# CEBAF Program Advisory Committee Nine
# Extension and Update Cover Sheet

This update must be received by close of business on Thursday, December 1, 1994 at:

CEBAF
User Liaison Office, Mail Stop 12 B
12000 Jefferson Avenue
Newport News, VA 23606

**Experiment:** E 94-017

**Check Applicable Boxes:**

- [x] Extension
- [ ] Update
- [ ] Hall B Update

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By: gp

PR 94-143

# THE NEUTRON MAGNETIC FORM FACTOR FROM PRECISION MEASUREMENTS OF THE RATIO OF QUASIELASTIC ELECTRON-NEUTRON TO ELECTRON-PROTON SCATTERING IN DEUTERIUM

6 GEV EXTENSION TO EXPERIMENT 94-017

*W. K. Brooks, CEBAF; M. F. Vineyard, U. Richmond*

## 1. Introduction

The approved measurement of the neutron magnetic form factor in Hall B may be significantly extended with the availability of a 6 GeV beam. This extension requests 15 days of new beam time at 6 GeV in addition to the previously approved time at 2.4 and 4.0 GeV. The experimental method is the same, as is the physics motivation for the measurement of this fundamental quantity. However, as will be described below, the relevance of the measurement to QCD calculations is expected to be much greater at the higher momentum transfers which are accessible with a 6 GeV beam.

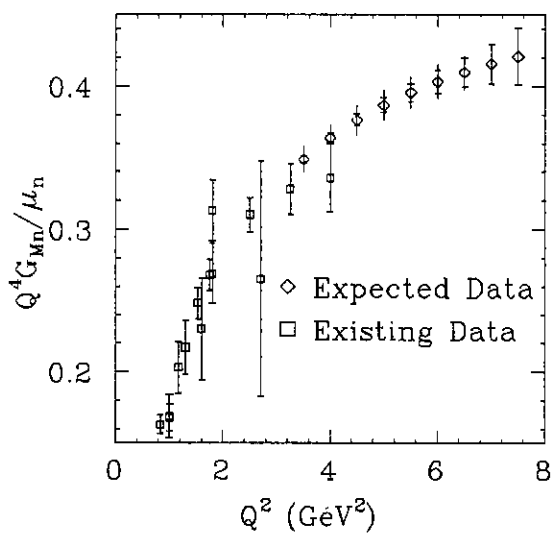


Figure 1: The current published values of $G_{M_n}$ at high $Q^2$ plotted together with the expected data from the CLAS with a 6 GeV beam.

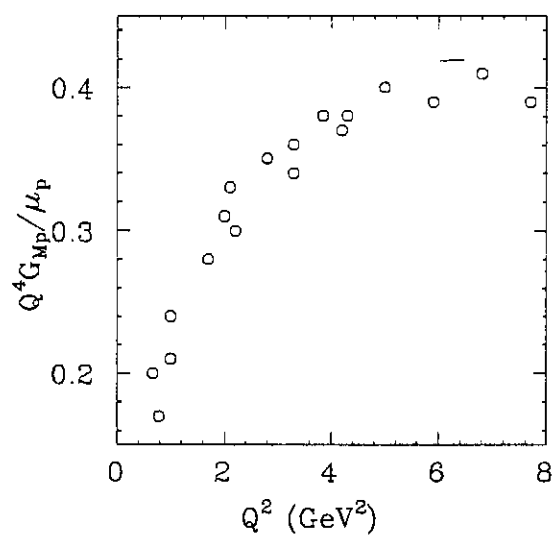


Figure 2: Proton data at high $Q^2$. The data is observed to form a plateau in the range $Q^2$ = 5-8 GeV$^2$.

## 2. Physics Interest

Elastic form factors for the nucleons at high momentum transfer have been measured with good precision only at SLAC[1]. The published data from the inclusive measurements of Ref. 1 extend to $Q^2$ = 8.83 GeV$^2$ for the proton, but only to $Q^2$ = 4.0 GeV$^2$ for the neutron.

