Measurement of the Neutron Magnetic Form Factor at High Q^2 Using the Ratio Method on Deuterium

A Letter of Intent to the Jefferson Lab Program Advisory Committee

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Abstract

In this Letter-of-Intent we propose to measure the magnetic form factor of the neutron using the 11 GeV electron beam in the upgraded CEBAF and CLAS12 detector. The measurement will cover the range $\mathrm{Q}^2 = 2 - 14$ GeV^2. The neutron's magnetic form factor is one of the fundamental quantities of nuclear physics and its value is an important constraint for the newly-developed generalized parton distributions that hold the promise of dramatically expanding our understanding of the nucleon. The form factors are also important challenges for lattice QCD to meet. This measurement is part of a broad assault on the four elastic nucleon form factors at Jefferson Lab. We will use the ratio of elastic $e - n$ to elastic $e - p$ scattering on deuterium. The ratio method is less vulnerable to uncertainties than previous methods and we will have consistency checks between different detector components and an overlap with our previous CLAS measurements. Precise measurements of G_M^n have already been made by our group and others at lower Q^2. This experiment can be done with the base equipment for CLAS12. The group behind this project have made significant commitments to the Jefferson Laboratory 12-GeV Upgrade.

1 Introduction

The internal structure of the nucleon represents a fundamental challenge for nuclear physics. The elastic electromagnetic form factors are the most basic observables that describe this internal structure and their evolution with Q^2 characterizes the distributions of charge and magnetization within the proton and neutron. These observables also provide stringent tests of non-perturbative QCD and are connected to generalized parton distributions (GPDs) via the appropriate sum rules. In this letter-of-intent we propose to extend our successful measurements of the neutron magnetic form factor G_M^n to the higher Q^2 that will be available with the 12-GeV upgrade of CEBAF. We will use the ratio of the quasielastic electron-neutron to electron-proton scattering on deuterium to extract G_M^n. In Section 2 we present more details on the scientific motivation for measuring G_M^n and review the world's data for this quantity. In Section 3 we outline the method for making the measurement, point out potential differences with our previous work at lower Q^2, and make an estimate of the anticipated quality of the data. We list the commitments of the co-authors of this letter of intent in Section 4 and draw conclusions in Section 5. In Table 1 we summarize the commitment of the Collaboration members supporting this letter-of-intent to the Jefferson Lab 12-GeV Upgrade.

Name	Institution	Project
G.P. Gilfoyle	University of Richmond	Software for event simulation and online/offline reconstruction.
M.F. Vineyard	Union College	Software for analysis, simulation, and controls.
W.K. Brooks, S. Stepanyan	JLab	Group leader for the electromagnetic calorimeters for CLAS12.
L.B. Weinstein, S.E. Kuhn, J.D. Lachniet	Old Dominion University	Construction of Region 1 drift chambers.
K. Hafidi	Argonne National Lab	Design, prototyping, construction, and testing of the new high-threshold Cerenkov counter.
M. Holtrop	University of New Hampshire	Software for simulation and design, prototyping, construction, and testing of the silicon vertex detector.
M. Garcon	DAPNIA/SPhN-Saclay	Design, prototyping, construction, and testing of the central tracker.

Table 1: Summary of commitments (subject to funding approval) of CLAS collaborators on this letter-of-intent to the Jefferson Lab, 12-GeV Upgrade.

2 Scientific Motivation

The nucleon elastic form factors are defined through the matrix elements of the electromagnetic current $J_\mu = \overline{\psi}\gamma_\mu\psi$ as

$$\langle N(P')|J_\mu(0)|N(P)\rangle = \overline{u}(P')\left(\gamma_\mu F_1(Q^2) + \frac{i\sigma_{\mu\nu}q^\nu\kappa}{2M}F_2(Q^2)\right)u(P) \tag{1}$$

where P and P' are the initial and final nucleon momenta, $q = P - P'$, $Q^2 = -q^2$, M is the nucleon mass, κ is the anomalous magnetic moment, and F_1 and F_2 are scalar functions of Q^2 that characterize the internal structure of the nucleon. These are the Dirac and Pauli form factors respectively. The differential cross section for elastic electron-nucleon scattering can then be calculated in the laboratory frame as [1]

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott}\left[\left(F_1^2 + \frac{\kappa^2Q^2}{4M^2}F_2^2\right) + \frac{Q^2}{2M^2}\left(F_1 + \kappa F_2\right)^2\tan^2\left(\frac{\theta}{2}\right)\right] \tag{2}$$

where θ is the electron scattering angle and σ_{Mott} is

$$\sigma_{Mott} = \frac{\alpha^2E'\cos^2(\frac{\theta}{2})}{4E^3\sin^4(\frac{\theta}{2})} \quad . \tag{3}$$

It is preferable to define different electromagnetic form factors that are related to the charge and magnetization density of the nucleon in the appropriate kinematics. These so-called Sachs form factors are defined as

$$G_E = F_1 - \frac{\kappa Q^2}{4M^2}F_2 \qquad G_M = F_1 + \kappa F_2 \tag{4}$$

so Equation 2 can be written as

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott}\left(G_E^2 + \frac{\tau}{\epsilon}G_M^2\right)\left(\frac{1}{1+\tau}\right) \tag{5}$$

where

$$\tau = \frac{Q^2}{4M^2} \qquad \text{and} \qquad \epsilon = \frac{1}{1 + 2(1+\tau)\tan^2(\frac{\theta}{2})} \quad . \tag{6}$$

The current status of our understanding of G_M^n is shown in Figure 1 where G_M^n is scaled by the dipole form factor $G_D(Q^2) = 1/(1 + Q^2/\Delta)^2$ and $\Delta = 0.71$ GeV^2. The parameter Δ is interpreted as the square of the effective meson mass. We focus here on $\mathrm{Q}^2 > 1.0$ GeV^2 where the neutron magnetic form factor agrees with the dipole form within 5-10%. This agreement can be qualitatively understood as a virtual photon interacting with the nucleon after the photon has fluctuated into a vector meson. There are, however, deviations from the dipole form that invite investigation. Some of the data have large error bars due largely to uncertainties in subtracting the contribution of the proton in these measurements using inclusive quasielastic scattering on deuterium [2]. The more precise measurements including the recent work by Lachniet, *et al.* and the E5 group (the red circles in Figure 1) [3, 4] and others [5, 6, 7, 8] use a ratio method that we propose to extend to higher Q^2 and which is described in Section 3 of this Letter of Intent.

