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Measurement of ^{3}He Diffractive Minima with Polarization Observables

R.E. McClellan*†[1], D.W. Higinbotham†[1], J. Bericic[1], V. Sulkosky†[2], T. Averett†[3], and S. Sirca[4]

[1]Jefferson Lab, Newport News, VA, 23606
[2]University of Virginia, Charlottesville, VA, 22904
[3]William and Mary, Williamsburg, VA, 23185
[4]University of Ljubljana, 1000 Ljubljana, Slovenia

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Abstract

We propose to precisely determine the locations of the first diffractive minima in the electric and magnetic form factors of ^{3}He using polarization observables. All existing ^{3}He elastic form factor data has come from unpolarized experiments which utilized the Rosenbluth formula to separate the electric and magnetic components. More recently, double-polarization experiments have found large disagreement, especially at high-Q^2, between proton form factors extracted via polarization observables and those from Rosenbluth-separated, unpolarized experiments. This discovery calls in to question the validity of Rosenbluth-separated, high-Q^2, elastic form factor measurement for other targets, such as ^{3}He. Additionally, the existing ^{3}He data disagrees with recent model calculations in the high-Q^2 region. Most strikingly, the models and the data clearly disagree on the locations of the first diffractive minima in both the electric and magnetic ^{3}He form factors. The double-polarization asymmetry is proportional to the product of the electric and magnetic form factors. Thus, the zeros of the asymmetry correspond to the diffractive minima of the form factors. By measuring a double-polarization asymmetry, our measurement will be free from many of the systematic effects that afflict Rosenbluth-separation extractions. We intent to perform the first determination of the locations of first diffractive minima in the electric and magnetic elastic form factors of ^{3}He using polarization observables.

*contact: email randallm@jlab.org
†co-spokesperson

1 Introduction

The electric and magnetic form factors, G_E and G_M respectively, have been measured for many nuclei using the Rosenbluth formula:

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{Mott}}}{1+\tau}\left[G_E^2 + \frac{\tau}{\epsilon}G_M^2\right] \tag{1}$$

where $\tau = \frac{Q^2}{4M^2}$, $\epsilon^{-1} = 1 + 2(1+\tau)\tan^2\frac{\theta}{2}$, and σ_{Mott} is the point-like cross section. By taking elastic electron scattering data at constant Q^2 while varying ϵ (through θ and E_{beam}), the data for a given Q^2 can be plotted versus ϵ and a linear fit can extract G_E^2 (intercept) and $\frac{1}{\tau}G_M^2$ (slope) independently. This is the classic Rosenbluth separation technique.

An alternative approach is to fit all the data (at various Q^2 and θ) with a sufficiently general parameterization of $|G_E|$ and $|G_M|$. This approach has been used by Amroun *et al* [1] to extract the charge and magnetic form factors for ^{3}He and ^{3}H.

Through unpolarized elastic electron scattering experiments, $|G_E|$ and $|G_M|$ have been mapped out for various nuclei over the Q-range $\sim 0\,\text{fm}^{-2}$ to $\sim 40\,\text{fm}^{-2}$. However, the precision of the extracted results in constraining the position of the first diffractive minima are somewhat limited, especially for G_M. The data points in Figure 1 show the results of Amroun *et al.* To date, these are the best data on the elastic form factors of ^{3}He. Although the data are extremely precise at low-Q^2, the locations of the first diffractive minima, at higher-Q^2, are not precisely constrained.

Furthermore, it has been demonstrated [2] that Rosenbluth separation and polarization techniques yield systematically different elastic form factor results at high-Q^2. One explanation for this difference is the increasing contribution of two-photon exchange as the scattering angle is increased. Since ^{3}He, like the proton, is a light, spin-$\frac{1}{2}$ particle, it is reasonable to suspect that two-photon exchange may also have a significant effect on Rosenbluth extractions of ^{3}He form factors. In double-polarization experiments, where the high-Q^2 data can be taken at relatively low electron scattering angle, two-photon effects will be greatly reduced.

In recent theoretical calculations ([3][4][5][6][7]), the predictions for the locations of the minima show striking disagreement with existing experimental results. Figure 1 shows recent Chiral Effective Field Theory calculations by Piarulli *et al* [7] for the charge and magnetic form factors of ^{3}He plotted with data from Amroun *et al.* The theoretical calculations predict the location of the first diffractive minimum in the charge form factor at higher Q^2 than the measurement by Amroun *et al.* The calculations for the magnetic form factor predict a lower-Q^2 minimum than observed by experiment.

