Scattering on Tritium: From EMC to SRC

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User Group Meeting, JLab, 20.06.18
Tritium Target: Once per Generation

- Isospin doublet and mirror nucleus with $^3$He
- High asymmetry $A/2Z = 1.5$ (larger than Pb $\approx 1.27$)
- Calculable by \textit{ab-initio} methods

<table>
<thead>
<tr>
<th>Lab</th>
<th>Year</th>
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<tbody>
<tr>
<td>SLAC</td>
<td>1963</td>
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<td>Bates</td>
<td>1984</td>
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<td>Saclay</td>
<td>1985/1992</td>
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<td>JLab</td>
<td>2018</td>
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Tritium@Jlab thanks to Dave Meekins
Tritium Spring Run Period

A graph showing the beam energy from January 1 to May 1, 2018, with annotations for MARATHON, (e,e′p) SRC, and (e,e′) SRC.
Experimental Setup – Hall A
Experimental Setup – Hall A
Electron Nucleus Scattering

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

\[ Q^2 = 4E_0E \sin^2 \left( \frac{\theta}{2} \right) \]

- Elastic
- Quasielastic

\[ \frac{d\sigma}{d\omega} \]

\[ \frac{Q^2}{2A} \]

- \( x_B = 1 \)
- \( x_B < 1 \)

Nucleus A
Electron Nucleus Scattering

Nucleus A

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

$$Q^2 = 4E_0E \sin^2\left(\frac{\theta}{2}\right)$$
Deep Inelastic Scattering (DIS)

\[
\frac{d\sigma}{d\Omega dE'} = \left(\frac{2\alpha E'}{Q^2}\right)^2 \times \left(\frac{1}{v} F_2 + \frac{2}{m} F_1 \tan^2 \frac{\theta}{2}\right)
\]

In infinite momentum frame

\[
F_1 = \frac{1}{2} \sum_i e_i^2 q_i (x) \quad F_2 = x \sum_i e_i^2 q_i (x)
\]

\[
F_2^p = x \left[ \left(\frac{2}{3}\right)^2 (u(x) + \bar{u}(x)) + \left(-\frac{1}{3}\right)^2 (d(x) + \bar{d}(x)) + \left(-\frac{1}{3}\right)^2 (s(x) + \bar{s}(x)) \right]
\]

\[
F_2^n = x \left[ \left(-\frac{1}{3}\right)^2 (u(x) + \bar{u}(x)) + \left(\frac{2}{3}\right)^2 (d(x) + \bar{d}(x)) + \left(-\frac{1}{3}\right)^2 (s(x) + \bar{s}(x)) \right]
\]

-> Access to u/d quark distributions via $F_2^p/F_2^n$ ratio
F_2 - Ratio

- From DIS measurements on proton and deuterium as neutron target
- Fermi-Motion and binding energy in deuterium
- Extraction of ratio depends on model
Tritium / $^3$He – Another Way for $F_2$ Ratio

\[
\frac{F_2^p}{F_2^n} = \frac{2R - \frac{F_2^{3He}}{F_2}}{2 \frac{F_2^{3He}}{F_2} - R}
\]

**Ratio** of EMC effect in tritium and $^3$He  
\[
R \equiv \frac{F_2^{3He}}{2F_2^p + F_2^n} \times \frac{2F_2^n + F_2^p}{F_2^{3H}}
\]

- A = 3 system well understood theoretically
- $R$ and $F_2$ ratio will be calculated in an iterative procedure
Marathon – Projected Results

see B. Schmooklers talk from morning

\[ F_2^A = Z F_2^P + N F_2^n + n_{SRC}^A (\Delta F_2^P + \Delta F_2^n) \]

SRC Model

- Analysis ongoing
- Total 6 PhD theses
- \( F_2 \) ratio and EMC data
Ongoing Analysis: Target Background

- Endcap background 1-3%

Normalized Counts

2.8% contamination

1.3% contamination

2.2% contamination

Courtesy of S. Alsalmi
Ongoing Analysis: Tritium Contamination from Decay

Coursesy of T. Kutz

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Electron Nucleus Scattering

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

\[ Q^2 = 4E_0E \sin^2\left(\frac{\theta}{2}\right) \]

E12-14-011:
(e,e’p) (QE/SRC)

E12-11-112: Isospin dependence (QE/SRC)

\[ x_B = 1 \]

\[ x_B < 1 \]
Momentum Distribution

Short Range Correlations (SRC)

Mean field

\[ \sim k_F \]

\[ \sim 80\% \]

\[ \sim 20\% \]
1. NN pair with **large relative momentum and small c.m. momentum**

2. Internucleon distance < size of nucleon
   - Account for ~ 20% of nucleons in nuclei
   - SRC dominates the nucleon momentum distribution for $k_F \geq 300$ MeV/c

SRC – np Dominance

• Probability for np-SRC ~18 times larger than pp-SRC.