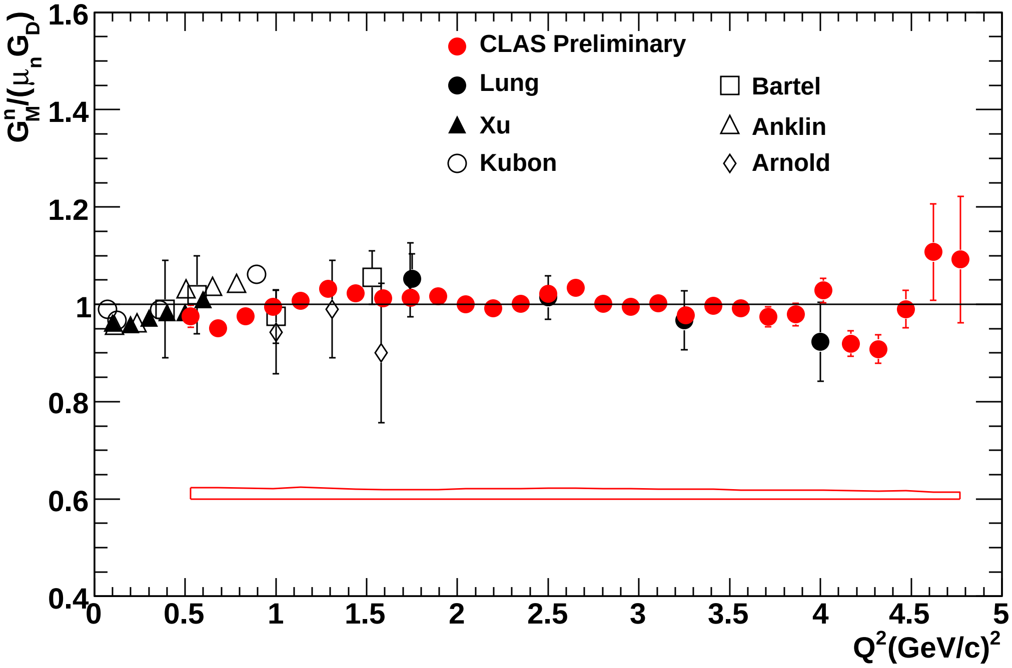

Figure 1: Selected results for the neutron magnetic form factor G_M^n in units of $\mu_n G_D$ as a function of Q^2. See Reference [3] and references therein.

Measuring G_M^n at higher Q^2 will shed light on important questions in hadronic physics. At asymptotically large Q^2, the elastic nucleon form factors can be rigorously calculated in perturbative QCD (pQCD) where the small wavelength of the virtual photon ensures that the quark substructure of the nucleon can be resolved [9]. It is assumed the nucleons can be treated as bound systems of point-like quarks governed by the properties of the strong interaction. Dimensional scaling predicts that only valence quarks will be important and those quarks interact via a hard-scattering process. These calculations reproduce the Q^2 dependence of the proton magnetic form factor for Q$^2 > 10$ GeV^2. The transition from the low-Q^2 dipole form to the pQCD regime is still unclear. Evidence from recent Jefferson Lab experiments and others suggest that non-perturbative effects still dominate the form factors for Q$^2 < 10$ GeV^2. For example, the Q^2 dependence of the ratio $\mu_p G_E^p / G_M^p$ is expected to be constant in pQCD, but surprising Jefferson Lab measurements of this ratio revealed significant Q^2 dependence up to Q$^2 = 5.0$ GeV^2 [10, 11, 12]. Figure 2 shows this quantity $\mu_p G_E^p / G_M^p$ for several experiments. The points labeled Punjabi and Gayou are the Jefferson Lab measurements and are not constant with Q^2. Higher Q^2 investigations show evidence of scaling behavior, consistent with predictions of quark dimensional scaling and perturbative QCD [10].

The elastic nucleon form factors are a fundamental challenge for lattice QCD calculations. Full calculations are still beyond our reach so existing ones use different approxima-

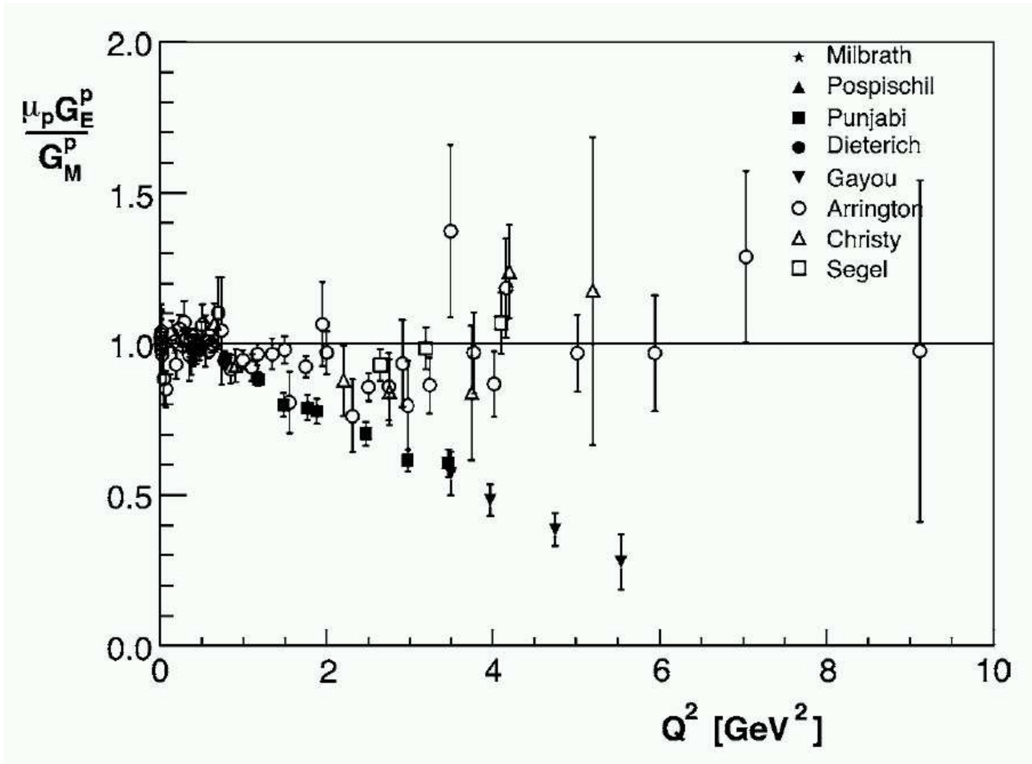

Figure 2: The ratio $\mu_p G_E^p/G_M^p$ from polarization transfer measurements, recent Rosenbluth data, and a reanalysis by Arrington of older SLAC data. See reference [2] and references therein.

tions. These include techniques like the 'quenched approximation' where dynamical effects of quarks on the vacuum are ignored and the use of quark masses much higher than the physical ones (by a factor of 5-20) [14]. Extrapolations are then made to the physical quark mass region. Some success has been achieved in reproducing the Q^2 dependence of G_M^n for $Q^2 < 1.0$ GeV^2, but the higher Q^2 region remains new territory [14].