To date, no experiments have used polarization observables to measure the elastic form factors of ^{3}He at high-Q^2. A double-polarization elastic scattering experiment would provide an important, independent measurement of the elastic form factors at high-Q^2, complementary to the unpolarized, Rosenbluth-separated extractions.

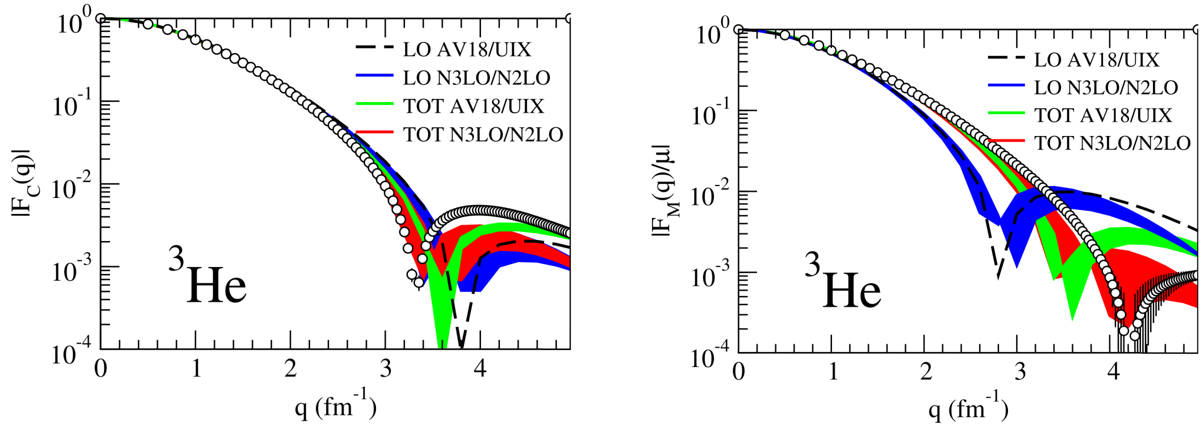

Figure 1: Predictions for the charge form factor (left) and magnetic form factor (right) of ^{3}He from Piarulli *et al* plotted vs data from Amroun *et al.* Plots taken from [7]

The asymmetry observable is given by:

$$A = \frac{-2\sqrt{\tau(1+\tau)}\tan\frac{\theta}{2}}{G_E^2 + \frac{\tau}{\epsilon}G_M^2}\left[\sin\theta^*\cos\phi^* G_E G_M + \sqrt{\tau[1+(1+\tau)\tan^2\frac{\theta}{2}]}\cos\theta^* G_M^2\right] \qquad (2)$$

where θ^* and ϕ^* are the polar and azimuthal angles of the polarization vector of the target (in the lab frame with $\hat{z}$ parallel with the virtual photon momentum, $\hat{q}$), and $\hat{x}$ in the scattering plane). The relative contributions of the cross term ($G_E G_M$) and the G_M^2 term can be experimentally controlled through the target polarization direction.

For the determination of the positions of the diffractive minima, the cross term is particularly compelling. Currently, knowledge of the diffractive minima for elastic scattering of light nuclei is constrained only by unpolarized experiments, which use the Rosenbluth formula to extract G_E^2 and G_M^2. By contrast, the double-polarization asymmetry is sensitive to the signs of G_E and G_M through the cross term. Since the diffractive minima of $G_E^2(Q^2)$ and $G_M^2(Q^2)$ correspond to the zeros of $G_E(Q^2)$ and $G_M(Q^2)$, a measurement of the zeros of the asymmetry cross term immediately determines the locations of the diffractive minima. Figure 2 shows a simple example of the double-polarization asymmetry versus Q^2. The exploitation of polarization observables should enable a more precise determination of the location of the first diffractive minima, especially for G_M, than is possible through Rosenbluth-style measurements of G_E^2 and G_M^2.

2 Proposed Procedure

We propose to precisely determine the locations of the first G_E and G_M diffractive minima of ^{3}He through the double-polarization asymmetry in elastic electron scattering off a polarized ^{3}He target in Hall C. Choosing the target polarization such that $\cos\phi^* \approx 1$ and $\theta^* \approx \pi/2$, the asymmetry becomes proportional to $G_E G_M$.

