Overview of the SRC/EMC experiments

Donal Day
Hall C Winter Meeting 2016

E12-06-105
E12-10-008
PAC Report

- E12-06-105 (x > 1): “Inclusive Scattering from Nuclei at x > 1 in the Quasi-elastic and Deep-inelastic Regimes”
- E12-10-008 (EMC high-x): “Detailed Studies of the Nuclear Dependence of F2 in the Light Nuclei”

The PAC considers this physics compelling. Although it is not yet clear that theory can directly connect these studies to the short-range part of the N-N interaction, the two are obviously related, and studies such as these may offer one of the few remaining routes to improving our knowledge of the N-N interaction in this corner of abiding uncertainty.

The PAC had a very similar impression of these two experiments: both are top-quality experiments whose design reflects impressive insight into the SRC area. Both experiments involve compelling observables that will provide qualitative new information on short-range correlations in nuclei. For example, the “x > 1” experiment (E12-06-105) will seek to establish or refute the existence of a second plateau at x > 2.2 in the heavy to deuteron ratio, hints of which have been observed in previous JLab data. Such a plateau would provide a dramatic signature of 3-body correlations at work and valuable information on their strength and isospin dependence.

The committee was equally fascinated by “EMC high-x” (E12-10-008) and the ingenious suggestion of a connection between the EMC effect and the local density of nuclear matter, supported by similarities in their A-dependence and isospin-dependence. The PAC enthusiastically supports the full beam requests of both experiments: 32 and 23 days for E12-06-105 and E12-10-008 respectively, both in Hall C.
Structure of the nucleus

Determined by N-N potential

- nucleons are bound
  - energy (E) distribution
  - shell structure
- nucleons are not static
- momentum (k) distribution

on average:
  binding energy: \(~ 8 \text{ MeV}\)
  distance: \(\approx 1.7 \text{ fm}\)

- Densely packed
  - at small distances multiples of NM

Gold nucleus - 60\% of the volume is occupied – very closely packed!

Medium modifications!
Inclusive Electron Scattering from Nuclei

Two distinct processes

Quasielastic from the nucleons in the nucleus

Inelastic and DIS from the quark constituents of the nucleon.

x = Q^2/(2m_\nu)

\nu, \omega = energy loss
The two processes share the same initial state

\[
\frac{d\sigma^2}{dQ_{e'}dE_{e'}} = \frac{\alpha^2 E'_e}{Q^4 E_e} L_{\mu\nu} W_{\mu\nu}
\]

However they have very different \(Q^2\) dependencies

\[
\sigma_{ei} \propto \text{elastic (form factor)}^2 \approx 1/Q^4
\]

\(W_{1,2}\) scale with \(\ln Q^2\) dependence

Exploit this dissimilar \(Q^2\) dependence
Strength is spread out in \( E \), all of which must be integrated over to get \( n(k) \).

\[ n(k) = \int dE \ S(k, E) \]

A ridge at approx \( E = k^2/2m \) reflects the correlation in the gs.
Integration limits over spectral function

The limits on the integrals are determined by the kinematics. Specific \((x, Q^2)\) select specific pieces of the spectral function.

Followed by electron- and muon-scattering data from SLAC, Fermilab, and the New Muon collaboration (NMC) at CERN

**Accepted behavior**

- the effect had a universal shape
- was independent of $Q^2$
- increased with nuclear mass number $A$
- scaled with the average nuclear density

**Everyone’s Model is Cool**

- bound nucleons are larger than free ones
- quarks in nuclei move in quark bags with 6, 9 and even up to $3A$ quarks,
- influence of nuclear binding,
- enhancement of pion-cloud effects and a nuclear pionic field
- …

**Shadowing:** Attributed to the hadronic structure of the photon: Interference between single and multiple interactions caused the reduction in the cross-section known as shadowing.

**EMC:** quarks in nuclei move throughout a larger confinement volume and, as the uncertainty principle implies, they carry less momentum than quarks in free nucleons.

No complete picture consistent with other data, i.e DY
Nuclear Dependence of the EMC Effect

SLAC E139 studied the nuclear dependence of the EMC effect at fixed $x$
Results consistent with
- Simple logarithmic $A$ dependence
- Average nuclear density

$^4\text{He}$ much lighter than $^{12}\text{C}$, but has similar average density
$^9\text{Be}$ much lower density than $^{12}\text{C}$, but similar mass
$^3\text{He}$ has low $A$ and low density

Many models of the EMC effect assume the size of the EMC effect scales with average nuclear density

Constraining form of nuclear dependence can confirm or rule out this assumption

Light nuclei help test scaling with mass vs. density

Enter JLab E03-103
JLab E03-103: Light nuclei

Consistent shape for all nuclei (curves show shape from SLAC fit)

If shape (x-dependence) is same for all nuclei: the slope (0.35<x<0.7) can be used to study dependence on A

EMC Effect and Local Nuclear Density

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

Credit: P. Mueller, via John Arrington
Independent Particle Shell Model

- Independent particle states of a uniform potential – a mean field.

