Neutron form factor measurements at MAMI

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1 Abstract

Measurements of the electric and the magnetic neutron form factors have been performed at the Mainz Microtron for more than 20 years. These MAMI experiments are reviewed in the context of measurements from other groups, and future measurements at MAMI are outlined.

2 Nucleon form factors

The electromagnetic structure of the nucleons can be probed systematically in electron scattering experiments. Fundamental quantities of interest, which can be accessed in dedicated scattering experiments, are the electric and magnetic Sachs form factors (FF) \( G_E \) and \( G_M \) of the proton and the neutron. The \( Q^2 \) dependance of these FFs encodes the distributions of charge and magnetization inside the nucleons. Therefore, precise measurements of the FFs over a wide \( Q^2 \) range are essential for a quantitative understanding of the nucleon structure: They are well suited for extraction of nucleon radii and for tests of nonperturbative QCD, and they provide constraints for phenomenological models of the nucleon structure. In addition, the FFs are key input to studies and searches in particle, nuclear, and atomic physics.

From measurements of unpolarized elastic electron scattering cross sections,

\[
\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \frac{1}{1 + \tau} \left[ G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2) \right],
\]

the electric and the magnetic FFs can be extracted by an LT-separation (i.e., measurement at a fixed \( Q^2 \)-value, but at different \( \varepsilon \)). Here, \( \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \) is the Mott cross section, \( \tau = \frac{Q^2}{4M^2} \), \( M \) the nucleon mass, and \( \frac{1}{\varepsilon} = 1 + 2(1 + \ldots
\]
with the electron scattering angle $\theta_e$. Alternatively, the FFs can directly be fitted to the measured cross sections. In addition to unpolarized measurements, the ratio of electric and magnetic FFs can be accessed in double-polarization experiments.

For the proton, high precision data have been collected within many decades (see [1] and references therein), the largest data set [2] comes from the Mainz Microtron (MAMI). Despite the high quality of the available proton data and the huge effort of the community, there are still unsolved issues. In particular, a significant discrepancy was found for the FF ratio $G_E^p/G_M^p$ when results from unpolarized data and from double-polarization data were compared [3, 4]. It became clear that two photon exchange effects are very important in order to solve that discrepancy. However, the very details are not yet perfectly understood (compare [5]). Also, the proton radius puzzle – the discrepancy between the proton charge radius extracted from a muonic hydrogen Lamb shift measurement and the best present value obtained from spectroscopy of electronic hydrogen and from elastic electron scattering experiments [6] – remains unexplained and represents a serious challenge of today’s nuclear physics. Dedicated experiments are set up and performed at various places to address that problem. Scattering experiments at low $Q^2$ are of actual interest, because the proton charge radius can be determined from

$$r_p^2 = -6 \frac{dG_E}{dQ^2} \bigg|_{Q^2=0}. \quad (2)$$

At MAMI, for instance, a novel experimental technique based on initial state radiation has been validated with the ultimate goal to precisely measure $G_E^p(Q^2)$ to unprecedented low $Q^2$-values [7].

In contrast, the neutron FFs, specifically the electric neutron FF, are much less accurately known – due to experimental challenges.

3 Challenges of neutron form factor measurements

Measurements of the neutron FFs are dramatically hindered by the fact that no free neutron targets with sufficient target densities are available. As a workaround scattering experiments on light nuclei are performed. For example, information on the neutron FFs can be obtained from elastic scattering on the nuclei (see for instance [8, 9] for an extraction of the electric neutron form factor from elastic $e-d$ scattering data), but large model uncertainties remain.
So to date, the best values for the neutron FFs come from quasielastic scattering experiments, where the electrons scatter on the bound neutrons inside the nuclei. Compared to the elastic scattering experiments on free protons, several severe complications arise:

When an inclusive measurement in quasielastic kinematics is performed, the large contributions from quasielastic scattering on the protons must be subtracted. Especially for a determination of the electric FF of the neutron, which is very small compared to the other FFs, this drastically limits the achievable accuracy. A modern example for an electric FF determination from an inclusive measurement can be found in [10], but the gross of recent experiments operated a (usually dedicated) neutron detector to distinguish between scattering on the protons and on the neutrons. Detection of fast neutrons poses a range of challenges, and so it is evident that, depending on the concrete experiment, the performance of the neutron detector may significantly limit the accomplishable results.

