Coulomb Sum Rule Experiment at JLab

Hadron Physics in LanZhou

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Outline

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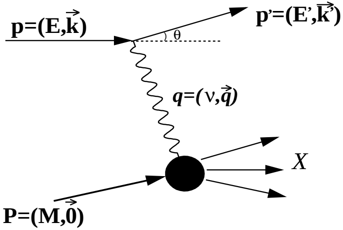
Motivation

- How nucleon properties are affected by the nuclear medium?

Outline

Inclusive electron scattering



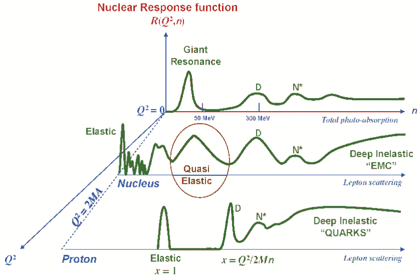


Figure 1: Inclusive (e, e') scattering where only the final electron is observed

Figure 2: Nuclear response function for the inclusive electron scattering off nucleus or nucleon

Elastic Scattering

Rosenbluth cross section

- Elastic scattering of electrons off the free nucleon

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott}\left(\frac{G_E^2(Q^2) + \frac{Q^2}{4M^2}G_M^2(Q^2)}{1 + \frac{Q^2}{4M^2}} + \frac{Q^2}{2M^2}G_M^2(Q^2)tan^2(\frac{\theta}{2})\right) \quad (1)$$

$$\sigma_{Mott} = \frac{\alpha^2 cos^2(\frac{\theta}{2})}{4E^2 sin^4(\frac{\theta}{2})} \qquad q = |\mathbf{q}| \qquad Q^2 = -\mathbf{q}^2 = q^2 - \omega^2$$

$G_E(Q^2)$ Electric form factor
$G_M(Q^2)$ Magnetic form factor

Quasi-Elastic Scattering

- Elastic scattering of electrons off the moving nucleons inside the nucleus

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

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

$R_L(q,\omega)$ Longitudinal Response Function
$R_T(q,\omega)$ Transverse Response Function

Separation of R_L and R_T

- Separation of the two response functions
  - Measure cross sections at least two different angles
  - keeping $-\mathbf{q}^2$ constant

$$R_L = \frac{q^4}{Q^4 \sigma_M} \frac{1}{(\varepsilon_f - \varepsilon_b)} (\varepsilon_f \sigma_f - \varepsilon_b \sigma_b)$$

$$R_T = \frac{q^2}{Q^2 \sigma_M} \frac{2\varepsilon_f \varepsilon_b}{(\varepsilon_f - \varepsilon_b)} (\sigma_b - \sigma_f)$$

forward angle (f) σ_f ε_f

backward angle (b) σ_b ε_b

Estimation of Accuracy of R_L and R_T

$$\frac{\Delta R_L}{R_L} = \frac{\Delta\sigma}{\sigma}\frac{1}{\Delta\varepsilon}\sqrt{(\frac{1}{R}+\varepsilon_f)^2+(\frac{1}{R}+\varepsilon_b)^2}$$

$$\frac{\Delta R_T}{R_T} = \frac{\Delta\sigma}{\sigma}\frac{R}{\Delta\varepsilon}\sqrt{\varepsilon_f^2(\frac{1}{R}+\varepsilon_b)^2+\varepsilon_b^2(\frac{1}{R}+\varepsilon_f)^2}$$

$R = \frac{\sigma_L}{\sigma_T}$ Ratio of longitudinal and transverse virtual photo-absorption cross section

$\Delta\varepsilon = \varepsilon_f - \varepsilon_b = 0.85$ At JLab

$\Delta\varepsilon < 0.5$ Previous Experiment

Coulomb Sum Rule

- Integrate the quasi-elastic $R_L(q,\omega)$ over the full range of energy loss ω at large enough three-momentum transfer $|\mathbf{q}| = q$

$$S_L(q) = \frac{1}{Z}\int_{\omega_{el}^{+}}^{\infty} \frac{R_L(q,\omega)}{\tilde{G}_E^2} d\omega = 1 \tag{3}$$

