# New data strengthen the connection between short range correlations and the EMC effect

O. Hen,[1] E. Piasetzky,[1] and L. B. Weinstein[2]
[1]*Tel Aviv University, Tel Aviv 69978, Israel*
[2]*Old Dominion University, Norfolk, Virginia 23529, USA*
(Received 15 February 2012; revised manuscript received 10 April 2012; published 26 April 2012)

Recently published measurements of the two-nucleon short range correlation ($NN$-SRC) scaling factors, $a_2(A/d)$, strengthen the previously observed correlation between the magnitude of the EMC effect measured in electron deep inelastic scattering at $0.35 \leqslant x_B \leqslant 0.7$ and the SRC scaling factor measured at $x_B \geqslant 1$. The new results improve precision and include previously unmeasured nuclei. The measurements of $a_2(A/d)$ for $^9$Be and $^{197}$Au agree with published predictions based on the EMC-SRC correlation. This Brief Report examines the effects of the new data and of different corrections to the data on the slope and quality of the EMC-SRC correlation, the size of the extracted deuteron in-medium correction effect, and the free-neutron structure function. The results show that the linear EMC-SRC correlation is robust and that the slope of the correlation is insensitive to most combinations of corrections examined in this work. This strengthens the interpretation that both $NN$-SRC and the EMC effect are related to high-momentum nucleons in the nucleus.

DOI: 10.1103/PhysRevC.85.047301 PACS number(s): 25.30.Fj, 13.60.Hb, 21.30.−x

*Introduction.* The per-nucleon lepton deep inelastic scattering (DIS) cross sections of heavy nuclei are less than those of deuterium at moderate to large four-momentum transfer, $Q^2 \geqslant 2$ (GeV/$c$)$^2$, and $0.35 \leqslant x_B \leqslant 0.7$ ($x_B = Q^2/2m\nu$, where $\nu$ is the energy transfer and $m$ is the proton mass). This "EMC effect" was discovered in 1982 by the European Muon Collaboration in the cross-section ratios of iron to deuterium [1] and confirmed by many measurements on a range of nuclei [2–7]. The latest data [7] show that for light nuclei the EMC effect does not increase monotonically with increasing average nuclear density. Although there is no generally accepted explanation of the EMC effect, proposed explanations generally need to include both nuclear structure effects (momentum distributions and binding energy) and modification of the bound nucleon structure.

A recent paper showed a strong correlation between the magnitude of the EMC effect and the short range correlation (SRC) scaling factor [8]. Because the per-nucleon cross-section ratios of nuclei to deuterium for $0.35 \leqslant x_B \leqslant 0.7$ decrease approximately linearly with $x_B$, in this range of $x_B$ the EMC effect can be quantified by the slope of this ratio, $dR_{\mathrm{EMC}}/dx_B$ [7]. The SRC scaling factor, $a_2(A/d)$, equals the ratio of the per-nucleon inclusive electron scattering cross section for nucleus $A$ to deuterium at $Q^2 > 1.4$ (GeV/$c$)$^2$ and $1.5 \leqslant x_B < 2$. In this range of $x_B$, the cross-section ratio is constant [9–12]. The constancy of the ratio in this range of $x_B$ is attributed to high-momentum components of the nuclear wave function. These high-momentum components have been shown to be almost entirely due to central and tensor nucleon-nucleon short range correlations [13–17].

This correlation between the magnitude of the EMC effect measured at $0.35 \leqslant x_B \leqslant 0.7$ and the SRC scale factor measured at $1.5 \leqslant x_B < 2$ was used to phenomenologically determine the ratio of the DIS cross section for a proton and neutron bound in deuterium to the DIS cross section for free (unbound) $pn$ pair and thus to determine the free-neutron cross section for $0.35 \leqslant x_B \leqslant 0.7$. The free-neutron cross section was then used to determine the ratio of the neutron to proton structure function, $F_2^n/F_2^p$, and hence the ratio of $d/u$ in this range of $x_B$.

Recently, high-precision measurements of the per-nucleon inclusive electron scattering cross-section ratio for different nuclei relative to deuterium at $Q^2 \sim 2.7$ (GeV/$c$)$^2$ and $1 < x_B < 2$ were published [18], covering more nuclei at greater precision than previous measurements. These ratios also show scaling behavior for $x_B > 1.5$. These new data allow us to reexamine the observed linear correlation between the strength of the EMC effect and the SRC scaling factor [8]. The analysis of the new data also includes various corrections to the measured cross-section ratios that were not included in previous analyses [11,12].

