Eur. Phys. J. C 10, 239–247 (1999)
Digital Object Identifier (DOI) 10.1007/s100529900107

The European Physical Journal C

Determination of the pattern of nuclear binding from the data on lepton–nucleus deep inelastic scattering*

G.I. Smirnov

Joint Institute for Nuclear Research, Dubna, Russia (G.Smirnov@cern.ch)

Received: 28 January 1999 / Revised version: 1 April 1999 / Published online: 3 August 1999

Abstract. Nucleon structure function ratios $r^A(x) = F_2^A(x)/F_2^{\rm D}(x)$ measured in the range of atomic masses $A \geq 4$ are analyzed with the aim of determining the pattern of the x and A dependence of $F_2(x)$ modifications caused by the nuclear environment. It is found that the x and A dependence of the deviations of the $r^A(x)$ from unity can be factorized in the entire range of x. The characteristic feature of the factorization is represented with the three cross-over points x_i, $i = 1$–3 in which $r^A(x) = 1$ independently of A. In the range $x > 0.7$ the pattern of $r^A(x)$ is fixed with $x_3 = 0.84 \pm 0.01$. The pattern of the x dependence is compared with theoretical calculations of Burov, Molochkov and Smirnov to demonstrate that the evolution of the nucleon structure as a function of A occurs in two stages: first for $A \leq 4$ and second for $A > 4$. The long-standing problem of the origin of the EMC effect is understood as a modification of the nucleon structure in the field responsible for the binding forces in a three-nucleon system.

1 Introduction

After nearly two decades of experimental and theoretical investigations of the EMC effect, we have rapidly accumulating evidence that nuclear binding is the only physical mechanism which can be responsible for the modification of the nucleon partonic structure by the nuclear medium. The modifications are usually observed as a deviation from unity of the ratio $r^{A/{\rm D}}(x) \equiv F_2^A(x)/F_2^{\rm D}(x)$, where $F_2^A(x)$ and $F_2^{\rm D}(x)$ are the structure functions per nucleon measured in a nucleus of mass A and in a deuteron, respectively.

The publication [1] of the results from SLAC added to the EMC effect controversy with the statement that the data on $r^A(x)$ do not directly correlate with the binding energy per nucleon. To clarify the role of binding forces I have suggested [2] to determine the pattern of $r^{A/{\rm D}}(x)$, which clearly conveys the message about saturation of the modifications of $F_2(x)$ already at $A = 4$. The saturation, according to [2], had to make itself manifest not in the amplitude of the oscillations, but in the pattern of the x dependence of $r^{A/{\rm D}}(x)$, namely in the positions of the three cross-over points x_i, in which $r^{A/{\rm D}}(x_i) = 1$. Such a pattern can clearly be seen from the re-evaluated ratios $r^{A/{\rm D}}(x)$ of SLAC [1] and NMC [3].

In the present paper I analyze all the data on the ratio of the F_2^A and $F_2^{\rm D}$ structure functions available from electron– and muon–nucleus deep inelastic scattering experiments (DIS) and extend my analysis to the range of $x \to 1$. Strictly speaking, the effect of modifications is a function of three variables, x, Q^2 and A. I will use the data which belong to the range $0.5 < Q^2 < 200\,{\rm GeV}^2$ and which are obtained on deuteron and nuclear targets from $A = 4$ to $A = 208$. Following the convention of the first EMC publication [4] I disregard modifications of $F_2(x)$ in a deuterium nucleus.

As is known from experiments (see [1,3]), the pattern of the EMC effect is Q^2 independent within a wide range of x. This is consistent with the results of [5], in which the Q^2 evolution of the modifications is considered in the leading order of QCD. It is shown in [5], that QCD evolution effect in the ratio of tin-to-carbon structure functions is smaller than experimental errors everywhere in the x range, except for the region of $x < 0.05$, in which the effect becomes comparable with errors. This gives the arguments to investigate, below, the x and A dependence of nuclear effects after integrating them over Q^2. The analysis includes recent measurements of the ratios $r^{A/{\rm C}}(x) \equiv F_2^A(x)/F_2^{\rm C}(x)$ [6].

As a result, I determine the pattern of the modification of the nucleon partonic structure which evolves in A independently of x if $A > 4$. I also show that the missing patterns of the EMC effect in the lightest nuclei, which have been recently obtained in [7], are decisive for the understanding the role of nuclear binding both for the x and for the A dependence of the effect as well as for the understanding origin of the EMC effect.

2 Distortion pattern as a function of x and A

As has been shown in [2,8], the pattern of the oscillations of $r^{A/{\rm D}}(x)$ has a universal shape in the range of $10^{-3} < x < 0.7$ and in the range of atomic masses $A \geq 4$,

* Electronic version: hep-ph/9901422

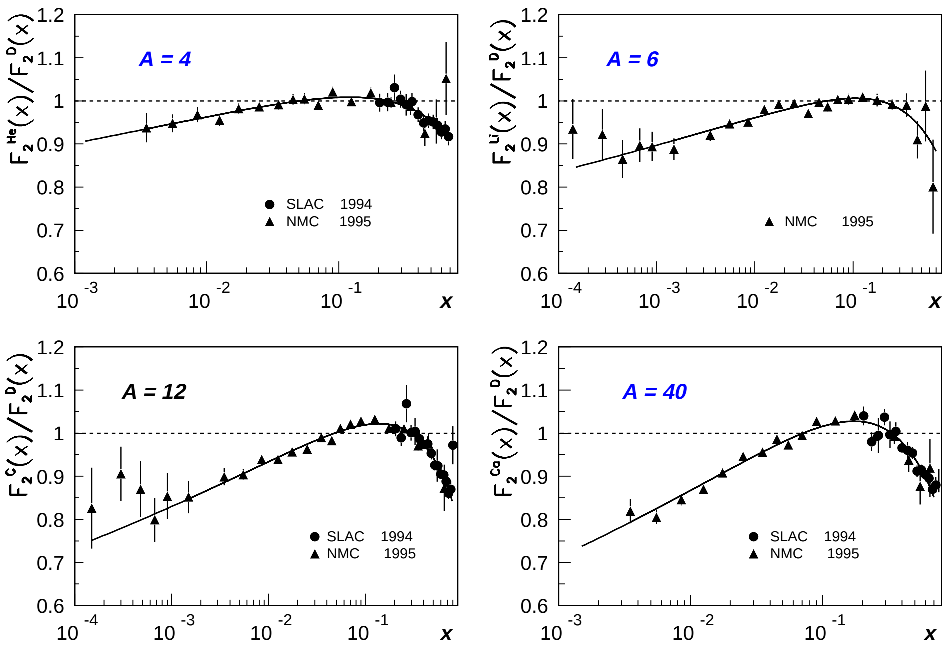

Fig. 1. The results of the fit with (1) of F_2^A/F_2^{D} measured by NMC and SLAC in the range $0.0001 < x < 0.7$

