Antishadowing in the Rescaling Model at $x \sim 0.1$

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Abstract—The antishadowing behavior of the sea and valence quark densities in nuclei is investigated in the framework of the rescaling model at the values of the Bjorken variable $x \sim 0.1$.

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1. INTRODUCTION

The analysis of deep-inelastic scattering (DIS) of leptons off nuclei carried out in the valence quark dominance region and first published by the European Muon Collaboration (EMC) [1] showed that there is a visible effect unexplainable by the naive picture of a nucleus as being a bound system of quasi-free nucleons. (for a review see, e.g., [2, 3]).

Nowadays there are two main approaches to studying this effect. In the first one, which is at present more common, nuclear parton distribution functions (nPDFs) are extracted from the global fits (see a recent review [4] and references therein) to nuclear data by using empirical parametrizations of their normalizations and the numerical evaluation of Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) equations [5]. The second strategy is based upon some models of nuclear PDFs (see different models in, for example, [6–9] and a review [10]).

Here we will follow the rescaling model [7, 8], which is based on suggestion [9] that the effective confinement size of gluons and quarks in the nucleus is greater than in a free nucleon. In the framework of perturbative QCD it was found [7–9] that such a change in the confinement scale predicts that nPDFs and usual (nucleon) PDFs can be related by simply rescaling their arguments. Therefore, it can be said that the rescaling model demonstrates features that belong to both above approaches: in its framework there are certain relations between usual and nuclear PDFs that result from shifting the values of kinematical variable $\mu^2$ and, at the same time, both densities obey DGLAP equations.

Originally, the rescaling model was established for the valence quark dominance region $0.2 \leq x \leq 0.8$. Recently its applicability to the region of small $x$ values has been extended in [11], where a certain shadowing effect has been found for the sea quark and gluon densities.

The aim of the present short paper is to extend our small $x$ results obtained in [11] to the range $x \sim 0.1$ and to assess an antishadowing effect in that region.

2. STRUCTURE FUNCTION $F_2$

The DIS structure function (SF) $F_2$ in the leading order (LO) approximation, which is dealt with in the present paper, has the following form

$$F_2(x, \mu^2) = e(f_q^S(x, \mu^2) + f_q^V(x, \mu^2)) + \Delta f_q^{NS}(x, \mu^2), \quad (1)$$

where $e = \left(\sum_q |\bar{q}^q|^2\right)/\langle f_q^q \rangle$ is an average of the squared quark charges, $\Delta$ is the difference between charges of upper quarks and the average $e$, and $f_q^S(x, \mu^2)$, $f_q^V(x, \mu^2)$ and $f_q^{NS}(x, \mu^2)$ are sea, valence and nonsinglet parts of quark parton density.

Below we will study only PDFs in the deuteron and, therefore, the contribution of the nonsinglet part $f_q^{NS}(x, \mu^2)$ can be omitted in the present analysis (see, for example, recent paper [12] that discusses this possibility). So, below we will restrict ourselves to considering sea and valence parts only.

Since we plan to extend the low $x$ PDF analysis obtained in [11] up to $x \sim 0.1$ the parton densities
\[ f_q^S(x, \mu^2) \text{ and } f_q^V(x, \mu^2) \text{ given above should be represented in the following form } [14] \]
\[ f_q^R(x, \mu^2) = f_q^R(x, \mu^2)(1 - x)^{\beta_0(s)}, \quad s = \ln \left( \frac{a_\mu^2}{a_{\mu_0}^2} \right), \]
\[ a_\mu^2 = \frac{\alpha_\mu^2}{4\pi} = \frac{1}{\beta_0 \ln(\mu^2/\Lambda_{LO}^2)}, \]
where hereafter \( R = S, V \) and \( a_\mu^2 \) is the strong coupling constant. In the above expressions the large \( x \) asymptotics, which starts to be important already at \( x - 0.1 \), is explicitly displayed. We would like to note that here it is possible to use the following
\[ \beta_0(s) = \beta_0(0) + \frac{16\pi^2}{3\beta_0}, \]
\[ \beta_0(0) - 3, \quad \beta_3(s) - \beta_3(0) + 2. \]

The last two relations come from the quark counting rules [15] and usually agrees with the results of fits (see, for example, [12, 13]).

### 2.1. Sea Part

At LO the small-\( x \) asymptotic expressions for sea quark and gluon densities \( f_q \) can be written as follows (the next-to-leading order (NLO) results can be found in [16]):
\[ f_q^s(x, \mu^2) = f_q^s(x, \mu^2) + f_q^s(x, \mu^2), \]
\[ f_q^d(x, \mu^2) = \left( A_q + \frac{4}{9} A_g \right) I_0(\rho) e^{-\rho s} + O(\rho), \]
\[ f_q^s(x, \mu^2) = \frac{f}{9} A_q + \frac{4}{9} A_g \right) I_1(\rho) e^{-\rho s} + O(\rho), \]
\[ f_q^d(x, \mu^2) = -\frac{4}{9} A_q e^{-\rho s} + O(x), \]
\[ f_q^s(x, \mu^2) = A_q e^{-\rho s} + O(x), \]
where \( I_\nu(\nu = 0, 1) \) are the modified Bessel functions with
\[ \sigma = 2 \sqrt{\sigma_\mu s \ln \left( \frac{1}{x} \right)}, \quad \rho = \frac{\sigma}{2 \ln(1/x)}, \]
\[ \hat{\sigma} = \frac{12}{\beta_0}, \quad \hat{\rho} = 1 + \frac{20 f}{27 \beta_0}, \quad d = \frac{16 f}{27 \beta_0}. \]
Here the factors \( \mu_0^2, A_q \) are free parameters obtained in [11] and given there in Table 1.

