Cross Sections on the $^{12}\text{C}(e,e'p)$ Reaction at High Missing Momentum

Vincent Sulkosky
Massachusetts Institute of Technology

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Nuclear Structure and Dynamics at Short Distances

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Outline

- Introduction: PWIA and Reaction Mechanisms
- Spectroscopic factors and N-N correlations
- Results from Quasi-elastic and $x_B < 1$
- Recent Results and Future Perspectives, $x_B > 1$
- Summary
Nucleons in the Nucleus

- Nucleons are comprised of quarks and gluons, but how do they put together from these constituents?
- We can study the constituents and their interactions or the nucleon and its interactions.
- If we take a nucleon and place it inside a nucleus, how is the nucleon modified in the nuclear medium?

Electron scattering has proven to be a valuable tool to understand and investigate nucleons inside the nucleus.
A(e,e’p)A-1 Kinematics

scattering plane

reaction plane

“out-of-plane” angle

Missing momentum:
\[ p_m = q - p = p_{A-1} = -p_0 \]
Difference between transferred and detected momentum

Missing energy:
\[ \varepsilon_m = \omega - T_p - T_{A-1} \]
Difference between transferred and detected energy
Simple Theory Of Nucleon Knock-out

Plane Wave Impulse Approximation (PWIA)

$q - p = p_{A-1} = p_m = -p_0$
Reaction Mechanisms in (e,e’p)

- **Final-State Interactions:**
  Interactions of the extracted proton with the residual nucleus.

- **Coulomb Distortion and Internal Radiative Corrections:**
  The momentum of the electrons at the reaction point is different to their asymptotic measured values.

- **External Effects (From atomic interactions in the target):**
  Energy Loss, External Radiative Corrections, Straggling, Proton Absorption.

- **Meson Exchange Currents (MEC)**

- **Intermediate excited nucleonic configurations:**
  e.g. Delta-isobar contributions

\[
\vec{p}_m = \vec{q} - \vec{p} = \vec{p}_{A-1} \neq \vec{p}_0
\]
Classic Result from \((e,e'p)\) Measurements


**Independent-Particle Shell-Model** is based upon the assumption that each nucleon moves independently in an average potential (mean field) induced by the surrounding nucleons.

The \((e,e'p)\) data for knockout of valence and deeply bound orbits in nuclei gives spectroscopic factors that are \(60 \sim 70\%\) of the mean field prediction.

**One Solution:** Correlations Between Nucleons
Long-range (> 2 fm) and short-range (< 1 fm)
Short-Range Correlations

BUT other effects such as Final State re-scattering have masked the signal in the past.
To observe the effects of correlations one must probe beyond the Fermi level:

\[ P_{\text{min}} > 275 \text{ MeV/c} \]
2bbu, 3bbu “Distorted” Spectral Functions

\[ \frac{d^6 \sigma}{dE_e dE_p d\Omega_e d\Omega_p} = K \cdot \sigma_{ep} \cdot S^D(E_m, p_m) \]

\[ \eta(p_m) = \int \left( \frac{d^6 \sigma}{dE_e dE_p d\Omega_e d\Omega_p} / K \cdot \sigma_{ep} \right) dE_m \]

Performed at High \( Q^2 \)

⇒ Reduced MEC, \( \Delta \) contributions

At \( p_m > p_F \) distorted spectral function is much larger for 3bbu than for 2bbu due to correlations (SRC)

Calculations reproduce both 2bbu and 3bbu – confidence


Compare \( S^D(E_m, p_m) \), \( n(p_m) \) to theoretical calculations

\( Q^2 = 1.5 \text{ [GeV/c]}^2 \)
$^3\text{He}(e,e'p)np$: 3bbu (High $E_m$) and High $p_m$

Pair SRC: large $p_{\text{rel}}$, small $p_{\text{CM}}$

Low $p_m$ (still $> k_f$): correlations

High $p_m$ dominated by FSI

$E_m - E_{\text{th}} \gg \frac{p_m}{2M_N}$

Data: F. Benmokhtar et al., PRL 94, 082305 (2005)
Calculations: C. Ciofi degli Atti et al.
Hall B (CLAS) D(e,e’p)n, $x_B < 1$ Data

See W. Boeglin’s talk from Feb. 19th

Black Paris Potential
Red AV-18 Potential

From Lowest To Highest
PWIA
PWIA+FSI
PWIA+FSI+MEC+NΔ

Recent Experimental Results

- **Carbon:**
  - $x_B > 1, \ Q^2 = 2 \ \text{GeV}^2$
  - Bound data, $p_m = 200 – 425 \ \text{MeV/c}$
  - Continuum data, $p_m = 200 – 600 \ \text{MeV/c}$

