Neutron Electromagnetic Form Factors

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Because of the lack of a free neutron target, deuterium targets had been used extensively in studying the neutron structure in the past from unpolarized electron-deuteron scattering experiments. Only recently polarized electron-deuteron scattering measurements have been performed which yield more precise information on the charge form factor of the neutron. The unique spin structure of the ^{3}He ground state wave function and the recent developments in polarized target technologies make polarized ^{3}He targets very effective neutron targets. Polarized ^{3}He targets have been employed in the last decade or so at all major electron accelerator facilities in experiments probing the neutron electromagnetic structure. In this talk, I review the experimental status of the neutron electromagnetic form factor studies. The recently completed Jefferson Lab experiment E95-001, a precision measurement of the neutron magnetic form factor at low Q^2 is discussed, also discussed are some of the future experiments.

1 Introduction

Electromagnetic form factors are of fundamental importance for an understanding of the underlying structure of nucleons. Knowledge of the distribution of charge, magnetization within the nucleons provides a sensitive test of models based on Quantum Chromodynamics (QCD), as well as a basis for calculations of processes involving the electromagnetic interaction with complex nuclei. The understanding of the nucleon structure in terms of quark and gluon degrees of freedom of QCD will provide basis to understand more complex strongly interacting matter at the level of quarks and gluons.

Electron scattering has been proven to be a very useful tool in probing structures of nucleon and nuclei. The leptonic part of the vertex is well understood from Quantum Electrodynamics (QED), thus it is a clean probe of the hadronic structure. Furthermore, the electromagnetic coupling constant is relatively weak, higher order diagrams are suppressed compared to the lowest order one-photon-exchange diagram. Proton electromagnetic form factors have been well studied over the years using the technique of Rosenbluth separation from elastic electron-proton scattering.

Lacking of a free neutron target, the neutron electromagnetic form factors are known with much less precision than proton electromagnetic form factors. They have been deduced in the past from unpolarized elastic or quasielastic electron-deuteron scattering. This procedure involves considerable model dependence and a subtraction of large proton contribution is involved. The other complication arises from the fact that the net charge of the neutron is zero. Thus, the neutron electric form factor G_E^n is much smaller than its magnetic form factor G_M^n at low Q^2. Furthermore, the magnetic part of the contribution dominates the cross section, making it very difficult to extract G_E^n from unpolarized cross section measurements using deuterium targets.

2 Existing data on G_E^n

The most precise information on G_E^n at low Q^2 prior to any polarization experiment is from elastic electron-deuteron scattering experiment by Platchkov *et al.* [1]. However, the extracted G_E^n values are extremely sensitive to the deuteron structure. Fig. 1 shows the G_E^n values extracted with the Paris potential together with the fit of the data (dash-dotted curve). Fits from fitting the G_E^n data extracted with the Nijmegen potential, the Argonne V14 (AV14) and the Reid-Soft Core (RSC) NN potentials are shown as solid, dashed and dotted curves, respectively. The large spread represents the uncertainty of G_E^n due to the deuteron structure, and the absolute scale of G_E^n contains a systematic uncertainty of about 50% from the measurement by Platchkov *et al.* [1].

The development of polarized targets and beams has allowed more complete studies of electromagnetic structure than has been possible with unpolarized reactions. In quasielastic scattering, the spin degrees of freedom introduce new response functions into the differential cross section, thus providing additional information on nuclear structure [2]. Experiments with longitudinally polarized electron beams and recoil neutron polarimeters have been carried out at MIT-Bates [3] and Mainz [4,5] and G_E^n has been extracted from the $d(\vec{e}, e'\vec{n})$ process. Recently, the neutron electric form factor was extracted for the first time [6] from $\vec{d}(\vec{e}, e'n)$ reaction in which a vector polarized deuteron target from an atomic beam source was employed. Using the polarization degrees of freedom, the proton contribution to the scattering process is suppressed and more precise information on the neutron charge form factor can be extracted.