where the data from SLAC and NMC have been obtained. Namely, the ratio $F_2^A(x)/F_2^{\mathrm{D}}(x)$ could be well approximated with the simplest phenomenological function,

$$r^{A/\mathrm{D}}(x) \equiv F_2^A(x)/F_2^{\mathrm{D}}(x) = x^{m_{\mathrm{sh}}}(1+m_{\mathrm{anti}})(1-m_{\mathrm{EMC}}x), \tag{1}$$

which contained only one free parameter m_i for each of the following three kinematic intervals: (1) *nuclear shadowing*, (2) *antishadowing* and (3) *EMC effect*. By definition, $m_i(A=2)=0$ and thus can serve for quantitative evaluation of the $F_2(x)$ modifications in nuclei with $A>2$.

The agreement between the results of SLAC and NMC experiments significantly improved after NMC had presented the re-evaluated data [3]. As a result, the agreement between the data and (1) (c.f. Fig. 1) has also improved, which allows for a better evaluation of the parameters m_i as a function of A. Approximation of the data for all available atomic masses A with (1) turned out to be convenient for the demonstration of the factorization of the x and A dependence of the $F_2(x)$ modifications in nuclei in a wide range of x. In other words, the evolution of the x dependence of $r^A(x)$ ceased either at $A=3$ or $A=4$ [2], which is very consistent with the phenomenon of *saturation* of nuclear binding forces in a few-nucleon system. This conclusion, of course, does not depend on the form which one uses for the approximation of $r^A(x)$. However, the number of parameters used for the approximation may be critical for the understanding of the modification pattern if the experimental errors in $r^A(x)$ are compared with its deviations for unity.

The magnitudes m_i of the distortions of $F_2(x)$ by the nuclear environment have been found to increase monotonically with A and to vary similarly [2,8] in all the intervals that used to be regarded as the domains for one particular mechanism of the $F_2(x)$ modifications. The A dependence of m_i can be approximated in each interval as

$$m_i(A) = M_i(1-N_{\mathrm{s}}(A)/A), \qquad i=1,2,3, \tag{2}$$

where the M_i are normalization parameters and $N_{\mathrm{s}}(A)$ is the number of nucleons on a nuclear surface evaluated with the Woods–Saxon potential and with parameters established in the elastic scattering of electrons off nuclei. I show below that (2) is also valid for the evaluation of A-dependent modifications of $F_2(x)$ beyond $x=0.7$, within the entire *binding* effects interval $0.3<x<0.96$:

$$m_{\mathrm{b}}(A) = M_{\mathrm{b}}(1-N_{\mathrm{s}}(A)/A). \tag{3}$$

As has been shown in a number of publications reviewed in [9,10], the pattern of the $F_2(x)$ modifications in the range $0.3<x<1.0$ could be qualitatively reproduced with nuclear binding effects and Fermi motion corrections. On the other hand, a quantitative description of the $r^{A/\mathrm{D}}(x)$ within the conventional nuclear-structure models has been getting worse with improvements of both the data quality and of the model considerations. The situation has been considered as indicating the presence of quark degrees of freedom in heavy nuclei, which could be used to motivate measurements of $F_2^A(x)$ at $x>1$. A number of models (c.f. [10]) were in contradiction with the frozen pattern of modifications of $F_2(x)$ found from experiment. Some recent publications have come up with statements that the nucleon structure is not very much affected by nuclear binding [11].

At the same time it was clear that the relation between the EMC effect and nuclear binding effects, recognized by many authors (c.f. [12–14]), could not be discussed regardless of the phenomenon of *saturation* of nuclear binding forces in the lightest nuclei. The first attempt to evaluate the evolution of $F_2(x)$ in the range $A\leq 4$ has been made in [7] by developing a relativistic approach for the consideration of nuclear binding effects in $F_2(x)$. The calculated pattern of the $r^{A=3/D}(x)$ turned out to be similar to that of $r^{\mathrm{Fe/D}}(x)$ determined from experiments, but smaller in magnitude of the deviation of the ratio from unity. This

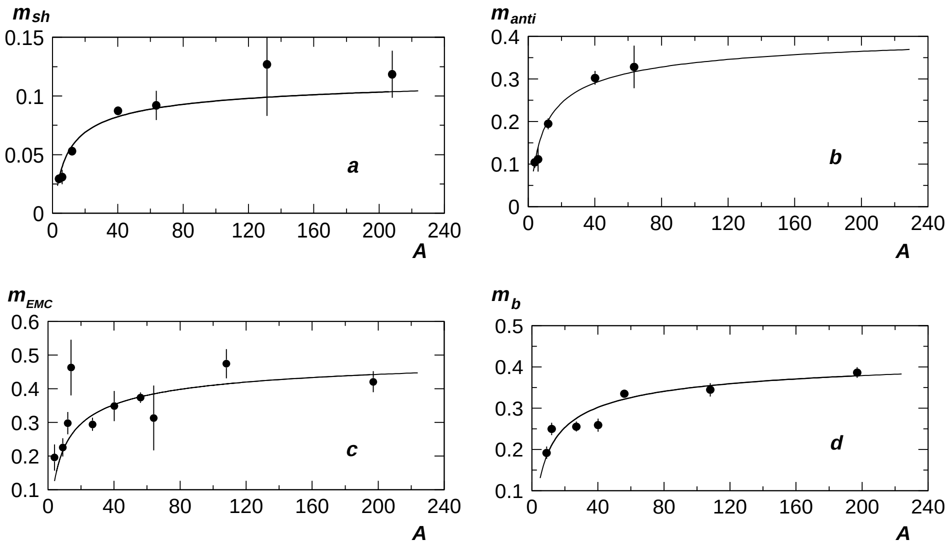

Fig. 2a–d. The parameters m, which define the magnitude of distortions of $F_2(x)$, determined in the regions of nuclear shadowing **a**, antishadowing **b**, EMC effect **c** and in the high x range **d**. The full lines in **a**–**c** are obtained with (2) and in **d** with (3). The number of nucleons $N_s(A)$ at the nuclear surface is given by the Woods–Saxon potential:
$N_S(A) = 4\pi\rho_0 \int\limits_{r_0(A)}^{\infty} \frac{\mathrm{d}r r^2}{1+\mathrm{e}^{[r-r_0(A)]/a}}$

