Precision Measurement of Longitudinal and Transverse Response Functions of Quasi-Elastic Electron Scattering in the Momentum Transfer Range
\[0.55 \text{ GeV}/c \leq |\mathbf{q}| \leq 0.9 \text{ GeV}/c\]

J. Morgenstern

*CEA Saclay DSM/DAPNIA/SPbN F91191, Gif-sur-Yvette Cedex, France*

J. Templon

*University of Georgia, Athens, GA 30602*


*Jefferson Lab, Newport News, VA 23606*

A. Adeluyi, A. T Katramatou, G. G. Petratos

*Kent State University, Kent, OH 44242*

W. Korsch

*University of Kentucky, Lexington, KY 40506*

W. Bertozzi, S. Gilad, S. Sirca, R. Suleiman

*Massachusetts Institute of Technology, Cambridge, MA 02139, USA*


*Rutgers University, Piscataway, NJ 08855*
Seonho Choi (Spokesperson), F. Butaru, A. Lukhanin, Z.-E. Meziani (Co-spokesperson), K. Slifer, P. Solvignon, H. Yao
Temple University, Philadelphia, PA 19122

N. Liyanage
University of Virginia, Charlottesville, VA 22901

T. Averett, T. Holmstrom, V. Sulkosky
College of William and Mary, Williamsburg, VA 23185

and

Hall A Collaboration

Contact: Seonho Choi (choi@jlab.org)

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Abstract

We propose to make a precision measurement of inclusive electron scattering cross sections in the quasi-elastic region for a wide range of momentum transfers for $^4$He, $^{12}$C, $^{56}$Fe and $^{208}$Pb. We will extract the longitudinal and transverse response functions in the momentum transfer range $0.55 \text{ GeV}/c \leq |q| \leq 0.9 \text{ GeV}/c$ with a precision of a few percent improving significantly on the precision of previous measurements in the overlap region. This should allow us to confirm/refute the presently controversial issue of the quenching of the longitudinal response function in medium weight nuclei and as importantly investigate the $|q|$ evolution of the Coulomb Sum Rule as we probe significantly shorter distances.
1 Introduction

The JLab proposal E01-016, entitled “Precision Measurement of Longitudinal and Transverse Response Functions of Quasi-Elastic Electron Scattering in the Momentum Transfer Range $0.55 \text{ GeV}/c \leq |q| \leq 1.0 \text{ GeV}/c$” was approved by PAC19 for 26 days with “A-” rating. Since the experiment has not been run or scheduled for the last three years, it is returning to the new PAC as a jeopardy proposal. We are providing an update composed of

- a brief summary of the original proposal, JLab E01-016
- study of the spectrometer background using a newly developed simulation program
- the one page PAC19 report on the original proposal
- a copy of the original proposal.

In the original proposal, we aimed to cover $|q|$ up to 1.0 GeV/c. But following the PAC19 suggestion to leave out the data at the highest $|q|$ values, in this update, we will limit the maximum $|q|$ value to 0.9 GeV/c.

2 Brief Summary of JLab Proposal E01-016

One of the important questions in nuclear physics is how nucleon properties are affected by the nuclear medium, since it might form a bridge from the strong interaction between nucleons to the underlying theory of Quantum ChromoDynamics (QCD). Since elastic scattering of electrons from a free nucleon has been well measured, quasi-elastic electron scattering off nuclei is a promising tool to investigate the properties of nucleons in nuclei. In particular, a Rosenbluth separation of the charge and magnetic responses of a nucleus can test a model-independent property known as the Coulomb Sum Rule (CSR).