^{3}He is an interesting nucleus for polarization studies because its ground state wave function is predominantly a spatially symmetric S state in which the spin of the nucleus is carried mainly by an unpaired neutron. Therefore, inelastic scattering of polarized electrons from polarized ^{3}He in the vicinity of the quasielastic peak should be useful for studying the neutron electromagnetic form factors.

The idea of using polarized ^{3}He nuclear target as an effective neutron target was first investigated by Blankleider and Woloshyn in closure approximation[7]. Friar *et al.* [8] have studied the model dependence in the spin structure of the ^{3}He wave function and its effect on the quasielastic asymmetry. The plane wave impulse approximation (PWIA) calculations performed independently by two groups [9,10] using spin-dependent spectral functions show that the spin-dependent asymmetries are very sensitive to the neutron electric or magnetic form factors at certain kinematics near the top of the quasielastic peak. Recently, Fadeev calculations have been carried out which include the final state interaction (FSI) [11], FSI and meson exchange current (MEC) [12]. These state-of-the-art three-body calculations are very important for extracting the neutron form factors from double polarization electron-^{3}He scattering experiments.

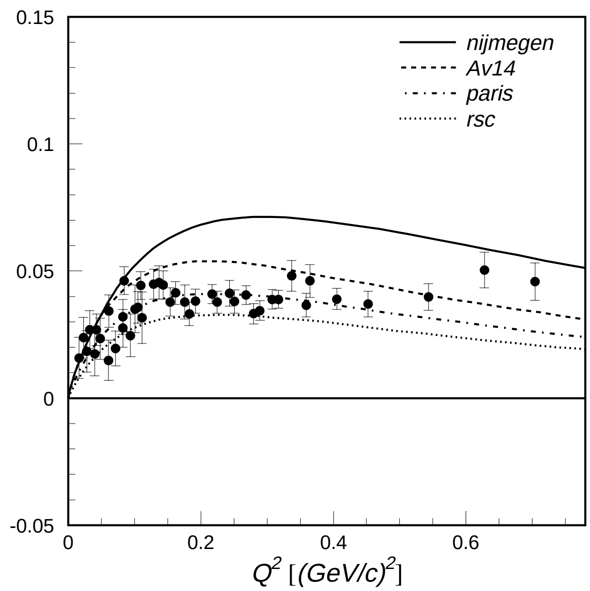

Figure 1: The electric form factor of the neutron as a function of four-momentum transfer from Platchkov *et al.* [1].

The measured asymmetry for the quasielastic $^3\vec{H}e(\vec{e},e'n)$ reaction can be expressed as follows in PWIA:

$$A = -P_e\ P_n\ D \left\{ \frac{2\sqrt{\tau(\tau+1)}tan(\vartheta_e/2)G_E^n G_M^n sin(\theta^*)cos(\phi^*)}{{G_E^n}^2 + {G_M^n}^2(\tau + 2\tau(1+\tau)tan^2(\vartheta_e/2))} \right. \ +$$

$$\left.\frac{2\tau\sqrt{1+\tau+(1+\tau)^2 tan^2(\vartheta_e/2)}tan(\vartheta_e/2){G_M^n}^2 cos(\theta^*)}{{G_E^n}^2+{G_M^n}^2(\tau+2\tau(1+\tau)tan^2(\vartheta_e/2))}\right\} . \quad (1)$$

Here P_e is the electron polarization, P_n is the neutron polarization, D is an overall dilution factor which contains dilution from (possible) unpolarized neutrons in the target and dilution from background neutrons generated in (p,n) reactions, e.g. in shielding walls. $\tau = (Q^2/4\ M_n^2)$, ϑ_e is the electron scattering angle, θ^* is the polar angle of the ^{3}He spin vector relative to the **q** vector, and ϕ^* is the azimuthal angle of the target spin vector relative to the scattering plane. Eqn. 1 shows the obvious sensitivity to G_E^n in the longitudinal-transversal interference term. Therefore, by aligning the target spin perpendicular to **q**, i.e. choosing θ^* equals 90°, and ϕ^* equals 0° the above equation can be rewritten in the following form:

$$G_e^n = -\frac{A_{perp}}{P_e P_n D}\cdot\frac{G_M^n(\tau+2\tau(1+\tau)tan^2(\vartheta_e/2))}{2\sqrt{\tau(1+\tau)}tan(\vartheta/2)} \quad (2)$$

