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Color fluctuation approximation for multiple interactions in leading twist theory of nuclear shadowing

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ABSTRACT

The leading twist theory of nuclear shadowing predicts the shadowing correction to nuclear parton distributions at small x by connecting it to the leading twist hard diffraction in electron–nucleon scattering. The uncertainties of the predictions are related to the shadowing effects resulting from the interaction of the hard probe with $N \geqslant 3$ nucleons. We argue that the pattern of hard diffraction observed at HERA allows one to reduce these uncertainties. We develop a new approach to the treatment of these multiple interactions, which is based on the concept of the color fluctuations and accounts for the presence of both point-like and hadron-like configurations in the virtual photon wave function. Using the developed framework, we update our predictions for the leading twist nuclear shadowing in nuclear parton distributions of heavy nuclei at small x.

1. Introduction

In this work, we consider the quark and gluon parton distribution functions (PDFs) in nuclei at small values of Bjorken x and their reduction as compared with the incoherent sum of the nucleon PDFs because of the phenomenon of nuclear shadowing. Most of experimental information on nuclear PDFs comes from inclusive deep inelastic scattering (DIS) with nuclear targets which measures the nuclear structure function $F_{2A}(x,Q^2)$. For $x < 0.05$, $F_{2A}(x,Q^2) < AF_{2N}(x,Q^2)$, which is called nuclear shadowing [$F_{2N}(x,Q^2)$ is the isoscalar nucleon structure function and A is the number of nucleons]. Because of the factorization theorem for DIS (for a review, see Ref. [1]), which relates $F_{2A}(x,Q^2)$ to nuclear parton distributions $f_{j/A}(x,Q^2)$ (j is the parton flavor), nuclear shadowing is also present in nuclear PDFs, $f_{j/A}(x,Q^2) < Af_{j/N}(x,Q^2)$ for $x < 0.05$, where $f_{j/N}(x,Q^2)$ is the PDF of the free nucleon. This finds evidence in the results of the global fits that extract nuclear PDFs from various data on hard scattering with nuclei [2–10].

Nuclear PDFs at small x play an important role in the phenomenology of hard scattering with nuclei. Their knowledge is required for the evaluation and interpretation of hard phenomena in proton–nucleus and nucleus–nucleus collisions at Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), in real photon–nucleus interactions in ultraperipheral collisions at the LHC [11], and in lepton–nucleus scattering at the future Electron–Ion Collider (EIC) [12,13]. In addition, nuclear PDFs at small x are needed for the quantitative estimation of the onset of saturation in ultra high energy interactions with nuclei, which can be studied at the LHC and the EIC.

A comparison of the results of the global fits for nuclear PDFs obtained by various groups [2–10] shows significant discrepancies in the predictions for nuclear PDFs at small x (uncertainties of individuals fits at small x are also very large [6,9]). The main reason for this is that the global fits are predominantly based on fixed-target data that do not cover the small-x region (by requiring that $Q^2 > 1\ \text{GeV}^2$ is sufficient for the applicability of the factorization theorem, one limits $x > 5 \times 10^{-3}$). In addition, the gluon nuclear PDF is determined indirectly from the scaling violations using the very limited data. Therefore, the extrapolation of the obtained nuclear PDFs to the low values of Bjorken x that will be probed at the LHC and the EIC is essentially uncontrolled. An alternative to the global fits is provided by the approaches that attempt to predict nuclear shadowing for nuclear PDFs using the high-energy dynamics of the strong interactions.

We use the so-called leading twist theory of nuclear shadowing [14]. It combines the technique used by Gribov to derive nuclear shadowing for the total hadron–deuteron cross section at high energies [15] and the QCD factorization theorems for inclusive [1] and

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diffractive [16] DIS. The numerical predictions employ the results of the leading twist QCD analyses of hard diffraction in lepton–proton DIS at HERA [17–19]. Although in the leading twist approach the hard probe interacts with one parton of the nucleus, in the target rest frame, nuclear shadowing appears as the effect of multiple interactions of the projectile (virtual photon) with several (all) nucleons of the target. The interaction with $N = 2$ nucleons is related in a model-independent way to the diffractive PDFs of the nucleon. The account of the interaction with $N \geqslant 3$ nucleons is model-dependent and sensitive to the underlying dynamics of the hard diffraction. The recent HERA data [17–19] revealed that the energy dependence of the hard diffraction in DIS (dependence on the light-cone fraction $x_{\mathbb{P}}$) is close to that of the soft processes. This indicates that the hard diffraction in DIS is dominated by large-size hadron-like configurations in the photon wave function. This observation allows us to improve the treatment of the contribution to nuclear shadowing coming from the interactions with $N \geqslant 3$ nucleons as compared to the simplified quasi-eikonal approximation used in our earlier papers [20] by taking into account the presence of both point-like and hadron-like configurations in the virtual photon. The goal of the present Letter is to present a new, improved treatment of such multiple interactions and to update predictions for nuclear shadowing in nuclear PDFs.

We emphasize that the presence of the small-size (point-like) configurations and, in general, configurations of different transverse sizes that interact with different cross sections (we call such configurations color or cross section fluctuations) is much more important for the virtual photon than for hadronic projectiles.

