Coulomb Sum Rule Experiment

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Overview

• Probing nucleons in nuclei with electrons
• Quasi-elastic scattering and Coulomb Sum Rule
• One of the long standing puzzles in nuclear physics
• New experiment at JLab
• Preliminary results and summary
Electrons as a Probe

- Electron scattering has been an excellent tool to study properties of nucleons, nuclei etc.
- **Charge/Magnetization distribution** of various nuclei
- **Elastic form factors** of nucleons free or inside nuclei
- Surprises from JLab on $\mu G_E^p/G_M^p$
- Polarization transfer from $^4$He
QE Scattering

• Elastic scattering on bound nucleons
• We can study the nucleon properties inside the nucleus
• Scattering on the moving nucleons
• Response functions instead of Form Factors
Response Functions

- Momentum Transfer
  \[ q = |k - k'| \]
- Energy Transfer
  \[ \omega = E - E' \]

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

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

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

- Roughly \( R_L \) corresponds to \( G_E^2 \)

- One complication: the separation of quasi-elastic and inelastic scattering is not a clear cut.

- Fortunately, inelastic scattering contributes mainly to \( R_T \), leaving \( R_L \) mostly from quasi-elastic
Coulomb Sum

• Integral of $R_L$ to be compared to $G_E$

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

• Denominator = contribution from electric form factors of protons and neutrons

\[ \tilde{G}_E^2(Q^2) = ([G_E^p(Q^2)]^2 + (N/Z)[G_E^n(Q^2)]^2) \frac{1 + Q^2/4M^2}{1 + Q^2/2M^2} \]
Coulomb Sum Rule in One Page

- Coulomb Sum Rule
  - $S_L(q) \rightarrow 1$ at sufficiently large $q$
- Deviation from unity
  - at small $q$
    - Pauli blocking
    - NN long range correlations
  - at large $q(\gg 2k_F)$
    - Short range correlations
    - Nucleon properties in the nuclear medium

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* McVoy and Van Hove, Physical Review 125, 1034 (1962)
Previous Measurements

• For the past 30 years, a large experimental program at Bates, Saclay and SLAC

• Saturation of the Coulomb sum still a puzzle

• Limited kinematic coverage in \( q \) and \( \omega \) due to machine limitations

• Unresolved issue on the control of systematics

  • background events for backward scattering

  • Coulomb corrections
Existing Data for CSR
CSR Puzzle

- Early data show significant quenching of the CSR
- With the addition of forward angle data, some analysis claims no significant quenching
  - Jourdan NPA 603, 117 (1996)
- Other, new analysis claims that quenching persists
  - Morgenstern & Meziani, PLB 515, 269 (2001)
Major Issues of the CSR Experiments

• Coulomb Corrections
  • Effect of the nuclear Coulomb field to the incoming and outgoing electrons
  • Actual incident & scattered energy inside the nucleus are modified
  • Corrections are necessary before the comparison of elastic & quasi-elastic

• Experimental Systematics
  • Machine limitations (too low or too high)
  • Relatively small lever arm for LT separation
  • Control of background events in the detector
Coulomb Corrections

• Up to now, two methods have been suggested
  • Approximated Distorted Wave Impulse Approximation (DWIA) calculations
    • Leading to LEMA (Local EMA)
  • Approximate corrections via Effective Momentum Approximation (EMA)
    • Morgenstern & Meziani, PLB 515, 269 (2001)
• To make things more complicated
  • MIT/Bates experiments have used LEMA
  • Saclay experiments used EMA
What is EMA?

- Corrections to incident and scattered electron energies by average potential $\overline{V_C}$

$$
\begin{align*}
E & \rightarrow E_{\text{eff}} = E - \overline{V_C} \\
E' & \rightarrow E'_{\text{eff}} = E' - \overline{V_C}
\end{align*}
\right\} \rightarrow q_{\text{eff}}, Q_{\text{eff}}^2
$$

- Response functions after EMA corrections are

$$
\frac{d^2\sigma}{d\Omega d\omega} = \sigma_{\text{Mott}}(E, E', \theta) \left[ \frac{Q_{\text{eff}}^4}{q_{\text{eff}}^4} R_L(q_{\text{eff}}, \omega) + \frac{Q_{\text{eff}}^2}{2q_{\text{eff}}^2} \frac{1}{\varepsilon_{\text{eff}}} R_T(q_{\text{eff}}, \omega) \right]
$$

- Comparison of positron vs electron scattering on Pb nuclei
New Development on Coulomb Corrections

- 4 independent theory groups have worked on the subject
  - A. Aste (Basel), K. Kim (Korea), J. Tjon (Maryland), J. Udias (Madrid), S. Wallace (Maryland), L. Wright (Ohio)
- Workshops organized by Jefferson Lab and College of William & Mary
  - Mini-workshop on Coulomb Corrections (Mar. 2005)
  - A session during JLab/INT workshop (Aug. 2005)
New Conclusions

• EMA is a reasonable approximation, especially
  • for medium-light nuclei
  • for incident electron energies higher than 500 MeV
  • EMA should be a reasonable approximation for Coulomb corrections up to $^{56}$Fe

• How good is EMA for $R_L$ in the case of $^{208}$Pb?
  • For different nucleus, the effect goes roughly as $\left(1 - \frac{V(0)}{E}\right)^2$
  • Coulomb corrections significant
  • Have to work with theorists
References for CC

- Wallace & Tjon, PRC78, 044604 (2008)
- Aste, NPA806, 191 (2008)
- Benhar, Day & Sick, RMP 80, 189 (2008)
- Aste & Trautmann, EPJA33, 11 (2007)
- Tjon & Wallace, PRC74, 064602 (2006)
- Kim & Wright, PRC72, 064607 (2005)
- Aste, von Arx & Trautmann, EPJA26, 167 (2005)

