Recent and Future Measurements of the Neutron Electric Form Factor

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I review recently conducted measurements of $G_{En}$ as well as precision form factor experiments at high momentum transfer that will be performed with 11 GeV electron beam at Jefferson Lab.

1 Introduction

Measurements of the electromagnetic nucleon form factors are of great importance in trying to understand the quark substructure of the nucleon. They provide important constraints on generalized quark distributions (GPDs) that complement one-dimensional picture of hadron structure as a distribution of longitudinal momentum and helicity of partons with spatial information in the plane perpendicular to the direction of movement ("nucleon tomography"). GPDs fits to the Pauli form factors of proton and neutron allow to estimate helicity flip distributions, which play an essential role in understanding how the total spin of the nucleon is made up from quarks and gluons. Since proton form factors, for which data are abundant, are dominated by $u$ quarks, new high-quality data on the neutron form factors in a wide $Q^2$-range (especially, for electric form factor of neutron, $G_{En}$ above 3 (GeV/c)$^2$) would be highly valuable for pinning down the expected drastic differences in the spatial distribution of $u$ and $d$ quarks.

A precision measurement of $G_{En}$ from quasielastic electron scattering cross section is difficult as the neutron’s net charge is zero, and $G_{En}$ is small compared to the magnetic form factor of the neutron, $G_{Mn}$; nevertheless, the availability of high-duty-factor polarized electron beams and polarized targets over last decade made possible to extract $G_{En}$ with high precision from polarization observables based on the interference of $G_{En}$ with $G_{Mn}$. Left panel of Fig. 1 shows a summary of all published data (as of year 2006) on the neutron form factors employing recoil nucleon polarimetry with polarized electron beams and unpolarized targets [1, 2, 3, 4, 5], beam-target asymmetry measurements with polarized electron beams and polarized targets [6, 7, 8, 9, 10], and an analysis combining data on the deuteron quadrupole form factor with polarization-dependent observables $t_{20}$ and $T_{20}$ [11].

In the absence of a free neutron target, determinations of $G_{En}$ are typically carried out using quasielastic electron scattering from $^2H$ or $^3He$ targets that introduces large model-dependent corrections and uncertainties due to uncertainties in the theoretical description of the target nucleus, mostly from final-state interactions and meson-exchange currents. In addition, the contribution from the protons in the target nucleus might introduce significant uncertainty into the final result and should be a subject of a special attention during experiment design and analysis periods. A flux of quasielastic protons from deuterium or helium target is few times higher than the flux of quasielastic neutrons; thus, relatively small misidentification of protons as neutrons might lead to serious proton contamination of neutron data. Though the results
dilution due to the leak of close-to-quasifree protons through veto detectors and analysis cuts can be reliably estimated with careful Monte-Carlo simulation of the detector setup and verified experimentally with liquid hydrogen target, the correction of the proton contribution from large-missing-momentum quasielastic and inelastic reactions is not straightforward. If the neutron detector aperture is not surrounded with thick shielding and not protected with high magnetic field (that deflects all protons away of the neutron detector) or large-area and high-efficiency PID system (viz., veto that covers whole detector materials including construction elements), the "non-quasifree" proton might hit the neutron detector material aside of the nominal active detector area and produce secondary particles (charged and neutral) that will make a "fake" hit (or hits) nearby "expected-quasifree-neutron" hit position (possibly, behind not-fired veto detector). Simulation and correction of such effect require knowledge of exact disposition of the experimental setup materials as well as include calculations of model-dependent polarization observables in non-quasifree region; these corrections might introduce significant systematic uncertainty in the final result.

Figure 1: Left panel (from paper [1]): The world data (as of year 2006) on $G_{En}$ versus $Q^2$ extracted from polarization measurements and an analysis of the deuteron quadrupole form factor [2, 3, 1, 4, 5, 6, 7, 8, 9, 10, 11]. The Galster parameterization [12] is shown as a solid curve. Right panel (from paper [14]): The world data from polarization measurements (see references in [14]). The solid circles show the results of BLAST experiment. The new BLAST parameterization of $G_{En}$ is shown as a solid line with one-sigma error band.