The primary impact of the proposed measurement would be to nearly double the $Q^2$ range over which $G_{M_n}$ is known. This may be seen in Fig. 1, where the highest

point shown is at $Q^2 = 7.5$ GeV$^2$. Moreover, this exclusive measurement of the D(e,e'p) and D(e,e'n) reactions accrues significantly less model dependence and has systematic errors very different in origin from those of an inclusive measurement. This provides the opportunity for a valuable comparison of the results of the two methods in the region of overlap.

The range of momentum transfer under discussion has a special significance in relationship to QCD. It has been observed that the proton magnetic form factor falls off with a $Q^{-4}$ behavior beginning at about 5-10 GeV$^2$, as seen in a plateau forming in this region in Fig. 2. A functional dependence of this type is predicted by quark dimensional scaling, but this level of interaction was expected to occur only at much higher momentum transfer. On the other hand, estimates of nonperturbative, soft contributions indicate that the soft terms are comparable to the data in magnitude[2]. This has fueled a great deal of controversy over the validity of perturbative QCD at such relatively low momentum transfer. Fig. 1 demonstrates that the current measurements for the neutron do not contribute to an understanding of this issue. The SLAC measurements are consistent with the dipole expression for the form factor, but also would be consistent with an early onset of purely $Q^{-4}$ scaling, and do not extend into the plateau region. The measurements proposed here would provide the first reliable measurement for the neutron of the asymptotic value of this plateau, a quantity which is intimately tied to QCD.

## 3. Technical Feasibility

### *3.1. Measurement Method*

The method of measurement is the same as described in proposal 94-017, and is summarized here. Data is taken simultaneously on separated hydrogen and deuterium targets. The proton target provides calibration data for the neutron detection efficiency, and in addition allows precise calibrations of several other important quantities (such as the neutron angle measurement) simultaneous to taking the deuteron data. The data from electron-proton and electron-neutron scattering in deuterium are treated in an identical way insofar as possible. The ratio of e-n scattering to e-p scattering in deuterium is measured directly; then the magnetic form factor of the neutron is extracted using the proton form factors, which are known more accurately. In computing this ratio, and by calibrating the neutron detection efficiency simultaneously, most of the systematic errors in the measurement are significantly reduced or eliminated.

### *3.2. Acceptance*

The primary consequence of higher beam energy for this measurement is the increase in the acceptance at high $Q^2$. The acceptance for quasielastic scattering is shown in Fig. 3 and for the calibration reaction in Fig. 4 at an incident beam energy of 6 GeV. While for the lower $Q^2$ measurement the existence of the two large-angle calorimeter modules was important (ref. Fig. 5 from the proposal), as may be seen

in these figures their contribution to the acceptance is small at high $Q^2$. There is no overlap between the acceptance for the approved 2.4 GeV beam time and the proposed 6 GeV data, however, the intermediate region is fully covered by the acceptance with the approved 4 GeV beam.

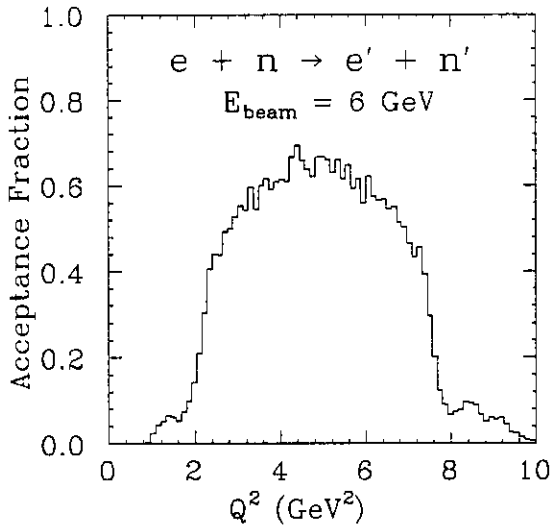


Figure 3: The CLAS acceptance for quasielastic scattering in deuterium.

