Measurement of the neutron electric formfactor $G_{E,n}$ in the quasifree $D(\vec{e}, e'\vec{n})p$ reaction

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The electric form factor of the neutron $G_{E,n}$ has been measured in the quasifree $D(\vec{e}, e'\vec{n})p$ reaction using the 855 MeV polarised c.w. electron beam of the Mainz Microtron MAMI. The polarisation of the scattered neutrons was analysed in a polarimeter consisting of two walls of plastic scintillators. The precession of the neutron spin in a magnetic field was used for the first time to circumvent the measurement of the effective analysing power of the polarimeter and the beam polarisation. In this way $G_{E,n}$ could be determined with little model dependence and experimental uncertainties. The result $G_{E,n}(0.34\ \mathrm{GeV}^2/\mathrm{c}^2) = 0.0611 \pm 0.0069_{stat} \pm 0.0055_{syst}$ is larger than previously assumed.

The internal structure of protons and neutrons at low energies is still an unsolved problem. At momentum transfers of the order $Q^2 \sim \Lambda^2_{QCD}$, where $\Lambda_{QCD} \approx 250\,\mathrm{MeV/c}$ is the scale parameter of quantum chromodynamics (QCD), perturbative solutions are not possible. Rather, the strictly nonlinear QCD has to be solved in the framework of lattice gauge theory or approximated by effective field theories. Sensitive tests of these solutions require the detailed comparison with low energy observables, such as the excitation spectrum of the nucleon or the electric and magnetic form factors. In particular the form factors, which are measured by elastic electron-nucleon scattering, contain the information on the spatial distribution of charge and magnetisation in the nucleon. The electric form factor of the neutron $G_{E,n}$ is of special significance since the charge of the neutron vanishes and a non–zero form factor must come from a non–uniform spatial distribution of valence quarks or the sea of correlated quark–antiquark pairs, e.g. pions.

The experimental information on $G_{E,n}$ is still unsatisfactory for two reasons. Firstly, the lack of a free neutron target requires the use of nuclear targets thus introducing binding effects. Secondly, the standard Rosenbluth separation of the longitudinal cross section arising from the electric form factor $G_{E,n}(Q^2)$ and the transverse cross section due to the magnetic form factor $G_{M,n}(Q^2)$ in

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{Mott}}{\epsilon(1+\tau)} \frac{E'}{E} \cdot \left(\epsilon G^2_{E,n} + \tau G^2_{M,n}\right)$$

is limited because $G^2_{E,n}(Q^2) \ll \tau G^2_{M,n}(Q^2)$. Here σ_{Mott} denotes the Mott cross section, $\tau = Q^2/4M^2$ and $\epsilon = \left[1 + 2(1+\tau)\tan^2\vartheta_e/2\right]^{-1}$. Recently, such a separation of $G_{E,n}$ in the range $Q^2 \simeq 1.75 - 4\ \mathrm{GeV}^2/\mathrm{c}^2$ yielded data compatible with $G_{E,n} \equiv 0$ [1].

More precise data at lower momentum transfers ($Q^2 < 1\,\mathrm{GeV}^2/\mathrm{c}^2$) came from the study of the deuteron structure function $A(Q^2)$, measured in elastic electron–deuteron scattering. $A(Q^2)$ provides a higher sensitivity to $G_{E,n}$ through the mixed term $G_{E,n} \cdot G_{E,p}$ in the square of the isoscalar form factor $(G_{E,n} + G_{E,p})^2$. However, the necessary unfolding of the deuteron wavefunction introduces a substantial model dependence in $G_{E,n}$ ([2,3] and Fig. 4).

