Hall C Proposal to JLab PAC39 May 4, 2012

Measurements of $A_\parallel$ and $A_\perp$ to Extract G_E^n and G_M^n at $Q^2 = 1 - 2.6$ (GeV/c)^2 from the Inclusive $^3\overrightarrow{\mathrm{He}}(\overrightarrow{\mathrm{e}},\mathrm{e}')$ Reaction

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Abstract

We propose a precision measurement of the double spin asymmetries $A_{\parallel}$ and $A_{\perp}$ from the inclusive $^3\overrightarrow{\mathrm{He}}(\overrightarrow{\mathrm{e}},\mathrm{e}')$ quasi-elastic reaction in order to perform an extraction of the neutron electromagnetic form factors G_E^n and G_M^n at $Q^2 = 1.1$, 1.5, 2.1 and 2.6 (GeV/c)^2. The electric form factor will be extracted via calculations using the plane-wave impulse approximation (PWIA) for the proton and neutron contributions to the ^{3}He quasi-elastic response functions by taking the ratio of the transverse-longitudinal to transverse asymmetries ($A_{TL'}/A_{T'}$) and using the well known form factors (G_E^p, G_M^p and G_M^n). Since we will be measuring the transverse asymmetry, we can directly extract G_M^n from $A_{T'}$ using the same PWIA calculations. A recent extraction of G_E^n at $Q^2 = 0.98$ (GeV/c)^2 using this method from a short test run demonstrated that the inclusive measurement technique can provide similar results as experiments that tag the neutron. The feasibility of this method became fruitful for the first time due to the falloff of the other form factors at high Q^2 (≥ 1 (GeV/c)^2) compared to the relative strength of G_E^n. The experiment will be performed at Jefferson Lab in Hall C as an extension to the already approved polarized ^{3}He target program; hence, this proposal does not require any additional equipment than what is already planned for the 12-GeV upgrade. This experiment will complement the completed E02-013 and proposed E12-09-016 experiments in which the neutron is tagged from $^3\overrightarrow{\mathrm{He}}$. With a total beam time 360 hours (15 days), we propose to achieve a total uncertainty of 4.5 to 6.5% on the extraction of G_E^n and G_M^n over the measured Q^2 range.

1 Introduction

The modern, high precision neutron form factor experiments have used polarized beams to dramatically improve our knowledge of the nucleon form factors. In particular for the electric form factor of the neutron, G_E^n, the A(e, e′n) reaction is often used either with a polarized target or with detection of the recoiling nucleon. Historically, only the magnetic part of the neutron's form factor was ever significantly determined from the inclusive reaction due to the overwhelming contribution of the proton channels making any kind of electric form factor determination impractical at Q^2 less then approximately 1 (GeV/c)^2 [1–3]. However, as Q^2 increases the proton form factors as well as the neutron's magnetic form factor continue to drop while the neutron's electron form factor stays relatively constant. Because of this, it has become feasible to determine the neutron's electric form factor via an inclusive measurement at $Q^2 \geq 1$ (GeV/c)^2.

As a proof of principle, this was done during a three day test measurement in Hall A by scattering a 3.6 GeV polarized electron beam from either a longitudinally or transversely polarized ^{3}He target. The result is shown in Fig. 1 as the solid-square near $Q^2 \sim 1$ (GeV/c)^2 [4], where the uncertainty is dominated by the statistics achieved on the longitudinal asymmetry measurement $A_\parallel$. Even in that short period of time, the experiment was able to determine the neutron's electric form factor to within better than 20% uncertainty. A paper reporting this result will appear on the archive within the next two weeks.

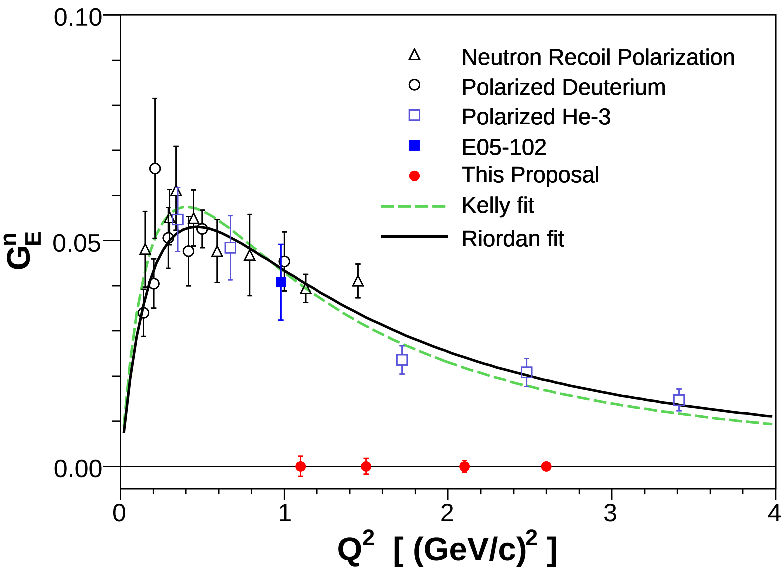

Figure 1: The G_E^n value from Experiment E05-012 (solid-square) and selected published data: open triangles [5–8], open circles [9–11], open squares [12–14] and parameterizations: Riordan *et al.* [14] and Kelly [15]. The solid circles show the Q^2 values of this proposal. The error bars for our projected data points show the absolute statistical and systematic uncertainties added in quadrature based on the value of G_E^n from the Riordan fit.

