Inclusive Scattering from Nuclei at x>1 in the quasielastic and deeply inelastic regimes

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Outline

• Goals of the Experiment
• Physics Background and Motivation
• The Experiment
• Request to PAC
• Institutional Commitments
Overall Goals

• Take data for light and heavy nuclei in a unique kinematic region that is largely unexplored

• Obtain precise ratios of heavy to light nuclei to expose role of multi-nucleon correlations

• Examine a regime that is sensitive to high momentum constituents (quarks or nucleons) generated by high density configurations

• Capture signatures of medium modifications in high density configurations

• Reach scaling region \( Q^2 > 15 \) out to very large \( x \) (1.4).
Inclusive Quasielastic and Deep Inelastic Scattering at High Momentum Transfers

Two distinct processes

Quasielastic from the nucleons in the nucleus

Inelastic, Deep Inelastic from the quark constituents of the nucleon.

Inclusive final state means no separation of the two dominant processes

\[ \vec{k} + \vec{q}, \ W^2 = M^2 \]

\[ W^2 \geq (M_n + m_{\pi})^2 \]
Nonetheless there is a rich, if complicated, blend of nuclear and fundamental QCD interactions available for study from these types of experiments.

The two processes share the same initial state

**QES in PWIA**
\[
\frac{d^2\sigma}{d\Omega dv} \propto \int dk \int dE \sigma_{ei} S_i(k,E) \delta() \]

**Spectral function**

\[
n(k) = \int dE S(k,E)
\]

**DIS**
\[
\frac{d^2\sigma}{d\Omega dv} \propto \int dk \int dE W_{1,2}^{(p,n)} S_i(k,E)
\]

**Spectral function**

However they have very different $Q^2$ dependencies

$\sigma_{ei}$ goes as the elastic (form factor)$^2$

$W_{1,2}$ scale with $\ln Q^2$ dependence

Exploit this $Q^2$ dependence
Physics Topics

• Short Range Correlations and Multi-nucleon correlations
  • Ratios of heavy to light nuclei
  • Absolute cross section measurements

• Momentum distributions and details of the spectral function $S(k, E)$.
  • Absolute cross sections of multiple few-body systems allow comparison to ‘exact’ calculations
  • Constrain role of FSI
  • Range of $A$ allows extrapolation to NM

• Nuclear Structure functions at large $x$
  • Distributions of ‘super-fast quarks’
  • High Sensitivity to non-hadronic configurations in nuclei – EMC effect, quark clusters ...

• Scaling of the nuclear structure functions at large $x$ – duality
In nuclei, the quasielastic peak (QE) is broadened by the Fermi-motion of the struck nucleon.

At low energy loss ($\nu$) the quasielastic contributions dominates the cross section even at moderate to high $Q^2$.

We can use $x$ and $Q^2$ as knobs to dial the relative contribution of QES and DIS.
Kinematic range to be explored

- Black - 6 GeV
- Red - CLAS
- Blue - 11 GeV

HMS

- HMS

SHMS

- SHMS

super-fast quarks,
quark distribution functions
medium modifications

- SRC, n(k), FSI, σ

$Q^2 (\text{GeV}/c^2)$

$X$
Short Range Correlations (SRCs)

Mean field contributions: $k < k_F$
Well understood
High momentum tails: $k > k_F$
Calculable for few-body nuclei, nuclear matter.
Dominated by two-nucleon short range correlations

Isolate short range interactions (and SRC’s) by probing at high $p_m$

Poorly understood part of nuclear structure
Sign. fraction have $k > k_F$
Uncertainty in SR interaction leads to uncertainty at $k \gg k_F$, even for simplest systems
**Short Range Correlations**

In the region where correlations should dominate, large $x$,

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

$$= \frac{A}{2} a_2(A) \sigma_2(x, Q^2) + \frac{A}{3} a_3(A) \sigma_3(x, Q^2) + \cdots$$

$a_j(A)$ are proportional to finding a nucleon in a $j$-nucleon correlation. It should fall rapidly with $j$ as nuclei are dilute.

$$\sigma_2(x, Q^2) = \sigma_{eD}(x, Q^2) \text{ and } \sigma_j(x, Q^2) = 0 \text{ for } x > j.$$ 

$$\Rightarrow \quad \frac{2 \sigma_A(x, Q^2)}{A \sigma_D(x, Q^2)} = a_2(A) \bigg|_{1 < x \leq 2}$$

$$\frac{3 \sigma_A(x, Q^2)}{A \sigma_{A=3}(x, Q^2)} = a_3(A) \bigg|_{2 < x \leq 3}$$

In the ratios, off-shell effects and FSI largely cancel.

