Short-range NN interactions: Experimental Past and Future

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For nuclei, $S_\alpha$ should be equal to $2j+1$ (number of protons in a given orbital).

However, it was found to be only $\sim 2/3$ of the expected value.

The bulk of the missing strength is thought to come from short range correlations.

\[
S_\alpha = 4\pi \int S(E_m, p_m) p_m^2 dp_m \delta(E_m - E_\alpha)
\]
High momentum nucleons

- Short Range Correlations

Nucleon momentum distribution in $^{12}$C
High momentum tails in A(e,e’p)

- E89-004: Measure of $^3$He(e,e’p)d
- Measured far into high momentum tail: Cross section is ~5-10x expectation

**Difficulty**
- High momentum pair can come from SRC (initial state)
- OR
- Final State Interactions (FSI) and Meson Exchange Contributions (MEC)

![Graph showing cross section vs. $p_{miss}$](image)

“slow” nucleons

PWIA

```
  e
  p
  n

```

“fast” nucleons

SRC

```
  e
  p

```

FSI

```
  e
  n
  p

```

MEC

```
  e
  n
  p
  π
```

A(e,e’p)

$^2$H(e,e’p) Mainz
PRC 78 054001 (2008)

$E = 0.855$ GeV
$\theta = 45^\circ$
$E’ = 0.657$ GeV
$Q^2 = 0.33$ GeV$^2$
$x = 0.88$

Unfortunately: FSI, MECs overwhelm the high momentum nucleons

FIG. 1: The experimental D(e,e’p)n cross section as a function of missing momentum measured at MAMI for $Q^2 = 0.33$ (GeV/c$^2$) compared to calculations with (solid curve) and without (dashed curve) MEC and IC. Both calculations include FSI. The low $p_m$ data have been re-analyzed and used in this work to determine $f_{LT}$ (color online).
High momentum nucleons

- Short Range Correlations

Try inclusive scattering!
Select kinematics such that the initial nucleon momentum $> k_f$
High momentum nucleons

- Short Range Correlations

\[ \frac{d\sigma^{QE}}{d\Omega dE} \propto \int d\vec{k} \int dE \sigma_{et} S_i(k, E) \delta(\text{Arg}) \]

\[ \text{Arg} = \nu + M_A - \sqrt{M^2 + p^2} - \sqrt{M_{A-1}^2 + k^2} \]

\[ F(y, q) = \frac{d^2\sigma}{d\Omega d\nu} \frac{1}{Z\bar{\sigma}_p + N\bar{\sigma}_n} \frac{q}{\sqrt{M^2 + (y+q)^2}} \]

\[ = 2\pi \int_{|y|}^{\infty} n(k)kd\nu \quad \text{Ok for } A=2 \]

Deuteronium

\[ Fomin et al, PRL 108 (2012) \]

\[ \theta = 18^\circ, \quad <Q^2> \approx 2.7 \]
\[ \theta = 22^\circ, \quad <Q^2> \approx 3.8 \]
\[ \theta = 26^\circ, \quad <Q^2> \approx 4.8 \]
\[ \theta = 32^\circ, \quad <Q^2> \approx 6.4 \]
High momentum nucleons

- Short Range Correlations


Nucleon momentum distribution in $^{12}$C

Blue - Fe Mage - C
Red - He3 Black - D
High momentum nucleons

- Short Range Correlations

Nucleon momentum distribution in $^{12}$C

High momentum from SRCs

Mean field

E02-019: 2N correlations in A/D ratios

<table>
<thead>
<tr>
<th>Λ</th>
<th>$\theta_e = 18^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$He</td>
<td>2.14±0.04</td>
</tr>
<tr>
<td>$^4$He</td>
<td>3.66±0.07</td>
</tr>
<tr>
<td>Be</td>
<td>4.00±0.08</td>
</tr>
<tr>
<td>C</td>
<td>4.88±0.10</td>
</tr>
<tr>
<td>Cu</td>
<td>5.37±0.11</td>
</tr>
<tr>
<td>Au</td>
<td>5.34±0.11</td>
</tr>
<tr>
<td>$\langle Q^2 \rangle$</td>
<td>2.7 GeV$^2$</td>
</tr>
<tr>
<td>$x_{\text{min}}$</td>
<td>1.5</td>
</tr>
</tbody>
</table>

$\langle Q^2 \rangle = 2.7$ GeV$^2$

Fomin et al, PRL 108 (2012)