Recent theoretical work has led to the development of generalized parton distributions (GPDs) where form factors and structure functions can be simultaneously embedded. These distributions hold the promise of performing nuclear tomography and developing a three-dimensional image (two spatial and one momentum coordinate) of the nucleon. They have 'tremendous potential to provide a quantitative description of the quark motion inside hadrons' [15]. GPDs are typically studied via deeply virtual Compton scattering or real Compton scattering at high momentum transfer. However, the elastic form factors (G_M^n, G_E^n, G_M^p, and G_E^p) are key constraints on GPDs. The lowest moments of the GPDs multiplied by the appropriate quark charges and summed over all quark flavors recover the form factors [16]. These sum rules hold for all values of Q^2 from zero to infinity. Measuring the nucleon form factors complements other proposed 12-GeV programs to measure deeply virtual exclusive (DVE) reactions at low momentum transfer $|t|$. The form factors connect to the GPDs at high $|t|$ (= Q^2 for elastic scattering) and so high-Q^2 data are needed to obtain the structure of the nucleon at small transverse distances [17]. A particularly interesting possibility is to extract the u- and d-quark contributions to G_M^n, but this analysis requires broad Q^2 coverage of all four elastic nucleon form factors. There are some indications that the u- and d-quark contributions behave differently at large Q^2 which may also shed light on the existence of dimensional scaling at low Q^2 [16].

We note that the effort to measure G_M^n in the range $Q^2 = 2 - 14$ GeV^2 is part of a larger Jefferson Lab program to increase our understanding of all four nucleon form factors and express them in terms of common GPDs. All four elastic form factors are needed to untangle the different quark contributions. However, at high Q^2 there is precise data only for the proton. The limited coverage can be seen by comparing Figure 1 with Figure 3 which shows the normalized proton magnetic form factor G_M^p. The G_M^p data extend out to $Q^2 = 30$ GeV^2 while the G_M^n data in Figure 1 are just now being extended to $Q^2 = 4.5$ GeV^2 (red circles in Figure 1 from Lachniet, *et al.* [3]). With the 12-GeV upgrade of CEBAF, G_E^p/G_M^p and G_M^n can be measured up to $Q^2 \approx 14$ GeV^2 and for G_E^n up to $Q^2 = 5$ GeV^2 [17]. This nucleon form factor program will be part of a 'great leap forward in our knowledge of hadron structure' [17].

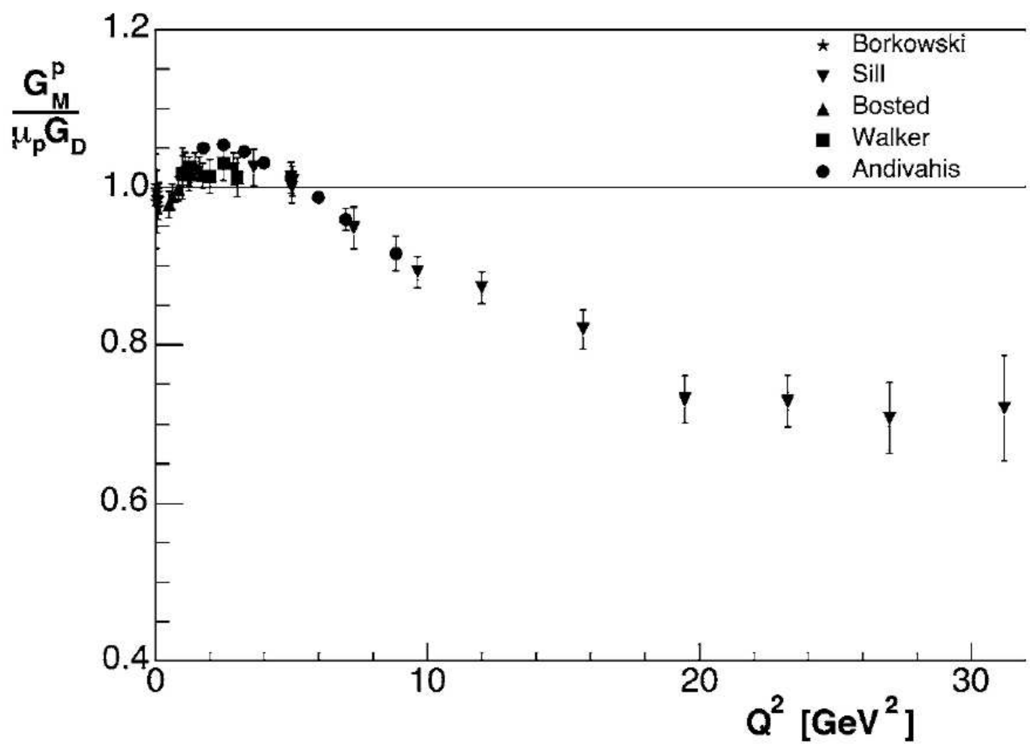

Figure 3: World data for proton magnetic form factor G_M^p, in units of $\mu_p G_D$, as a function of Q^2. See [2] and references therein. Compare with Figure 1.

3 The Experiment

We propose to use the ratio of quasielastic $e-n$ to $e-p$ scattering from a deuterium target to measure G_M^n in the range $\mathrm{Q}^2 = 2-14$ GeV^2. This technique has been shown to significantly reduce the uncertainties associated with other methods and has already been used by us [3, 4] and others to measure G_M^n [2, 5, 6, 7, 8]. See Figure 1 for the results of the E5 measurement and other data on G_M^n. The method is based on the ratio

$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))} \tag{7}$$

for quasielastic kinematics. It is nearly equal to the ratio of the free nucleon $e-n$ to $e-p$ cross sections. In terms of the free nucleon form factors

$$R = a(Q^2)\frac{\frac{{G_E^n}^2+\tau {G_M^n}^2}{1+\tau} + 2\tau {G_M^n}^2 \tan^2(\frac{\theta}{2})}{\frac{{G_E^p}^2+\tau {G_M^p}^2}{1+\tau} + 2\tau {G_M^p}^2 \tan^2(\frac{\theta}{2})} \quad . \tag{8}$$

Deviations from this 'free ratio' assumption are parametrized by the factor $a(Q^2)$ which can be calculated from deuteron models and is close to unity at large Q^2. Once the model corrections have been applied to R, the results of other measurements of the proton form factors (see Figures 2 and 3) and the neutron electric form factor (see Figure 4) can be used to extract G_M^n. The neutron electric form factor shown in Figure 4 is small and its contribution is kinematically suppressed at large Q^2 so it has little effect on extracting G_M^n in this way.

