In Medium Nucleon Structure Functions, SRC, and the EMC Effect

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Proposal PR12-11-107, O Hen (contact), L. Weinstein, S. Gilad, S.A. Wood
Scientific Rating: B+, 40 days of beam time
Outline

- Short Range Correlations
- The EMC Effect and nucleon modification
- The EMC – SRC correlation
- 12 GeV Measurement of nucleon modification
Short-Range Correlations (SRC)

\[ Q^2 = -q_\mu q^\mu = q^2 - \omega^2 \]
\[ \omega = E' - E \]
\[ x_B = \frac{Q^2}{2m_N\omega} \]

\( E, E' \approx 3-5 \text{ GeV} \)
\( Q^2 \geq 1.5 \text{ GeV}^2 \)
\( 0 \leq x_B \leq A \)

\( x_B \) counts the number of nucleons involved: \( x_B > n \)

\( \Rightarrow \) at least \( n+1 \) nucleons

\( x_B \) and \( Q^2 \) also determine the minimum momentum of struck nucleon in nucleus (the \( y \) of \( y \)-scaling)
A(e,e') ratios: Universality of SRC (Scaling)

- At high nucleon momenta, strength is different but shapes of distributions are similar

- Scaling!

\[ n_A(k) = C_A \cdot n_D(k) \]

Adapted from Ciofi degli Atti

Ratio predictions by Frankfurt, Strikman, and Sargsian


<table>
<thead>
<tr>
<th>Nucleus</th>
<th>% 2N corr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>4.1 ± 0.8</td>
</tr>
<tr>
<td>(^3)He</td>
<td>8.0 ± 1.6</td>
</tr>
<tr>
<td>(^4)He</td>
<td>15.4 ± 3.2</td>
</tr>
<tr>
<td>(^{12})C</td>
<td>19.8 ± 4.4</td>
</tr>
<tr>
<td>(^{56})Fe</td>
<td>23.9 ± 5.3</td>
</tr>
</tbody>
</table>
Use $^{12}\text{C}(e,e'p)$ as a tag to measure $^{12}\text{C}(e,e'pN)/^{12}\text{C}(e,e'p)$

**Optimized kinematics:**

- $Q^2 \approx 2.0$
- $x_B \approx 1.2$
- "Semi anti-parallel" kinematics
Looking for correlated partners

- Almost **all** protons with \( p_i > 300 \) MeV/c in \(^{12}\text{C}(e,e'p)\) have a paired proton or neutron with similar momentum in opposite direction.

\[
\frac{^{12}\text{C}(e,e'pn)}{^{12}\text{C}(e,e'p)} = 96^{+4}_{-23}\% 
\]

\[
\frac{^{12}\text{C}(e,e'pp)}{^{12}\text{C}(e,e'p)} = 9.5 \pm 2\% 
\]

np SRC is \(~18\) times pp (nn)

Ratios corrected for acceptance, det. efficiency and SCX

R. Subedi et al., Science **320** (5882), 1476 (2008)

What do we know about SRC?

1. The probability for a nucleon to have momentum $\geq 300$ MeV / c in medium nuclei is $\sim 25\%$.

2. More than $\sim 90\%$ of all nucleons with momentum $\geq 300$ MeV / c belong to 2N-SRC.

3. $\sim 80\%$ of kinetic energy of nucleon in nuclei is carried by nucleons in 2N-SRC.

