Nuclear Shadowing and Extraction of $F_2^p - F_2^n$ at Small x from Deuteron Collider Data

L. Frankfurt
School of Physics and Astronomy, Tel Aviv University, 69978, Tel Aviv, Israel

V. Guzey
Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany

M. Strikman
Department of Physics, The Pennsylvania State University, State College, Pennsylvania 16802, USA
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We demonstrate that leading twist nuclear shadowing leads to large corrections for the extraction of the neutron structure function F_2^n from the future deuteron collider data both in the inclusive and in the tagged structure function modes. We suggest several strategies to address the extraction of F_2^n and to measure at the same time the effect of nuclear shadowing via the measurement of the distortion of the proton spectator spectrum in the semi-inclusive $eD \to e' pX$ process.

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One of the important components of the electron-ion collider project (EIC) [1] is the measurement of the nonsinglet structure function of the nucleon, $F_2^p - F_2^n$, down to rather small values of Bjorken x. A similar program is discussed for HERA III. The main objective of using deuteron beams at HERA is obtaining more accurate information on the nonsinglet structure function of the nucleon at small x. Since F_2^p and F_2^n are rather close at small x, nuclear shadowing significantly affects $F_2^p - F_2^n$, when extracted from the deuterium data. Indeed, while $R \equiv (F_2^p - F_2^n)/F_2^p \leq 4 \times 10^{-2}$ for $x \leq 10^{-2}$, the shadowing correction modifies F_2^D by 1%–2% and, hence, R is modified by twice as much. Therefore it is crucial to determine the value of the nuclear shadowing correction, as well as its uncertainties, both to the inclusive structure function F_2^D and to the tagged structure function, when the spectator proton (a proton with momentum ≤ 0.1 GeV$/c$ in the deuteron rest frame) is detected ensuring the kinematics maximally close to the scattering off a free nucleon.

In this Letter, we analyze both of the above-mentioned structure functions using the theory of leading twist nuclear shadowing [2], which is based on the existence of the deep connection between the phenomena of high energy diffraction and nuclear shadowing demonstrated within the Reggeon calculus for hadron-deuteron scattering by Gribov [3], and the Collins factorization theorem for hard diffraction [4]. In the case of the tagged structure functions, we also use the Abramovskiĭ, Gribov, Kancheli (AGK) cutting rules [5], which relate shadowing effects for the total and partial cross sections. We formulate the requirements necessary for the extraction of F_2^n from the deuterium data and demonstrate that a detector with good proton momentum resolution will be able to determine the value of the shadowing correction.

We begin by discussing nuclear shadowing in inclusive deep inelastic scattering (DIS) off deuterium. On the qualitative level, the Gribov result for nuclear shadowing off the deuteron [3] could be understood as a consequence of the interference between the amplitudes for diffractive scattering of the projectile off the proton and off the neutron of the deuterium target. Such interference is possible for small x, $x \leq 5 \times 10^{-2}$, where the minimum momentum transfer to the nucleon, $\sim x m_N$, becomes smaller than the average nucleon momentum in the deuteron. The corresponding double scattering diagram for the $\gamma^* D$ scattering is presented in Fig. 1. The nuclear shadowing correction to the total $\gamma^* D$ cross section is given by the imaginary part of this diagram, which is obtained by making all possible unitary cuts (denoted by dashed lines in Fig. 1). The application of the AGK cutting rules explicitly demonstrates that the imaginary part of the interference graph decreases the total $\gamma^* D$ cross section by the factor proportional to $(1 - \eta^2)(\text{Im}\,\mathcal{A})^2$, where

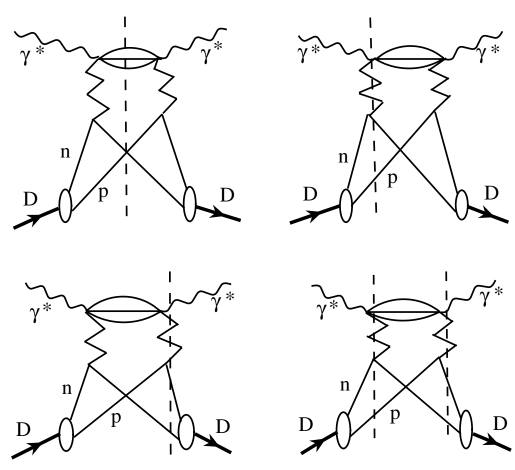

FIG. 1. All possible unitary cuts of the interference diagram giving rise to nuclear shadowing correction to $\gamma^* D$ cross section.

