PROBING THE ISOSPIN STRUCTURE OF SHORT RANGE CORRELATIONS IN INCLUSIVE QUASIELASTIC SCATTERING

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Thesis Experiment: JLAB E12-11-112

- *Precision measurement of the isospin dependence in the 2N and 3N SRC region*

- **Spokesperson** P. Solvignon, J. Arrington, D. B. Day, D. Higinbotham
- **Schedule** 2016 fall @ Hall A, Jefferson Lab, VA
- **Kinematics** $E=2.2$ and $4.4\;\text{GeV}$, $Q^2\sim 1.5\;\text{(GeV)}^2$, $1<x<3$
- **Type** $(e, e')$
- **Beam** unpolarized, 20 $\mu$A
- **Target** gaseous $^2\text{H}$, $^3\text{H}$, $^3\text{He}$, $^{12}\text{C}$ foil
- **Error** 4.6%

High Resolution Spectrometer (HRS)
Nuclear Structure

Schrödinger Equations

http://www.ehs.utoronto.ca/services/radiation/radtraining/module1.htm
Independent Particle Shell Model (IPSM)

- Low energy, non-relativistic:

\[
\left[ \sum_i -\frac{\hbar^2}{2m_N} \nabla_i^2 + \sum_{i<j} v_2(x_i, x_j) + \sum_{i<j<k} v_3(x_i, x_j, x_k) + \ldots \right] \Psi_A = E_A \Psi_A
\]

- Nucleons move independently in an averaged potential induced by the rest of the nucleus system:

\[
\left[ -\frac{\hbar^2}{2m_N} \nabla_i^2 + U(x) \right] \phi_\alpha(x_i) = \epsilon_\alpha \phi_\alpha(x_i).
\]
Missing Strength

- The closed orbits are NOT fully occupied, ~30% of strength is missing.
- Nucleons can live in orbits above Fermi level ($k > k_F$)

Spectroscopic strength (occupation probability)

=1 if fully occupied
Nucleon momentum distribution

\[ \int_0^\infty dk \ k^2 n(k) = 1 \]

\[ 1 \text{ fm}^{-1} \sim 200 \text{ MeV/c} \]

Momentum \( k \)
High momentum tails

Distribution function $n(k)$

$$\int_0^\infty dk \, k^2 n(k) = 1$$

$1 \text{ fm}^{-1} \sim 200 \text{ MeV/c}$

Momentum $k$
High momentum tails

Distribution function $n(k)$

\[ \int_0^{\infty} dk \, k^2 n(k) = 1 \]

1 $\text{fm}^{-1} \sim 200 \text{ MeV/c}$

Momentum $k$
High momentum tails

• 20% of Nucleons have momentum above Fermi level
• There is a universal shape of the high momentum tails

\[ n(k) \]

\( k \) (GeV/c)

Shell model

Blue - Fe
Mage. - C
Red - He3
Black - D

Atti and Simula, 1995
Short Range Correlation (SRC) of Nucleons

Proton radius ~ 0.84 fm

Inter-nucleon separation in nuclear matter (A→inf): 1.6 fm

In short distance

- Largely overlapped wave functions
- In-medium quarks/gluons interactions
Deuteron (np) potential

![Graph showing the potential between neutrons and protons as a function of separation. The graph has a red line indicating the attractive potential and a shaded area indicating the repulsive region.](image)
R = 1.7 fm (typical inter-nucleon distance in heavy nuclei)

Deuteron (np) potential

Density

Generated by J. Arrington

Separation
Deuteron (np) potential

\[ R = 1.2 \text{ fm} \]
Deuteron (np) potential

\[ R = 0.6 \text{ fm} \]

Large back-to-back momentum (>\(k_F\))

\[ p_1 + p_2 \rightarrow 0 \]

Density

Separation

\[ V(r) \text{ MeV/100} \]

\[ r(\text{fm}) \]

\[ p_1 \]

\[ p_2 \]
Quasi-elastic Electron Scattering

• Momentum transfer
  \[ q = k_1 - k_2 \]
• Energy transfer
  \[ \nu = E_1 - E_2 \]
• Initial momentum
  \[ p = p_X - q \]

\[ Q^2 = -q^2 \]
\[ x = \frac{Q^2}{2m_N\nu} \]
Inclusive Quasi-elastic Scattering

