ELECTROMAGNETIC FORM FACTORS OF THE NUCLEON

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Elastic form factors provide information about the low energy structure of composite particles. Recent double polarization coincidence experiments significantly improved our knowledge of proton and neutron form factors. Recoil polarization measurements in the $p(\vec{e}, e'\vec{p})$ reaction proved that at momentum transfers above $Q^2 \simeq 1.5 \text{(GeV/c)}^2$ the electric form factor of the proton falls significantly faster than the dipole expectation. The close-to-dipole shape at low $Q^2$ of the neutron magnetic form factor is now confirmed by independent measurements. For the neutron electric form factor $^3\text{He}(\vec{e}, e'n)$, $D(\vec{e}, e'n)$ and $D(\vec{e}, e'\vec{n})$ double polarization experiments have provided model independent results, within their statistical errors in agreement with the Galster parameterization.

1. Introduction

In todays view the nucleon is composed of pointlike, almost massless current quarks and gluons as the mediators of the color forces between them. The dynamics is described by the quantum field theory of strong interaction, QCD. It is well tested at very high energies and momentum transfers, where the mutual interaction is weak enough for perturbative methods to be applicable. The nucleon appears dramatically different at low energies (where we find our surrounding matter). Here the non-linearity of QCD prohibits any exact ab initio calculation of hadron properties. This is the regime of constituent quarks as effective, multi-body degrees of freedom and the light mesons as the Goldstone bosons of chiral symmetry breaking. As for any composite, non–pointlike quantum mechanic particle a whole excitation spectrum builds upon the nucleon ground state. Although there remain decisive problems concerning the total number and individual nature of states, the basic properties of the spectrum can be successfully reproduced by constituent quark models. However, the transition between
the current and constituent quark regimes is not understood. Lattice QCD and chiral extrapolations yield hints for the masses of effective constituents, but dynamically generated constituent quarks could not yet been identified. Nevertheless, first promising results have been obtained for ground state properties like magnetic moments, polarizabilities and form factors.

The intimate connection of ground state observables to the high energy structure is made explicit by the concept of generalized parton distributions $H, \tilde{H}, E, \tilde{E}$ in exclusive deep inelastic reactions. At vanishing (Mandelstam) $t \to 0$ they fade to the usual unpolarized and polarized parton distributions for quarks and antiquarks, $H \to q(x), \tilde{H} \to \Delta q(x)$, whereas in the non–perturbative regime of small but finite $t$ integration over Bjørken $x$ yields the Dirac, Pauli and axial form factors

$$\int_{-1}^{1} dx H = F_1(t) \quad \int_{-1}^{1} dx E = F_2(t)$$

$$\int_{-1}^{1} dx \tilde{H} = g_A(t) \quad \int_{-1}^{1} dx \tilde{E} = h_A(t).$$

The elastic form factors parameterize the ability of the composite nucleon to incorporate a momentum transfer, $\vec{q}$, coherently, i.e. without excitation and particle emission. They are related to the distribution of charge and currents and therefore of fundamental importance for the understanding of nucleon structure.

Lepton scattering is a unique tool for the investigation of the electromagnetic structure of the nucleon. In the simplest approximation, it is characterized by the exchange of one virtual photon, which transfers the momentum $\vec{q}$ and the energy $\omega$. Electron scattering covers the spacelike region, because the squared four-momentum transfer, $q^2 = \omega^2 - \vec{q}^2$, is always negative. It is therefore usually expressed by the positive quantity $Q^2 = -q^2 > 0$. The timelike region, where $Q^2 < 0$, can be accessed through electron-positron annihilation into a pair of proton and anti-proton or neutron and anti-neutron.