Nucleon charge form factor:

$$\tilde{G}_E(Q^2) = ([G_E^p(Q^2)]^2 + (N/Z)[G_E^n(Q^2)])\frac{1+Q^2/4M^2}{1+Q^2/2M^2}$$

Saturation/Deviation of Coulomb Sum Rule

- Saturation of the Coulomb Sum $S_L(q) \to 1$ at the sufficienlty large q
- Deviation of the Coulomb Sum
  - at small q
    - Pauli blocking
    - Nucleon-nucleon long-range correlation
  - at large q ($\gg 2K_F$)
    - Short-range correlation $<$ 10%
    - Modification of the free nucleon electromagnetic properties inside the nuclear medium
- One of the long-lasting questions in nuclear physics

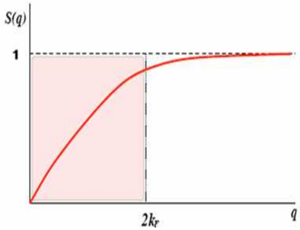


Figure 3: Saturation and Deviation of Coulomb Sum Rule

Outline

Overview

- Comprehensive measurements of the Coulomb Sum at various labs for over 20 years
  - Limited range in q and ω
    - At Bates(MIT) and Saclay ALS(France) q $\leq$ 550 MeV/c
    - At SLAC(Stanford) q = 1140 MeV/c

Previous Measurements

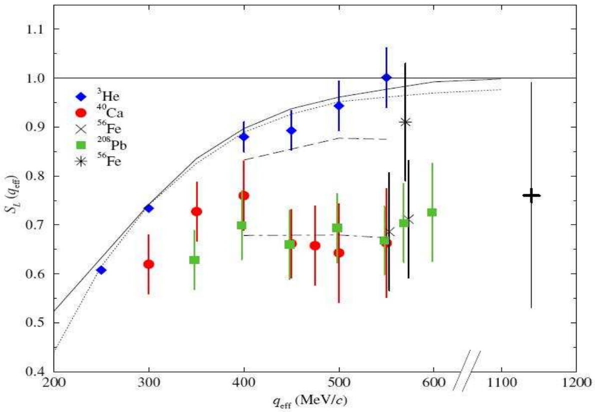
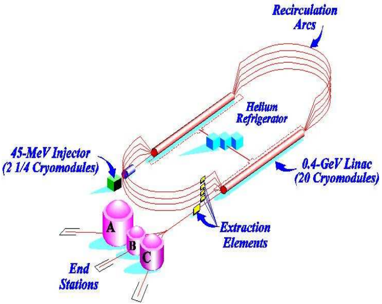


Figure 4: S_L obtained in the EMA as a function of q_{eff} using Saclay data combined with SLAC NE3 and Bates data. The ^{56}Fe SLAC NE9 result right cross and that of the Jourdan analysis (star) are also shown

Outline

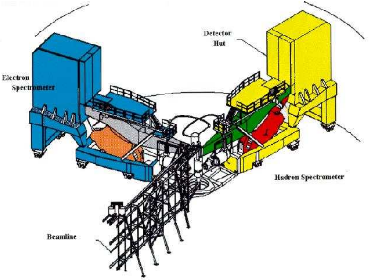
JLab Accelerator

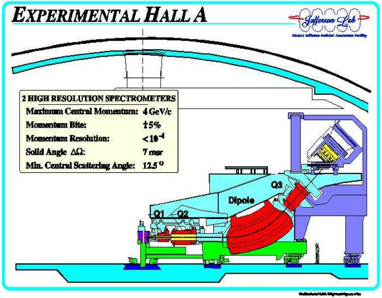
- Commissioned in early 1990s, first experiment in 1994
- High luminorsity electron beam:$10^{39}cm^{-2}s^{-1}$
- High density target
- Maximum current 200 μA
- The gain of each linac is adjustable 400MeV/c$\sim$600MeV/c, Maximum Energy 6 GeV