With Jefferson Lab's 11 GeV beam and the Super High-Momentum Spectrometer (SHMS) at angles between 5.5° and 10°, the Mott cross section for Q^2 at 1 (GeV/c)^2 is about a factor of 8 larger compared to the short run in Hall A and aids in extremely high precision asymmetry measurements to extract the neutron's electromagnetic (EM) form factors in a relatively short time. The Mott's cross section enhancement coupled with the high luminosity polarized ^{3}He target planned for 12 GeV experiments allows for much greater precision and Q^2 reach. This measurement is an extension of the already approved Hall C polarized ^{3}He experiments, A_1^n (E12-06-110) [16] and d_2^n (E12-06-121) [17], and does not require any additional equipment for a modest beam-time allocation of 15 days.

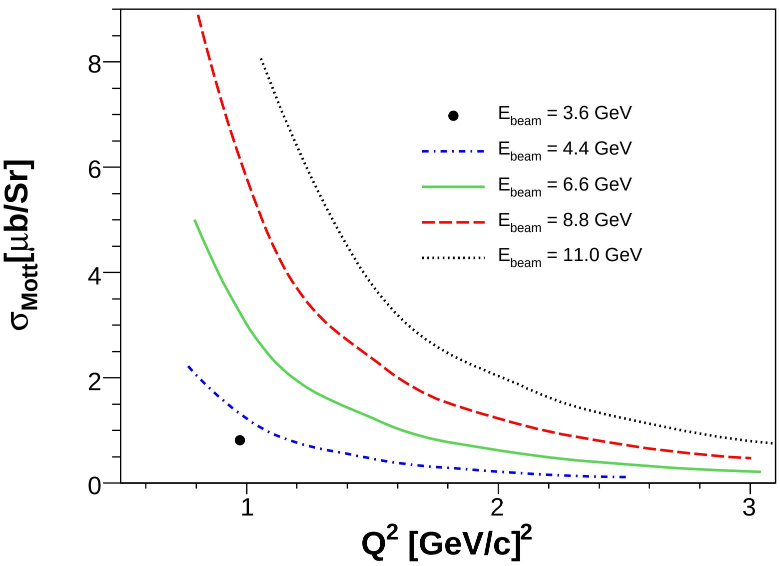

Figure 2: The Mott cross section versus Q^2 for different beam energies. The solid circle represents the point from Fig. 1.

2 Physics Motivation

2.1 Experimental Effort

Several methods of measuring G_E^n have been utilized, which include Rosenbluth separations [18, 19] from an unpolarized deuteron target, a neutron recoil polarimeter [5–8], and either a polarized deuteron target [9–11] or a polarized ^{3}He target [12–14] from $\overrightarrow{\mathrm{A}}(\overrightarrow{e}, e'n)$ reactions. Quasi-elastic inclusive measurements of the neutron electric form factor G_E^n were also tried [1, 2] at low $Q^2 \sim 0.2$ (GeV/c)^2; however, they resulted in uncertainties comparable with the extracted quantity. As mentioned in Section 1, an extraction of G_E^n at $Q^2 \sim 1$ (GeV/c)^2 was performed from measurements of asymmetries in the $^3\overrightarrow{\mathrm{He}}(\overrightarrow{e}, e')$ reaction with improved statistical precision and reduced systematic uncertainties. The extracted value is consistent with the world data, which showed the feasibility of this method at $Q^2 \geq 1$ (GeV/c)^2. The details of the extraction method will be discussed in Section 4.

Some measurements of G_E^n already exist in this region using either a neutron recoil polarimeter [8] or a polarized ^{3}He target [14]. In both sets of measurements, a neutron is detected. In Fig. 1, there appears to be a potential discrepancy between the neutron recoil measurement from a deuteron target and the measurement from ^{3}He around 1.5 (GeV/c)^2 of several standard deviations. This could indicate a possible systematic difference between extracting the neutron form factors from the two light nuclei. We believe it will be extremely useful to have high precision data from both targets in this region to investigate this issue.

An additional motivation for this proposal is to utilize the inclusive data to illuminate the assumptions made about the inclusive reaction mechanism that spin-dependent final state interactions (FSI) and meson exchange currents (MEC) are negligible at high Q^2. This will require the availability of form factor data with similar or better precision from other measurements as discussed in Section 3.

2.2 Theoretical Calculations

In this section, we briefly highlight the calculations that are available to compare with our planned results. These include a relativistic constituent quark model (RCQM) [20, 21], a calculation that is based on Dyson-Schwinger equations (DSE) [22, 23], and predictions based on generalized parton distributions (GPDs) [24, 25] and vector meson dominance (VMD) [26, 27]. The two predictions were fit to the available data at the time.