In elastic electron-nucleon scattering the charge-current density of the nucleon can be written in the form

$$\bar{N} \Gamma_\mu N = \bar{N} \left[ \gamma_\mu F_1(Q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_N} \kappa F_2(Q^2) \right] N.$$
cterizes the effect of the anomalous magnetic moment, $\kappa$, as motivated by the Gordon decomposition of the electromagnetic current. Linear combinations of $F_1$ and $F_2$ constitute the electric and magnetic Sachs form factors

$$G_{E,n,p}^n(Q^2) = F_{1,n,p}^n(Q^2) - \tau \kappa_{n,p} F_{2,n,p}^n(Q^2)$$

(5)

$$G_{M,n,p}^n(Q^2) = F_{1,n,p}^n(Q^2) + \kappa_{n,p} F_{2,n,p}^n(Q^2)$$

(6)

where $\tau = Q^2 / 4 m_N^2$ is a dimensionless measure of the squared four-momentum transfer in units of the nucleon rest mass, $m_N$. At $Q^2 \to 0$ these form factors correspond to the total charge and magnetic moment of protons and neutrons:

$$G_{E,n,p}^n(Q^2 \to 0) = 0, 1$$

(7)

$$G_{M,n,p}^n(Q^2 \to 0) = -1.91, 2.79.$$  

(8)

In the particular reference frame with vanishing energy transfer, the Breit frame, $G_E$ and $G_M$ have been interpreted as the Fourier transforms of the corresponding distributions of charge and magnetism. Recently, the possibility of interpretation of $G_E$ in terms of the intrinsic charge distribution was controversially discussed again.

With the Sachs form factors the cross section for elastic electron-nucleon scattering can be written in the famous Rosenbluth form,

$$\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \cdot \left( G_E^2 + \tau G_M^2 \frac{1 + \tau}{1 + \tau} + 2 \tau G_M^2 \tan^2 \vartheta_e \frac{\vartheta_e}{2} \right),$$

(9)

where $\left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}}$ is the Mott cross section for electron scattering off a pointlike spin-$\frac{1}{2}$ object and $\vartheta_e$ denotes the electron scattering angle. Due to their different angular weights in Eq.9, $G_E$ and $G_M$ can be experimentally separated at constant $Q^2$.

The measurement of all Sachs form factors of proton and neutron enables the decomposition into isoscalar and isovector parts, important for the comparison to model calculations. Furthermore, using isospin invariance it is possible to extract $u/d$ flavour specific form factors from $G_{E,M}^p$ and $G_{E,M}^n$. The extension to the electric and magnetic strange quark contributions requires additional observables. From parity violating elastic electron scattering the cross section asymmetry with regard to the helicity $+/-$ flip of the electron beam

$$A_{PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

(10)
is extracted, which is due to the interference of $\gamma$ and $Z^0$ exchange. It determines the $Z$ form factors

$$G_{E,M}^Z = G_{E,M}^p - G_{E,M}^n - 4 \sin^2 \Theta_W (G_{E,M}^p - G_{E,M}^s),$$

from which the strange form factors $G_{E,M}^s$ can be extracted, provided the Weinberg mixing angle, $\Theta_W$, and the nucleon form factors $G_{E,M}^p$ and $G_{E,M}^n$ are sufficiently well known.

This talk reviews the current experimental status of the electromagnetic elastic nucleon form factors. Recent results concerning the proton electric form factor at high $Q^2$ are summarized in the next section. The neutron form factors are discussed in section 3. Measurements of $G_M^n$ are addressed in subsection 3.1. Special emphasis is given to recent measurements of the neutron electric form factor using double polarization techniques in section 3.2. The paper concludes with a summary and outlook.

