JUPITER e-A - L/T (Longitudinally and Tranverse) Separated Structure Functions at low $Q^2$ on Nuclei at Jefferson Lab
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E04-001/E02-109 ~ 2 weeks of beam time in Hall C during Jan’05 (~1/3 of approved time) to measure the low $Q^2$ (0.3 < $Q^2$ < 2) part of a continuing ongoing program:

- E94-110: L/T separated structure functions protons - done
- E02-109: L/T separated structure functions deuterons - new
- E04-001: L/T separated structure functions on nuclei - new

Also taken during Jan 05 run:

Dedicated very Low $Q^2$ cross section measurements for the neutrino community K2K, MiniBoone, MINOS, MINERvA (part of JUPITER e-A /MINERvA Program).
**JUPITER e-A Physics includes:**

- **(0.3 < Q^2 < 5)** Resonance Region \( F_1 \) and \( F_L \) for deuterons and nuclei (**Fundamental**) & combine with proton data and extract neutron data - Related by CVC to \( vA \) Vector \( F_1, F_L \)

- QCD moments of deuteron, nuclei -  
  & combine with proton-data and extract neutron data.
- Quark-Hadron duality in nuclei.

- Nuclear dependence of \( F_1 \) and \( F_L \) in Resonance Region for a Range in \( Q^2 \).
- E.g. for excess-pions in nuclei

- Quasielastic scattering on nuclear Targets at Low Q2 (in collaboration with the neutrino physics community)
- Coulomb Sum Rule
Neutrino Experiments Need:

- Neutrino experiments need good models of cross sections and final states to extract cross sections
  - Neutrino Monte Carlo models must be based on understanding of the physics, and checked by data
- A collaborative program between the high and medium energy communities to develop reliable global models linking electron and neutrino scattering measurements
- Nuclear data necessary for comparison with neutrino measurements
- No L/T separated structure function measurements exist on nuclei in the resonance region
- In the resonance region, nuclear effects may be large, different from the DIS region, and $Q^2$ dependent.
R = L/T directly effects neutrino, anti-neutrino cross section models - aim at $\Delta R = \pm 0.02$ (factor of 10 better than previous data)

$\sigma^{\nu N}$ fractional error $\sim 0.5 \Delta R$

$\sigma^{\nu N}$ fractional error $\sim 1.5 \Delta R$

$\Delta R = \pm 0.2$ implies 10% error on $\sigma^{\nu N}$, 30% error on $\sigma^{\nu N}$

(Neutrino, Anti-neutrino cross sections / Energy) versus E

$$R = \frac{2K}{(Q + \overline{Q})}$$

$$\sigma^{\nu N} = \frac{G_F^2 M E_v}{\pi(1 + Q^2/M_W^2)^2} \left[ Q^{\nu N} + (1/3) \overline{Q}^{\nu N} + K^{\nu N} \right]$$

$$\sigma^{\overline{\nu} N} = \frac{G_F^2 M E_v}{\pi(1 + Q^2/M_W^2)^2} \left[ \overline{Q}^{\overline{\nu} N} + (1/3) Q^{\overline{\nu} N} + K^{\overline{\nu} N} \right]$$
HMS -> High Momentum Spectrometer $p < 6 \text{ GeV}/c$
used by JUPITER to measure the scattered electron $e^-$

SOS  Short Orbit Spectrometer $p < 1 \text{ GeV}/c$
used by JUPITER to measure $e^+$
(background from Pi0/Gamma conversion)
Hall C hosts the **High Momentum Spectrometer (HMS) and the Short Orbit Spectrometer (SOS)**. The acceptance is high (respectively 18% and 40%). The HMS spectrometer has been made to detect high momentum particles (up to 6 GeV/c protons).

The SOS is shorter and limited at 1 GeV/c,

- Additional technical details for Jlab experts,
- Need *stable* beam currents (60uA) and Beam Current Monitors - so keep current at this value
- For some small $Q^2 \cdot C$ data, rates is very large => so reduce current< 10uA for these runs.
Acceptance HMS Monte Carlo - Geometry and spectrometer modelling only

- MC not used for physics, just ray tracing

- Excellent agreement between different experiments!
- Acceptance is determined to < 1% pt-pt in the kinematics.

