Small x nuclear shadowing in deep inelastic scattering

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We estimate the perturbative nuclear shadowing in the nuclear structure function $F_2^A(x,Q^2)$, mainly at the kinematic region of HERA using the Glauber-Mueller approach. The contributions of the quark and gluon sectors to the nuclear shadowing are estimated. We predict that the nuclear shadowing corrections are important and that saturation of the ratio $R_1=F_2^A(x,Q^2)/AF_2^N(x,Q^2)$ occurs at $Q^2\geqslant 1\ \text{GeV}^2$ once the shadowing in the gluon sector is considered. [S0556-2813(99)05010-4]

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The future ultrarelativistic heavy-ion collider experiments at the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC) are expected to exhibit new phenomena associated with an ultradense environment that may be created in the central collision region of these reactions [1]. The main conclusion emerging from the analysis of nucleus-nucleus collisions for RHIC energies and beyond, is that the most of the entropy and transverse energy is presumably produced already during very early times (within the first 2 fm after the nuclear contact) by frequent, mostly inelastic, semihard gluonic collisions involving typical momentum transfers of only a few GeV [2]. However, one is still far from a complete and detailed picture, as reflected by the considerable uncertainty in perturbative QCD predictions for global observables in nucleus-nucleus (AA) collisions at collider energies, such as particle multiplicities and transverse energy production [3]. The inability to extrapolate accurately from the pp ($p\bar{p}$) data to heavy ion AA collisions is due to the current poor knowledge about the nuclear and dense medium effects. One of these effects is the nuclear shadowing. It is of interest in high-energy nucleus-nucleus collisions because it could influence significantly the initial conditions in such reactions. Some processes strongly affected by nuclear shadowing at collider energies include the minijet production, heavy quarks, their bound states, and dilepton production [3]. Consequently, the nuclear shadowing is one of the major theoretical issues in modeling the QCD processes in nuclear collisions.

In recent years several experiments have been dedicated to high precision measurements of deep inelastic lepton scattering (DIS) off nuclei. Experiments at CERN and Fermilab focus especially on the region of small values of the Bjorken variable $x=Q^2/2M\nu$, where $Q^2=-q^2$ is the squared four-momentum transfer, ν is the energy transfer, and M is the nucleon mass. The data [4,5], taken over a wide kinematic range $10^{-6}\leqslant x\leqslant 0.1$ and $0.002\ \text{GeV}^2\leqslant Q^2\leqslant 100\ \text{GeV}^2$, show a systematic reduction of the nuclear structure function $F_2^A(x,Q^2)/A$ with respect to the free nucleon structure function $F_2^N(x,Q^2)$. This phenomena is known as *the shadowing effect*. The analysis of the shadowing corrections for the nuclear case in deep inelastic scattering (DIS) has been extensively discussed [6]. It is motivated by the perspective that in the near future an experimental investigation of the nuclear shadowing at small x and $Q^2\geqslant 1\ \text{GeV}^2$ using eA scattering could occur at the DESY Hadron Electron Ring Accelerator (HERA).

The deep inelastic scattering off a nucleus is usually interpreted in a frame where the nucleus is going very fast. In this case the nuclear shadowing is a result of an overlap in the longitudinal direction of the parton clouds originated from different bound nucleons [7]. Recently, a perturbative approach has been developed to calculate the gluon distribution in a nucleus [8] using perturbative QCD at small x. This approach, known as the Glauber-Mueller approach is formulated in the target rest frame, takes into account the fluctuations of the hard probe. It includes the shadowing corrections (SC'S) due to parton rescatterings inside the nucleus, and provides the SC to the nuclear gluon distribution using the solution of the DGLAP evolution equations [9] to the nucleon case. As a result the behavior of related observables ($F_2^A,F_L^A,\ldots$) at high energies can be calculated.