2. Proton form factors

The method of Rosenbluth-separation has been used in elastic electron-proton scattering \(^{17,18}\) to determine $G_E^p$ and $G_M^p$ up to $Q^2 \simeq 9 \text{(GeV/c)}^2$. At higher $Q^2$ up to 30 (GeV/c)^2, $G_M^p$ dominates the cross section and has thus been determined directly \(^{19}\). The result was that both $G_M^p$ and $G_E^p$ approximately follow the so-called dipole form and scale with the magnetic moment, $\mu_p$:

$$G_E^p \simeq G_D = \left(1 + \frac{Q^2}{0.71 \text{(GeV/c)}^2}\right)^{-2},$$

$$G_M^p \simeq \mu_p G_D. \quad (13)$$

However, due to the insensitivity of the cross section to $G_E$ at higher $Q^2$, the Rosenbluth separation yields large uncertainties for this quantity. Much improved sensitivity is obtained using double polarization observables in electron-nucleon scattering \(^{20,21}\). The components of the recoil polarization in the $N(e,e'N)$ reaction read

$$P_x = -P_e \frac{\sqrt{2\tau(1-\epsilon)}}{\epsilon(G_E^p)^2 + \tau(G_M^N)^2} G_M^N,$$

$$P_y = 0,$$

$$P_z = P_e \frac{\tau(1-\epsilon)}{\epsilon(G_E^p)^2 + \tau(G_M^N)^2}, \quad (16)$$

where $\hat{x}$ is in the electron scattering plane perpendicular to the direction of the momentum transfer, $\hat{y}$ is normal to the scattering plane, and $\hat{z}$ points
Figure 1. Results for $\mu_p G_E^p/G_M^p$ from unpolarized Rosenbluth $^{29,30,31,32}$ and recoil polarization measurements $^{23,24,25,27,28}$.}

into the direction of the momentum transfer, $\vec{q}$; $\epsilon = (1 + 2|\vec{q}|^2 \tan^2 \vartheta_e)\frac{1}{2}$ is the photon polarization parameter and $P_e$ denotes the longitudinal polarization of the electron beam. In particular, $P_x$ is linear in $G_E$ and the polarization ratio $P_x/P_z$ is directly related to $G_E/G_M$.

The measurements of the Hall A collaboration at Jefferson Laboratory using a recoil polarimeter in one of the high resolution spectrometers $^{22}$ show with high statistical precision a linear decrease of $G_E^p/G_M^p$ up to $Q^2 = 5.6\ (GeV/c)^2$ $^{23,24,25}$ (c.f. Fig. 1). The results have been included in new empirical form factor fits $^{26}$. At low $Q^2$ recoil polarization measurements $^{27,28}$ are in agreement with form factor scaling, i.e. $\mu_p G_E^p/G_M^p = 1$.

3. Neutron form factors

Generally, the measurement of the neutron form factors raises more difficulties, because there is no free neutron target available which is suited for electron scattering experiments. The best possible approximation of free electron-neutron scattering is quasi–free scattering off the lightest nuclei. In $D(e,e')$ single arm experiments the dominating proton contribution has to be subtracted, with corresponding large uncertainties $^{33}$. A Rosenbluth–separation has nevertheless been achieved $^{34}$ up to $Q^2 = 4\ (GeV/c)^2$. At
low $Q^2$ nuclear effects and final state interaction are well enough under control to permit an extraction of $G_M^n$ from inclusive quasi–elastic $^3\text{He}(e,e')$ scattering with polarized beam and polarized target. $D(e,e'n)$ coincidence experiments allow the explicit tagging of electron-neutron scattering. The influence of binding effects can be minimized through the simultaneous measurement of the $D(e,e'n)$ reaction. Similar to $G_M^p$, the neutron magnetic form factor also roughly exhibits the dipole behaviour,

$$G_M^n \simeq \mu_n G_D.$$  

(17)

