Short Range Correlations in $(e, e'N)$ Experiments

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All high-momentum nucleons have a correlated partner.

$p$ scattering from Carbon:
- Always a correlated partner
- Anti-parallel momenta

E. Piasetzky et al., PRL 97 162504 (2006)
Between 300–600 MeV, *np* pairs predominate.

![Graph showing SRC pair fraction vs. missing momentum]

**References and Notes**

E. Piasetzky et al., PRL 97 162504 (2006)
R. Shneor et al., PRL. 99, 072501 (2007)
$np$ dominance may reduce at higher momentum.

Korover et al., PRL 113, 022501 (2014)
Data mining has been a productive source of information.

Open questions

1. How can we distinguish between competing reactions?
2. How does $np$ dominance evolve at very high momentum?
3. How does pairing change with nuclear size/asymmetry?
4. How/where do pairs form?
5. What is the role of SRCs in the EMC effect?
Short-Range Correlations Collaboration
Today I will cover:

1. Where are we?
2. Where are we going?
3. Where can the EIC take us?
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CLAS is well-suited for data mining.

- Large acceptance
- Open trigger
CLAS data mining confirmed the absence of high-momentum $pp$ pairs.

Meytal Duer has identified high-momentum neutrons for the first time.

M. Duer et al., submitted to Nature
Neutrons efficiencies and resolutions were calibrated using the \( d(e, e' p \pi^+ \pi^-) n \) reaction.

![Graph showing neutron momentum and ECal efficiency](image-url)
The poor neutron resolution was studied by “smearing” protons.

![Smeared Protons vs Neutrons](chart.png)
\[
\frac{\sigma_A(e, e'n)}{\sigma_{en}} \bigg/ \frac{\sigma_A(e, e'p)}{\sigma_{ep}}
\]

$n/p$ ratio is constant with asymmetry!
SRC fraction for neutrons saturates.

\[
\text{SRC Fraction} \equiv \frac{\sigma_{\text{SRC}}^{A}(e,e'N)}{\sigma_{\text{MF}}^{A}(e,e'N)} / \frac{\sigma_{\text{SRC}}^{C}(e,e'N)}{\sigma_{\text{MF}}^{C}(e,e'N)}
\]
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\]

Protons and neutrons super ratios

High-Momentum Fraction

\[
\frac{A(e,e'N)_{\text{high}}}{A(e,e'N)_{\text{low}}}
\]

Neutron Excess \([N/Z]\]

Our simple model works
$np/pp$ ratio is constant over all species.
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$^3$He and $^4$He analysis is under way.
Inclusive electron scattering can already tell us about short range interactions.

\[
\frac{3 \cdot \sigma_A}{A \cdot \sigma_{^3\text{He}}} \\
\frac{2 \cdot \sigma_A}{A \cdot \sigma_{d}}
\]


Fomin et al., PRL 108, 092502 (2012)
At high $x$, quasielastic scattering can only proceed from a high-momentum nucleon.
$a_2$ plateaus tell us that high-momentum tails are universal.

\[ \frac{3 \cdot \sigma_A}{A \cdot \sigma_{^3\text{He}}} \]


Scaling constant $a_2$:

\[ \sigma_A = a_2 \times \frac{A}{2} \sigma_d \]
The $a_2$ plateau correlates with the size of the EMC effect.
New CLAS inclusive analysis on C, Al, Fe, Pb

Barak Schmookler et al., in preparation
New CLAS inclusive analysis on C, Al, Fe, Pb

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SRC-EMC correlation

![Graph showing the correlation between EMC Slope (-dR/dx) and Density of SRC-pairs (a²) for different elements.](image-url)
SRC-EMC correlation

This work

EMC Slope ($-dR/dx$)

Density of SRC-pairs ($a_2$)
SRC-EMC correlation

![Graph showing SRC-EMC correlation with density of SRC-pairs and EMC slope.](image-url)
Saturation with per-neutron normalization

![Graph showing neutron normalization](image)

- **EMC Slope (−dR/dx)**
- **Density of SRC-pairs (a₂)**
No saturation with per-proton normalization

Proton normalization

EMC Slope (−dR/dx) vs. Density of SRC-pairs ($a_2$)
Other analyses underway...

1. Center-of-mass momentum distributions for $pp$ pairs

2. $^3$He, $^4$He, $pp$ to $p$ ratio

3. Recoil-tagged inclusive scattering
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Upcoming SRC Experiments

- $(e, e'p)$ in SRC kinematics
  - Tritium
  - CaFe
- Recoil-tagged DIS on deuterium
  - BAND
  - LAD
Protons in tritium tell us about neutrons in $^3\text{He}$.