Table 1. Splitting of range of x in four intervals

(1)	*nuclear shadowing*	10^{-3}	$< x <$	0.1 ,
(2)	*antishadowing* region	0.1	$< x <$	0.3 ,
(3)	*EMC effect* region	0.2	$< x <$	0.65,
(4)	*nuclear binding*	0.3	$< x <$	0.96.

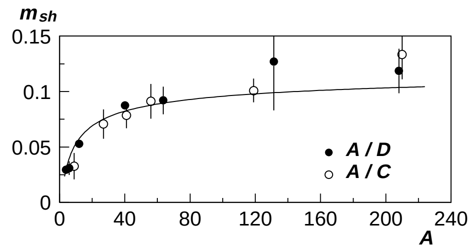

Fig. 3. The parameter m_{sh} evaluated from the data on $F_2^A(x)/F_2^{\mathrm{D}}(x)$ (full circles) and from $F_2^A(x)/F_2^C(x)$ (open circles). A full line is defined by (2)

means that the deviations found in the system $A = 3$ can be scaled to $A = 56$ with the x-independent parameter ρ:

$$1 - F_2^{\mathrm{Fe}}(x)/F_2^{\mathrm{D}}(x) = \rho(1 - F_2^{A=3}(x)/F_2^{\mathrm{D}}(x)). \quad (4)$$

The relation has to be considered as a theoretical justification of the factorization of the x and A dependence known from the data analysis of [2]. The purpose of my new analysis was to find from the experimental data the exact pattern of binding effects in the ratio $F_2^A(x)/F_2^{\mathrm{D}}(x)$ in the entire range of x, and to verify how well the theoretical calculations for $A \leq 4$ [7] could be made consistent with the available data for $A \geq 4$. I evaluate below the A dependence of the nucleon structure function distortions by splitting the range of x as shown in Table 1 in four intervals.

Even if there had existed four different mechanisms responsible for the x and A dependence of $r^{A/\mathrm{D}}(x)$ in these four intervals it would have been unlikely that they would have sharp boundaries in x. Therefore one can allow for an overlap in selection of the intervals.

2.1 Nuclear shadowing

In the range $x \ll 1$, which corresponds to the nuclear shadowing region, (1) reduces to

$$r^{A/\mathrm{D}}(x) = C^{A/\mathrm{D}} x^{m_{\mathrm{sh}}^{A/\mathrm{D}}}. \quad (5)$$

The available data on $r^{A/\mathrm{D}}(x)$ from the EMC [15], NMC [3,16] and E665 [17,18] collaborations are well approximated with (5), demonstrating thus the feasibility of the factorization of the x and A dependence in the shadowing region. The obtained parameters $m_{\mathrm{sh}}^{A/\mathrm{D}}$ as a function of A are displayed in Fig. 2a. The full line is defined by (2) with $M_{\mathrm{sh}} = 0.129$.

It is also clear that the same pattern holds for the ratio of any pair of nuclei and therefore the deuteron can be replaced by some other reference nucleus, for instance by carbon:

$$r^{A/\mathrm{C}}(x) \equiv F_2^A(x)/F_2^{\mathrm{C}}(x) = C^{A/\mathrm{C}} x^{m_{\mathrm{sh}}^{A/\mathrm{C}}}. \quad (6)$$

I find that the recent NMC results on the structure functions ratios measured on Be, Al, Ca, Fe, Sn and Pb targets with respect to carbon [6] are well approximated with (6). From a comparison of (5) and (6) I obtain the relation between the distortion magnitudes m_{sh} determined from the A/D and A/C data:

$$m_{\mathrm{sh}}^{A/\mathrm{D}} = m_{\mathrm{sh}}^{A/\mathrm{C}} + m_{\mathrm{sh}}^{\mathrm{C/D}}. \quad (7)$$

I apply (7) to the distortion parameters $m_{\mathrm{sh}}^{A/\mathrm{C}}$ evaluated from the data of [6] and plot the results in Fig. 3 together with the results of direct determination of $m_{\mathrm{sh}}^{A/\mathrm{D}}$. Larger errors from the A/C experiment are explained by a considerably larger nuclear shadowing effect in the carbon nucleus, which results in smaller differences between cross-sections measured on nuclear targets and on a carbon target. Within the experimental errors both experiments are consistent.

2.2 Antishadowing

As follows from the chosen form of the approximation function (1), the deviations of the parameter $m_{\mathrm{anti}}^{A/\mathrm{D}}$ from zero would detect nuclear medium effects in the *antishadowing* region. Antishadowing has not been studied so far quantitatively because of evident problems of the measurements of the effect it being comparable with experimental errors. This is why one cannot rely on the data which do not cover a considerably wider range than $0.1 < x < 0.3$. This concerns the data of BCDMS [19], E665 [18] and also the SLAC data [1] for some targets (Be, Al, Fe, Ag, Au). On the other hand, the SLAC and NMC [3] data on ^{4}He, C and Ca combined cover nearly the full x range and are very well suited for the studies of the small antishadowing effect. Equally good proved to be the data of NMC [16] for Li and of EMC [15] for the Cu targets. The obtained parameters $m_{\mathrm{anti}}^{A/\mathrm{D}}$ as a function of A are displayed in Fig. 2b. A full line is defined by (2) with $M_{\mathrm{anti}} = 0.456$.