This sum rule states that when integrating the charge response of a nucleus over the full range of energy loss $\omega$ at large enough three-momentum transfer $|q|$, one should count the number of protons ($Z$) in a nucleus. This simple picture can be spoiled by a modification of the free nucleon electromagnetic properties in the nuclear medium and the presence of nucleon-nucleon short-range correlations. However, it is expected that around the momentum transfer of 550 MeV/c, the CSR should not deviate by more than a few percent due to $N - N$ correlations,
and reach saturation at higher momentum transfer, independent of the \( N - N \) force chosen. Thus a deviation from the CSR in the range \(|q| \approx 550\,\text{MeV}/c\) might indicate a possible modification of the nucleon electric properties in the nuclear medium.

In the last twenty years, a large experimental program has been carried out at Bates, Saclay and SLAC aimed at the extraction of these two response functions for a variety of nuclei from \(^4\text{He}\) to \(^{208}\text{Pb}\). Overall consistency of the data set between different laboratories has been observed except for \(^{40}\text{Ca}\). And in the case of medium-weight and heavy nuclei, conclusions reached by different experiments ranged from a full saturation of the CSR to its violation by 30\%. Furthermore, a recent analysis \([1, 2]\) argued that the “so-called quenching is mostly due to the limited significance of the data” and that including data at high energy loss leads to the result that “no \(A\)-dependent quenching is observed.”

In a new analysis \([3]\), it was argued that if one uses the effective momentum approximation (EMA) for performing the Coulomb corrections (as supported by \(e^+e^-\) data to theory comparisons), the quenching still persists even when the world data were included. It was pointed out that consistency among different data sets is observed when the Coulomb corrections were included using the EMA. Figure 1 shows the results obtained for \(S_L\) of \(^{40}\text{Ca}\), \(^{48}\text{Ca}\), \(^{56}\text{Fe}\) and \(^{208}\text{Pb}\) in this new analysis\([3]\). The results are compared to theoretical calculations for nuclear matter \([4]\) (solid black curve) and \(^4\text{He}\) \([5]\) (dashed curve); the results in these two cases as expected are very similar and exhibit only a few percent quenching beyond \(q_{\text{eff}} \sim 500\,\text{MeV}/c\). The experimental results are to be compared with the long-dashed curve which corresponds to the same calculations as the solid curve but integrated within the experimental limits of excitation energy \(\omega\). A quenching of between 20\% and 30\% in medium weight nuclei persists.

Kinematics covers the momentum transfer range \(0.55\,\text{GeV}/c \leq |q| \leq 0.9\,\text{GeV}/c\) with the beam energies ranging from 400 MeV to 3.6 GeV. For a Rosenbluth separation of longitudinal response function \(R_L\), we chose four scattering angles: 15\°, 60\°, 90\° and 120\°. The minimum number of necessary angles for a Rosenbluth separation is two. However, having additional angles enables us to check for any angle dependent systematic errors and the linearity of the Rosenbluth plot. The uncertainty on the spectrometer angle can be reduced to 0.2 mrad with additional calibration data at each angle, as shown in \([7]\). With this choice of kinematics, at each \(|q|\), the excitation energy range covers the quasi-elastic peak and part of \(\Delta\)-resonance where \(R_L\) is expected to be small or close to zero\([8]\).
Figure 1: $S_L$ obtained in the EMA as a function of $q_{\text{eff}}$ using Saclay data combined with SLAC NE3 and Bates. The $^{56}\text{Fe}$ SLAC NE9 result [6] (right cross) and that of [1, 2] (star) are also shown.

We will use four different targets, $^4\text{He}$, $^{12}\text{C}$, $^{56}\text{Fe}$ and $^{208}\text{Pb}$ with beam current up to $50\mu\text{A}$. The two spectrometers of Hall-A will do independent measurements at a given beam energy and we shall optimize the angle settings to minimize the overhead of momentum and angle change. The estimated systematic uncertainty is 1.7% for the solid targets and 2.2% for the gas target. The final estimate of systematic uncertainties are plotted on Figure 2.

3 Study of Spectrometer Background

One of the issues raised by the PAC19 is the experimental backgrounds. In response to their suggestions, we started to address the background issues by simulations, analysis of existing data and new, dedicated tests to study the background.
This section presents the result of the simulations.