* References only after 2005 CC Workshop have been listed.
New Experiment at JLab

- Beam: 16 energies from 0.4 to 4.0 GeV
- Scattering angles: 15°, 60°, 90°, 120°
- Targets: $^4$He, $^{12}$C, $^{56}$Fe, $^{208}$Pb
- Spectrometer momenta range from 4 GeV down to 100 MeV
- Covers $q$ from 550 to 1000 MeV/c
Jefferson Lab / Experimental Hall A

- Up to ~6 GeV polarized electron beam
- 100 μA for Hall A / C
- Now under 12 GeV upgrade with Hall D construction
Jefferson Lab Hall-A

Electron beam from the accelerator

Nuclear target

Two spectrometers

To the beam dump
Spectrometer
What’s New?

- Comfortable high values of $q$
  - From 550 MeV/$c$ to 1000 MeV/$c$
  - High enough for clean observation of CSR
  - Previously unexplored region

- Comprehensive single experiment
  - Largest lever arm
  - Measurement at 4 angles

- Better control of background with NaI detector
Kinematic Coverage

15°

60°

90°

120°
Kinematic Coverage

\(q_{\text{eff}} \) (MeV/c)

\(\omega \) (MeV)

- 15°
- 60°
- 90°
- 120°

\(W = 938/1232/1300 \text{ MeV} \)
Lever arm for Rosenbluth Separation

\[ \Delta \varepsilon \]

| q | = 550 MeV/c
| q | = 750 MeV/c
| q | = 900 MeV/c

\[ \omega \xi (\text{MeV}) \]
Nal Detector

• Electrons reflected inside the spectrometer
  • Source of background at low energy backward angle

• Reduction of the background
  • Careful geometry cut at the focal plane

• Independent energy measurement of the electrons using Nal detector
Nal Detector

- Nal Crystal given from BNL
- About 400 crystals of 2.5”\times2.5”\times12”
- Refurbished at JLab: polishing, assembly in new boxes, sealing
- Final product: 3 boxes of 90 crystals (9\times10 arrangement) each
- Covers whole focal plane of L-HRS
Installation of NaI detector
Performance

- Blue: NaI Geometry Cut
- Green: Cerenkov + NaI
People


Hall-A Collaboration

Students  Post-docs  Run Coordinators  Collaborators  Spokespersons
Data Taking

  86 calendar days - 2 holiday shutdowns
- Data taken: about 3TB over 7000 runs
- Most of the runs are 5 minutes long
  - Frequent changes of target and spectrometer momentum
Analysis

- Measurement of absolute cross sections
- Comparison of two absolute cross sections for two different kinematic conditions
  - Forward vs backward angle
  - High vs low beam energy
  - Almost two extremes of spectrometer momentum configuration
- Finally subtraction of two large numbers to find the small difference
Spectrometer Optics Calibration

7-foil Carbon target

Sieve Slit
Spectrometer Optics

Red lines: Surveyed positions and angles of the target and slit holes

Before Optimization

After Optimization
Spectrometer Acceptance

- Realistic acceptance with full simulation considering
  - Effect of energy loss
  - Multiple coulomb scattering
  - Detector resolutions
Spectrometer Acceptance

With Geometrical Acceptance

With Realistic Acceptance
Elastic Cross Sections

E-C Elastic Scattering

PRELIMINARY
LT Separation

\[ R \equiv \sigma / \sigma_M = \frac{Q^4}{q^4} R_L + \frac{Q^2}{2q^2} \frac{R_T}{\varepsilon} \]

\[ \varepsilon = \left[ 1 + \frac{2q^2}{Q^2} \tan^2(\theta/2) \right]^{-1} \]

$^{12}\text{C}$

$q = 650\text{MeV/c}$

\[ \varepsilon R = \varepsilon \frac{Q^4}{q^4} R_L + \frac{Q^2}{2q^2} R_T \]

Slope

Intercept

PRELIMINARY
LT Separation

$^{12}$C

$q = 650 \text{ MeV/c}$

$\omega = 230 \text{ MeV}$

PRELIMINARY
LT Separation

$^{12}$C
$q = 650$ MeV/c
$\omega = 170$ MeV

PRELIMINARY
LT Separation

\[
^{12}\text{C} \\
q = 650 \text{ MeV/c} \\
\omega = 290 \text{ MeV}
\]
Expected Error

\begin{align*}
  S_L(\langle q_{\text{eff}} \rangle) &= \frac{3}{4} \left[ \frac{\theta_3}{\theta_1} + \frac{\theta_3}{\theta_2} + \frac{\theta_4}{\theta_1} + \frac{\theta_4}{\theta_2} \right] \\
  &\approx \frac{3}{4} \left( \frac{1}{\theta_1} + \frac{1}{\theta_2} + \frac{1}{\theta_1} + \frac{1}{\theta_2} \right) \\
  &= \frac{3}{2} \left( \frac{1}{\theta_1} + \frac{1}{\theta_2} \right)
\end{align*}

\text{Expected Error on } ^{56}\text{Fe}
Summary

• Precision measurement of $R_L$ and $R_T$ over the QE scattering range
  • Momentum transfer: 550 MeV/c - 1000 MeV/c
  • On four nuclei: $^4$He, $^{12}$C, $^{56}$Fe and $^{208}$Pb
• Analysis in the final stage
  • Checking systematic errors etc
  • Cross check from two independent analyses
• Absolute cross section measurement
  • Cross check with e-C elastic etc
• Help solve the puzzle on Coulomb Sum Rule
  • Learn properties of nucleon inside the nuclear medium