Short-range correlations and their implications for isospin-dependent modification of nuclear quark distributions

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Abstract. The past decade has provided a much clearer picture of the structure of high-momentum components in nucleons, associated with hard, short-distance interactions between pairs of nucleons. Recent Jefferson Lab data on light nuclei suggest a connection between these so-called 'short-range correlations' and the modification of the quark structure of nucleons in the nuclear environment. In light of this discovery that the detailed nuclear structure is important in describing the nuclear quark distributions, we examine the potential impact of the isospin-dependent structure of nuclei to see at what level this might yield flavor-dependent effects in nuclear quark distributions.

1 Introduction

A small but important part of the Jefferson Lab (JLab) program involves studies of the high-momentum structure of nuclei, which requires high-energy interactions to probe cleanly [1]. After the initial observation of identical structure in the high-momentum components of nuclei at SLAC [2], measurements at JLab have mapped out the kinematic region where SRCs dominate [3, 4], mapped out the contribution of SRCs in various light and heavy nuclei relative to the deuteron [5, 6], and determined that the SRCs are dominated (at the ∼90% level) by neutron-proton pairs [7–10].

Because these high-momentum components are associated with short-distance pairs, and thus high-density configurations in nuclei, it is natural to think that there could be a connection between SRCs and the nuclear dependence of nuclear parton distribution functions (pdfs). First it was noted [11] that the common scaling of SRCs and the EMC effect with density might suggest a connection between the two phenomena. Precise measurements of the EMC effect could be extended at JLab, taking advantage of the extended scaling in nuclei [12, 13]. Measurements of both the EMC effect [14] and SRCs [6] in light nuclei both showed that ^{9}Be deviated from the simple density dependence observed in heavier nuclei. While it seemed unlikely that the simple density-dependent or mass-dependent fits to data on heavy nuclei would apply to light nuclei, previous data on ^{4}He and ^{9}Be did not have sufficient precision to show deviations from these simple scaling models. For both the EMC effect and contribution of SRCs, ^{9}Be behaved like a rather dense nucleus, even though its average density is quite low [15, 16] due to its significant cluster structure. This led to more detailed examinations of the correlation, suggesting the possibility that the EMC effect may be related to either the large momenta or high density of SRCs in nuclei [17–19].

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Many calculations of the EMC effect include a binding contribution which explains a significant portion of the effect [20]. The average separation energy enters into these binding calculations, and a large part of this is associated with SRCs. It has also been argued that off-shell effects in these high-momentum nucleons could yield additional nucleon modification [21–24]. There have been direct measurements using electron scattering from a deuterium target, using a high-momentum spectator proton to tag scattering from high-momentum neutrons [25]. Existing data show effects consistent with such a modification of the neutron structure have been observed, but the interpretation is difficult due to potential final-state interactions. Future measurements are planned at Jefferson Lab [26]. More recently, such tagged measurements focusing on low-momentum nucleons have allowed for the extraction of the free neutron structure function [27, 28], and have been used to make the first direct extraction of the nuclear effects in the deuteron relative to the free proton and neutron [29]. At present, these measurements do not have sufficient precision or kinematic reach to differentiate between different models, but future measurements may provide further insight into the origin of the EMC effect [30]. One can also try to isolate SRCs by examining scattering at $x > 1$, while going to Q^2 values where one expects to be sensitive to the parton distributions in the region dominated by SRCs. Existing data suggest an onset of scaling at relatively low Q^2 for nuclei [12, 13, 31], and an experiment has been approved to extend such measurement to the maximum Q^2 available with the 12 GeV upgrade at Jefferson Lab [32].

Another channel for examining off-shell protons is the comparison of the proton form factors, extracted by recoil polarization, to the same polarization ratio for proton knockout from a nucleus [33, 34]. Again, questions about potential final-state interactions have been raised [35], but other polarization observables have some sensitivity to these effects [36] and future measurements will be able to map out the behavior in more detail [37]. For both the binding and off-shell contributions, the large momenta and energies, associated mainly with nucleons in short-range correlations, are the direct cause of the EMC effect, yielding the observed correlation between the EMC effect and presence of SRCs.