A more promising approach to measure $G_{E,n}$ is offered by the use of polarisation observables. For elastic $n(\vec{e}, e'\vec{n})$ scattering of longitudinally polarised electrons the polarisation of the recoiling neutron is given in the (x,y,z)–frame of Fig. 1 by [4]:

$$\begin{aligned}\vec{P}^n &= h \cdot P_e \cdot \left(P^n_x \hat{e}_x + P^n_y \hat{e}_y + P^n_z \hat{e}_z\right) \\ &= \frac{h \cdot P_e}{\epsilon G^2_E + \tau G^2_M} \cdot \Big[- \sqrt{2\tau\epsilon(1-\epsilon)}\, G_{E,n}\, G_{M,n} \cdot \hat{e}_x \\ &\quad + \tau\sqrt{1-\epsilon^2}\, G^2_{M,n} \cdot \hat{e}_z \Big] \qquad (1)\end{aligned}$$

where P_e denotes the absolute value of the electron polarisation and $h = \pm 1$ the electron helicity. In the ratio P^n_x / P^n_z the unpolarised cross section as well as the

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electron polarisation P_e cancel out providing a sensitive experimental access to the ratio $G_{E,n}/G_{M,n}$:

$$\frac{P_n^x}{P_n^z} = \frac{-\sqrt{2\epsilon}}{\sqrt{\tau(1+\epsilon)}} \cdot \frac{G_{E,n}}{G_{M,n}}. \tag{2}$$

However, when using light nuclei as neutron targets one still has to pay attention to nuclear binding effects. In first order (i.e. PWBA, no final state interactions) the scattering from the neutron and the spectral function factorise in the cross section so that the latter cancels in the polarisation components given by eq.(1). In more detail it was shown by Arenhövel and collaborators [5] that in the case of a deuteron target meson exchange (MEC) and isobar currents (IC) have a negligible effect in quasifree kinematics as does the choice of the N-N potential so that there is essentially no dependence on the deuteron wave function. Within these calculations final state interactions (FSI) lead to a relative reduction of the neutron polarisation of less than 4% at $Q^2 \approx 0.35\,\mathrm{GeV}^2/\mathrm{c}^2$. At lower momentum transfer ($Q^2 < 0.2\,\mathrm{GeV}^2/\mathrm{c}^2$) a strongly rising influence of FSI, especially of charge exchange reactions, is found [6]. A measurement of $G_{E,n}$ in this low Q^2–range along with a detailed study of the kinematic dependence of FSI will be presented in a forthcoming paper [9].

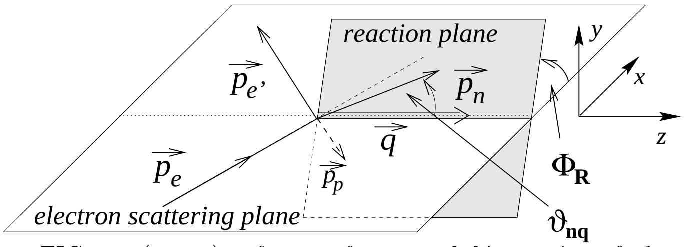

FIG. 1. (x, y, z) reference frame and kinematics of the $D(\vec{e}, e'\vec{n})p$ reaction.

A real experiment cannot be restricted to the strictly quasifree case ($\vartheta_{nq} = 0$) but will cover a finite range in ϑ_{nq} and Φ_R (Fig. 1). Finite angles ϑ_{nq} and Φ_R correspond to the so called Wigner–rotation of the quantisation axes and lead to a mixing of the polarisation components P_x^n and P_z^n which averages out in case of an azimuthally symmetric event population. A comparison with the calculations of Arenhövel et al. shows that this mixing dominates the ϑ_{nq} and Φ_R dependence of the neutron polarisation for angles $\vartheta_{nq} < 10°$ at $Q^2 > 0.2\,\mathrm{GeV}^2/\mathrm{c}^2$ [8].

This letter presents a determination of $G_{E,n}$ at $Q^2 = 0.34\,\mathrm{GeV}^2/\mathrm{c}^2$ using the $D(\vec{e}, e'\vec{n})p$ reaction and the 855 MeV, longitudinally polarised c.w. beam of the Mainz Microtron MAMI [10]. The polarised–electron source is based on photoelectron emission of GaAsP [11]. At the cylindrical, 5 cm thick, liquid deuterium target an average beam current of $2\mu A$ was available with an typical polarisation of $\overline{P_e} = 75\%$. The helicity of the beam was reversed during the experiment with a frequency of 1 Hz to eliminate instrumental asymmetries. The electron polarisation was measured at the source (100 keV) with a Mott polarimeter and before the target (855 MeV) by Møller scattering. A bremsstrahlung-transmission Compton polarimeter, situated in the electron beam dump, provided continuous monitoring of beam polarisation throughout the experiment [12].