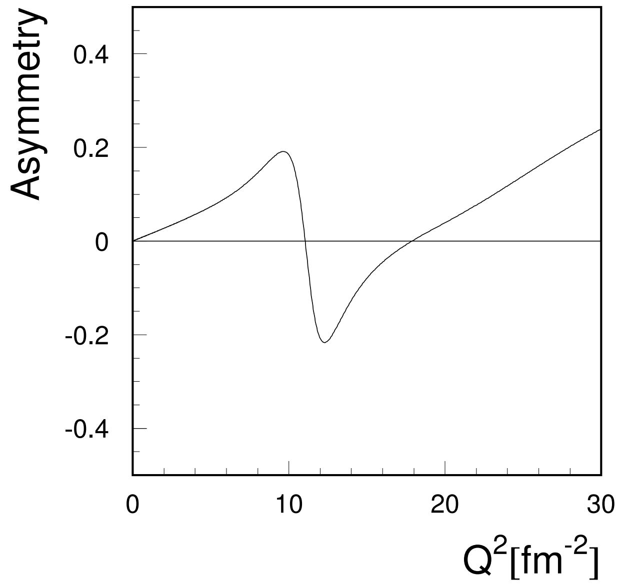

Figure 2: Example double-polarization asymmetry. The zero-crossings in the asymmetry correspond to the diffractive minima in G_E and G_M.

Table 1: Expected ^{3}He Target Characteristics

Length [cm]	Max Rate [μA]	Degree of Polarization
40	30	55%

We will take elastic $^3\text{He}(e, e')$ data in the Q^2 regions near the first diffractive minima of $|G_E|$ and $|G_M|$. Interpolating the locations of the zeros of the asymmetry, we will measure the precise locations of the diffractive minima.

2.1 Apparatus

The required apparatus is nearly identical to the approved E12-06-110 experiment. We require only SHMS (and possibly HMS) in standard configuration. For the target, we will use the new ^{3}He target being developed for E12-06-110 and E12-06-121. The expected target characteristics are listed in Table 1.

Due to the requirement of low electron scattering angle, this experiment will likely require small collimators to be placed around the endcaps of the target cell.

2.2 Beam Requirements

The primary trade-off is between the increase in statistical precision due to an increased Mott cross section at higher beam momentum and the increase in systematic uncertainty due to a smaller asymmetry amplitude at smaller θ.

Table 2: Choices of SMHS Central Kinematics

$E_{\mathrm{beam}}[GeV]$	Label	$\theta[^\circ]$	$Q^2[fm^{-2}]$	σ_{Mott}
4.4	k1	8.6	11.0	0.0213
	k2	11.1	18.1	0.0076
	k3	12.5	22.7	0.0047
6.6	k4	5.75	11.1	0.0476
	k5	7.35	18.0	0.0177
8.8	k6	5.5	18.1	0.0319
	k7	5.8	20.1	0.0258

Table 2 lists the central kinematics for some possible settings of SHMS. We anticipate requesting $30\,\mu A$ beam at 4.4 GeV, 6.6 GeV, and/or 8.8 GeV.

Based on very preliminary simulations, we expect to request approximately one week in Hall C.

2.3 Analysis

It is important to consider the systematic shift in the zeros of the asymmetry caused by the contributions from the G_M^2 term. In the ideal case, with perfect target polarization alignment and an infinitesimal acceptance, the G_M^2 term is completely removed due to the $\cos\theta^* = 0$ factor. However, in practice, there is always some non-zero contribution. If the target polarization is *centered* on the ideal alignment, then the positive and negative contributions from $\cos\theta^*$ will mostly cancel out. However, if a beamline-aligned target polarization is used then the polarization vector will be $\sim 10^\circ$ away from perpendicular to the q-vector, and there will be no G_M^2 self-cancellation. In this case, $|\cos\theta^*| \approx 0.17$.

The G_M^2 contribution to the asymmetry is also suppressed by a kinematic factor, $T \equiv \sqrt{\tau[1+(1+\tau)\tan^2\frac{\theta}{2}]}$. For the kinematic settings required for this experiment, T ranges from ~ 0.12 to ~ 0.17. Therefore, in the worst case, the coefficient suppressing the G_M^2-term is ~ 0.03.

3 Related Experiments

Since Amroun *et al* reported their unpolarized elastic form factor results for ^{3}He in 1994, no new experimental results have reported measurements of the diffractive minima. No current or proposed experiments plan to extract the ^{3}He elastic form factors in the vicinity of the diffractice minima.

Two approved experiments will make use of the polarized ^{3}He target for deep inelastic scattering. E12-06-110 will measure the neutron spin asymmetry, A_1^n. E12-06-121 will measure the neutron spin structure function, g_2^n.

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