Precision Measurement of $R_L$ and $R_T$ of Quasi-Elastic Electron Scattering

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Hall-A Collaboration

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Precision Electroweak Interactions
Outline

- Summary
- Systematic Errors and Beam Time
- Coulomb Corrections
- Background Studies
- Lab Proposal and Previous PACS
- Introduction and Motivation
Coulomb Sum

- **Response Functions in Quasi-Elastic Scattering**

\[
\frac{d^2 \sigma}{d\Omega d\omega} = \sigma_{\text{Mott}} \left[ \frac{Q^4}{q^4} R_L(q, \omega) + \frac{Q^2}{2q^2} \frac{1}{\varepsilon} R_T(q, \omega) \right]
\]

\[
\varepsilon = \left[ 1 + \frac{2q^2}{Q^2} \tan^2 \frac{\psi}{2} \right]^{-1}
\]

- **Coulomb Sum**

\[
S_L(q) = \int_{\omega_{el}^+}^{\infty} d\omega \frac{R_L(q, \omega)}{Z \tilde{G}_E^2(Q^2)}
\]

\[
\tilde{G}_E^2(Q^2) = \left( [G_E^p(Q^2)]^2 + \frac{N}{Z} [G_E^n(Q^2)]^2 \right) \frac{1 + Q^2/4M^2}{1 + Q^2/2M^2}
\]
Saturation/Quenching of the Coulomb Sum

- Saturation of the Coulomb Sum
  - $S_q(q) \to 1$ at sufficiently large $q$

- Deviation of the Coulomb Sum
  - at small $q$
    - Pauli blocking
    - Nucleon–nucleon long-range correlations
  - at large $q$
    - Short range correlations
    - Modification of the free nucleon electromagnetic properties inside the nuclear medium

- One of the long lasting questions in physics
Overview

- Comprehensive measurements of the Coulomb sum at various labs for over 20 years
  - Limited range in $q$ and $\omega$
  - Saturation/Quenching of the Coulomb sum still controversial

- Proposed experiment (ex-E01-016) at JLab
  - Covers a region up to $q = 900$ MeV/$c$
    - Free of long range correlations/Pauli blocking
    - Effect of short range correlations, at most 10%
  - Largest lever arm for Rosenbluth separation in a single experiment
  - Better control of systematic uncertainties
  - Better control of experimental backgrounds
Previous Measurements

- For the past twenty years, a large experimental program at Bates, Saclay and SLAC
- Limited kinematic coverage in $q$ and $\omega$ due to machine limitations
Approved for 26 days in Hall A with rating A−

The PAC recognized the importance of performing a definitive study of the Coulomb sum rule at JLab

Recommendations, suggestions
- careful study of experimental backgrounds
- close cooperation with theorists for Coulomb distortions
Jeopardy Return at PAC25 (Jan. 2004)

• On the motivation, PAC agrees that
  – Clear evidence for such effects would be of great interest in attempting to define the limits of a baryon–meson picture of the nucleus

• But PAC raises a major concern on Coulomb Corrections

• Deferred
Proposed Experiment at JLab

- Scattering Angles 15, 60, 90, 120
  - compromise between counting rates and lowest momentum setting
  - two more angles at ~ equally spaced e – improved systematic uncertainties
- Beam Energy 0.4 to 3.6 GeV
- Range of \( q \) 550 MeV/c to 900 MeV/c
- Targets \( ^4\text{He}, ^{12}\text{C}, ^{56}\text{Fe}, ^{208}\text{Pb} \)
  - study A or density dependent effect
  - Coulomb corrections (small for \(^4\text{He}\) or \(^{12}\text{C}\), but large for \(^{208}\text{Pb}\))
- Scattered energy Covers complete range of QE peak and beyond
Study of the Spectrometer Background