An example of a RCQM is the light front cloudy bag model, which includes a pion cloud. Prior to the polarization transfer experiments, RCQMs predicted the decrease of ratio of the proton form factors with Q^2 [28]. The light front cloudy bag model has reasonably reproduced the measured form factor data over a sizable range of Q^2. This calculation respects both Poincaré invariance and chiral symmetry. The calculations have good agreement with the proton form factor ratio results from double-polarized measurements. However, in regards to the neutron, the model rises faster with Q^2 than the data.

The DSE calculation dynamically generates the constituent quark mass and assumes that two of the quarks couple into a di-quark. However, pion-cloud effects are not include, since only three constituent quarks are considered. The DSE calculation of Ref. [22, 23] is closest to the recent polarized ^{3}He data at high Q^2, and also shows good consistency with the high Q^2 proton form factor ratio data. The moderate values of Q^2 and the high precision data of this proposal should allow an investigation into effects such as di-quarks in the nucleon.

3 Planned Neutron Form Factor Measurements at JLab

Measurements of the EM form factors are an important part of the physics program with the 12-GeV upgraded accelerator. In this section, the experiments that are related to the neutron and to our proposal are outlined.

3.1 Hall A Neutron Recoil Proposal

A new proposal submitted to PAC 39 aims to make a high precision measurement of the ratio G_E^n/G_M^n via the $^2\mathrm{H}(\overrightarrow{e}, e'\overrightarrow{n})$ reaction [29]. In that proposal, the form factor ratio will be measured at five values of $Q^2 = 1.5$, 2.0, 3.0, 4.0 and 6.0 (GeV/c)^2 with a relative (statistical and systematic) uncertainty in the ratio of 4 – 10%. Hence, both our proposal on polarized ^{3}He and the neutron recoil proposal will have nice overlap below 3 (GeV/c)^2 and comparable uncertainties. We emphasize that our measurement represents a different technique and the systematics will be very different.

3.2 Hall C Neutron Recoil Proposal

Hall-C experiment E12-11-009 [30] has been approved to measure G_E^n/G_M^n also by neutron recoil polarimetry with the SHMS and a neutron polarimeter with $Q^2 = 3.95$, 5.22 and 6.88 (GeV/c)^2. Since this experiment measurements are above our planned values of Q^2, we will not have any overlap between our data sets.

3.3 Hall A Polarized ^{3}He Experiment (GEn(2))

The approved experiment E12-09-016 [31], known as GEn(2), plans to measure the double-spin asymmetry in the quasi-elastic $^3\overrightarrow{\mathrm{He}}(\overrightarrow{e}, e'n)$ channel to extract the ratio G_E^n/G_M^n. This measurement will use large acceptance spectrometers such as BigBite and a large hadron calorimeter known as HCAL and an updated polarized ^{3}He target that will be discussed in Section 5.2. The proposed Q^2 range includes points at 1.5, 3.7, 6.8 and 10.2 (GeV/c)^2. The main difference between our proposal and this one is that we do not require detection of an out going neutron, which minimizes the uncertainty due to effects such as charge-exchange in the material between the target and the neutron detector. Also our choice of using the SHMS results in different systematics, since we are not using an open geometry detector. At $Q^2 = 1.5$ (GeV/c)^2, we will be able to check the systematic differences between the two extraction methods.

3.4 Measurements of the Neutron Magnetic Form Factor

There are two approved experiments to measure G_M^n up to 13.5 (GeV/c)^2:

- Experiment E12-09-019 [32] in Hall A using the Super BigBite Spectrometer (SBS) plans to measure the cross section ratio of the $^2\mathrm{H(e, e'n)}$ and $^2\mathrm{H(e, e'p)}$ quasi-elastic scattering processes from a deuteron target.
- The ratio method above will also be used with CLAS12 [33] to measure in a fine grid of Q^2.

4 Form Factor Extractions from Double Polarization Measurements

With the advancement in polarized beam and target technology, the double polarization technique to measure the EM form factors has shown that our understanding of the nucleon is far from complete. The measurement of the neutron electric form factor, G_E^n, has been especially challenging for two reasons: the the difficulty in obtaining a high density pure neutron target and the form factor's small value. Physicists have had to rely on light nuclei, such as the deuteron or ^{3}He, where the neutron is bound inside the nucleus. In this proposal, we discuss the potential of using polarized ^{3}He as an effective polarized neutron target to gain access to the EM form factors of the neutron.