Aligning the target spin parallel to $\vec{q}$ reduces Eqn. 1 to (${G_E^n}^2 \approx 0$):

$$A_{long} = -P_e P_n D\frac{2\sqrt{1+\tau+(1+\tau)^2 tan^2(\theta_e/2)}tan(\theta_e/2)}{1+2(1+\tau)tan^2(\theta_e/2)}. \quad (3)$$

This equation is completely independent of the neutron form factors and serves as an excellent calibration reaction. Thus, one can combine the above two equations and obtain

$$G_E^n = \sqrt{\tau+\tau(1+\tau)tan^2(\theta_e/2)}\frac{A_{perp}}{A_{long}}G_M^n. \quad (4)$$

The first experiments [13,14] which investigated the feasibility of using polarized ^{3}He targets to study the neutron electromagnetic structure from the inclusive quasielastic scattering were performed at the MIT-Bates Linear Accelerator Center. Following these two experiments, the first measurement of G_E^n from $^3\vec{H}e(\vec{e},e'n)$ was reported by Meyerhoff *et al.* [15] in which a high pressure polarized ^{3}He target achieved by the metastability-exchange optical pumping technique and the compression method was employed. Fig. 2 shows the published result of G_E^n from these double polarization experiments together with those discussed earlier in which either a recoil neutron polarimeter or a vector polarized deuteron target was employed. The results extracted from the elastic deuteron response using three different NN potentials [1] are also shown. The NIKHEF G_E^n value and the Mainz G_E^n value ($Q^2 = 0.15$ (GeV/c)^2) were obtained using the full calculation of Arenhövel [16]. The correction to G_E^n from final state interaction is significant at low Q^2 in the deuteron case and the correction to G_E^n due to FSI effect is expected to be more significant in the case of $^3\vec{H}e(\vec{e}, e'n)$. The remaining values of G_E^n shown in Fig. 2 were based on PWIA. In addition to these published double-polarization experiments, several measurements from quasielastic $^3\vec{H}e(\vec{e}, e'n)$ reaction have been carried out recently at Mainz [17] and NIKHEF [18] and the results of G_E^n from these experiments with FSI effect taken into account [19] are expected to be released in the very near future. The first Jefferson Lab experiment of G_E^n measurement from quasielastic $\vec{D}(\vec{e}, e'n)$ reaction [20] was partially completed and the preliminary result of G_E^n at $Q^2 = 0.5, 1.0$ (GeV/c)^2 is expected soon [21].

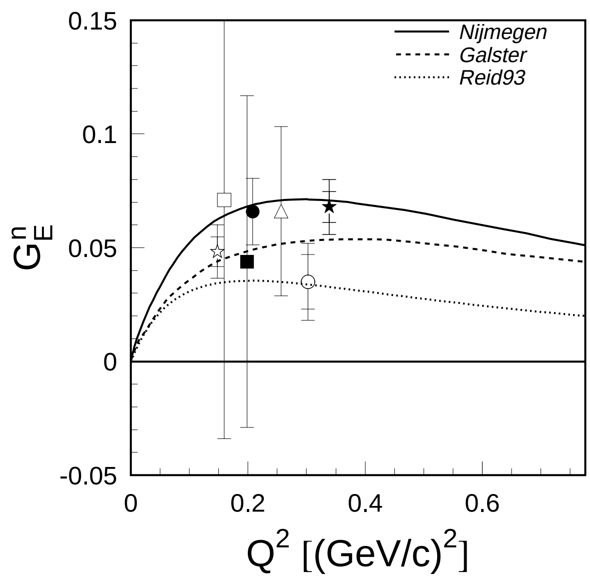

Figure 2: The electric form factor of the neutron as a function of four-momentum transfer from double polarization experiments. The open and the close stars are the Mainz results from the recoil neutron polarization measurements by Herberg *et al.* and by Ostrick *et al.*, respectively. The solid circle is the NIKHEF result, the open triangle is from Eden *et al.* (MIT-Bates) and the open circle is from Meyerhoff *et al.* (Mainz). The open and solid squares are from Jones *et al.* and Thompson (MIT-Bates) *et al.*, respectively.