In this Brief Report we examine the consistency of the old and new data and the effects of different corrections to the cross-section ratios and therefore on the slope of the EMC-SRC correlation. We also examine the effects of these on the ratio of the bound to free $pn$ DIS cross sections and on the free-neutron structure function [19].

*The new data.* New measurements by Fomin *et al.* [18] of the SRC scaling factor $a_2(A/d)$ have about four times smaller uncertainties than previous ones by Egiyan *et al.* [11,12]. They also include two nuclei, $^9$Be and $^{197}$Au, for which the SRC scaling factors were previously predicted based on their measured EMC effect [3,7] and the linear EMC-SRC correlation [8]. $^9$Be is of particular interest due to the anomalous density dependence of its EMC effect (its EMC effect is larger than that of $^4$He although its average density is much smaller) [7]. It therefore presents a challenging test for the prediction made in Ref. [8] and for the validity of the EMC-SRC correlation in general.

The different measurements have different corrections applied to their results. Both sets of measurements applied radiative corrections to their measured cross-section ratios. Egiyan *et al.* [11,12] also applied isoscalar corrections to correct for differences in the per-nucleon cross-section ratio for asymmetric nuclei due to the difference between the elementary electron-proton and electron-neutron cross

 

TABLE I. A comparison of SRC scaling factors, $a_2(A/d)$, extracted from different data sets with different corrections. Column 2 shows the scaling factors from Egiyan *et al.* [12]. Column 3 shows the prediction of Ref. [8] based on the EMC data of Refs. [3,7]. Columns 4 through 6 show the data of Fomin *et al.* [18] with different corrections. Column 4 shows the data with the same corrections used by Egiyan *et al.*, column 5 shows the data as published, and column 6 shows the data excluding their correction for the c.m. motion of the SRC pair. Column 7 shows the results from SLAC [10]. Column 8 shows the slopes of the EMC effect from Refs. [3,7] as cited in Ref. [8]. See the text for more details.

| Nucleus | Egiyan *et al.* [12] | EMC-SRC prediction [8] | Fomin *et al.* [18] (analysis as in Ref. [12]) | Fomin *et al.* [18] | Fomin *et al.* [18] (excluding the c.m. motion correction) | SLAC [10][a] | EMC slope [8] $dR_{EMC}/dx$ |
|---|---|---|---|---|---|---|---|
| $^3$He | $1.97 \pm 0.10$[b] | | $1.87 \pm 0.06$ | $1.93 \pm 0.10$ | $2.13 \pm 0.04$ | $1.7 \pm 0.3$ | $-0.070 \pm 0.029$ |
| $^4$He | $3.80 \pm 0.34$ | | $3.64 \pm 0.07$ | $3.02 \pm 0.17$ | $3.60 \pm 0.10$ | $3.3 \pm 0.5$ | $-0.197 \pm 0.026$ |
| $^9$Be | | $4.08 \pm 0.60$ | $4.15 \pm 0.09$ | $3.37 \pm 0.17$ | $3.91 \pm 0.12$ | | $-0.243 \pm 0.023$ |
| $^{12}$C | $4.75 \pm 0.41$ | | $4.81 \pm 0.10$ | $4.00 \pm 0.24$ | $4.75 \pm 0.16$ | $5.0 \pm 0.5$ | $-0.292 \pm 0.023$ |
| $^{56}$Fe($^{63}$Cu) | $5.58 \pm 0.45$ | | $5.29 \pm 0.12$ | $4.33 \pm 0.28$ | $5.21 \pm 0.20$ | $5.2 \pm 0.9$ | $-0.388 \pm 0.032$ |
| $^{197}$Au | | $6.19 \pm 0.65$ | $5.29 \pm 0.16$ | $4.26 \pm 0.29$ | $5.16 \pm 0.22$ | $4.8 \pm 0.7$ | $-0.409 \pm 0.039$ |
| EMC-SRC slope $a$ | $0.079 \pm 0.006$ | | $0.082 \pm 0.004$ | $0.106 \pm 0.006$ | $0.084 \pm 0.004$ | | |
| $\frac{\sigma(n+p)}{\sigma_d}\|_{x_B=0.7}$ | $1.032 \pm 0.004$ | | $1.033 \pm 0.004$ | $1.043 \pm 0.005$ | $1.034 \pm 0.004$ | | |
| $\chi^2/ndf$ | 0.7688/3 | | 4.742/5 | 4.078/5 | 4.895/5 | | |

[a]The SLAC ratios [10] used cross sections from different experiments at different kinematics. They interpolated the deuterium cross sections to the kinematics of the cross sections measured for heavier nuclei and have larger uncertainties than the later measurements. They are included here for completeness.