JLab Hall A

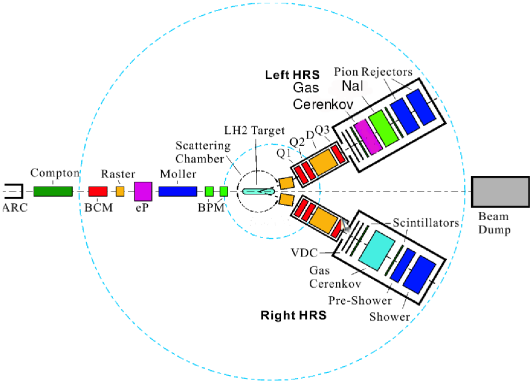
High Resolution Spectrometer(HRS)





Hall A Beamline and Spectrometers

- ARC: Beam energy
- eP : Beam energy
- BCM: Beam charge
- Raster & BPM: Beam position



Outline

1. Introduction
   - Motivation
   - Coulomb Sum Rule
   - Brief History
2. Coulomb Sum Rule Experiment (E05-110) at JLab Hall-A
   - Jefferson Lab
   - CSR Experiment at JLab Hall A
3. Summary

- Scattering Angles $15^\circ, 60^\circ, 90^\circ, 120^\circ$
  - compromise between counting rates and lowest Momentum setting
  - two more angles at $60^\circ, 90^\circ$, equally spaced $\varepsilon \Rightarrow$ improved systematic uncertainties
- Beam Energy 0.4 to 4.0 GeV
- Range of q$\sim$ 550MeV/c to 1000MeV/c
- Targets ^{4}He, ^{12}C, ^{56}Fe, ^{208}Pb
  - study A or density dependent effect
  - study of Coulomb corrections (small for ^{4}He or ^{12}C, but large for ^{208}Pb)
- Scattered Energy covers complete range of QE peak and beyond

Kinematic Coverage

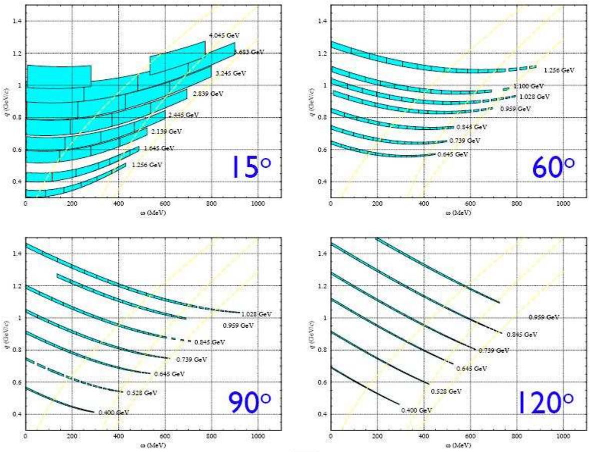


Figure 5: CSR experiment kinematic coverage

Data info

- Dates: Oct. 23, 2007 -Jan. 16, 2008
- Data taken: about 3TB over 7000 runs
- Many kinematic setting,frequent changes of the target and spectrometer momentum

Background reduction

- 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 NaI detector

Installation of NaI detector

3 boxes
each box: 9×10 crystals
each crystal:
$2.5\text{in} \times 2.5\text{in} \times 12\text{in}$

Figure 6: Installation of NaI detector

NaI Performance

Run 3925, E=739MeV, P=539MeV/c, 60°, Carbon Left
Run 3813, E=739MeV, P=121 MeV/c, 120°, Lead

