Short-Range Structure of Nuclei

Or Hen
Tel-Aviv University
Spectroscopic factors from (e,e'p) measurements yield only 60-70% of the expected single particle strength.

**Missing:**
- Long Range Correlations (accounts for ~20%)
- High momentum nucleons (Short Range Correlations)

Independent particle models do not produce enough high momentum nucleons.

Many-body calculations predicts that the high momentum distribution for all nuclei has the same shape:

$$n_A(k)/n_d(k) = a_2 (A/d)$$
A hard process with the resolving power to probe the partonic structure of the nucleus

$x_B$ counts the number of nucleons involved in the reaction

→ for $x_B > j$, at least $j$ nucleons are involved in the reaction

Kinematics:

$E, E' \ 3 - 5 \ \text{GeV}$

$Q^2 \ 2 - 3 \ \text{[GeV/c]}^2$

$1 \leq x_B \leq A$
Inclusive Electron Scattering at $x_B > 1$

- A hard process with the resolving power to probe the partonic structure of the nucleus
- $x_B$ counts the number of nucleons involved in the reaction
- At high $Q^2$, $x_B$ determines a minimum initial momentum for the scattered nucleon ($y$)

$$x_B = \frac{Q^2}{2m_\omega}$$

$momentum\ scaling \leftrightarrow x_B\ scaling$
High Precision Results from Hall-C

| $a_2(A/d)$ |  
|---|---|
| $^3\text{He}$ | $1.93 \pm 0.10$ |
| $^4\text{He}$ | $3.02 \pm 0.17$ |
| $^9\text{Be}$ | $3.37 \pm 0.17$ |
| $^{12}\text{C}$ | $4.00 \pm 0.24$ |
| $^{63}\text{Cu}$ | $4.33 \pm 0.28$ |
| $^{197}\text{Au}$ | $4.26 \pm 0.29$ |

$n_A(k) = a_2(A/d) \cdot n_d(k)$


Short Range Correlations (SRC)

- 2N-SRC are pairs of nucleons that:
  - Are close together (overlap) in the nucleus.
  - Have high relative momentum and low c.m. momentum, where high and low is compared to the Fermi momentum of the nucleus.
Short Range Correlations (SRC)

- SRC Dominance at High Momentum
- Momentum Distributions
- IsoSpin Structure
- Medium Modification?
- Nuclear Structure
- Nucleon-Nucleon Interaction
- Neutron Stars
- EMC Effect

How? Using exclusive measurements
Exclusive SRC Studies

\( A(e,e'pN): \) detect electron + two nucleons

- **Pros:** Measure the “full” 2N final state to **characterize** the 2N-SRC pairs

- **Cons:**
  - **Interpretation difficulties:** Competing processes, FSI, Transparency.
  - **Experimental difficulties:** Large BG, Low statistics, Large Installation, Dedicated detectors

Who knew nuclear physics can be so complicated.
Measurement Concept:

1. Hard knock out of a high momentum proton

2. Reconstruct the initial (missing) momentum of the struck nucleon

3. Look for a recoil nucleon with momentum that balanced that of the struck proton

\[ \vec{p}_{\text{miss}} \cdot \vec{q} - \vec{p}_p = -\vec{p}_{\text{initial}} \]
Goal: Study both \textbf{pn and pp SRC} in $^{12}\text{C}$ over an (e,e'p) missing momentum range of 300-600 MeV/c

Kinematics:
- High $Q^2$ to minimize MEC
- $x_B > 1$ to suppress isobar contributions
- Almost anti-parallel kinematics to confine FSI to within the 2N-SRC pair
JLab Hall-A

Physicists Tend To Fill Empty Space

© D. Higinbotham
Clear Back-to-Back correlation between $p_{\text{initial}}$ and $p_{\text{recoil}}$!

Simulation with a Gaussian c.m. distribution with $\sigma=136$ MeV/c

The \((e,e'pN)/(e,e'p)\) ratio gives the probability for a high momentum proton to be part of a pN-SRC pair.

All high \(p_{\text{initial}}\) protons have a correlated partner.

np pairs dominate.