[b]The $^3$He SRC scaling factor in column 2 from Ref. [12] was determined primarily from the calculated ratio of the $^3$He and $d$ momentum distribution above the scaling threshold ($p_{thresh} = 0.275 \pm 0.025$ GeV/$c$).

sections. Fomin *et al.* [18] did not apply the isoscalar correction but did apply corrections for the nuclear Coulomb field, inelastic contributions, and SRC-pair center-of-mass motion. Inspired by results of exclusive $^{12}$C$(p, ppn)$ and $^{12}$C$(e, e'pN)$ measurements, which showed that two-nucleon ($NN$)-SRC pairs are dominated by neutron-proton pairs (∼18 times more neutron-proton than proton-proton pairs were observed) [13–17], Fomin *et al.* assumed that at $x_B > 1.4$, electrons scatter mainly off neutron-proton pairs and therefore isoscalar corrections are unnecessary. The largest correction made by Fomin *et al.* is a correction for enhancement of the cross-section ratio (and therefore of the SRC scaling factors) due to the SRC-pair center of mass (c.m.) motion for $A > 2$. The c.m. correction is defined as the ratio of the convolution of the pair c.m. motion and deuteron momentum distributions to the deuteron momentum distribution. This ratio was calculated in Ref. [18] for $^{56}$Fe using the SRC-pair momentum distributions of Ciofi degli Atti and Simula [20]. It was then scaled to other nuclei based on the $A$ dependence of the pair motion. Because of the uncertainties in the calculation, including its $x_B$ and $A$ dependence, they applied an uncertainty equal to 30–50 % of the calculated correction.

Table I lists the per-nucleon cross-section ratios for all nuclei measured by Fomin *et al.* The second column shows the ratios measured by Egiyan *et al.* that were used in the original EMC-SRC analysis [8]. Fomin *et al.* measured $^{63}$Cu, which was not measured by Egiyan *et al.*; we assume the SRC scaling factor of $^{63}$Cu to be the same as that of $^{56}$Fe. The values of $^9$Be and $^{197}$Au in the third column are those predicted by Ref. [8] based on their measured EMC effect and the linear EMC-SRC correlation. The fourth column shows the Fomin *et al.* results, analyzed in the same manner as the Egiyan *et al.* data (i.e., including radiative and isoscalar corrections only). The fifth column shows the Fomin *et al.* results as published (i.e., including inelastic, radiative, Coulomb, and center of mass motion corrections). The sixth column shows the as-published Fomin *et al.* results with the center of mass motion correction removed (i.e., including inelastic, radiative, and Coulomb corrections). Comparing the second and fourth columns, one can see that the measured values of $a_2(A/d)$ from the two measurements agree within uncertainty when analyzed with the same corrections (radiative and isoscalar corrections only). Applying the radiative, Coulomb field, and inelastic (but not the isoscalar) corrections changes the measured scale factors by about 10%. Applying the SRC-pair center-of-mass motion correction decreases the ratios by 10–20 %. The last column of Table I shows the magnitude of the EMC effect for the different nuclei as measured by Refs. [3,7] and averaged by Ref. [8].

*The EMC-SRC correlation.* The quality of the correlation between the magnitude of the EMC effect and the newly measured SRC scaling factors, $a_2(A/d)$, is shown in Fig. 1. Because of the large uncertainties of the SRC-pair center-of-mass motion correction, Fig. 1 shows the data of Fomin *et al.* as published but without that correction. Figure 1 also shows the results of a one-parameter fit to the EMC slopes as a function of the SRC scaling factors. Because the point for the deuteron is fixed at $dR_{EMC}/dx = 0$ and $a_2(A/d) = 1$, the fitted slope is also the negative of the intercept of the line.

To test the robustness of the EMC-SRC correlation, we made a series of one-parameter linear fits to the EMC slopes (Table I, column 8) as a function of the different SRC scaling factors shown in Table I. The $\chi^2$ per degree of freedom for each of these fits was approximately 1, indicating an excellent fit. In addition, the values of $a_2(A/d)$ predicted for $^9$Be and $^{197}$Au by Ref. [8] agree within uncertainties with the new values measured by Fomin *et al.* with the radiative and isoscalar corrections from Ref. [12].