2N-SRC dominated by np pairs

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DIS and the EMC Effect

\[ Q^2 = -q_\mu q^\mu = q^2 - \omega^2 \]
\[ \omega = E' - E \]
\[ 0 < x_B = \frac{Q^2}{2m_N\omega} < 1 \]

EMC Scale: several GeV
Nuclear binding energy scale: several MeV

Expectation: DIS of bound nucleons ≠ DIS of a free nucleons

**EMC:** DIS off bound N ≠ DIS off free N

Origin of EMC effect unknown!!
Nucleon modification needed.
\( \approx 10^3 \) publications
EMC Effect: Universal

\[
\frac{2}{A} \cdot \frac{\sigma^A}{\sigma^d}
\]

Very linear for \(0.3 < x < 0.7\)
(note that the lines shown are not fits)

Size of effect ("depth" or slope) grows with \(A\)

J. Seely, PRL 103, 202301 (2009)
J. Gomez, PRD 49, 4348 (1994)
EMC Effect: Theory

- Nuclear Effects:
  - Fermi motion
  - Binding energy
- Full Calculation
  - Nucleon modification
  - Nuclear pions
  - shadowing

Nucleon modification:
Phenomenological change to bound nucleon structure functions, change proportional to virtuality ($p^2$)

Kulagin and Petty, PRC 82, 054614 (2010)
Eureka Moment!

“...effect scales with the local environment of the nucleons...”

Local density?

- SRC is a local-density effect related to high-momentum nucleons
- Effective number of high-momentum nucleons in SRC is given by $a_2$
- Is EMC related to modified SF of high-momentum nucleons?

J. Seely et al., PRL 103 (2009) 202301
Correlations Between EMC and SRC!

High local density
High nucleons momenta

Is EMC related to high-momentum nucleons?

JLab data
J. Seely et al., PRL 103 (2009) 202301

EMC data
SLAC (Gomez et al.)
JLab Hall C (Seely et al.)

 SRC data
SLAC (Day et al.)
JLab Hall B (Egiyan et al.)
JLab Hall C (Fomin et al.)

Free p+n?

Weinstein et al., PRL 106, 052301 (2011)
O. Hen et al., PRC 85, 047301 (2012)
Suggested Explanation of Correlation between SRC and EMC

- EMC effect does not occur (or is very small) for mean-field nucleons
- Both SRC and EMC are related to high-momentum (high virtuality) nucleons in nuclei
- High momentum (high virtuality) nucleons in the medium are modified
  Hmm..

- Let’s measure the in-medium modified(?) structure function $F_2$ in DIS

\[
\frac{d^3\sigma}{d\Omega dE'} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left[ \frac{1}{\omega} F_2(x_B, Q^2) + \frac{2}{M} F_1(x_B, Q^2) \tan^2 \left( \frac{\theta_e}{2} \right) \right]
\]

($F_1$ and $F_2$ are related by $R$, the measured ratio of longitudinal and transverse cross sections. Thus measuring the cross section yields $F_2$.)
Predicted Dependence of $F_2$ on Momentum

Dependence on:

- Models
- Nucleon's momentum and $x_B$
- Nucleon's momentum, not $x_B$


\[ R = \frac{F_2'}{F_2} \]

$R = \frac{F_2'}{F_2}$

Explore Connection between EMC and SRC

If we are right, we should measure a large EMC effect by selecting high-momentum nucleons?

**Deuteron**

- Is there an “EMC” effect in the deuteron?
- Is there a large “EMC” effect in the high-momentum tail of the deuteron?
- Does the structure function $F_2$ depend on nucleon momentum (virtuality)?

$$\sigma_d^{DIS} \neq \sigma_p^{DIS} + \sigma_n^{DIS}$$

\[
\frac{\sigma_d}{\sigma_p + \sigma_n} = 1 - \frac{(0.082 \pm 0.004)(0.6 - 0.31 \pm 0.04)}{0.6} \approx 0.976
\]

\[
\frac{\sigma_d}{\sigma_p + \sigma_n} (x_B = 0.6) \approx 0.976
\]

\[
\frac{\sigma_p^*}{\sigma_n^*} \approx 2.4% \quad \frac{\sigma_p}{\sigma_n} \approx 5% \quad \approx 0.5
\]
Experimental method

- Use deuteron as a target in DIS

- Tag high-momentum nucleons with high-momentum backward-recoiling (“spectator”) partner nucleon as in SRC using the reaction $d(e,e'N_S)$
Experimental Method

Use factorization of the $d(e,e'N_S)$ cross section into the cross section ($F_2$) and the distorted momentum distribution.