The detector setup is shown schematically in Fig. 2. The scattered electrons were detected in a segmented Pb–glass calorimeter with an angular resolution of $\delta\vartheta_e \approx \delta\varphi_e < \pm 0.2°$. The energy resolution of $\delta E/E \approx 20\%$ was sufficient to suppress inelastic events resulting from π–production. This was cross checked using a high resolution BGO/BaF_2 calorimeter with reduced solid angle and a beam current of a few nA [13].

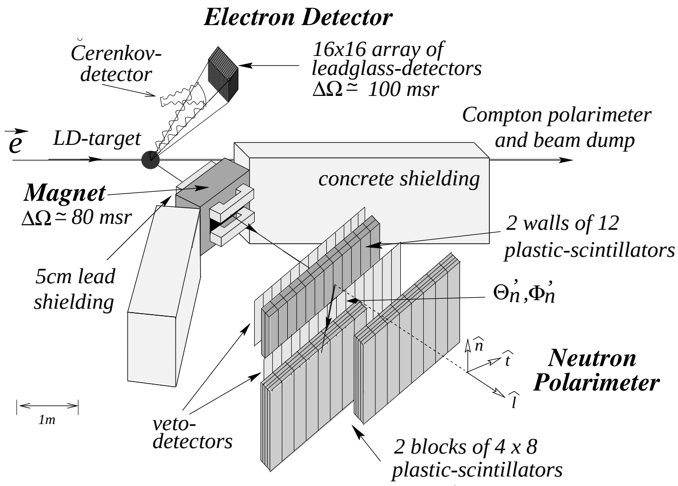

FIG. 2. Detector setup and the $(\hat{t}, \hat{n}, \hat{l})$ reference frame in the neutron scattering plane defined by the neutron momentum and the beam direction.

The neutrons were detected in coincidence with the electrons by two large area walls of plastic scintillators well shielded by concrete and lead. The first wall [14] consisted of 24 vertical bars each equipped with photomultipliers on both ends and operated as a time of flight spectrometer: $\delta\vartheta_n \approx \pm 1.5°$; $\delta\varphi_n < \pm 1.0°$; $\delta\beta_n/\beta_n \approx 6\%(FWHM)$ for neutron energies relevant in this experiment. 5 variables $(\vartheta_e, \varphi_e, \vartheta_n, \varphi_n, \beta_n)$ were determined, allowing the complete kinematic reconstruction of the 3–body final state. The systematic error for the reconstructed direction of momentum transfer ($\delta\Theta_q^{syst} \approx \pm 0.4°$) is dominated by systematic uncertainties in the measurement of the neutron time of flight. The contribution of $p \to n$ charge exchange reactions in the lead shielding to the total neutron yield in the detector was measured to be smaller than 1.5% [15]. A possible depolarisation of neutrons in lead was investigated by Eden et al. [16] and no significant effects were found.

For the analysis of the neutron polarisation the detection process itself can be used. As has been demonstrated by Taddeucci et al. [17], np–scattering in plastic scintillators offers a reasonable analysing power $\mathcal{A}_{\rm eff}(\Theta'_n, T_n) \approx$ 20–40% at neutron energies from 100 to 200 MeV leading to an asymmetry in the azimuthal angle, Φ_n, of the secondary scattered neutrons:

$$N^h(\Theta'_n, \Phi'_n) \; = \; N_0 \cdot \Big(1 + h \cdot P_e \cdot \mathcal{A}_{\rm eff}(\Theta'_n, T_n) \\ \cdot \Big[P^n_{\hat{t}} \cdot \sin\Phi'_n + P^n_{\hat{n}} \cdot \cos\Phi'_n\Big]\Big).$$