Our goal in this work is to estimate the perturbative nuclear shadowing to the nuclear structure function $F_2^A(x,Q^2)$, using the Glauber-Mueller approach proposed in [8] at HERA-A kinematic region. We compute the nuclear shadowing corrections to the structure function F_2^A associated with the rescatterings of the $q\bar{q}$ pair on the nucleons inside a nucleus using the Glauber-Mueller approach. Our results are dependent on the behavior of the nucleon gluon distribution. We then consider two possibilities. First we contemplate the unshadowed gluon distribution, which we denote as the quark sector contribution for the nuclear shadowing. Second, the shadowed gluon distribution, which we denote as the gluon sector contribution for the nuclear shadowing. This contribution is calculated using the Glauber-Mueller approach. Our work is motivated by our recent results in the analysis of scaling violations of the proton structure function [10]. The ZEUS data for the F_2^p slope [11] presents a turnover which can be successfully described considering the contribution of both sectors. Here we estimate the contribution of both sectors to the ratio $R_1=F_2^A(x,Q^2)/AF_2^N(x,Q^2)$ and we show that the inclusion of the contribution of the gluon sector modify strongly the behavior of this ratio.

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Before we calculate the perturbative SC at F_2^A some comments are in order. As $x \approx Q^2/s$, where s is the squared CM energy, the data in the region of small-x values are for small values of Q^2 ($\leqslant 1$ GeV^2). In this region the application of the perturbative QCD cannot be justified. The SC in this region are dominated by soft contributions, as can be concluded considering some approaches [12–15] that describe these data. For instance, the New Muon Collaboration (NMC) experimental results [4] can be described using the DGLAP evolution equations [9] with adjusted initial parton distributions, following Refs. [14,15]. Since the initial parton distributions are associated with nonperturbative QCD this approach intrinsically includes the nonperturbative contributions to the shadowing corrections. Therefore, we consider that the nuclear shadowing corrections observed in the NMC [4] and E665 data [5] at small x are dominated by soft contributions. The determination of the soft contributions to the nuclear shadowing is not the goal of this work.

Let us start from the Glauber-Mueller approach proposed in [8]. In the small-x region the gluon distribution governs the behavior of the observables. In the nucleus rest frame we can consider the interaction between a virtual colorless hard probe and the nucleus via a gluon pair (gg) component of the virtual probe. In the region where $x \ll 1/2mR$ (R is the size of the target), the gg pair crosses the target with fixed transverse distance r_t between the gluons. Moreover, at high energies the lifetime of the gg pair may substantially exceeds the nuclear radius. The cross section for this process is written as [8]

$$\sigma^{g^*A} = \int_0^1 dz \int \frac{d^2 r_t}{\pi} |\Psi_t^{g^*}(Q^2, r_t, x, z)|^2 \sigma^{gg+A}(z, r_t^2), \tag{1}$$

where g^* is the virtual colorless hard probe with virtuality Q^2, z is the fraction of energy carried by the gluon and $\Psi_t^{g^*}$ is the wave function of the transverse polarized gluon in the virtual probe. Furthermore, $\sigma^{gg+A}(z, r_t^2)$ is the cross section of the interaction of the gg pair with the nucleus.

To estimate the nuclear shadowing we have to take into account the rescatterings of the gluon pair inside the nucleus. The contributions of the rescatterings were estimated using the Glauber-Mueller approach in Ref. [8]. One of the main results is that the nuclear gluon distribution is given by (see primarily [8] and [12–18] for details)

$$xG_A(x,Q^2) = \frac{2R_A^2}{\pi^2} \int_x^1 \frac{dx'}{x'} \int_{1/Q^2}^{1/Q_0^2} \frac{d^2 r_t}{\pi r_t^4} \{C + \ln(\kappa_G(x', r_t^2)) + E_1(\kappa_G(x', r_t^2))\}, \tag{2}$$

where C is the Euler constant, E_1 is the exponential function, the function $\kappa_G(x, r_t^2) = (3\alpha_s A/2R_A^2)\pi r_t^2 x G_N(x, 1/r_t^2)$, A is the number of nucleons in a nucleus, and R_A^2 is the mean nuclear radius. If Eq. (2) is expanded for small κ_G, the first term (Born term) will correspond to the usual DGLAP equation in the small-x region, while the other terms will take into account the shadowing corrections.