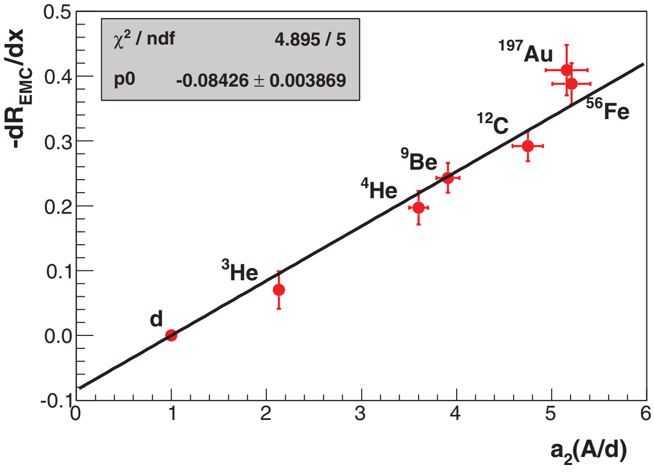


FIG. 1. (Color online) The slope of the EMC effect for $0.35 \leqslant x_B \leqslant 0.7$ plotted vs $a_2(A/d)$, the SRC scaling factor (the relative amount of $NN$-SRC pairs), in a variety of nuclei. The uncertainties include both statistical and systematic uncertainties added in quadrature. The values of $a_2(A/d)$ are taken from Fomin *et al.* [18] as published except for the SRC-pair center-of-mass motion corrections. The fit parameter, $a = -0.084 \pm 0.004$, is the intercept of the line and also the negative of the slope of the line.

Following Ref. [8], the value $a_2(A/d) = 0$ corresponds to the limit of free nucleons with no SRC. If we extrapolate the linear fit to this point, this should give us the EMC ratio for a free (unbound) $pn$ pair to the deuteron, the so-called in-medium correction (IMC) effect. The IMC effect then equals the negative of the fitted EMC-SRC slope. This value ranges from $|dR_{\mathrm{IMC}}/dx| = 0.079 \pm 0.006$ to $0.084 \pm 0.004$ for the different data sets with the different corrections (excluding the c.m. motion correction). If we include the SRC-pair center-of-mass motion correction, then the linear fit is still excellent. However, the slope and hence the intercept increases by about 20% to $0.106 \pm 0.006$.

Since the EMC effect is linear for $0.3 \leqslant x_B \leqslant 0.7$, we have (also following Ref. [8])

$$\frac{\sigma_d}{\sigma_p + \sigma_n} = 1 - a(x_B - b),$$

where $\sigma_d$ and $\sigma_p$ are the measured DIS deuteron and proton cross sections, $\sigma_n$ is the unmeasured free-neutron cross section, $a = |dR_{\mathrm{IMC}}/dx| \approx 0.08$, and $b = 0.31 \pm 0.04$ is the average value of $x_B$ where the EMC effect is unity (i.e., where the per-nucleon cross sections are equal). Evaluating this at $x_B = 0.7$ gives the ratio of the free $pn$ cross section to the bound $pn$ (deuteron) cross section, which ranges from $1.032 \pm 0.004$ to $1.034 \pm 0.004$ for the different data sets and corrections (again excluding the c.m. motion correction). If we include the c.m. motion correction, then this ratio changes to $1.043 \pm 0.005$.

The agreement of the slope of the EMC-SRC correlation, and therefore of the deuteron IMC effect at $x_B = 0.7$, among all combinations of data sets and corrections is a clear indication of the robustness of the EMC-SRC correlation. This also indicates that the deuteron IMC effect and the free-neutron structure function extracted in Ref. [8] and used in Ref. [19] do not change due to the new data and/or analysis. If the center-of-mass motion correction is included, then the linearity of the EMC-SRC relation improves slightly and the deuteron IMC effect increases by about 20% to $dR_{\mathrm{IMC}}/dx = 0.106 \pm 0.006$.

*Conclusions and outlook.* New higher-precision data [18] strengthen the phenomenological correlation between the strength of the EMC effect and the relative amount of SRC-correlated $NN$ pairs in a nucleus [8]. The new measurements are consistent with the SRC scaling factors for $^9$Be and $^{197}$Au that were predicted based on this EMC-SRC correlation. Different corrections for the SRC cross-section ratio were examined and all were shown to be consistent with a linear correlation between the strength of the EMC effect and the relative amount of SRC-correlated $NN$ pairs in nuclei. The linearity of the EMC-SRC correlation, regardless of the exact corrections considered, is a clear indication of the robustness of the EMC-SRC correlation. This strengthens the speculation presented in Ref. [8] that both the EMC effect and the $NN$-SRC originate from high-momentum nucleons in the nucleus.

