Eur. Phys. J. A 1, 193–200 (1998)

THE EUROPEAN
PHYSICAL JOURNAL A

On approaches to measure the electromagnetic polarizabilities of the neutron

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Received: 25 August 1997 / Revised version: 5 November 1997
Communicated by B. Povh

Abstract. The present experimental state of the neutron polarizabilities is discussed. Two possibilities to extract the neutron polarizabilities from experiments are considered: i) quasi-free Compton scattering from the bound neutron and ii) scattering of slow neutrons in the Coulomb field of heavy nuclei. The latter experiments have led to an intense discussion from which we conclude that all attempts to measure the neutron polarizabilities using this method have failed. It is shown that quasi-free Compton scattering from the neutron bound in the deuteron at photon energies from 200 MeV to 300 MeV is the most promising method of measuring the neutron polarizabilities. To arrive at an experimental accuracy of $\pm 2 \cdot 10^{-4}\mathrm{fm}^3$ when extracting the electric polarizability $\bar{\alpha}_n$, one has to measure the differential cross section in the energy range from 200 MeV to 300 MeV at backward photon scattering angles with a precision of 5%. It is shown that theoretical uncertainties of the method are mainly due to the dependence of the cross section on the selection of multipole analysis of single pion photoproduction. At present they prevent the extraction of $\bar{\alpha}_n$ with an accuracy better than $\pm 2 \cdot 10^{-4}\mathrm{fm}^3$.

PACS. 13.60.Fz Elastic and Compton scattering – 25.20.-x Photonuclear reactions

1 Introduction

The electric and magnetic polarizabilities $\bar{\alpha}$ and $\bar{\beta}$ are fundamental properties of the nucleon. They describe the response of the nucleon to an external electromagnetic field. In a classical sense, $\bar{\alpha}$ is related to the separation of charges inside the nucleon. It measures the ease how an electric dipole moment is induced. The magnetic polarizability $\bar{\beta}$ consists of two parts: 1) the paramagnetic part describes the alignment of the internal magnetic moments to an external magnetic field; 2) in a classical picture the diamagnetic part is related to the currents induced by the external magnetic field. These currents produce an additional magnetic field opposing the external one and give rise to an induced magnetic moment. Thus, the polarizabilities are not static structure constants as mass, charge and magnetic moment, but also carry information about the dynamics inside the nucleon.

The polarizabilities $\bar{\alpha}$ and $\bar{\beta}$ of the proton can be measured via Compton scattering at low energies. In the low-energy expansion of the scattering amplitude, neglecting terms containing the anomalous magnetic moment, the polarizabilities appear in the order of E_γ^2,

$$f = \left\{ -\frac{Q^2}{M} + 4\pi\bar{\alpha}E_\gamma E_{\gamma'} \right\} \boldsymbol{\varepsilon}\,' \cdot \boldsymbol{\varepsilon} + 4\pi\bar{\beta}\,(\boldsymbol{\varepsilon}\,'\times\boldsymbol{k}') \cdot (\boldsymbol{\varepsilon}\times\boldsymbol{k})\,, \qquad (1)$$

where Q is the charge, M the mass of the particle, E_γ (E'_γ) the incident (scattered) photon energy, $\boldsymbol{\varepsilon}$ ($\boldsymbol{\varepsilon}\,'$) denotes the polarization of the incident (scattered) photon and $\boldsymbol{k}$ ($\boldsymbol{k}'$) its momentum. The term $-Q^2/M$ is the Thomson amplitude which vanishes in the case of the neutron due to its zero charge. Including also spin and anomalous magnetic moment [1,2], one obtains the corresponding differential cross section for Compton scattering from the proton:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Po}} - \frac{Q^2}{4\pi M}\left(\frac{E_{\gamma'}}{E_\gamma}\right)^2 E_\gamma E_{\gamma'} \times \left[\frac{\bar{\alpha}+\bar{\beta}}{2}(1+\cos\Theta)^2 + \frac{\bar{\alpha}-\bar{\beta}}{2}(1-\cos\Theta)^2\right]. \qquad (2)$$

Here, the first term of the r.h.s is the Powell cross section [3] for photon scattering from a charged particle with spin $\frac{1}{2}$ and anomalous magnetic moment. The second term is the interference of the Thomson and the polarizability amplitude. Equation (2) shows that in the case of the proton this term becomes measurable, even at rather small photon energies (above 50 MeV). The neutron polarizabilities start manifesting themselves only in the E_γ^4-order. Consequently, the corresponding cross section can be measured only at higher energies.