$P^n_{\hat{t}}$ and $P^n_{\hat{n}}$ ($(\hat{t}, \hat{n}, \hat{l})$–frame in Fig. 2) denote the polarisation components with respect to the neutron scattering plane perpendicular to the direction of the neutron momentum. In the case $\vartheta_{nq} = 0$ they are given by P^n_x and P^n_y, respectively. The scattering angles Θ'_n und Φ'_n can be reconstructed through the hit position in the second scintillator wall [18]. The Φ'_n asymmetry $A(\Phi'_n)$ was determined through the ratio

$$A(\Phi'_n) \; = \; \frac{\sqrt{N^+(\Phi'_n)N^-(\Phi'_n+\pi)} - \sqrt{N^-(\Phi'_n)N^+(\Phi'_n+\pi)}}{\sqrt{N^+(\Phi'_n)N^-(\Phi'_n+\pi)} + \sqrt{N^-(\Phi'_n)N^+(\Phi'_n+\pi)}} \\ =: a_{\hat{t}} \cdot \sin\Phi'_n + a_{\hat{n}} \cdot \cos\Phi'_n$$

in which the detector efficiencies and helicity dependent luminosity fluctuations cancel. The determination of the desired neutron recoil polarisation from the amplitudes $a_{\hat{t}} = P_e \cdot \mathcal{A}_{\rm eff} \cdot P^n_{\hat{t}}$ and $a_{\hat{n}} = P_e \cdot \mathcal{A}_{\rm eff} \cdot P^n_{\hat{n}}$ requires the knowledge of the effective analysing power $\mathcal{A}_{\rm eff}$ of the polarimeter which depends crucially on the kinematic cuts applied to select the np–scattering events in the first detector plane. An absolute calibration can be circumvented by measuring the ratio $a_{\hat{t}}/a_{\hat{l}} = P^n_{\hat{t}}/P^n_{\hat{l}}$ in which the analysing power as well as the electron polarisation cancel. Therefore, the longitudinal polarisation component $P^n_{\hat{l}}$ has also to be determined. This was achieved by using the spin precession in a magnetic field. On their path L through a dipole magnet with a vertical field $\vec{B} = B \cdot \hat{n}$ the neutron spins precess through the angle

$$\chi = \frac{-1.91 \cdot e}{m_p\, \beta_n\, c} \cdot \int_L B(l) dl. \tag{3}$$

in the neutron scattering plane due to their anomalous magnetic moment $\mu_n = -1.91 \cdot \mu_K$. The field integral $|\int B(l)dl|$ was varied between 0.15 Tm ($|\chi| \approx 10^o$) and 1.3 Tm ($|\chi| \approx 90^o$) and was measured to an accuracy of 0.005 Tm over the whole acceptance of the magnet. In the data analysis only events with precession angles deviating by less than 1% from eq.(3) due to non-vertical field components, were accepted. After the precession by χ the transverse amplitude $a_{\hat{t}}(\chi)$ receives contributions from both, $P^n_{\hat{t}}$ and $P^n_{\hat{l}}$:

$$a_{\hat{t}}(\chi) \; = \; P_e \mathcal{A}_{\rm eff} \left(P^n_{\hat{t}} \cdot \cos\chi \; - \; P^n_{\hat{l}} \cdot \sin\chi\right) \\ =: A_0 \cdot \sin(\chi - \chi_0). \tag{4}$$

The angle of zero crossing of the amplitude $a_{\hat{t}}$, χ_0, is directly related to the ratio of the polarisation components and depends neither on the analysing power of the polarimeter nor on the polarisation of the electron beam

$$\tan\chi_0 = \frac{P_e \mathcal{A}_{\rm eff}}{P_e \mathcal{A}_{\rm eff}} \cdot \frac{P^n_{\hat{t}}}{P^n_{\hat{l}}}$$

Asymmetry data for various precession angles χ are shown in Fig. 3. Kinematic cuts on the analysing reaction change the amplitude of $a_{\hat{t}}$ (i.e. the effective analysing power) but not the zero crossing angle χ_0. This has been investigated for a variety of different conditions [8,9].

