (2)

where $f(x, Q^2)$ is the effective shadowing function, $T_A(b)$ is the nuclear density profile normalized to unity and standard DIS variables are used. Following [6, 7] in choice of parameters and kinematics, one can get the shadowing function as

$$f(x, Q^2) = 4\pi \int_{x}^{x_{BP}^{max}} dx_{BP} B(x_{BP}) \frac{F_2^{(3)}(x_{BP}, Q^2, \beta)}{F_2(x, Q^2)} F_A^2(t_{min}) .$$  \hspace{1cm} (3)

Here $B(x_{BP}) = 0.184 - 0.02 \ln(x_{BP})$ fm$^2$, and $F_A$ is the form factor of the nucleus.

Calculations are made both for $x_{BP}^{max} = 0.1$ as in [3] and for $x_{BP}^{max} = 0.03$ as in [3]. The structure functions $F_2(x, Q^2)$ and $F_2^{(3)}(x_{BP}, Q^2, \beta)$ are determined from experiment. At small x, gluon shadowing is found to be dominant. Quark contribution to the structure functions is not considered in what follows. Shadowing due to quarks, obtained within the same approach, was discussed in [3].

The gluon parton distribution functions (PDF) for nucleon and Pomeron were measured at intermediate $Q^2$ at the HERA experiments ZEUS and H1, correspondingly. The next to leading order (NLO) ZEUS-S QCD fit for the gluon PDF of the nucleon [3] at $Q^2 = 7$ GeV$^2$, and the gluon PDF for the Pomeron (diffractive structure function) [7] at $Q^2 = 6.5$ GeV$^2$ were both parametrized by

$$x g(x, Q^2) = Ax^{-\delta} (1-x)^\gamma ,$$  \hspace{1cm} (4)

where the fitting parameters $\{A, \delta, \gamma\} = \{1.9, 0.19, 6.7\}$ were obtained for the nucleon and $\{0.38, 0.28, 0.17\}$ for the Pomeron case, respectively. The $Q^2$-dependence of the fitting parameters is weak for moderate $Q^2$, and so we neglect it for the sake of simplicity.
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\[ \text{x} = 10^{-5} \]

\[ \text{x} = 10^{-4} \]

\[ \text{x} = 10^{-3} \]

\[ \text{x} = 10^{-2} \]

\[ \text{x} = 10^{-1} \]

\[ \text{x} = 10^{0} \]

\[ \text{x} = 10^{1} \]

\[ \text{x} = 10^{2} \]

\[ \text{x} = 10^{3} \]

\[ \text{Ca} / N \]
\[ \text{Pd} / N \]
\[ \text{Pb} / N \]

\[ \text{Sch} \]
\[ \text{R} \]

\[ \text{Armesto et.al. [10]} \]
\[ \text{Frankfurt et. al. [8]} \]
\[ \text{New HIJING [11]} \]

\[ \text{Glauber-Gribov, x_{max} = 0.03} \]

Fig. 1. Gluon shadowing for heavy ions. Fig. 2. Comparison of theoretical predictions for the Pb/nucleon ratio, at fixed \( Q^2 \).

3. Numerical results

Gluon shadowing for various heavy ions (Ca, Pd and Pb) from (2) is presented in Fig. 1. The gluon shadowing is very strong at small \( x \), and disappearing at \( x = x_{\text{max}}^D \). This is a consequence of the coherence effect in the form factor, and the vanishing integration domain in (3). Gluon shadowing is as low as 0.2 for the Pb/nucleon ratio.

A comparison of our results for Pb/nucleon ratio at \( Q^2 = 6.5 \text{ GeV}^2 \) with \( x_{\text{max}}^D = 0.03 \), with those of others, calculated at \( Q^2 = 5 \text{ GeV}^2 \) is presented in Fig. 2. For \( x \leq 10^{-3} \) our model predicts the stronger gluon shadowing compared to [10] (dashed-dotted line) and [8] (dotted line), while [11] (dashed line) predicts the strongest effect down to \( x \sim 10^{-4} \).

4. Shadowing effects in d+Au collisions

The model is now employed to study multiplicity reduction in d+Au collisions at ultra-relativistic energies. Deuteron is treated as a point-like particle in impact parameter space, but with the shadowing found from (2). The collision is described by two-jet kinematics through \( x_p(t) = c p_T e^{\pm t} / \sqrt{s} \), where \( p_T \) is the transverse momentum of the particle, and fixed at \( Q^2 \). We assume that most of the high- \( p_T \) particles come from jets \( c \) times more energetic than the measured one. The theoretical prediction is given by [12]

\[ R_{d+Au}^{\text{theo}} = R_d^{Sch}(x_p) R_{Au}^{Sch}(x_t) \]

From here one obtains the multiplicity reduction due to shadowing compared to the Glauber model. Then the model predictions for nuclear modification factor (NMF) at forward rapidities are compared to BRAHMS data at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) [13].
We exclude the gluon shadowing effects in the BRAHMS NMF at $\eta = 0$ by defining $R_{dAu}^{\text{norm}} = [R_{dAu}^{\text{exp}} / R_{d-Au}^{\text{theo}}]_{\eta=0}$. The multiplicity reduction due to shadowing effects will appear when we compare the NMF at forward rapidities, $\eta = 1, 2.2, 3.2$ to $R_{dAu}^{\text{norm}}$. The ratio $\bar{R} = [R_{dAu}^{\text{exp}} / R_{dAu}^{\text{norm}}]$ is plotted in Fig. 3 together with the predictions of (5) for two different values of the parameter $c$. Statistical errors are denoted by the thick solid line, while the systematic and statistical errors added up are denoted by the dashed line. Cronin effect is assumed to be rapidity independent and is cancelled out in the ratio. The choice of $c$ does not affect the result. Within the presented framework, one can conclude that suppression of the nuclear modification factor at forward rapidities is mostly due to gluon shadowing in the nuclei.

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