Or Hen et al., Science 346, 614 (2014)
Nucleon Momentum Ratio

\[
\frac{n_p(k)}{n_n(k)} \quad k \text{ [MeV/c]}
\]

Simple Nucleon Counting

\[
\begin{align*}
R \; \Rightarrow \; R > 2
\end{align*}
\]
Nucleon Momentum Ratio

\[ R > 2 \]

Simple Nucleon Counting

np SRC
\[ R = 1 \]

Transition Region
Nucleon Momentum Ratio

\[ \frac{np}{n_p} \]

\[ R > 2 \]

Simple Nucleon Counting

Transition Region

np SRC

\[ R = 1 \]

Measurement of ratio via mirror nuclei \(^3\text{H}\)

\[ \frac{^3\text{He}(e, e'p)}{^3\text{He}(e, e'n)} \approx \frac{^3\text{He}(e, e'p)}{^3\text{H}(e, e'p)} \]

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The A(e,e')p Reaction

What we want:

\[ \sigma_{\text{PWIA}} = k \cdot \sigma_{ep} \cdot S_p (E_{\text{miss}}, p_{\text{miss}}) \]

\[ E_{\text{miss}} = \omega - T_p - T_{A-1} \]

\[ p_{\text{miss}} = q - p' = -p_{\text{init}} \]

What we might get:

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The A(e,e′)p Reaction

What we want:

\[ \sigma_{PWIA} = k \cdot \sigma_{ep} \cdot S_p (E_{\text{miss}}, p_{\text{miss}}) \]
\[ E_{\text{miss}} = \omega - T_p - T_{A-1} \]
\[ p_{\text{miss}} = q - p' = -p_{\text{init}} \]

What we might get:

\[ Q^2 > 1.8 \text{ GeV}^2 \]
\[ x > 1 \]
Minimizing FSI Effects

$^3\text{He}(e,e'p)np$

Ratio of FSI to PWIA calculations

$p_{\text{miss}} = 0.5 \text{ GeV/c}$

$0.4 \text{ GeV/c}$

$0.2 \text{ GeV/c}$

Choose $\theta_{rq} < 40^\circ$

$P_{\text{miss}}$ antiparallel to $q$
Minimizing FSI Effects

\[
\frac{\sigma(^3\text{He}(e,e'p))}{\sigma(^3\text{H}(e,e'p))} \approx S_{3\text{He}}(E_m,p_m) / S_{3\text{H}}(E_m,p_m)
\]

Choose \( \theta_{rq} < 40^\circ \)

Take ratios to cancel residual FSI

\[ Q^2 = 2 \text{ GeV}^2 \]

\[ \theta_{rq} = 30^\circ \]

Calculations by M. Sargsian

\[ P_{\text{miss}} (\text{GeV/c}) \]

PWIA Calculation

Full Calculation

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Preliminary Results

Preliminary Data

Projected results
Preliminary Results (2)

![Graph showing preliminary results](image)

- \( A(e,e'p) / d(e,e'p) \) vs. \( |P_{\text{miss}}| \) [MeV/c]
- Data points indicate preliminary results for \( ^3\text{He}/d \) and \( ^3\text{H}/d \).
Summary

• Once in a generation tritium target at HallA at JLab
• Successful spring operation of tritium experiments
• MARATHON will impact uncertainties in high-x F_2 ratio
  • Analysis ongoing
  • Results by next year
• SRC (e,e’p) experiment
  • Preliminary results agree with np dominance for high momentum nucleons
  • Expected final results by the end of the year
• Tritium running will continue in fall with SRC inclusive and (e,e’K) experiment
Backup Slides
Marathon EMC Measurements

![Graph showing data points and trend lines for $2F_2^A/AF_2^d$ with $x_B$ on the x-axis. The graph includes data from Seely et al., Hall C, $^3$He/d and MARATHON projected. Annotations indicate trends for 'Without isoscalar corr.' and 'Isoscalar-corrected.'
F₂ and u/d Ratio

\[ \frac{F_{2n}}{F_{2p}} \]