3 G_M^n and $^3\vec{H}e(\vec{e}, e')$ process

The inclusive spin-dependent asymmetry for longitudinally polarized electrons scattered from a polarized spin-$\frac{1}{2}$ nuclear target can be written [2] as

$$A = -\frac{\cos\theta^* v_{T'} R_{T'} + 2\sin\theta^* \cos\phi^* v_{TL'} R_{TL'}}{v_L R_L + v_T R_T}, \tag{5}$$

where the v_K are kinematic factors, and θ^* and ϕ^* are the polar and azimuthal angles of the target spin with respect to the 3-momentum transfer vector $\mathbf{q}$. $R_L(Q^2,\omega)$ and $R_T(Q^2,\omega)$ are the longitudinal and transverse nuclear response functions associated with the unpolarized cross section and are functions of the square of the 4-momentum transfer, Q^2, and the electron energy transfer ω. $R_{T'}(Q^2,\omega)$ and $R_{TL'}(Q^2,\omega)$ are the two response functions arising from the polarization degrees of freedom. $R_{T'}$ is a transverse response function and $R_{TL'}$ represents the interference between the transverse and the longitudinal multipoles. By orienting the target spin at $\theta^* = 0°$ or $\theta^* = 90°$, corresponding to the spin direction either along the 3-momentum transfer vector $\mathbf{q}$ or normal to it, one can select the transverse asymmetry $A_{T'}$ (proportional to $R_{T'}$) or the transverse-longitudinal asymmetry $A_{TL'}$ (proportional to $R_{TL'}$).

For inclusive quasielastic $^3\vec{H}e(\vec{e},e')$ process, the transverse asymmetry $A_{T'}$ can be written within PWIA as:

$$A_{T'} \sim \frac{\sigma_n {G_M^n}^2}{\sigma_n + 2\sigma_p} \tag{6}$$

The sensitivity of $A_{T'}$ to the neutron magnetic form factor is clear from Eqn. 6 based on the simple PWIA picture which neglects the FSI and MEC effects. Recent calculations which include FSI [11], FSI and MEC [12] verified that $A_{T'}$ near top of the quasielastic peak is extremely sensitive to ${G_M^n}^2$. Thus, one can extract information on G_M^n by measuring the quasielastic transverse asymmetry $A_{T'}$ from $^3\vec{H}e(\vec{e},e')$ process.

Fig. 3 shows the measured ^{3}He inclusive spin-dependent quasielastic transverse asymmetry $A_{T'}$ [22], as a function of the electron energy transfer, ω, together with the two PWIA [23,24] calculations and the calculation by Ishikawa *et al.* [11]. The deviation of the result by Ishikawa *et al.* [11] from those of PWIA calculations [23,24] is significant away from the quasielastic peak. The agreement between the data on $A_{T'}(\omega)$ and the calculation by Ishikawa *et al.* is excellent in terms of the magnitude of the asymmetry and also the shape. Unfortunately, because of the large errors associated with the measured $A_{T'}(\omega)$ as shown in Fig. 3, it is not possible to put constraints on the theoretical calculations of the ^{3}He inclusive spin-dependent quasielastic asymmetry.

Because of the limitation of the statistics of the MIT-Bates measurement [22], the measured quasielastic asymmetry, $A_{T'}(\omega)$, averaged over the experimental ω acceptance was used in extracting ${G_M^n}^2$ using the calculation of Ishikawa *et* *al.* [11]. The extracted G_M^n value from the Bates experiment was shown as solid circle in Fig. 4.