The ratio method has several advantages. It is insensitive to the luminosity, electron acceptance, electron reconstruction efficiency, trigger efficiency, the deuteron wave function, and radiative corrections. The price one pays is the technique requires a precise measurement of the neutron detection efficiency and careful matching of the neutron and proton acceptances. The experiment performed in CLAS in the E5 run period used a unique dual-cell target, containing collinear deuterium and hydrogen cells to make *in-situ* calibration measurements simultaneously with data collection on deuterium. We plan to follow a similar path at higher Q^2. Below we discuss more details on the challenges posed by this measurement.

A precise knowledge of the neutron detection efficiency is essential to keep the uncertainties of the ratio method under control. The reaction $ep \to e'\pi^+ n$ on the hydrogen part of the dual-cell target in CLAS12 will provide a source of tagged neutrons that can be used to measure the neutron detection efficiency simultaneously with the data collection on deuterium. First, the electron and positive pion will be identified. Neutron candidates will be identified using a missing mass cut ($ep \to e'\pi^+ X$) and the direction of the neutron will be inferred from the missing momentum of the $ep \to e'\pi^+(n)$ reaction. A ray will be drawn from the $e' - \pi^+$ vertex in the direction of the missing momentum to the face of the electromagnetic calorimeter (EC). If the intersection of this ray and the EC is outside of the fiducial region of the EC, the event will be dropped. If the event is inside the EC fiducial region it is classified as a reconstructed event. If the same event is found to have an EC neutron hit in the region of the intersection, then the event is counted as a found event. The neutron detection efficiency is the ratio of found to reconstructed events. These events will also be subject to other cuts to reduce background, improve particle identification, *etc.*

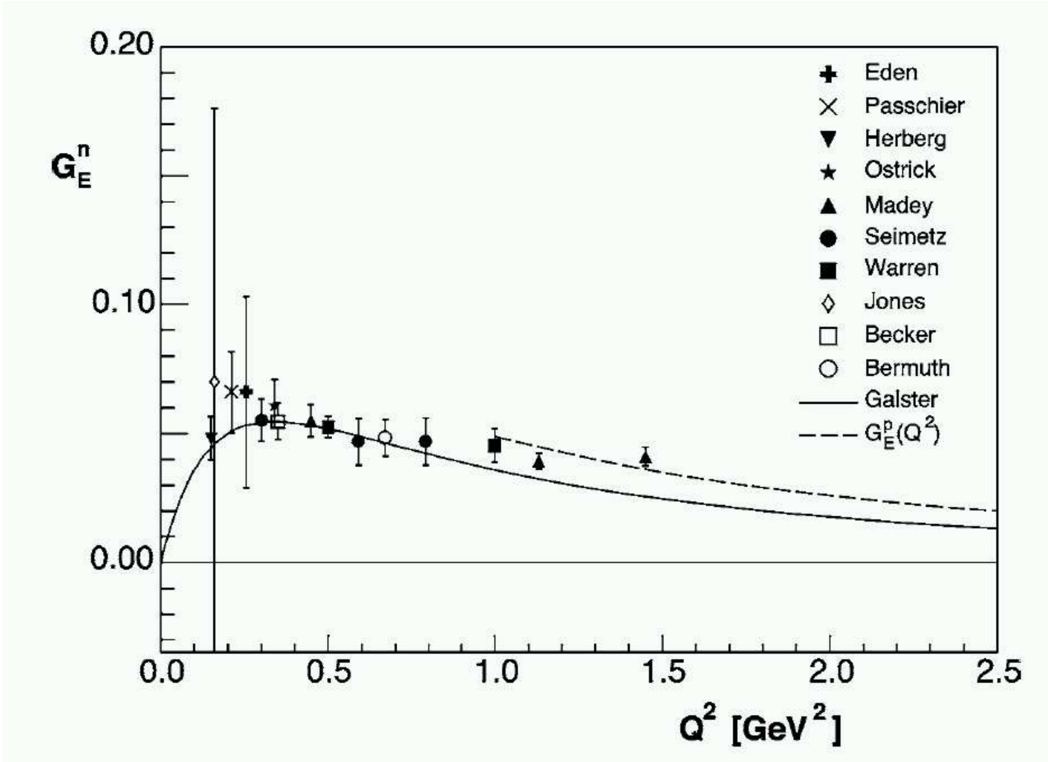

Figure 4: The neutron electric form factor G_E^n as a function of Q^2. See [2] and references therein. Results from ^{3}He are indicated by open symbols. The full curve shows the Galster (72) parameterization; the dashed curve represents the Q^2-behavior of G_E^p.

A second overlapping measurement of the neutron detection efficiency can be made using the time-of-flight (TOF) system in CLAS12. The same calibration reaction ($ep \rightarrow e'\pi^+n$) will be used and a similar procedure followed to reconstruct a neutron event except the event is required to produce a signal in one of the TOF paddles. As before, the efficiency is the ratio of found events to reconstructed ones. Other cuts will be used to reduce background events which likely will be higher in the TOF system than in the EC. For example, we found in the E5 analysis that requiring a minimum amount of energy deposited in the TOF reduced the photon background. This second measurement of the neutron efficiency will provide a useful cross check on the analysis.

The proton efficiency measurement will be done using the hydrogen target and elastic *ep* scattering as a source of tagged protons. The kinematics of the scattered electron will be used to calculate the mass of the recoiling system W and a cut applied to select a proton. For these *ep* events, a track will be calculated going from the electron vertex, through the CLAS12 magnetic field, to a TOF paddle. If the track misses the fiducial region of CLAS12, it will be dropped. If the event is inside the fiducial region of CLAS12 it will be classified as a reconstructed event. If the same event is found to have a hit in the predicted TOF paddle, then it will be classified as a found event. The proton detection efficiency is the ratio of found to reconstructed events. These events will be subject to other cuts to reduce background and improve particle identification.

To precisely determine R it is also essential to select a 'clean' sample of quasielastic events. Events from the $D(e,e'p)n$ and $D(e,e'n)p$ reactions are first filtered by requiring cuts on W and θ_{pq} to be satisfied. This angle, θ_{pq}, is the angle between the 3-momentum of the virtual photon $\vec{q}$ and the final nucleon 3-momentum (neutron or proton). Calculations have shown that most of the quasielastic cross section is concentrated in a narrow cone centered on the $\vec{q}$ vector. The effect of the θ_{pq} cut without the W cut on the $4-$ GeV, E5 data is shown in Figure 5. The θ_{pq} cut effectively eliminates most of the inelastic cross section leaving a small tail that can be removed with a W cut. For quasielastic scattering we