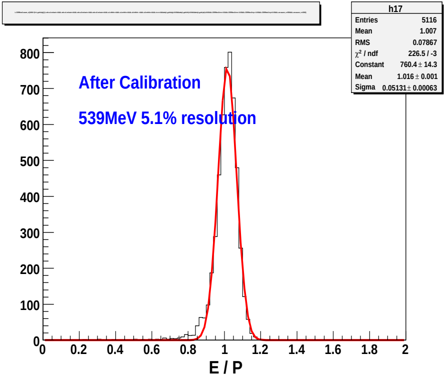


Figure 7: After calibration for middle box

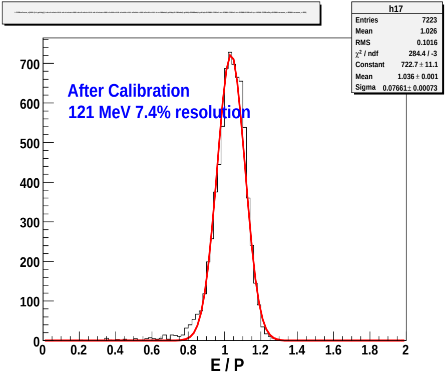


Figure 8: After calibration for middle box

Data and Simulation by Snake/Geant3 and Geant4

Run 3925, E=739MeV, P=539MeV/c, 60°, Carbon Left

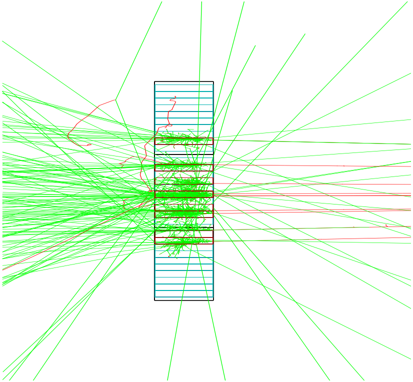


Figure 9: Geant4 simulation for NaI

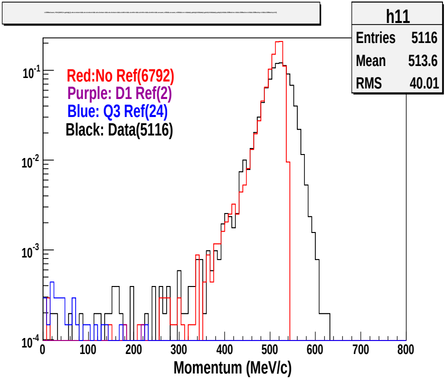


Figure 10: Comparison between simu(color) and data(black)

Data and Simulation by Snake/Geant3 and Geant4

Run 3813, E=739MeV, P=121MeV/c, 120°, Lead

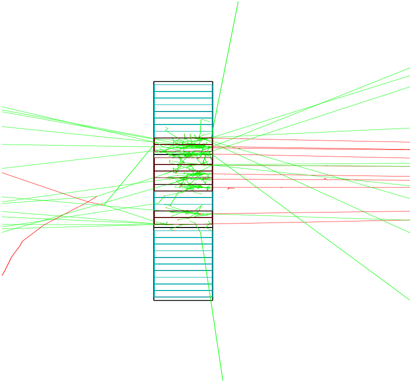


Figure 11: Geant4 simulation for NaI

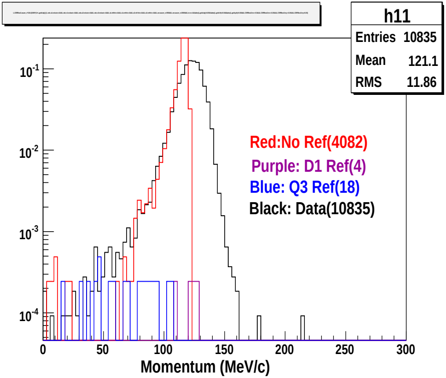


Figure 12: Comparison between simu(color) and data(black)