The inspection of (2) shows that at forward angles it is sensitive to the sum of $\bar{\alpha}$ and $\bar{\beta}$, at backward angles to their difference and at 90° to $\bar{\alpha}$ only. For forward scattering one obtains the Baldin [1] sum rule when applying dispersion relations and using the measured total photon-proton cross section [4,5]:

$$\bar{\alpha}_p + \bar{\beta}_p = \frac{1}{2\pi^2} \int_{m_\pi}^{\infty} \frac{\sigma_{tot}(E_\gamma)}{E_\gamma^2}\, dE_\gamma = 14.2 \pm 0.3, \qquad (3)$$

in units of 10^{-4} fm^3 which will be used henceforth. Proton Compton scattering experiments below the π-production threshold have been performed at various scattering angles [6] using tagged and untagged bremsstrahlung. MacGibbons's analysis [6] gives the following values for the proton [7]:

$$\bar{\alpha}_p = 12.1 \pm 0.8(\text{stat.}) \pm 0.5(\text{syst.}),$$
$$\bar{\beta}_p = 2.1 \mp 0.8(\text{stat.}) \mp 0.5(\text{syst.}). \qquad (4)$$

Thus, the electric polarizability of the proton is measured with an accuracy of 10% and the magnetic one with an accuracy of about 60%. A new experimental attempt has been made to determine the electromagnetic polarizabilities of the proton at the tagged photon facility at MAMI (Mainz, Germany), using the TAPS detector system. An angular range from 30° to 150° and an energy range from 30 MeV to 170 MeV has been covered. The expected statistical accuracy is 5% for the measured differential cross sections. This experiment will also allow to test the Baldin sum rule.

2 Status of the neutron electric polarizability

In Fig. 1 the experimental status of the electric polarizability of the neutron is summarized and compared with theoretical predictions. There are two different approaches to measure $\bar{\alpha}_n$: i) scattering of low energy neutrons in the Coulomb field of heavy nuclei; ii) quasi-free Compton scattering from the neutron bound in the deuteron. Note here, that in the neutron experiments the so-called static polarizability α_n is measured, rather than the 'generalized static' one $\bar{\alpha}_n$. To obtain $\bar{\alpha}_n$, a small relativistic correction $\Delta\alpha_n$=0.62 [18,19] must be added to α_n.

Up to 1991 there seemed to be a convergence of the data obtained for $\bar{\alpha}_n$. However, there has been a controversial discussion on the systematic uncertainties of the neutron scattering experiments. After Schmiedmayer [13] had published his value of

$$\alpha_n = 12.0 \pm 1.5(\text{stat.}) \pm 2.0(\text{syst.}), \qquad (5)$$

Nikolenko and Popov [20,21] raised serious doubts concerning the smallness of the quoted errors. The value has been obtained from the total neutron-nucleus cross section of ^{208}Pb. Taking into account resonance contributions, capture cross sections, neutron-electron and Schwinger scattering, Schmiedmayer had obtained the total scattering cross section in the energy interval 50 eV to 50 keV in the form of the following expression:

$$\sigma_s(k) = 11.508(5) + 0.69(9)k$$
$$-448(3)k^2 + 9500(400)k^4. \qquad (6)$$

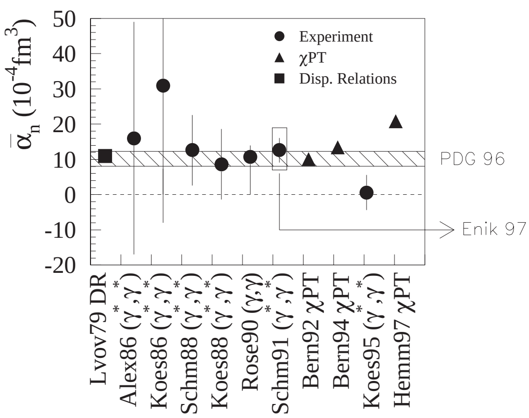

Fig. 1. A compilation of experimental data [8-14] and theoretical predictions [5], [15-17] for the neutron electric polarizability (see text for more details). Neutron scattering experiments are indicated by (γ^*, γ^*). The *dashed area* represents the Particle Data Group value [7]