We have studied the background generated by the interaction of electrons with inside materials of the spectrometer using a Monte-Carlo simulation. The simulation is based on one of the Hall-A simulation programs, SNAKE. In the original version of SNAKE, the electrons hitting internal boundaries of the spectrometer were considered lost. But in our modified new version of the simulation program, those electrons undergo a GEANT simulation for one of two possibilities of

- a single, large angle scattering on the surface, a process analogous to bouncing off the surface, or
- generation of secondary particles from interactions inside the surface material.
Then these bounced-off-electrons or secondary particles were re-inserted into the SNAKE simulation to be traced to the focal plane.

Since no major loss of electrons was found on the pole tips of the dipole magnet in earlier SNAKE simulations, we have focused on the interaction of electrons in the Q3 magnet. Intuitively, due to the proximity of the Q3 magnet to the focal plane, electrons bouncing off the surface of the Q3 magnet would have a higher probability of survival.

The result of the simulation shows that the background generated in this process is about 2% of the clean events at a spectrometer momentum setting of 1.0 GeV/c. We find that the ratio decreases to 1.4% at a momentum setting of 0.1 GeV/c, the lowest momentum setting among our proposed kinematics.

Figures 3 and 4 show the energy distribution of clean events and background events for two different spectrometer momentum settings, 0.1 GeV/c and 1.0 GeV/c. As shown in Figure 3 and Figure 4, most of the background events are low energy secondary particles. A few background events with energy comparable to clean events are coming from a single, large angle scattering on the surface of the Q3 magnet.

As Figure 5 shows, these background events cover a much wider area in the focal plane than clean events with almost uniform distribution. With a conservative cut on the position on the focal plane, about 80% of the background events were eliminated (83% at 0.1 GeV/c momentum setting and 85% at 1.0 GeV/c momentum setting). This result is in agreement with an independent analysis [12], where it was suggested that most of such background can be eliminated by tracing back VDC tracks to the Q3 magnet.

The remaining background events after focal plane position cut can be eliminated by an independent energy measurement such as calorimeter used in the DVCS experiment. The DVCS calorimeter is composed of 132 blocks of PbF$_2$ of size $3 \times 3 \times 18.6$ cm$^3$. Arranged in $6 \times 22$ array, it will cover an area of $18 \times 66$ cm$^2$ which is roughly 18% of the focal plane ($36 \times 180$ cm$^2$). We will add additional blocks to cover $18 \times 132$ cm$^2$. By placing calorimeter around the center of the focal plane, we can maximize the acceptance. Furthermore, the events on the edges of the focal plane will be cut out to remove the background events, so the loss of the acceptance by not covering the whole focal plane is not significant. This type of calorimeter has an energy resolution of $3\%/\sqrt{E}$ and is enough to cut out 96% of the low energy background at 0.1 GeV/c momentum setting (98% at 1.0 GeV/c configuration).

From this study, it was found that up to 2% of background events can be generated by reflection on the Q3 magnet. However, we have shown that this type
of background can be reduced significantly by

- a cut on focal plane position and angle from the VDC tracking information
- and an independent energy measurement using calorimeters.

As mentioned earlier, the current version of the simulation program does not include any pole-tip reflections from other magnets (especially dipole magnet). We are in the process of implementing reflection from other surfaces along the path of the electron and the result will be available by the PAC presentation.

The results of the simulation will be further corroborated by the analysis of existing data and dedicated measurements in the future. Currently, we don’t see any significant benefit of putting an additional collimator (active or passive) inside the magnets. If future tests show significant amount of background from other sources, we will consider various options including collimator to reduce the background level.

4 Coulomb Distortions

The PAC19 has also suggested to seek close collaboration with theorists to resolve the issues involving the Coulomb distortions. We have contacted a number of theorists to address this issue and a number of theoretical papers[9, 10, 11] were published recently. Theoretical activities are on-going and are expected to intensify once the experiment is scheduled.