The situation concerning the neutron electric form factor, $G_E^n$, is most unfavourable. It must vanish in the static limit, $G_E^n(Q^2 \rightarrow 0) = 0$, due to the zero charge of the neutron. The smallness of $(G_M^n)^2$ compared to $\tau(G_E^n)^2$ makes a Rosenbluth decomposition according to Eq.9 very difficult. Due to the corresponding large errors in the small quantity the extracted values for $G_E^n$ are compatible with zero. Therefore, in the momentum transfer range $Q^2 < 1\,(\text{GeV}/c)^2$ the most precise data came from elastic electron-deuteron scattering, where the structure function $A(Q^2)$ depends on the isoscalar form factor $(G_E^p + G_E^n)^2$ and thus provides a higher sensitivity to $G_E^n$ through its interference with the large $G_E^p$. However, the necessary unfolding of the deuteron wavefunction introduces a substantial model dependence in the extracted neutron electric form factor. Reduced model dependence has been obtained analyzing the $e-d$ elastic quadrupole form factor. The model dependence can be overcome by exclusive $(e,e'n)$ double polarization experiments with polarized beam and either polarized target or recoil polarimetry.

3.1. Recent $G_M^n$ experiments

Precise determinations of $G_M^n$ come from unpolarized coincidence experiments at Bates, NIKHEF, ELSA, and MAMI. Except the Bates experiment, which measured the absolute $D(e,e'n)$ cross section, these experiments determined $G_M^n$ from the ratio $R = \frac{\sigma(e,e'n)}{\sigma(e,e'p)}$ of quasi–free neutron over proton cross sections off the deuteron with simultaneous neutron/proton detection in one single hadron detector. In this ratio nuclear binding effects cancel to a large extent. Moreover, this method is also experimentally insensitive to luminosity fluctuations and detector acceptances.

Nevertheless, detailed control of the hadron detectors absolute detection efficiency for protons and, particularly, neutrons is essential. The setups of
the various experiments have been very similar, with the electrons detected in a magnetic spectrometer and coincident n/p-detection in a well shielded plastic or mineral oil scintillator telescope. However, different approaches have been used to determine the absolute neutron detection efficiency. For the Bates and ELSA measurements "in situ" methods were chosen with a bremsstrahlung radiator positioned in front of the experimental target in order to exploit the $D(\gamma,p)n$ or $p(\gamma,\pi^+)n$ reactions, respectively, to tag neutrons in the telescope. In contrast, the hadron detectors which were used at MAMI and NIKHEF were calibrated at the PSI neutron beam in a kinematically complete $p(n,p)n$ experiment. This method relies on the good control and portability of the effective detector thresholds.

Figure 2 shows a comparison of the recent results from Bates 36,37,40, ELSA 42, JLab 38,39, NIKHEF 41, and MAMI 43,44. Despite the individual errors of down to 2 %, the MAMI data are approximately 10 - 15 % below the ELSA ones. The probable origin of this discrepancy is the absolute neutron detection efficiency calibration. In this respect, the possible impact of un-tagged electroproduction events has been discussed for the in situ method 48,49.

The measurement of the transverse asymmetry $A_{T'}$ from inclusive quasi–elasic $^3\text{He}(\vec{e},e')$ scattering provides an alternative method for the extraction of $G_M^n$, which is completely independent of efficiency calibrations 36,37,38. However, full Fadeev calculations are required with inclusion of final state interaction and meson exchange currents. Those are currently available for $Q^2 = 0.1$ and $0.2 \ (\text{GeV/c})^2$ 35,38, the results of a PWIA analysis for $Q^2$ up to 0.6 $\ (\text{GeV/c})^2$ 39. The extracted values of $G_M^n$ agree with the unpolarized measurements of Anklin et al. 41,43 and Kubon et al. 44.