Our Letter is organized as follows. In Section 2, we briefly review the leading twist theory of nuclear shadowing and present a new formalism for the treatment of the multiple interactions of the virtual photon with the nucleons of the nuclear target, which is based on the concept of color (cross section) fluctuations. In Section 3, we show that the complete treatment of color fluctuations can be well approximated by the so-called color fluctuation approximation. In Section 4, we present updated predictions for the effect of nuclear shadowing in nuclear parton distributions. We focus on the predictions for heavy nuclei at small x since modifications of the predictions for light nuclei (where the $N = 2$ term dominates) are rather small. Our results are summarized in Section 5.

2. Leading twist theory of nuclear shadowing and cross section fluctuations for multiple interactions

The phenomenon of nuclear shadowing is fairly well-understood: in the target rest frame, nuclear shadowing arises as the result of multiple interactions of the projectile (virtual photon) with several nucleons of the nuclear target. The number of the interactions increases with decreasing Bjorken x, which is a result of the space-picture of the strong interactions, see e.g., Ref. [21]. At sufficiently high energies (small Bjorken x), the virtual photon can interact with all the nucleons of the target that are located in the photon's path.

The graphs that contribute to the nuclear structure function $F_{2A}(x, Q^2)$ are presented in Fig. 1, where we used the optical theorem to relate the imaginary part of the γ^*A forward scattering amplitude to the nuclear structure function. In the figure, graphs a, b, and c correspond to the interaction with one, two, and three nucleons of the nuclear target, respectively. Note that the graphs for the interaction with four or more nucleons are not shown, but assumed. Graphs b, c and higher scattering terms are responsible for nuclear shadowing in $F_{2A}(x, Q^2)$.

The contribution of graph a, which is conveniently denoted $F_{2A}^{(a)}(x, Q^2)$, is

$$F_{2A}^{(a)}(x, Q^2) = A F_{2N}(x, Q^2), \tag{1}$$

where $F_{2N}(x, Q^2)$ is the isospin-averaged structure function of the nucleon. In Eq. (1), we neglected the deviation from the many-nucleon approximation for the description of nuclei and the Fermi motion effect, which are numerically unimportant at small x.

The calculation of the contribution of graph b, $F_{2A}^{(b)}(x, Q^2)$, is fairly straightforward, but lengthy [22]. The detailed derivation, including the effect of the real part of the diffractive amplitude, is given in Ref. [20]. Here we present the final result for $F_{2A}^{(b)}(x, Q^2)$,

$$F_{2A}^{(b)}(x, Q^2) = -8\pi A(A-1)\,\Re e\frac{(1-i\eta)^2}{1+\eta^2} B_{\text{diff}} \int_x^{0.1} dx_{\mathbb{P}}\, F_2^{D(3)}(x, Q^2, x_{\mathbb{P}}) \int d^2\vec{b} \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2\, \rho_A(\vec{b}, z_1)\rho_A(\vec{b}, z_2) e^{i(z_1-z_2)x_{\mathbb{P}}m_N}, \tag{2}$$

where $F_2^{D(3)}$ is the nucleon diffractive structure function measured in hard γ^*p inclusive diffraction; ρ_A is the nuclear density; $\eta \approx 0.17$ is the ratio of the real to imaginary parts of the γ^*p diffractive amplitude; $B_{\text{diff}} = 6\ \text{GeV}^{-2}$ is the slope of the t dependence of the diffractive γ^*p cross section; $x_{\mathbb{P}}$ is the light-cone fraction of the nucleon momentum carried by the Pomeron (see the discussion below); m_N is the nucleon mass.

The nuclear density ρ_A depends on the transverse coordinate (impact parameter), $\vec{b}$, and the longitudinal coordinates, z_1 and z_2, of the interacting nucleons. The ordering $z_2 > z_1$ follows from the space–time evolution of the scattering process. The $e^{i(z_1-z_2)x_{\mathbb{P}}m_N}$ factor accounts for the excitation of the intermediate diffractive state denoted by X in Fig. 1. At high energies, the γ^*N interaction that leads to nuclear shadowing is diffractive in character. This is represented by the zigzag lines in Fig. 1. It is convenient to think of the zigzag lines as depicting effective Pomeron exchanges. In this case, $x_{\mathbb{P}}$ represents the light-cone fraction of the nucleon momentum carried by the Pomeron, $x_{\mathbb{P}} \approx (M_X^2 + Q^2)/(W^2 + Q^2)$, where M_X is the invariant mass of the diffractive state X, and W is the invariant γ^*p energy. The lower limit of integration over $x_{\mathbb{P}}$ in Eq. (2) corresponds to $M_X = 0$; the upper limit is determined by the typical cut on M_X, $M_X^2 \leqslant 0.1W^2$, which arises because of the nuclear form factor. Note that Eq. (2) is valid independently of the validity of the leading twist approximation for the hard diffraction.

One of the key features of the leading twist theory of nuclear shadowing [14,20] is the possibility to predict nuclear shadowing at the level of parton distributions. Using the QCD factorization theorems for inclusive DIS and hard diffraction in DIS, one can replace the observable structure functions by the corresponding parton distribution. This is shown in Fig. 2, which represents the multiple scattering series for the quark distribution in nuclei. A similar graphical representation can also be given for the gluon distribution using a hard probe directly coupled to gluons.