- E12-14-001 (Hall A)
- Tritium and Helium-3 gas targets
- $(e, e'p)_{^3\text{He}}/(e, e'p)_{^3\text{H}}$ as a function of $p_{\text{miss}}$
- 10 days of running, fall 2018
Protons in tritium tell us about neutrons in $^3\text{He}$. 

![Graph showing the ratio $n_{^3\text{He}}(k) / n_{^3\text{H}}(k)$ as a function of missing momentum ($P_{\text{miss}}$). The graph indicates the expected statistical uncertainties in the proposed measured cross section ratios of $^3\text{He}(e, e_0p)/^3\text{H}(e, e_0p)$ as a function of missing momentum (see Eq. 2). The red band shows the total expected uncertainty of the experimental integration.]

Data points labeled VMC, Nogga (AV18), Sargsian, Kaptari, and Projected Results are plotted against the $P_{\text{miss}}$ in MeV/c. The graph demonstrates the comparison between theoretical predictions and experimental results.
CaFe: disentangling size and asymmetry

- E12-17-005 (Hall C)
- $^{40}\text{Ca} \leftrightarrow ^{48}\text{Ca} \leftrightarrow ^{54}\text{Fe}$
- Sensitive to pairing from different orbitals
- Approved for 9 days, 2017 PAC
- Measure:
  - $(e, e'p)_{\text{SRC}}/(e, e'p)_{\text{MF}}$
  - $(e, e'p)_{A_1}/(e, e'p)_{A_2}$
  - Double-ratios
We will test the SRC-EMC hypothesis with recoil-tagging experiments.

Advantages of a deuterium target:

- Minimal final-state interactions
- Spectator has exactly opposite momentum
- 5% of the wave-function is short-range configuration
DEEPS showed little FSI at back angles.

Klimenko et al., PRC 73 035212 (2006)
What we want to measure:

\[
\frac{F_2(x', Q^2, \alpha_s)}{F_2(x, Q^2)} \approx \frac{\sigma_{\text{DIS}}(x', Q^2, \alpha_s)}{\sigma_{\text{DIS}}(\text{low x}', Q_0^2, \alpha_s)} \times \frac{\sigma_{\text{DIS}}(\text{low x}, Q_0^2)}{\sigma_{\text{DIS}}(x, Q^2)} \times R_{\text{FSI}}
\]
What we want to measure:

\[
\frac{F_2(x', Q^2, \alpha_s)_{\text{bound}}}{F_2(x, Q^2)_{\text{free}}} \approx \frac{\sigma_{\text{DIS}}(x', Q^2, \alpha_s)_{\text{bound}}}{\sigma_{\text{DIS}}(\text{low } x', Q^2_0, \alpha_s)_{\text{bound}}} \times \frac{\sigma_{\text{DIS}}(\text{low } x, Q^2_0)_{\text{free}}}{\sigma_{\text{DIS}}(x, Q^2)_{\text{free}}} \times R_{\text{FSI}}.
\]

Tagged DIS measurement Input \approx 1
What we want to measure:

\[
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\]

Tagged DIS measurement \quad \text{Input} \quad \approx 1

At low \( x \), the EMC effect should be small:

\[
\sigma_{\text{DIS}}(\text{low } x', Q_0^2, \alpha_s)_{\text{bound}} \approx \sigma_{\text{DIS}}(\text{low } x, Q_0^2)_{\text{free}}
\]
Different models predict different $F_2$ ratios.

BAND will detect recoiling spectator neutrons.
BAND will surround the upstream beamline.
BAND Experiment Details

Experiment

- Experiment E12-11-003A
- Approved for 90 days
  - Run group B
  - late 2018 / early 2019
- Extended LD$_2$ target
- 11 GeV $e^-$ beam
- $10^{35}$ cm$^{-2}$s$^{-1}$

Backward Angle Neutron Detector

- Currently being built at MIT
- 5 rows of 21 bars
- $160^\circ$–$170^\circ$
- $\approx 60\%$ azimuthal coverage
We have developed a detailed simulation of the experiment.
The limit will be random coincidence background.

- Can be subtracted using “off-time” events
- Statistical variation can drown signal

\[
\frac{\delta N}{N} = \frac{\sqrt{S+B}}{S}
\]

Any reduction in background buys us statistics!
Background will be higher at large $x'$. 