Here, $\sigma_s(k)$ is given in units of barns, $k = 2.1968\times 10^{-4}\sqrt{E}A/(A{+}1)$ (k in fm^{-1} and E in eV, A is the nuclear mass number) is the neutron wave number. The term linear in k corresponds to polarizability scattering. Nikolenko and Popov [20] created pseudo-experimental cross sections according to expression (6), assuming different statistical errors of the scattering cross section. When reproducing the first term on the r.h.s in (6) with the same error, the term linear in k obtained the much larger error of 0.69(56). They concluded that from this experiment only an upper limit can be deduced: $\alpha_n < 20$. In 1995 Koester et al. [14] published a value, also obtained from neutron-nucleus experiments, which is compatible with zero:

$$\alpha_n = 0 \pm 5. \qquad (7)$$

Again, there was a discussion about the extraction method used to obtain the electric polarizability. Alexandrov [22] pointed out that the determination of α_n requires a statistical precision of the total neutron cross section of $\Delta\sigma/\sigma \approx 10^{-3}$. At this high level of statistical precision it seems to be very difficult to remove possible sources of background. He also focuses on the problems arising from small angle scattering, the proper treatment of p-wave scattering and also the inclusion of the term proportional k^3 which is missing in (6). In 1997 Enik et al. [23] continued the discussion on the neutron scattering experiments. They investigated the physical interpretation of the coefficients in expression (6), concluding that there might be some problems with the cross section measured by Schmiedmayer due to background contributions. It has been pointed out that a term proportional to k^3 also has to be taken into account. The outcome of Enik's paper is that the systematic error in Schmiedmayer's value for α_n was underestimated by a factor of $3-4$ and the result should be taken as

$$\alpha_n \sim 7 - 19. \qquad (8)$$

In this paper we do not contribute to the discussion of neutron scattering experiments. We rather quote ongoing work [20-23] in order to illustrate that there is a need for measurements of the neutron polarizabilities by a different method, which may be provided by quasi-free Compton scattering.

The only existing experiment on quasi-free Compton scattering by the neutron bound in the deuteron, carried out by Rose et al. [12], was successful in the sense that the relevant effect, i.e. coincidence-events between Compton-scattered photons and recoil neutrons, was definitely identified. It was possible to extract the value $\bar{\alpha}_n$=10.7 for the electric polarizability from the experimental data with an upper error of +3.3. The determination of a lower error failed because the rather large lower error of 18% of the differential cross section did not correspond to a possible electromagnetic polarizability (see also Sect. 3). In order to avoid this difficulty, the lower error of the differential cross section should have been 10% or smaller.

There have also been many attempts to calculate the nucleon polarizabilities in various models [5,15-17,24-29]. Here we will mention only few of them. For example, in a dispersion calculation [5] the following values were obtained:

$$\bar{\alpha}_p = 9.0 \pm 2.0, \quad \bar{\beta}_p = 5.2 \pm 2.0, \tag{9}$$
$$\bar{\alpha}_n = 11.1 \pm 2.0, \quad \bar{\beta}_n = 4.7 \pm 2.0, \tag{10}$$

where the quoted errors characterize the uncertainty of the model used to calculate the two-pion contributions in the evaluation of the dispersion integrals. Another more principal source of uncertainty is the 2π (σ-meson) exchange in the t-channel used to model the asymptotic contribution to $\bar{\alpha} - \bar{\beta}$ [30]. In dispersion theories this asymptotic contribution dominates the difference $\bar{\alpha} - \bar{\beta}$ and can either be taken from the linear σ-model or from the t-channel processes $N\bar{N} \to \pi\pi$, $\pi\pi \to \gamma\gamma$. Because of the principal uncertainties involved we consider $\bar{\alpha} - \bar{\beta}$ as an independent input parameter of dispersion theories which has to be determined through Compton scattering experiments.

Today, one of the most promising methods of low energy hadron physics is the chiral perturbation theory (ChPT). The first calculation of the nucleon polarizabilities to one loop order in ChPT [15] gave

$$\bar{\alpha}_p = 7.4, \quad \bar{\beta}_p = -2.0, \tag{11}$$
$$\bar{\alpha}_n = 10.1, \quad \bar{\beta}_n = -1.2. \tag{12}$$

The electric polarizabilities are in reasonable agreement with the data, whereas the values obtained for the magnetic polarizabilities contradict the experimental ones because of their negative sign. A possible reason for this could be the disregarding of the Δ-contribution in [15].

In a subsequent publication of the same group [16] a calculation at $O(p^4)$ was performed and the Δ-contribution was taken into account, leading to

$$\bar{\alpha}_p = 10.5 \pm 2.0, \quad \bar{\beta}_p = 3.5 \pm 3.6, \tag{13}$$
$$\bar{\alpha}_n = 13.4 \pm 1.5, \quad \bar{\beta}_n = 7.8 \pm 3.6, \tag{14}$$

where the uncertainties are due to the counterterm contribution from the Δ and from a K, η loop effect.