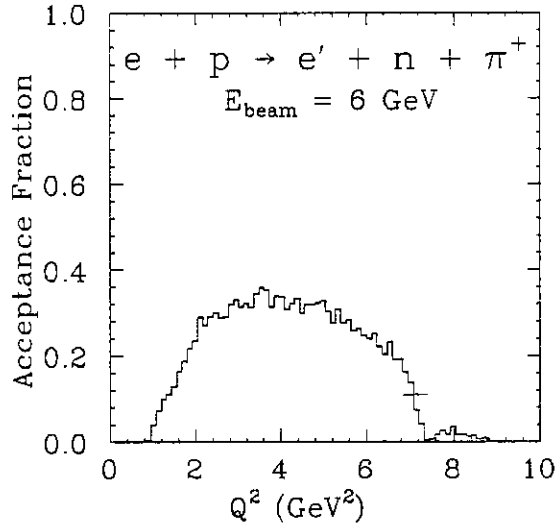


Figure 4: The CLAS acceptance for single charged pion production from hydrogen with the electron and the pion detected.

*3.3. Constraints on the Data*

In total, four cuts on the deuteron data are planned. First, a fiducial cut on the electron angles eliminates detector edge effects. Second, a cut on the angle between the virtual photon and the detected nucleon eliminates most of the data not associated with quasielastic scattering. Third, a cut on the missing mass spectrum calculated from the electron kinematics further removes events coming from resonant and non-resonant processes at higher mass. Finally, a cut on the *number* of detected particles will eliminate final states including one or more pions with fairly high efficiency, further suppressing unwanted reactions.

At lower values of $Q^2$ this procedure is extremely effective at isolating quasielastic events. At higher $Q^2$ some background remains, as can be seen in Fig. 22 of proposal 94-017 (which does not have the multiparticle cut mentioned last) and in Fig. 5. This produces one of the larger contributions to the final systematic error.

One comment on this method made by PAC 8 was that any momentum cuts may not treat the proton and neutron data identically. This comment is quite relevant to the lower-$Q^2$ data, since the lowest-momentum protons begin to approach the intrinsic limits of uniform reconstruction efficiency of the spectrometer; in addition, the quality of the neutron momentum measurement varies greatly over the momentum range of interest. Because the CLAS is a non-focusing spectrometer, there is not a definite maximum momentum for detecting charged particles. For the high-$Q^2$ measurements proposed here, no explicit momentum cut is needed since essentially all data will be well within the intrinsic momentum limits of the spectrometer. The momenta of the detected nucleons will be equal to that of elastically scattered nucleons, smeared by the longitudinal component of the Fermi momentum. Since the spread in the latter is only of order one hundred MeV, it is expected that the number of particles removed by the intrinsic reconstruction limits of the spectrometer will be vanishingly small.

### *3.4. Sources of Error*

Of the several sources of systematic error inherent in the experimental method, four can be significant at higher momentum transfer. These include the knowledge of the neutron detection efficiency; the ratio of the solid angle of the nucleons, which is limited by the measured neutron angle; the accuracy with which the proton form factors are known; and the extent to which inelastic reactions are suppressed. Other errors, discussed in the original proposal, are expected to be small. such as the theoretical correction for charge exchange reactions; studies of such effects are currently in progress[3].

#### 3.4.1. Neutron Detection Efficiency

At high neutron momentum the detection efficiency of the electromagnetic shower calorimeter saturates at a plateau value which will be well determined by the high rate reaction $ep \rightarrow en\pi^+$ reaction at lower $Q^2$. At high $Q^2$ the rate will be considerably lower and the statistical error in a few hundred MeV momentum bin is expected to be in the 5-10% range. The extrapolation to the quasielastic energy (ref. Fig 10 from proposal) is essentially linear and would be well-determined over several GeV in neutron momentum; a 4% error in this extrapolation has been assumed to be possible.