2.3 EMC effect region

As will be shown below, the physics of the modifications of $F_2(x)$ in this range of x is understood as nuclear binding effects. Still, for the moment I consider the data in the region $0.25 < x < 0.65$ separately from the high x range because the largest number of data have been collected in this very region (10 nuclear targets) and they can all be reasonably well approximated with a linear equation:

$$r^{A/\mathrm{D}}(x) = a - m_{\mathrm{EMC}}x. \tag{8}$$

The obtained parameters $m_{\mathrm{EMC}}^{A/\mathrm{D}}$ as a function of A are displayed in Fig. 2c. A full line is defined by (2) with $M_{\mathrm{EMC}} = 0.553$.

2.4 Nuclear binding

As has been found in [7], modifications of the x dependence of $F_2(x)$ result from nuclear binding and are strongest in the four-nucleon system, ^{4}He. Modifications predicted for the three-nucleon system were found to be identical in form and different in amplitude from those experimentally observed in heavy nuclei. To verify the latter statement I introduce, below, two equations for an approximation of the data in the range $x > 0.3$,

$$r^{A/\mathrm{D}}(x) = 1 - m_b(A)a_{\mathrm{osc}}^{A=3}(x), \qquad A \neq 4, \tag{9}$$

$$r^{A=4/\mathrm{D}}(x) = 1 - m_b(A=4)a_{\mathrm{osc}}^{A=4}(x), \tag{10}$$

where $m_b(A)$ is a free parameter, $m_b(A=4) = 0.24$, and $a_{\mathrm{osc}}^{A=3(4)}(x)$ is defined as the relative difference between the structure functions of the 3(4)-nucleon system $F_2^{A=3(4)}(x)$ and that of the deuteron:

$$a_{\mathrm{osc}}^{A=3(4)}(x) \equiv \frac{1}{m_b(A=3(4))}(1 - F_2^{A=3(4)}(x)/F_2^{\mathrm{D}}(x)). \tag{11}$$

The evolution of the isoscalar nucleon structure function $F_2^{\mathrm{N}}(x)$ from $A = 1$ to $A = 4$, according to [7], is defined largely by a series of terms containing derivatives of $F_2^{\mathrm{N}}(x)$, $F_2^{\mathrm{D}}(x)$ and $F_2^{A=3}(x)$. In the simplest case of the input $F_2^{\mathrm{N}}(x) \sim (1-x)^3$ the modifications are represented as a power series of $1/(1-x)$ terms. Applying the well-established boundary condition $a_{\mathrm{osc}}(x_2) = 0$, I obtain a simple analytical equation which describes the modifications of the parton distributions caused by binding forces in the lightest nuclei:

$$a_{\mathrm{osc}}^{A=3(4)}(x) = \left(1 - \lambda^{A=3(4)}x\right) \times\left\{\left(\frac{1}{u} - \frac{1}{c}\right) - \mu^{A=3(4)}\left(\frac{1}{u^2} - \frac{1}{c^2}\right)\right\}, \tag{12}$$

where $u = 1-x$, $c = 1-x_2$, $\lambda^{A=3(4)} = 0.5$ (1.0). The parameter μ^A is defined by the requirement $a_{\mathrm{osc}}(x_3) = 0$ and its numerical value obtained in [7] corresponds to $\mu^{A=3(4)} = m_\pi/M$ $(m_\pi/2M)$, where m_π and M are the pion and nucleon masses.

It is important to note that (12) does not contain any free parameter except c, which is constrained by experimental results for x_2 and, as shown below, can also be expressed through the value of x_3. When evaluated with (12), $a_{\mathrm{osc}}^A(x)$ virtually coincides with numerical values of [7] for $x > 0.3$.

As obtained in [7], the coordinate x_3 for $A = 4$ is twice as close to the kinematic boundary as that for $A = 3$: $(1 - x_3^{A=3})/(1 - x_3^{A=4}) \approx 2$, which is reflected in the relation between the parameters $\mu^{A=3}$ and $\mu^{A=4}$ of (12). This makes the pattern of distortions for ^{4}He different from the rest of nuclei. It is compared with the data in Fig. 4. Experimental results for $A > 4$ in Fig. 4 are approximated with (9) with one free parameter $m_b(A)$. The results of the approximation are displayed in Fig. 4 as a function of x and in Fig. 2d as a function of A. A full line in Fig. 2d is defined by (3) with $M_{\mathrm{b}} = 0.473$. From the good agreement between theory and data, which is evident from Fig. 4, I find that the x dependence of the deviations from $r^{A/\mathrm{D}}(x) = 1$ remains unmodified in the entire range of atomic weights A and is well described by *scaling* the amplitude a_{osc} of deviations evaluated for $A = 3$. This means that modifications of $F_2(x)$ in heavy nuclei *saturate* even faster than in the lightest nuclei.

As demonstrated with Figs. 1–4, the x and A dependence of the modifications can be factorized in the entire range of x. The phenomenon is nicely reproduced with (1) and (2) in the range $x < 0.7$ and with (9) and (3) in the range $x > 0.3$. This gives one a simple tool to plot the two-dimensional pattern of modifications of the nucleon struc-