### 3.2. $G_E^n$ double polarization experiments

Double polarization observables in exclusive quasi–free electron-deuteron scattering with longitudinally polarized electrons offer high sensitivity to $G_E^n$, due to an interference with the large $G_M^n$, combined with negligible dependence on the deuteron wavefunction 50, e.g. in the recoil polarization observables of Eqs. 14 and 16. In the completely equivalent scattering $n(\vec{e},e'n)$ of longitudinally polarized electrons off a polarized neutron target the cross section asymmetry with regard to reversal of the electron beam polarization is given by

$$A = -P_e \frac{\sqrt{2\tau(1-\epsilon)G_E^n G_M^n} \cdot \hat{P}_x + \tau \sqrt{1-\epsilon^2(G_M^n)^2} \cdot \hat{P}_z}{\epsilon(G_E^n)^2 + \tau(G_M^n)^2},$$

(18)
Figure 2. Results of recent $G_M^n$ experiments. Gao et al. \cite{36,37} (grey cross) and Xu et al. \cite{38,39} (black crosses) exploited the $^{3}\text{He}(e,e')$ cross section asymmetry. The open circles are the result of the $D(e,e'n)$ experiment of Markowitz et al.\cite{40}. The ELSA \cite{42} (full squares), NIKHEF \cite{41} (grey diamonds) and MAMI \cite{43,44} (full circles) measurements made use of the ratio method as described in the text.

where now $\tilde{P}_{\perp} = P_{x,z}$ are the components of the initial state neutron polarization. The polarized target neutrons can be provided by polarized $^{3}\text{He}$ \cite{51,52,53}, where the neutron carries approximately 87% of the polarization of the nucleus \cite{54}, or by vector polarized $^{2}\text{He}$ \cite{55,56}. The measurement of asymmetry ratios yields independence of the absolute degree of the target polarization \cite{57,55}.

3.2.1. Polarized target experiments

First experiments aimed at the extraction of $G_E^n$ from the inclusive quasi–elastic reaction $^{3}\text{He}(e,e')$. The feasibility of such kind of experiments was successfully demonstrated, but the statistical accuracy remained unsatisfactory.

The magnetic moment of $^{3}\text{He}$ within 10% agrees with the free neutron one. Therefore the proton contribution in the measured asymmetries first was expected to be small \cite{54}. Later calculations, however, showed that
the remaining impact of the protons on the measured asymmetries is large enough to prohibit a reliable extraction of $G_E^{\gamma}$.\textsuperscript{58}

This problem can be overcome, if the occurrence of e-n scattering is explicitly tagged through the detection of the outgoing neutron in coincidence with the scattered electron. Such an exclusive $^3\text{He}(e',e'n)$ experiment was performed for the first time by the A3-collaboration at MAMI\textsuperscript{57} at a squared four-momentum transfer of $Q^2 = 0.31 \text{(GeV/c)}^2$. With the detector-setup described in the following section the statistics was improved later on\textsuperscript{59}. The most recent experiment at $Q^2 = 0.67 \text{(GeV/c)}^2$ used the 3-spectrometer setup\textsuperscript{60} of the A1-collaboration at MAMI\textsuperscript{61,62}.

In this experiment the target gas was polarized by metastable optical pumping and subsequently compressed to 6 bars. The relaxation time of approximately one day required twice a day the replacement of the target cell by a freshly polarized one. Quasi-elastic measurements were performed with target spin aligned perpendicular and parallel to the momentum transfer direction in order to access both the transverse asymmetry, $A_x$, and the longitudinal asymmetry, $A_z$. This enabled a measurement of the ratio $A_x/A_z$, which is directly proportional to $G_E^{\gamma}/G_M^{\gamma}$ but independent of both the absolute degrees of beam and target polarization, $P_e$ and $P_T$, respectively. Furthermore, the product $P_e \cdot P_T$ was monitored through the elastic measurement $^3\text{He}(e,e')$ in spectrometer B of the 3-spectrometer setup.

![Figure 3. Target area of the $^3\text{He}(e,e'n)$ experiment at MAMI. The cell with polarized gas is magnetically shielded against the spectrometers fringe fields.](image-url)
The quasi–elastically scattered electrons were detected in spectrometer A (c.f. Fig.3), the neutrons in coincidence in a dedicated neutron detector provided by the University of Basel. It consisted of four layers of five plastic scintillators of dimensions $50 \times 10 \times 10 \text{ cm}^3$, which were equipped with photomultipliers at both ends. Charged particles could be rejected by means of two layers of 1 cm thick $\Delta E$-counters. The neutron detector was shielded with 2 cm of lead against direct target sight in order to reduce the charged background.