Comparison of MC to E99-118 data using E94-110 resonance region model.
Charge Symmetric Background

If the CS background is not too large then a multiplicative correction factor can be applied to the electron yield, as

\[
\text{CScor} = \frac{Y^{-} - Y^{+}}{Y^{-}}
\]
A Program of Inclusive Structure Function Measurements in Hall C at Jefferson Lab

- E94-110: L/T Hydrogen Resonance Region - all done
- E99-118: L/T Low x, Q$^2$ A-Dependence
- E00-002: L/T Low Q$^2$ Deep Inelastic H, D
- E00-116: High Q$^2$ H,D
- E04-001: L/T Nuclear Dependence, Neutrino Modeling - JUPITER e-A
- E02-109: L/T Deuterium Resonance Region
- E02-109: x>1, A-Dependence
- E03-103: EMC effect
- Use all of these data to get a complete picture of the vector structure functions
**HMS Spectrometer**

**Detector Stack**
(view from above)

<table>
<thead>
<tr>
<th>2 sets of vertical + horizontal Drift Chambers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertically Segmented Hodoscope</td>
</tr>
<tr>
<td>4-layer Electromagnetic Calorimeter</td>
</tr>
<tr>
<td>Gas Cerenkov</td>
</tr>
<tr>
<td>horizontally Segmented Hodoscope</td>
</tr>
</tbody>
</table>

**HMS Properties (pt-pt tune)**

<table>
<thead>
<tr>
<th>Kinematic Range:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum:</td>
<td>0.5 – 7.5 GeV/c</td>
</tr>
<tr>
<td>Angular:</td>
<td>10.5° - 80°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Acceptance:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔΩ:</td>
<td>~6.5 msr</td>
</tr>
<tr>
<td>Δp/p:</td>
<td>+/-9%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resolution:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Δp/p:</td>
<td>&lt; 0.1 %</td>
</tr>
<tr>
<td>Θ:</td>
<td>~ 1 mrad</td>
</tr>
</tbody>
</table>

*Cer + Cal provide p rejection factor ~ 10000/1 At 1 GeV*

✬ **HMS Acceptance is dominated by the octagonal collimator!**
PID Detectors and $\pi^-$ elimination

Cerenkov # photo-electrons

Calorimeter energy deposition
Experimental Considerations for L/Ts

General Considerations:

- Want multiple $\varepsilon$ points to reduce uncertainty in linear fit => take data at as many beam energies as possible.
- Need adequate $\varepsilon$ spread to perform L/T separations.
- For $Q^2 > 1$, the maximum $\varepsilon$ is at the largest $E_{\text{beam}}$ (4.612 GeV) and forward angles.
- Minimum $\varepsilon$ is at smallest beam energy (1.201 GeV) and larger angles... However, for HMS $E'_{\text{min}} \sim 0.45$, $W^2_{\text{max}} = 2.2 \text{ GeV}^2$. Change energies between 4.612 (highest) to 1.201 (lowest).

Hall C base equipment:

- Measure inclusive $e^-$ cross sections in HMS (high momentum spectrometer $p < 6 \text{ GeV/c}$)
- Measure $e^+$ for charge-symmetric corrections in SOS ($p < 1 \text{ GeV/c}$) (single orbit spectrometer) where needed - at the same time.
Need different $E_{\text{beam}}$ for different $\varepsilon$ at same $W^2$, $Q^2$.

Increasing $\theta$ at fixed $E_{\text{beam}}$ slides fixed $Q^2$ range to larger $W^2$.

$\Delta \varepsilon = 0.4$ for $W^2 = 3.5$, $Q^2 \sim 0.4$

$E=2.3$, 30 degrees

$E=4.0$, 10 degrees
Jan 05 e-D and e-A data:

~85 different kinematics

- Targets: $D_2$, C, Al, Fe for L/Ts
- $H_2$ for checks against completed H data set.

Also: Carbon data at very low $Q^2$ in the Quasielastic region for $\nu$ cross section modelling (no L’T ‘s possible for these very low $Q^2$ Quasielastic kinematics)

- Total runs ~375 with ~15 minutes per run
- Overhead for kinematic / target changes ~doubles time requirements

-- Because of frequent High Momentum Spectrometer magnet trips => So scan by angle instead of usual scan by momentum (technical detail)
Analysis Methodology

\[ H_2, \quad E = 3.489 \text{ GeV}, \quad \Theta = 14 \]

- Bin efficiency corrected e\(^-\) yield in \( \delta p/p - \theta \).
  \((\delta p/p = +/- 8\%, \quad Dq = +/- 35 \text{ mrad})\)
- Subtract scaled dummy yield bin-by-bin to remove e\(^-\) Al background.
- Subtract charge symmetric e\(^-\) yield bin-by-bin.
- Apply acceptance correction for each \( \delta-\theta \) bin.
- Apply radiative corrections bin-by-bin.
- Apply \( \theta \) bin-centering correction and average over \( \theta \Rightarrow \) for each \( \delta \) bin.

\[ \begin{align*}
\text{HMS Momentum} & \\
2.75 \text{ GeV} & \quad \bullet \\
2.36 \text{ GeV} & \quad \odot \\
2.0 \text{ GeV} & \quad \circ \\
1.75 \text{ GeV} & \quad \blacklozenge
\end{align*} \]
E94-110 e-\(p\) Rosenbluth Separations

\[
\frac{d\sigma}{d\Omega dE'} = \Gamma \left[ \sigma_T(x, Q^2) + \varepsilon \sigma_L(x, Q^2) \right]
\]

- Extract \(F_L(L)\), \(F_1(T)\), and \(R = \sigma_L/\sigma_T\)
- 180 separations total (most with 4-5 \(\varepsilon\) points)
- Small movement is \(Q^2\) is sometimes needed
- Spread of points about the linear fits is fairly Gaussian with \(\sigma \sim 1.6\%\), (consistent with estimated pt-pt uncertainties)

2005: e-\(p\) Data submitted for publication and available on-line
New e-p Rosenbluth Extractions of $R$

- Red: All previous world data at all $Q^2$
- Blue new e-p data: Only one of many $Q^2$ range shown
- **JUPITER** - measure same accuracy for the deuteron (less well measured), and Nuclei no resonance $L/T$ data-existed.