4.1 Asymmetry Formalism

If both the target nucleon or nucleus (^{3}He) and incident electron beam are polarized, the cross section can be written as the sum of the spin-independent (Σ) and polarized (Δ) components following the formalism of Donnelly and Raskin [34]:

$$\sigma = \Sigma + h\Delta, \tag{1}$$

where $h = \pm 1$ is the helicity of the electron. The asymmetry is then defined as

$$A \equiv \frac{\Delta}{\Sigma} = -\frac{v_{T'} R_{T'}^{^3\mathrm{He}} \cos\theta^* + v_{TL'} R_{TL'}^{^3\mathrm{He}} \sin\theta^* \cos\phi^*}{v_L R_L^{^3\mathrm{He}} + v_T R_T^{^3\mathrm{He}}}, \tag{2}$$

where ϕ^* and θ^* are the polar and azimuthal angles of the target polarization vector as shown in Fig. 3. The response functions R_k are functions of Q^2 and ν (the electron energy

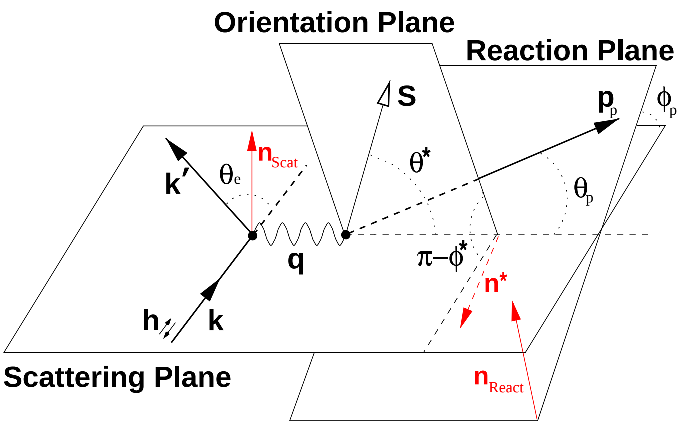

Figure 3: Kinematics for electron scattering from polarized targets. The target polarization is shown by the angles θ^* and ϕ^*.

transfer); the spin-independent responses are R_L and R_T, and the spin-dependent responses are $R_{T'}$ and $R_{TL'}$. The v_k's are kinematic factors provided in Ref. [34].

When the target polarization is parallel to $\overrightarrow{q}$, $\theta^* = 0$, one can measure the transverse asymmetry

$$A_{T'} = -\frac{\sigma_{\rm Mott} v_{T'} R_{T'}^{^3{\rm He}}}{\Sigma}, \tag{3}$$

and if the target polarization is perpendicular to $\overrightarrow{q}$, $\theta^* = \pi/2$ and $\phi* \simeq 0$, the asymmetry is called the transverse-longitudinal asymmetry

$$A_{TL'} = -\frac{\sigma_{\rm Mott} v_{TL'} R_{TL'}^{^3{\rm He}}}{\Sigma}, \tag{4}$$

where $\sigma_{\rm Mott}$ describes relativistic electron scattering from a point-like Dirac particle. The transverse asymmetry is sensitive to G_M^n, and measurements of this asymmetry have been used to extract this form factor at $Q^2 \leq 0.6$ (GeV/c)^2 [35]. On the other hand, the transverse-longitudinal asymmetry is sensitive to $G_E^n G_M^n$. The next section will discuss an extraction method for the neutron's EM form factors utilizing these two asymmetries.

4.2 Extraction Method

Different models can be used to calculate the ^{3}He response functions, which include full Faddeev calculations [36] in the nonrelativistic kinematic region and plane-wave impulse approximation (PWIA) calculations, which neglect FSI and MEC. The extraction method that will be discussed in this proposal is based on the PWIA extraction of Kievsky *et al.* [37]. The effects of FSI and MEC will also be included in the discussion.

Following the calculation in Ref. [37], the polarized ^{3}He transverse (transverse-longitudinal) response functions $R_{T'(TL')}^{^3{\rm He}}$ near the quasi-elastic peak can be written as

$$R_{T'}^{^3{\rm He}} = \frac{Q^2}{2qM}\{2[G_M^p]^2 H_{T'}^p + [G_M^n]^2 H_{T'}^n\} \tag{5}$$

and

$$R_{TL'}^{^3{\rm He}} = -\sqrt{2}\{2G_M^p G_E^p H_{TL'}^p + G_M^n G_E^n H_{TL'}^n\}, \tag{6}$$

where the $H_{T'(TL')}^{p(n)}$ represent the proton (neutron) contributions to the response functions. The $H_{T'(TL')}^{n(p)}$ functions were calculated using models for the nucleon polarizations and momentum distributions in the ^{3}He nuclei and are approximately constant over a wide Q^2 range as shown in Fig. 4.

By forming the ratio of Eq. (4) to Eq. (3) and substituting Eq. (5) and Eq. (6), the unpolarized cross section Σ and $\sigma_{\rm Mott}$ cancel out in the ratio, resulting in the ratio of asymmetries:

$$\frac{A_{TL'}}{A_{T'}} = -\frac{v_{TL'}\sqrt{2}\{2G_M^p G_E^p H_{TL'}^p + G_M^n G_E^n H_{TL'}^n\}}{v_{T'}\frac{Q^2}{2qM}\{2[G_M^p]^2 H_{T'}^p + [G_M^n]^2 H_{T'}^n\}}. \tag{7}$$

By using measured values of $A_{T'}$ and $A_{TL'}$ and the well known form factors (G_M^p, G_M^n and G_E^p), the value of G_E^n can be extracted using the proton and neutron contributions to the