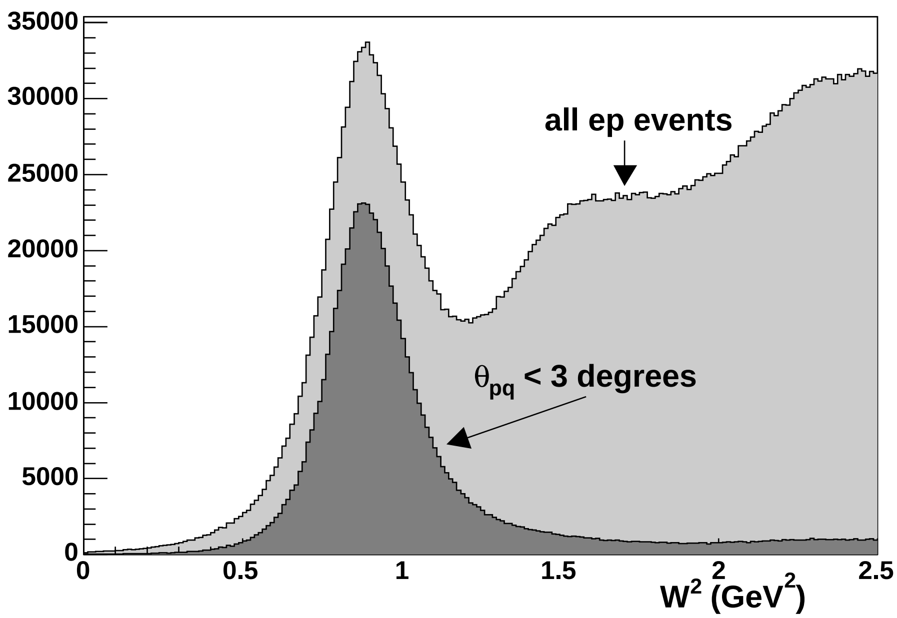

Figure 5: Effect of the cut on θ_{pq}, the angle between the direction of the virtual photon and the direction of the nucleon for the $4-$ GeV, E5 data [3].

expect this angle to be even smaller than in the $4-$ GeV case and to shrink as Q^2 increases so the selectivity of the θ_{pq} cut will improve.

For the ratio method to be successful, careful matching of the geometric acceptance for $e-p$ and $e-n$ events from deuterium must be done. To make sure the proton and neutron acceptances are equal a common fiducial region will be required for both nucleons. This can be done event-by-event in the following manner. The expected 3-momentum of the neutron or proton is determined from the electron kinematics assuming elastic scattering from a stationary nucleon. The effect of the internal motion of the nucleons in deuterium is discussed below. Assuming the event has a neutron, a ray is drawn from the electron vertex out to the TOF or EC systems and required to be in the respective fiducial region of the TOF or EC. Next, the event is assumed to have a proton and the track 'swum' from the electron vertex, through the magnetic field of CLAS12, to the TOF system; again requiring that it fall in the fiducial region of CLAS12. If either one of these conditions (neutron or proton predicted to be in the CLAS12 fiducial region based on the electron kinematics) is not met, then the event will be dropped. If both conditions are met, then the event is searched for a neutron or proton event in the predicted location. This analysis will ensure the neutron and proton have the same geometric acceptance.

There are several other corrections to R which must be considered in this experiment. The Fermi motion of the nucleons bound inside the deuteron can push events to different scattering angles so that they do not fall in the predicted detector component and could be lost. For the E5 experiment we have simulated this effect and found the correction factor to the $e - n/e - p$ ratio to be in the range 1-2% roughly independent of beam energy. The uncertainty on this correction was found to be small by using drastically different physics models in the event generator for the simulation and getting similar results in the correction to the ratio R. Radiative corrections will also be applied in this experiment. For the E5 analysis we have calculated radiative corrections using a modified version of the code EXCLURAD written by Afanasev, *et al.* for exclusive electro-nuclear reactions [18, 19]. The corrections can be large (up to 30%) for $\mathrm{Q}^2 < 4$ GeV^2 for the individual cross sections σ_{ep} and σ_{en}, but these radiative corrections to R nearly cancel in the $e - n/e - p$ ratio (to less than 0.2%) [3, 19]. The quantity of interest in this project is the ratio of free $e - n$ scattering to $e - p$ scattering so corrections for the effect of nuclear binding in the deuteron must be applied. For the E5 analysis we used two calculations from S. Jeschonnek and H. Arenhoevel to estimate these effects and both were found to be small (less than 0.3%) [3]. For this experiment, we will pursue other calculations appropriate for this kinematic region.

With the upgrade of CEBAF to 12 GeV, the range of Q^2 available in Hall B will be approximately $\mathrm{Q}^2 = 2 - 14$ GeV^2. We anticipate the mixture of factors that effect this measurement will be similar to what we encountered for the $4 -$ GeV measurement with the existing CLAS. However, the importance of the different factors changes. For example, the neutron detection efficiency reaches a plateau at the neutron momentum $p_n \approx$ 2.0 GeV/c as we found in the analysis of the E5 data. This feature is displayed in Figure 6 which shows the neutron detection efficiency for the E5 measurement measured with the CLAS electromagnetic calorimeter. This correction to R will be more stable at higher Q^2 and our results less sensitive to variations in neutron momentum. Another example is the nuclear correction described above for the effect of the binding in deuterium. We expect this correction to decline at higher energy.

The ratio method also relies on knowledge about the other three form factors. We expect the contribution of the neutron electric G_E^n to decrease with increasing Q^2 because it's already measured to be small (see Figure 4) and it's kinematically suppressed (see Equations 5-6). Even if it remains unmeasured over part of the Q^2 range it will not severely increase the uncertainty of the G_M^n measurement. The $12 -$ GeV upgrade preliminary Conceptual Design Report (pCDR) proposes measuring G_E^n out to $\mathrm{Q}^2 = 5$ GeV^2. The proton magnetic form factor is already known out to $\mathrm{Q}^2 = 30$ GeV^2, but high-equality measurements of G_E^p now only extend to $\mathrm{Q}^2 = 5$ GeV^2. It is proposed in the pCDR to extend these measurements out to $\mathrm{Q}^2 = 14$ GeV^2 by measuring the ratio G_E^p/G_M^p. The Q^2 range of this last measurement will match the range of the G_M^n experiment.

