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Determination of the neutron electric form factor in the $D(\mathbf{e},e'\mathbf{n})p$ reaction and the influence of nuclear binding*

C. Herberg[1a], M. Ostrick[1a], H.G. Andresen[1], J.R.M. Annand[2], K. Aulenbacher[1], J. Becker[3], P. Drescher[3], D. Eyl[1], A. Frey[1], P. Grabmayr[4], S.J. Hall[2], P. Hartmann[1], T. Hehl[4], W. Heil[3], J. Hoffmann[3], D. Ireland[2], J.D. Kellie[2], F. Klein[5], K. Livingston[2], Ch. Nachtigall[3], A. Natter[4], E.W. Otten[3], R.O. Owens[2], E. Reichert[3], D. Rohe[3], H. Schmieden[1], R. Sprengard[1], M. Steigerwald[3], K.-H. Steffens[1], Th. Walcher[1], and R. Watson[2]

[1] Institut für Kernphysik, Universität Mainz, D-55099 Mainz
[2] Department of Physics and Astronomy, University of Glasgow, Glasgow, U. K.
[3] Institut für Physik, Universität Mainz, D-55099 Mainz
[4] Physikalisches Institut, Universität Tübingen, D-72076 Tübingen
[5] Physikalisches Institut, Universität Bonn, D-53115 Bonn

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Abstract. The electric form factor of the neutron $G_{E,n}$ has been determined at the Mainz Microtron MAMI at the low momentum transfer $Q^2 = 0.15\,$(GeV/c)^2 in a measurement of the recoil polarisation ratio P_x/P_z in the quasifree reaction $D(\mathbf{e},e'\mathbf{n})p$. At this Q^2 the influence of the nuclear binding is strong. A purely kinematical model is used to get some insight into the effect of the initial Fermi momentum distribution of the neutron. The influence of the final state interaction is determined quantitatively by a model of Arenhövel et al.. After the corresponding corrections a value of $G_{E,n}(0.15\,(\text{GeV/c})^2) = 0.0481 \pm 0.0065_{stat} \pm 0.0053_{syst}$ is obtained.

PACS. 25.30.Fj Nuclear Reactions: Inelastic electron scattering to continuum – 14.20.Dh Properties of Specific Particles: Protons and neutrons – 13.40.Gp Electromagnetic form factors – 25.10.+s Nuclear reactions involving few–nucleon systems

The electric form factor of the neutron as determined in elastic scattering of electrons provides information about the distribution of the charged constituents, i.e. the valence quarks and the quark-antiquark fluctuations appearing effectively as mesons [1]. In order to access this information a sufficiently broad range of low four-momentum transfers ($0 < Q^2 < 1$ (GeV/c)^2) has to be measured. Since no free neutron target exists such measurements must use quasifree scattering from neutrons bound in light nuclei. As will be discussed below experiments using polarized particles provide the most promising method to take the influence of nuclear binding into account. A first measurement using the $D(\mathbf{e},e\mathbf{n})p$ reaction proved the feasibility but had limited statistical significance [2] (see also Fig. 5). Recently new results have been obtained in the two quasifree reactions $D(\mathbf{e},e'\mathbf{n})p$ [3] and $^3\mathbf{He}(\mathbf{e},en)pp$ [4–6] at $Q^2 = 0.34$ and $0.68\,$(GeV/c)^2. The measurement of $G_{E,n}$ using the $D(\mathbf{e},e\mathbf{n})p$ reaction presented in this letter uses the same method as described in ref. [3] but at the low squared four momentum transfer $Q^2 = 0.15\,$(GeV/c)^2. Therefore, only the salient points of the method are mentioned as they are needed to explain the corrections of the effects due to nuclear binding which are expected to rise strongly at low Q^2.