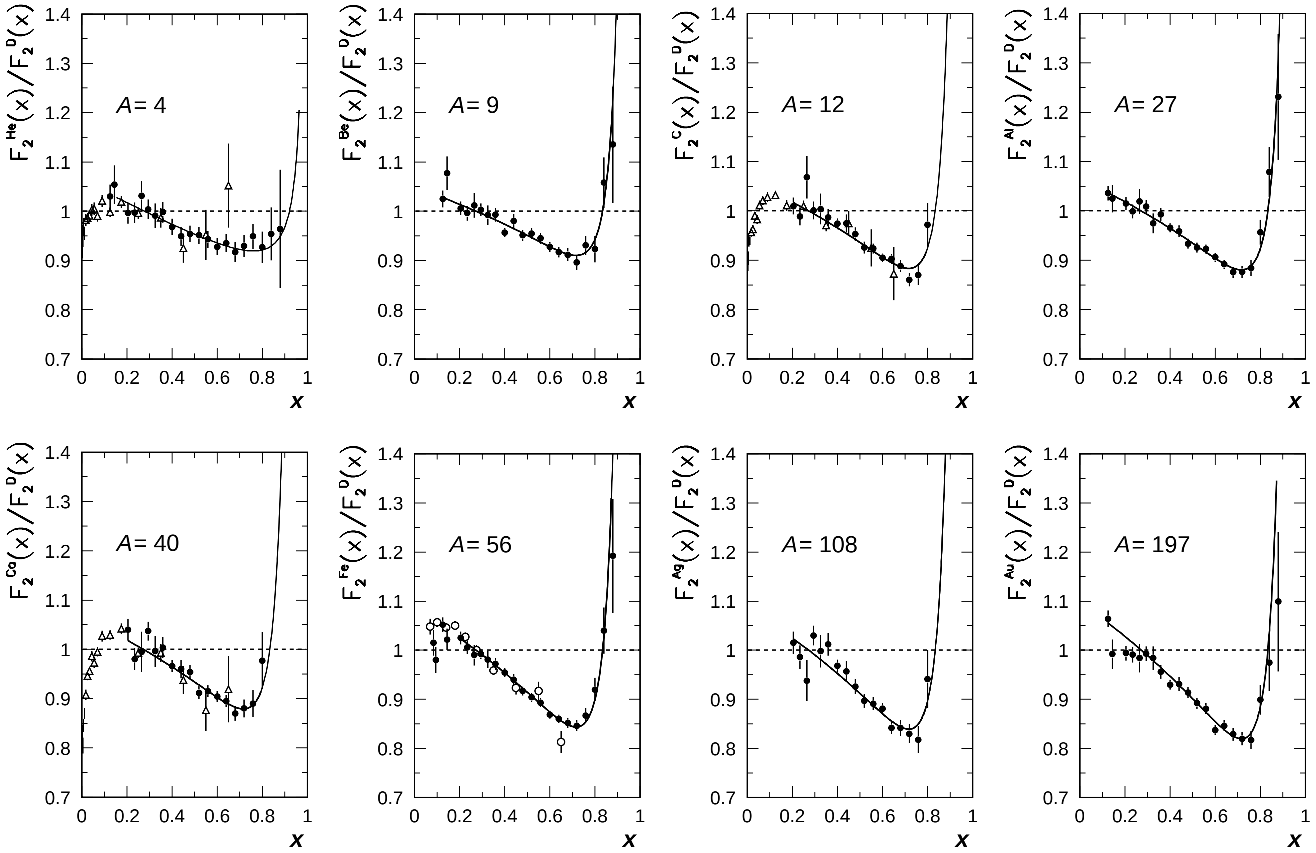

Fig. 4. Comparison of F_2^A/F_2^D, measured by SLAC [1] ●, BCDMS [19] ○ and NMC [3,16] △, in the range $x > 0.2$, with theoretical calculations [7] for ^{4}He ($A = 4$) and ^{3}He ($A \geq 9$). Only one normalization parameter $m_b(A)$ is used to adjust theoretical results for ^{3}He with the data

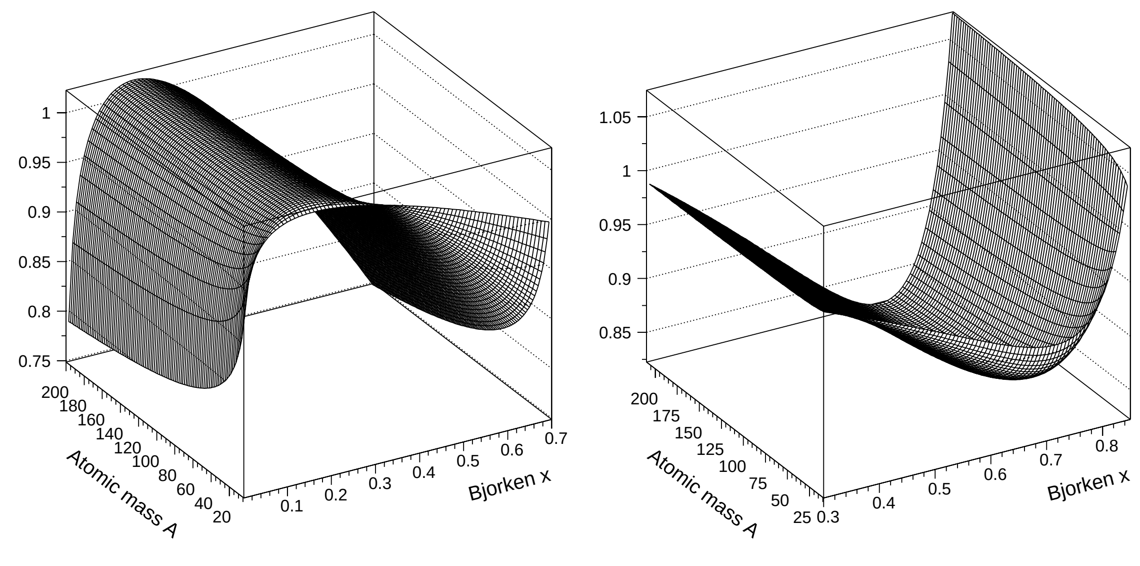

Fig. 5. Approximation of the pattern of the EMC effect as a function of x and A in the range (1) $x < 0.7$, $A \geq 4$ (left frame) and (2) $x > 0.3$, $A \geq 9$ (right frame)

