# Short Range Correlations and the EMC Effect

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# Short Range Correlations and the EMC Effect

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This paper shows quantitatively that the magnitude of the EMC effect measured in electron deep inelastic scattering (DIS) at intermediate $x_B$, $0.35 \leq x_B \leq 0.7$, is linearly related to the Short Range Correlation (SRC) scale factor obtained from electron inclusive scattering at $x_B \geq 1$. The observed phenomenological relationship is used to extract the ratio of the deuteron to the free $pn$ pair cross sections and $F_2^n/F_2^p$, the ratio of the free neutron to free proton structure functions. We speculate that the observed correlation is because both the EMC effect and SRC are dominated by the high virtuality (high momentum) nucleons in the nucleus.

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Inclusive electron scattering, $A(e,e')$, is a valuable tool for studying nuclei. By selecting specific kinematic conditions, especially the four-momentum and energy transfers, $Q^2$ and $\omega$, one can focus on different aspects of the nucleus. Elastic scattering has been used to measure the nuclear charge distribution. Deep inelastic scattering at $Q^2 > 2$ GeV$^2$, and $0.35 \leq x_B \leq 0.7$ ($x_B = Q^2/2m\omega$, where $m$ is the nucleon mass) is sensitive to the nuclear quark distributions. Inelastic scattering at $Q^2 > 1.4$ GeV$^2$ and $x_B > 1.5$ is sensitive to nucleon-nucleon short range correlations (SRC) in the nucleus. This paper will explore the relationship between deep inelastic and large-$x_B$ inelastic scattering.

The per-nucleon electron deep inelastic scattering (DIS) cross sections of nuclei with $A \geq 3$ are smaller than those of deuterium at $Q^2 \geq 2$ GeV$^2$, and moderate $x_B$, $0.35 \leq x_B \leq 0.7$. This effect, known as the EMC effect, has been measured for a wide range of nuclei [1–7]. There is no generally accepted explanation of the EMC effect. In general, proposed explanations need to include both nuclear structure effects (momentum distributions and binding energy) and modification of the bound nucleon structure due to the nuclear medium. Comprehensive reviews of the EMC effect can be found in [8–11] and references therein. Recent high-precision data on light nuclei [7] suggest that it is a local density effect and not a bulk property of the nuclear medium.

The per-nucleon electron inelastic scattering cross sections of nuclei with $A \geq 3$ are greater than those of deuterium for $Q^2 > 1.4$ GeV$^2$ and large $x_B$, $1.5 \leq x_B \leq 2$. The cross section ratio for two different nuclei (*e.g.*, carbon and helium) shows a plateau when plotted as a function of $x_B$ (*i.e.,* it is independent of $x_B$). This was first observed at SLAC [12] and subsequently at Jefferson Laboratory [13, 14]. The plateau indicates that the nucleon momentum distributions of different nuclei for high momentum, $p \geq p_{thresh} = 0.275$ GeV/c, are similar in shape and differ only in magnitude. The ratio (in the plateau region) of the per-nucleon inclusive $(e,e')$ cross sections for two nuclei is then the ratio of the probabilities to find high momentum nucleons in those two nuclei [15, 16].

These high-momentum nucleons were shown recently in hadronic [17, 18] and leptonic [19, 20] two-nucleon knockout experiments to be almost entirely due to central and tensor nucleon-nucleon Short Range Correlations (SRC) [21–24]. SRC occur between pairs of nucleons with high relative momentum and low center of mass momentum, where low and high are relative to the Fermi momentum in heavy nuclei. Thus, we will call the ratio of cross sections in the plateau region the "SRC scale factor".

This paper will show quantitatively that the magnitude of the EMC effect in nucleus $A$ is linearly related to the SRC scale factor of that nucleus relative to deuterium. This idea was suggested by Higinbotham *et al.* [25].