The identification of quasielastic events at higher Q^2 proposed here will be more difficult than the previous E5 analysis. The quasielastic cross section is dropping as roughly $1/Q^4$ while the relative contribution from other, higher-W processes is increasing. In addition

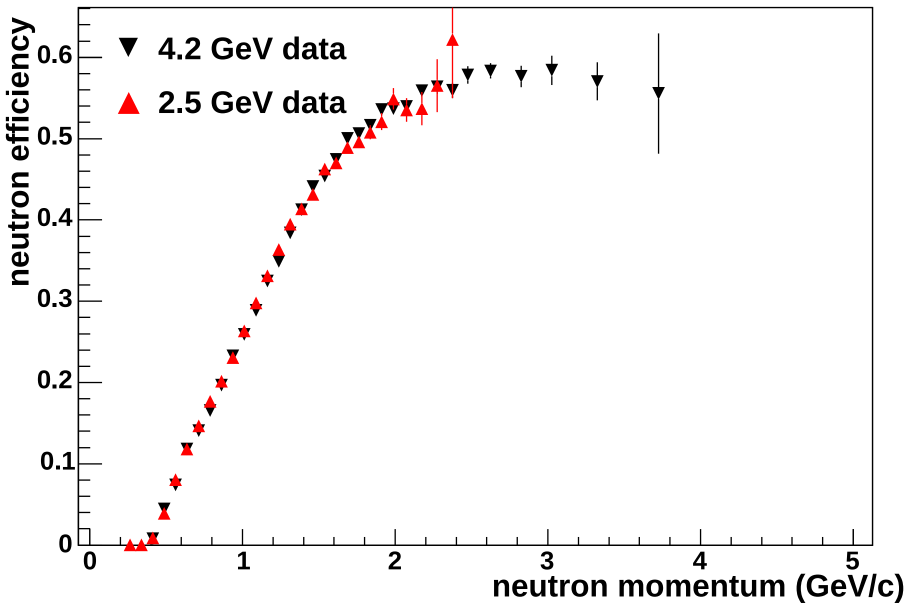

Figure 6: A comparison of the neutron detection efficiency measured in the EC from the E5 run, as measured at two different beam energies. In this figure, the efficiency has been integrated over all six sectors [3].

kinematic broadening of the quasielastic peak in W will tend to wash out the quasielastic peak and increase the size of the tail from higher-W processes that contaminate the quasielastic peak. This has been seen at high Q^2 in inclusive electron scattering [20]. Two strategies to overcome this limitation are (1) to use the cut on θ_{pq} described above to select quasielastic events (see Figure 5 where we show the results of this cut in the E5 analysis) and (2) take advantage of the increased hermiticity of CLAS12 and its improved capability for detecting neutrals. In CLAS12, the torus coils will be instrumented to improve the solid angle coverage especially at forward angles. These improvements mean that we can identify in-time particles that are not consistent with quasielastic scattering and veto those events. Developing and demonstrating strategies to identify quasielastic $e-p$ and $e-n$ events will be a major goal of the full proposal.

We have estimated the rate of the $D(e,e'p)n$ and $D(e,e'n)p$ reactions to determine how much beam time would be needed to obtain data of similar quality to the E5 run period. We used Equations 3-6 and made the following assumptions about the form factors

$$G_E^p \approx G_D = \frac{1}{(1+Q^2/\Delta)^2} \qquad G_M^p \approx \mu_p G_D \qquad G_M^n \approx \mu_n G_D \qquad G_E^n \approx 0 \tag{9}$$

where μ_n and μ_p are the neutron and proton magnetic moments and $\Delta = 0.71$ GeV^2. The results are shown in Figure 7 along with existing data on G_M^n [21]. The blue, open points show the expected Q^2 coverage and uncertainties for 45 days of beam time. The uncertainties include both statistical and systematic uncertainties (see below for more details). The red

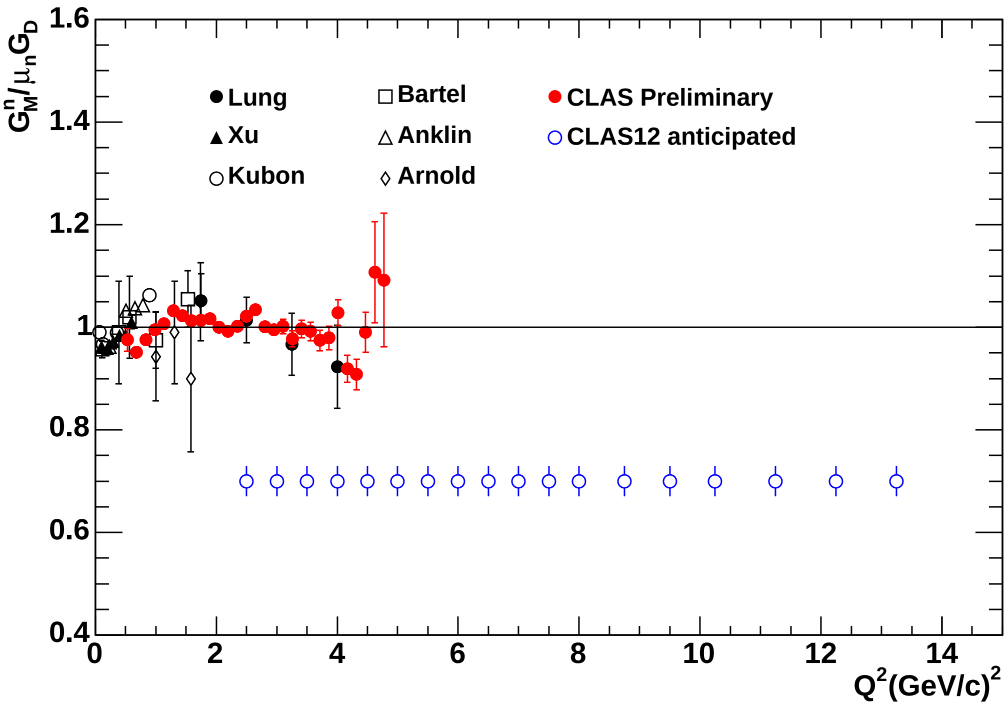

Figure 7: Selected data and estimated results for the neutron magnetic form factor G_M^n for 45 days of running time with CLAS12 (blue, open circles) in units of $\mu_n G_D$ as a function of Q^2. The red circles at low Q^2 represent the preliminary results from the E5 experiment [3, 21].

points at low Q^2 are the preliminary results of the measurement of G_M^n by Lachniet, *et al.* [3]. It is worth noting the large overlap of the CLAS12 measurement with the preliminary CLAS one. This overlap gives us another useful consistency check. The proposed measurement will significantly expand our understanding of the neutron magnetic form factor.

An essential goal of this experiment is to achieve low ($\approx$ 3%) uncertainties on G_M^n. This is about the same level of precision we reached in the CLAS G_M^n measurement with the electromagnetic calorimeter for neutron detection. The uncertainties on the TOF measurements of the neutrons were higher. We found that the biggest contributor to the systematic uncertainty in both cases was the determination of the neutron detection efficiency. We were in a neutron momentum range where the detection efficiency was changing rapidly (see Figure 6) so fits to the data to extract the efficiency curve had significant ($\approx 1-2\%$) errors. The rest of the inventory of sources of uncertainty in the CLAS measurement is small [3]. We expect to reach similar levels of precision with CLAS12. Most of the new data will be at higher neutron momentum where the efficiency curve will be flatter and less sensitive to variations in neutron momentum. None of the other sources of error in the CLAS measurement showed signs of significant increases with higher beam energy so we are encouraged that we can achieve the desired precision. We also note here that the absolute uncertainties for the neutron magnetic form factor will be similar to the absolute uncertainties for the proton magnetic form factor (G_M^p is larger). This situation improves precision when one takes the difference of proton and neutron magnetic form factors to compare with non-singlet form factors from lattice QCD or as part of a flavor separation. A detailed investigation of the sources of uncertainty will be a component of the full proposal.