2 Measurements at Low $Q^2$

To study low-$Q^2$ region in a systematic manner and provide improved nucleon form factor data, the Bates large acceptance spectrometer toroid (BLAST) experiment was operated at the MIT-Bates Linear Accelerator Center in 2004/2005 [13]. The experiment used a longitudinally polarized ($\sim 70\%$) electron beam of $\sim 200$ mA stored in the South Hall Storage Ring; an internal polarized ($\sim 80\%$) gas target of deuterium provided by an atomic beam source, and a left-right symmetric detector based on a toroidal spectrometer with tracking ($\delta p/p \approx 3\%$, $\delta \theta \approx 0.5^\circ$), time-of-flight, Cherenkov, and neutron detectors. This advanced PID system provided clean identification of neutrons and protons in the detector acceptance of $\theta \approx 20-80^\circ$ and $\phi \approx \pm 15^\circ$; and with beam-target luminosity $L = 6 \times 10^{31}$ cm$^{-2}$s$^{-1}$, the $g \equiv G_{En}/G_{Mn}$ was extracted from beam-target asymmetries $A_{cd}^V = P_e P_n V (a \sin \theta^* \cos \phi^* g + b \cos \theta^*)/(cg^2 + 1)$ at $Q^2 = 0.14, 0.20, 0.29$ and $0.42$ (GeV/c)$^2$ with statistical uncertainty of about 12-16\%. In the formula above, $P_e$ and $P_n$ are the beam and the target polarizations, $V$ is dilution factor, $\theta^*$ and $\phi^*$ are the target
spin orientation angles with respect to momentum transfer vector, and \(a, b, \text{ and } c\) are kinematic factors. A systematic uncertainty of \(\sim 6.5\%\) was dominated by target spin angles uncertainties. Experiment results were published in [14] and shown in the right panel of Fig. 1; more BLAST measurements in \(Q^2\)-range between 0.6 and 0.8 (GeV/c)^2\) are expected. The distribution of all \(G_{E_n}\) data shown in the right panel of Fig. 1 was parameterized by BLAST collaboration as a function of \(Q^2\) based on the sum of two dipoles, \(\sum a_i/(1 + Q^2/b_i)\) \((i = 1, 2)\). The new data from BLAST do not show a bump structure at low \(Q^2\) as suggested in [5] (shown as a dash-dotted line in the right panel of Fig. 1); the improved precision of the data provides strong constraints on the theoretical understanding of the meson cloud in nucleon and important for extraction of weak form factors.

3 Measurements at High \(Q^2\) via recoil polarimetry

JLab E93-038 collaboration carried out measurements of \(G_{E_n}\) in 2000/2001 at three values of \(Q^2\) (viz., 0.45, 1.13, and 1.45 (GeV/c)^2\) [1]. The reported values of the ratio of the neutron electric to magnetic form factor ratio, \(G_{E_n}/G_{M_n}\), represent both the highest \(Q^2\) extraction and most precise published determinations of \(G_{E_n}\) with relative statistical uncertainties of 8.4% and 9.5% at the two highest \(Q^2\) points and relative systematic uncertainties of 2-3%. In the recoil polarimetry technique, value of \(g \equiv G_{E_n}/G_{M_n}\) is extracted from measurements of the neutron’s recoil polarization in the quasielastic scattering of longitudinally polarized electrons from unpolarized neutrons in deuterium; in the one-photon-exchange approximation, \(g = -(K_L/K_S)(P'_S/P'_L)\), where \(P'_S\) and \(P'_L\) are the transverse and longitudinal components of the neutron’s recoil polarization, and \(K_L\) and \(K_S\) are kinematic factors. Ratio of polarization components is accessed via measurement of the ratio of up/down asymmetries of the recoil neutron scattering in the neutron polarimeter for 2 angles of the neutron spin precession in the dipole magnet in the front of the polarimeter (see left panel of Fig. 2). A significant advantage of the recoil polarimetry technique is that both the electron beam polarization \(P_e\) and the polarimeter analyzing power \(A_p\) cancel in the \(P'_S/P'_L\) ratio, resulting in small systematic uncertainties; the nuclear corrections are small in this ratio technique. Also, the cross-ratio technique used for extraction of up/down asymmetries is insensitive to beam charge asymmetry and the polarimeter geometrical asymmetry.