Jlab E02-019
Inclusive Scattering

- Relative measurement
- Reduced FSI
- Test scaling in $x$ and $Q^2$
- No direct information on isospin structure
  - Only via target isospin structure
- No direct information on momentum distribution for $A>2$
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Inclusive Scattering

- Relative measurement
- Reduced FSI
- **Test scaling in x and Q^2**
  - No direct information on isospin structure
    - Only via target isospin structure
  - No direct information on momentum
Test scaling in x and $Q^2$

$$\alpha = 2 - \frac{q^- + 2M}{2M} \left(1 + \frac{\sqrt{W^2 - 4M^2}}{W}\right)$$
2N knockout experiments establish NP dominance

- Knockout high-initial-momentum proton, look for correlated nucleon partner.
- For $300 < P_{\text{miss}} < 600$ MeV/c all nucleons are part of 2N-SRC pairs: 90% np, 5% pp (nn)


R. Shneor et al., PRL 99, 072501 (2007)
2N knockout experiments establish NP dominance


R. Shneor et al., PRL 99, 072501 (2007)
NP dominance

96 ± 2%

R. Shneor et al., PRL 99, 072501 (2007)


9.5 ± 2%

also

Ciofi and Alvioli PRL 100, 162503 (2008)
Sargsian, Abrahamyan, Strikman, Frankfurt PR C71 044615 (2005)
Data mining using CLAS
NP dominance continues for heavy nuclei

Assuming scattering off 2N-SRC pairs:
- $(e,e'p)$ is sensitive to $np$ and $pp$ pairs
- $(e,e'pp)$ is sensitive to $pp$ pairs alone

$\Rightarrow (e,e'pp)/(e,e'p)$ ratio is sensitive to the $np/pp$ ratio

*O. Hen et al. (CLAS Collaboration), Science 346, 614 (2014)*
2N correlations

Have not solved the nuclear dependence
Linear relationship with EMC effect

- Fit the slope of the ratios for $0.3 < x < 0.7$:
  \[
  \frac{dR_{EMC}}{dx}
  \]

More nucleons in a correlation

1.4 < x < 2 => 2 nucleon correlation
2.4 < x < 3 => 3 nucleon correlation

\[ \sigma(x, Q^2) = \sum_{j=1}^{A} A \frac{1}{j} a_j(A)\sigma_j(x, Q^2) \]

\[ = \frac{A}{2} a_2(A)\sigma_2(x, Q^2) + \]

\[ + \frac{A}{3} a_3(A)\sigma_3(x, Q^2) + \ldots \]
3N correlations ($x>2$ inclusive scattering)

\begin{align*}
\langle Q^2 \rangle &\quad (\text{GeV}^2): \quad \text{CLAS: 1.6} \quad \text{E02-019: 2.7}
\end{align*}
Have we actually seen 3N SRC in ratios?

Comment on “Measurement of 2- and 3-nucleon short range correlation probabilities in nuclei”

Douglas W. Higinbotham¹ and Or Hen²
3N correlations

\[
\frac{\sigma_{\text{He4}}}{\sigma_{\text{He3}}} \times \frac{3}{4}
\]

- **E02019 Data (18^0, Q^2=2.7 \text{ GeV/c}^2)**
- **CLAS Data**
- **25^0: 1.514<Q^2<1.898 (GeV/c^2)**
- **23^0: 1.469<Q^2<1.636 (GeV/c^2)**
- **21^0: 1.257<Q^2<1.386 (GeV/c^2)**
3N correlations – are we there yet?

Where does 2N contribution become negligible?
Coming very soon: [Jlab E12-11-112]

- Quasielastic electron scattering with $^3$H and $^3$He
- Study isospin dependence of 2N and 3N correlations
- Test calculations of FSI for well-understood nuclei
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\[ p_3 = p_1 + p_2 \]
\[ p_3 = p_1 = p_2 \]
Jlab E12-06-105 & E12-10-008

- short-range nuclear structure
  - Isospin dependence
  - A-dependence
- Super-fast quarks
Jlab E12-06-105 & E12-10-008

- short-range nuclear structure
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Summary

• SRCs and EMC effect have been under the microscope for many decades – 6GeV era at Jlab has yielded interesting data

• 12 GeV experiments continue the search

• Upcoming experiments in Halls A/C
  → Study short range correlations in 3He/3H
  → Map out nuclear dependencies of clustering
  → Study how quark distributions are modified in nuclei over free nucleons

• New results in the next few years!
By popular demand

\[ \sigma_{A1}/\sigma_{A2} \]

No hint of a second plateau at \( x > 1.6 \) for \( Au/(A \geq 12) \)