What does the EMC-SRC Correlation tell us about isospin dependence (and origin) of the EMC Effect?

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Exploring QCD with light nuclei at EIC
January 21-24, 2020
Isospin dependence of the EMC effect?

- Always assumed that EMC effect is **identical for proton and neutron**

- **Becoming hard to believe, at least for non-isoscalar nuclei**
  - Calculations show difference for u-, d-quark, as result of scalar and vector mean-field potentials in asymmetric nuclear matter
    [I. Cloet, et al, PRL 109, 182301 (2012); PRL 102, 252301 (2009)]
  - $^{48}$Ca, $^{208}$Pb expected to have significant neutron skin: neutrons preferentially sit near the surface, in low density regions
  - EMC-SRC correlation + n-p dominance of SRCs suggests enhanced EMC effect in minority nucleons
    - In $^3$H, np-dominance suggests single proton generates same high-momentum component as two neutrons → larger EMC effect in ‘high-virtuality’ picture

**All of these imply increased EMC effect in minority nucleons**
Key 6 GeV inclusive measurements

JLab E02-019: JA, D. Day, B. Filippone, A. Lung
- Scatter from light nuclei at x>1
  - Probe high-momentum nucleons in nuclei
  - Study short-distance (high-density) structures in nuclei

JLab E03-103: JA and D. Gaskell, spokespersons
- DIS from light nuclei in high-x region
  - EMC effect: Nuclear dependence of quark distributions
EMC, SRCs in light nuclei

Density determined from ab initio few-body calculation
*S.C. Pieper and R.B. Wiringa,*

EMC effect increases with density, as expected, except for $^9$Be

Detailed nuclear structure, beyond mass or average density, impact nuclear pdfs
EMC, SRCs in light nuclei

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SRCs are both short-distance and high-momentum components

Which matters for EMC effect?? (or neither, or some combination?)

J. Seely, et al., PRL103, 202301 (2009)

L. Weinstein, et al., PRL 106, 052301 (2011)
JA, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon,
PRC 86, 065204 (2012)
Short-distance behavior and the EMC effect

1. EMC effect driven by average density of the nucleus

If EMC effect and SRC contributions both scaled with density, it would explain the EMC-SRC correlation.

It would not explain the anomalous result for 9Be

Note: in some cases, e.g. Frankfurt and Strikman review, average density was used to represent probability of nucleon overlap – conceptually consistent with idea of large 9Be EMC effect
Short-distance behavior and the EMC effect

1. EMC effect driven by average density of the nucleus

2. EMC effect is driven by Local Density (LD) – overlap of nucleons
   [J. Seely et al., PRL 103, 202301, 2009]
   SRCs generated by interactions in short-distance (high-density) np pairs
   EMC effect driven by high-density nucleon configurations (pairs, clusters)

3. EMC effect driven by High Virtuality (HV) of the nucleons
   [L. Weinstein et al, PRL 106, 052301, 2011]
   SRC measurements directly probe high-momentum nucleons
   EMC effect driven by off-shell effects in high-momentum nucleons

First comparison of HV/LD explanations of EMC-SRC correlation:
## Two Hypotheses for EMC-SRC correlation

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Fit type</th>
<th>$\chi^2_\nu$</th>
<th>EMC(D)</th>
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<tr>
<td>High Virtuality</td>
<td>2-param</td>
<td>1.26</td>
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<td>No constraints</td>
<td>(0.57) 0.74</td>
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</table>


**Graphs:**
- **HV: Strict D Constraint**
  - $\chi^2_\nu = 1.47$
  - $m = 0.0893 +/- 0.0035$
- **LD: Strict D Constraint**
  - $\chi^2_\nu = 0.57$
  - $m = 0.0520 +/- 0.0023$
New, closely related, approach

If EMC effect due to high-momenta (our HV hypothesis), can extract universal modification of \((F_{2p}+F_{2n})/F_{2d}\) in a deuteron

\[
F_{\text{univ}}^{HV} = \frac{(\sigma_A/\sigma_D) - (Z - N) \frac{F_{2p}}{F_{2d}} - N}{(A/2)a_2 - N}
\]

For isoscalar nuclei, simplifies to \((R_{\text{EMC}-1})/(a_2-1)\)

More detailed way of looking at EMC-SRC correlation (and isospin structure of EMC effect)

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If EMC effect due to high-momenta ("HV" hypothesis), can extract universal modification of \((F_{2p}+F_{2n})/F_{2d}\) in a deuteron

\[
F^\text{HV}_{\text{univ}} = \frac{(\sigma_A/\sigma_D) - (Z - N) \frac{F_{2p}^p}{F_{2q}^q} - N}{(A/2)a_2 - N}
\]

Observation of universal function shows data are consistent with the HV picture. How much better (worse) is this than an isospin-independent picture?

Define similar function under assumption that all NN pairs contribute with no isospin dependence:

\[
F^\text{LD}_{\text{univ}} = \frac{R_{\text{EMC}} - 1}{R_{2N} \frac{A(A-1)}{2ZN} - 1}
\]

In both versions, isoscalar corrections from the data sets unified correction applied [different \(F_{2n}/F_{2p}\) in our analysis, but correction nearly identical for \(x<0.7\)]

We used SLAC + JLab(Hall C) EMC data; have not included new CLAS results.
HV picture: np-dominance generates predicable isospin dependence of EMC effect

LD picture: EMC effect from short-distance pairs, assumed to be isospin independent

Both give a good description in terms of a universal modification

As in 2012 EMC-SRC analysis, somewhat better description in isospin-independent LD picture
HV picture: EMC effect from np-SRC, generates known isospin dependence
LD picture: Driven by short-distance pairs, assumed to be isospin independent
**HV picture:** EMC effect from np-SRC, generates known isospin dependence

**LD picture:** Driven by short-distance pairs, assumed to be isospin independent

**Differences in formulae/analyses:**
- CLAS EMC data not included in JA/Fomin
- $a_2$ vs. $R_{2N}$
- np pairs vs. all NN pairs
- Flavor indep vs. flavor dependent EMC
Impact of new CLAS EMC data

Combined slope still favors HV picture:

HV: slope = $(6.75 \pm 2.06) \times 10^{-3}$
LD: slope = $(1.65 \pm 1.01) \times 10^{-3}$
What drives the difference?