Importance of tensor force at \(0.3 < p_{\text{initial}} < 0.6\) GeV/c

2N-SRC from inclusive and exclusive measurements

1. The probability for a nucleon to have \( p \geq 300 \text{ MeV/c} \) in medium nuclei is 20-25%.

2. More than \( \sim 90\% \) of all nucleons with \( p \geq 300 \text{ MeV/c} \) belong to 2N-SRC.

3. 2N-SRC dominated by np pairs

   → Tensor interaction

~80% of kinetic energy of nucleon in nuclei is carried by nucleons in 2N-SRC.
Ongoing Inclusive and Exclusive Analysis

Inclusive Analysis, E08-014 (Hall-A 2011):

1) Study the IsoSpin structure of 2N-SRC by comparing \(^{40}\text{Ca}\) to \(^{48}\text{Ca}\)

2) Study the \(Q^2\) Dependence of the 3N-SRC plateau

Exclusive Analysis

1) E07-006 (2011): Second generation Hall-A measurements on \(^4\text{He}\).
   Pushing towards the repulsive core of the nucleon-nucleon interaction @ \(400 \leq P_{\text{miss}} \leq 750\) MeV/c

2) Hall-B Data Mining Project
Ongoing Inclusive and Exclusive Analysis

Inclusive Analysis, E08-014 (Hall-A 2011):

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Exclusive Analysis

   Pushing towards the repulsive core of the nucleon-nucleon interaction @ $400 \leq P_{\text{miss}} \leq 750$ MeV/c

2) Hall-B Data Mining Project
Hall-B Data Mining Project

“Short Distance Structure of Nuclei: Mining the Wealth of Existing Jefferson Lab Data”

Current analysis focuses on the EG2 data-set:

- A double solid+deuterium target set-up
- Open inclusive (e,e') trigger
- Run in 2004. Full CLAS calibration and PID schemes are available
- Previous analysis already passed the Hall-B publication committees
Data Mining: Exclusive pp-SRC

- Study pp-SRC in $^{12}\text{C}$, $^{27}\text{Al}$, $^{56}\text{Fe}$, and $^{208}\text{Pb}$ nuclei
- EG2 data-set covers an (e,e'p) missing momentum range of 300~900 MeV/c
- Anti-Parallel, high $Q^2$, $x_B > 1.2$ kinematics
Opening angle Distribution

$^{12}$C

$^{208}$Pb

$^{56}$Fe

$^{27}$Al

$\cos(\theta_P^{\text{P recoil}})$
A dependence of the pp-SRC c.m. momentum distribution

PRELIMINARY
pp-SRC Probabilities

Not Corrected for CLAS Acceptance

Preliminary
2N-SRC (Even Before 12GeV)

- IsoSpin Structure at high $P_{\text{miss}}$
- c.m. momentum distribution
- SRC Universality
- np-SRC Dominance ($^{40,48}\text{Ca}$)
- High Precision 3N-SRC Probabilities
EMC Effect
DIS $\sigma(e,e') A/d$: The EMC Effect

Bound nucleon DIS ≠ Free nucleon DIS

30 years, ~1000 papers, no accepted explanation

$x$ is interpreted as momentum fraction of the struck quark
Hall-C Measurements in Light Nuclei

- Precise DIS measurements on light nuclei
- EMC does not scale as the average nuclear density
  → Not a bulk property of the nuclear medium

**EMC IS A LOCAL EFFECT**

EMC-SRC Correlation

Deuteron IMC Effect:

\[ \sigma_d \neq \sigma_n + \sigma_p \]

\[ \frac{\sigma_n + \sigma_p}{\sigma_d} (x_B = 0.7) = 1.034 \]

\[ a = 0.084 \pm 0.004 \]

\[ \frac{F_n^2}{F_p^2} = \frac{2 F_d^2/F_p^2}{1 - a(x_B - b)} - 1 \]


\[
\lambda = \frac{\partial \Lambda^2}{\partial \log p^2} \bigg|_{p^2=M^2} = -2 \frac{\delta R_N \delta p}{R_N M^2},
\]

Swelling Level
Average Nucleon Virtuality
Smearing Function
Free Nucleon S.F.
Off-Shell Correction
IMC Constrain on $d/u$ at $x_B \rightarrow 1$

$d/u(x_B \rightarrow 1) = 0.23 \pm 0.09$

SRC @ 12GeV
Hall-C program to study both EMC effect and SRC scaling plateaus is a wide variety of nuclei:

\(^{3,4}\)He, \(^{6,7}\)Li, \(^{9}\)Be, \(^{10,11}\)B, \(^{12}\)C, \(^{48,40}\)Ca, \(^{63}\)Cu, \(^{197}\)Au

- Study the nuclear dependence of both the EMC effect and 2N-SRC and their correlation