Recently a further calculation of the nucleon polarizabilities within heavy baryon ChPT has been performed [17]. The result is isospin independent and reads:

$$\bar{\alpha}_{p,n} = 20.8, \quad \bar{\beta}_{p,n} = 14.7. \tag{15}$$

These values reveal a very serious disagreement with the experimental ones. Possible reasons for this are discussed in [17].

In any case, the theoretical situation concerning the nucleon polarizabilities is far from being satisfactory. One should mention here that in [15–17] the 'empirical' inequality $\alpha_n^{exp} > \alpha_p^{exp}$ is often referred to. We would like to emphasize that, as follows from the above discussion, such an inequality has not been verified since the electric polarizability of the neutron has not yet been measured.

3 Quasi-free compton scattering from the bound neutron

After the unsatisfactory discussion concerning neutron scattering experiments the only promising method of determining the electric polarizability of the neutron is quasi-free Compton scattering from the neutron bound in the deuteron[1]:

$$\gamma d \to \gamma' np. \tag{16}$$

A detailed calculation of the reaction (16) has been carried out by Levchuk et al. [34]. The main graphs contributing to this reaction are outlined in Fig. 2. Graphs a) and b) describe the quasi-free scattering from the neutron and the proton, respectively. The sum of these graphs is often referred to as the plane wave impulse approximation (PWIA). In the case of quasi-free scattering, the non-interacting nucleon behaves as a spectator. Rescattering, i.e. final state interaction (FSI), graphs c) and d), and the influence of meson exchange currents (MEC) and isobar configurations (IC) described by the graphs e) and f) also have to be taken into account.

The computer code of Levchuk et al. has been used for a detailed theoretical investigation of the reaction (16). If not stated otherwise, all the results presented below have been obtained with the deuteron wave function and np-scattering amplitude for the non-relativistic version, OBEPR, of the Bonn potential [35]. The nucleon Compton scattering amplitudes have been taken from the dispersion model [30] using the multipole analysis [36] of single pion photoproduction on the nucleon. The observable is the triple differential cross section $d^3\sigma/d\Omega_{\gamma'} d\Omega_n dE_n$ for a photon-neutron pair in the final state, showing a clear peak (neutron-quasi-free-peak, NQFP) around the expected energy for free scattering. Taking into account

[1] The neutron polarizabilities can also be measured in the elastic Compton scattering from the deuteron [31,32]. This method, however, is applicable only below the pion threshold [33]

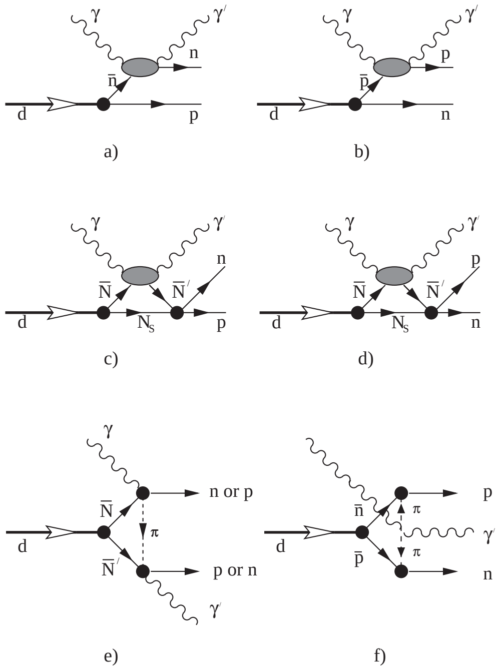

Fig. 2. Main graphs contributing to the reaction $\gamma d \rightarrow \gamma' np$

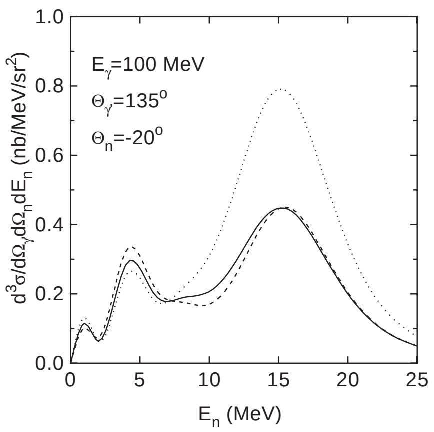

Fig. 3. Dependence of the differential cross section on $\bar{\alpha}_n$ at E_γ=100 MeV, $\Theta_{\gamma'} = 135°$ and $\Theta_n = -20°$. *Dashed, solid*, and *dotted lines*: $\bar{\alpha}_n = 0$, 10, and 20, respectively

Baldin's sum rule prediction for the neutron, which L'vov et al. [5] obtained as

$$\bar{\alpha}_n + \bar{\beta}_n = 15.8 \pm 0.5, \tag{17}$$

the cross section can be determined via the difference $(\bar{\alpha}_n - \bar{\beta}_n)$ at large scattering angles.