If the EMC effect is driven by the 'local density' observed by the struck nucleon, e.g. is due to direct quark exchange between nucleons with substantial overlap, then all short-distance configurations - nn, np, and pp pairs - will contribute. In this case, the presence of these short-distance configurations is the source of both the EMC effect (due to quark modification in the overlapping nucleons) and the high-momentum nucleons in SRCs (due to the strong interaction of the short-range components of the N-N potential. In this case, the EMC-SRC correlation occurs because both effects have a common origin in these small, dense, two-body configurations in nuclei. This implies a slightly different prediction for the detailed EMC-SRC correlation, as the EMC effect is sensitive to all short-distance NN pairs while SRCs are generated predominantly in np pairs. In this case, the connection between the EMC effect and SRCs in the nucleus will also depend on the number of potential nn, np, and pp pairs in the nucleus, implying an A- and Z-dependent correction to the simple linear correlation assumed in [11]. The detailed scaling of the EMC effect and SRCs were examined in Ref. [17], along with a comparison of the two pictures above, where the correlation is the result of either local-density or high-virtuality (HV) effects. Including a simple pair-counting correction to account for the difference in nn, np, and pp pairs, the correlation was found to be better (reduced χ^2 value and improved extrapolation to the deuteron value) under the local density hypothesis. However, the difference is not large and the χ^2 test is of somewhat limited use given the potential for correlated errors between the measurements on different nuclei, so it is far from a definitive test.

One new direction that has not yet been studied in detail is the flavor-dependence of the EMC effect. The connection between the EMC effect and presence of SRCs, combined with the isospin structure of SRCs suggests the potential for significant flavor-dependent effects in nuclear pdfs. This

provides a new observable that can be used to examine the EMC effect and to test models of the nuclear modification. While this idea has been discussed [1, 38], exisint data on the EMC effect are been insufficient to claim an flavor-dependent effect.

2 Flavor dependence of the EMC effect

While the nature of the correlation between the EMC effect and the presence of SRCs is not understood, most explanations, conventional or exotic, imply that the isospin structure of the correlations would impact the flavor dependence of the EMC effect. In conventional binding calculations, the fact that the high-momenta nucleons are generated mainly in n-p pairs implies that a nucleus with significant neutron excess will have a larger *fraction* of it's protons at high momenta, yielding a larger separation energy and thus a larger binding effect for protons. The same is true if the correlation is due to off-shell effects in the high-momentum nucleons of the SRCs. If the EMC effect is driven by local-density effects, then a similar isospin dependence is natural in nuclei with a large neutron skin. Nuclei with significant neutron excess typically have a larger neutron radius, meaning that the lower density surface region will have more neutrons, again yielding a larger average EMC effect for protons. Thus, any of these explanations, as well as recent QCD-based models of nuclear parton distributions [39], all predict the same effect: an enhanced EMC effect for protons (and up-quarks) in neutron rich nuclei.

In the past, the EMC effect was generally assumed to scale with simple bulk properties of the nucleus, either mass or average nuclear density. The data on light nuclei [14] demonstrate that these models are not sufficient, and details of the nuclear structure must be accounted for. We examine here a variety of simple assumptions for the A dependence which account for the nuclear structure.

The observed EMC-SRC correlation has generally been interpreted based on the idea that the EMC effect is driven by either local density effects, where overlapping nucleon pairs can have direct quark exchange or contributions from more exotic states (hidden color or six-quark bags) [40–42], or by the presence of high-momentum nucleons, due to binding or off-shell effects. These yield slightly different predictions for the quantitative nature of the relation between the EMC effect and SRCs, as all NN pairs can contribute to high-density configurations, while the high-momentum components are dominated by np pairs [1], and will also yield different predictions for the relative effect on protons and neutrons in the nucleus. All of these yield an increased EMC effect for protons for nuclei with a neutron excess.