Furthermore, in quasielastic scattering one has to deal with nuclear binding effects. The target nucleons are not free particles at rest, but they are off-shell, and instead of the simple kinematics of a two-body scattering process, the correlation between electron and nucleon four-momenta is smeared out due to Fermi motion / momentum of the residual system. This complicates the analysis of the experiment, and it influences the quasielastic event selection capability, e.g., discrimination of inelastic contributions (like pion production) is less clean. Moreover, the extraction of the neutron FFs involves corrections for Final State Interaction (FSI), Meson Exchange Currents (MEC) and other effects, which can be huge.

4 Magnetic neutron form factor measurements at MAMI

The unpolarized cross section $|\sigma|^2$ for electron–neutron scattering is dominated by the contribution of $G_M^n$ due to the smallness of $G_E^n$. Hence, the magnetic FF can be deduced from absolute cross section measurements by using an estimate for the electric FF. In quasielastic scattering, however, the scattering on the protons must be separated from the scattering on the neutrons.

Early experiments employed inclusive quasielastic scattering on the deuteron without explicit detection of the knocked out neutrons. The results of these experiments were dominated by systematic errors (specifically related to the deuteron model, FSI and MEC corrections) rather than by statistical ones.
To minimize the sensitivity to the nuclear structure, one can extract $G_n^m$ from a measurement of the ratio $R$ of neutron knockout to proton knockout cross sections in quasi-free kinematics,

$$R = \frac{d\sigma(e,e'n)/d\Omega}{d\sigma(e,e'p)/d\Omega}. \quad (3)$$

This ratio is insensitive to the wave function, the $e - p$ cross section is well known, and FSI and MEC contributions are small and well understood in the quasielastic peak [19]. Besides a few other laboratories, such measurements [18,19] were performed at MAMI [13-16]. Electrons from the MAMI accelerator impinged on a liquid deuterium target in the spectrometer hall of the A1 collaboration [11]. The scattered electrons were detected with a high-resolution magnetic spectrometer, and the ejected nucleons (neutrons as well as protons) were detected with a nucleon detector in coincidence with the electrons. The simultaneous measurement of the proton and the neutron knockout yields made the measured ratio independent of the luminosity, dead time effects and the detection efficiency of the electron arm. The major experimental challenge was the determination of the nucleon detector efficiency, which is needed for the determination of the ratio $R$ from eq. (3). Especially the neutron detection efficiency determination is difficult. It was performed using a tagged high energy neutron beam at the Paul Scherrer Institute. Detailed studies finally allowed to extract the magnetic form factor with an accuracy < 2%, an order of magnitude improvement compared to the previous determinations using inclusive measurements. With these fine data, the authors were courageous enough to extract for the first time a purely experimental value for the magnetic radius of the neutron [18].

Results for $G_n^m$ relative to the standard dipole parametrization

$$G_{\text{dipole}}(Q^2) = \left(1 + \frac{Q^2}{0.71 \text{ GeV}^2}\right)^{-2} \quad (4)$$

are shown in Fig. 1. The MAMI experiments provided very accurate data in the important $Q^2$-range up to 1 GeV$^2$. To some extent there are tensions between the different data sets shown in the figure, but the overall picture is quite consistent. In a wide $Q^2$-range, the magnetic form factor can be well described with the dipole parametrization, some refined parametrizations are also shown in the figure.
Figure 1: Selected results for $G_n^m$ relative to the standard dipole FF parametrization (4). Different techniques have been used: Neutron to proton knockout cross section ratio measurements [17–20], inclusive measurements in the quasielastic regime [21,22], a quasi coincidence experiment, where the absence of a recoiling proton was identified as a quasielastic scattering event on the neutron [23], and asymmetry measurements in spin-dependant electron scattering on a polarized $^3$He-target [24, 25]. Measurements performed at MAMI are highlighted. Also shown is a recent fit result of selected world data on $G_n^m$ by [45] (red line), the result of a dispersion analysis [46] (black line), and the frequently used FF parametrization of [47] (blue line), uncertainties for these parametrizations are not shown.
5 Electric neutron form factor measurements at MAMI

Measurements of $G_n^e$ are very difficult in unpolarized reactions since $G_n^e$ is small due to the vanishing net charge of the neutron, thus contributions of the neutron electric FF to unpolarized cross sections are small. In unpolarized quasielastic measurements, the competing contributions from the proton and from the neutron magnetic FF are overwhelming dominant.