Wood-Saxon

- Long mean free paths
- No two-body interactions
- The single-particle energies $\xi_\alpha$ and wave function $\Phi_\alpha$ are the basic quantities – can be accessed in knockout reactions
- The spectral function should exhibit a structure at fixed energies with momentum distributions characteristic of the shell (orbit).

$$S(\vec{p}, E) = \sum_\alpha |\Phi_\alpha(p)|^2 \delta(E + \xi_\alpha)$$

NN potential – AV18

- Enormous strong force acting
- So many nucleons to collide with
- How can nucleons possibly complete whole orbits ($10^{21}$/s) without interacting?

Correlations must exist – and they do
How do we know short range correlations exist?

Central density is saturated - nucleons can be packed only so close together: $p_{ch} \times (A/Z) = \text{constant}$

Occupation numbers scaled down by a factor $\sim 0.65$. 
What many calculations indicate is that the tail of $n(k)$ for different nuclei has a similar shape – reflecting that the NN interaction, common to all nuclei, is the source of these dynamical correlations.

$$n(k) = \int dE \ S(k, E)$$

Theory suggests that SRCs are a common feature for all nuclei.
Simple SRC Model:

- 1N, 2N, 3N contributions dominate at \( x \leq 1, 2, 3 \)
- 2N, 3N configurations “at rest” (total \( p_{\text{pair}} = 0 \))
- Isospin independent

Experimental observations:

- Clear evidence for 2N-SRC at \( x>1.5 \)
- Suggestion of 3N-SRC plateau (?)
- Isospin dependence?
Connection between SRCS and EMC effect: Importance of two-body correlations?

Given the fact that the inclusive data integrate over very different parts of the spectral function this probably deserves more study.

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

L. Weinstein, et al., PRL 106, 052301 (2011)
Detailed study of nuclear dependence of EMC effect and SRCs does not favor either picture. Can we distinguish between these two pictures via some new observable? → Flavor dependence of the EMC effect.

\[ \alpha_2 \propto \text{number of high momentum nucleons (pn) pairs} \]

\[ \frac{N_{\text{tot}}}{N_{\text{iso}}} R_{2N} \] accounts for difference in pair counting for EMC/SRC; nucleons close together.

Arrington et al, PRC 86, 065204 (2012)
Flavor dependence and SRCs

$^4$He 2-body density from

High momentum nucleons from SRCs emerge from tensor part of $NN$ interaction – $np$ pairs dominate

→ Probability to find 2 nucleons “close” together nearly the same for $np$, $nn$, $pp$

For $r_{12} < 1.7$ fm:

$$P_{pp} = P_{nn} \approx 0.8P_{np}$$

If EMC effect due to *high virtuality*, flavor dependence of EMC effect emerges naturally

→ If EMC effect from *local density*, $np/pp/nn$ pairs all contribute (roughly) equally

Flavor dependence and SRCs

High momentum nucleons in the nucleus come primarily from np pairs

\[ n_p^A(p) \approx \frac{1}{2x_p} a_2(A, y) n_d(p) \quad \quad x_p = \frac{Z}{A} \]

\[ n_n^A(p) \approx \frac{1}{2x_n} a_2(A, y) n_d(p) \quad \quad x_n = \frac{A - Z}{A} \]

\[ u_A = \frac{Z \tilde{u}_p + N \tilde{d}_p}{A} \quad d_A = \frac{Z \tilde{d}_p + N \tilde{u}_p}{A} \]

\[ -dR_{EMC}/dx \]

Under the assumption the EMC effect comes from “high virtuality” (high momentum nucleons), effect driven by protons (u-quark dominates) \( \rightarrow \) similar flavor dependence is seen in some “mean-field” approaches

Flavor Dependence of the EMC Effect

Mean-field calculations predict a flavor dependent EMC effect for $N \neq Z$ nuclei

Medium modified quark distributions

Free nucleon quark distributions

Isovector-vector mean field ($\rho$) causes $u$ ($d$) quark to feel additional vector attraction (repulsion) in $N \neq Z$ nuclei

Experimentally, this flavor dependence has not been observed directly
Flavor dependence from $^{40}\text{Ca}$ and $^{48}\text{Ca}$

CBT model predicts a ~3% effect for $^{48}\text{Ca}$ at $x=0.6$

\[ \rightarrow N/Z = 1.4 \]