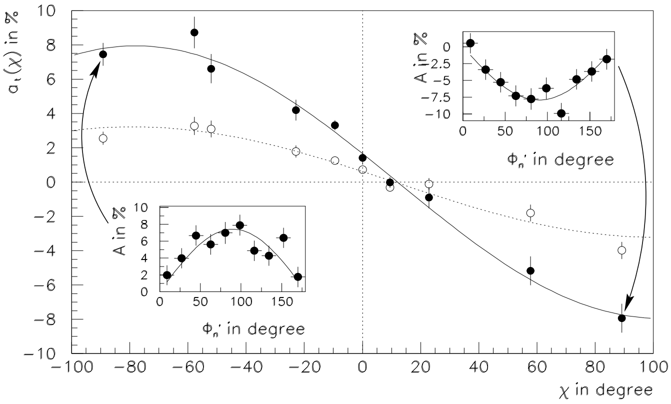

FIG. 3. Measured amplitudes $a_{\hat{t}}(\chi)$ of reconstructed Φ'_n asymmetries (two examples are given in the inlays) for various precession angles χ averaged over the detector acceptance, with two different kinematic cuts on the analysing np reaction.

On the other hand, the observed ratio $P^n_{\hat{t}}/P^n_{\hat{l}}$ in the $D(e, e'n)p$ reaction does depend on the degree of deviation from the free $n(e, e'n)$ kinematics, as outlined above. In order to extract the ratio P^n_x/P^n_z (eq.(2)) from the measured ratio $P^n_{\hat{t}}/P^n_{\hat{l}} = \tan\chi_0$ the effect of the kinematic acceptance was corrected using the reconstructed reaction kinematics. The relative size of this correction ($\approx$ –3%) is smaller than the systemactic error (± 7.5%) caused by the uncertainty in the momentum-transfer direction (Θ_q) being the dominant contribution to the systematic uncertainty (Table I).

The electric form factor can be calculated by means of eq.(2). For the magnetic form factor the empirical dipole fit $G_{M,n}(Q^2) = \mu_n \cdot (1 + Q^2/0.71\,{\rm GeV}^2/{\rm c}^2)^{-2}$ was used. This form has recently been confirmed in the range $Q^2 \approx$ 0.3–0.4 GeV^2/c^2 with a statistical error of 2% [19]. Systematic errors in $G_{M,n}$ are still under discussion [20] and are not included here. The extracted values for $G_{E,n}$ in 3 different Q^2–bins are given in Table II.

source	$(\Delta G_{E,n})^{syst}/G_{E,n}$
$\vec{q}$–direction	±7,5%
contribution of non–quasifree events	−4%
final state interactions (FSI)	+4%
determination of precession angle χ	±2%
experimental uncertainty in $G_{M,n}$	±2%
kinematic factor in eq.(2)	±1%
square sum	±9%

TABLE I. Summary of contributions to the systematic error relative to the $G_{E,n}$ value averaged over the whole Q^2 acceptance

Q^2 in GeV^2/c^2	$G_{E,n} \pm (\Delta G_{E,n})^{stat} \pm (\Delta G_{E,n})^{syst}$
0.29 ± 0.02	0.059 ± 0.011 ± 0.0055
0.34 ± 0.03	0.074 ± 0.012 ± 0.0055
0.42 ± 0.05	0.049 ± 0.013 ± 0.0055
$0.34^{+0.13}_{-0.07}$	0.0611 ± 0.0069 ± 0.0055

TABLE II. Results for $G_{E,n}$.