From precise cross section measurements in elastic electron–deuteron scattering, parametrizations for $G_n^e$ could be obtained in a reasonable $Q^2$-range from comparison with theoretical predictions [8, 9]. Anyhow, a large model dependance associated to the choice of the nucleon-nucleon potential remains. In Fig. 2 results from [9] are shown for analysis using two different $NN$ potentials (dotted gray lines).

Sensitivity to $G_n^e$ can be tremendously enhanced in double-polarization experiments where polarized electrons scatter quasielastically on deuterons or $^3$He, and either the target is polarized or the polarization of the ejected neutrons is determined [50]. Observables in such measurements can particularly be sensitive to the FF ratio $G_n^e/G_m^n$. Using $G_m^n$ from other measurements or parametrizations, $G_n^e$ can be obtained. These experiments are rather complex and time consuming, so the number of existing data points is quite limited (especially when compared to proton FF measurements), a large fraction of those comes from MAMI. There, these measurements were started within the A3 collaboration, a collaboration dedicated to the measurement of the electric FF of the neutron, making use of the new technological developments which allowed high-performance double-polarization experiments. Two different reactions were used, $d(\vec{e}, e'n)p$ and $^3$He$(\vec{e}, e'n)pp$, but both experiments used a common detector setup. After completion of the spectrometer hall of the A1 collaboration at MAMI [11], further such experiments were performed there.

5.1 Neutron recoil polarization experiments

The MAMI results published in [36,37] were obtained in the reaction $d(\vec{e}, e'n)p$. Polarized electrons from the MAMI accelerator impinged on a liquid deuterium target. The helicity of the beam was reversed during the experiments with a frequency of 1 Hz. The scattered electrons were detected in an electron detector (a leadglass-detector array in [37], a high-resolution magnetic spectrometer [11] in [36]). The neutrons were detected in coincidence with the electrons by neutron polarimeters, charged particles were identified by
thin veto detectors. The polarimeters provided an analysis of recoil polarization components of the neutrons (compare Fig. 5) from which the FF ratio can be obtained: The recoil polarization for scattering on a free neutron is given by

\[ P_n^x = -h_e \sqrt{2 \epsilon(1 - \epsilon)} \sqrt{\epsilon G_n^2 + \tau G_{Mn}^2} \cdot G_E^n G_M^n, \tag{5} \]

\[ P_n^y = 0, \tag{6} \]

\[ P_n^z = h_e \sqrt{1 - \epsilon^2} \tau \sqrt{\epsilon G_n^2 + \tau G_{Mn}^2} \cdot G_M^2, \tag{7} \]

where \( h = \pm 1 \) denotes the electron helicity and \( P_e \) the beam polarization degree; \( \tau, \epsilon \) as in eq. (1). The quantization axis for \( \vec{P}_n \) is the direction of the momentum transfer \( \vec{q} \). From the ratio \( P_n^x / P_n^z \) the FF ratio can be obtained:

\[ \frac{P_n^x}{P_n^z} = \frac{-\sqrt{2 \epsilon}}{\sqrt{1 + \epsilon}} \cdot \frac{G_E^n}{G_M^n}. \tag{8} \]

Again, nuclear binding effects have to be considered. The effects of FSI, MEC and isobar configuration currents (IC) on the polarization components had been calculated based on a model [42]. Corrections were found to be in the few percent range, except for the lowest \( Q^2 \) measurement at \( Q^2 = 0.15 \text{ GeV}^2 \), where the correction factor exceeded 60%. Results for these experiments are depicted in Fig. 2 and Fig. 3.