Keeping the recoil kinematics fixed and measuring x-section ratios at 2 different $x'$, the ratio is:

$$\frac{d^4\sigma}{dx_1'dQ^2d\vec{p}_s}/\frac{d^4\sigma}{dx_2'dQ^2d\vec{p}_s} = (K_1/K_2)\left[ F_2^*(x_1',\alpha_S,p_T,Q_1^2)/F_2^*(x_2',\alpha_S,p_T,Q_1^2) \right]$$

For $x_1' \approx 0.45 - 0.6$ and $x_2' \approx 0.3$ we shall measure:

$$F_2^*(x_1',\alpha_S,p_T,Q_1^2)/F_2^*(x_2',\alpha_S,p_T,Q_1^2) = \left( \frac{d^4\sigma}{dx_1'dQ^2d\vec{p}_s}/K_1 \right)/\left( \frac{d^4\sigma}{dx_2'dQ^2d\vec{p}_s}/K_2 \right)$$

Integrating over $\theta_{pq} > 107^\circ$ (small FSI), we’ll compare the measured ratio $f(\alpha_S)$ to the BONUS results for free neutron, and to the free proton SF in $d(e,e'N_S)$

$$x' = \frac{Q^2}{2\vec{p}_\mu q^\mu} = \frac{Q^2}{2[(M_d - E_S)\omega + \vec{p}_S \cdot \vec{q}]}$$

$x'$ is x-Bjorken for the moving struck nucleon

$$\alpha_S = (E_S - p^z_S)/m_s$$

$\vec{p}_S$ maps to $(\alpha_S,p_T)$
Minimize experimental and theoretical uncertainties by measuring cross-section ratios.

\[
\frac{\sigma_{\text{DIS}}(x'^{\text{high}}, Q_1^2, \vec{p}_s)}{\sigma_{\text{DIS}}(x'^{\text{low}}, Q_2^2, \vec{p}_s)} \cdot \frac{\sigma_{\text{DIS}}^{\text{free}}(x_{\text{low}}, Q_2^2)}{\sigma_{\text{DIS}}^{\text{free}}(x_{\text{high}}, Q_1^2)} = \frac{F_2^{\text{bound}}(x'^{\text{high}}, Q_1^2, \vec{p}_s)}{F_2^{\text{free}}(x_{\text{high}}, Q_1^2)}
\]

\[x' = x \text{ from a moving nucleon}\]
\[x'^{\text{high}} \geq 0.45\]
\[0.25 \geq x'^{\text{low}} \geq 0.35 \text{ No EMC is expected}\]

\[x_B^{\text{d}} = \frac{Q^2}{2p_\mu q_\mu} = \frac{Q^2}{2[(M_d - E_S)\omega + \vec{p}_s \cdot \vec{q}]}\]
\[x_B = \frac{Q^2}{2m_N\omega}\]
CLAS6 Results: $d(e,e'p_s)$

Inconclusive!

Klimenko et al, PRC 73, 035212 (2006)
$x_B' = \frac{Q^2}{2p_\mu q^\mu}$

$D(e,e'N)$ no FSI

$x_B \rightarrow \frac{Q^2}{2m_N \omega}$

$x_B'$ vs. $x_B$ (Why $x'$?)
How to Deal with FSI?

We know that FSI:
- Decrease with $Q^2$
- Increase with $W'$
- Not sensitive to $x'_B$
- Small for $\theta_{pq} > 107^\circ$

We shall:
- Involve theoretical colleagues
- Take data at large recoil angles
- Take data at $90^\circ$ (to characterize FSI)
- Take data at two $x'$
- Use low $x'$ data to study FSI dependence on $Q^2, W'^2, \theta_{pq}$