The recoil polarisation for a free neutron is given by [7]:

$$\begin{aligned} P_x^n &= -hP_e \cdot \frac{\sqrt{2\tau\epsilon(1-\epsilon)}}{\epsilon G_E^2 + \tau G_M^2} \cdot G_E G_M \\ P_y^n &= 0 \\ P_z^n &= hP_e \cdot \frac{\tau\sqrt{1-\epsilon^2}}{\epsilon G_E^2 + \tau G_M^2} \cdot G_M^2 \ , \end{aligned} \tag{1}$$

where $h = \pm 1$ denotes the electron helicity and P_e the absolute value of the electron polarisation. The parameters $\tau = Q^2/4M^2$ und $\epsilon = [1 + 2(1+\tau)\tan^2\vartheta_e/2]^{-1}$ are determined by the kinematics. The planes of reference and the kinematical variables are defined in Fig. 1. The quantisation axis for $\mathbf{P}^n$ is the direction of $\mathbf{q}$ which is also the direction of the recoil momentum $\mathbf{p}_f$ for a free neutron. In the ratio P_x^n/P_z^n the electron polarisation P_e cancels providing a sensitive experimental access to the ratio $G_{E,n}/G_{M,n}$:

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

The driving idea behind these double polarisation experiments is that for a bound neutron the model dependence of the extracted form factor, which occurs via the dependence of the

[a] comprises parts of Ph.D. thesis
*Dedicated to Hartmut Arenhövel at the occasion of his 60th anniversary

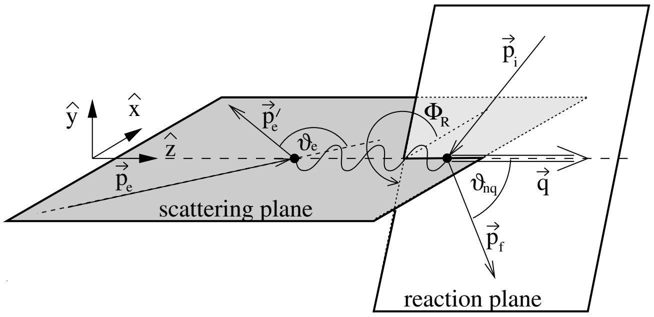

Fig. 1. Definition of scattering plane and reaction plane.

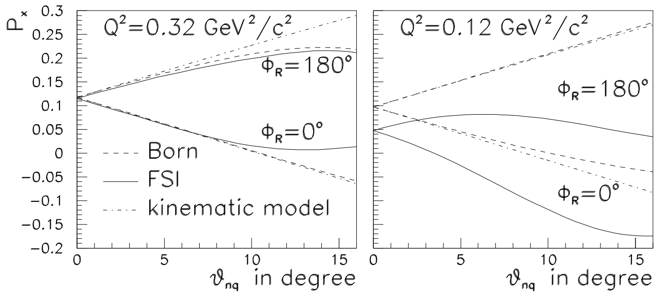

Fig. 2. Dependence of P_x on neutron kinematics and final state interaction for two different momentum transfer squared Q^2 (for details see text).

neutron wave function on the nuclear binding, cancels in these polarisation observables in leading order. Of course, there are higher order corrections caused by final state interactions (FSI), meson exchange currents (MEC), isobaric currents (IC) and relativistic effects (RE). In the case of the $D(\mathbf{e}, e\mathbf{n})p$ reaction Arenhövel et al. [8] have shown that these corrections are negligible in quasifree kinematics when the momentum of the neutron $\mathbf{p}_f$ is in the direction of the three-momentum transfer $\mathbf{q}$ for Q^2 larger than about 0.25(GeV/c)^2 but are important for smaller Q^2. It has been argued that at favourable kinematics the validity of the model of Arenhövel et al. has been checked experimentally in the $D(\mathbf{e}, e\mathbf{p})n$ reaction [9]. In addition, the possibility that $G_{E,n}$ may be changed by nuclear binding has also to be considered.

These generally accepted ideas have, however, to be adapted to experiments using by necessity relatively large solid angle detectors. Due to Fermi motion the recoil momentum $\mathbf{p}_f$ deviates from the direction of momentum transfer $\mathbf{q}$ (see Fig. 1). This effect is of course included in the calculations of Arenhövel et al., but additional insight is gained from a simple kinematical model presented below. The effect on the recoil polarisation is given by a rotation of the quantization axes in the reaction plane to the direction of $\mathbf{p}_f$:

$$\mathbf{P}^n \to W(\vartheta_w, \Phi_R)\, \mathbf{P}^n \tag{3}$$

with

$$W = \begin{pmatrix} \cos^2\Phi_R\, \cos\vartheta_w \,+\, \sin^2\Phi_R & 0 & -\cos\Phi_R \sin\vartheta_w \\ \cos\Phi_R\, \sin\Phi_R(\cos\vartheta_w - 1) & 0 & -\sin\Phi_R \sin\vartheta_w \\ \cos\Phi_R\, \sin\vartheta_w & 0 & \cos\vartheta_w \end{pmatrix},$$

where ϑ_w is called the Wigner angle [10]. For low initial momenta it is practically given by $\vartheta_w \approx \vartheta_{nq}$. The effect of the Fermi motion on the polarisation has been calculated using the Fourier transform of Hulthén-wave functions [11] and is shown in Fig. 2. For the $G_{E,n}(Q^2)$ the parametrisation given in [14] has been used. For $\vartheta_{nq} \neq 0°$ the transverse polarisation component P_x gets an admixture of the component P_z^n given by eq.(3), which averages out in case of an event population symmetric with respect to Φ_R. For comparison the results of Arenhövel [12] are plotted based on a deuteron wave function calculated with the Paris potential in the initial state and a free neutron and proton in the final state without (Born) and with final state interaction (FSI). The good agreement between the simple kinematical model and the calculations of Arenhövel in the Born approximation for both momentum transfers up to $\vartheta_{nq} \approx 10°$ shows that this dependence is dominated by the initial motion of the neutron. Including FSI between the recoil neutron and the proton of the deuteron target in the calculations does not strongly affect the recoil polarisation at a momentum transfer of $Q^2 = 0.32\,$(GeV/c)^2 (Fig.2, left). However, at a $Q^2 = 0.12\,$(GeV/c)^2 (right) the transverse recoil polarisation is lowered by $\approx 50\%$ keeping the general features of the dependence on the neutron kinematics. The other effects, MEC, IC, RE or different nucleon-nucleon potentials, have no practical influence.

The strong influence of final state interactions on P_x^n at low Q^2 can be traced back to the p–n charge exchange via one pion exchange. Since the magnetic moment of the proton has the opposite sign compared to the neutron the polarisation transfer P_x^p will have the opposite sign, too. If the reaction happens at protons which turned into neutrons via charge exchange in FSI the recoil polarisation component P_x^n of these neutrons will effectively reduce the measured ratio P_x/P_z which is averaged over all events. At low Q^2 this effect increases as the p–n charge exchange cross section increases but is insensitive to $G_{E,n}$, the quantity one wants to extract from the data. This insensitivity can be seen by an investigation of the correction:

$$\Delta(\frac{P_x}{P_z}) := \frac{P_x^n}{P_z^n} - \frac{P_x^{FSI}}{P_z^{FSI}} \tag{4}$$

in the framework of the calculations of Arenhövel [8]. For a change of $G_{E,n}$ in the order of the difference between the two results of Ref. [5] and [3] of $\Delta G_{E,n} = 0.034$ the change of $\Delta(P_x/P_z)$ is 1% at $Q^2 = 0.12\,$(GeV/c)^2 . Even when setting artifically $G_{E,n} = 0\;\; \Delta(P_x/P_z)$ changes by 10% only.

Other mechanisms like the spin-orbit–interaction in the final state lead to a depolarisation proportional to $G_{E,n}$ and are apparently not important. In summary, a determination of $G_{E,n}$ in the quasifree reaction $D(\mathbf{e}, e\mathbf{n})p$ at low momentum transfer is possible if the experimental ratio P_x/P_z is identified with P_x^{FSI}/P_z^{FSI} and the desired ratio P_x^n/P_z^n is determined via eq.(4).

Such a determination has been performed at $Q^2 = 0.15$ (GeV/c)^2 using the Mainz Microtron MAMI. The recoil polarisation of the neutron is analysed by a polarimeter consisting of two scintillator walls suspending a solid angle of 80 msr. In the first wall the spin-orbit interaction in the n-p scattering produced an azimuthal asymmetry which was determined by a second detection of the neutron in the second wall [13]. The great problem of calibrating the analysing power $\mathcal{A}$ of the polarimeter and the degree of polarisation of the electrons P_e was circumvented by precessing the spin in front of the polarimeter by means of a dipole magnet [3]. As seen from eq.(1) the precession angle χ_0 for which the transverse neutron polarisation P_t vanishes is given by

$$\tan\chi_0 = P_x/P_z \tag{5}$$

independent of $\mathcal{A}$ and P_e [3].