In 2009, JLab PAC34 approved proposal 09-006 [15] to extend precision extractions of \(G_{E_n}\) to 4.0, 5.2, and 6.9 GeV^2 with 12-GeV upgrade at JLab. The experimental arrangement was similar in principle to the one used in E93-038. With the polarized (\(\sim 80\%) electron beam current of 80 \(\mu\)A and 40-cm liquid deuterium target, the expected beam-target luminosity \(L = 1.02 \times 10^{39}\) is
few orders of magnitude higher than the luminosities of competing experiments with polarized $^3\text{He}$ target at JLab (E02-013 and E09-016). The polarimeter to be used for these measurements (see right panel of Fig. 2) is an enhanced version of the one used for E93-038. Increased vertical acceptance of the polarimeter was better matched with high-resolution electron spectrometer (SHMS); in order to increase the polarimeter efficiency, more thick polarimeter analyzer is used as well as 3-cm steel converters were inserted ahead of each layer in the rear detector arrays. The thickness of the converters was optimized to maximize the gain in the detection efficiency for neutrons. The polarimeter was located in the bunker with the collimator that was small enough to allow illumination of the active area of the polarimeter analyzer only; used for spin precession 4.5-Tm dipole magnet removed almost all charged particles (including protons) from the polarimeter acceptance. With deuteron target, missing momentum of the quasielastic scattering can be obtained with high accuracy from high-precision scattered electron kinematics information ($\delta p_e/p_e = 0.03 - 0.08\%$) and a direction the recoil neutron trajectory without usage of not-very-accurate measurement of high recoil neutron momentum via TOF; an accurate cut on the missing momentum allows efficiently select quasielastic events.

Recently, to increase the efficiency of the neutron polarimeter and access neutron scattering at relatively small angles (where the maximum of analyzing power is located), an updated version of the polarimeter was proposed to be used for these measurements (see left panel of Fig. 3). At high $Q^2$ values, the higher energy of the quasielastic neutron from the target allows detection of the recoil proton (instead of detection of the scattered neutron as was proposed in the original proposal to PAC34). In the updated polarimeter, the scintillation detectors of the former rear array are re-arranged and located above and below the front array to cover the solid angle expected for the recoil protons. The front array consists of six columns of scintillators with a 20-cm spacing between columns. Each column consists of one layers of six 10-cm thick scintillators. This segmented structure of the “scintillator analyzer” minimizes the absorption of the recoil proton inside the front array and provides about 17, 21, and 26% recoil-proton detection efficiencies for the 4-15-degree range of quasielastic neutron scattering at $Q^2 = 4.0, 5.2,$ and $6.9$ (GeV/c)$^2$; in contrast, the neutron polarimeter in the PAC34 proposal had an efficiency of only 2-3% for detecting the scattered neutron. The increased efficiency of the polarimeter allows to use a 60-cm high front array (instead of 120-cm-high front array in the PAC34 proposal) and thereby facilitates the search for the high-field (about 4.5 Tm) dipole magnet that is needed for optimal precession of the quasielastic neutron spin. A double layer of veto/tagger detectors is located ahead of the front array. The thin scintillator detectors are located in between the top/bottom arrays and the front array; analysis of the amplitudes of signals from these detectors together with the signal amplitudes from the detectors of the top/bottom arrays will provide $\Delta E-E$ identification of the recoil protons (in addition to the measurements of TOF between the front and top/bottom array detectors). High segmentation of the scintillator detectors in the polarimeter will allow one to reconstruct reliably the polar angle of the recoil proton with an accuracy of 5-6 degrees that will permit controlling the angle of the neutron scattering in the front array with an accuracy of 1.5-2 degrees (to maximize the FOM) and practically eliminate the loss of statistics associated with accidental coincidences of the quasielastic neutrons and detected background particles in the front array. The new polarimeter increases the experiment FOM by a factor of about 3, and allows to reach the statistical uncertainties of about 13, 16, and 26% at $Q^2 = 4.0, 5.2,$ and $6.9$ (GeV/c)$^2$ (see Fig. 4). The projected total systematic uncertainties are on the order of 3%; a few of the larger systematic uncertainties resulted from fluctuations in the beam polarization (between measurements of the asymmetries at different neutron spin precession angles) and uncertainties in the spin precession angle.
Further dramatic improvement of the FOM of the experiment can be reached with use of a tank with liquid hydrogen instead of the scintillator analyzer in the neutron polarimeter (see right panel of Fig. 3). A liquid-hydrogen-analyzer concept was considered more than 10 years ago by HARP collaboration at NIKHEF to measure $G_{En}$ with high precision in the range of $Q^2$ in between 0.5 and 1 (GeV/c)$^2$ [16], but that project was not realized (because of significant cost of the project and visible absorption of the recoil protons in the analyzer materials). In high-$Q^2$ range of E09-006, insignificant absorption of the recoil protons in the liquid hydrogen compensates a relatively small effective thickness of 150-cm-long analyzer, and well-known analyzing power for $np$ scattering is 2-2.5 times higher than one for $CH_2$ [17] that results in the statistical uncertainties of about 6 and 15% at $Q^2 = 4$ and 6.9 (GeV/c)$^2$. Most probably, long and expensive development and production will be needed for about 300-litter $LH_2$ tank to satisfy the safety requirements in Jefferson Lab; nevertheless, advantages of use of the liquid-hydrogen analyzer remove all principal limits of $G_{En}$ measurements at even higher $Q^2$ values.