![Graph showing signal and random background with $Q^2 > 2 \text{ GeV}^2$ and $W' > 1.8 \text{ GeV}$]
Even with background, we expect good statistical precision.
Even with background, we expect good statistical precision.
LAD will detect recoiling spectator protons.
LAD is three panels of scintillator bars, originally from the CLAS-6 ToFs.
LAD Experiment Details

Experiment
- Experiment E12-11-107
- Approved for 820 hours
- Extended LD$_2$ target
- 11 GeV e$-$ beam
- $10^{36}$ cm$^{-2}$s$^{-1}$
- Low $x$ and high $x$ settings

Large Acceptance Detector
- 5 panels of 11 bars
- 1.5 sr at back angles
- 90°–160°
- ±18° out-of-plane
Energy deposition in LAD must match velocity.
We plan to add GEMs to assist in vertexing.
We plan to add GEMs to assist in vertexing.
Expected Impact

![Graph showing the relationship between Bound F2 / Free F2 and \( \alpha_s \). The graph includes lines for Binding, Rescaling, PLC suppression, and alpha_s values ranging from 1 to 1.6.]
Expected Impact

![Graph showing the expected impact of various parameters on Bound $F_2 / Free F_2$ against $\alpha_s$. The parameters include Binding, Rescaling, PLC suppression, and LAD/BAND. The graph illustrates the trend and variability with error bars for Bound $F_2 / Free F_2$ across different $\alpha_s$ values.](image-url)
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Possibilities at the EIC

1. Tagging
   - DIS or QE
   - very forward spectator
   - “zero momentum” spectators are now detectable

2. Detection of the \(A-2\) system
   - very forward residual nucleus
Small differences in initial momentum become large in the collider frame.
Spectators will be within $2^\circ$ of beamline.
Possibilities at the EIC

1. Tagging
   - DIS or QE
   - very forward spectator
   - “zero momentum” spectators are now detectable

2. Detection of the $A - 2$ system
   - very forward residual nucleus
Inverse kinematics at Dubna: detecting the nuclear remnant.

C beam (4 GeV/u) → Hydrogen Target → Proton Arms → Dipole → Zero-degree calorimeter

NeuLAND
Detecting the $A - 2$ system is essential for rejecting non-SRC background.

\[ P_{\text{miss}} < 0.25 \text{ GeV/c} \]
\[ P_{\text{miss}} > 0.25 \text{ GeV/c} \]
both

Counts

$P_{\text{miss}}$ (GeV/c)
Detecting the $A-2$ system is essential for rejecting non-SRC background.

Identification of $A-2$ leads to $x10$ mean field reduction

Counts

$P_{\text{miss}} < 0.25$ GeV/c

$P_{\text{miss}} > 0.25$ GeV/c

both
Residual nucleus can be determined from $dE/dx$. 

![Graph showing pulse height distribution with peaks for Li, Be, B, and C]
This will be truly exclusive: $p(^{12}\text{C},^{10}\text{Bppn})$
This will be truly exclusive: $p(^{12}\text{C},^{10}\text{B}ppn)$

This experience will help us plan for the EIC.
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New results

Neutron Excess [N/Z]

Protons and neutrons super ratios

\[ \frac{\sigma_A(e,e'n)/\sigma_{en}}{\sigma_A(e,e'p)/\sigma_{ep}} \]

Neutron normalization

EMC Slope (−dR/dx)

Density of SRC-pairs (a^2)

Proton normalization

EMC Slope (−dR/dx)

Density of SRC-pairs (a^2)
New results

\[
\frac{\sigma_A(e,e'n)/\sigma_{en}}{\sigma_A(e,e'p)/\sigma_{ep}}
\]

Neutron Excess [N/Z]

Neutron normalization

Proton normalization

Protons and neutrons super ratios

Higgs-Momentum Fraction

\[
\frac{A(e,e'N)_{\text{high}}}{A(e,e'N)_{\text{low}}}
\]

\[
\frac{12C(e,e'N)_{\text{high}}}{12C(e,e'N)_{\text{low}}}
\]
Upcoming measurements

Protons Dynamics in Neutron Rich Nuclei

Focused Study of SRC dynamics in $^{48}$Ca by comparing to the $^{40}$CaFe triplet.

$^{48}$Ca - 8 neutrons + 6 protons

G. Hagen et al., Nature Physics 12, 186 (2016)

Deuterium
Spectator neutron
BAND 11 GeV e–
CLAS12 JLab Hall B

Spectator proton
JLab Hall C

LAD
SHMS
HMS
GEMs
Upcoming measurements

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Upcoming measurements
Conclusions

- There is still so much we don’t know about short range correlations.

- Our upcoming experiments with tagging and inverse kinematics will provide crucial experience as we plan for the EIC.