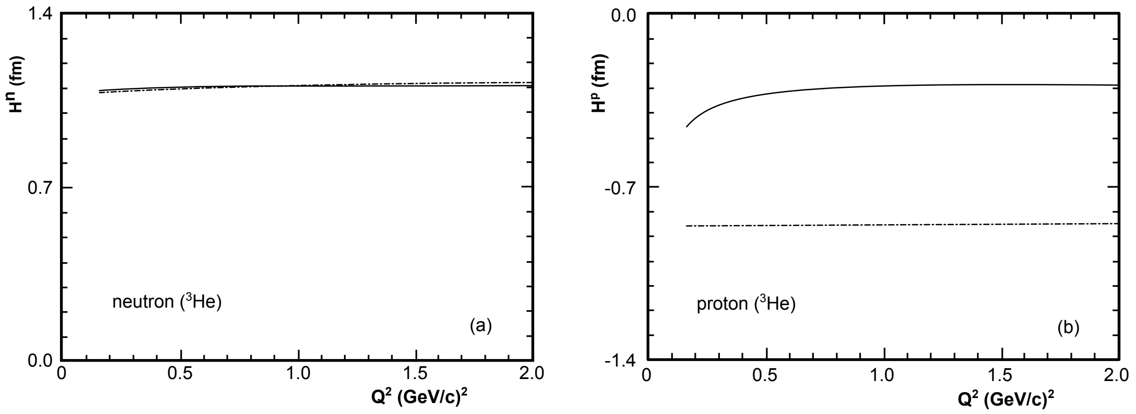

Figure 4: The functions $H^n_{T'(TL')}$ for the neutron in ^{3}He (left-hand side), and $H^p_{T'(TL')}$ for a proton in ^{3}He (right-hand side). The curves are solid line: $H^{n(p)}_{T'}$ and dot-dashed line: $H^{n(p)}_{TL'}$. Reproduced from Ref. [37].

response functions from Fig. 4. This method of course requires that the ^{3}He structure and the reaction mechanisms are properly handled. We also would like to note that by taking $A_{T'}$ on its own, we can make an independent extraction of G^n_M using the same PWIA calculation. A precise ($\sim 2 - 3\%$) determination of G^n_M using this method is discussed in Ref. [35].

4.3 Discussion of FSI and MEC

In PWIA, FSI and other current exchanges are ignored, and hence, this can be a concern for using this extraction method. For the kinematics of the proposed experiment, $Q^2 = 1 -$ 2.6 (GeV/c)^2, the struck nucleon has a relativistic kinetic energy, and Faddeev calculations cannot be used in the extraction of the form factors. J. M. Laget [38] studied the FSI and MEC effects in $^3\vec{\mathrm{He}}(\vec{e}, e'n)$ and found that these effects significantly affect the asymmetries at low Q^2 but they become negligible for $Q^2 > 0.3$ (GeV/c)^2. The work of Ref. [39] provides additional support to the conclusion that spin-dependent FSI's become negligible for this region of Q^2. As mentioned previously in Section 4.1, G^n_M was extracted in the range Q^2 = 0.1 - 0.6 (GeV/c)^2 by measuring the transverse asymmetries $A_{T'}$ [40]. The PWIA calculation [37] discussed in this proposal was also used in that extraction, and the effects of FSI were found to significantly decrease above Q^2 of 0.5 (GeV/c)^2 down to $1 - 2\%$ based on an extrapolation beyond 0.4 (GeV/c)^2 from the Faddeev calculations. The effects from MEC were found to decrease exponentially as Q^2 increases, which is based on Golak's full calculation [36] and from the observations in Ref. [40].

In the PWIA calculations, the response functions require an off-shell EM nucleon tensor for the convolution formulas. The effect of different prescriptions for the off-shell cross sections was studied, and it was found [41] that they produce a negligible contribution to the uncertainty.

5 Experimental Equipment and Methods

We propose to measure the double-spin asymmetries $A_{\parallel}$ and $A_{\perp}$ in Hall C for the $^3\overrightarrow{\mathrm{He}}(\overrightarrow{\mathrm{e}}, \mathrm{e}')$ reaction via quasi-elastic electron scattering from a longitudinally and transversely (in the plane of the scattered electron) polarized ^{3}He target. This experiment can be conducted in sequence with the already approved A_1^n [16] and d_2^n [17] experiments. The quasi-elastically scattered electrons will be detected in the SHMS at central Q^2 values of 1.25 (GeV/c)^2 and 2.36 (GeV/c)^2. For this proposed experiment, no new equipment is required beyond what is already planned for the 12-GeV upgraded Hall C.

5.1 SHMS Parameters

For the rate estimations, we used the current SHMS design as reported in Refs. [16, 17] for the momentum and solid angle acceptances. We assume a maximum DAQ rate of $\sim$ 7 kHz with a deadtime of less than 20%, which has recently been demonstrated in Hall A during experiment E08-027 [42].