Recently, another QED correction, namely the two-photon exchange correction, has received special attention. This is in relation to the discrepancy observed between the determination of the ratio of the electric to magnetic proton form factors by Rosenbluth separations compared to the determination of the same ratio by means of polarization measurement of the knock-out proton in elastic scattering. It was proposed that the two-photon exchange correction, although small in absolute value has a variation as a function of the virtual photon polarization. This would have an impact on the Rosenbluth method but not on the polarization measurement method. Our best estimate in the range $|q| \approx 1 \text{ GeV/c}$ shows that this effect is small in our case[13, 14].
Figure 3: Energy distribution of clean events (blue dashed line) and background events (red solid line) at spectrometer momentum setting of 0.1 GeV/c.
Figure 4: Energy distribution of clean events (blue dashed line) and background events (red solid line) at spectrometer momentum setting of 1.0 GeV/c.
Figure 5: Distribution in focal plane of clean events (blue boxes) and background events (red boxes) at spectrometer momentum setting of 0.1 GeV/c. Actually, the background events have much wider distribution outside of the plot which are not shown here.
References


**Individual Proposal Report**

**Proposal:** E-01-016

**Scientific Rating:** A

**Title:** Precision Measurement of Longitudinal and Transverse Response Functions of Quasi-Elastic Electron Scattering in the Momentum Transfer Range $0.55 \text{ GeV/c} < q < 1.0 \text{ GeV/c}$.

**Spokespersons:** Seonho Choi, J.-P. Chen and Z.-E. Meziani

**Motivation:** The $q$-dependence of the integral over the energy transfer, $\omega$, of the longitudinal response function $R_L$ in quasi-elastic scattering from nuclei, known as the Coulomb sum rule, can yield information on nucleon-nucleon correlations and possible modifications of nucleon properties in a nucleus. Existing data for $R_L$ do not extend beyond $q=600$ MeV/c and sometimes scatter widely. The goal of the proposal is to obtain a consistent and accurate data set for the nuclei $^4\text{He}$, $\text{C}$, $\text{Fe}$ and $\text{Pb}$, in order to get a definitive answer on the evolution of the Coulomb sum rule as a function of $q$ up to a $q$-value of $1.0 \text{ GeV/c}$.

**Measurement and Feasibility:** Values for $R_L$ are obtained by performing a Rosenbluth separation of cross sections obtained at the same value of $q$ and $\omega$ for different values of the polarization parameter, $\epsilon$. In previous experiments, most of which were done at accelerators with maximum energies below 1 GeV, the range in $\epsilon$ was limited and the maximum value of $q$ was about 600 MeV/c. In the proposed experiment the range in $\epsilon$ will be as large as 0.85 and the data can be extended up to a value $q=1.0 \text{ GeV/c}$. Interpolation uncertainties and uncertainties in the radiative corrections will be minimized by taking data for a well covered range in $q$. Data will be obtained at four $\epsilon$ points in order to check systematic uncertainties in the Rosenbluth separation. Different ways to treat the Coulomb corrections for the heavier nuclei lead at this moment to rather different results.

**Issues:** The PAC recognizes the importance of performing a definitive study of the Coulomb sum rule. The quality of the CEBAF beams and experimental equipment should allow that. In the past some data sets have been plagued by experimental backgrounds. These should be studied carefully, using all possible means. Also one should perform checks with the $^1\text{H}(e,e'p)$ reaction for every choice of kinematics. Given the increase in the anticipated (systematic) uncertainties at increasing values of $q$, and the expected flattening of the sum rule at high $q$, the PAC recommends leaving out the data at the highest $q$ values. It is also suggested to seek close collaboration with theorists to resolve the issues involving the Coulomb distortions.

**Recommendation:** Approve for 26 days in Hall A.