The dependence of the measured P_x/P_z on the initial neutron kinematics can be demonstrated by plotting it in two different ϑ_{nq} bins, $0 < \vartheta_{nq} < 5$ and $5 < \vartheta_{nq} < 10$ summed over the respective event populations belonging to $\Phi_R \approx 0^0$ and $\Phi_R \approx 180^0$. The results are shown in Fig. 3 as full circles. The

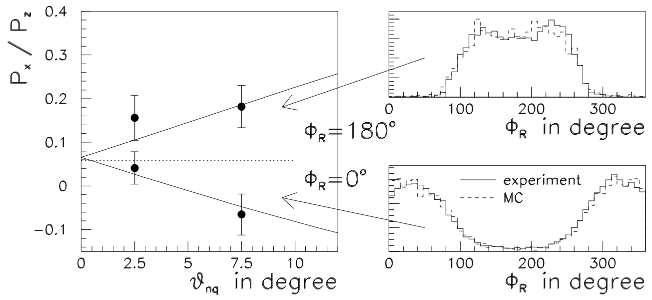

Fig. 3. Measured dependence of P_x/P_z on initial neutron kinematics at $Q^2 = 0.15\,$(GeV/c)^2. The solid lines show the predictions of the kinematical model. The absolute value at $\vartheta_{nq} = 0^o$ has been shifted to the value given by the Arenhövel calculation (see Fig. 2). The dotted line indicates the average of the measured values. The panels at the right show the underlying experimental event populations for $\Phi_R \approx 0^0$ and $\Phi_R \approx 180^0$.

comparison shows that the kinematical model indeed describes the observed ϑ_{nq} and Φ_R dependence of the polarisation ratio. In ref. [3] this model has been used to correct the influence of the experimental Φ_R acceptance on the determination of $G_{E,n}$ at $Q^2 = 0.34\,$(GeV/c)^2. The influence of FSI was included in the systematic error of this reference. The complete correction will be presented below together with the low Q^2 determination of this letter.

As mentioned before, at low Q^2 a more refined correction including FSI as provided by Arenhövel is essential. In order to adapt his calculations to the present experiments they have to be weighted with the event population. This has been done in a Monte-Carlo analysis using a lattice of points which cover the acceptance of the electron Pb-glass detector and the neutron polarimeter. At each lattice point the difference $\Delta(P_x/P_z)$ was calculated. The value of P_x/P_z measured in each bin of the electron Pb-glass matrix was corrected by interpolating and adding $\Delta(P_x/P_z)$. The corrected ratios were averaged over the experimental acceptance weighted with the event population. Fig. 4 shows the experimental results of both measurements of the polarisation ratio P_x/P_z at $Q^2 \approx 0.34\,$(GeV/c)^2 [3] and $Q^2 \approx 0.15\,$(GeV/c)^2 [this work] each split into three independent bins.

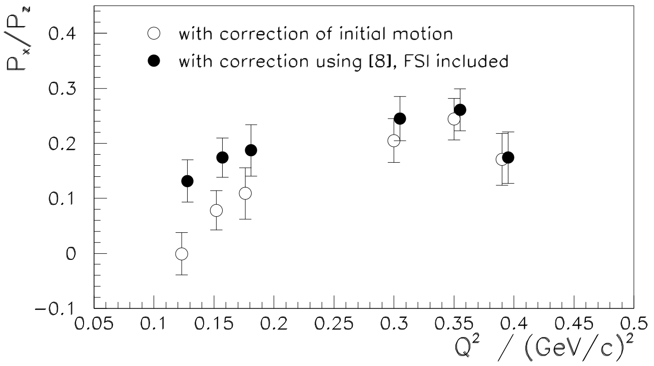

Fig. 4. Polarisation ratio P_x/P_z as a function of the momentum transfer squared. Open circles: correction due to the kinematical model eq.(3). Full circles: correction using the calculations of Arenhövel et al. [8] including FSI. The open circles are shifted in Q^2 for the presentation. Note the offset of the ordinate.

The open circles depict the results with the statistical error after the correction of the initial Fermi motion using the kinematical model. The full circles give the result after the full correction including FSI using the calculations of Arenhövel.