5.2 Updated Polarized ^{3}He Target

For the proposed asymmetry measurements, we will utilize a polarized ^{3}He target based on the same general principles as used in Hall A [43] from 1997 until 2003; however, the target is being upgraded for the planned 12-GeV experiments. The upgrade takes advantage of the improvements that were made for the experiments between 2006 and 2009 [14, 44], including spin exchange optical pumping (SEOP) using a Rb-K mixture [45] for the alkali vapor and spectrally narrowed lasers. During the 2008-2009 experiments, an average in-beam target polarization of up to 55% was achieved as shown in Fig. 5.

With the recent advancements in polarized ^{3}He technology, a factor of 8 improvement is expected in the polarized luminosity as is required and discussed in the Hall A GEn(2) proposal [31]. The spokespersons for the A_1^n experiment [16] stated in their update to PAC 36 that they intend to use the same target and design as the GEn(2) target. In addition to the use of a hybrid-alkali mixture for SEOP and spectrally narrowed lasers, the future target will make use of two additional technical developments:

- A "dual transfer tube" target cell design that will allow for convective mixing of the polarized ^{3}He gas from the pumping chamber to the target chamber. Using convection instead of diffusion will greatly improve the transfer rate of the ^{3}He between the two chambers, compensating for beam depolarization at higher beam currents in the target chamber.
- Additional diagnostics that provide direct measurements of the ^{3}He and alkali-vapor polarizations and of the alkali-vapor number densities.

In this proposal, we plan to use the same target and cell design as the Hall C A_1^n experiment

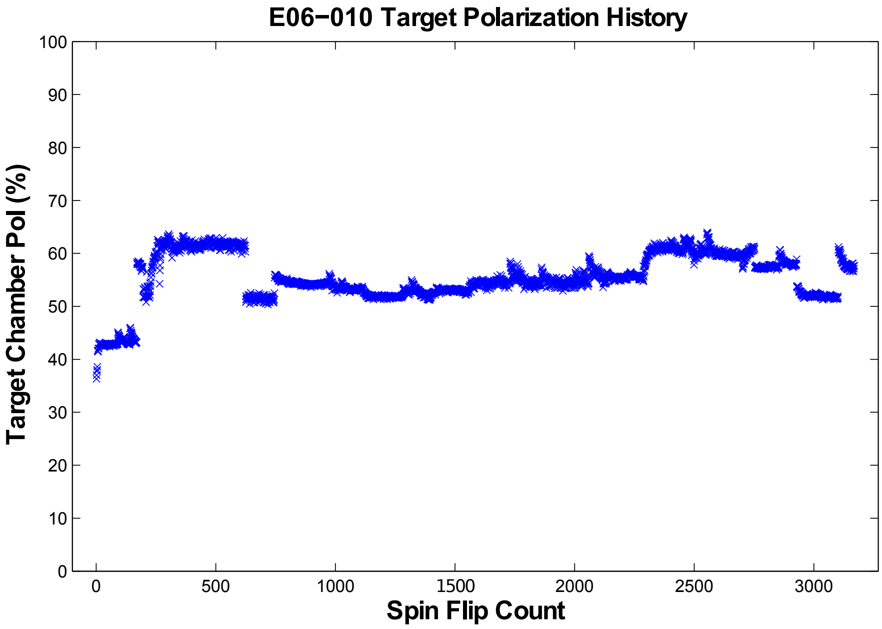

Figure 5: The ^{3}He target polarization during the Hall A Transversity (E06-010/E06-011) experiment [44].

(See Fig. 6) with a 60 cm long target chamber and two transfer tubes for convection of the polarized gas. The plan is to replace the glass target chamber with a non-magnetic metal chamber, which will help avoid radiation damage and mitigate potential cell ruptures. The pumping chamber will remain glass for transparency for the laser light. The goal of this target is to achieve 60% target polarization with a beam current of 60 μA. In the rate estimates below, we assume a target density of 12 amg, which has been realized in past ^{3}He experiments.

6 Kinematics and Rate Estimate

For this proposal, we request 360 hours (15 days) of beam time to measure the double spin asymmetries, $A_{\|}$ and $A_{\perp}$, which can be expressed as linear combinations of $A_{T'}$ and $A_{TL'}$ using Eq. (2). This time estimate includes 24 hours for calibrations and overhead. The SHMS, target and beam parameters used in the rate estimates are provided in Table 1.

The Quasi-Free Scattering (QFS) model of J. Lightbody and J. O'Connell [47] with modifications to include external radiative corrections was used for the rate estimates [47]. The calculated rates were compared to data taken during experiment E05-102 and found to have reasonable agreement after accounting for the rate from the glass windows. The statistical uncertainty assumes we will cut out the target windows, which results in an effective target length of 42 cm. This conservative target length cut may not be necessary if indeed the rather thick glass windows are replaced with thinner metal or Be windows. This cut was determined by scaling the cut (± 16 cm) used to remove the cell windows from the data