- **Helium-4:**
  - $x_B > 1, \ Q^2 = 2 \ \text{GeV}^2$
  - Bound data, $p_m = 150 – 500 \ \text{MeV/c}$
  - Continuum data, $p_m = 150 – 800 \ \text{MeV/c}$
Kinematics

- $e$, $e'$
- $n$
- $p$
- 19.5°, 32°, 99°

- BigBite Magnet
- BigBite Detectors
- Lead Wall
- Neutron Detector
12C(e,e’p) Data

High $p_m$: 300-600 GeV/c
probe small inter-nucleon distances

High $Q^2$: 2 [GeV/c]$^2$
probe small distances
less ambiguity about struck nucleon
can handle FSI using GA or GEA

High $x_B \sim 1.2$
more than 1 quark share momentum
reduce MEC, $\Delta$ contributions

Anti-parallel kinematics
reduce FSI
interaction with more than one nucleon

- $^{12}$C(e,e’p)
- Quasi-Elastic shaded in Blue
- Resonance Even at $x_B > 1$
$^{12}\text{C}(e,e'p)^{11}\text{B}$ Cross Sections

Results from P. Monaghan; arXiv:1301.7027
$^{12}\text{C}(e,e'p)^{11}\text{B}$ Cross Sections

Results from P. Monaghan; arXiv:1301.7027
Distorted Momentum Distribution

\[ n_{\text{distorted}}(P_m) = \frac{\left\langle \frac{d^5 \sigma}{d\Omega_e d\Omega_p dE_e} \right\rangle_{\text{exp}}}{\langle K \sigma_{cc2} \rangle_{\text{unit}}} \]

![Graph showing distorted momentum distribution with various data points and curves representing different models: PWIA, RMSGA, RMSGA + FSI_{SRC}, WS+Glauber.](chart.png)
$^{12}\text{C}(e,e'p)$ Continuum Results

Results from P. Monaghan’s thesis

![Graph showing missing energy distribution](image-url)
Extracted Spectral Functions

Kinematics 1 and 3 with lower and higher $p_m$ range are also available.
Distorted Momentum Density

\[
\eta(p_{\text{miss}}) = \frac{\int_{E_{\text{min}}}^{E_{\text{max}}} \left\langle \frac{d^6 \sigma}{d\Omega_e d\Omega_p dE_e dE_p} \right\rangle_{\text{exp}}}{\langle K \sigma_{cc2} \rangle_{\text{unit}} dE_{\text{miss}}}
\]
E07-006: $^4\text{He}(e,e'pN)pn$ SRC

- **$^4\text{He}$ Target**
- **$P_m$: 400 – 800 MeV/c**
- **Pushing Limits of NN Potential**
  - Long range attraction
  - Short range repulsion

<table>
<thead>
<tr>
<th>E01-015</th>
<th>E07-006</th>
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</thead>
<tbody>
<tr>
<td>$x_B &gt; 1, \ Q^2 = 2 [\text{Gev/c}]^2$</td>
<td>$x_B &gt; 1, \ Q^2 = 2 [\text{Gev/c}]^2$</td>
</tr>
<tr>
<td>300 – 600 MeV/c</td>
<td>400 – 800 MeV/c</td>
</tr>
<tr>
<td>Tensor Force</td>
<td>Tensor to Repulsive core</td>
</tr>
<tr>
<td>Target – $^{12}\text{C}$</td>
<td>Target – $^4\text{He}$ (Less FSI)</td>
</tr>
<tr>
<td>BigBite and HAND</td>
<td>BigBite with MWDCs Upgraded HAND (new lead wall)</td>
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</table>

See Igor Korover’s talk this afternoon
$^4\text{He}(e,e'p)$ Preliminary Results

<table>
<thead>
<tr>
<th>$P_{\text{miss}}$ [MeV/c]</th>
<th>Charge [C]</th>
<th>$^4\text{He}(e,e'p)$ Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>2.0</td>
<td>3000</td>
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<tr>
<td>625</td>
<td>2.5</td>
<td>1900</td>
</tr>
<tr>
<td>755</td>
<td>3.9</td>
<td>2000</td>
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</tbody>
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$P_m = 500$ MeV/c
Low $P_m$ Results

### Missing Momentum

<table>
<thead>
<tr>
<th>$P_m$ [GeV/c]</th>
<th>Charge [C]</th>
<th>Raw Counts</th>
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<tbody>
<tr>
<td>0.153</td>
<td>500</td>
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<tr>
<td>0.353</td>
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<tr>
<td>0.353</td>
<td>8800</td>
<td>0.153</td>
</tr>
</tbody>
</table>