More data are required to further map out and understand this correlation. Several experiments approved to run as part of the 12 GeV program at Jefferson Lab will measure both the SRC scaling factors and the EMC effect at high precision over a wide range of light and heavy nuclei [21–23]. Another experiment [24] will search for medium modification of the structure function of deeply bound, high-momentum nucleons. This will be done by performing DIS scattering off high-momentum nucleons in deuterium and tagging the partner (high-momentum) recoil nucleon. The results of this experiment will allow comparison of the structure function of free and bound nucleons and gain insight on the connection of the EMC effect to high-momentum nucleons in the nucleus.

*Acknowledgements.* We are grateful for many fruitful discussions with John Arrington, Nadia Fomin, Leonid Frankfurt, Doug Higinbotham, Sebastian Kuhn, Jerry Miller, and Mark Strikman. This work was supported by the U.S. Department of Energy, the Israel Science Foundation, and the US-Israeli Bi-National Science Foundation.

[1] J. Aubert *et al.*, Phys. Lett. B **123**, 275 (1983).
[2] J. Ashman *et al.*, Phys. Lett. B **202**, 603 (1988).
[3] J. Gomez *et al.*, Phys. Rev. D **49**, 4348 (1994).
[4] M. Arneodo *et al.*, Phys. Lett. B **211**, 493 (1988).
[5] M. Arneodo *et al.*, Nucl. Phys. B **333**, 1 (1990).
[6] D. Allasia *et al.*, Phys. Lett. B **249**, 366 (1990).
[7] J. Seely *et al.*, Phys. Rev. Lett. **103**, 202301 (2009).
[8] L. B. Weinstein, E. Piasetzky, D. W. Higinbotham, J. Gomez, O. Hen, and R. Shneor, Phys. Rev. Lett. **106**, 052301 (2011).
[9] D. B. Day *et al.*, Phys. Rev. Lett. **59**, 427 (1987).
[10] L. L. Frankfurt, M. I. Strikman, D. B. Day, and M. Sargsyan, Phys. Rev. C **48**, 2451 (1993).
[11] K. Egiyan *et al.* (CLAS Collaboration), Phys. Rev. C **68**, 014313 (2003).

[12] K. Egiyan *et al*. (CLAS Collaboration), Phys. Rev. Lett. **96**, 082501 (2006).
[13] A. Tang *et al*., Phys. Rev. Lett. **90**, 042301 (2003).
[14] E. Piasetzky, M. Sargsian, L. Frankfurt, M. Strikman, and J. W. Watson, Phys. Rev. Lett. **97**, 162504 (2006).
[15] R. Shneor *et al*., Phys. Rev. Lett. **99**, 072501 (2007).
[16] R. Subedi *et al*., Science **320**, 1476 (2008).
[17] H. Baghdasaryan *et al*. (CLAS Collaboration), Phys. Rev. Lett. **105**, 222501 (2010).
[18] N. Fomin *et al*., Phys. Rev. Lett. **108**, 092502 (2012).
[19] O. Hen, A. Accardi, W. Melnitchouk, and E. Piasetzky, Phys. Rev. D **84**, 117501 (2011).
[20] C. Ciofi degli Atti and S. Simula, Phys. Rev. C **53**, 1689 (1996).
[21] J. Arrington and D. Day, Inclusive scattering from nuclei at $x > 1$ in the quasielastic and deeply inelastic regimes, Jefferson Lab Experiment No. E12-06-105, 2006 (unpublished).
[22] P. Solvignon-Slifer and J. Arrington, Precision measurement of the isospin dependence in the 2N and 3N short range correlation region, Jefferson Lab Experiment No. E12-11-112, 2011, (unpublished).
[23] J. Arrington, D. Gaskell, and A. Daniel, Detailed studies of the nuclear dependence of $F_2$ in light nuclei, Jefferson Lab Experiment No. E12-10-008, 2010 (unpublished).
[24] O. Hen, L. Weinstein, S. Wood, and S. Gilad, In medium nucleon structure functions, SRC, and the EMC effect, Jefferson Lab Experiment No. E12-11-107, 2011 (unpublished).