The setup of the JLab Hall C $\vec{D}(\vec{e}, e' n)$ experiment in principle is similar. Here the scattered electrons are detected in the HMS spectrometer in coincidence with neutrons in a segmented plastic scintillator. At the required luminosity of $1 \cdot 10^{35} \text{ cm}^{-2} \text{s}^{-1}$ a 40% polarization of the ND$_3$ target is achieved by the technique of dynamic nuclear polarization. The deuteron nuclei are polarized by microwave irradiation at temperatures around 1 K in a strong magnetic field of 5 T. In the measurement of $A_x$, this field deflects the incoming electron beam by as much as 4°. This has to be compensated by a magnetic chicane in order to guarantee horizontal beam at the center of the target. Data have been taken in the $Q^2$ range between 0.5 and 2 $(\text{GeV/c})^2$, first results are available at the lowest $Q^2$.

In contrast to MAMI and JLab, the NIKHEF $\vec{D}(\vec{e}, e' n)$ experiment was performed with a vector polarized internal gas target at the AmPS electron storage ring. The scattered electrons were detected in coincidence simultaneously with protons and neutrons. Thus the asymmetry ratio between the $\vec{D}(\vec{e}, e' n)$ and $\vec{D}(\vec{e}, e' p)$ reactions could be determined.

3.2.2. The $D(\vec{e}, e' n)$ recoil polarization experiment at MAMI

As in the case of polarized targets a pioneering recoil polarization experiment was performed at MIT-Bates. Electrons and neutrons from the $D(\vec{e}, e' n)$ reaction were detected in coincidence and the transverse neutron polarization, $P_z$, was measured. However, due to the low duty cycle of the Bates linac only modest statistical accuracy could be achieved. Furthermore, the external absolute calibration of the neutron polarimeter’s effective analyzing power remained unsatisfactory.

The full potential of the recoil polarization method was exploited for the first time at MAMI. Fig.4 shows the experimental setup of this experiment. The longitudinally polarized electron beam ($I \simeq 2.5 \mu A, P_e \simeq 75\%$) impinged on a 5 cm long liquid deuterium target and the scattered electrons were detected in a 256 element lead glass array, which covered a solid
Figure 4. Setup of the $D(\vec{e}, \vec{e}')$ experiment at MAMI

Figure 5. Schematics of the spin precession

angle of $\Delta \Omega \simeq 100$ msr. The energy resolution of $\delta E/E \simeq 25\%$ was sufficient to suppress pion production events. Only the electron angles, which were measured with an accuracy of approximately 3.5 mrad entered the
event reconstruction, which became kinematically complete through the measurement of the neutrons time-of-flight and hit position in the front plane of the neutron detector.

Figure 6. Transverse asymmetries as a function of the spin precession angle. The zero crossing is not affected by the different effective analyzing powers obtained by different conditions in the offline analysis (full and open points).

The neutron polarization can be analyzed in the detection process itself. This required a second neutron detection in one of the rear detector planes, which yielded the polar and azimuthal angles, $\Theta'_n$ and $\Phi'_n$, of the analyzing scattering in the front wall. With the number of events $N^\pm(\Phi'_n)$ for $\pm$ helicity states of the electron beam the azimuthal asymmetry, $A(\Phi'_n)$, was determined through the ratio

$$\frac{1 - A(\Phi'_n)}{1 + A(\Phi'_n)} = \sqrt{\frac{N^+(\Phi'_n) \cdot N^-(\Phi'_n + \pi)}{N^-(\Phi'_n) \cdot N^+(\Phi'_n + \pi)}},$$