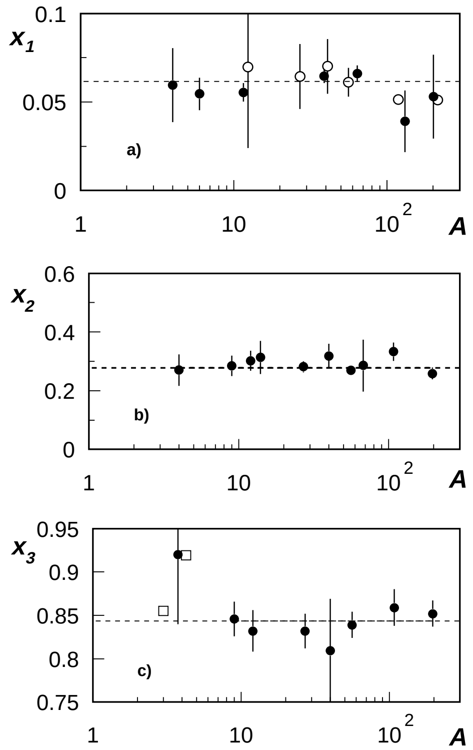

Fig. 6a–c. The coordinates of the cross-over points x_1 **a**, x_2 **b** and x_3 **c** as a function of the atomic mass A. The data on F_2^A/F_2^{D} have been used to obtain results plotted with full circles. The results for x_1 shown in **a** with open circles have been obtained from the data on F_2^A/F_2^{C}. The average values are shown with the dashed lines: $\overline{x_1} = 0.0615$, $\overline{x_2} = 0.278$, $\overline{x_3} = 0.84$. Theoretical values for x_3 evaluated for $A = 3$ and 4 are shown with empty squares

ture function in a nuclear environment, which is shown in Fig. 5. It should be underlined that the A dependent evolution represented by the plot is largely the result of the variation of the nuclear surface-to-volume ratio, while the evolution of the partonic distribution remains with the lightest nuclei, $A \leq 4$.

The pattern shown in Fig. 5 is obtained for the measured range of x and A only. Its extrapolation to larger values of x and A can be justified by the consistency between the experimental data analysis and calculations of [7].

3 Role of the partonic structure in the pattern of binding

An important feature of the factorization of the x and A dependence of the modifications in the range $A > 4$, is the A independence of the coordinates of the three cross-over points x_i. There are reasons to believe that they are constrained by the inner structure of the nucleon and therefore are strongly correlated. Nevertheless, there exists a rich literature which discusses the role of different mechanisms responsible for the nuclear effects in the low and high x range and which insists that the coordinates must be considered as unrelated. This motivated the tests of the A independence of x_1 [2] and x_2 [8]. Below I refresh the experimental status of the coordinates $x_{i=1,2}$ and present new results of the determination of x_3. The latter can now be compared with the theoretical calculations of [7].

There is a definite advantage to relate x_i with the pattern of $r^{A/\mathrm{D}}(x)$ because of two reasons:

(1) the coordinates x_i are much less dependent on the form of the approximation functions, which makes them more sensitive to a possible A dependence than the functions themselves, and

(2) the coordinates x_i can easily be obtained as fully independent from each other in the space of the Bjorken variable x, which is important for the understanding of the question which physics is responsible for the pattern.

3.1 First cross-over

I find x_1 as an intersection point of a straight line $r^{A/\mathrm{D}}(x) = 1$ with $r^{A/\mathrm{D}}(x)$ given by (5). The parameters C and m_{sh} have been found by fitting the data in the range $0.001 < x < 0.08$ on He, Li, C and Ca obtained by NMC [3,16], on Cu by EMC [15] and on Xe [17] and Pb [18] by E665. The value x_1 as a function of A is plotted in Fig. 6a. Within experimental errors the results are consistent with $x_1 =$ const (χ^2/d.o.f. = 6.1/7) and correspond to $\overline{x_1} = 0.0615 \pm 0.0024$.

3.2 Second cross-over

I used the same data sample to obtain the coordinate of the second cross-over point x_2 as for the determination of m_{EMC}. It is found as an intersection point of the straight line $r^{A/\mathrm{D}}(x) = 1$ with $r^{A/\mathrm{D}}(x)$ given by (8):

$$x_2(A) = (a(A) - 1)/m_{\mathrm{EMC}}. \tag{13}$$

The results are plotted in Fig. 6b. As in the case for x_1 I find that $x_2 =$ const (χ^2/d.o.f. = 7.4/9). The mean value is denoted with the dashed line and corresponds to $\overline{x_2} = 0.278 \pm 0.008$.

3.3 Third cross-over

The experimental results for the third cross-over point x_3 play a decisive role in the understanding of the pattern of binding effects in $F_2(x)$. Since there are few data available above x_3 one has to find some reasonable approximation function in the range $x > 0.3$ to avoid correlations between data collected on different nuclear targets and between coordinates of x_2 and x_3. I have chosen the function with four free parameters $a_{i=1-4}$ as follows:

$$r^{A/\mathrm{D}}(x) = a_1(a_2 - x)\frac{exp(-a_3x^2)}{(1 - a_4x)^{2-a_1}}. \tag{14}$$

The results of the determination of x_3 are plotted in Fig. 6c as full circles. Again I find that x_3 is independent of A

within experimental errors (χ^2/d.o.f. = 1.9/6). The mean value is denoted by the dashed line and corresponds to $\overline{x_3} = 0.84 \pm 0.01$. In the same plot I show results of the theoretical calculations [7] for the three- and four-nucleon systems.

Two important conclusions follow from the obtained results:

(1) One finds that the three determined coordinates are fairly well correlated, namely

$$\overline{x_1} + \overline{x_2} \approx 1/3, \tag{15}$$

$$\overline{x_2} \approx \overline{x_3}/3, \tag{16}$$

$$\overline{x_3} \approx 5/6. \tag{17}$$

The relations (15)–(17), as will be discussed in the next section, might play a fundamental role in understanding both the free nucleon partonic structure and the mechanism of its modification in a nuclear environment. In particular, (16) establishes the relationship between the theoretically defined x_3 and the still poorly understood x_2. The precise value of x_2 has not been critical for the theory of [7] which considered the range $x > 0.3$. On the other hand it has been helpful in bringing the theory to better agreement with data when (12) was used. The employment of (16) allows one to get rid of the free parameters in (12).

(2) The A independence of the three cross-over points serves as the evidence that the pattern of distortions cannot be related with properties of the nuclear medium. On the contrary, it is a message about the nucleon structure which reveals itself in the presence of binding interactions in a few nucleon system.

4 Discussion

The analysis of the world data on the structure function ratios performed in this paper has demonstrated that the relativistic theory of nuclear binding [7] is in very good agreement with experiment. I observe also that the agreement is considerably better than that obtained by recent explanations of the EMC effect in the QCD inspired model [20] or in the phenomenological double Q^2-rescaling model [21].