This is plotted in Fig. 3 for E_γ=100 MeV at fixed photon scattering and neutron emission angles: $\Theta_{\gamma'} = 135°$, $\Theta_n = -20°$ (note here that at a given photon scattering angle $\Theta_{\gamma'}$ the neutron angle Θ_n in the NQFP is approximately given by: $\Theta_n \approx -(\pi - \Theta_{\gamma'})/2$). The cross section is very small (about 1 nb/MeV/sr^2), which only allows experiments with untagged bremsstrahlung beams. On the other hand, the predicted cross sections for $\bar{\alpha}_n = 0$ and 10 are almost indistinguishable. Therefore, at photon energies below the pion threshold it is difficult but not impossible to obtain a lower limit for $\bar{\alpha}_n$ (see Section 2) provided the value for $\bar{\alpha}_n$ is close to 10 as predicted in many theoretical calculations (see Equations (10), (12), (14)).

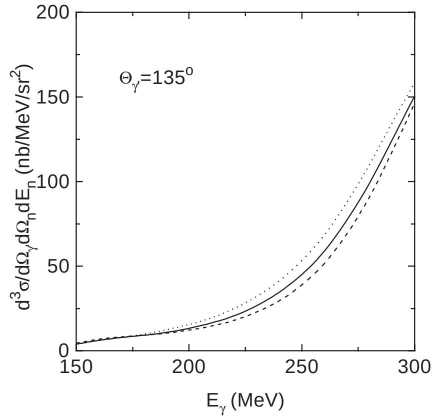

Fig. 4. Dependence of the cross section on $\bar{\alpha}_n$ at $\Theta_{\gamma'} = 135°$ in the center of the NQFP. *Dotted, solid*, and *dashed lines*: $\bar{\alpha}_n = 7$, 11, and 15, respectively

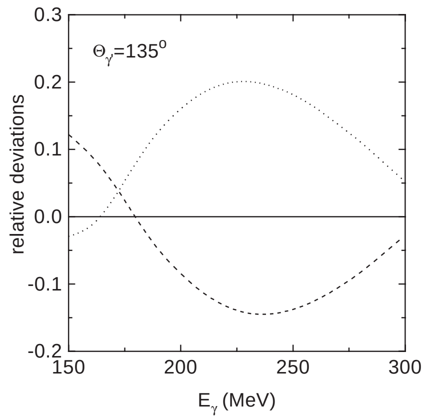

Fig. 5. Difference of the cross sections with $\bar{\alpha}_n = 15$ (*dashed*) and $\bar{\alpha}_n = 7$ (*dotted*), relative to the cross sections with $\bar{\alpha}_n = 11$ in the center of the NQFP at $\Theta_{\gamma'} = 135°$

At energies above 200 MeV these difficulties vanish (see Figs. 4 and 5). The cross section at the NQFP is of measurable size, i.e. tagged photon beams can be used. In addition, at energies between 200 MeV and 300 MeV the cross section is very sensitive to $\bar{\alpha}_n$. For example, varying $\bar{\alpha}_n$ from 7 to 15 in this energy region the cross sections change by more than 20%. This means that an accuracy of about 5% must be achieved in the center of the NQFP in order to extract the electric polarizability with a precision of ± 2 (experimental only) from these experiments. An interesting energy range is around 175 MeV, where the cross section has no sensitivity on $\bar{\alpha}_n$ at all. Near this energy the used model is free of parameters so that a measurement of the differential cross section at 175 MeV would give an additional test for the reliability in calculating the FSI, MEC, and IC performed in [34]. Although in Figures 4 and 5 we present our results for the scattering

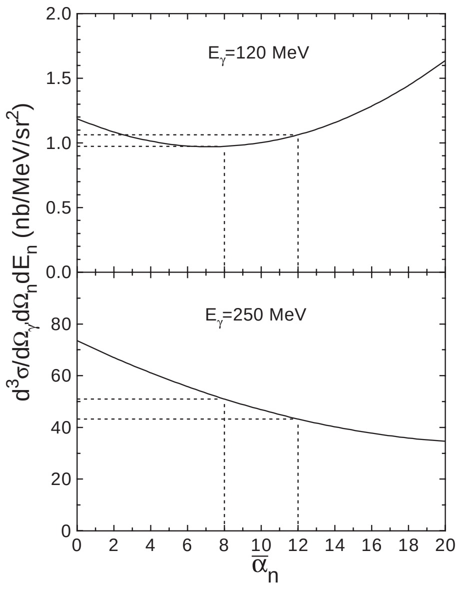

Fig. 6. The differential cross section in the center of the NQFP at $\Theta_{\gamma'} = 135°$ as a function of $\bar{\alpha}_n$ at incident photon energies of 120 MeV and 250 MeV. The *dashed lines* indicate values of $\bar{\alpha}_n = 10 \pm 2$

angle $\Theta_{\gamma'} = 135°$ the conclusions above hold true also in an angular region from 120° to 180°.