A. V. Klimenko et al., PRC 73, 035212 (2006)
HMS and SHMS detect electrons.
LAD detect recoiling nucleon.

Central values of kinematics

**Low $x'$**

- $E_{\text{in}} = 10.9$ GeV
- $E' = 4.4$ GeV
- $\theta_e = 13.5^\circ$
- $Q^2 = 2.65$ GeV$^2$
- $|\vec{q}| = 6.7$ GeV/$c$
- $\theta_q = -8.8^\circ$
- $x = 0.217$

**High $x'$**

- $E_{\text{in}} = 10.9$ GeV
- $E' = 4.4$ GeV
- $\theta_e = -17^0$
- $Q^2 = 4.19$ GeV$^2$
- $|\vec{q}| = 6.8$ GeV/$c$
- $\theta_q = 10.8^0$
- $x = 0.34$

Collect both LAD–HMS and LAD–SHMS coincidences.

$\theta_{pq}$

- SHMS/LAD: 95–185$^0$
- HMS/LAD: 75–165$^0$
Experimental Set Up – Hall C

[Diagram showing the setup with labels for SHMS, LAD, HMS, e', 10 cm LD₂ target, GEM, and beam]
Large Acceptance Detector (LAD)

Use retired CLAS-6 TOF counters. 132, 5-cm thick counters in 12 panels. 1.5 sr, ~20% neutron detection efficiency
1. Design (Dan Young) and build (Hall C shop)
   1. 12 storage and support frames - Done
   2. 2 storage carts - Done
2. Remove large angle CLAS TOF panels from Hall B
   1. Panel4: July 6-7
   2. Panel3: August–September
3. Move the TOF detectors to the new frames
4. Test and Refurbish the detectors

One frame on cart with TOF detectors
Frame under construction

Frames stacked on cart

Goal: All frames on cart with TOF detectors
LAD Performance

- Singles rates measured in Hall A at 90°
- Overestimates larger angle backgrounds
- Detailed signal to background simulations

Momentum resolution \((300 < p < 500 \text{ MeV/c}) \approx 0.7\%\)

<table>
<thead>
<tr>
<th>(\alpha_s)</th>
<th>1.2</th>
<th>1.3</th>
<th>1.4</th>
<th>1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>(x'_B &gt; 0.45)</td>
<td>1:1</td>
<td>1:2</td>
<td>1:2</td>
<td>1:2</td>
</tr>
<tr>
<td>(x'_B \approx 0.3)</td>
<td>3:1</td>
<td>1:1</td>
<td>1:1</td>
<td>1:1</td>
</tr>
</tbody>
</table>
Neutron Detection

- 5 LAD layers
- Veto charged particles using GEM and 1\textsuperscript{st} layer
- 5 MeVee threshold to reduce backgrounds
- Experience from scintillator neutron detection in Halls A and B
- Detailed, bin-by-bin, background simulation
  - 1:200 S/BG ratio at high $x'$ before cuts
    - $x'$, and $W'$ cuts
    - $\theta_{pq} > 110^\circ$
  - 1:20 S/BG at high $x'$ after cuts
- Subtract random background with mixed events
Kinematic Coverage

Scattered electrons

Recoiling nucleons

Recoil nucleon virtuality

\[ E'[\text{GeV}] \]

\[ P_{\text{recoil}} \]

\[ x'_{B} \]

\[ \theta_{e'} \]

\[ Q^2 > 2 \]

\[ W' > 2 \]

\[ x'_{e} < 0.35 \]

\[ x'_{e} > 0.5 \]
**Expected Results**

\[ \alpha_s = \frac{(E_s - p_S^Z)}{m_s} \]

- \( \alpha_s \) - Geff/G^n
- \( \alpha_s \) - Geff/G^p

- **Systematic uncertainty (4-7% total)**
  - SHMS and HMS efficiency and acceptances (1-2%)
  - LAD efficiency (3% protons, 5% neutrons)
  - Al walls subtraction (1%)
  - FSI ratio (4%)
  - Free nucleons structure functions ratio (1% protons, 4% neutrons)
Summary – Nucleon Medium Modification