The new precise picture of the x and A dependence, which stems from this analysis, serves to explain the observed evolution of $F_2(x)$ in nuclei with the variation of nuclear density and geometry of a nucleus in agreement with the Woods–Saxon potential. The evolution does not modify the partonic distributions if $A > 4$, which is particularly important for the understanding of the role of the nuclear environment. It follows that two options only are left for the explanation of the origin of the EMC effect: it is either $F_2^{A=4}(x)$ or $F_2^{A=3}(x)$, which is different from $F_2^{\mathrm{D}}(x)$ due to nuclear binding effects. Good agreement between $\overline{x_3}$ and the theoretical result for x_3 obtained for the three-nucleon system [7] favors the second option. Accordingly, I conclude that it is essentially the binding forces of the three-nucleon system which define the pattern of the $F_2(x)$ modifications if $A > 4$.

Taking into consideration the good agreement between the theory and the ^{4}He/D data one can conclude that the overall picture is consistent with a two-stage evolution of the nucleon structure as a function of A, one for $A \leq 4$, and another one for $A > 4$. Such a conception naturally explains the experimentally observed factorization of the x and A dependence on the $F_2(x)$ modifications. It follows then that the partonic structure found for the three-nucleon system can be understood as the basic structure for all nuclear systems with two exceptions: (1) deuteron, as a loosely bound system and (2) ^{4}He, as an anomalously tightly bound system. When the phenomenon is confirmed with experiments on ^{3}He target the EMC effect might obtain new non-trivial formulation: the pattern of partonic structure, which is typical for metals, is identical to that of ^{3}He and ^{3}H.

The possibility of the factorization of the x and A dependence in a restricted kinematic range has been discussed in early publications on the EMC effect. In [22] the A dependence of $r^A(x = 0.55)$ has been predicted by considering a realistic nucleon density function obtained from charge-density functions. The factorization has also been considered in a number of subsequent publications [23] which studied the effect in the range $0.3 < x < 0.7$ but did not relate it with the saturation of the binding forces in the lightest nuclei.

The factorization in the nuclear shadowing region has been introduced in [24] as an empirical relation to describe $r^A(x)$. A reasonable description of the data has required nine free parameters.

A somewhat different motivation of the factorization as compared to the present paper and my previous analysis [2,8], but still relevant either to the structure of the three-nucleon system or to the property of nuclear binding, can be found in [14,25,26]. The model of the three-gluon self-interaction in a three-nucleon system has been suggested in [26]. It explains the factorization in question and provides a physical basis for the quantitative description of the data in the range $0.02 < x < 0.65$ when a five-parameter fit for the $r^A(x)$ is used [27].

Very close to our conception of the two-stage evolution is the suggestion of [14] to study the nucleon structure modifications in the infinite nuclear matter (INM) framework. The nuclear matter cross section is found from the finite-nucleus data by extrapolating them to mass number $A = \infty$ using the $A^{-1/3}$ law. Such an approach strongly advocates the nuclear binding mechanism for describing the origin of the effect and has to rely on a theoretical description of the INM. A quantitative description of the effect can be smeared by the uncertainties of the extrapolation which is not needed in our approach.

Thus, apart from this analysis and the theoretical consideration of the binding effects in the lightest nuclei [7] it is only [26,27] which recognize, however with different arguments, a three-nucleon system as a decisive object for the understanding of the EMC effect origin.

The results of the present paper may serve not only for the clarification of the role of the nuclear environment in the nucleon structure, but also for a better understanding of the free nucleon structure. Indeed, in the framework of the theory of $F_2(x)$ evolution [7], $F_2^A(x) = F_2^{\rm D}(x)$ if the sum of terms with $\mathrm{d}F_2^{\rm D}(x)/\mathrm{d}x$ and $\mathrm{d}F_2^{\rm N}(x)/\mathrm{d}x$ changes sign. Thus the positions of x_i indicate the kinematic regions in which it is desirable to increase the accuracy of the $F_2(x)$ and to measure it in a fine x binning. Evidently, one should think about planning new DIS experiments on proton, deuteron and ^{3}He targets. Besides, the information on the derivatives of $F_2(x)$ might be used for a realistic parametrization of the structure functions. Similar considerations apply to the spin-dependent structure functions $g_1^{\rm P}$ and $g_1^{\rm D}$. The spin degrees of freedom are expected to magnify the effects in the vicinity of x_i due to the Pauli exclusion principle.

A plausible explanation of the correlations expressed with (15) and (16) can be given by assuming a decomposition of the obtained values into contributions from the nucleonic and partonic mechanisms. One might suggest that the three-nucleon field produces a fairly small redistribution of the partonic momenta in a bound nucleon in the momentum range $x < 0.3$, where exchange pions are expected to contribute to the nuclear binding forces. If one assumes that the redistribution is of the order $m_\pi/3M$ one finds that what is obtained from the present analysis can be reasonably well approximated as follows:

$$1 - \overline{x_1} \approx 1 - m_\pi/3M, \tag{18}$$

$$1 - \overline{x_2} \approx 2/3 + m_\pi/3M, \tag{19}$$

$$1 - \overline{x_3} \approx 1/6. \tag{20}$$

The position of x_1, as has been shown in [2], is consistent with explanations of nuclear shadowing by an overlap of the partons belonging to a three-nucleon system.

Contrary to the situation with x_1 and x_3, the problem of a precise evaluation of the second cross-over, x_2, represents a challenge for the theories and even for the models of the EMC effect. Evidently, a parton redistribution effect represented by (19) is not a task to be solved either in a quark model or in a conventional nuclear structure model alone.

5 Conclusions

The world data on the EMC effect in the range of $A > 4$ have been analyzed to determine the *pattern* of modifications of the free nucleon structure function $F_2(x)$ in the nuclear environment. It is found that the pattern is defined with the three A independent cross-over points.