$a_j(A)$ is proportional to probability of finding a $j$-nucleon correlation.
Short Range Correlations

\[
\frac{2 \sigma_A}{A \sigma_D} = a_2(A); \ (1.4 < x < 2.0)
\]

\(a_j(A)\) is proportional to probability of finding a \(j\)-nucleon correlation.
Ratios and SRC

There are suggestions that FSI spoil the analysis of these ratios: Benhar et al.: FSI includes a piece that has a weak $Q^2$ dependence and is $A$ dependent

This experiment:

- Direct ratios to $^2\text{H}$, $^3\text{He}$, $^4\text{He}$ out to large $x$ and over wide range of $Q^2$
- Study $Q^2$ dependence (FSI)
- Absolute Cross section to test exact calculations and FSI
- Extrapolation to NM
Momentum distributions and the spectral function $S(k,E)$.

Comparison to exact calculations will allow one to set limits on FSI and extract high momentum piece of gs wave function.
Sensitivity to SRC

We want to be able to isolate and probe two-nucleon and multi-nucleon SRCs

Dotted = mean field approx.
Solid = +2N SRCs.
Dashed = +multi-nucleon.

11 GeV can reach $Q^2 = 20(13)$ GeV$^2$ at $x = 1.3(1.5)$
- very sensitive, especially at higher $x$ values
Medium Modifications in high density configurations

Nucleons are already closely packed in nuclei
Ave. separation $\sim 1.7$ fm in heavy nuclei
nucleon charge radius $\sim 0.86$ fm

Nucleon separation is limited by the short range repulsive core

Even for a 1 fm separation, the central density is $\sim 4 \times$ nuclear matter

Comparable to neutron star densities!

High enough to modify nucleon structure?
Sensitivity to non-hadronic components

5% 6-quark bag

$x < 1$

5% 6-quark bag

$x > 1$

Ratio: With/Without

$F_2$ with 6q / $F_2$ only p+n

Ratio: With/Without

$F_2$ with 6q / $F_2$ only p+n
Quark distributions at $x > 1$

Two measurements (very high $Q^2$) exist so far:

- **CCFR (ν-C):** $F_2(x) \propto e^{-sx}$ \quad s = 8
  - Limited $x$ range, poor resolution

- **BCDMS (μ-Fe):** $F_2(x) \propto e^{-sx}$ \quad s = 16
  - Limited $x$ range, low statistics

With 11 GeV beam, we should be in the scaling region up to $x \approx 1.4$
\[ \nu W^A_2 = \nu \cdot \frac{\sigma^\text{exp}}{\sigma_M} \left[ 1 + 2 \tan^2(\theta/2) \cdot \left( \frac{1 + \nu^2/Q^2}{1 + R} \right) \right]^{-1} \]

**x and \( \xi \) scaling**

**Carbon E02-019**
Approach to Scaling - Deuteron

Dashed lines are arbitrary normalization (adjusted to go through the high $Q^2$ data) with a constant value of $\frac{\text{d} \ln (F_2)}{\text{d} \ln (Q^2)}$.

Filled dots - this experiment.

Next slide.
Approach to Scaling

Scaling appears to work well at \( \xi = 0.8 \) nearly to the point where QES dominates.

We can expect that any scaling violations will melt away as we go to higher \( Q^2 \)

Convolution model
QES
RR \((W^2 < 4)\)
DIS \((W^2 > 4)\)
Predictions for 11 GeV

Quark distributions at $x > 1$

Convolution model
QES
DIS + RR

Deuteron is worst case as narrow QE peak makes for larger scaling violations
Convolution model
QES
DIS + RR

Quark distributions at $x > 1$

Predictions for 11 GeV

$\theta = 32$, $E = 11$
Carbon

$13.2 \text{ (GeV/c)}^2$

$\theta = 55$, $E = 11$
Carbon

$17.3 \text{ (GeV/c)}^2$
Experimental Details

• Hall C
• Cryogenic Targets: H, $^2$H, $^3$He, $^4$He
• Solid Targets: Be, C, Cu, Au
• Spectrometers: HMS and SHMS
• Angles: 8–26 (SHMS), 32 –55 (HMS)
• Detector Packages similar
  • Drift Chambers
  • Hodoscopes
  • Good PID
  • Calorimeter
  • Cerenkov
Data taking with both spectrometers simultaneously
## Particle ID/Backgrounds/Corrections

