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THE ELECTRIC FORM-FACTOR OF THE NEUTRON BY RECOIL POLARIMETRY

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Jefferson Lab experiment 93–038 is designed to measure the ratio of the electric to the magnetic form-factor of the neutron from the quasielastic $^2\mathrm{H}(\vec{\mathrm{e}}, \mathrm{e}'\vec{\mathrm{n}})^1\mathrm{H}$ reaction.

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1. *Scientific background and motivation*

The electric form-factor G_E^n of the neutron is a fundamental quantity needed for the understanding of both nucleon and nuclear structure. Knowledge of G_E^n is essential for testing quark models of particle structure, extracting the strange quark content of the proton from measurements of parity violating asymmetries, and making microscopic calculations of nuclear structure. The dependence of G_E^n on Q^2, the squared four–momentum transfer, is determined by the charge distribution within the neutron. The value for G_E^n is small and poorly known for all Q^2 except for the slope at $Q^2 = 0$, which was obtained to $\approx 2\%$ accuracy by scattering neutrons from atomic electrons [1]; however, the relationship between the neutron–electron scattering length and the slope of G_E^n suffers from a 20% model dependence that occurs when resonance corrections are applied [2]. Away from $Q^2 = 0$, information on G_E^n has been obtained from quasielastic and elastic e–d scattering. Results from elastic electron–deuteron scattering, where G_E^n is extracted indirectly from the charge structure function $A(Q^2)$ of the deuteron for $Q^2 < 0.75$ (GeV/c)^2, depend on the choice of deuteron wave functions [3,4]. The most recent results from a Rosenbluth separation of quasielastic electron–deuteron scattering cross sections at $Q^2 \geq 1.75$ (GeV/c)^2 yielded values of $(G_E^n)^2$ consistent with zero; however, the effects of final–state interactions (FSI) and meson–exchange currents (MEC) may be important [5]. With the recent advent of polarized electron beams and polarized nuclear targets, a new era for obtaining information about the charge structure of the neutron commenced.

2. Brief description of the experiment

A neutron polarimeter detects the recoil neutron from the quasielastic ^{2}H($\vec{\mathrm{e}}$,e'$\vec{\mathrm{n}}$)^{1}H reaction and measures up–down scattering asymmetries $\xi_{S'}$ and $\xi_{L'}$ related to $P_{S'}$ and $P_{L'}$, the non–zero transverse and longitudinal polarization components of the neutron, respectively. The scattered electron from the ^{2}H($\vec{\mathrm{e}}$, e'$\vec{\mathrm{n}}$)^{1}H reaction is detected with the high–momentum spectrometer (HMS) in coincidence with the recoil neutron. A dipole magnet placed in front of the neutron polarimeter with sufficient magnetic field strength to precess the neutron longitudinal polarization $P_{L'}$ into the transverse direction permits measuring the neutron scattering asymmetry $\xi_{L'}$. With another measurement of $\xi_{S'}$ (with the dipole magnet turned off) for the same kinematics as that of the measurement of $\xi_{L'}$, the ratio G_E^n and G_M^n is simply the ratio of the scattering asymmetries scaled by a kinematic function K_R:

$$g \equiv \frac{G_E^n}{G_M^n} = -K_R \left(\frac{\xi_{S'}}{\xi_{L'}} \right) \quad . \tag{1}$$

For a given Q^2, the kinematic function K_R is determined by the electron scattering angle θ_e in the ^{2}H($\vec{\mathrm{e}}$, e'$\vec{\mathrm{n}}$)^{1}H reaction.

A significant advantage of this technique for measuring the ratio of the two scattering asymmetries is that the scale and systematic uncertainties are minimal because the relative uncertainty in the analyzing power of the polarimeter does not enter into the ratio. The same is true for the beam polarization provided P_L does not change during the sequential measurement of $\xi_{S'}$ and $\xi_{L'}$. In contrast, the systematic uncertainties are larger in an analogous polarized–target experiment because the uncertainties in the target and the beam polarization must be included; also, the polarized target experiment has to make subtractions for the scattering asymmetry from the nitrogen in the ^{15}ND$_3$ target.