Figure 4: Predictions of selected models compared with neutron data. Solid-star symbols are located according to the BLAST $G_{En}$ parameterization and represent projected uncertainties in JLab E09-006 experiment with distributed scintillator analyzer.

### 4 Measurements at High $Q^2$ via beam-target asymmetry

In 2006, E02-013 collaboration at JLab conducted measurements of $G_{En}$ in $Q^2$ range between 1.2 and 3.4 (GeV/c)$^2$ via measurements of asymmetries of recoil neutron fluxes from interaction of
polarized (∼75%) electron beam with polarized (∼50%) $^3$He target. Main idea of the experiment was to match large acceptance of scattered electrons detection in the BigBite spectrometer (∼76 msr) with large acceptance of the neutron detector (∼80 msr). Relatively small (about 1250 times lower than in the JLab E09-006 experiment) beam-target luminosity of about $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$ (that corresponds to a 12 μA electron beam with 40-cm $^3$He gas target at about 10 atmospheres pressure) was declared in the original proposal [18], and was limited by abilities of charge track reconstruction system of open-acceptance BigBite spectrometer. With this declared luminosity, the expected statistical uncertainty was about 14% at high $Q^2$ point. The final results of this experiment are not published yet; nevertheless, neutron detector in E02-013 experiment had no neutron aperture collimator and was not shielded from charged particles with magnet field; open exposure of the neutron detector to the intensive flux of protons from the target might lead authors to reconsider the expected in the original proposal systematic uncertainty of about 10%. Direct comparison of the $G_{En}$ result from E02-013 at $Q^2$ in the range of 1.2-1.5 (GeV/c)$^2$ with the high-precision measurements of E93-038 experiment as well as with the result of recently conducted experiment of A1 group at Mainz with polarized $^3$He target at $Q^2 = 1.5$ (GeV/c)$^2$ [19] might help estimate systematics in E02-013 measurements.

In 2009, JLab PAC34 approved proposal 09-016 [20] to extend measurements of $G_{En}$ with $^3$He target to 5.0, 6.8, and 10.2 GeV$^2$ with 12-GeV beam upgrade at JLab, upgraded Super-BigBite spectrometer, and enhanced neutron detector located at the small angle of 17 degrees in respect to the beam direction. With significantly higher than in E02-013 electron beam current of ∼65 μA, authors expect to reach the statistical uncertainty of about 20%; the expected systematic uncertainty is about 8%.

5 Conclusions

Recently conducted and planning $G_{En}$ experiments at Jefferson Lab, MIT and Mainz will extend the covered $Q^2$ range to be similar to the $Q^2$ range covered by other electromagnetic nucleon form factor measurements. Direct comparison of the experimental $G_{En}$ results is required for analysis of systematic uncertainties introduced by different measurement techniques.

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