Hall-A measurements of both the EMC effect and SRC scaling plateaus in \(^{3}\)He and \(^{3}\)H

- Study the IsoSpin dependence of 2N-SRC
- \(^{3}\)He/\(^{3}\)H DIS ratios will be used to extract \(F_2^n/F_2^p\)

J. Arrington and D. Day, Experiment No. **E12-06-105**
P. Solvignon-Slifer and J. Arrington, Experiment No. **E12-11-112**
J. Arrington, D. Gaskell, and A. Daniel, Experiment No. **E12-10-008**
G. G. Petratos, J. Gomez, R. J.Holt, and R. D. Ransome, Experiment Proposal No. **C12-10-103**
Semi-Inclusive Measurement

- Study the DIS $d(e,e'N_{\text{recoil}})$ reaction tagged by high momentum backwards recoil nucleons
  - Study the virtuality dependence of the proton and neutron structure functions

LAD Detector:  

Projected Uncertainties:

Future SRC Studies @ 12GeV

Quark Distribution Modification in Nuclei

3N-SRC

Non-Nucleonic Degrees of Freedom

Momentum Distributions of SRC pairs

Why 12GeV?

High Statistics
High Nucleon Momentum
High Momentum Transfer
Thank You!
Robustness against different theoretical corrections

Correction “Bank”:
1. Radiative Corrections
2. ISO Corrections
3. c.m. Corrections
4. Coulomb Corrections
5. Inelastic Subtraction

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<td>4.08 ± 0.60</td>
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<td>4.75 ± 0.41</td>
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<td>EMC-SRC slope $a$</td>
<td>0.079 ± 0.006</td>
<td>0.082 ± 0.004</td>
<td>0.106 ± 0.006</td>
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<td>$\frac{\sigma(n+p)}{\sigma_d}</td>
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IMC Corrected $F_2^n/F_2^p$
IMC Constrain on d/u at $x_B \to 1$

IMC Constraining on $d/u$ at $x_B \to 1$

$\frac{d}{u}(x_B \to 1) = 0.23 \pm 0.09$

Deep Inelastic Scattering (DIS)

\[ E = Q^2 - q^2 - \omega^2 \]

\( \omega = E' - E \)

\[ \chi_B = \frac{Q^2}{2m\omega} \]

\( 0 \leq x_B \leq 1 \)

\( x_B \) gives the fraction of nucleon momentum carried by the struck parton.

Incident lepton

\((\omega, q)\)

scattered lepton

nucleon

Final state Hadrons

Inclusive electron scattering \( A(e, e') \)

\( 0 \leq x_B \leq A \)

\( x_B \) counts the minimum number of nucleons involved.

Nucleons

Incident lepton

\((\omega, q)\)

scattered lepton

nucleus

\( E \)

\( E' \)
DIS off a bound nucleon $\neq$ DIS off a free nucleon

Hundreds of theoretical papers tried to explain the effect

- **Nuclear Effects**: binding effects, pion enhancement, 6-quark clusters, and many more...
- **Modification of the nucleon structure**: dynamical rescaling, point like configuration suppression, structure function modification in the mean field, and many more...

G. Miller: EMC = Every Model is Cool
EMC Effect in $^4$He, $^9$Be, and $^{12}$C

J. Seely et al. PRL 103, 202301 (2009)
EMC Effect in $^3$He

J. Seely et al. PRL 103, 202301 (2009)
$^{12}\text{C}/d$ for $4 < Q^2 < 6$ [GeV/c]$^2$
$Q^2$ independence

EMC slope vs. average of $X_B = 0.4 - 0.6$

Based on data from J. Gomez et al., Phys. Rev. D 49, 4348 (1994)
BNL Measurements

[SRC Dominance at High Momentum]

Study the $^{12}$C(p,2p+n) reaction in parallel kinematics

Results: SRC Dominance
92±18% of high momentum (275<$P_{\text{miss}}$ <550 MeV/c) proton knockout events were accompanied by single neutron emission

$p_0 =$ incident proton
$p_1$ and $p_2$ are detected

BNL Measurements

[SRC Dominance at High Momentum]

Study the $^{12}$C(p,2p+n) reaction in parallel kinematics

**Results II: (SRC Threshold?)**

Recoil neutrons above $\sim$275 Mev/c have back to back angular correlation with the $^{12}$C(p,2p) missing momentum vector