The master formula (2) is obtained in the double logarithmic approximation (DLA) [8]. As shown in [8] the DLA does not work quite well in the accessible kinematic region ($Q^2 > 1$ GeV^2 and $x > 10^{-4}$). A more realistic approach must be considered to calculate the nuclear gluon distribution xG_A, which implies the subtraction of the Born term of Eq. (2) and the sum of the GRV parametrization [8]. This procedure gives

$$xG_A(x,Q^2) = xG_A^{\mathrm{master}}[\mathrm{Eq.~(4)}] + AxG_N^{\mathrm{GRV}}(x,Q^2) - A\frac{\alpha_s N_c}{\pi} \int_x^1 \int_{Q_0^2}^{Q^2} \frac{dx'}{x'} \frac{dQ'^2}{Q'^2} x' G_N^{\mathrm{GRV}}(x', Q'^2). \tag{3}$$

The above equation implies $AxG_N^{\mathrm{GRV}}(x,Q_0^2)$ as the initial condition for the gluon distribution and gives $AxG_N^{\mathrm{GRV}}(x,Q^2)$ as the first term of the expansion with respect to κ_G. Therefore, this equation is an attempt to include the full expression for the anomalous dimension for the scattering off each nucleon, while the use of the DLA takes into account all SC. In [8] this procedure was applied to obtain the shadowing corrections to the nuclear gluon distribution, demonstrating that the suppression due to the shadowing corrections increases with $\ln 1/x$ and is much bigger than the nucleon case. For calcium ($A = 40$) the suppression varies from 4% for $\ln 1/x = 3$ to 25% for $\ln 1/x = 10$.

Expression (3) estimates the SC to the gluon distribution using the Glauber-Mueller approach. The modification in the nuclear gluon distribution represents the contribution of the gluon sector for the nuclear shadowing.

The Glauber-Mueller approach can be extended to the nuclear structure function considering that in the rest frame of the target the virtual photon decays into a quark-antiquark ($q\bar{q}$) pair long before the interaction with the target. The $q\bar{q}$ pair subsequently interacts with the target. In the small-x region, where $x \ll 1/2mR$, the $q\bar{q}$ pair crosses the target with fixed transverse distance r_t between the quark and the antiquark. Considering the s-channel unitarity and the eikonal model and following the same steps used in the case of the nuclear gluon distribution, the nuclear structure function can be written as

$$F_2^A(x,Q^2) = \frac{R_A^2}{2\pi^2} \sum_1^{n_f} \epsilon_i^2 \int_{1/Q^2}^{1/Q_0^2} \frac{d^2 r_t}{\pi r_t^4} \{C + \ln(\kappa_q(x, r_t^2)) + E_1(\kappa_q(x, r_t^2))\}, \tag{4}$$

where $\kappa_q = 4/9\kappa_G$. Similarly as made in the case of the nuclear gluon distribution, to obtain a more realistic approach the Born term should be subtracted and the GRV parametrization should be added. Therefore, the nuclear structure function is given by

$$F_2^A(x,Q^2) = F_2^A(x,Q^2)[\mathrm{Eq.~(6)}] - F_2^A(x,Q^2)[\mathrm{Born}] + A\,F_2(x,Q^2)[\mathrm{GRV}], \tag{5}$$

where $F_2^A(x,Q^2)$[Born] is the first term in the expansion in κ_q of Eq. (4), and $F_2(x,Q^2)[\mathrm{GRV}]=\Sigma_{u,d,s}\epsilon_q^2[xq(x,Q^2)+x\bar{q}(x,Q^2)]+F_2^c(x,Q^2)$ is calculated using the GRV parametrization. The charm component of the structure function is calculated considering the charm production via boson-gluon fusion [18]. In this work we assume $m_c=1.5$ GeV.

Expression (5) estimates the SC to the nuclear structure function using the Glauber-Mueller approach. We see that the behavior of F_2^A is directly associated with the behavior of the gluon distribution used as input, which is usually described by a parametrization of the parton distributions [18]. In this case the shadowing in the gluon distribution is not included explicitly. We denote the quark sector contribution for the nuclear shadowing effect in the nuclear structure function obtained using the Glauber-Mueller approach and the usual parametrization (unshadowed) as input.