- QE cross section

\[ x = \frac{Q^2}{2m_N \nu} \]
SRC in **Exclusive** Quasi-elastic Scattering

**Isospin structure:**

- $T = 1$: np, pp, nn
- $T = 0$: np **Deuteron-like**

np:pp?
SRC in **Exclusive** Quasi-elastic Scattering

Detect the 2N SRC events exclusively
In the Triple-coincidence measurement
SRC in **Exclusive** Quasi-elastic Scattering

- 20% of events with high momentum pairs
- ~90% of high momentum pairs detected in $^{12}$C are Deuteron-like np pairs!
Inclusive Quasi-elastic Scattering

- QE cross section

JLab E02-019 data from N. Fomin

\[ x = \frac{Q^2}{2m_N \nu} \]
SRC in Inclusive Quasi-elastic Scattering

Cross section:

\[ \sigma_A = \sigma_{QE} + a_2(A)\sigma_2 + a_3(A)\sigma_3 + \ldots \]
SRC in Inclusive Quasi-elastic Scattering

$1.3 < x < 2$:

$$\sigma_A = \sigma_{QE} + a_2(A)\sigma_2 + a_3(A)\sigma_3 + \ldots$$

$$\sigma_A \approx a_2(A) \cdot \sigma_{2H}$$

$$\frac{\sigma_A}{\sigma_{2H}} \approx \frac{a_2(A)}{a_2(2H)} = \text{const}$$
SRC in Inclusive Quasi-elastic Scattering

1.3 < x < 2:

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Plateaus!
SRC in Inclusive Quasi-elastic Scattering

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\[ \frac{\sigma_A}{\sigma_{2H}} \approx \frac{a_2(A)}{a_2(2H)} = \text{const} \]

= 0.04

\[ a_2(^{12}C) \approx 0.04 \times 5 = 0.2 \]


Plateaus!
SRC in Inclusive Quasi-elastic Scattering

$1.3 < x < 2$:

$$\sigma_A = \sigma_{QE} + a_2(A)\sigma_2 + a_3(A)\sigma_3 + \ldots$$

$$\sigma_A \approx a_2(A) \cdot \sigma_{2H}$$

$$\frac{\sigma_A}{\sigma_{2H}} \approx \frac{a_2(A)}{a_2(2H)} = \text{const}$$

Final state interaction and systematic errors are cancelled.
SRC in Inclusive Quasi-elastic Scattering

\[ \sigma_A = \sigma_{QE} + a_2(A)\sigma_2 + a_3(A)\sigma_3 + \ldots \]

- $^3$H? $^3$He?
- $Q^2$ too low?
- 3N SRC dominant?

From Zhihong Ye
SRC in Quasi-elastic Scattering

• Nucleons in $^{12}$C:


• Isospin dependence in 2N SRC
• Possible 3N SRC at x>2

Thesis experiment:
• $^3$H, $^3$He, ($^3$H+$^3$He)/2
• Precision ~4.6%
Thesis Experiment: JLAB E12-11-112

- Precision measurement of the isospin dependence in the 2N and 3N SRC region

- Schedule 2016 fall @ Hall A, Jefferson Lab, VA
- Kinematics $E=2.2$ and $4.4$ GeV, $Q^2 \sim 1.5 \text{ (GeV)}^2$, $1 < x < 3$
- Type $(e, e')$
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- Error 4.6%

High Resolution Spectrometer (HRS)
Thesis Experiment: JLAB E12-11-112

- Kinematics

- High $Q^2$: suppress final state interaction
- Low energy transfer: suppress meson exchange current
Thesis Experiment: JLAB E12-11-112

- **Target:**
  - 25 cm x 1.25 cm Al cell
  - room temperature
  - hold 1000 Ci $^3$H, $^2$H or $^3$He
Thesis Experiment: JLAB E12-11-112

• Goal 1: Check the isospin dependence in 2N SRC at 1<x<2

• np pair dominant:

\[
\frac{\sigma_{3He}}{\sigma^3_H} = \frac{\sigma_{np} + \sigma_p}{\sigma_{np} + \sigma_n} \approx \frac{\sigma_{np}}{\sigma_{np}} = 1
\]