#### 3.4.2. Solid Angle Ratio of Nucleons

The solid angle ratio error is determined by the neutron angular measurement error. At high $Q^2$ the cut on the data must be placed in a region where very little of the quasielastic data is removed (ref. Fig. 17 of proposal), because the distribution in $\theta_{\gamma n}$ is extremely narrow around zero degrees ($\sigma \approx 0.78^\circ$ for $Q^2$=6 GeV$^2$). With a relatively loose cut of 2.0° in this angle it is expected that the systematic error due to this cut is at the percent level. The consequence of this, however, is that the discrimination against inelastic processes is less effective, and in practice some optimization of these two effects will be necessary.

3.4.3. Inelastic Background Suppression

The missing mass spectrum at high $Q^2$ has been simulated in order to determine the efficacy of the cuts mentioned above. The simulation was constrained by measured data[4] at high $Q^2$. Fig. 5 shows the result of this study for the neutron spectrum. It may be seen that only about 10% of the inelastic events remain under the quasielastic peak after all cuts have been made; for the proton data this number is expected to be 4%. This background can be modeled and tested in a number of ways against the measured CLAS data. It is anticipated that the error in the ratio due to the uncertainty in subtracting this background can be limited to 3.5% at $Q^2$=6 GeV$^2$, increasing to 5% at $Q^2$=7.5 GeV$^2$.

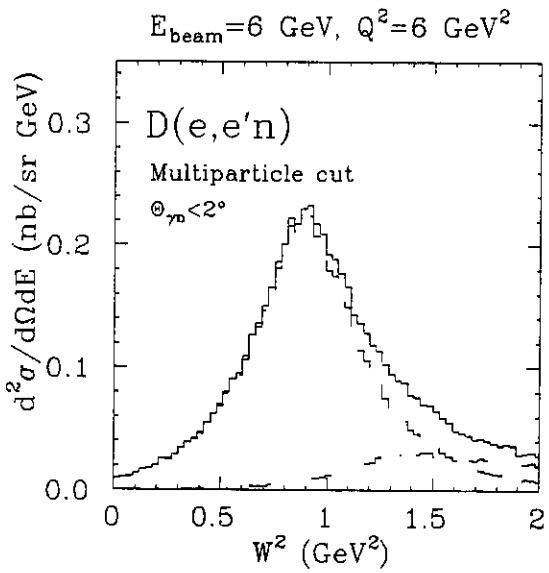


Figure 5: The missing mass spectrum as calculated from electron kinematics for $Q^2$=6 GeV$^2$ and a beam energy of 6 GeV. Events have been removed which had a detectable third particle in the final state ("multiparticle cut") and which had an angle between the neutron and the virtual photon of greater than 2 degrees.

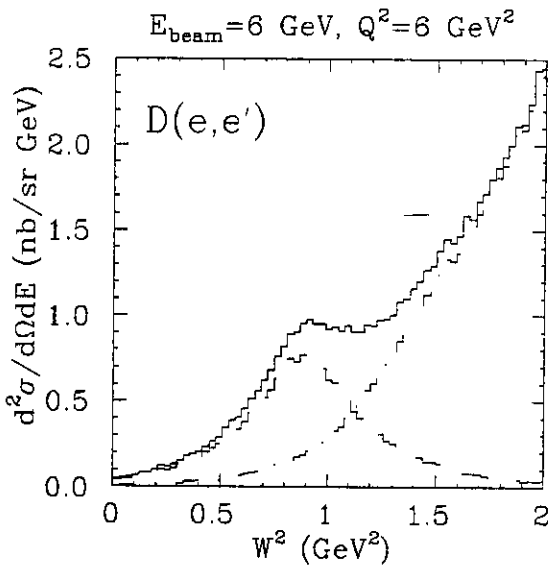


Figure 6: The raw missing mass spectrum for the indicated beam energy and momentum transfer from the Monte Carlo simulation, showing the contribution from quasielastic and inelastic events. This simulation reproduces a measured spectrum at the same momentum transfer(see text).