<table>
<thead>
<tr>
<th>$E'$ (GeV/c)</th>
<th>$\pi/e$ ratio</th>
<th>Rejection</th>
<th>Status</th>
</tr>
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<tbody>
<tr>
<td>$&gt; 5-6$</td>
<td>$&lt; 50:1$</td>
<td>100:1</td>
<td>50:1</td>
</tr>
<tr>
<td>$&lt; 5$</td>
<td>$\leq 1000:1$</td>
<td>50:1</td>
<td>200:1</td>
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</tbody>
</table>

### Low-density $\hat{C}$ required for SHMS

### Charge Symmetric Backgrounds

- Worst case: 55 degrees and high Z -> 10%
- Much better for low Z, decreases rapidly with $\theta$

### Coulomb Corrections

- Worst case: < 20% for Au, < 10% Cu, and smaller for lighter nuclei: calculations improving

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PR12-06-101: Fpi
PR12-06-103: pion photo
# Beam Request Cu (LD2)

<table>
<thead>
<tr>
<th>$\theta$ (deg)</th>
<th>$E'$ (GeV)</th>
<th>$x$</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>time (hrs)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0</td>
<td>10.6</td>
<td>0.7-4.0</td>
<td>2.1-2.3</td>
<td>10</td>
<td>SHMS (17 hrs. for cryotargets)</td>
</tr>
<tr>
<td>10.0</td>
<td>10.4</td>
<td>0.7-3.0</td>
<td>3.0-3.5</td>
<td>10</td>
<td>SHMS (17 hrs. for cryotargets)</td>
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<tr>
<td>12.0</td>
<td>9.8</td>
<td>0.7-2.6</td>
<td>4.0-5.0</td>
<td>10</td>
<td>SHMS (17 hrs. for cryotargets)</td>
</tr>
<tr>
<td>22.0</td>
<td>5.7,7.0</td>
<td>0.7-1.55</td>
<td>8.1-12</td>
<td>3+8=11</td>
<td>SHMS</td>
</tr>
<tr>
<td>26.0</td>
<td>4.8,6.0</td>
<td>0.7-1.45</td>
<td>9.5-14</td>
<td>3+8=11</td>
<td>SHMS (use HMS for cryotargets)</td>
</tr>
<tr>
<td>32.0</td>
<td>3.3,3.9,4.6</td>
<td>0.7-1.35</td>
<td>11-17</td>
<td>(1+5+10)</td>
<td>HMS</td>
</tr>
<tr>
<td>40.0</td>
<td>2.4,2.8,3.3</td>
<td>0.7-1.25</td>
<td>12-18</td>
<td>(1+5+10)</td>
<td>HMS</td>
</tr>
<tr>
<td>55.0</td>
<td>1.5,1.7,2.0</td>
<td>0.7-1.20</td>
<td>13-20</td>
<td>(2+8+10)</td>
<td>HMS</td>
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<tr>
<td></td>
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<td>12</td>
<td>$e^+$ data</td>
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<td></td>
<td>6</td>
<td>overhead</td>
</tr>
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<td></td>
<td></td>
<td>6</td>
<td>dummy targets (cryotargets only)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>70 (87)</td>
<td>Total time for Cu (LD2)</td>
</tr>
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</table>
# Request to PAC

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time (hours)</th>
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<tbody>
<tr>
<td>Solid target running</td>
<td>259</td>
</tr>
<tr>
<td>Cryotarget running</td>
<td>383</td>
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<tr>
<td>HMS/SHS cross calibration</td>
<td>16</td>
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<tr>
<td>Hydrogen elastics</td>
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<tr>
<td>Target Boiling Studies</td>
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<tr>
<td>Target Changeover</td>
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<tr>
<td>BCM calibrations</td>
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<tr>
<td>Beam spot monitoring</td>
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<tr>
<td>checkout/calibration</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>758</strong></td>
</tr>
<tr>
<td></td>
<td><em>(32 days)</em></td>
</tr>
</tbody>
</table>
Summary

• Target ratios (and absolute cross sections) in quasielastic regime: map out 2N, 3N, 4N correlations

• Measure nuclear structure functions (parton distributions) up to $x = 1.3 - 1.4$

• Extremely sensitive to non-hadronic configurations

• Targets include several few-body nuclei allowing precise test of theory.
Institutional Commitments

- Argonne
  - SHMS optics, field maps and verification
- University of Virginia
  - Atmospheric Cherenkov for SHMS