We characterize the strength of the EMC effect for nucleus $A$ following Ref. [7] as the slope of the ratio of the per-nucleon deep inelastic electron scattering cross sections of nucleus $A$ relative to deuterium, $dR_{EMC}/dx$, in the region $0.35 \leq x_B \leq 0.7$. This slope is proportional to the value of the cross section ratio at $x \approx 0.5$, but is unaffected by overall normalization uncertainties that merely raise or lower all of the data points together. For $^3$He, $^4$He, $^9$Be and $^{12}$C we use the published slopes from [7] measured at $3 \leq Q^2 \leq 6$ GeV$^2$. We also fit the ratios, measured in Ref. [3], as a function of $x_B$ for $0.36 \leq x_B \leq 0.68$. The results are averages over all measured $Q^2$ (*i.e.,* $Q^2 = 2, 5$ and 10 GeV$^2$ for $x_B < 0.6$ and $Q^2 =$ 5 and 10 GeV$^2$ for larger $x_B$). The results from the two measurements for $^4$He and $^{12}$C are consistent and we use the weighted average of the two. See Table I. The uncertainties are not meant to take into account possible effects of the anti-shadowing region at $x_B \approx 0.15$ and the Fermi motion region at $x_B > 0.75$ extending into the region of interest.

The SRC scale factors determined from the isospin-corrected per-nucleon ratio of the inclusive $(e,e')$ cross sections on nucleus $A$ and $^3$He, $a_2(A/^3\mathrm{He}) =$

| Nucleus | $dR_{EMC}/dx$ (Ref. [7]) | $dR_{EMC}/dx$ (Ref. [3]) | $dR_{EMC}/dx$ (combined) |
|---|---|---|---|
| Deuteron | | | 0 |
| $^3$He | $-0.070 \pm 0.029$ | | $-0.070 \pm 0.029$ |
| $^4$He | $-0.199 \pm 0.029$ | $-0.191 \pm 0.061$ | $-0.197 \pm 0.026$ |
| $^9$Be | $-0.271 \pm 0.029$ | $-0.207 \pm 0.037$ | $-0.243 \pm 0.023$ |
| $^{12}$C | $-0.280 \pm 0.029$ | $-0.318 \pm 0.040$ | $-0.292 \pm 0.023$ |
| $^{27}$Al | | $-0.325 \pm 0.034$ | $-0.325 \pm 0.034$ |
| $^{40}$Ca | | $-0.350 \pm 0.047$ | $-0.350 \pm 0.047$ |
| $^{56}$Fe | | $-0.388 \pm 0.032$ | $-0.388 \pm 0.032$ |
| $^{108}$Ag | | $-0.496 \pm 0.051$ | $-0.496 \pm 0.051$ |
| $^{197}$Au | | $-0.409 \pm 0.039$ | $-0.409 \pm 0.039$ |

TABLE I. The measured EMC slopes $dR_{EMC}/dx$ for $0.35 \leq x_B \leq 0.7$.

$(3/A)(\sigma_A(Q^2, x_B)/\sigma_{^3\mathrm{He}}(Q^2, x_B)$ are listed in Table II using data from [14]. We used the ratio of deuterium to $^3$He determined in Ref. [14] primarily from the calculated ratio of their momentum distributions above the scaling threshold ($p_{thresh} = 0.275 \pm 0.025$ GeV/c). We combined the statistical and systematic uncertainties in quadrature to give the total uncertainties shown in the table. The SRC scale factors for nucleus $A$ relative to deuterium, $a_2(A/d)$, are calculated from the second column.

The value of the SRC scale factors was shown to be $Q^2$ independent for $1.5 \leq Q^2 \leq 2.5$ GeV$^2$ [13] and more recently for $1.5 \leq Q^2 \leq 5$ GeV$^2$ [26]. Similarly, the EMC effect was shown to be $Q^2$ independent for SLAC, BCDMS and NMC data for $2 \leq Q^2 \leq 40$ GeV$^2$ [3]. This $Q^2$-independence allows us to compare these quantities in their different measured ranges.