Table 1 lists the magnitudes of all systematic errors in $G_{E,n}$ at $Q^2 = 0.15\,$(GeV/c)^2 [15,3]. The dominant systematic error results from an uncertainty in the reconstruction of ϑ_{nq} and Φ_R due to the time of flight resolution. Other experimental errors originate from a misidentification of quasifree events, the uncertainty in the determination of the spin precession angle and $\mathbf{p} \to \mathbf{n}$ charge exchange reactions in the lead shielding. For the magnetic form factor of the neutron the dipole form has been used. The difference between this form and a recent high precision determination at MAMI [16] is less than 2% and has been included in the systematic error. The systematic difference to another recent measurement [17] is, however, not considered. The results for $G_{E,n}$ in the different Q^2 bins are given in Table 2 along with the results of [3] when the correction due to FSI is applied.

Fig. 5 shows the recent results for $G_{E,n}$ from double polarisation experiments. For the measurements of the reaction $D(\mathbf{e},e\mathbf{n})p$ at the Mainz Microtron MAMI the influence of the final state interaction is indicated by arrows. According to the model of Arenhövel et al. [8] the corrections $\Delta(P_x/P_z)$ amount

	$(\delta G_E^n)_{syst.}/G_E^n$
kinematic reconstruction	$\pm 9.3\%$
contribution of non–quasifree events	$\pm 4.3\%$
determination of precession angle χ	$\pm 1.2\%$
$p \to n$ reactions in the lead shielding	$\pm 1.0\%$
beam polarisation	$\pm 0.5\%$
G_E^n dependence (FSI correction)	$\pm 0.6\%$
NN-potential (FSI correction)	$\pm 1.2\%$
MEC, IC, relativistic (FSI correction)	$\pm 2.5\%$
statistical MC error (FSI correction)	$\pm 1.2\%$
experimental uncertainty in G_M^n	$\pm 2.0\%$
total	$\pm 11\%$

Table 1. Systematic error in $G_{E,n}$ at $Q^2 = 0.15\,$(GeV/c)^2.

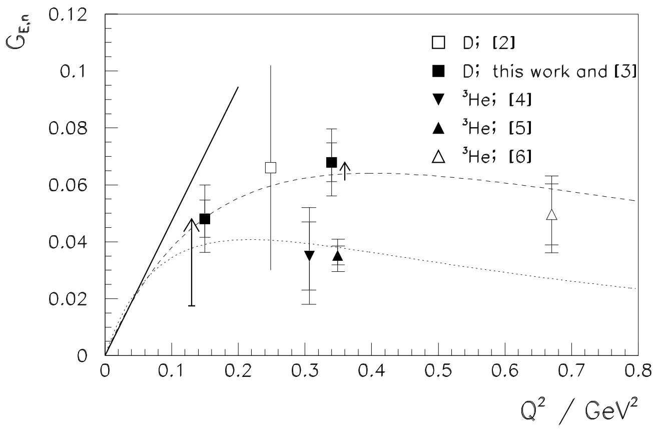

Fig. 5. Results of $G_{E,n}$ (for explanations see text).

to $(8 \pm 3)\,\%$ for $Q^2 = 0.34\,$(GeV/c)^2 and $(65 \pm 3)\,\%$ for $Q^2 = 0.15\,$(GeV/c)^2 of the value unperturbed by FSI. After this correction the two results are consistently higher than the result perferred by Platchkov et al. [18] who analysed the elastic scattering from the deuteron $D(e, e)D$ using the Paris N-N potential (dotted line). However, other N-N potentials used in [18] give results in accord with those from the $D(\mathbf{e}, e\mathbf{n})p$ reaction and the high Q^2 point of the $^3\mathbf{He}(\mathbf{e}, en)pp$ reaction. The solid line shows the slope of $G_{E,n}(Q^2 = 0)$ as given by the charge radius of the neutron [19]. The triangle symbols represent measurements of the reaction $^3\mathbf{He}(\mathbf{e}, en)pp$ at the Mainz Microtron MAMI for $Q^2 \approx 0.3\,$(GeV/c)^2 [4,5] with a polarised target. They are significantly below the measurements of the reaction $D(\mathbf{e}, e\mathbf{n})p$. The ^3He experiment has been analysed under the assumption of quasifree scattering from a neutron with an initial Fermi momentum distribution. The influence of the NN–potential as well as of the final state interaction is more difficult to quantify for ^3He than for D. First Fadejev calculations of Glöckle et al. indicate a correction towards a value about $25\,\%$ higher [20] than the values shown in Fig.5. However, for the measurement of $G_{E,n}$ in the reaction $^3\mathbf{He}(\mathbf{e}, en)pp$ at $Q^2 = 0.67\,$(GeV/c)^2 a smaller influence of the final state interaction can be expected due to the higher momentum transfer [6].