3.4.4. Proton Form Factors

At high momentum transfer the uncertainty in the proton magnetic form factor

enters in a nearly 1:1 ratio with the resulting error in the extracted neutron magnetic form factor. The sensitivity of $G_{M_n}$ to uncertainty in the proton electric form factor is only about 3% of that of the magnetic form factor, and is therefore relatively small even though the point-to-point errors on $G_{E_p}$ range[1] from 15 - 25 % out to $Q^2 = 7$ $GeV^2$.

The proton magnetic form factor has been measured out to $Q^2$=8.83 $GeV^2$ in experiment NE11[1]. A cumulative error of 1% in the value of $G_{M_p}$ has been assumed in the errors here, as reported in Ref. 1. Further measurements of these quantities are likely to be performed in the near future [5].

It is to be emphasized that the fundamental quantity being measured is the *ratio* of quasielastic e-n to e-p scattering. The error due to the present accuracy of the proton form factors discussed here does not contribute to the errors on the ratio measurement. The ratio is the most accurately measured quantity, and is of interest in its own right. For example, it is insensitive to quark wave functions in most quark models, and may therefore be used to determine parameters within those models independent of uncertainties in the wave functions.

## 4. Comparison to Previous Measurements

The published SLAC measurements of $G_{M_n}$ at $Q^2$ up to 4.0 $GeV^2$ were performed essentially by subtracting the normalized proton and target endcap contributions from the deuterium inclusive spectrum to obtain the neutron spectrum. The quasielastic and background contributions are then extracted from this spectrum by fitting to predictions of a variety of relativistic models. This procedure becomes increasingly less accurate at higher $Q^2$ because the quasielastic peak becomes increasingly indistinguishable from the background as may be seen in Fig. 6. After subtraction of the smeared proton data from such a spectrum, the resulting neutron spectrum is essentially featureless and the fitting procedure becomes significantly less constrained than at lower $Q^2$. In addition, the sensitivity to model uncertainties can only be estimated by trying different models. The method proposed in this extension clearly has much less model dependence and in general very different systematic errors from the previous measurements. Consistency between the two methods in the region of overlap would be compelling evidence that the neutron magnetic form factor is well-determined.

## 5. References


1. SLAC Publication SLAC-PUB-6462 (March 1994), SLAC-PUB-6235 (May 1993).
2. A. Radyushkin, "Nonperturbative QCD and Elastic Processes at CEBAF Energies," CEBAF Theory Preprint CEBAF-TH-94-15, 1994.
3. B. Keister, F. Gross, private communication.
4. S. Rock et. al, Phys Rev. D **46**, 24 (1992).
5. G. Petratos, "Elastic Form Factors at Higher CEBAF Energies", *Workshop on CEBAF at Higher Energies*, 263 (1994).

# HAZARD IDENTIFICATION CHECKLIST

CEBAF Proposal No.: _____ Date: _____
(For CEBAF User Liaison Office use only.)

Check all items for which there is an anticipated need.