Another presentation of the present results is given in Fig. 6. At 120 MeV the cross section shows a local minimum at $\bar{\alpha}_n \approx 7$. There, the differential cross section is fixed and not sensitive to $\bar{\alpha}_n$. This observation also holds true at other energies below the pion threshold. Therefore, a definite determination of the lower limit for $\bar{\alpha}_n$ is hardly possible, as experienced in the previous experiment of Rose et al. [12] and discussed in Section 2. At energies above 200 MeV this difficulty vanishes (see picture at the bottom of Fig. 6). There, the cross section is a monotonic function of $\bar{\alpha}_n$, which allows one to extract a definite value and upper and lower limits from the experiment.

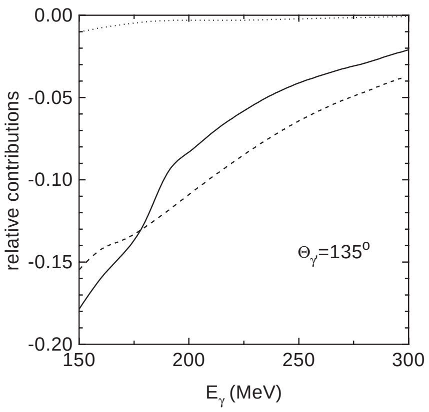

Fig. 7. Contributions of the different diagrams to the cross section at $\Theta_{\gamma'} = 135°$ in the center of the NQFP relative to that of diagram 2a). *Dotted, dashed*, and *solid lines*: 2b), 2b) to 2d), 2b) to 2f), respectively

To estimate the uncertainties arising from the theoretical modeling of the quasi-free reaction (16), we calculated the cross sections using three versions of the Bonn OBEPR potential [35,37] and a separable approximation [38] of the Paris potential [39]. All models were found to give almost the same predictions. The relative deviation is less than 1.2% in the NQFP region at $\Theta_\gamma = 135°$ reaching maximum values for the OBEPR model [35] and the Paris potential. This result can be easily understood if one takes into account that the total effect of FSI decreases from about 11% to 4% in the energy region 200 MeV to 300 MeV (see Fig. 7). The MEC and IC contribute even less to the cross section, as shown in Fig. 7. Therefore, any uncertainties in the parameters defining the MEC and IC contributions have a negligible impact on the extracted values of the polarizabilities.

A more serious source for uncertainties when extracting the neutron polarizabilities from the experimental data of the reaction (16) may stem from the multipole analysis of pion photoproduction on the nucleon, which is necessary to evaluate the nucleon Compton scattering amplitudes exploited in our calculations. To check the sensitivity of our results to the choice of multipole analysis, we performed calculations with three analyses [36,40, 41]. One should keep in mind however that the analysis [36] does not provide the correct value for the E_{0+} multipole in the threshold region [42]. The magnitude of the E_{0+} multipole is about 10% smaller as compared to a recent dispersion calculation [43]. The threshold values of the amplitude from [36] are 24.9 and -29.3 (in units of $10^{-3}/m_{\pi^+}$) for the $\pi^+ n$ and $\pi^- p$ channels, respectively. They should be compared with the following values : 28.0 [44], 28.2±0.6 [45] (both theoretical), 28.3±0.2 [46] (experimental) for the $\pi^+ n$-channel. Correspondingly -31.7, -32.7±0.6 (both theoretical), and -31.8±0.2 (experimental) for the $\pi^- p$-channel. To estimate a possible effect of the E_{0+} multipole, we have performed a calculation with the analysis [36] in which this multipole has been changed according to the following prescription [42]:

$$E_{0+} \to E_{0+} \times [1 \ + \ 0.10(2 - E_\gamma/150)], \qquad (18)$$

with E_γ in MeV. Such a replacement provides a 10% enhancement of the E_{0+} multipole in the threshold region and leads only to small corrections in the Δ-region.