### 2.2. Valence Part

For the valence part we have (see, for example, [14] and references therein)
\[ \tilde{f}_q^V(x, \mu^2) = \tilde{f}_q^V(x, \mu^2) = A_q(s)x^{\lambda_0}, \quad A_q(s) = A_q(0)e^{-d_0 \ln(1 - \lambda_0)s}, \]
where
\[ d_{NS}(n) = \frac{16}{3\beta_0} \left[ \Psi(n + 1) + \gamma_e - \frac{3}{4} - \frac{1}{2n(n + 1)} \right], \]
and the quantities \( \lambda_0^i \) and \( A_q(0) \) are free parameters obtained in [14] (quoted there in Table 1) and \( \Psi(n + 1) \) is a Euler \( \Psi \)-function.

It is also interesting to consider parametrization of the valence part proposed in [17], where it is expressed as a combination of the corresponding contributions of \( u \) and \( d \) quarks:
\[ \tilde{f}_q^V(x, \mu^2) = \sum_{i=1,2} \tilde{f}_q^{V_i}(x, \mu^2), \quad \tilde{f}_q^{V_i}(x, \mu^2) = A_{q_i}(s)x^{\lambda_0^i}, \]
\[ \lambda_0^i = q_i = u, \quad q_2 = d. \]

The values for \( A_{q_i}(0) \equiv N_i \) and \( \lambda_0^i = a_i \) can be found in Table 1 of [17].

We note that all the results will be obtained by using the analytic coupling constant [18] (see discussion in [11]), which usually leads to stable results at low \( \mu^2 \) values [19].

Note also that the Eqs. (4), (6) and (8) are in principle dealing with different \( s \) values, because results obtained in [14, 16, 17] contain similar but not equal values of the parameters \( \mu^2 \)-evolutions. However, it is not as important for the presentation and therefore in what follows we keep always the same parameter \( s \).

### 3. Rescaling Model

In the rescaling model [8] SF \( F_2(x, \mu^2) \) and parton densities, are modified by rescaling \( \mu \) variable in the case of a nucleus \( A \). Note that it is usually convenient to study the following ratio
\[ R_{F_2}^{AP}(x, \mu^2) = \frac{F_2^A(x, \mu^2)}{F_2^P(x, \mu^2)}, \]
since the nuclear effect in a deuteron is very small\(^1\).

We can suggest that
\[ F_2^D(x, \mu^2) = e^{f_2^D(x, \mu^2)} + f_2^V(x, \mu^2), \]
\[ F_2^A(x, \mu^2) = e^{f_2^{AS}(x, \mu^2)} + f_2^{AV}(x, \mu^2), \]
\[ f_2^{AS}(x, \mu^2) = f_2^{A+}(x, \mu^2) + f_2^{A-}(x, \mu^2), \]
\[ f_2^{AV}(x, \mu^2) = f_2^{AV}(x, \mu^2), \]
\[ f_2^{A+}(x, \mu^2) = f_2^{A+}(x, \mu^2), \]
\[ f_2^{A-}(x, \mu^2) = f_2^{A-}(x, \mu^2). \]

\(^1\) The study of nuclear effects in a deuteron can be found in the recent paper [20], which also contains short reviews of preliminary investigations.
where $f_{g}^{V}(x, \mu^2)$ and $f_{q}^{V}(x, \mu^2)$ are given in Eqs. (4), (5) and (6) with

$$\delta_{k}^{AD} = \ln \left( \frac{\mu_{0}^{2}}{\Lambda^{2}} \right) \times \ln \left( \mu_{0}^{2} \Lambda^{2} \right) = s + \ln(1 + \delta_{k}^{AD}),$$

(11)
i.e. the nuclear modification of the basic variable $s$ depends only on the parameters $\delta_{1}^{AD}$ and $\delta_{2}^{AD}$, which are $\mu^{2}$, $\mu_{0}^{2}$ and $\Lambda$ independent (see [11]).

The results for $\delta_{1}^{AD}$ and $\delta_{2}^{AD}$ are obtained in [11]. In the lead case they are as follows:

$$\delta_{1}^{AD} = -0.346, \quad \delta_{2}^{AD} = -0.779, \quad \delta_{3}^{AD} = 0.14.$$ (12)

4. RESULTS

A positive modification of $R_{F2}^{AD}(x, \mu^2)$ at $x \sim 0.1$ was predicted [21] by using the momentum sum rule. Similar behavior was also suggested [22] on the basis of interference in the multiple scattering description.

The Fermilab E772 Drell–Yan experiment indicated [23] no nuclear modification in antiquark distributions, so that the antishadowing in $R_{F2}^{AD}$ should be ascribed to the valence quark modifications. It is demonstrated in Fig. 1 by EPPS16 results [24], where the blue line shows a sea contribution while the red points represent a complete contribution. It is this observation that was behind the motivation to consider the valence density $f_{V}^{q}(x, \mu^2)$ in the present analysis.

The obtained results for $R_{F2}^{AD}(x, \mu^2)$, which are for $x \leq 10^{-2}$ very close to those derived in [11], show (see Fig. 1) an appearance of the antishadowing effect for $x \sim 0.06$ and it rise with increasing $x$ values all the way up to $x \geq 0.1$, which is a limit of the current consideration. The results are actually shown up to $x \sim 0.2$; however, for the values higher than $x \sim 0.1$ they cannot be as accurate.

The results obtained for two differently parameterized valence quark densities, proposed in [14] and [17], are close to each other. It is seen that GJR08 parametrization exhibits a weaker antishadowing effect. Both curves lie a bit higher than the EPPS16 ones. However, all the results are completely consistent within uncertainties of the EPPS16 analysis (see the pink band).

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