The same enhancement in the minority nucleons occurs in a calculation of nuclear pdfs through the quark-meson coupling arising in the NJL model [39, 43]. The model results are obtained for asymmetric nuclear matter, using a Z/N ratio that matches finite nuclei as a rough estimate for finite nuclei. The nuclear matter results are likely overestimates of the isospin dependence in finite nuclei, although these are mean-field calculations which do not include realistic nuclear structure for the finite nuclei. So for example, it does not include any effect connected to short-range correlations or the isospin-dependent density in a nucleus with a large neutron skin discussed above. Because all of the effects increase the EMC effect for up-quarks in neutron-rich nuclei, there could be an additional contribution if any of the nuclear structure effects are also present.

We examine a total of four updated scaling assumptions for the A dependence of the EMC effect:

- High-momentum fraction: We take the nucleon momentum distribution, $n(k)$, and assume that the EMC effect scales with the fraction of the distribution above 300 MeV/c.

- Average kinetic energy: We take the average kinetic energy of the nucleons, $\langle k^2 \rangle / 2M$, evaluated from $n(k)$.
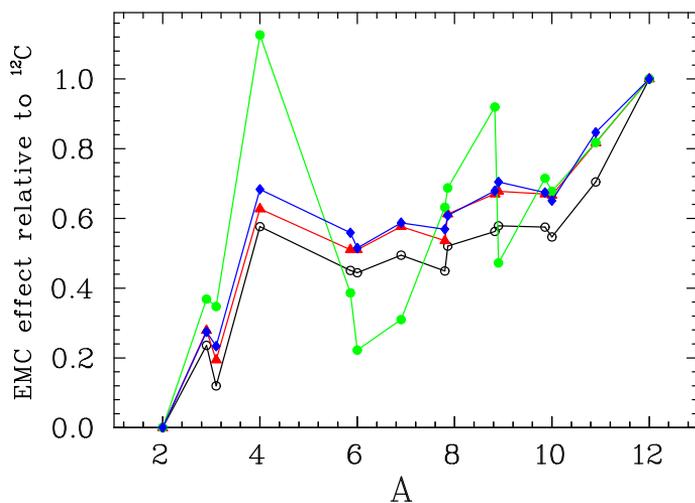
Figure 1. A dependence of the EMC effect for the four scaling assumptions: Fraction of momentum distribution above 300 MeV/c (black open circles), average kinetic energy (red triangles), average density (green circles), and probability to be within 1 fm of another nucleon (blue diamonds). The results are shown relative to Carbon, and a slight offset in A is added to differentiate nuclei with different N/Z ratios.

- Average density: We evaluate the average density of the nucleus as seen by an individual proton or neutron, using the one-body densities for the proton and neutrons

- Overlap probability: We determine the probability of a proton or neutron being within 1 fm of another nucleon, based on the two-body densities.

The first two quantities, high-momentum fraction and average kinetic energy are related to the idea that some combination of off-shell effects and the separation energy in conventional binding calculations are the source of the EMC effect through the presence of high-momentum nucleons. The average density is the traditional simple model used for scaling of the EMC effect in nuclei. The overlap probability is one method of examining the impact of local density, using the probability of two nucleons having significant overlap as an overall measure of the possible contribution to pdf modification due to the possible contribution from direct quark exchange between the nucleons or more exotic 6-quark or hidden color configurations. This set of quantities can be calculated from *ab initio* calculations of nuclear structure for light nuclei, providing predictions for the EMC effect in light nuclei, which will be measured in an approved experiment at Jefferson Lab [44]. We can also examine the difference between the EMC effect for protons and neutrons in asymmetric nuclei for each of these predictions, which can be examined in the comparison of ^{40}Ca and ^{48}Ca [44], as well as in parity-violating electron scattering measurements from asymmetric nuclei such as ^{9}Be and ^{48}Ca, where the parity-violating asymmetry, related to the ratio of weak to electromagnetic deep inelastic scattering, is insensitive to any flavor-independent rescaling of the nuclear pdfs.