The results of the calculations are presented in Fig. 8. The relative deviation of the analyses [41] and [36] is about 7%. A possible effect of the enhancement of the E_{0+}-magnitude is estimated to be less than 5% in the energy region from 200 to 300 MeV. Nevertheless, the dependence of the cross sections on the choice of the analysis does exist and prevents us from predicting the cross sections for given $\bar{\alpha}_n$ with an accuracy better than ±5%. This in turn means that theoretical uncertainties on the determination of the neutron polarizability $\bar{\alpha}_n$ are about ±2. To further reduce the dependence on the multipole analysis, new measurements on neutron pion-photoproduction would be very useful. In this sense, it would be desirable to simultaneously study the process $\gamma d \to \pi^\circ np$ in the neutron quasi-free peak [47] together with reaction (16).

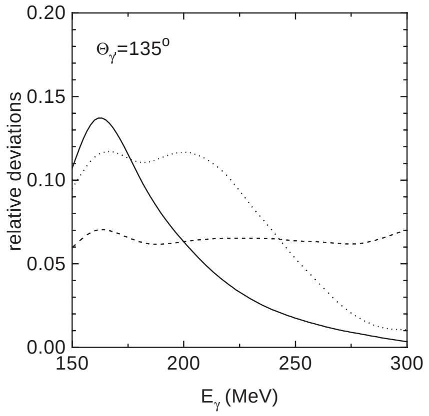

Fig. 8. Difference of the cross sections calculated with analyses [40] (*dotted*), [41] (*dashed*), relative to the ones calculated with the latest analysis [36]. The *full line* shows the results for the analysis [36] with the enhanced E_{0+} multipole (see text). All the curves were obtained in the center of NQFP for $\Theta_{\gamma'} = 135°$ at $\bar{\alpha}_n = 11$

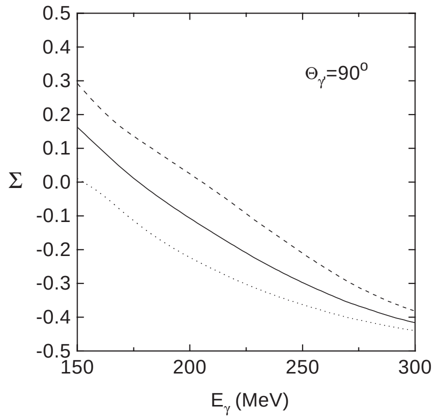

Fig. 9. Energy dependence of the photon asymmetry Σ on $\bar{\alpha}_n$ in the center of the NQFP at $\Theta_{\gamma'} = 90°$. Meaning of the curves as in Fig. 4

Even more, because up to now there are no data on $\pi°$-photoproduction on the neutron in the energy region below 300 MeV.

The extraction of $\bar{\alpha}_n$ from the differential cross section at backward photon scattering angles relies on the Baldin sum rule. In our calculations we have used a value for $\bar{\alpha}_n + \bar{\beta}_n$ [5] which is given in (17). Until recently this has been the only evaluation of the Baldin sum rule for the neutron. A new analysis [48] including recent results of photoabsorption cross section measurements gives

$$\bar{\alpha}_n + \bar{\beta}_n = 14.40 \pm 0.66, \tag{19}$$

which is not consistent with the previous value [5]. This smaller value may be attributed to the use of the multipole analysis [36] from which the authors obtained the photoabsorption cross section in the threshold region up to 200 MeV. As already stated above, the analysis [36] gives a too small value for the E_{0+} multipole at the threshold. An enhancement of this multipole by about 10% could lead to an increased value of about 15.1-15.3 [42]. The uncertainty $\pm\Delta_{\bar{\alpha}_n+\bar{\beta}_n}$ of the Baldin sum rule leads to an uncertainty in the extracted value $\bar{\alpha}_n$ of $\pm\frac{1}{2}\Delta_{\bar{\alpha}_n+\bar{\beta}_n}$ if one measures the differential cross section at backward angles. This means, the difference between the extracted values $\bar{\alpha}_n$ using a value of $\bar{\alpha}_n+\bar{\beta}_n$ from reference [5] and [48], respectively, would be about 0.7. Assuming that the value of [48] is approximately 15.2 the difference reduces to about 0.3 which can be taken as the uncertainty in $\bar{\alpha}_n$ derived from the accuracy of the Baldin sum rule for the neutron.

Another observable that can be measured in inelastic Compton scattering from the deuteron and which may give additional information on the neutron polarizabilities is the photon asymmetry defined as

$$\Sigma = \frac{d\sigma^{\perp} - d\sigma^{\parallel}}{d\sigma^{\perp} + d\sigma^{\parallel}}, \tag{20}$$

where $d\sigma^{\perp}$ ($d\sigma^{\parallel}$) is the differential cross section for incoming photons polarized perpendicular (parallel) to the plane of the outgoing photon and neutron.