| | | |
|---|---|---|
| **Cryogenics**<br>_____ beamline magnets<br>_____ analysis magnets<br>_____ target<br>type: _____<br>flow rate: _____<br>capacity: _____ | **Electrical Equipment**<br>_____ cryo/electrical devices<br>_____ capacitor banks<br>_____ high voltage<br>_____ exposed equipment | **Radioactive/Hazardous Materials**<br>List any radioactive or hazadorous/ toxic materials planned for use:<br>_____<br>_____<br>_____<br>_____ |
| **Pressure Vessels**<br>5mm inside diameter<br>2o-50atm operating pressure<br>kapton window material<br>10 mg/cm$^2$ window thickness | **Flammable Gas or Liquids**<br>type: Hydrogen,Deuterium<br>flow rate: 0<br>capacity: 100 cc @ 1 atm<br><br>**Drift Chambers**<br>type: _____<br>flow rate: _____<br>capacity: _____ | **Other Target Materials**<br>___ Beryllium (Be)<br>___ Lithium (Li)<br>___ Mercury (Hg)<br>___ Lead (Pb)<br>___ Tungsten (W)<br>___ Uranium (U)<br>___ Other (list below)<br>_____<br>_____ |
| **Vacuum Vessels**<br>10 in. inside diameter<br>Vacuum operating pressure<br>Kapton window material<br>15 mg/cm$^2$ window thickness | **Radioactive Sources**<br>_____ permanent installation<br>_____ temporary use<br>type: _____<br>strength: _____ | **Large Mech. Structure/System**<br>_____ lifting devices<br>_____ motion controllers<br>_____ scaffolding or<br>_____ elevated platforms |
| **Lasers**<br>type: _____<br>wattage: _____<br>class: _____<br><br>Installation:<br>_____ permanent<br>_____ temporary<br><br>Use:<br>_____ calibration<br>_____ alignment | **Hazardous Materials**<br>____ cyanide plating materials<br>____ scintillation oil (from)<br>____ PCBs<br>____ methane<br>____ TMAE<br>____ TEA<br>____ photographic developers<br>____ other (list below)<br>_____<br>_____ | **General:**<br><br>Experiment Class:<br><br>_____ Base Equipment<br>_____ Temp. Mod. to Base Equip.<br>_____ Permanent Mod. to Base Equipment<br>_____ Major New Apparatus<br><br>Other: _____<br>_____ |

# BEAM REQUIREMENTS LIST

CEBAF Proposal No.: _____ Date: _____
(For CEBAF User Liaison Office use only.)

List all combinations of anticipated targets and beam conditions required to execute the experiment. (This list will form the primary basis for the Radiation Safety Assesment Document (RSAD) calculations that must be performed for each experiment.)

| Condition # | Beam Energy (MeV) | Beam Current (μA) | Polarization and Other Special Requirements (e.g., time structure) | Target Material (use multiple rows for complex targets — e.g., w/windows) | Target Material Thickness (mg/cm²) |
|---|---|---|---|---|---|
| 1 | 6000 | 1-30 nA | -- | Hydrogen gas | 200-500 |
| 1 | 6000 | 1-30 nA | -- | Deuterium gas | 200-500 |
| 1 | 6000 | 1-30 nA | -- | Kapton | 10 |
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The beam energies, $E_{Beam}$, available are: $E_{Beam} = N \times E_{Linac}$ where N = 1, 2, 3, 4, or 5. For 1995, $E_{Linac}$ = 800 MeV, i.e., available $E_{Beam}$ are 800, 1600, 2400, 3200, and 4000 MeV. Starting in 1996, in an evolutionary way (and not necessarily in the order given) the following additional values of $E_{Linac}$ will become available: $E_{Linac}$ = 400, 500, 600, 700, 900, 1000, 1100, and 1200 MeV. The sequence and timing of the available resultant energies, $E_{Beam}$, will be determined by physics priorities and technical capabilities.

# LAB RESOURCES REQUIREMENTS LIST

CEBAF Proposal No.: _____ Date: _____
(For CEBAF User Liaison Office use only.)

List below significant resources — both equipment and human — that you are requesting *from CEBAF* in support of mounting and executing the proposed experiment. Do not include items that will be routinely supplied to all running experiments, such as the base equipment for the hall and technical support for routine operation, installation, and maintenance.

***Major Installations*** *(either your equip. or new equip. requested from CEBAF)*

None

New Support Structures: _____

***Data Acquisition/Reduction***

Computing Resources: _____

New Software: _____

***Major Equipment*** All standard CLAS equipme

Magnets _____

Power Supplies _____

Targets _____

Detectors _____

Electronics _____

Computer Hardware _____

Other _____

***Other***

special target, being built in collaboration with CEBAF and the University of Richmond.