2.1 Results

For each of the scaling models discussed in the previous section, we calculate the quantity of interest using the Quantum Monte Carlo calculation [45] for all particle-stable nuclei. The scaling parameter is determined independently for protons and neutrons, and for the conventional EMC effect, we combine these with a weight for the number of protons and neutrons and the relative e-p and e-n cross sections for deep-inelastic scattering at large x. The results are all plotted relative to ^{12}C, as only the A-dependence and not the overall scale is predicted by these simple scaling assumptions.

Figure 1 shows the prediction for the scaling of the EMC effect in light nuclei, taking the cross section and N/Z weighted average of the proton and neutron predictions. The assumption of a simple
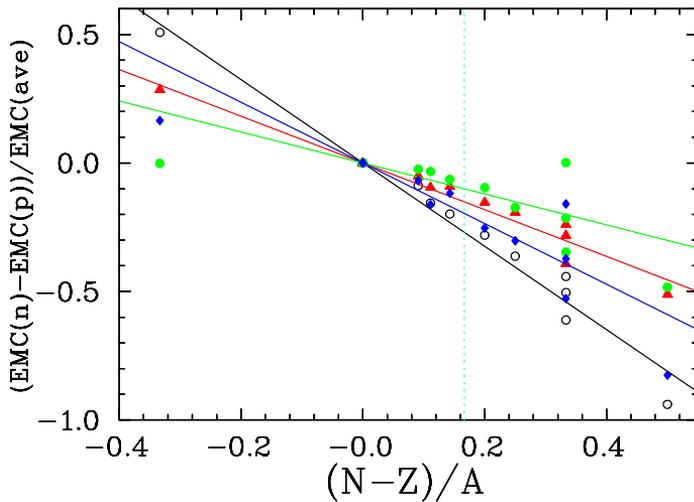
Figure 2. Isospin dependence of the EMC effect vs. fractional neutron excess of the nucleus for the four scaling models (same models as Fig. 1). The lines are simple unweighted linear fits. The short-dashed line shows the N/Z value corresponding to ^{48}Ca.

density-dependent scaling is significantly different from the others, and is ruled out by the existing data on ^{3}He, ^{4}He, ^{9}Be, and ^{12}C [14]. This is not surprising, as the simple density dependence picture was already excluded based on these data, but this demonstrates that accounting for the difference between proton and neutron distributions does not yield a significant improvement in the prediction. The other models all show a very similar A dependence for the EMC effect, and are qualitatively consistent with the observation that the modification is large and similar for ^{4}He, ^{9}Be, and ^{12}C. There is a small difference between the predictions, in particular for the first scaling model (fraction of high-momentum nucleons), but they are in generally good qualitative agreement.

Figure 2 shows the fractional difference between the proton and neutron EMC effect versus the fractional neutron excess of the nuclei. The lines are simple unweighted linear fits which provide a rough guide as to the overall size of the effects, but note that the behavior is not linear with fractional neutron excess, in particular for ^{3}H and ^{3}He. The predicted isospin dependence shows a significantly larger spread in the predictions for different nuclei, with very large differences between the EMC effect in protons and neutrons. The largest neutron excess shown in this figure are not easy to access experimentally while ^{3}H and ^{3}He, which have $|(N - Z)/A| = 1/3$, could be measured, but there are technical difficulties using a ^{3}H target and the sensitivity will be limited because the EMC effect in A=3 nuclei is small, making it difficult to extract even a relatively large fractional effect. Measurements on nuclei such as ^{9}Be and ^{48}Ca are straightforward, and these nuclei have a significant EMC effect as well as the potential to have significant sensitivity to different models via their isospin-dependence.