Assuming no flavor dependence, difference between $^{40}\text{Ca}$ and $^{48}\text{Ca}$ should be less than < 1%

Will be measured at JLab @ 12 GeV

E12-10-008
Spokespersons: Arrington, Gaskell, Daniel
In OPE, $F_2^0$ (not $F_2$) should be independent of $Q^2$ in the absence of QCD evolution and higher twists:

$$F_2(x, Q^2) = \frac{x^2}{\xi^2 r^3} F_2^0(\xi, Q^2)$$

$$+ \frac{6 M^2 x^3}{Q^2 r^4} h_2(\xi, Q^2) + \frac{12 M^4 x^4}{Q^4 r^5} g_2(\xi, Q^2)$$

PDFs at $x > 1$ sensitive to SRC. The bulk of the strength for $x \geq 1.1$–$1.2$ come from the high momentum nucleons generated by short range correlations in nuclei.

Large $Q^2$, large $x$ additionally sensitive to small admixtures of exotic components - e.g. 5% 6q cluster in D leads to dramatic effect on large $x$ pdfs: Mulders and Thomas

Quark pdfs at $x > 1$
Red - QES, Blue - RR, Green - DIS, line total (convolution model)

Sensitivity to non-hadronic components

$Q^2 \approx 2$

$Q^2 > 17$ for $x > 1$

$5\%$ 6-quark bag

$x < 1$

$x > 1$
....few remaining routes to improving our knowledge of the N-N interaction in this corner of abiding uncertainty.

### N-N interaction

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<th>S</th>
<th>J</th>
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Possible Two Nucleon states

The SR NN attraction dominated tensor interaction, which yields high momentum isosinglet (np) pairs.

Absent in the isotriplet channel (pp, nn, np).

The two-body distribution should be identical to the deuteron distribution, \( n_2(k) = n_D(k) \), and the ratio of scattering cross sections between a heavy nucleus A and the deuteron to yield \( a_2(A, Z) \)

Explains the SRC ratios, isospin asymmetry
Tensor force responsible for dominant part of SRC and correlations are largely of pn pairs

Schiavilla et al. PRL 98, 132501 (2007), VMC and AV18/UIX

JLAB A(e,e’NN) data from Hall A
R. Subedi et al.
What's planned?

- XEMC part 2
- HMS
- SHMS

\[ Q^2 (\text{GeV}^2) \]

- super-fast quarks
- quark distribution functions
- medium modifications

\[ x \]

- SHMS, \( x > 1 \)
- HMS, \( x > 1 \)
- EMC

- SRC, \( n(k) \), \( \sigma \), FSI
E12-10-008 Overview in greater detail

- Request 23 days of beam time in Hall C
  - Higher $Q^2$, expanded range in $x$
    - Lower-$x$ coverage improves shape comparison
    - Large expansion in high-$x$ DIS region
    - Angle scan to test $Q^2$-independence
  - More complete set of light nuclei
  - $^{40}$Ca, $^{48}$Ca comparison
  - Improved $^3$He extraction

$\theta=20^\circ$ for most nuclei:
$W^2>2 \rightarrow 0.1<x<0.88$ with high cross section, small pion and charge-symmetric backgrounds, reasonable radiative corrections

$\theta=35^\circ$ for high-$x$ coverage:
$W^2>2 \rightarrow 0.3<x<0.92$; improved high-$x$ coverage, mainly needed for "isoscalar" ratios, e.g. $^3$He/(D+p)

Main 6 GeV setting

$E_{beam}=11$ GeV

Kinematics
dotted black lines (E03-103)

11 GeV DIS range

6 GeV DIS range

Main 6 GeV setting
We like to add additional heavier nuclei:
- Vary N/Z for approximately fixed mass
- Vary mass for approximately fixed N/Z

Isotopes with measured charge radii:

EMC/SRC target set:
Start trying to disentangle A dependence and N/Z dependence

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Average Density

Seek out ranges of n/p ratios for isospin dependence studies
E12-10-008 and E12-06-105

Hall C experiments will provide more inclusive data
→E12-06-105 x>1
→E12-10-008 EMC Effect

Will provide additional data on light and medium-heavy targets
→\(^2\)H, \(^3\)He, \(^4\)He
→\(^6\)Li, \(^7\)Li, Be, \(^{10}\)B, \(^{11}\)B, C
→Al, \(^{40}\)Ca, \(^{48}\)Ca, Cu

First running in Hall C after completion of 12 GeV Upgrade will include a few days for EMC/x>1 measurements on \(^{10}\)B, \(^{11}\)B, and Al (parasitic) - begins????

Beam Time request for 2018?