Physics:
- SRC and EMC are linearly correlated
- Both phenomena are likely related to high-momentum nucleons
- EMC effect strongly implies that bound nucleons are modified
  - We want to measure highly virtual bound nucleon structure functions

Experiment:
- E12-11-107 will measure $F_2$ for highly virtual nucleons in the deuteron and compare that to $F_2$ for free nucleons
  - Use spectator tagging to select highly virtual nucleons in DIS
  - Minimize systematic uncertainties by measuring ratios

- Are nucleons modified in the nucleus?
- Can this explain the EMC effect?
- How is this related to short range correlations?
Backup slides
EMC Effect: $Q^2$ Independence


J. Seely et al, PRL 103, 202301 (2009)

No $Q^2$ dependence for $2 < Q^2 < 40 \text{ GeV}^2$
## Robustness of SRC-EMC Correlations

O. Hen et al., arXiv:1202.3452 [nucl-ex]

### Table: Comparing Predictions and Results

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Egiyan et al. [12]</th>
<th>EMC-SRC Prediction [8]</th>
<th>Fomin et al. [18] [Analysis as in Ref. [12]]</th>
<th>Fomin et al. [18] excluding the CM motion correction</th>
<th>SLAC [10]**</th>
<th>EMC Slope $dR_{EMC}/dx$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$He</td>
<td>1.97 ± 0.10*</td>
<td>1.87 ± 0.06</td>
<td>1.93 ± 0.10</td>
<td>2.13 ± 0.04</td>
<td>1.7 ± 0.3</td>
<td>-0.070 ± 0.029</td>
</tr>
<tr>
<td>$^4$He</td>
<td>3.80 ± 0.34</td>
<td>3.64 ± 0.07</td>
<td>3.02 ± 0.17</td>
<td>3.60 ± 0.10</td>
<td>3.3 ± 0.5</td>
<td>-0.197 ± 0.026</td>
</tr>
<tr>
<td>$^9$Be</td>
<td>4.75 ± 0.41</td>
<td>4.15 ± 0.09</td>
<td>3.37 ± 0.17</td>
<td>3.91 ± 0.12</td>
<td>-0.243 ± 0.023</td>
<td></td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>5.58 ± 0.45</td>
<td>4.81 ± 0.10</td>
<td>4.00 ± 0.24</td>
<td>4.75 ± 0.16</td>
<td>5.0 ± 0.5</td>
<td>-0.292 ± 0.023</td>
</tr>
<tr>
<td>$^{56}$Fe($^{63}$Cu)</td>
<td>6.19 ± 0.65</td>
<td>5.29 ± 0.12</td>
<td>4.33 ± 0.28</td>
<td>5.21 ± 0.20</td>
<td>5.2 ± 0.9</td>
<td>-0.388 ± 0.032</td>
</tr>
<tr>
<td>$^{197}$Au</td>
<td>6.19 ± 0.65</td>
<td>5.29 ± 0.12</td>
<td>4.26 ± 0.29</td>
<td>5.16 ± 0.22</td>
<td>4.8 ± 0.7</td>
<td>-0.409 ± 0.039</td>
</tr>
</tbody>
</table>

**Note:**
- EMC-SRC slope $a = \frac{\sigma(n+p)}{\sigma_d} | z_B = 0.7$
- $\chi^2/ndf$

### Calculations:

- $0.079 \pm 0.006$
- $1.032 \pm 0.004$
- $0.7688/3$

### Summary:

- **Insensitive to:**
  - Isoscalar corrections
  - Radiative corrections
  - Coulomb corrections
  - Inelastic contributions

- **Pair C.M. motion correction for A > 2:**
  - Reduces x-sections by ~20%
  - Reduces intercept by ~20%

- Does not make a qualitative change to conclusions
Nucleons Modified at High Momentum

M. Paolone et al. PRL 105,072001 (2010)

This is in quasi-elastic scattering, not DIS!

Our experiment will cover the range of virtuality 0.2 – 0.5