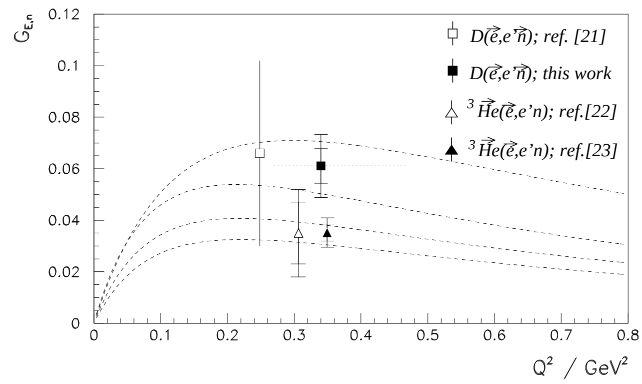

FIG. 4. The result of this work (■) with statistical and systematic errors (vertical bars) and the Q^2–range (point curve) with other $G_{E,n}$ measurements in double polarisation experiments [21–23] and the best fits to data extracted from the elastic deuteron response using 4 different NN–potentials [3] (dashed lines).

The result averaged over the whole Q^2–acceptance is shown in Fig. 4 along with results from other double polarisation experiments [21–23] and the results extracted from the elastic deuteron response using 4 different NN–potentials [3]. A measurement of $G_{E,n}$ in the $^3\overrightarrow{He}\ (\vec{e},e'n)pp$ reaction which was performed with an almost identical detector setup [23] resulted in a significantly lower value. As already mentioned, charge exchange reactions in the final state of the $D(\vec{e},e'\vec{n})p$ reaction reduce $P^n_{\hat{t}}$ significantly at $Q^2 = 0.15\,\mathrm{GeV}^2/\mathrm{c}^2$. Due to the much stronger binding of the neutron in $^3\overrightarrow{He}$ this FSI might remain important up to higher values of Q^2 in $^3\overrightarrow{He}\ (\vec{e},e'n)pp$.

In summary the neutron recoil polarisation in $D(\vec{e},e'\vec{n})p$ has been measured using the spin precession in a magnetic field for the first time. In this way experimental calibration factors could be eliminated and a value for $G_{E,n}$ at $Q^2 = 0.34\,\mathrm{GeV}^2/\mathrm{c}^2$ with little residual model dependence was obtained. The result lies at the upper limit of the model dependence in [3] and higher than the preferred result therein.

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[1] A.Lung et al., Phys.Rev.Lett. 70, 718 (1993)
[2] S. Galster et al., Nucl.Phys. B32, 221 (1971)
[3] S.Platchkov et al., Nucl.Phys. A510, 740 (1990)
[4] R.G. Arnold et al., Phys.Rev.C23, 363 (1981)
[5] H. Arenhövel, Z.Phys. A331, 123 (1988);
[6] H. Arenhövel, private communication
[7] D.R. Giebink, Phys. Rev. C32, 502 (1985)
[8] M. Ostrick PhD Thesis, Univ. Mainz (1998)
[9] C.Herberg, PhD Thesis, Univ. Mainz (1998), publication in preparation
[10] J. Ahrens, H. Backe, D. von Harrach, K.H. Kaiser, F.Klein, R. Neuhausen and Th. Walcher, Nuclear Physics News 2, 5 (1994)
[11] K.Aulenbacher et. al., Nucl.Inst.Meth. A 391, 498 (1997)
[12] H. Schmieden, Spin 1996 proceedings, 819 Ed. C.W. de Jager et. al., Amsterdam 1997
[13] R. Sprengard, Diploma thesis, Univ. Mainz 1995
[14] J. Annand et al., Nucl.Inst.Meth. A 262(1987)329
[15] M. Ostrick, Diploma thesis, Univ. Mainz 1994
[16] T.Eden et al., Nucl. Instr. Meth. A338, 432 (1994)
[17] T.N.Taddeucci et al., Nucl.Inst.Meth. A241, 448 (1985)
[18] P.Grabmayr et. al., Nucl.Inst.Meth. A 402, 85 (1998)
[19] H.Anklin et al., Phys. Lett. B428, 248 (1998)
[20] E.Bruins et al., Phys. Rev. Lett. 79, 5187 (1997); J.Jourdan et al., Phys. Rev. Lett. 79, 5186 (1997)
[21] T.Eden et al., Phys. Rev. C50, R1749, (1994)
[22] M.Meyerhoff et al., Phys.Lett. B327, 201 (1994)
[23] J.Becker et. al., PhD Thesis, Univ. Mainz (1998), publication in preparation