- Major concern: background originating inside the spectrometer
- Combination of SNAKE (ray tracing) and GEANT (physics)
- Electrons hitting Dipole or Q3
  - Rescattering or secondary particles by GEANT
  - Re-insertion into SNAKE
- Rescattering from the Dipole
  - Mostly from the elastic events
  - Negligible ($1.5 \times 10^{-4}$ of the elastic yield)
- Some background events from the Q3
  - About 2\% of the clean events
  - Reconstructed energy ≠ true energy
Cleaning up the background

• Reduction of background events from Q3
  – Different position/angle distributions for clean and un-clean events
  – Cut on the position/angle at the Q3 Exit
  – Geometric cut reduces the background by factor 10
    • After cut, background is only 0.2% of the clean events

• Further reduction using calorimeter
  – DVCS calorimeter (132 blocks)
  – 3 x 3 cm² arranged in 3 x 44 array
  – cover central region of the focal plane
  – In situ calibration of the simulation for each spectrometer configuration
  – Energy resolution: 3%/√E
Coulomb Corrections

- Need to take into account the effect of the nucleus Coulomb field to the incoming/outgoing electrons
- Approximate corrections via Effective Momentum Approximation (EMA)
- Full treatment of Coulomb corrections via Distorted Wave Born Approximation (DWBA)
- Another approximation: Local Effective Momentum Approximation (LEMA)
- Disagreement between EMA & LEMA
Workshop on Coulomb Distortions

- First workshop on this issue
- Presentations and round-table discussions with 4 different theory groups
  - L. Wright (Ohio), J. Tjon (JLab & Maryland), A. Aste (Basel), J. Udias (Madrid)
- Some conclusions from the workshop
  - All agreed that the issue can be resolved with a coordinated effort
  - All agreed to work on the issue until reaching a consensus
- http://www.jlab.org/~choi/CSR/workshop
L. Wright’s Conclusions

- Using “plane-wave-like” approach we have a very good approximate DW for potential for use in \((e,e'p)\). It does require finding at least two Coulomb phases, and is not amenable to an expansion in Spherical Harmonics.
- For \((e,e')\) reactions we developed a further *ad-hoc* treatment that does permit expansion in Spherical Harmonics.
- Both approximations work very well for lepton energies above 300 MeV and for 3-momentum transfers above about 250 MeV/c.
- Let the Experiments Continue!
Conclusions from the mini-workshop

- J. Tjon’s concluding remark: (with Eikonal’s expansion)
  - Results indicate that simple approximations are possible to account for Coulomb distortion
- Aste’s conclusion:
  - Probably both effects (focusing and change of momentum) can be described quite accurately by a common parameter, such that EMA is a viable method to calculate Coulomb corrections
- J. Udias agrees with the other conclusions, will do calculations to confirm.
After the Workshop

- New calculations in progress
  - e.g. from A. Aste
    - It is still interesting to observe that the exact calculations (his) agree so well with EMA, although the two approaches are completely unrelated from the calculational point of view. (June 18)
    - I feel very convinced that EMA is a very effective method for the description of CC. (June 24)
    - See A. Aste et al., nucl-th/0502074

- A session on Coulomb Corrections during JLab/INT workshop at W&M in August
Wright’s new paper

- Nucl-th/0505032:
  - EMA-f getting better at higher $E_{\text{in}}$, perhaps can be used as a basic analysis tool
  - Proposed $D_L$, $D_T$ to take into account Coulomb Correction;
  - at $E_{\text{in}} > 600$ MeV, good to < 5%.
In EMA, $\frac{E \rightarrow E - |V_C|}{E' \rightarrow E' - |V_C|}$ \rightarrow q_{\text{eff}}, Q_{\text{eff}}$ with $|V_C| = 19.0 \pm 1.5$ MeV for $^{208}\text{Pb}$

P. Gueye et al., Physical Review C 60 044308 (1999)
In EMA, \[ \frac{E \rightarrow E - |V_C|}{E' \rightarrow E' - |V_C|} \] \[ \rightarrow q_{\text{eff}}, Q_{\text{eff}}^2 \] with \( |V_C| = 19.0 \pm 1.5 \text{ MeV} \) for \( ^{208}\text{Pb} \)