Optics analysis

Run 4057, E=739 MeV, P0=735.1 MeV/c, 23°, Optics target

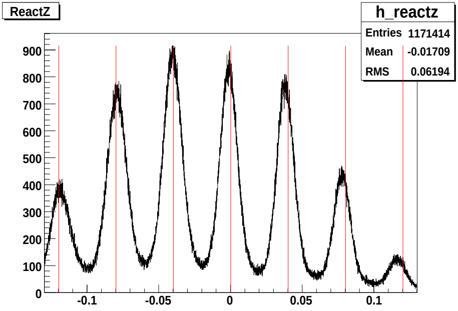


Figure 13: Original ReactZ

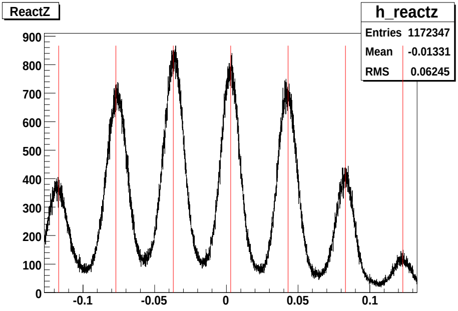


Figure 14: Final ReactZ

Optics analysis

Run 4057, E=739 MeV, P0=735.1 MeV/c, 23°, Optics target

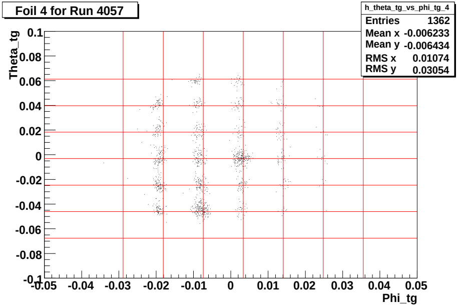


Figure 15: Original Theta_tg vs Phi_tg

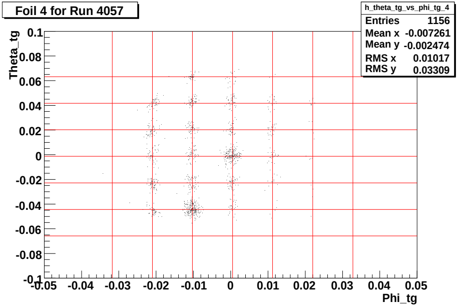
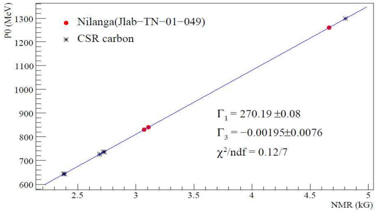