5.2 Polarized target experiments

FF ratio measurements can also be performed in double-polarization experiments using polarized targets. Besides polarized deuterium targets, polarized \(^3\text{He}\) can be used as an effective polarized neutron target due to its special spin structure, with a high relative neutron polarization, while the mean proton polarization is small [56–59]. Pioneering double-polarization measurements [40, 41], performed in the inclusive reaction \(^3\text{He}(\vec{e}, e'n)pp\) [26–29], did not provide very useful information on \( G_E^n \). Detection of the recoiling neutrons could significantly improve the sensitivity of the experiments and so, several \( G_E^n / G_M^n \) measurements have been performed at MAMI using a polarized \(^3\text{He}\) target in the reaction \(^3\text{He}(\vec{e}, e'n)pp\) [26–29].

Longitudinally polarized electrons from the MAMI accelerator were scattered on a polarized \(^3\text{He}\) target (see [12] for details on the most recent target setup). The helicity of the beam was reversed during the experiments with a
Figure 2: Results for the electric neutron FF $G_E^n$ from double-polarization experiments. All the experiments measured observables sensitive to the FF ratio $G_E^n/G_M^n$. $G_E^n$ was obtained by inserting values for the relatively well known $G_M^n$. Different techniques have been used: Measurements of beam helicity asymmetries in the reaction $^{3}\text{He}(\vec{e}, \vec{e}'\text{n})p$ [26–30], symmetry measurements in $\vec{d}(\vec{e}, e'\text{n})p$ [31–34], and measurements of the neutron’s recoil polarization in $d(\vec{e}, e'\vec{n})p$ [35–38]. Measurements performed at MAMI are highlighted. Also shown is a recent fit result of world data by [45] (red line), and the widely used parametrizations of [47] (blue line) and [49] (gray line), uncertainties for these parametrizations are not shown. In addition, $G_E^n$ results from analysis of precise elastic electron–deuteron scattering data are shown [9] (dotted gray lines; for two different nucleon-nucleon potentials used in the FF evaluation).
Figure 3: Results for $\mu_n G^n_E/G^n_M$ from double-polarization experiments. Different techniques have been used: Measurements of beam helicity asymmetries in the reaction $^3\text{He}(\vec{e}, e'\vec{n})^3\text{He}$ [26–30], asymmetry measurements in $\vec{d}(\vec{e}, e'\vec{n})p$ [31–34], and measurements of the neutron’s recoil polarization in $d(e, e'\vec{n})p$ [35–38]. Measurements performed at MAMI are highlighted. Also shown are the results of recent calculations based on general parton distributions [52] (solid line), dispersion analysis [53] (gray band), a quark-diquark model with a pion cloud [54] (dashed line) and the extended Lomon-Gari-Krümpelmann model of nucleon electromagnetic FF [55] (dotted lines, for two different parametrizations of resonance widths).
Figure 4: Asymmetries of the reaction $^{3}\text{He}(\vec{e}, e'n)pp$ can be measured for different target polarization orientations. The asymmetries obtained in Setup 2 and Setup 4, that correspond to a polarization direction in the scattering plane and perpendicular to the (mean) momentum transfer, are sensitive to $G_E^n/G_M^n$. Asymmetries measured in Setup 1 and Setup 3 can be used for normalization and reduction of systematic errors.

Beam helicity asymmetries $A$ have been measured for different orientations of the target polarization. In the one-photon exchange approximation and for scattering on a free neutron, $A$ is sensitive to the FF ratio for a target polarization orientation in the scattering plane and perpendicular to the momentum transfer $\vec{q}$ (see Fig. 4),

$$A_\perp = -\frac{a(G_E^n/G_M^n)}{(G_E^n/G_M^n)^2 + d} \cdot P_e P_n.$$  \hspace{1cm} (9)