SLAC + Hall C only (PRL)
Blue = HV (full flavor dependent version)
Red = LD
Black = HV with $R_{2N}$ instead of $a_2$
Changes scale, not overall behavior
Green = ‘naïve’ EMC-SRC correlation
Slope = EMC slope / $a_2$

$HV \rightarrow (R_{EMC}^{-1})/(a_2^{-1})$ for isoscalar nuclei.
Differs from naïve approach due to explicit isospin dependence for non-isoscalar nuclei, but impact is small (blue vs green points)
What drives the difference?

SLAC + Hall C only (PRL)
Blue = HV (full flavor dependent version)
Red = LD
Black = HV with $R_{2N}$ instead of $a_2$
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Difference comes from pair counting: $N^*Z$ np pairs vs. $A(A-1)/2$ NN pairs
[SCRs measure np pairs; we translate to total pairs]

<table>
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<tr>
<th>A</th>
<th>#np</th>
<th>#pp</th>
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<th>#NN</th>
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<td>190</td>
<td>2.11</td>
<td>780</td>
<td>1.95</td>
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</tbody>
</table>
Simple modeling of flavor dependence

Future experimental directions
Quantum Monte Carlo EMC estimates for light nuclei

- Provides ab initio calculations of several important quantities up to A=12
  - n(k): Fraction of high-momentum nucleons, ave. kinetic energy of nucleons
  - Density distributions: Average density of nucleus
  - Two-body densities: Average ‘overlap’ (local density) of nn, pn, pp pairs

- Predict A-dependence of unpolarized EMC effect [JLab E12-10-008]
  - Cross section weighted average of proton and neutrons

- Can calculate each of these for protons and neutron separately
  - Isospin/flavor dependence as function of fractional neutron excess: (N-Z)/A

A-dependence of unpolarized EMC effect

4 simple models of EMC scaling:

*Fraction of n(k) above 300 MeV*

*Average Kinetic Energy*

*Average Density*

*Nucleon Overlap (r_{12} < 1 fm)*

Fixed normalizations for $^2$H for $^{12}$C

A-dependence of light nuclei already excludes *average density*

**High-momentum tail** has small, systematic difference for most nuclei
Isospin dependence vs fractional neutron excess

4 simple models of EMC scaling:

*Fraction of n(k) above 300 MeV*

*Average Kinetic Energy*

*Average Density*

*Nucleon Overlap (r_{12} < 1 fm)*

EMC effect isospin asymmetry:
(neutron-proton)/average

Cloet estimates \((^{9}\text{Be}, {^{48}\text{Ca}})\): scaled from nuclear matter

Can be probed directly in parity-violating electron scattering

\(^{48}\text{Ca}\) measurements proposed at JLab

- Need detailed structure calculations for \(^{48}\text{Ca}\)

Light nuclei (e.g. \(^{9}\text{Be}\)) may also have good sensitivity; help disentangle effects
Unpolarized EMC measurements: JLab@12 GeV

SRCs at $x>1$ at 12 GeV
[E06-105: JA, D. Day, N. Fomin, P. Solvignon]

EMC effect at 12 GeV
[E10-008: JA, A. Daniel, D. Gaskell]
Quark distributions of SRC: “Super-fast” quarks

D(e,e’) at very high $Q^2$ and $x>1$ (SRC-dominated region) could provide a clear signature of exotic states in nuclei.

Experiment approved to map out superfast quark distributions at JLab

Dramatic increase in $Q^2$ range with an EIC
Disentangling A dependence and isospin effects

Additional nuclei added since original proposal
- Vary N/Z for approximately fixed mass
- Vary mass for approximately fixed N/Z

Sensitivity to N/Z small in comparing EMC-SRC correlation → systematic study

\(^{112}\text{Sn}, \, ^{124}\text{Sn}\) also possible

[Lee Sobotka, WUSTL]
EMC effect in Parity-Violating electron scattering

Knowing \( d(x)/u(x) \) for the proton and assuming flavor-independent EMC effect, can calculate e-A PV-DIS response

**PV asymmetry** is independent of overall size of EMC effect; **only sensitive to difference in EMC effect for** \( u \) and \( d \) quarks

Cloet, et al. calculations predicts 5% deviation at large \( x \) – comparable to larger predictions from simple models

SoLID spectrometer planned for Hall A at Jefferson Lab can make \(~1\%\) measurements of PVDIS on non-isoscalar nuclei

**Best (only?) option for a clean, quantitative measurement of flavor dependence**
Summary

Measurements of the EMC effect in light nuclei show **importance of detailed nuclear structure**, connection with short-range correlations.

This, along with recent calculations, suggest that **there must be a flavor dependence to the EMC effect in neutron rich nuclei**

- Important to separate A dependence from isospin dependence
- Provides information on underlying causes

**Very limited information from unpolarized EMC effect vs N/Z**

- No indication of flavor dependence
- 12 GeV provides broader, systematic study; still limited
- SIDIS (flavor-tagging with $\pi^\pm$ – questions about clean interpretation)

**Direct Parity-violating scattering measurements possible using SoLID**

- $^{48}$Ca: flavor dependence of EMC effect
- Light nucleus ($^9$Be) may also be important to disentangle effects