Q^2 /(GeV/c)^2	$G_{E,n} \pm (\Delta G_{E,n})_{stat} \pm (\Delta G_{E,n})_{syst}$
0.12 ± 0.01	$0.037 \pm 0.011 \pm 0.005$
0.15 ± 0.02	$0.052 \pm 0.011 \pm 0.005$
0.18 ± 0.01	$0.058 \pm 0.015 \pm 0.005$
0.15 ± 0.04	$0.0481 \pm 0.0065 \pm 0.0053$
0.29 ± 0.02	$0.072 \pm 0.011 \,^{+0.0060}_{-0.0065}$
0.34 ± 0.03	$0.077 \pm 0.010 \,^{+0.0060}_{-0.0065}$
$0.40 \,^{+0.07}_{-0.03}$	$0.051 \pm 0.013 \,^{+0.0060}_{-0.0065}$
$0.34 \,^{+0.13}_{-0.07}$	$0.0679 \pm 0.0068 \,^{+0.0060}_{-0.0065}$

Table 2. Results for $G_{E,n}$ from the $D(\mathbf{e}, e'\mathbf{n})$ reaction at MAMI.

The results of the double polarisation experiments after a correction of FSI effects are described by the parametrisation [14]

$$G_{E,n}(Q^2) = -\frac{\tau \mu_n}{1 + p\tau} \cdot \frac{1}{(1 + Q^2/0.71\,(\mathrm{GeV/c})^2)^2}$$

with $p = 3.4$ (dashed line in Fig. 5). In summary the results of this work indicate that the electric form factor of the neutron is almost a factor of two larger than assumed until now.

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References

1. D. Drechsel et al., in Chiral Dynamics: Theory and Experiment, Proceedings, Mainz 1998, Eds. A. Bernstein, D. Drechsel, and Th. Walcher; Lecture Note in Physics LNP 513, Springer, Heidelberg 1998
2. T.Eden et al., Phys. Rev. C **50**, R1749, (1994)
3. M. Ostrick et al., PhD Thesis, Univ. Mainz (1998) and to be published in Phys.Rev.Lett.
4. M.Meyerhoff et al., Phys.Lett. B **327**, 201 (1994)
5. J.Becker et. al., PhD Thesis, Univ. Mainz (1997), publication in preparation
6. D. Rohe, PhD thesis, Univ. Mainz (1998), publication in preparation
7. R.G. Arnold et al., Phys.Rev.C **23**, 363 (1981)
8. H. Arenhövel et al., Z.Phys. A **331**, 123 (1988)
9. F. Klein et al., Phys. Rev. Lett. **81**, 2831 (1997)
10. D.R. Giebink; Phys. Rev. C **32**, 502 (1985)
11. L. Hulthén and M. Sugawara in Handbuch der Physik, Band XXXIX, Ed. S. Flügge, Springer Verlag, Heidelberg 1957
12. H. Arenhövel, private communication
13. T.N.Taddeucci et al., Nucl.Inst.Meth. A **241**, 448 (1985)
14. S. Galster et al., Nucl.Phys. B **32**, 221 (1971)
15. C. Herberg, PhD thesis, Univ. Mainz (1998)
16. H. Anklin et al., Phys.Phys. Lett. B428, 248 (1998).
17. E.Bruins et al., Phys. Rev. Lett. 75, 21 (1995).
18. S.Platchkov et al., Nucl.Phys. A **510**, 740 (1990)
19. S.Kopecki et al., Phys. Rev. C **56**, 2229 (1997)
20. G. Ziemer, PhD thesis, Univ. Bochum (1998)