$\mathcal{A}$ is the amplitude for the photon-nucleon diffractive scattering and $\eta = \text{Re}\,\mathcal{A}/\text{Im}\,\mathcal{A}$.

A consideration of the individual unitary cuts in Fig. 1 demonstrates that the interference diagram decreases the cross section of inelastic interactions with a single nucleon (top right and bottom left graphs) by the factor proportional to $4(\text{Im}\,\mathcal{A})^2$, and also results in simultaneous inelastic interactions with two nucleons (botton right graph) with $\sigma_{\text{double}} = 2(\text{Im}\,\mathcal{A})^2$. Also, the interference diagram increases the probability of diffraction on the nucleus by the factor proportional to $(1+\eta^2)(\text{Im}\,\mathcal{A})^2$ (top left graph) (see Ref. [6]).

Within the framework of the Gribov theory of nuclear shadowing, the deuterium inclusive structure function reads

$$F_2^D(x,Q^2) = F_2^p(x,Q^2) + F_2^n(x,Q^2) - 2\frac{1-\eta^2}{1+\eta^2}\int_x^{x_0} dx_{\mathbb{P}}\, dq_t^2\, F_2^{D(4)}(\beta,Q^2,x_{\mathbb{P}},t) \times \rho_D[4q_t^2 + 4(x_{\mathbb{P}} m_N)^2], \quad (1)$$

where $F^{D(4)}$ is the nucleon diffractive structure function, ρ_D is the deuteron form factor, and $|t| = q_t^2 + (x_{\mathbb{P}} m_N)^2$. Since the t dependence of ρ_D is rather moderate (compared to heavier nuclei), the integral in Eq. (1) is sensitive to $F^{D(4)}(t)$ up to $-t \leq 0.05\ \text{GeV}^2$. Also, in Eq. (1), the factor $(1-\eta^2)/(1+\eta^2)$, where

$$\eta = -\frac{\pi}{2}\frac{\partial \ln(\sqrt{f_{i/N}^D})}{\partial \ln(1/x_{\mathbb{P}})} = \frac{\pi}{2}[\alpha_{\mathbb{P}}(t=0) - 1] \quad (2)$$

accounts for the real part of the amplitude for the diffractive scattering [7] and leads to a reduction of the shadowing by about 20%. Note that, in the Reggeon calculus derivation [3], it was assumed that $\eta = 0$, which is natural for the amplitudes slowly increasing with energy. This is not the case for DIS and, hence, η should be taken into account.

Using the QCD factorization theorem for hard diffraction [4], it is possible to extend the Gribov theory in order to calculate nuclear shadowing for the quark and gluon parton densities of the deuteron, $f_{j/D}$, at small x as follows (see Ref. [2] and subsequent publications [8,9]):

$$f_{j/D}(x,Q^2) = f_{j/p}(x,Q^2) + f_{j/n}(x,Q^2) - 2\frac{1-\eta^2}{1+\eta^2}\int_x^{x_0} dx_{\mathbb{P}}\, dq_t^2\, f_{j/N}^D(\beta,Q^2,x_{\mathbb{P}},t) \times \rho_D[4q_t^2 + 4(x_{\mathbb{P}} m_N)^2]. \quad (3)$$

The results of the calculation of the ratios $F_2^D/(F_2^p + F_2^n)$ and $g_D/(2g_N)$ using the H1 diffractive fit [10] for $F^{D(3)}$ are presented in Figs. 2 and 3 for a range of x and Q. In this calculation, we used the Paris NN potential. One can see that substantial shadowing is expected for the small x region.