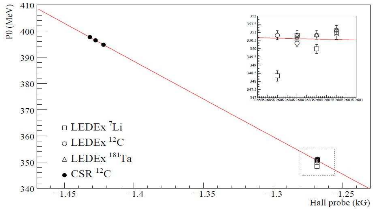
Figure 16: Final Theta_tg vs Phi_tg

HRS momentum calibration



Using $N(e,e')N^{(*)}$

- P0 $>$ 450 MeV
  $B_{NMR} \longrightarrow$ P0



- P0 $<$ 450 MeV
  $B_{Hall} \longrightarrow$ P0

Preliminary result with no radiative correction

E=739 MeV, $\theta = 60^\circ$

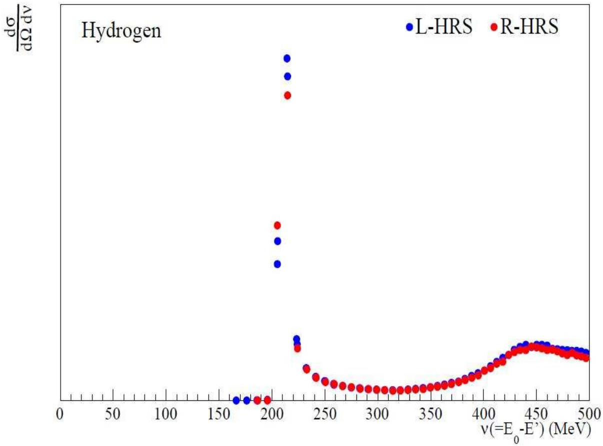


Figure 17: Cross section for different target

Preliminary result with no radiative correction

E=739 MeV, $\theta = 60^\circ$

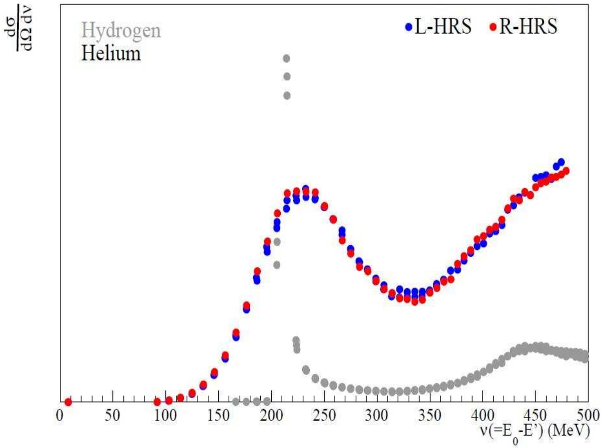


Figure 18: Cross section for different target

Expected Error

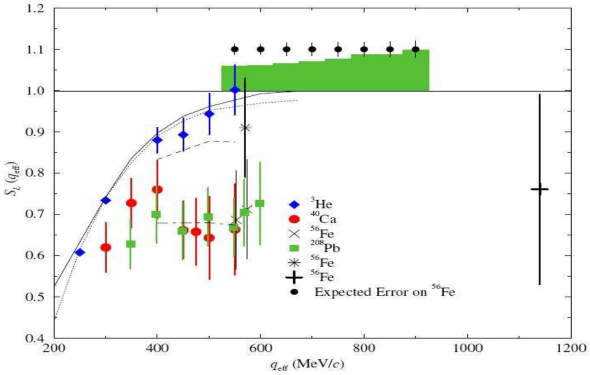


Figure 19: Comparison of expected statistical uncertainty on the Coulomb Sum from Jefferson Lab with the world data. Horizontal band represents estimated systematic uncertainties

Summary

- New features of Jefferson Lab CSR Experiment
  - High enough momentum transfer, previously unexplored
  - Comprehensive single experiment
    - Largest lever arm
    - Measurement at 4 angles
  - Independent energy measurement for background reduction (NaI)
- Analysis in smooth progress
- Will settle the long-standing issue of CSR quenching
- Shed light on modification of nucleon properties in nuclear medium

Coulomb Sum Rule (E05-110)

Kalyan Allada, Korand Aniol, John Arrington, Todd Averett, Herat Bandara, Werner Boeglin, **Alexandre Camsonne**, Mustafa Canan, **Jian-Ping Chen**, Wei Chen, Khem Chirapatpimol, **Seonho Choi**, Eugene Chudakov, Evaristo Cisbani, Francesco Cusanno, Raffaele De Leo, Chiranjib Dutta, Cesar Fernandez-Ramirez, Salvatore Frullani, Haiyan Gao, Franco Garibaldi, Ronald Gilman, Oleksandr Glamazdin, Brian Hahn, Ole Hansen, Douglas Higinbotham, Tim Holmstrom, Bitao Hu, Jin Huang, Florian Itard, Liyang Jiang, Xiaodong Jiang, Hoyoung Kand, Joe KatichMina Katramatou, Aidan Kelleher, Elena Khrosinkova, Gerfried Kumbartzki, John LeRose, Xiaomei Li, Richard Lindgren, Nilanga Liyanage, Joaquin Lopez Herraiz, Lagamba Luigi, Alexandre Lukhanin, Maria Martinez Perez, Dustin McNulty, **Zein-Eddine Meziani**, Robert Michaels, Miha Mihovilovic, Joseph Morgenstern, Blaine Norum, **Yoomin Oh**, Michael Olson, Makis Petratos, Milan Potokar, Xin Qian, **Yi Qiang**, **Arun Saha**, **Brad Sawatzky**, **Elaine Schulte**, Milan Shabestari, Simon Sirca, Patricia Solvignon, **Jeongseog Song**, **Nikolaos Sparveris**, **Ramesh Subedi**, **Vincent Sulkosky**, Jose Udias, Javier Vignote, Eric Voutier, Youcai Wang, John Watson, Yunxiu Ye, **Xinhu Yan**,**Huan Yao**, Zhihong Ye, Xiaohui Zhan, Yi Zhang, Xiaochao Zheng, Lingyan Zhu

and

Hall-A Collaboration