We propose to use a collinear, dual-cell target containing deuterium (for the primary measurement) and hydrogen (for calibrations). A requirement for the ratio method described above to be successful is an accurate measurement of the neutron detection efficiency using the $p(e, e'\pi^+)n$ reaction. The dual-cell target will allow us to take calibration data at the same time we are collecting data for the primary measurement. This method has two important advantages. First, we will collect high-statistics, calibration data across a wide neutron momentum range. Second, the calibration data will be subject to the same running conditions as the primary measurement. Any variation in the attributes of electron beam or CLAS12 (*e.g.* dead wires, changes in beam position on target, ...) will effect both the hydrogen calibration data and the primary measurement.

Our initial studies suggest there will be adequate statistics for the neutron efficiency measurement. The requirement here is to obtain an adequate number of calibration neutrons produced by the $p(e, e'\pi^+)n$ reaction on the hydrogen part of the dual-cell target. These calibration neutrons should cover the same neutron momentum range (as much as possible) as the quasielastic, $e - n$ events from deuterium. To begin to study this question, we have examined the Q^2 behavior of the π^+ production at the kinematic limits of CLAS12. The cross section for the $p(e, e'\pi^+)n$ reaction is not well known across the Q^2 range that will be accessible with CLAS12 ($\mathrm{Q}^2 \approx 2 - 14$ GeV^2) other than it decreases rapidly with Q^2. If we have adequate calibration neutrons from this reaction at high Q^2 where the rate is low, then we will likely have enough calibration events across the full neutron momentum range. To estimate the statistics at the high-Q^2 end of the range (where the number of events will be lowest), we have used preliminary results from the E1-6 running period for the production of the S_{11} resonance. This is a conservative estimate since we consider only a single resonance where we can use tagged neutrons from other resonances for our measurement of the neutron detection efficiency. The beam energy during the E1-6 in Hall B at JLab running period was $E = 5.77$ GeV and we used the measured data rates in the range $\mathrm{Q}^2 = 2.5 - 3.5$ GeV^2 combined with the FastMC Monte Carlo simulation of CLAS12 [22]. We first calculate the rate for the same Q^2 range for an upgraded CEBAF with beam energy $E = 11$ GeV by adjusting the measured $5.77 -$ GeV event rate for differences in virtual photon flux, solid angle, CLAS versus CLAS12 acceptance, and luminosity. To extrapolate to high Q^2 we use the FastMC simulation of CLAS12 and assume the cross section has a dipole form so $\sigma \propto (1/(1 + Q^2/\Delta_S)^2)^2$ where $\Delta_S = 1.6$ GeV^2. We used the ranges $\mathrm{Q}^2 = 11.5 - 12.5$ GeV^2 and $W = 1.435 - 1.635$ GeV (centered on the S_{11}) in the final result. We found that for 45 days of beam time, we would accumulate about 60,000 calibration neutrons (from the S_{11} resonance) in this high Q^2 bin. We expect even more neutron events available for calibration by using a wider W bin. The full range of W and Q^2 that is available is shown in Figure 8. The calculation above was for a slice in W of $1.435 - 1.635$ GeV. Figure 8 is the result of a FastMC simulation of the $p(e, e'\pi^+)n$ reaction in CLAS12 for $E = 11$ GeV, $5^\circ < \theta_e < 90^\circ$, 1.1 GeV $< W <$ 3.0 GeV, and a torus current of 2250 A [22]. This result shows that we will have abundant calibration neutrons from the $p(e, e'\pi^+)n$ reaction across the full

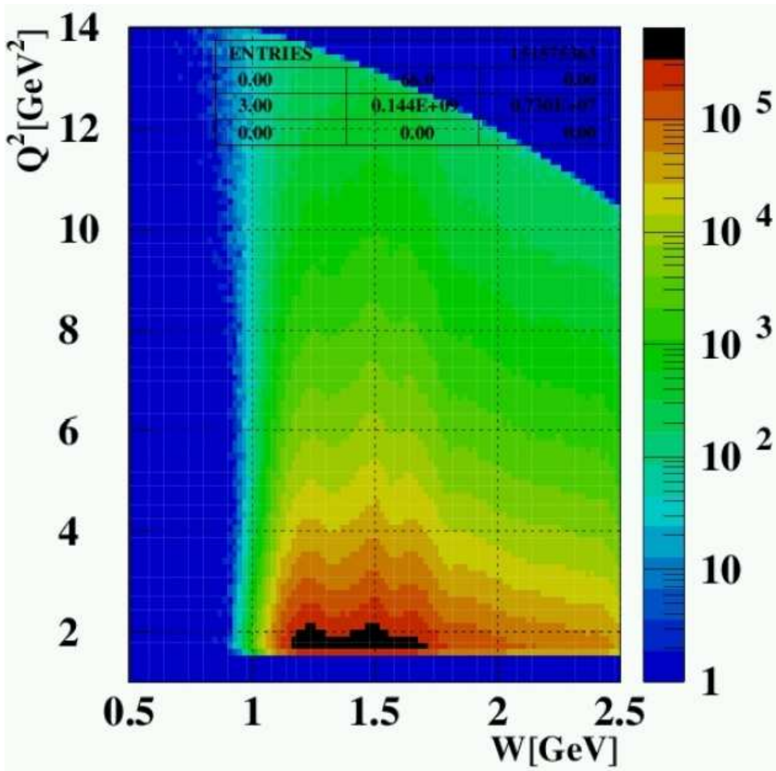

Figure 8: FastMC simulation of the $p(e, e'\pi^+)n$ reaction in CLAS12 for $E = 11$ GeV, $5° < \theta_e < 90°$, 1.1 GeV $< W <$ 3.0 GeV, and a torus current of 2250 A [22]. The plot shows the results of a high-statistics calculation to precisely map out the CLAS12 acceptance. The statistics are not representative of the expected ones for the experiment.

acceptance of CLAS12 for the proposed 45-day experiment which will likely cover the full neutron momentum range. We need to study in detail the neutron momentum distribution from this calibration reaction for these kinematics to validate this expectation. Such a study of the neutron detection efficiency measurement will be part of the full proposal.

This measurement will be done with the base equipment for CLAS12. The dual-cell target will fit in the target region of CLAS12 and we may even be able to use the target from the E5 run in CLAS12. If that option is not available, then a new target could be built at modest cost.