| Nucleus | Measured $a_2(A/^3\mathrm{He})$ | Measured $a_2(A/d)$ | Predicted $a_2(A/d)$ |
|---|---|---|---|
| Deuteron | $0.508 \pm 0.025$ | 1 | |
| $^3$He | 1 | $1.97 \pm 0.10$ | |
| $^4$He | $1.93 \pm 0.14$ | $3.80 \pm 0.34$ | |
| $^{12}$C | $2.41 \pm 0.17$ | $4.75 \pm 0.41$ | |
| $^{56}$Fe | $2.83 \pm 0.18$ | $5.58 \pm 0.45$ | |
| $^9$Be | | | $4.08 \pm 0.60$ |
| $^{27}$Al | | | $5.13 \pm 0.55$ |
| $^{40}$Ca | | | $5.44 \pm 0.70$ |
| $^{108}$Ag | | | $7.29 \pm 0.83$ |
| $^{197}$Au | | | $6.19 \pm 0.65$ |

TABLE II. The SRC scale factors for nucleus $A$ with respect to $^3$He and to deuterium. The third column is calculated from the second. The resulting uncertainties are slightly overestimated since the uncertainty in the $d/^3$He ratio of about 5% is added to all of the other ratios. The predicted values (fourth column) are calculated from the values in Table I and Eq. 1.

Fig. 1 shows the EMC slopes versus the SRC scale factors. The two values are strongly linearly correlated,

$$-dR_{\mathrm{EMC}}/dx = (a_2(A/d) - 1) \times (0.079 \pm 0.006) \quad . \quad (1)$$

This implies that both stem from the same underlying nuclear physics, such as high local density or large nucleon virtuality ($v = P^2 - m^2$ where $P$ is the four momentum).

This striking correlation means that we can predict the SRC scale factors for a wide range of nuclei from Be to Au using the linear relationship from Eq. 1 and the measured EMC slopes (see Table II). Note that $^9$Be is a particularly interesting nucleus because of its cluster structure and because its EMC slope is much larger than that expected from a simple dependence on average nuclear density [7]. The EMC slopes and hence the predicted SRC scale factors may saturate for heavy nuclei but better data are needed to establish the exact $A$ dependence.

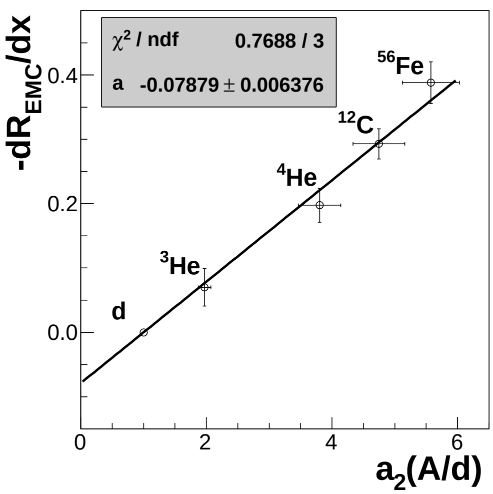


FIG. 1. The EMC slopes versus the SRC scale factors. The uncertainties include both statistical and systematic errors added in quadrature. The fit parameter is the intercept of the line and also the negative of the slope of the line.

This correlation between the EMC slopes and the SRC scale factors also allows us to extract significant information about the deuteron itself. Due to the lack of a free neutron target, the EMC measurements used the deuteron as an approximation to a free proton and neutron system and measured the ratio of inclusive DIS on nuclei to that of the deuteron. This seems like a reasonable approximation since the deuteron is loosely bound ($\approx$ 2 MeV) and the average distance between the nucleons is large ($\approx$ 2 fm). But the deuteron is not a free system; the pion tensor force binds the two nucleons even if weakly.

To quantify the effects of the binding of nucleons in deuterium, we define the In-Medium Correction (IMC) effect as the ratio of the DIS cross section per nucleon bound in a nucleus relative to the free (unbound) $pn$ pair cross section (as opposed to the EMC effect which uses the ratio to deuterium).