$a$ and $d$ are kinematic factors, $P_e$ and $P_n$ the electron and neutron polarizations, respectively. Precise measurement of these asymmetries yield the FF ratio. In order to minimize systematic errors, also asymmetry measurements for a parallel target polarization orientation were performed during all MAMI experiments. In this case, the asymmetry is almost FF independant,

$$A_\parallel = -\frac{b}{(G_E^n/G_M^n)^2 + d} \cdot P_e P_n,$$  \hspace{1cm} (10)

because of the smallness of the ratio, $(G_E^n/G_M^n)^2 \ll d$. $b$ is another kinematic
factor. The ratio of these asymmetries leads to

$$G^n_E / G^n_M = b/a \cdot \frac{(P_e P_n)_\parallel}{(P_e P_n)_\perp} A_\perp / A_\parallel$$  \hspace{1cm} (11)$$

with great benefits: calibration factors for the beam and target polarization measurements cancel, and only a relative monitoring is necessary. In particular, the precise value for the relative neutron to helium polarization (smaller than 1, and only the helium polarization can be measured directly) is irrelevant. Also, unpolarized background drops in the ratio. That is of special interest concerning unavoidable background from quasielastic electron–proton scattering (this is, for instance, the dominant contribution to the systematic error in [36]): The polarization of the protons is small inside the $^3$He nucleus, and so their contribution is almost unpolarized and drops out in the asymmetry ratio.

Results for these experiments are also shown in Fig. 2 and Fig. 3. Since eq. (11) is only valid for scattering on free neutrons, corrections for nuclear effects had to be applied. The earliest of these experiments [29] was uncorrected for nuclear physics effects, which possibly explains the deviation from other data; the result is included in the figures only for completeness. This experiment was later repeated with much better statistics, the “raw” result from this experiment [28] was corrected for FSI and MEC contributions in an independent publication [43] (where the systematic experimental error was ignored), based on Faddeev calculations. The data point shown in the figures corresponds to the FSI-corrected result from [43] but with the relative systematic error from the original paper [28] added for a fair representation of the result of that experiment. For the analysis of [27] corrections for FSI were estimated by scaling available calculations of [44], performed at a smaller $Q^2$, to the $Q^2$ of the experiment. This resulted in a total FSI correction of 3.4%. For the kinematics of the experiment at $Q^2 = 1.58 \text{ GeV}^2$ [26], no significant FSI and MEC effects were expected, calculations based on the generalized eikonal approximation [51] were performed and confirmed that. As a fact, further measurements had been performed at MAMI using a polarized $^3$He target at lower momentum transfers of $Q^2 = 0.25 \text{ GeV}^2$ (see [39]) and even at $Q^2 = 0.15 \text{ GeV}^2$. The necessary corrections due to FSI and MEC were found to be huge and non-constant over the detector acceptances causing severe problems (especially for the lowest $Q^2$ measurement), the analyses have not been finalized.

Taking all the dedicated double-polarization experiments together, the shape of $G^n_E(Q^2)$ has been nicely elaborated, with strong contributions coming from MAMI. With the experiments mentioned above, the full $Q^2$-range

\hspace{1cm} (11)
accessible at MAMI has been exploited: At smallest $Q^2 \leq 0.2\text{GeV}^2$, analyses become unreliable as a result of the increasing size of nuclear binding effects on the observables. A significant increase of the momentum transfer beyond $1.6\text{GeV}^2$ is not possible due to the limited beam energy of the accelerator (1.6 GeV).

6 Planned measurements

In the light of the initial difficulties to get a handle on the neutron electric FF, it is in a way astonishing to see how well all these $G_E^n$ measurements from different laboratories, from the study of different reactions, using different approaches for nuclear binding effects corrections, align. Considering that the necessary corrections to the data are partly excessive and that eventually not all relevant effects have been accounted for (maybe the structure of a free neutron, a neutron bound in a deuteron, and a neutron bound in a $^3\text{He}$-nucleus is not identical but differs significantly? see [60, 61] for investigations of that subject in the proton case), the diversity of the experiments is excellent. Clearly, the data quality is different than in the case of the proton, but altogether the global efforts of experimentalists, engineers, and theoreticians have been worth it.

However, there are also limitations with the existing data sets. How to interprete deviations of the data, for instance in the region $Q^2 \approx 1.5\text{GeV}^2$? Revealing structures in the FF is difficult when data from different experiments, each single one featuring its own systematics, are compared.