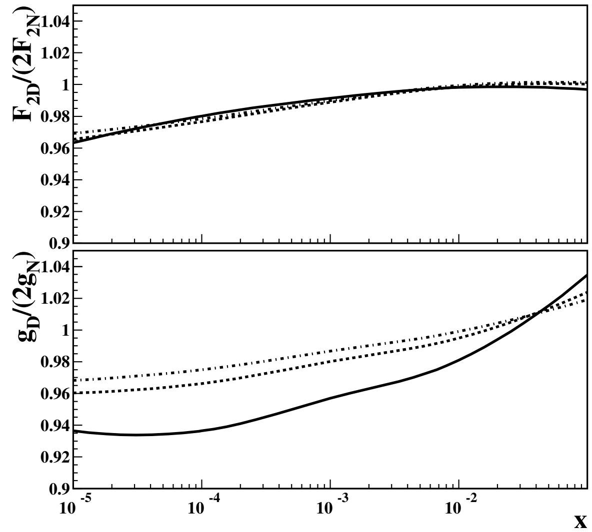

FIG. 2. The ratios $F_2^D/(F_2^p + F_2^n)$ and $g_D/(2g_N)$ as functions of x. The solid curve corresponds to $Q = 2$ GeV; the dashed curve corresponds to $Q = 5$ GeV; the dash-dotted curve corresponds to $Q = 10$ GeV.

Note also that the nuclear shadowing correction to F_2^D for $Q^2 \leq 1\ \text{GeV}^2$ is expected to be substantially larger than that for $Q^2 \sim 4$. The enhancement of diffraction at small Q^2 by higher twist effects such as, for instance, vector meson production, will increase nuclear shadowing up to a factor of 2. Note that the application of the Gribov formalism to nuclear shadowing in the New Muon

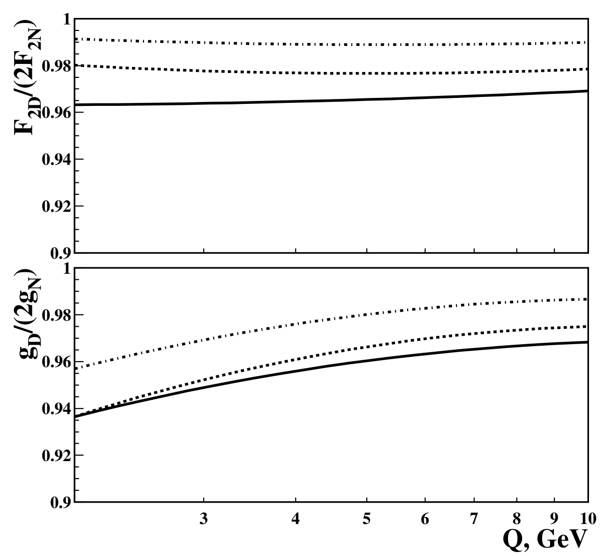

FIG. 3. The ratios $F_2^D/(F_2^p + F_2^n)$ and $g_D/(2g_N)$ as functions of Q. The solid curve corresponds to $x = 10^{-5}$; the dashed curve corresponds to $x = 10^{-4}$; the dash-dotted curve corresponds to $x = 10^{-3}$.

Collaboration kinematics ($Q^2 \leq 2\ \mathrm{GeV}^2$), where the double scattering term dominates, leads to a very good description of the data (see, e.g., [11]).

Since the diffractive cross sections are likely to be known with accuracy of about 10% for small t, it appears that the accuracy of the calculation of the nuclear shadowing correction to the inclusive cross section will be better than 0.2% for a wide range of Q^2. Correspondingly, the theoretical uncertainty for the ratio of F_2^n/F_2^p will not exceed 0.4%, which is likely to be smaller than possible experimental systematic errors.

A strategy, which is complimentary to the inclusive measurement of F_2^D, is to use the neutron and proton tagging. We will primarily focus on tagging of scattering off a neutron via the detection of the spectator protons and will comment only briefly on other possibilities.

It was pointed out above that, according to the AGK cutting rules [5], the overall correction of the nuclear shadowing effect for nondiffractive events is 4 times larger than for the inclusive scattering. However, it is concentrated at relatively large transverse momenta (k_t) of the protons and depends on k_t rather strongly. Hence, two strategies will be possible. One would be to select only very low p_t protons with a gross loss of statistics. The other, more promising approach is to measure the p_t dependence of the spectrum up to $p_t \sim 250\ \mathrm{MeV}/c$ and then to use this for the verification of the theory and for the measurement of the effects of the rescattering (nuclear shadowing) in an independent way with the subsequent correction of the data for this effect. Provided good momentum resolution of the proton spectrometer, one would be able to make longitudinal momentum cuts to suppress/increase the shadowing effect (the shadowing effects are minimal for $|2p_N/p_D - 1| \leq 0.1$).