There is still considerable work to be done to develop this project into a full proposal. We need a more complete simulation for use with the CLAS12 FastMC code to make better estimates of the rates for the primary reactions ($D(e, e'p)n$ and $D(e, e'n)p$) and the calibration reactions ($p(e, e'\pi^+)n$ and elastic ep scattering) on the hydrogen target. We will also study the effect of lower signal-to-noise ratio and kinematic broadening on our ability to separate quasielastic events from higher-W processes and test strategies to improve the selection of quasielastic events. We will explore the Q^2 dependence of the set of corrections (Fermi, nuclear, radiative) that were made in the E5 analysis and study ways to optimize the dual-cell target design. The source of uncertainties of the measurement of G_M^n need to investigated in more detail to make sure they are under control.

4 Technical participation of research groups

4.1 University of Richmond

The University of Richmond group is actively involved in this letter of intent, as well as in one other proposal using CLAS12.

Among CLAS12 baseline equipment, the group intends to take responsibility for the design, prototyping, development and testing of software for event simulation and reconstruction. One faculty member along with 2-3 undergraduates each year are likely to work at least part time on this project in the next few years. The group has a 100-CPU computing cluster solely for nuclear physics supported by a linux-trained, technical staff member. The cluster was funded by NSF and the University. The University also supports routine travel to Jefferson Lab and undergraduate summer stipends. Funding for the group is from DOE. Additional sources of funding will be sought as appropriate.

4.2 Old Dominion University

The Old Dominion University group is actively involved in this letter of intent, as well as several other proposals using CLAS12. Other members of our group are pursuing a proposal for Hall A, but their contributions are not included here.

Among CLAS12 baseline equipment, the group intends to take responsibility for the design, prototyping, construction and testing of the Region 1 Drift Chamber. Five faculty (including one research faculty) and one technician are likely to work at least part time on this project in the next few years. Funding for the group is from DOE and from the university (75% of research faculty salary, one regular faculty summer salary, 50% of the technician).

The university has also provided 6000 square feet of high bay laboratory space with clean room capabilities for our use. We will seek other sources of funding as appropriate.

Gail Dodge is the chair of the CLAS12 Steering Committee and the user coordinator for the CLAS12 tracking technical working group.

Beyond the baseline equipment, the group is also interested in exploring improvements to the BoNuS detector and a future RICH detector for CLAS12.

4.3 Argonne National Laboratory

The Argonne National Laboratory Medium Energy Group is actively involved in this letter of intent as well as the quark propagation proposal using CLAS12. Among CLAS12 baseline equipment, the group intends to take responsibility for the design, prototyping, construction, and testing of the high-threshold Cerenkov counter. Three faculty members (research staff) and two engineers are likely to work at least part time on this project in the next few years. Funding for the group is from DOE. Additional sources of funding will be sought as appropriate.

4.4 Union College

The Union College group is actively involved in this letter of intent and other parts of the CLAS12 physics program. The group plans to work with the CLAS12 software group on the development of software for analysis, simulation, and controls. One faculty member and 2-3 students will work at least part time on this project over the next few years. The group has a 20-CPU Beowulf cluster provided by Union College to support the work at Jefferson Lab. The College also provides stipends for undergraduate students involved in research during the summer. The group is also funded by DOE.

4.5 University of New Hampshire

The University of New Hampshire is a supporter of this letter of intent as well as actively involved in four other proposals using CLAS12.

The UNH group is committed to significant contributions in the development of the CLAS12 software. Maurik Holtrop is currently chair of the CLAS12 GEANT4 simulation group to which one of the UNH post-doctoral fellows (Hovanes Egiyan) is also contributing. Since currently the main software efforts for CLAS12 are in the area of simulation we are also part of and contributing to the general CLAS12 Software group. Current manpower commitments to this effort are 0.15 FTE of a faculty member and 0.4 FTE of one post-doc. We expect to increase this effort as our CLAS activities wind down and our CLAS12 activities pick up and we expect to attract some talented undergraduate students to this project.

Among CLAS12 baseline equipment, the group intends to take responsibility for design, prototyping, construction, and testing of the silicon vertex detector and perhaps the inner detector's silicon tracking detectors. Faculty member Maurik Holtrop is likely to work at least part time on this project in the next few years and is likely to be joined by Jim Connel, a cosmic ray experimentalist with a background in nuclear physics, who is very interested in joining the vertex detector project. He has considerable experience with silicon detectors for space observations. Funding for the group is from DOE and additional sources of funding will be sought for this project to bring aboard Dr. Connel. If funded we are likely to attract a post-doc, graduate students, and one or two undergraduate students to this project.

Beyond the baseline equipment, the group is also interested in exploring an extended inner calorimeter for CLAS12.

4.6 DAPNIA/SPhN-Saclay

The DAPNIA/SPhN-Saclay group expressed interest in this letter of intent. It is actively involved in two proposals using CLAS12, and one other proposal for Hall A.

Among CLAS12 baseline equipment, the group intends to take responsibility for the design, prototyping, construction and testing of the central tracker (both the cylindrical part and the forward part). The group has started working on an option based on cylindrical Micromegas detectors. Provided this is shown to work as designed, the group anticipates that this option will be examined in comparison with the Silicon Strip tracker, toward the end of 2007 or the beginning of 2008. Four research staff members and four technicians/engineers are likely to work at least part time on this project in the next few years. Funding for the group is from CEA-France. Additional sources of funding (ANR-France, European Union 7th PCRD) will be sought as appropriate.

In case the Micromegas option is not suitable, or not selected for valid reasons, the group would study other technical participations in the CLAS12 baseline equipment.

Beyond the baseline equipment, the group is also interested in exploring neutral particle detection (mostly neutrons) in the central detector of CLAS12, in the so far empty space between the TOF scintillators and the solenoid cryostat.

5 Conclusion

In this Letter-of-Intent we propose to measure the magnetic form factor of the neutron using the 11 GeV electron beam in the upgraded CEBAF and CLAS12 detector. The measurement will be in the range $Q^2 = 2 - 14$ GeV^2. The neutron's magnetic form factor is one of the fundamental quantities of nuclear physics and its value is an important constraint for the newly-developed generalized parton distributions that hold the promise of dramatically expanding our understanding of the nucleon. The form factors are also important challenges for lattice QCD to meet. This measurement is part of a broad assault on the four elastic nucleon form factors at Jefferson Lab. We will use the ratio of elastic $e - n$ to elastic $e - p$ scattering on deuterium described in Section 3. The ratio method is less vulnerable to uncertainties than previous methods and we will have consistency checks between different detector components (*e.g.*, the TOF and EC) and a large overlap with our CLAS measurements. Precise measurements of G_M^n have already been made by our group and others at lower Q^2 [3, 5, 6, 7]. The group of university-based CLAS collaborators that are part of this Letter-of-Intent have made significant commitments to the 12-GeV upgrade program.

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