On the similarity of the parton distributions in nuclei with more than three nucleons

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Abstract

It is shown that the latest results from NMC and E665 on the $F_A^2(x)/F_D^2(x)$ obtained in the shadowing region, bring new evidence of the universal $A$-dependence of distortions of a free nucleon structure function by nuclear medium. The universality holds in the entire $x$-range and can be explained as a saturation of the distortions of the parton distributions in a four-nucleon system.

The effects of the distortion of a free-nucleon structure by a nuclear medium are usually observed as a deviation from unity of the ratio $r_A(x)\equiv F_A^2(x)/F_D^2(x)$, where $F_A^2(x)$ and $F_D^2(x)$ are the structure functions per nucleon measured in a nucleus of mass $A$ and a deuteron, respectively.

Below we compare the $A$ dependence of distortions found in the analysis of recent data collected from the DIS of muons on nuclei in the range $10^{-3}<x<0.7$ by the NMC (CERN) [3, 4] and E665 (Fermilab) [5] collaborations with the distortions which we obtain from the analysis of SLAC and BCDMS data obtained in the range of $x>0.2$ [6].

We consider structure function distortions as independent of the $Q^2$ at which $r_A(x)$ is measured. This is justified by conclusions about the $Q^2$ independence of $r_A$ in the range $0.2\text{ GeV}^2<Q^2<200\text{ GeV}^2$ (c.f. Refs. [3]–[7]).

In Refs. [1, 2] it was found that the $x$ dependence of $r_A(x)$ can be factorized into three parts in the region $0.001<x<0.7$, in accordance with the differences in the $r_A(x)$ behaviour found in the three intervals of the considered range — namely the (1) shadowing, (2) anti-shadowing and (3) EMC effect regions:

$$r_A(x)\equiv F_A^2(x)/F_D^2(x) = x^{m_1}(1+m_2)(1-m_3x).$$

(1)

The parameters $m_i$, $i=1-3$, can be treated as the distortion magnitude of the nucleon structure function introduced for each interval. There are two physical reasons for parametrizing $r_A(x)$ in the form of Eq. (1). First, as was shown in Ref. [8], the nucleon structure function behaves as $F_2(x)\sim x^{-\lambda}$ in the range of small $x$, which is motivated by BFKL dynamics. Hence, combinations such as $F_A^2(x)/F_D^2(x)$ should obey a power law as well. Second, the parameters $m_2$ and $m_3$ enter Eq. (1) in a manner similar to the suggestion of Ref. [9], whereby local nuclear density is related to the deviation of $r_A(x)$ from unity in the range $x>0.3$. 
The parameters $m_i$ were determined by fitting $r^A(x)$, measured on seven nuclear targets — He $[3, 6]$, Li $[4]$, C $[4, 6]$, Ca $[3, 6]$, Xe $[10]$, Cu $[11]$ and Pb $[5]$ — with Eq. (1). We used in the fit the total experimental error determined by adding statistical and systematic errors at each point in quadrature. For each of seven nuclei, good agreement ($\chi^2$/d.o.f.$\leq 1$) with Eq. (1) was found, thus proving that the characteristic pattern of the structure function modifications, well described for the helium nucleus by Eq. (1), remains unchanged for heavier nuclei. We consider this a manifestation of the universality of the $x$ dependence of the distortions of the free-nucleon structure function in a nuclear environment.

The results of the fit are given by the solid line in Fig. 1 for $^4$He, Li, C and Ca nuclei. The experiment in the SLAC electron beam $[6]$ used a larger set of nuclear targets. The data however belong to a limited $x$-range, $0.2 < x < 0.9$, that does not allow to study $r^A(x)$ in the shadowing and anti-shadowing regions. On the other hand they are the only data, which can be used for the study of the distortions of nucleon structure functions in the range $x > 0.7$. In order to perform such analysis we approximate the data of Refs. $[6, 7]$ with Eq. (1) modified by introducing one more parameter $m'_4$:

$$r^A(x) \equiv F^A_2(x)/F^D_2(x) = x^{m'_1(1 + m'_2)}(1 - m'_3x)\frac{exp(-(m'_4x)^2)}{(1-x)^{m'_4}}. \quad (2)$$
Figure 2: The results of the fit with Eq. (3) of the $F_A^2/F_D^2$ measured on $^4$He [6], Be [6], Ca [6] and Fe [6,7] $r^A(x)$ in the high-$x$ range.

Though Eq. (4) represents only rough approximation of nuclear effects when $x \to 1$, it provides good description of the data available in the high-$x$ range (c.f. Fig. 2) and thus serves our purpose of quantitative determination of the distortions of the nucleon structure function. The obtained parameters $m_i$, which are displayed in Fig. 3, increase from their minimum value $m_i$(He) at $A = 4$ to $m_i(A) \approx 3m_i$(He) for $A > 40$, indicating that distortions in heavy nuclei are independent of the size of the nucleus.