P. Gueye et al., Physical Review C 60 044308 (1999)
## Systematic Error Estimate on $R_L$

<table>
<thead>
<tr>
<th>Source</th>
<th>Solid Target</th>
<th>Gas Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy ($4 \times 10^{-4}$)</td>
<td>$&lt; 0.3%$</td>
<td>$&lt; 0.3%$</td>
</tr>
<tr>
<td>Momentum Reconstruction</td>
<td>$&lt; 0.3%$</td>
<td>$&lt; 0.3%$</td>
</tr>
<tr>
<td>Detector Inefficiency</td>
<td>$&lt; 0.3%$</td>
<td>$&lt; 0.3%$</td>
</tr>
<tr>
<td>Dead Time Corrections</td>
<td>$&lt; 0.3%$</td>
<td>$&lt; 0.3%$</td>
</tr>
<tr>
<td>Interpolation</td>
<td>$&lt; 0.3%$</td>
<td>$&lt; 0.3%$</td>
</tr>
<tr>
<td>Beam Current</td>
<td>$0.3%$</td>
<td>$0.3%$</td>
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<tr>
<td>Scattering Angle (0.2mrad)</td>
<td>$0.5%$</td>
<td>$0.5%$</td>
</tr>
<tr>
<td>Background</td>
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<td>$0.5%$</td>
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<tr>
<td>Target Density</td>
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<td>$1.0%$</td>
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<tr>
<td>Radiative Corrections</td>
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<td>$1.0%$</td>
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<tr>
<td>Acceptance&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>$1.0%$</td>
<td>$1.0%$</td>
</tr>
<tr>
<td><strong>Total</strong>&lt;sup&gt;2)&lt;/sup&gt;</td>
<td><strong>1.7%</strong></td>
<td><strong>2.2%</strong></td>
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</table>

1) Contributions from the relative change between forward and backward angles
2) Conservative limit
<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>No. of Pref.</th>
<th>Total Time (Hours)</th>
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<td>11.3</td>
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<tr>
<td>500.0</td>
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</tr>
<tr>
<td>3500.0</td>
<td>1</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Total Time (hours) with 2 Spectrometers: 276
# Overhead

<table>
<thead>
<tr>
<th>Item</th>
<th>Time (Hour)</th>
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</thead>
<tbody>
<tr>
<td>Linac Energy Change</td>
<td>$6 \times 16 = 96$</td>
</tr>
<tr>
<td>Pass Change</td>
<td>$7 \times 8 = 56$</td>
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<tr>
<td>Beam Energy Measurement</td>
<td>$14 \times 2 = 28$</td>
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<tr>
<td>Beam Current Calibration</td>
<td>$4 \times 1 = 4$</td>
</tr>
<tr>
<td>Acceptance Calibration</td>
<td>$24 \times \frac{3}{4} = 18$</td>
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<tr>
<td>Spectrometer Change</td>
<td>$255 \times \frac{1}{2} \times 0.7 = 89$</td>
</tr>
<tr>
<td>Target Change</td>
<td>$128 \times 5 \times \frac{1}{12} = 53$</td>
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<tr>
<td>Set-up and Test</td>
<td>$3 \times 24 = 72$</td>
</tr>
<tr>
<td><strong>Total Overhead</strong></td>
<td><strong>416 (=17.3 days)</strong></td>
</tr>
</tbody>
</table>

Total time needed for the experiment: 610 hours (≈ **26 days**).
Summary

- Precision measurement of $R_L$ and $R_T$ over the QE scattering range
  - Momentum transfer: $550 \text{ MeV} / c \leq q \leq 900 \text{ MeV} / c$
  - On four nuclei: $^4\text{He, } ^{12}\text{C, } ^{56}\text{Fe and } ^{208}\text{Pb}$
- Spectrometer background well under control
- Progress in Coulomb Correction Studies
- Study the evolution of the Coulomb Sum in a clear region
- Shed light on nucleon property inside the nuclear medium

26 days of beam time
Expected Uncertainty on Coulomb Sum