I have obtained experimental evidence of the factorization of the x and A dependence of the $F_2(x)$ modifications for nuclei with $A > 4$ in the entire range of x which signifies that distortions of the parton distributions in a nuclear environment are saturated at $A \leq 4$. The phenomenon of saturation is a natural consequence of the nuclear binding effects in $F_2(x)$, which have been evaluated in a relativistic field theory of nuclei ($A \leq 4$) by Burov, Molochkov and Smirnov. Excellent agreement with the available ^{4}He/D data allows one to conclude that nuclear binding is the only physical mechanism responsible for the EMC effect.

The agreement with the theory is even more spectacular when predictions are confronted with the $A \geq 4$ data, by simply scaling the modifications of $F_2(x)$ for $A = 3$ with the x independent factor defined by conventional nuclear structure considerations. One can identify the partonic structure in the three-nucleon system found by Burov, Molochkov and Smirnov as the basic structure for all nuclear systems with two exceptions only: D and ^{4}He.

The observation provides a clear-cut explanation of the EMC effect origin: the nucleon partonic structure is modified by *nuclear binding* forces and modifications are the strongest in ^{4}He. The partonic structure, which develops in *a three-nucleon system*, evolves to higher nuclear masses by changing the amplitude of the deviations of $F_2^A(x)/F_2^{\rm D}(x)$ from unity in full agreement with the variation of the nuclear density and geometry of a nucleus.

Acknowledgements. I would like to thank V.V. Burov and A.V. Molochkov for helpful discussions of the problem of the relativistic binding effects in the structure of the lightest nuclei. I have also benefited from discussions with S.V. Akulinichev, A.M. Baldin, K. Eskola, H.G. Fischer, S.B. Gerasimov, R.L. Jaffe, S.A. Kulagin and Yu.M. Shabelskii. It is my pleasure to thank S. Barshay, M. Ericson and V.R. Pandharipande for some stimulating remarks.

References

1. SLAC, J. Gomez et al., Phys. Rev. D **49**, 4348 (1994)
2. G.I. Smirnov, Phys. Lett. B **364**, 87 (1995)
3. NMC, P. Amaudruz et al., Nucl. Phys. B **441**, 3 (1995)
4. EMC, J.J. Aubert et al., Phys. Lett. B **123**, 275 (1983)
5. K.J. Eskola, V.J. Kolhinen, P.V. Ruuskanen, Nucl. Phys. B **535**, 351 (1998)
6. NMC, M. Arneodo et al., Nucl. Phys. B **481**, 3239 (1996)
7. V.V. Burov, A.V. Molochkov, G.I. Smirnov, JINR Rapid Communications No. 3[89]–98, pp. 47–56, Dubna, 1998; V.V. Burov, A.V. Molochkov, Nucl. Phys. A **637**, 31 (1998)
8. G.I. Smirnov, Phys. At. Nucl. **58**, No. 9, 1613 (1995)
9. I.A. Savin, G.I. Smirnov, Fiz. Elem. Chastits At. Yadra **22**, 1005 (1991); English translation: Soviet Journal of Particles and Nuclei, **22**, 489 (1991)
10. M. Arneodo, Phys. Rep. **240**, 301 (1994)
11. M. Vänttinen et al., Eur. Phys. J. A **3**, 351 (1998)
12. S.V. Akulinichev, S.A. Kulagin, G.M. Vagradov, Phys. Lett. B **158**, 485 (1985); S.V. Akulinichev et al., Phys. Rev. Lett. **55**, 2239 (1985); G.V. Dunne, A.W. Thomas, Nucl. Phys. A **455**, 701 (1986); H. Jung, G.A. Miller, Phys. Lett. B **200**, 351 (1988); B.L. Birbrair, E.M. Levin, A.G. Shuvaev, Nucl. Phys. A **491**, 618 (1989); S.A. Kulagin, Nucl. Phys. A **500**, 653 (1989); C. Ciofi degli Atti, S. Liuti, Phys. Lett. B **225**, 215 (1989); S. Sholmo, G.M. Vagradov, Phys. Lett. B **232**, 19 (1989); S.V. Akulinichev, S. Sholmo, Phys. Lett. B **234**, 170 (1990); A.E.L. Dieperink, G.A. Miller, Phys. Rev. C **44**, 866 (1991); F. Gross, S. Liuti, Phys. Rev. C **45**, 1374 (1992); V. Barone et al., Z. Phys. C **58**, 541 (1993); S.A. Kulagin, G. Piller, W. Weise, Phys. Rev. C **50**, 1154 (1994); S.V. Akulinichev, Phys. Lett. B **357**, 451 (1995)

13. D. Indumathi, Wei Zhu, Z. Phys. C **74**, 119 (1997)
14. O. Benhar, V.R. Pandharipande, I. Sick, JLAB-THY-98-12, 1998 (unpublished)
15. EMC Collab., J. Ashman et al., Z. Phys. C **57**, 211 (1993)
16. NMC Collab., M. Arneodo et al., Nucl. Phys. B **441**, 12 (1995)
17. E665 Collab., M.R. Adams et al., Phys. Rev. Lett. **68**, 3266 (1992)
18. E665 Collab., M.R. Adams et al., Z. Phys. C **67**, 403 (1995)
19. BCDMS, A.C. Benvenuti et al., Phys. Lett. B **237**, 599 (1990)
20. J.-J. Yang, G.-L. Li, Z. Phys. C **76**, 287 (1997)
21. Z. He et al., Eur. Phys. J. C **4**, 301 (1998)
22. R.L. Jaffe et al., Phys. Lett. B **134**, 449 (1984); F.E. Close et al., Phys. Rev. D **31**, 1004 (1985)
23. S. Date et al., Phys. Rev. Lett. **52**, 2344 (1984); C.A. Garcia Canal, E.M. Santangelo, H. Vucetich, Phys. Rev. Lett. **53**, 1430 (1984); L. Frankfurt, M. Strikman, Nucl. Phys. B **250**, 143 (1985); L. Frankfurt, M. Strikman, Phys. Rep. **160**, 235 (1988)
24. W. Z. Ben, Z. Phys. C **46**, 293 (1990)
25. I. Sick, D. Day, Phys. Lett. B **274**, 16 (1992)
26. S. Barshay, Z. Phys. C **27**, 443 (1985)
27. S. Barshay, D. Rein, Z. Phys. C **46**, 215 (1990)