- Whitlow et al.
- Melnitchouk and Thomas
- Bodek et al.

\[ Q^2 = 10 \text{ GeV}^2 \]

- QCD fit
- CTEQ4M
- CTEQ4M (modified)

fitted range
Ongoing Analysis

Analysis Plan

Benchmark database, replay roostlies

Calibrations

Pass 1 Analysis

Data

Efficiency

Correction

Ongoing Analysis

Run conditions check:
- BCM / BPM
- magnetic fields
- target temperature
- Scatter counts
- HV
- PMT pedestal / gain
- Deadtime
- normalized yield

Simulation: understand acceptance
draw acceptance cuts
compare yield with cross section model

Target Cells:
- Envelope contamination / mis-reconstruction
target density v.s. beam current
draw targeted (C) cut to use
- Tritium decay rate

Trigger:
- So, S2, Cerenkov

Tracking:
- no tracks
- multi-tracks
- projected track deviates from fixed detectors

Cuts:
- acceptance cuts, Q1 aperture cut
- Cerenkov
- Calorimeters
- time of flight

Delta Calibration (L vs. R) with e/p data

Plot by S. Li
• Dominant NN force in the 2N-SRC is tensor force

• The high momentum tail is dominated by L = 0,2  S= 1 np-SRC pairs
Previous Hall-A $^3$He $(e,e'p)X$ measurements

$^3$He$(e,e'p)d$ $^3$He$(e,e'p)np$

- Dominated by FSI at large momentum
- Well described by theory

Data: Rvachev et al., PRL94 192302 (2005); Benmokhtar et al., PRL94 082305 (2005)
Theory: Ciofi degli Atti and Kaptari, PRL95 052502 (2005); Alvioli et al., PRC81 021001 (2010)
The A = 3 System

• $^3$He and $^3$H are mirror nuclei
  • Neutron in $^3$He = Proton in $^3$H
• Two-ways to study the proton-to-neutron momentum distribution ratio in $^3$He:
  • Measure the $^3$He(e,e'p) / $^3$He(e,e'n) ratio
    (Low accuracy due to the neutron measurement)
  • Measure the $^3$He(e,e'p) / $^3$H(e,e'p) ratio.
    (Tritium Target necessary, available at Jefferson Lab Hall-A (MARATHON))
SRC and Kinetic Energy Sharing

Pauli-Principle:

\[ \langle T \rangle \text{(Majority)} > \langle T \rangle \text{(Minority)} \]

SRC np pairs

\[ \langle T \rangle \text{(Majority)} < \langle T \rangle \text{(Minority)} \]
VMC Prediction for $<T>$

| $\frac{|N-Z|}{A}$ | $<T_p>$ | $<T_n>$ | $<T_p> - <T_n>$ |
|-----------------|--------|--------|-----------------|
| $^8\text{He}$  | 0.50   | 30.13  | 18.60           | 11.53           |
| $^6\text{He}$  | 0.33   | 27.66  | 19.06           | 8.60            |
| $^9\text{Li}$  | 0.33   | 31.39  | 24.91           | 6.48            |
| $^3\text{He}$  | 0.33   | 14.71  | 19.35           | -4.64           |
| $^3\text{H}$   | 0.33   | 19.61  | 14.96           | 4.65            |
| $^8\text{Li}$  | 0.25   | 28.95  | 23.98           | 4.97            |
| $^{10}\text{Be}$ | 0.2    | 30.20  | 25.95           | 4.25            |
| $^7\text{Li}$  | 0.14   | 26.88  | 24.54           | 2.34            |
| $^9\text{Be}$  | 0.11   | 29.82  | 27.09           | 2.73            |
| $^{11}\text{B}$ | 0.09   | 33.40  | 31.75           | 1.65            |

$<T>$ (Minority) $\mathbf{v}$ $<T>$ (Majority)

R. Wiringa et al. (Phys. Rev. C 89, 024305 (2014))
Kinetic Energy Sharing - Estimated Results

Mapping of Inversion
Marathon Target

- Open cell design allows a wide range of scattering angles
- Wall thickness 0.018” Al (120 mg/cm$^2$)
- Entrance and exit windows: 0.010” Al (65 mg/cm$^2$)
- The proton HRS will not see the cell windows

Adopted from David Meekins