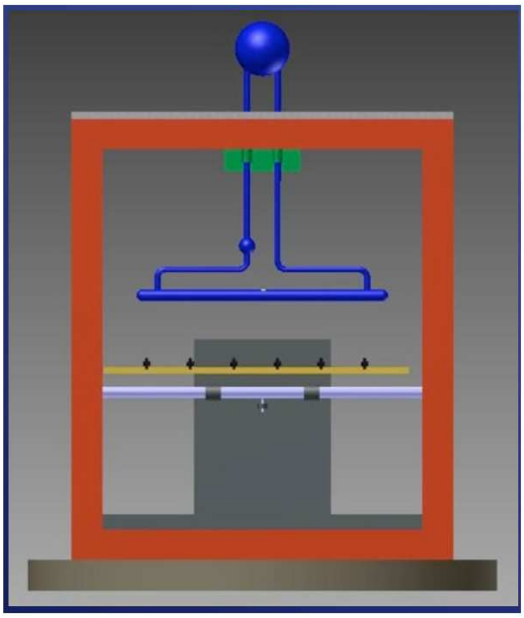

Figure 6: Planned 12-GeV polarized ^{3}He target design. Reproduced from G. Cates [46].

for 40 cm long target cells. Detailed kinematic settings and rate estimates are presented in Table 2. From the measurements of two SHMS central angle settings, $\theta_{\mathrm{SHMS}} = 6°$ and $8.5°$, we plan on splitting the data into four Q^2 points taking advantage of the solid angle acceptance of the SHMS. For the lab angle, θ, we show the angle range for each Q^2 in the SHMS acceptance. The rates and time estimates are for the SHMS angle setting and not the individual Q^2 points.

7 Systematic Uncertainties

7.1 Experimental Systematic Uncertainties

The dominant experimental systematic uncertainties for the measured asymmetries are the uncertainty in the target polarization (4%), the radiative corrections (3%), the dilution factor (1%) and the beam polarization (1.5%) [48]; all uncertainties are relative to the asymmetry.

However, in the ratio of the asymmetries from Eq. (7), several of these systematic uncertainties are significantly reduced. For corrections such as the beam and target polarizations, their absolute values cancel out to first order, and only their relative changes during the measurement contribute to the uncertainty. We estimate that the uncertainty on the asymmetry ratio from the beam and target polarizations are $\sim 1.5\%$ and 1%, respectively. Similarly, the dilution factors cancel each other out and contribute negligibly to the overall uncertainty. The effect of the radiative corrections are positively correlated for the $A_{\parallel}$ and $A_{\perp}$ asymmetries on the quasi-elastic peak. From the measurement shown in Fig. 1, if the corrections are varied within their uncertainties, then the ratio of asymmetries changes by $\ll 1\%$. In

Parameter	Value
Beam energy	11 GeV
Beam current	60 μA
Beam polarization	80%
Scattering angle	6.0° and 8.5°
Momentum range	-10% to +22%
Quasi-elastic range	2.25%
z-acceptance	30 cm (at 90°)
Solid angle	5 msr
Livetime	80%
Target length	60 cm
Target polarization	60%
Target density	12 amg

Table 1: Target and SHMS parameters used for the rate estimates

E_0 [GeV]	E' [GeV]	θ_{SHMS} [deg]	Range of θ_{lab} [deg]	Q^2 (GeV/c)^2	e^- rate [kHz]	$t_{\parallel}$ [hrs]	$t_{\perp}$ [hrs]	$\Delta A_{\parallel}$ [$\cdot 10^{-4}$]	$\Delta A_{\perp}$ [$\cdot 10^{-4}$]
11.0	10.437	6	5 – 6	1.057					
11.0	10.229	6	6 – 7	1.446	7.70	48	6	0.8	2.2
11.0	9.874	8.5	7.5 – 8.5	2.114					
11.0	9.612	8.5	8.5 – 9.5	2.604	0.37	240	36	1.6	4.1

Table 2: Kinematics and estimated quasi-elastic count rates for the SHMS with an effective target length of 42 cm. The uncertainties for $A_{\parallel}$ and $A_{\perp}$ are statistical only.

fact, the largest difference we see is if we take the ratio of the asymmetries with no radiative corrections compared to the ratio with radiative corrections; in this case, the difference in the asymmetry ratios is $\sim 1.5\%$. For this proposal, we take 1% to be the uncertainty from the RC. Finally the measurement of the asymmetries is sensitive to the target polarization angles θ^*. The implementation of a precision air compass have reduced the uncertainty in the measurement of this angle to better than 0.1°, which results in a 1% uncertainty in the ratio. We estimate the total experimental systematic uncertainty to be 2.3% for the ratio of the asymmetries.

7.2 Form Factor and Model Uncertainties

With the measured values of $A_{\parallel}$ and $A_{\perp}$ and the other well known form factors [49–51], the value of G_E^n can be extracted using the values of $H^p_{TL'} = -0.085$, $H^n_{TL'} = 1.1$, $H^p_{T'} = -0.031$ and $H^n_{T'} = 1.1$ as determined from Fig. 4. This extraction will be sensitive to uncertainties from the form factors and specifics of the PWIA model [37]. In this section, we will list the expected uncertainties from these contributions to the extraction of the neutron EM form factors.

For this proposal, we make the following reasonable approximations about the uncertainties for G_E^p and G_M^p [50]:

- G_E^p: 1% for 0.5 – 1 (GeV/c)^2 and a linear increase up to 3% at 3 (GeV/c)^2.
- G_M^p: 1% over the full Q^2 range.