E08-009 Data
$^4\text{He}(e,e'p)^3\text{H}$ Preliminary Results

Results from S. Iqbal

Madrid theory:
Single particle model using relativistic QM wave functions

No energy loss corrections
Summary

- Quenching of spectroscopic strength might be an indication of N-N correlations.
- Reaction dynamics unfortunately complicate the picture and make isolating N-N SRC difficult.
- Recent data for $^{12}\text{C}(e,e'p)$ and $^{4}\text{He}(e,e'p)$ at kinematics favorable to correlations:
  - High $P_m$, High $Q^2$, $x_B > 1$, “semi anti-parallel”
  - Analysis of carbon bound state data is complete and shows good agreement with theory: arXiv:1301.7027
- Publication on continuum results expected soon
- Helium-4 is data being analyzed

- Theoretical calculations and input are desired
Acknowledgements

✓ Peter Monaghan (Hampton)
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✓ Konrad Aniol (California State)
✓ Sophia Iqbal (California State)
Thank You!
Electron Scattering \((e,e')\) at Fixed \(Q^2\)

\[
\frac{d^2\sigma}{d\omega d\Omega} = \frac{Q^2}{2M} \quad \frac{Q^2}{2m} \quad \frac{Q^2}{2m} + 300\text{MeV}
\]

\(\omega = (e - e')\)

Nucleus

Proton

Generic Inclusive Electron Scattering at fixed momentum transfer

Elastic

Quasielastic

\(\Delta\)

Deep Inelastic

\(N^*\)
Spectral Function

In nonrelativistic PWIA:

\[
\frac{d^6 \sigma}{d\omega d\Omega_e dp d\Omega_p} = K \sigma_{ep} S(p_m, \varepsilon_m)
\]

For bound state of recoil system:

\[
\rightarrow \frac{d^5 \sigma}{d\omega d\Omega_e d\Omega_p} = K' \sigma_{ep} |\Phi(p_m)|^2
\]
Reaction Mechanisms

Example: Final State Interactions (FSI)

\[ \vec{q} - \vec{p} = \vec{p}_{A-1} \neq \vec{p}_0 \]
Distorted Wave Impulse Approximation (DWIA)

This is modeled by an optical potential from elastic (p,p) data. Proton is described by Distorted Waves.

\[
d^6\sigma = K \sigma_{ep} S^D(p_m, \varepsilon_m, p)
\]

"Distorted" spectral function

**DWIA:** If the struck nucleon re-interacts with the rest of the nucleus, then the cross section still factorizes (mostly) but we measure a **distorted** spectral function.
Madrid Theory
Relativistic wave functions from solutions of the Dirac equation with both scalar and vector mean field potentials used for the initial and final states.

The optical potential is a folding potential with effective NN interactions phenomenologically fitted to elastic proton scattering on light nuclei at energies of interest for this experiment. For more details see: **Relativistic Description of $^3\text{He}(e,e'p)^2\text{H}**

The calculation for $^4\text{He}$ followed similar lines for the final state interactions/optical potential, while the bound state of $^4\text{He}$ is a simple mean field solution.
Relativistic Approaches:

- Relativistic Distorted Wave Impulse Approximation (RDWIA):
  The wave functions are four-component spinor solutions of the Dirac equation with scalar and vector potentials and their lower components are dynamically enhanced with respect to a solution of Dirac equation without potentials (a free spinor).

Groups: A. Picklesimer, J.W. Van Orden and S. J. Wallace
The Madrid Group (J. Udías et al.)
J. J. Kelly (Effective Momentum Approximation)
A. Meucci et al.

Far from a complete list of approaches and contributors!
Relativistic Approaches:

- **Relativistic Multiple Scattering Glauber Approximation (RMSGA):** Also uses the EA but instead evaluates multiple scattering by the nucleon-nucleon interaction directly rather than through a mean field. Bound-state wave functions are solutions to Dirac equation with scalar and vector potentials fitted to ground state nuclear properties.

  Group: Ghent (J. Rychkebusch *et al.*)

- **Relativistic Optical-Model Eikonal Approximation (ROMEA):** Employs an Eikonal Approximation (EA) that should be equivalent to RDWIA for large $Q^2$, but a partial-wave expansion is avoided. Difference compared to RDWIA is the use of EA to compute the scattering wave functions.

  Group: M. Radici *et al.*
Theoretical Review III

C. Ciofi degli Atti and H. Morita:
- Mean field calculation using the Woods-Saxon form for the wave function.
- FSI modeled using Glauber approach to describe rescattering of the struck proton. Glauber approximation assumed A-1 spectator nucleons are stationary during any rescattering of the struck nucleon.

J. M. Laget:
- Microscopic calculation of continuum cross section including a PWIA calculation with correlations but no FSI, and successive implementation of various interaction effects.
- Both single and double NN scattering as well as meson exchange and Δ formation are included.
- Nucleon and meson propagators are relativistic and no Glauber approximations have been made. For FSI used a global parameterization of the NN scattering amplitudes from experiments.