The following analysis demonstrates the dependence of the nuclear shadowing correction to the $\gamma^* D \to pX$ cross section on the transverse momentum of the spectator proton p_t. The impulse approximation expression for the differential cross section of interest reads

$$\left.\frac{d\sigma^{\gamma^* D\to pX}}{d^3p}\right|_{\mathrm{IA}} = \sigma^{\gamma^* n}(2-2x_L)[u^2(p)+w^2(p)], \quad (4)$$

where $x_L = E_p/E_D \approx (1 - p_z/m_N)/2$ is the Feynman x of the spectator proton; $p = (p_t, p_z)$ is the three momentum of the detected (spectator) proton in the deuteron rest frame; u and w are the S-wave and D-wave components of the deuteron momentum space wave function normalized as $4\pi \int dp\, p^2[u(p)^2 + w(p)^2] = 1$; the factor $2 - 2x_L$ is the Müller flux factor. The presence of leading twist nuclear shadowing adds a nuclear shadowing correction to Eq. (4), so we find the following for the complete cross section:

$$\frac{d\sigma^{\gamma^* D\to pX}}{d^3p} = \sigma^{\gamma^* n}(2-2x_L)[u^2(p)+w^2(p)] - \frac{3-\eta^2}{1+\eta^2} \times \int_x^{x_0} dx_{\mathbb{P}} \int \frac{d^2q_t}{\pi} F_2^{D(4)}(\beta, Q^2, x_{\mathbb{P}}, t)\left[u(p)u(p') + w(p)w(p')\left(\frac{3}{2}\frac{(p\cdot p')^2}{p^2p'^2} - \frac{1}{2}\right)\right], \quad (5)$$

where $p' = p + q_t + (x_{\mathbb{P}} m_N)e_z$. The additional factor of $3 - \eta^2$ in front of the shadowing correction is a reflection of the AGK cutting rules. In the considered case, the shadowing correction is given by the sum of the two top graphs in Fig. 1. The left graph corresponds to the enhancement of the diffractive processes by the factor of $(1 - \eta^2)(\mathrm{Im}\,\mathcal{A})^2$, while the right graph corresponds to screening from the single inelastic subprocesses and is proportional to $-4(\mathrm{Im}\,\mathcal{A})^2$. In Eq. (5), the factor $u(p)u(p') + w(p)w(p')[3(p\cdot p')^2/(2p^2p'^2) - 1/2]$ is simply the unpolarized deuteron density matrix. Also, we neglected production of deuterons in the diffractive channel, which would somewhat increase the shadowing effect.

As one can see from Eq. (5), nuclear shadowing suppresses the spectrum of the produced protons. This effect can be quantified by considering the ratio R of the complete expression given by Eq. (5) to the impulse approximation expression given by Eq. (4). Figure 4 depicts the ratio R as a function of Bjorken x for $p_t = (0, 100, 200)\ \mathrm{MeV}/c$ and $p_z = 0$ (top panel) and for $p_t = 0$ and $|p_z| = 100\ \mathrm{MeV}/c$ (bottom panel). The calculation is made at $Q = 2$ GeV.

Two features of Fig. 4 are of interest and importance. First, nuclear shadowing works to decrease the ratio R as p_t increases. This is expected from the general picture of nuclear shadowing since large p_t corresponds to small transverse distances between the two nucleons, which leads to their shadowing, as was first pointed out by Glauber [12] and later generalized by Gribov [3]. Second, the suppression of R at large p_t is strikingly large. This is a common feature of semiexclusive reactions with nuclei. Indeed, at large p_t, while the impulse approximation term is suppressed by the nuclear wave function, the rescattering term survives and gives the dominant contribution. An example of this effect in electron-deuteron interactions in the Thomas Jefferson National Accelerator Facility kinematics can be found in Ref. [13].