On the other hand, $A_{TL'}$ from quasielastic ${}^3\vec{H}e(\vec{e},e')$ at low Q^2 ($Q^2 \leq 0.3\ (GeV/c)^2$) is dominated by the proton contribution because of the smallness of ${G_E^n}^2$ together with the non S-state part of the ^{3}He ground state wave function. Thus, it is questionable to extract information on G_E^n at low Q^2 from ${}^3\vec{H}e(\vec{e},e')$ because of the large proton contribution to $A_{TL'}$. It is possible to go to higher Q^2 ($Q^2 > 0.3$ (GeV/c)^2) to extract G_E^n with respectable accuracy from quasielastic ${}^3\vec{H}e(\vec{e},e')$ measurement where the proton contribution to $A_{TL'}$ is under better control.

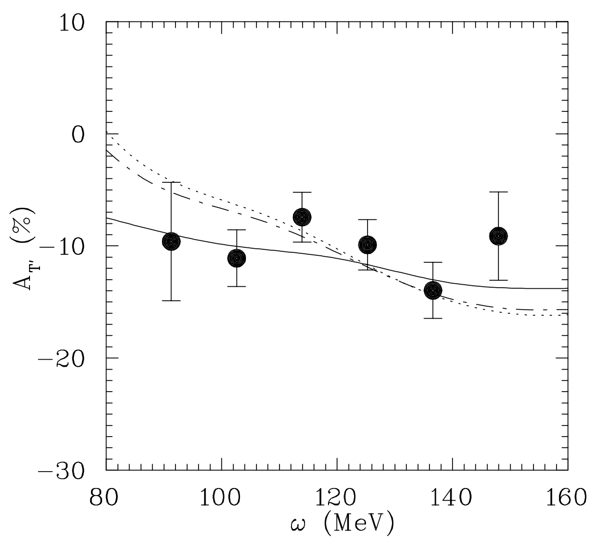

Figure 3: Transverse asymmetry $A_{T'}$ from MIT-Bates experiment [22] as a function of electron energy loss ω. The data are shown with statistical uncertainties only. The solid line is the calculation of Ishikawa *et al.*[11], the dashed line and the dash-dotted line are PWIA calculations of Salmè *et al.*[23] and Schulze & Sauer[24], respectively.

4 Jefferson Lab Experiment E95-001

To extract precise information on G_M^n from inclusive quasielastic $A_{T'}$ measurement, it is important to measure $A_{T'}$ with high precision across the ${}^3He$ quasielastic peak. As away from the quasielastic peak, predictions from different models deviate. Thus, one can constrain theoretical model using high precision data on $A_{T'}$ in the wings of the QE peak. To extract precise information on G_M^n, one can then use the measured $A_{T'}$ on top of the quasielastic peak, this is a procedure much less sensitive to model dependence. Recently, such a precision measurement, Jefferson Lab experiment E95-001 [25], of the inclusive quasielastic transverse asymmetry $A_{T'}$ has been carried out at the Jefferson Lab in a Q^2 range between 0.1 to 0.6 (GeV)^2.

Experiment E95-001 was carried out in Hall A at Jefferson Lab in January and February of 1999. The experiment was performed with longitudinally polarized electrons at beam energies of 0.778 and 1.727 GeV scattering off a high pressure polarized ^{3}He target. There are two High Resolution Magnetic Spectrometers (HRS) in Hall A, HRSe and HRSh stand for the electron arm and the hadron arm, respectively. The HRSe was employed for detecting quasielastically scattered electrons during E95-001. The hadron arm was used simultaneously during the experiment to detect elastically scattered electrons so as to measure the elastic asymmetry of longitudinally polarized electrons scattering off polarized ^{3}He nuclei. With the precise information on the ^{3}He elastic form factors determined from previous experiment [26], measuring the elastic asymmetry serves as a good monitor of the product of the beam and target polarizations. This technique allows the determination of the beam and target polarization product with unprecedented systematic accuracy than what can be achieved from any other polarimetry. A total number of 3.3 TB of data have been collected during this experiment. Currently, the data analysis of E95-001 is in progress.