• No isospin preference:

\[
\frac{\sigma_{3He}}{\sigma^3_H} = \frac{\sigma_n + 2\sigma_p}{2\sigma_n + \sigma_p} \quad \sigma_p \approx 3\sigma_n 
\]
Thesis Experiment: JLAB E12-11-112

- **Goal 2** Probing the possible 3N SRC at $2<x<3$

- 3N plateaus:
  - 3He-like?
  - 3H-like?
  - average?
Thesis Experiment: JLAB E12-11-112

- **Goal 2** Probing the possible 3N SRC at 2<x<3

- Isospin structure

Isospin independent:

\[
\frac{\sigma_{3He}}{\sigma_3^H} = \frac{\sigma_n + 2\sigma_p}{2\sigma_n + \sigma_p} \approx 3\sigma_n
\]

\[
\Rightarrow 1.4
\]
Thesis Experiment: JLAB E12-11-112

- **Goal 3**: Check the A dependence in 2N SRC at $1<x<2$

Cross section ratio with isoscalar correction (blue hollow) and without it (red dot)

S. Egiyan et al., PRL 96, 082501 (2006)
Why SRC is interesting to you?

- Nuclear physics:
  - Go beyond mean field theory to explain high momentum nucleons in nuclear systems
  - Understand the repulsive core in 2N potential
  - Study the local-density-related properties of nuclei, e.g. EMC effect
- QCD:
  - In-medium modification of PDFs

Thank you!
BACKUP
SRC in Quasi-elastic Scattering

$ k_F \approx 220 \text{ MeV/c} $

Directional correlation between recoiled neutron momentum and the angle $\gamma$ in $A(p, p'pn)$.

~90% of SRC pairs are np pairs.

The ratio of np to pp pairs are 18:1 in 12C
np Pair Dominance at Short Inter-nucleon Distance

- Free nucleon-nucleon potential = Repulsive core + attractive tensor force
  - Tensor operator

\[ S_{12} = 2 \left[ 3 \frac{(\vec{S} \cdot \vec{r})^2}{r^2} - \vec{S}^2 \right] \]

- \( T = 1, S = 0 \): np, pp, nn pairs. \( S_{12} = 0 \), no attractive tensor force
- \( T = 0, S = 1 \): Deuteron-like np pair.
Lines: np pair. Symbols: pp pair

![Graph showing nucleon-nucleon correlation function for different isotopes](image-url)
Tests of Shell Model

Experiment: Quasi-elastic (QE) electron scattering provides a clean picture on single nucleon wave function.

- QE cross section:

\[
\frac{d^6 \sigma}{dp_x dE'} = K \sigma_{ep} S(p, E_m)
\]

Spectral function: probability of knocking off a nucleon with initial momentum $p$ and removal energy $E_m$

\[
\int S(k, E_m = \epsilon_{\alpha}) dk = 2j + 1
\]

probability of knocking off a nucleon in orbit $\alpha$
Tests of Shell Model

Occupation number
Momentum Distribution

The closed orbits are NOT fully occupied.
Nucleons can live in orbits above Fermi level

\[ \int \frac{S(k, \epsilon_\alpha) \, dk}{2j+1} \]

Spectroscopic strength
EMC and SRC

Higinbotham et al., arXiv:1003.4497.

\[ Q^2 = 2.5 \text{ [GeV/c]}^2 \]
SRC and EMC Correlation


![Graph showing the SRC and EMC correlation with data points and a linear fit.](image)
X scaling onset
Neutron magnetic form factor
SRC in Inclusive Quasi-elastic Scattering

$1.3 < x < 2$:

$$\sigma_A = \sigma_{QE} + a_2(A)\sigma_2 + a_3(A)\sigma_3 + \ldots$$

$$\sigma_A \approx a_2(A) \cdot \sigma_{2H}$$

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$$a_2(^{12}C) \approx 0.04 \times 5 = 0.2$$

Legend:
- Blue - Fe
- Mage. - C
- Red - He3
- Black - D

Graph with $N(p_i)$ vs $p_i$ (GeV/c) showing 20% threshold.