Note also that there is a nonspectator contribution to the nucleon spectrum, which originates predominantly from diffractive scattering off the proton and dominates at large p_t, $p_t \geq 300\ \mathrm{MeV}/c$. As a result of the AGK cancellations, the nonspectator contribution is given by the impulse approximation. The contribution has a broad p_t distribution, $\propto e^{-Bp_t^2}$ with $B \sim 7\ \mathrm{GeV}^{-2}$, and can be

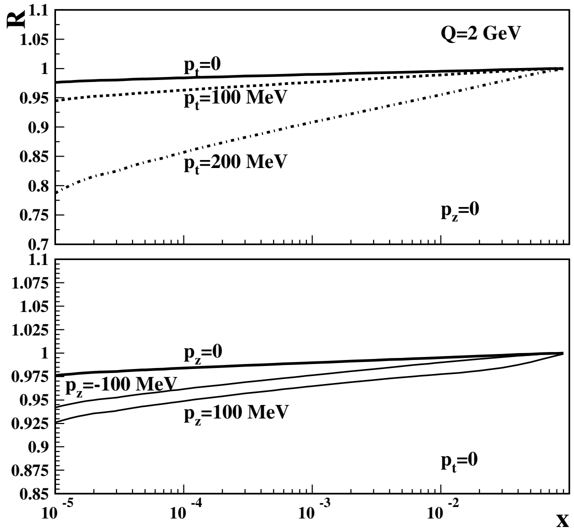

FIG. 4. The suppression of the proton spectrum by the nuclear shadowing correction. Top panel: The solid curve corresponds to $p_t = 0$; the dashed curve corresponds to $p_t = 100\,\mathrm{MeV}$; the dash-dotted curve corresponds to $p_t = 200\,\mathrm{MeV}$. Bottom panel: $p_t = 0$ and $p_z = (0, -100, +100)\,\mathrm{MeV}/c$.

subtracted using the measurements at, for instance, $p_t \geq 400\ \mathrm{MeV}/c$. It appears that it will be possible to use most of the spectator protons from most of the deuteron wave function in the tagged method. Hence, the spectator tagging will not lead to a loss of statistics. The method will allow one to introduce corrections for nuclear shadowing for small p_t with high precision, which would lead to theoretical errors in the determination of F_2^n at the level of a fraction of percent.

One can also use simultaneous tagging of protons and neutrons, when both neutron and proton are detected in the reactions $\gamma^* D \to nX$ and $\gamma^* D \to pX$. In this case, nuclear shadowing will cancel in the ratio $\sigma^{\gamma^* D \to nX}/\sigma^{\gamma^* D \to pX}$ and the main errors in the measurement of F_2^n will be due to the determination of relative efficiencies of the proton and neutron taggers.

One could also try to obtain the ratio F_2^n/F_2^p from the comparison of the rate of the tagged proton scattering events with the neutron spectator to inclusive eD scattering. Such a strategy could also have certain merits as it avoids the issue of luminosity and does not require a leading proton spectrometer. The disadvantage of this strategy is the sensitivity to the nuclear shadowing effects and errors in the acceptance of the neutron detector. One possible way to deal with the latter problem will be to perform measurements at very small x and large energies, where the ep and en cross sections are equal to better than a fraction of 1% and, hence, one would be able to cross-check acceptances of the proton and neutron detectors.

Note also that taking proton data from an independent run will potentially lead to another set of issues such as relative luminosity, the use of different beam energies, etc., which is likely to be on the level of 1%.

In our analysis, we neglect possible non-nucleonic components of the deuteron wave function such as kneaded (six-quark) components, etc. Current estimates put an upper limit on the probability of such components on the level of less than 1%, and they are expected to modify predominantly the high-momentum component of the deuteron wave function. Hence, the non-nucleonic components should give a very small (less than 1%) correction for the spectator momenta $\leq 200\ \mathrm{MeV}/c$. Moreover, the experiments at the EIC looking for production of baryons such as Δ and N^* in the spectator kinematics, $x_L(\Delta, N^*) \geq 1/2$, would allow one to put a more stringent upper limit on (discover) non-nucleonic components of the deuteron wave function.

In conclusion, we have demonstrated that a combined analysis of inclusive and semi-inclusive scattering off the deuteron coupled with a high resolution proton spectrometer will allow for the measurement of F_2^n at small x with the theoretical uncertainty of better than 0.5%. It would be a challenge to reduce the experimental systematic errors to a comparable level. The measurement of the shape of the spectator spectrum would allow one to determine nuclear shadowing in the deuteron with precision by far exceeding that possible in the inclusive measurements.

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