The deuteron IMC effect can be extracted from the data in Fig. 1. If the IMC effect and the SRC scale factor both stem from the same cause, then the IMC effect and the SRC scale factor will both vanish at the same point. The value $a_2(A/d) = 0$ is the limit of free nucleons with no SRC. Extrapolating the best fit line in Fig. 1 to $a_2(A/d) = 0$ gives an intercept of $dR_{EMC}/dx = -0.079 \pm 0.006$. The difference between this value and the deuteron EMC slope of 0 is the deuteron IMC slope:

$$\left|\frac{dR_{IMC}(d)}{dx}\right| = 0.079 \pm 0.006 \quad . \tag{2}$$

This slope is the same size as the EMC slope measured for the ratio of $^3$He to deuterium [7]. It is slightly smaller than the deuterium IMC slope of $\approx 0.10$ derived in [3] assuming that the EMC effect is proportional to the average nuclear density and the slope of 0.098 deduced by Frankfurt and Strikman based on the relative virtuality of nucleons in iron and deuterium [16] and the iron EMC slope [3].

The IMC effect for nucleus $A$ is then just the difference between the measured EMC effect and the value $dR_{EMC}/dx = -0.079 \pm 0.006$. Thus

$$\left|\frac{dR_{IMC}(A)}{dx}\right| = \left|\frac{dR_{EMC}(A)}{dx}\right|_{meas} + 0.079 \pm 0.006 \quad . \tag{3}$$

This is true when the slopes are small compared to one.

The free neutron cross section can be obtained from the measured deuteron and proton cross sections using the observed phenomenological relationship presented in Fig. 1 to determine the nuclear corrections. Since the EMC effect is linear for $0.3 \le x_B \le 0.7$, we have

$$\frac{\sigma_d}{\sigma_p + \sigma_n} = 1 - a(x_B - b) \quad \text{for} \quad 0.3 \le x_B \le 0.7, \tag{4}$$

where $\sigma_d$ and $\sigma_p$ are the measured DIS cross sections for the deuteron and free proton, $\sigma_n$ is the free neutron DIS cross section that we want to extract, $a = |dR_{IMC}(d)/dx| = 0.079 \pm 0.006$ and $b = 0.31 \pm 0.04$ is the average value of $x_B$ where the EMC ratio is unity (*i.e.,* where the per-nucleon cross sections are equal $\sigma_A(x_B)/A = \sigma_d(x_B)/2$) as determined in Refs. [3, 7] and taking into account the quoted normalization uncertainties.

Our results imply that $\sigma_d/(\sigma_p + \sigma_n)$ decreases linearly from 1 to 0.97 over the range $0.3 \le x_B \le 0.7$. (More precisely, that it decreases by $0.031 \pm 0.004$ where the uncertainty is due to the fit uncertainties in Eq. 3.) This depletion (see Eq. 4) is similar in size to the depletion calculated by Melnitchouk using the weak binding approximation smearing function with target mass corrections and an off-shell correction [27]. However, the distribution in $x_B$ is very different. Melnitchouk's calculated ratio reaches its minimum of 0.97 at $x_B \approx 0.5$ and increases rapidly, crossing 1 at $x_B \approx 0.7$.

If the structure function $F_2$ is proportional to the DIS cross section (*i.e.,* if the ratio of the longitudinal to transverse cross sections is the same for $n, p$ and $d$ [see discussion in [8]]), then the free neutron structure function, $F_2^n(x_B, Q^2)$, can also be deduced from the measured deuteron and proton structure functions:

$$F_2^n(x_B, Q^2) = \frac{2F_2^d(x_B, Q^2) - [1 - a(x_B - b)]F_2^p(x_B, Q^2)}{[1 - a(x_B - b)]} \tag{5}$$

which leads to

$$\frac{F_2^n(x_B, Q^2)}{F_2^p(x_B, Q^2)} = \frac{2\frac{F_2^d(x_B,Q^2)}{F_2^p(x_B,Q^2)} - [1 - a(x_B - b)]}{[1 - a(x_B - b)]} \quad . \tag{6}$$

This is only valid for $0.35 \le x_B \le 0.7$.

Fig. 2 shows the ratio of $F_2^n/F_2^p$ extracted in this work using the IMC-based correction and the $Q^2 = 12$ GeV$^2$ ratio $F_2^d/F_2^p$ from Ref. [28]. Note that the ratio $F_2^d/F_2^p$ is $Q^2$-independent from $6 \le Q^2 \le 20$ GeV$^2$ for $0.4 \le x_B \le 0.7$ [28]. The dominant uncertainty in this extraction is the uncertainty in the measured $F_2^p/F_2^d$. The IMC-based correction increases the extracted free neutron structure function (relative to that extracted using the deuteron momentum density [28]) by an amount that increases with $x_B$. Thus, the IMC-based $F_2^n$ strongly favors model-based extractions of $F_2^n$ that include nucleon modification in the deuteron [29].