The parameters $m_i$ vary similarly with $A$ in all four intervals in which the distortions were depicted. The points in Fig. 3 are approximated by the following equation:

$$m_i(A) = N_i \left(1 - \frac{A_S}{A}\right).$$

This coincides, except for the normalization parameter $N_i$, with the factor $\delta(A)$ suggested in Ref. [12] for explaining the $A$ dependence of the EMC effect by variation of the nuclear surface-to-volume ratio with $A$. The number of nucleons $A_S$ at the nuclear surface was obtained in Ref. [12] using a Woods–Saxon potential with parameters taken from Ref. [13].

The four lines in Fig. 3, a, b, c and d, differ only in the normalization factor $N_i$. The observed similarity in variations of $m_i$ give evidence for a universal $A$ dependence of the distortion magnitudes $m_i$ of the nucleon structure function in all four regions. This universality can be expressed in terms of the relative distortions, measured in nuclei $A_1$ and $A_2$ with the following relation:

$$\frac{m_1(A_2)}{m_1(A_1)} = \frac{m_2(A_2)}{m_2(A_1)} = \frac{m_3(A_2)}{m_3(A_1)} = \frac{m_4(A_2)}{m_4(A_1)}.$$

One can as well define the value of structure function distortion in units of that measured in the helium nucleus, $s_h = m_i(A) / m_i$(He). By definition, $s_h = 1$ for $A = 4$, and, as follows from the obtained numerical values of $m_i$, $s_h$ increases with $A$ to $\sim 3$ for heavy nuclei, independent of $x$. Eqs. (1) and (3) provide the approximation of $F_A^2(x)/F_D^2(x)$ in two dimensions displayed in Fig. 4 valid in the range of the present analysis, $A \geq 4, 10^{-3} < x < 0.7$. 

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Figure 3: The parameters $m_i, i=1-4$, determined in the regions of nuclear shadowing (a), anti-shadowing (b), EMC effect (c) and in the high $x$-range (d). Full lines show a variation in nuclear density given by the Woods–Saxon potential, with parameters fixed from the data on elastic electron–nucleus scattering.
We suggest that modifications to the parton distributions of the nucleon bound in a nucleus evolve as a function of atomic mass $A$ in two stages. In the first stage, the distributions of partons belonging to the lightest nuclei, $2 < A \leq 4$, are modified drastically compared to those of a free nucleon, thus distorting the structure function $F_2(x)$. These distortions, which can be observed in a $^4$He nucleus as a characteristic oscillation of $r^A$ around the line $r^A = 1$, remain frozen in shape in the second stage of distortions, which occur in nuclei with mass $A > 4$. In contrast to the first stage, in the second there is no restructuring of parton distributions, which can change the shape of the oscillation described by Eq. (1). Instead, the distortions increase in magnitude throughout the entire $x$ range, following the functional form (3).

There are evidently two different mechanisms behind this picture, which we denote as hard or soft distortions, depending on whether $A \leq 4$ or $A > 4$. Quantitatively, this can be expressed with the parameter $s_h$, which rapidly changes in the range of hard distortions, from 0 to 1 ($\Delta A = 2$), and only slowly in the range of soft distortions, from 1 to $\sim 3$ ($\Delta A \approx 200$). A particular case of the hard distortion mechanism, which works at $A = 4$, has been considered in Refs. [14, 15], in which EMC effect was explained by the 12-quark structure of nuclei. The dynamical model for the EMC effect, in which gluons and exchanged quarks (antiquarks) are responsible for the interaction between three (or four) nucleons, has been suggested in Refs. [12, 16].

In terms of the two-mechanism model, the experimental observations can be interpreted as follows: hard distortions are saturated at $A = 4$, which can be understood if modifications of parton distributions in the nuclear environment are closely related to short-range nuclear forces. In this picture functional form of $r^A(x)$ and, therefore, positions of the three cross-over points with the line $r^A = 1$ should be different when they are obtained in $^3$He and $^4$He nuclei. Before such data are available one can not exclude the possibility that the saturation is reached at $A = 3$.

In summary, we have shown that the recent data on the DIS of electrons and muons off nuclei bring new evidence for the universality of the $x$ and $A$ dependence of distortions of a free-nucleon structure function, $F_2(x)$, by a nuclear medium, when $A \geq 4$. Such universality imply that hard distortions of parton distributions are saturated at $A = 4$ (or even at $A = 3$) and that the observed differences between the DIS cross-sections for nuclei with masses $A_1$, $A_2 \geq 4$ are due to soft distortions. The latter are similar in the entire $x$-range and vary from 1 in $^4$He to $\sim 3$ in $^{207}$Pb. They can be well understood as a nuclear density effect if the surface nucleons are excluded from consideration.

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Figure 4: Approximation of the $F_2^A(x)/F_2^D(x)$ as a function of atomic mass $A$ and $x$ in the range $A \geq 4, 10^{-3} < x < 0.7$. 