Fig. 4 shows the expected precision of G_M^n measurement from Jefferson Lab experiment E95-001 (solid squares), together with the recently published measurements of G_M^n. The data by Markowitz *et al.* [27] shown as diamonds are from d(e,e'n) cross section measurement. In recent years, there has been significant progress in G_M^n measurements at low Q^2 with deuterium targets by measuring the ratio of $d(e,e'n)/d(e,e'p)$ to minimize the uncertainties associated with a deuterium target. The technical difficulty involved in the ratio measurement is again the absolute determination of the neutron detection efficiency. The data by Anklin *et al.* [28] (the triangle at $Q^2 \sim 0.1$ (GeV/c)^2) and Bruins *et al.* [29] (stars) were obtained from $D(e,e'n)/D(e,e'p)$ ratio measurements. The most recent data from Mainz [30] (triangles) were also obtained from the ratio measurement with a deuterium target. The MIT-Bates measurement [22] with a polarized ^{3}He target is shown as a solid circle. The Jefferson Lab experiment E95-001 will provide the most precise measurement of this fundamental quantity with a polarized ^{3}He target.

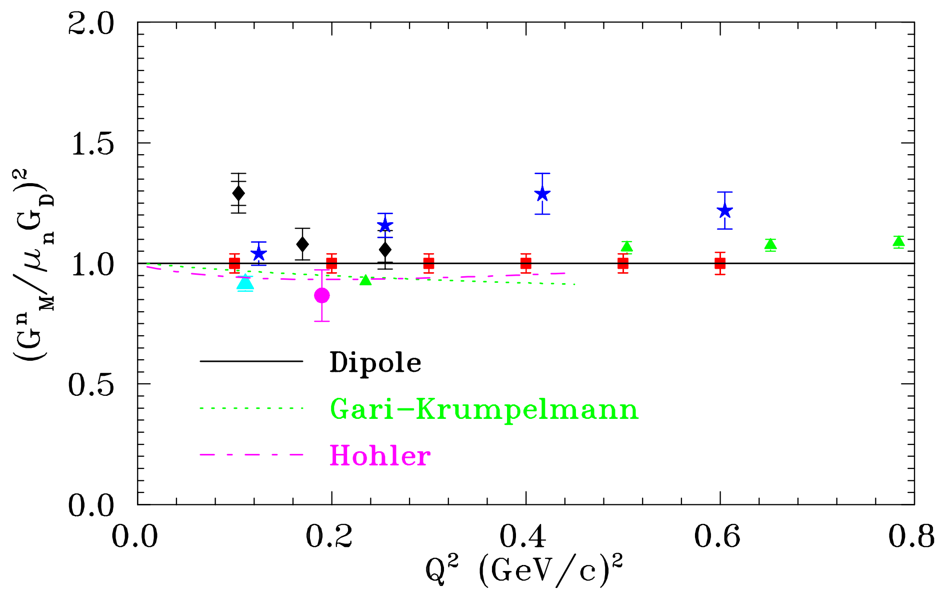

Figure 4: The square of the neutron magnetic form factor ${G_M^n}^2$, in units of the standard dipole parameterization, $(\mu_n G_D)^2$, in the low Q^2 region. The expected precision of the $(G_M^n)^2$ measurement from Jefferson Lab experiment E95-001 are shown as solid squares.

5 Future outlook

Significant progress has been made in understanding the neutron electromagnetic structure in the last decade or so mostly from double polarization experiments using both the deuterium and the ^{3}He targets. Many future experiments are planned at several electron accelerator facilities. At the new electron accelerator facility, Jefferson Lab, measurements of the neutron electromagnetic form factors at moderate and high Q^2 are planned [31]. At MIT-Bates, an extensive program [32] to carry out complete studies of spin-dependent responses in the few-body system with the South Hall Ring, Bates Large Acceptance Spectrometer Toroid (BLAST), and internal polarized targets (H/D, ^{3}He) is planned. The BLAST program is expected to provide the most precise information on the neutron electric form factor at low Q^2.

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