The total modification in the structure function associated with the nuclear shadowing is the sum of the shadowing corrections in both sectors. The main difference between quark and gluon sectors stems from the much larger cross section $\sigma_N^{gg}=(9/4)\sigma_N^{q\bar{q}}$, i.e., $\kappa_G=(9/4)\kappa_q$, which in turn leads to a much larger gluon shadowing. Therefore, at small values of x the contribution of the gluon sector cannot be disregarded in a reliable calculus of the nuclear structure function. In a general case, the shadowing corrections for F_2^A should be estimated considering also these corrections for the gluon distribution, i.e., in the quark and gluon sectors. Recently, we propose a procedure to estimate the SC in both sectors to describe the turnover in the F_2 slope observed in the ZEUS data [11]. Using the procedure here, we estimate the nuclear structure function considering both sectors (quark + gluon sectors) of NS using the solution of Eq. (3) for the nucleon case ($A=1$) as an input in expression (5).

Using expression (5) we can estimate the nuclear shadowing (NS) corrections. We assume that the mean radius of the nucleus R_A^2 is equal to $R_A^2=2/5R_{\mathrm{WS}}^2$, where R_{WS} is the size of the nucleus in the Woods-Saxon parametrization. We choose $R_{\mathrm{WS}}=r_0A^{1/3}$, with $r_0=1.3$ fm. We calculate the ratio

$$R_1=\frac{F_2^A(x,Q^2)}{AF_2^N(x,Q^2)}, \tag{6}$$

where $F_2^A(x,Q^2)$ is the structure function for a nucleus with A nucleons and $F_2^N(x,Q^2)$ is the nucleon structure function. In our calculation we approximate the nucleon structure function $F_2^N=(F_2^p+F_2^n)/2$ by the proton structure function F_2^p, which is a good approximation at small values of x [19,20].

In Fig. 1 we present our results for the ratio R_1 as a function of $\ln 1/x$ at different virtualities and considering the different sectors for the calcium case ($A=40$). In Fig. 1(a) we present the results of the NS for the ratio considering only the quark sector, while in Fig. 1(b) we present the results of NS corrections considering the quark+gluon sectors. We can see that in both cases the perturbative nuclear shadowing is an important correction to the behavior of the nuclear structure function. The suppression varies from 1% for $\ln 1/x=3$ to 20% for $\ln 1/x=10$. Therefore, our result demonstrates that the suppression due to shadowing corrections is proportionally smaller in the nuclear structure function than in the nuclear gluon distribution. This result is in disagreement with the result obtained in Ref. [13] which uses the Gribov formula and a Regge parametrization for the diffractive structure function. We believe that this disagreement occurs since that approach is dominated by soft physics. Furthermore, we can see that when only the contribution of the quark sector is considered no saturation in the ratio R_1 is observed, which agrees with the result obtained in [20]. However, if the contribution of the gluon sector is considered, i.e., if a shadowed gluon distribution is used, the ratio saturates in the HERA-A kinematical region. This is a new result, since in general the saturation in ratio R_1 has been characterized as essentially a nonperturbative effect [20]. Therefore, a saturation in the perturbative region ($Q^2>1$ GeV^2) evidentiates the large shadowing corrections in the gluon sector.

In Fig. 2 we present our results for the ratio R_1 as a function of Q^2 at different values of x and different sectors for the calcium case ($A=40$). As the behavior of the ratio R_1 in the region $Q^2\leqslant 2.5$ GeV^2 is strongly dependent of the initial conditions [20], we present only our predictions in the region of larger Q^2. We can see that the ratio is dependent on Q^2 in the region $Q^2\leqslant 10$ GeV^2 and that at large Q^2 the

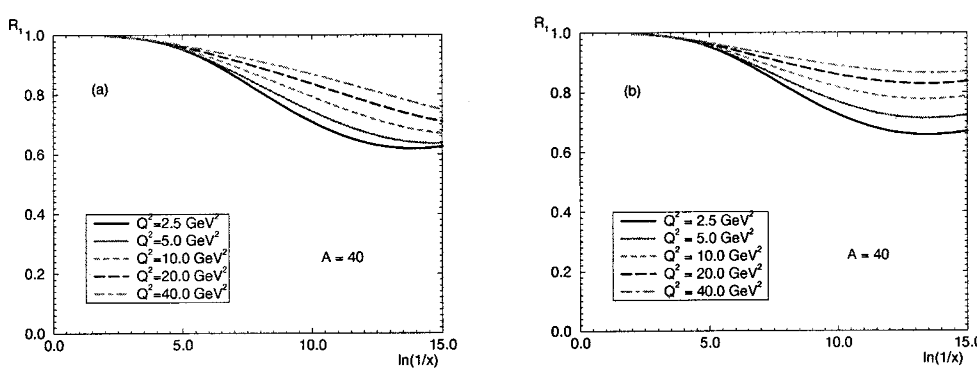

FIG. 1. The ratio $R_1=F_2^A(x,Q^2)/A\,F_2^N(x,Q^2)$ as a function of ln $1/x$ at different virtualities and different sectors: (a) quark sector and (b) quark+gluon sector. In the calcium case $A=40$.