which is insensitive to variations of detector efficiency and luminosity. The extraction of $P_x$ from $A(\Phi'_n) = \epsilon_{\text{eff}} \cdot P_x \cdot \sin \Phi'_n$ requires the calibration of the effective analyzing power, $\epsilon_{\text{eff}}$, of the polarimeter. This, however, varies strongly with the event composition as determined by hardware conditions during data taking and software cuts applied in the offline analysis.
The problem of calibration of the effective analyzing power has been avoided by controlled precession of the neutron spins in the field of a dipole magnet in front of the polarimeter\footnote{13}. This is schematically depicted in Fig. 5. After precession by the angle $\chi$ the transverse neutron polarization behind the magnet, $P_\perp$, is a superposition of $x$ and $z$ components, and likewise is the measured asymmetry:

$$A_\perp = A_x \cos \chi - A_z \sin \chi.$$  \hspace{1cm} (20)

In the particular case of the zero crossing, $A_\perp(\chi_0) = 0$, one immediately gets the relation

$$\tan \chi_0 = \frac{A_x}{A_z} = \frac{\epsilon_{\text{eff}} \cdot P_e \cdot \sqrt{2\tau \epsilon(1-\epsilon)} \cdot G_E \cdot G_M}{\epsilon_{\text{eff}} \cdot P_e \cdot \tau \sqrt{1-\epsilon^2} (G_M^0)^2}.$$  \hspace{1cm} (21)

Obviously, this ratio is independent of both the degree of electron beam polarization, $P_e$, and the polarimeter’s effective analyzing power. It therefore directly yields $G_E^0/G_M^0$. Different effective analyzing powers do change the magnitude of the transverse asymmetry, $A_\perp$, but not the zero crossing angle, $\chi_0$\footnote{13}. This is demonstrated in Fig. 6, where $A_\perp$ is plotted for two different cut conditions in the offline analysis (full and open points) as a function of the spin precession angle, $\chi$. The magnitude of the asymmetry is affected but the zero crossing remains unchanged.

Using the established method of neutron spin precession a very similar experiment of the A1 collaboration at MAMI covers the extended $Q^2$ range up to 0.8 (GeV/c)$^2$\footnote{66,67,68,69}. Given the maximum beam energy of 880 MeV this requires neutron detection at forward angles of $\Theta_{\text{lab}} \simeq 27^\circ$ in a highly segmented neutron polarimeter.

3.3. Results

Even for quasi–free $D(e, e' n)$ scattering FSI effects are substantial below $Q^2 \simeq 0.3$ (GeV)$^2$ and have been taken into account in the recent analyses using the calculations of Arenhövel\footnote{50}. They drop rapidly with increasing $Q^2$, increasing $G_E^0$ for the MAMI/A3 data sample by almost a factor of two at $Q^2 = 0.12$ (GeV)$^2$ but only $\simeq 10\%$ at 0.32 (GeV)$^2$\footnote{71}. Despite its size, the required correction of the $G_E^0/G_M^0$ ratio has only small uncertainties, because it is insensitive to the choice of N-N potential and $G_E^0$ parameterization\footnote{50,70}. Therefore, even at $Q^2 = 0.12$ (GeV/c)$^2$ a reliable extraction of $G_E^0/G_M^0$ is possible. This has been done relying on the dipole values for $G_M^0$ (Eq.17).
Fig. 7 gives a summary of the recent double polarization measurements with statistical (inner) and systematical (outer) errors. The recoil polarization experiments are depicted by circles, full for the MAMI results \(^{66,71}\) and open for the Bates one \(^{64}\). The triangles indicate the NIKHEF \(^{55}\) and JLab \(^{56}\) measurements with polarized deuteron target. The squares represent the MAMI results for \(^3\)He(\(e, e' n\)) \(^{59,61,62}\). For the \(^3\)He experiments FSI is expected to be small at \(Q^2 = 0.67\) (GeV/c)\(^2\) \(^{61,62}\), due to the large kinetic energy of the ejected neutron. Contrary, at \(Q^2 = 0.36\) (GeV/c)\(^2\) (open squares) \(^{59}\) first, still incomplete, Faddeev calculations indicate a substantial correction of the \(^3\)He(\(e, e' n\)) data point towards larger \(G^n_E\). At the present status of calculation where no meson exchange currents are yet included the central value of the extracted \(G^n_E\) is shifted by approximately 50\%. \(^{35}\) Due to the kinematical reconstruction the average \(Q^2\) is also affected. Despite the small statistical error, this data point is subject to the largest systematical and theoretical (model) uncertainty, which is not included in the depicted error.