$\Delta R = 0.2$ implies 10% error on $\sigma^{\nu N}$, 30% error on $\sigma^{\nu N}$.

$\Delta R = \pm 0.2$
Alekhin NNLO

MRST NNLO

MRST NNLO with Barbieri Target Mass Corrections

Smooth transition from DIS (solid squares) to resonance region

Resonances oscillate about perturbative curves

Target mass corrections large and important

Preprint JLab Hall C - nucl-ex/0410027
e-p : submitted for publication: L/T Separated Structure Functions: shown are results for $F_L$ (Hydrogen)

- Smooth transition from DIS (solid squares) to resonance region
- Resonances oscillate about perturbative curves
- Target mass corrections large and important
- Resonances in $F_1$ and $F_L$ are different

Alekhin NNLO
MRST NNLO
MRST NNLO with Barbieri Target Mass Corrections

Preprint- JLab Hall C nucl-ex/0410027
L/T Separations on Deuterium: JLab E02-109

E02-109 (Hall C) runs at the same time as E04-001 and measures separate deuterium structure functions in the Resonance Region for 0.3 < Q^2 < 4.5

Data quality and kinematic range similar to that shown for the proton

At low Q^2, data largely at x < 0.7 can extract low Q^2 neutron structure functions and moments with minimal nuclear extraction uncertainty
Deuterium Cross Sections Jan 05

$E_{\text{Beam}} = 3.4$ GeV, Target = D

$\theta = 14.00^\circ$

$\theta = 20.00^\circ$

$\theta = 28.00^\circ$

$\theta = 36.00^\circ$

$\theta = 40.00^\circ$

$\theta = 45.00^\circ$
LOTS of new, L/T separated, low $Q^2$ nuclear data en route...

$E_{\text{Beam}} = 4.6$ GeV, Target = C

Very preliminary raw data no radiative corrections (just obtained January 2005)

H,D,C,Al,Cu,Fe,Au resonance region

Models:

D resonance - JLab
n/p - d/u = 1/5
EMC - SLAC
DIS - F2allm
(NMC)

R - JLab e99118

Here Red curves are un-radiated
LOTS of new, L/T separated, low $Q^2$ nuclear data en route

Raw Data (no radiative corrections: will be used for:

- Nuclear duality
- Neutrino modeling
- Deuterium (neutron) moments
- $R$ on deuterium in resonance region
- $A$-dependence of structure functions (and moments) at low $Q^2$
- Search for nuclear pions (G. Miller prediction)

Here Red curves are un-radiated
Much more to come …

Fast track analysis at the 5% level of quasielastic cross sections on Carbon for low energy neutrino cross section modelling is moving well - Checks nuclear models and nucleon binding effects on nucleon form factors.

Inelastic cross sections on nuclear targets available soon!

*L/T separations will take a bit longer to reduce cross section errors to < 2%.*
Proton L/T Separated Structure Functions at low $Q^2$

- Data smoothly transitions from DIS to resonance region
- Resonances oscillate about DIS Fits ... duality in **BOTH** channels!
- Large $x$-range $\rightarrow$ extract moments from data.
- TM corrections can be quite large, especially in $F_L$!
Carbon Cross Sections Jan 05

$E_{\text{Beam}} = 3.4 \text{ GeV}, \ Target = C$

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$d\sigma/d\Omega/dE/A (\text{nb/sr/GeV})$

\[ \theta = 14.00^\circ \]

\[ \theta = 20.00^\circ \]

\[ \theta = 28.00^\circ \]

\[ \theta = 36.00^\circ \]

\[ \theta = 40.00^\circ \]

\[ \theta = 45.00^\circ \]

$W^2 (\text{GeV}^2)$
Resonance Region L-Ts Needed For spin structure - move out

Extracting spin structure functions from spin asymmetries

\[
A_1 \propto \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \propto \frac{S_{1/2} - S_{3/2}}{F_1 T}
\]

\[
(2xF_1 \propto \sigma_{1/2} + \sigma_{3/2})
\]

\[
\frac{\Delta A_1}{A_1} = \varepsilon \Delta R
\]

\[
g_1 \propto \frac{F_1(A_1 - g A_2)}{1 + g^2}
\]

From measurements of \(F_1\) and \(A_1\) extract \(s_{1/2}\) and \(s_{3/2}\)!

(Get complete set of transverse helicity amplitudes)