$p_f = p_1 + p_2 - p_0$

$p_0 =$ incident proton

$p_1$ and $p_2$ are detected

Study the $^{12}\text{C}(p,2p+n)$ reaction in parallel kinematics

**Results III: (c.m. Momentum)**

The c.m. momentum distribution was measured to be Gaussian with
$\sigma = 143 \pm 17$ MeV/c

$p_f = p_1 + p_2 - p_0$

$p_0 = \text{incident proton}$

$p_1$ and $p_2$ are detected

Jlab Hall-A E01-015

[Triple Coincidence \((e,e'pp)\) and \((e,e'pn)\) TOF Spectra]

\(^{12}\text{C}(e,e'pp)\)
S:BG \(\approx 2:1\)

\(^{12}\text{C}(e,e'pn)\)
S:BG \(\approx 1:3\)
Missing energy spectrum from $^{12}\text{C}(e,e'p)$ at $P_{\text{miss}} = 300$ MeV/c kinematics

Hall-A E01-015 kinematics

$\chi_B$ Distribution

![Graph showing $\chi_B$ distribution with entries, mean, and RMS values.](image)
Hall-A E01-015 kinematics

$Q^2$ Distribution

$Q^2 \approx 1.8$
Hall-A E01-015 kinematics

$^{12}$C(e,e'p) $P_{\text{miss}}$ Distribution

![Graph showing distributions K1, K2, and K3 with counts on the y-axis and $P_{\text{miss}}$ [GeV/c] on the x-axis.]
Large $E_{\text{miss}}$ is associated with Delta production

Delta events are killed by cutting on: $\theta_{pmiss} > 77-88^\circ$ (left) or $x_B > 1$ (right)
Hall-A E01-015 Delta Contamination

$\theta_{\text{miss}}$ Cut

K1

K2

K3
Scaling of Inclusive A(e,e') Cross Section Ratios

- First observed in SLAC by D. Day et al.
- Validates the expected momentum scaling
- Interpreted using the 2N-SRC model
- Extract the relative number of 2N(3N) SRC pairs in nuclei

\[
\frac{r(A,^3\text{He})}{r(B,^3\text{He})}
\]


$a_2(\text{Fe/d})$ $Q^2$ independence

From J. Arrington talk in “High Energy Nuclear Physics and QCD” meeting, FIU, Miami,
### High Precision Results from Hall-C

\[ Q^2 = 2.5 \, \text{[GeV/c]}^2 \]

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\[ n_A(k) = a_2(A/d) \cdot n_d(k) \]

Short Range Correlations From Inclusive Measurements

- Scaling onset corresponds to \( P_{\text{min}} \approx 275 \text{ MeV/c} \)

\[
\int_{0}^{\infty} n_d(k) k^2 dk = 100\% \quad \Rightarrow \quad \int_{P_{\text{min}}}^{\infty} n_d(k) k^2 dk = 4\% 
\]

- In nuclei with \( A > 12 \), 2N-SRC account for:
  - \( \sim 20\% \) of the nucleons in the nuclei
  - \( \sim 80\% \) of the kinetic energy carried by the nucleons

- 3N-SRC are an order of magnitude less abundant than 2N-SRC
E08-014 (main objectives):

1) Inclusive study of the 3N-SRC plateau at $x_B > 2$

2) Study on IsoSpin structure of 2N-SRC by comparing $^{40}\text{Ca}$ to $^{48}\text{Ca}$

Studies the $Q^2$ dependence of the 3N-SRC plateau over a range of $Q^2 = 1.4-2.4$ [GeV/c]$^2$
E07-006: Second generation Hall-A experiment, pushing towards the repulsive core of the NN interaction

Covered a $^4\text{He}(e,e'p)$ missing momentum range of 400-750 MeV/c
2N-SRC (Even Before 12GeV)

1) The probability for a nucleon to have $p \geq 300$ MeV/c in medium nuclei is 20-25%

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

3) 2N-SRC dominated by np pairs (for $P_{\text{miss}} < 600$ MeV/c)

4) 2N-SRC probabilities, c.m. motion and IsoSpin structure at high $P_{\text{miss}}$ in a wide variety of nuclei

5) Quantum numbers of pp(np?)-SRC pairs

6) np dominance from inclusive measurements ($^{48,40}\text{Ca}$)

7) Three nucleon SRC are present in nuclei

8) High precession extraction of the 3N(4N?)-SRC plateau and it's $Q^2$ dependence