In the cross–ratio method of analysis of the scattering asymmetry measured in the polarimeter, Ohlsen and Keaton [6] showed that false asymmetries cancel to all orders from helicity–dependent errors in charge integration or system dead times, or in errors from detection efficiencies and acceptances; and that false asymmetries cancel to first order from misalignments with respect to the three–momentum transfer $\vec{q}$, or from a difference in the beam polarization for the two helicity states of the electron beam. The cross ratio is the ratio of two geometric means $(N_U^+ N_D^-)^{1/2}$ and $(N_U^- N_D^+)^{1/2}$, where $N_U^+(N_D^-)$ is the yield in the peak for scattering neutrons up (down) when the helicity of the beam is positive (negative).

The dipole magnet CHARYBDIS precesses the longitudinal component of the neutron polarization through 90°. This magnet has a 10-inch gap, which is large enough to illuminate fully the front detector of our neutron polarimeter (50-cm high × 100-cm wide). The CHARYBDIS magnet will permit measurements at five values of Q^2 [viz., $Q^2 = 0.52$, 1.00, 1.35, 1.61 and 1.81 (GeV/c)^2] with the neutron polarimeter and its shielding fixed at 46.0° for a beam energy per pass of 960 MeV. With a one-pass beam at an energy of 845 MeV, a point at $Q^2 = 0.43$ (GeV/c)^2 is accessible. The neutron energy resolution is sufficient to discriminate against neutrons associated with pion production.

The special advantage of this polarization–transfer measurement from the exclusive quasielastic $^2\mathrm{H}(\vec{\mathrm{e}}, \mathrm{e}'\vec{\mathrm{n}})^1\mathrm{H}$ reaction is that theoretical calculations predict the result to be insensitive to final–state interactions, meson–exchange currents, isobar configurations, leading–order relativistic effects, and the choice of deuteron wavefunction [7–10].

3. World data on G_E^n from polarized electrons on deuterium and polarized helium-3 targets and projections

Shown in Fig. 1 are the world's data on G_E^n extracted from measurements with a polarized electron beam on unpolarized deuterium and polarized helium–3 targets.

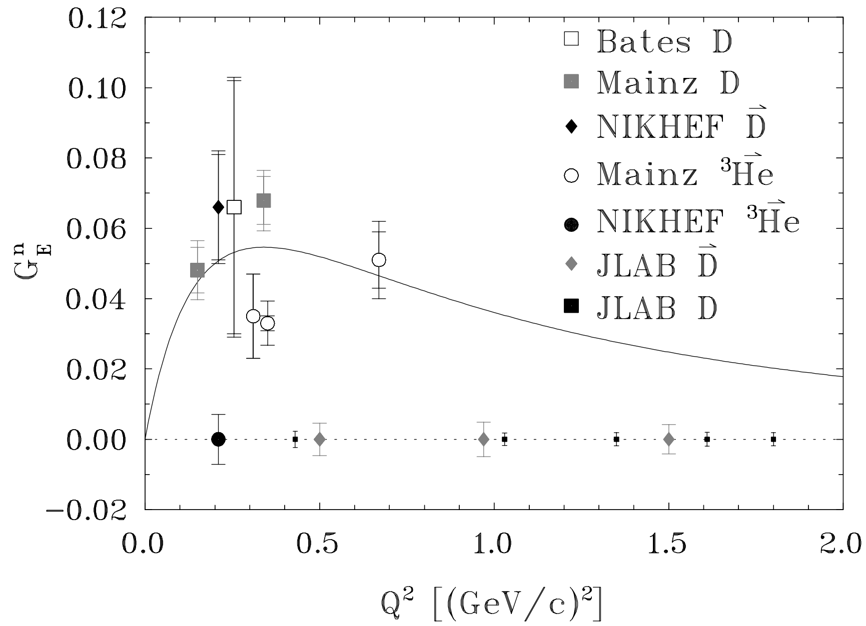

Fig. 1. The electric form-factor of the neutron G_E^n as a function of Q^2. The parameterization is from the work of Galster et al., where $G_E^n = -\tau\mu_n G_D(1 + 5.6\tau)^{-1}$. See text for explanation of points.

The pioneering measurement, carried out at Bates and reported by Eden et al. [11], is plotted as an open circle at $Q^2 = 0.255$ (GeV/c)^2. Subsequent recoil polarimetry measurements at Mainz are plotted as solid squares at $Q^2 = 0.15$ [12] and 0.34 [12] (GeV/c)^2; and subsequent measurements at Mainz with a polarized ^{3}He target are plotted as an open triangle at $Q^2 = 0.31$ (GeV/c)^2 [13] and open squares at $Q^2 = 0.35$ [14] and 0.67 [15] (GeV/c)^2; and a measurement at NIKHEF with an internal LD_2 target is shown as a solid diamond at $Q^2 = 0.21$ (GeV/c)^2 [16]. The inner error bars are statistical; the outer error bars represent the quadrature combination of systematic and statistical uncertainties. Two earlier measurements with a polarized ^{3}He target that were carried out at Bates at $Q^2 = 0.16$ [17] and 0.20 [18] (GeV/c)^2 are not shown because the error bars would extend beyond the scale shown in Fig. 1.