An approved experiment at Jefferson Lab [44] will measure the EMC effect for light nuclei (^{3,4}He, ^{6,7}Li, ^{9}Be, ^{10,11}B, and ^{12}C) to examine the sensitivity of the EMC effect to the detailed nuclear structure in these well-understood nuclei. In addition, it will have some sensitivity to the isospin dependence through the comparison of light non-isoscalar nuclei and the comparison of ^{40}Ca and ^{48}Ca. However, the EMC effect has limited to the isospin dependence, even where it is large. This is in because there are two effect which partially cancel in neutron rich nuclei. Increasing the number of neutrons increases the EMC effect for the protons (up quarks) which dominate the cross section for isoscalar nuclei, but it also increases the fraction of neutrons (down quarks) which have a decreased EMC effect. Thus, the sensitivity to a change in N/Z is enhanced when going to proton-rich nuclei and suppressed for neutron-rich nuclei, as seen in the calculations of Ref. [43].

A much more sensitive test of the isospin dependence of the EMC effect is party-violating deep-inelastic electron scattering from non-isoscalar nuclei [39]. The parity-violating asymmetry is sensitive to the interference between Z- and photon-exchange amplitudes relative to the photon-exchange amplitude squares [46, 47], making it sensitive to the ratio of the weak charge to electromagnetic charge of the quarks. From Ref. [39], the a_2 parity-violating asymmetry has the following simplified form when expanding around the $u(x) = d(x)$ limit:

$$a_2(x) = \frac{9}{5} - 4\sin^2(\theta_W) - \frac{12}{25}\frac{u(x) - d(x)}{u(x) + d(x)}. \tag{1}$$

An isoscalar nucleus will have a constant a_2 asymmetry, while a non-isoscalar nucleus will have a small x dependence which is independent of any isospin-independent EMC effect. The asymmetry expected from any nucleus in the absence of a flavor-dependent EMC effect can therefore be calculated with minimal uncertainty, based on the small difference between the up- and down-quark distributions in the excess protons or neutrons. This is relatively well known at low-to-modest values of x [27, 48–51], with further measurements planned to improve our knowledge at larger x values. Any deviation of the measured asymmetry from the predicted value is sensitive to an isospin-dependent EMC effect that would modify the ratio of up and down quarks [39].

3 Conclusions

Given what we have learned about the isospin structure of short-range correlations, combined with the importance of detailed nuclear structure for both SRCs and the EMC effect, it is now difficult to believe that the EMC effect could be flavor independent, in particular for non-isoscalar nuclei. As such, a detailed understanding of the EMC effect requires an understanding of the effect in terms of both A-dependent and isospin-dependent effects.

Measurements of the EMC effect in light nuclei (including several non-isoscalar nuclei), along with comparisons of ^{3}H and ^{3}He, along with ^{40}Ca and ^{48}Ca will provide some sensitivity to flavor-dependent effects. The comparison of ^{3}H and ^{3}He depends on having reliable understanding of the d/u ratio of the nucleon pdf, and is limited in sensitivity by the small size of the nuclear effects for A=3. The comparison of the Calcium isotopes should provide more sensitivity to isospin-dependent effects, but relies on comparison to a theoretical expectation for the difference between the EMC effect for A=40 and A=48 in the absence of isospin-dependent effects. This was assumed to be well understood based on earlier assumptions that the EMC effect had a simple scaling with the nuclear mass or average density. Because the recent data on light nuclei [14] demonstrated the impact of more complicated aspects of nuclear structure, including both clustering and isospin-structure, the comparison may be more sensitive to the assumed scaling in heavy nuclei than previously assumed.

Pion-induced Drell-Yan scattering has also been proposed as a way to study the flavor dependence of the EMC effect [52]. Such measurements would be possible at COMPASS or J-PARC, but there are no formal plans to make these measurements at present. The cleanest and most precise way to isolate flavor-dependent effects on the nuclear parton distributions is through measurements of the parity-violating DIS scattering from nuclei [39]. The initial estimates for the isospin dependence of the EMC effect presented here, along with similar calculations for medium-heavy nuclei, will allow for an optimization of the program, providing a separation of the A-dependence and isospin-dependence of the EMC effect. This will also provide the best approach for discriminating between different assumptions about the physics behind the EMC effect, as illustrated in Fig. 2.

Acknowledgements

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