For G_M^n, we use the high precision data from Hall B [51], which has uncertainites between 2% and 2.4% in our Q^2 range. We estimated the uncertainty in the extraction of G_E^n by varying the inputs in Eq. (7) by the the amounts discussed above. We found that the uncertainty in the extracted value of G_E^n varied by 1.7% to 2.0% from the lowest to highest values of Q^2 in proposal. In Table 3, the contribution to the systematic uncertainty from each of the form factors is presented. We found that the uncertainty from G_E^p is approximately flat, whereas it decreases for G_M^p and increases for G_M^n with increasing Q^2.

Q^2 (GeV/c)^2	G_E^p [%]	G_M^p [%]	G_M^n [%]	Model [%]	$\left(\sigma_{syst}^{exp}\right)$ [%]
1.057	1.4	1	0.1	2.0	2.3
1.446	1.4	0.8	0.5	2.0	2.3
2.114	1.4	0.6	0.9	2.0	2.3
2.604	1.4	0.5	1.3	2.0	2.3

Table 3: The relative systematic uncertainties from the other nucleon form factors in the extraction of G_E^n, the model and experimental $\left(\sigma_{syst}^{exp}\right)$.

The authors of Ref. [35] presented a careful study of the model uncertainties in their extraction of G_M^n. The affects that were considered included contributions from the nucleon-nucleon (NN) potential model, relativistic effects, FSI, MEC, off-shell effects, three-body forces and Coulomb corrections. The total model uncertainty in the extraction of the neutron magnetic form factor was $\sim 2\%$ for $Q^2 \geq 0.5$ (GeV/c)^2. For this proposal, we have taken this value as the uncertainty for our extraction. We plan to seek further theory support to either verify or reduce the uncertainty for the PWIA extraction method.

Adding the experimental, form factor and model systematic uncertainties in quadrature results in a total systematic uncertainty for the experiment to be 3.6%. The projected data points are shown in Fig. 7, where the estimated values of G_E^n were obtained from the fit of Riordan *et al.* [14]. The figure also shows a few theoretical calculations as discussed in Section 2.2 with which the precision of our proposed data will allow us to distinguish between them.

8 Summary

We propose high precision asymmetry measurements of the $^3\overrightarrow{\mathrm{He}}(\overrightarrow{e}, e')$ channel in the quasi-elastic region to extract the electric form factor of the neutron. This measurement is an

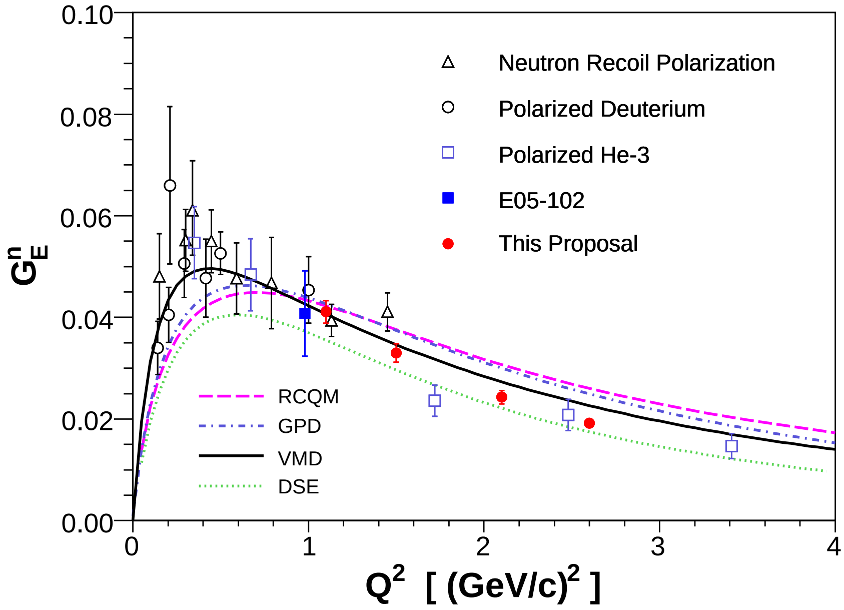

Figure 7: The solid circles show the Q^2 values of this proposal with the statistical and systematic uncertainties added in quadrature. The data are the same as described in Fig. 1. The calculations are RCQM (dashed line) [20, 21], GPD (dot-dashed line) [24, 25], VMD (solid line) [26, 27] and DSE (dotted line) [22, 23].

extension of the already approved Hall C polarized ^{3}He experiments and does not require any additional equipment. The experimental method proposed herein is unique from the other Jefferson Lab neutron electromagnetic form factor experiments and proposals in that it does not require detection of an out going neutron thus minimizing the uncertainty due to effects such as charge-exchange to which the other techniques are sensitive and will provide an important independent check in the determination of the neutron EM form factors.

With 15 days of beam, this proposal will measure G_E^n from 1 to 2.6 (GeV/c)^2 with a series of points with $4.5 - 6.5\%$ uncertainties.

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