All polarization data lie above the so far favored result from elastic \(D(e, e')\) scattering, where the Paris potential has been used for the unfolding of the wave function contribution \(^{46}\). They are compatible with the older...
Galster parameterization

\[ G^n_E = -\frac{\mu_n T}{1 + \eta T} \cdot G_D \]  

(22)

with \( \eta = 5.6 \), which is indicated by the line in Fig. 7.

4. Summary and Outlook

Elastic form factors are related to the distribution of charge and current and thus fundamental quantities characterizing the nucleon ground state. In the context of this conference they are a prerequisite for the extraction of strangeness–specific information from parity violating elastic electron scattering.

From single arm \( e - p \) scattering precise proton magnetic form factor data are available up to \( Q^2 = 30 \) (GeV/c)^2, roughly exhibiting dipole behaviour. Electric and magnetic contributions have been separated using the Rosenbluth technique; the results are in agreement with with \( p(\vec{e}, e'\vec{p}) \) measurements at low \( Q^2 \). Above \( Q^2 \approx 1.5 \) (GeV/c)^2 the double polarization experiments have shown the ratio \( \mu_p G^n_p / G^n_M \) to linearly fall below unity, \( G^n_p \) remaining only about 30% of the dipole value at \( Q^2 = 5.6 \) (GeV/c)^2.

The neutron magnetic form factor, \( G^n_M \), could be extracted up to \( Q^2 = 4 \) (GeV/c)^2 from single arm \( D(\vec{e}, e') \) quasi–elastic scattering. Below \( Q^2 = 1 \) (GeV/c)^2, recent coincidence experiments allowed a precise determination of \( G^n_M \) from the ratio \( R = \frac{\sigma(e,e'n)}{\sigma(e,e'p)} \) of quasi–free electron scattering cross sections off the deuteron. Despite their individual statistical errors of only 2%, two datasets from ELSA and MAMI/NIKHEF differ by as much as 10 - 15%. This discrepancy contributed a substantial error to the extraction of strange form factors from parity violation. Recent independent results from \( ^3\text{He}(\vec{e}, e'n) \) measurements at \( Q^2 \leq 0.6 \) (GeV/c)^2 agree with the MAMI/NIKHEF dataset, however partially still relying on a simplified PWIA analysis. The full solution of this problem is also important with regard to the normalization of the recent double polarization experiments \( ^3\text{He}(\vec{e}, e'n) , D(\vec{e}, e'n) \) and \( D(\vec{e}, e'n) \) at various laboratories, where the neutron electric form factor is extracted from the ratio \( G^n_E / G^n_M \) of electric to magnetic neutron form factors.

In the \( D(\vec{e}, e'n) \) experiment at MAMI the neutron polarimeter was supplemented by a spin precessing dipole magnet. This technique, which is also adopted for the corresponding JLab experiment, avoids the polarimeters analyzing power calibration. The influence of final state interaction has been quantitatively evaluated for the \( D(\vec{e}, e'n) \) reaction. All recent double
polarization experiments are compatible with the old Galster parameterization.

It will be important to continue these $G_E^n$ experiments at larger $Q^2$. At JLab and MAMI there are further measurements underway, both with polarized target $^{63,72}$ and recoil polarimetry $^{73,67}$. These experiments will further exploit the potential of double polarized quasi-elastic electron scattering.

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