In that sense a complementary measurement program is planned at MAMI with the aim to collect a consistent data set over a wide $Q^2$-range ($Q^2 = 0.2 - 1.5\text{GeV}^2$) using the $d(\vec{e}, e'\vec{n})p$ reaction as described before. For this purpose, a new highly segmented neutron polarimeter is being set up, see Fig. 5. The neutron polarimeter will be operated in conjunction with the high-resolution magnetic spectrometers of the A1 collaboration for precise electron detection.

The recoiling neutrons will pass a dipole magnet, where the vertical field can be used to precess the neutron spins about a vertical axis. Analysis scattering of the neutrons takes place in the front wall of the neutron detector in vertically aligned plastic scintillator bars (scintillator: EJ-200, PMT: 9142SB). For charged particle identification, thin veto layers are placed in front of the wall.

The scintillators of a second wall will be arranged horizontally in two blocks above and below the electron scattering plane. Study of $\sim$up-down asymmetries for different settings of the dipole magnet allows the extraction
of the recoil polarization components $P_x^n$ and $P_z^n$ of the neutrons, the fraction of those components yields $\frac{G_n^e}{G_n^M}$, compare eq. \[8\].

7 Summary

Nucleon electromagnetic FFs are fundamental quantities describing the electromagnetic structure of the proton and the neutron. These FFs can be determined in electron scattering experiments. A serious complication for the measurements of the neutron FFs is the lack of free neutron targets, the FFs are extracted from measurements on light nuclei therefore. Contributions related to the protons inside the nuclei limit the accuracy of the experiments, especially the electric neutron form factor is hard to measure because it is small compared to the other form factors, and so its contribution to the observables is in general small, too.

With technological improvements, sophisticated experiments could be set up. Continuous-wave accelerators provided excellent electron beams, high-resolution magnetic spectrometers could be used for precise electron detection, the recoiling neutrons could be detected in coincidence, allowing a clean selection of quasielastic electron–neutron scattering events. In addition, polarization degrees of freedom became available and were proofed to be very beneficial in order to access the electric neutron FF.

A substantial number of data points has been obtained at the Mainz Microtron. Both the magnetic and the electric FF were measured at various momentum transfers in the range $Q^2 = 0.15 - 1.58 \text{ GeV}^2$. The magnetic FF was determined from measurements of the neutron to proton cross section ratio in quasielastic electron scattering, the dominant error source – the neutron detector efficiency – was encountered by supplemental efficiency measurements using a tagged neutron beam. The electric FF was determined from measurements of the electric to magnetic FF ratio combined with measurements of the magnetic FF. Utilizing a polarized electron beam, this ratio was either determined from a measurement of the neutron recoil polarization components, or from the study of beam helicity asymmetries in scattering on an effective polarized neutron target.

Although the quality of the available neutron FF data, including the significant contributions from MAMI, is of course not as good as it is for the proton FFs, the situation is quite satisfactory. The shape of both magnetic and electric FF has been worked out well with some space for interpretation.

New recoil polarization measurements are planned, with the goal to consistently scan the electric FF over the $Q^2$-range accessible at MAMI.
Figure 5: Sketch of a neutron polarimeter for neutron FF measurements at MAMI (side view). Spin dependant scattering takes place in the detector material of the front wall, leading to an asymmetry in the azimuthal angle of the secondary scattered neutrons. The analysis scattering is only sensitive to the transverse neutron spin components. A non-vanishing neutron spin component perpendicular to the neutron momentum direction in the horizontal plane leads to an “up-down” asymmetry. This asymmetry can be measured by use of the rear wall. Frequent reverses of the electron beam helicity provide suppression of false asymmetries related to a non-constant detector efficiency and so forth. A vertical spin component would cause a “left-right” asymmetry, but as result of eq. (6) that component approximately vanishes in electron–neutron scattering. By means of a dipole in front of the detectors, the neutron spins can be rotated about a vertical axis, making the polarimeter setup sensitive to the longitudinal spin component of the incident neutrons. The analyzing power of the detector material does not change, and therefore largely cancels in the ratio of the measured polarization components, together with the absolute value of the electron beam polarization.
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