The IMC-based $F_2^n$ appears to be constant or slightly increasing in the range from $0.6 \le x_B \le 0.7$. The $d/u$ ratio is simply related to the ratio of $F_2^n/F_2^p$ in the deep inelastic limit, $x^2 \ll Q^2/4m^2$ [28], $d/u = (4F_2^n/F_2^p - 1)/(4 - F_2^n/F_n^p)$. While it is quite hazardous to extrapolate from our limited $x_B$ range all the way to $x_B = 1$, these results appear to disfavor models of the proton with $d/u$ ratios of 0 at $x_B = 1$ (see [29] and references therein).

By using the deuteron IMC slope, these results take into account both the nuclear corrections as well as any possible changes to the internal structure of the neutron in the deuteron. Note that this assumes either that the EMC and $F_2$ data are taken at the same $Q^2$ or that they are $Q^2$-independent for $6 \le Q^2 \le 12$ GeV$^2$. The fact that the measured EMC ratios for nuclei with $A \ge 3$ decrease linearly with increasing $x_B$ for $0.35 \le x_B \le 0.7$ indicates that Fermi smearing is not significant in this range.

We now speculate as to the physical reason for the EMC-SRC relation presented above. Assuming that the IMC/EMC effect is due to a difference in the quark distributions in bound and free nucleons, these differences could occur predominantly in either mean field nucleons or in nucleons affected by SRC.

According to Ref. [30], the IMC/EMC effect is mainly associated with nucleons at high virtuality. These nucle-

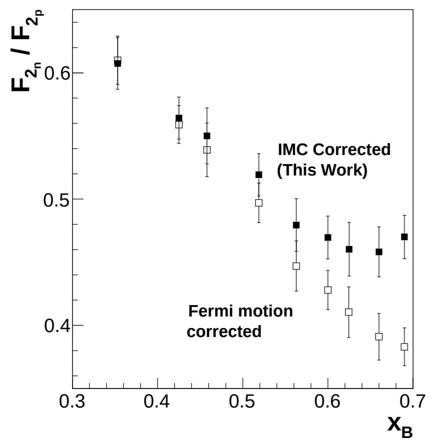


FIG. 2. The ratio of neutron to proton structure functions, $F_2^n(x_B,Q^2)/F_2^p(x_B,Q^2)$ as extracted from the measured deuteron and proton structure functions, $F_2^d$ and $F_2^p$. The filled symbols show $F_2^n/F_2^p$ extracted in this work from the deuteron In Medium Correction (IMC) ratio and the world data for $F_2^d/F_2^p$ at $Q^2 = 12$ GeV$^2$ [28]. The open symbols show $F_2^n/F_2^p$ extracted from the same data correcting only for nucleon motion in deuterium using a relativistic deuteron momentum density [28].

ons, like the nucleons affected by SRC, have larger momenta and a denser local environment than that of the other nucleons in the nucleus. Therefore, they should exhibit the largest changes in their internal structure.

The linear correlation between the strength of the EMC and the SRC in nuclei, shown in Fig. 1, indicates that possible modifications of the quark distributions occur in nucleons affected by SRC. This also predicts a larger EMC effect in higher density nuclear systems such as neutron stars. This correlation may also help us to understand the difficult to quantify nucleon modification (offshell effects) that must occur when two nucleons are close together.

To summarize, we have found a striking linear correlation between the EMC slope measured in deep inelastic electron scattering and the short range correlations scale factor measured in inelastic scattering. The SRC are associated with large nucleon momenta and the EMC effect is associated wth modified nucleon structure. This correlation allows us to extract the free neutron structure function model-independently and to place constraints on large $x_B$ parton distribution functions. Knowledge of these PDFs is important for searches for new physics in collider experiments [31] and for neutrino oscillation experiments.

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