TABLE 1. Estimate of systematic uncertainties for JLab E93–038.

Uncertainty	$\Delta g/g$ (%)
Precession Angle	0.7
Beam Polarization	1.0
Neutron Detector Threshold (with Pulse–Height Stabilization)	< 1.0
Traceback & Positioning	1.3
False Asymmetry/Dilution: $(\vec{\mathrm{e}}, \mathrm{e}'\vec{\mathrm{p}}) + \mathrm{Pb}(\vec{\mathrm{p}}, \vec{\mathrm{n}})$	$2 \rightarrow 0$
Total	$3.6 \rightarrow 2.3$

TABLE 2. Estimate of systematic uncertainties for JLab E93–026.

Uncertainty	$\Delta g/g$ (%)
Target Polarization	5.0
Nitrogen Dilution	3.0
Beam Polarization	2.0
Neutron Detector Threshold	2.0
Traceback & Positioning	1.3
Total	6.6

Also shown in Fig. 1 on the $G_E^n = 0$ line are the predicted statistical uncertainties from three experiments planned or underway: One at NIKHEF [E94-05 (filled circle)], and two at Jefferson Lab [E93–026 (filled diamonds) and E93–038 (small filled squares)]. E93–038 plans to extract G_E^n at three of the five accessible Q^2 points. JLab E93–026 uses polarized-deuterium target; NIKHEF E94–05 uses a polarized ^{3}He target; and JLab E93–038 uses a neutron polarimeter [19] to measure the scattering asymmetry from an unpolarized deuterium target. Because the rear detectors in this polarimeter are shielded from the direct flux of particles from the target, this polarimeter can operate in a high luminosity environment. The statistical uncertainties for E93–038 utilize the analyzing powers and the efficiencies of the neutron polarimeter measured in Saturne E276 [20]. For JLab E93–038, the projected uncertainties are shown for Q^2 points of 0.43, 1.00, 1.35, 1.61 and 1.81 $(\mathrm{GeV}/c)^2$. For JLab E93–026, projected uncertainties are plotted for Q^2 values of 0.50, 1.00 and 1.50 $(\mathrm{GeV}/c)^2$. The statistical uncertainties from the polarimeter experiment [JLab E93–038] are expected to be significantly smaller than (typically one–half to one–third) those from the polarized target experiment [JLab E93–026]. Also the systematic uncertainties from E93–038 are expected to be typically one–half to one–third of those from E93–026. Estimated systematic uncertainties are listed in Table 1 for E93–038 and Table 2 for E93–026. Although the false asymmetry in E93–038 becomes negligible at $Q^2 \simeq 1.61$ $(\mathrm{GeV}/c)^2$ because the polarization–transfer coefficient becomes negligible at this Q^2, there is still a dilution of the measured asymmetry from the two-step process $^2\mathrm{H}(\vec{\mathrm{e}},\mathrm{e'}\vec{\mathrm{p}})+\mathrm{Pb}(\vec{\mathrm{p}},\vec{\mathrm{n}})$. The contribution to the systematic uncertainty $(\Delta g/g)_{2-\mathrm{step}}$ is assessed by running with liquid-hydrogen target long enough that it does not contribute significantly to the overall systematic uncertainty $(\Delta g/g)$. The value $(\Delta g/g)_{2-\mathrm{step}}$ is expected to be typically one-third of the statistical uncertainty at each Q^2.

4. *Conclusion*

Measurements of the neutron electric form-factor G_E^n from an unpolarized deuterium target by recoil polarimetry has the scientific potential for achieving significantly smaller statistical and systematic uncertainties than measurements of G_E^n from polarized targets.

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ELEKTRIČNI FAKTOR OBLIKA NEUTRONA POMOĆU ODBOJNE POLARIMETRIJE

Za mjerenje omjera električnog i magnetskog faktora oblika neutrona pomoću kvazielastične reakcije $^2\mathrm{H}(\vec{\mathrm{e}}, \mathrm{e}'\vec{\mathrm{n}})^1\mathrm{H}$ postavljen je eksperiment Jefferson Lab 93–038.