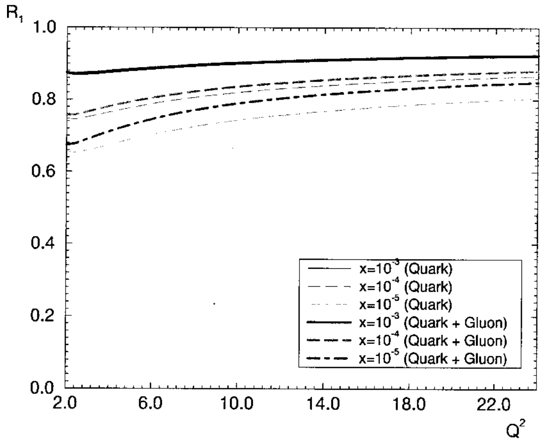

FIG. 2. The ratio $R_1 = F_2^A(x,Q^2)/A\, F_2^N(x,Q^2)$ as a function of Q^2 at different values of x and different sectors (quark and quark +gluon). In the calcium case $A=40$.

nuclear shadowing corrections diminish but do not vanish, i.e., it is not a higher twist effect. In addition, for $x \geqslant 10^{-3}$ the curves associated with the quark and quark+gluon sector coincides, which represents that gluon sector do not contribute in this kinematical region. The dependence of the ratio R_1 on Q^2 occurs mainly at small values of x, but the general behavior of the curve does not depend on the sector considered.

In Fig. 3 we present our results of the ratio R_1 as a function of A at different values of Q^2 and x for the different sectors. We can see that the nuclear shadowing corrections increases with the growth of A and with the decrease of x. The nuclear shadowing corrections for the ratio R_1 are larger for smaller Q^2 values and smaller if the gluon sector is considered.

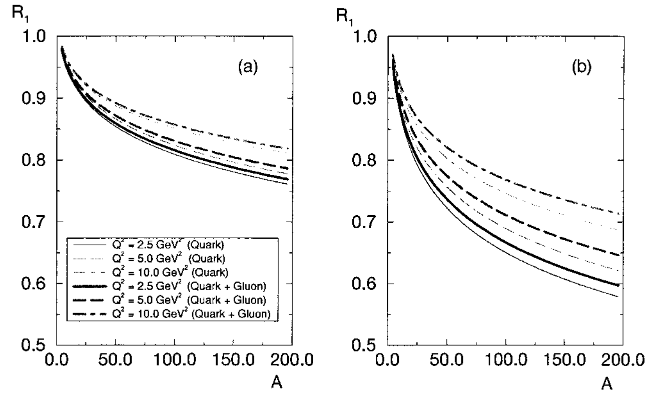

FIG. 3. The ratio $R_1 = F_2^A(x,Q^2)/A\, F_2^N(x,Q^2)$ as a function of A at different values of Q^2, different sectors (quark and quark +gluon), and (a) $x=10^{-3}$, (b) $x=10^{-4}$.

In summary, the perturbative nuclear shadowing corrections for HERA-A are analyzed in this work in the context of the Glauber-Mueller approach. This approach predicts important results for the perturbative nuclear shadowing: the nuclear shadowing corrections are very large in the HERA-A kinematical region; saturation of the nuclear shadowing corrections will occur in this kinematical region if the contribution of the gluon shadowing is considered; the shadowing in the nuclear gluon distribution is larger than in the nuclear structure function. We expect that these results motivate the running of nucleus at HERA in the future, since the precise determination of nuclear shadowing corrections is fundamental to estimating the cross sections of the processes with a nucleus, which will be studied in the future accelerators RHIC and LHC.

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