As shown in [34], the photon asymmetry Σ is most sensitive to the polarizabilities at photon scattering angles near 90°. This sensitivity of Σ in the NQFP region is shown in Fig. 9. One can see that, for example at 250 MeV, Σ changes from -0.23 to -0.37 at variation of $\bar{\alpha}_n$ from 7 to 15. Therefore, to reach the accuracy $\Delta\bar{\alpha}_n \sim \pm 2$, one has to measure the asymmetry with a precision of 10%.

Again the question concerning propagations of the uncertainties in the calculated FSI, MEC, and IC contributions into the determination of the polarizabilities emerges. As in the case of the differential cross section we performed our calculations with the four models for the NN-interaction mentioned above. The difference in the predicted values of Σ was found to be less than 4.5% in the energy region between 200 MeV and 300 MeV. The very

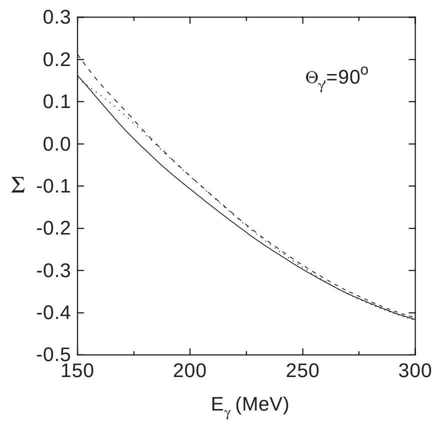

Fig. 10. Contributions of the different diagrams to the photon asymmetry Σ at $\Theta_{\gamma'} = 90°$ in the center of the NQFP. *Dotted, dashed*, and *solid lines*: 2a), 2a) to 2d) and 2a) to 2f), respectively. The contribution of diagram 2b) is negligible and not explicitly shown in the Figure

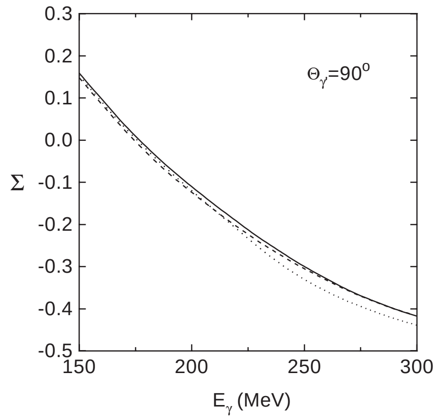

Fig. 11. The asymmetry Σ calculated with analyses [40] (*dotted*), [41] (dashed) and [36] (*full*). All the curves were obtained in the center of NQFP for $\Theta_{\gamma'} = 90°$ at $\bar{\alpha}_n = 11$

small dependence of Σ on the choice of the NN-potential can be attributed to the following reasons: i) the effect of FSI is negligible in the energy range considered (see Fig. 10); ii) the only difference in the NN-potentials entering into our calculation of MEC and IC is the cutoff parameter Λ_π. For the OBEPR(B) version from [37] we used $\Lambda_\pi = 2000$ MeV/c, for all other potentials $\Lambda_\pi = 1300$ MeV/c. This difference does not influence the calculation of the MEC and IC contributions. Therefore, although the contribution of MEC and IC is more pronounced in Σ, it is about 20% at 200 MeV and decreases rapidly with increasing photon energy, the effect of the different NN-potentials is negligible.

Calculations of the asymmetry with different multipole analyses have shown that all the new analyses [36,41] give very closely the same values for Σ (see Fig. 11). An effect of the variation of the E_{0+} multipole is very small and it is not presented in this figure. However, some disagreement has been found for results obtained with the older one [40]. In the energy region from 200 to 300 MeV the absolute values of Σ for the analysis [40] are smaller by about 10%. Of course, there are firm reasons for believing that the new analyses are more accurate than the older ones. Therefore, we expect the sensitivity of the asymmetry to the choice of the multipole analysis to be very small. An inspection of Figs. 9 and 11 shows that uncertainties due to this choice lead to the same effect as a variation of $\bar{\alpha}_n$ by about ± 0.5.

4 Summary

Previous experimental determinations of the electromagnetic polarizabilities of the neutron remained very unsatisfactory. For experiments on neutron scattering in the Coulomb field of heavy nuclei, the extracted value of the electric polarizability strongly depends on the extraction method and therefore remains rather uncertain. The latest value for α_n has been estimated by Enik et al. [23], leading to $\alpha_n \sim 7 - 19$. The most promising method of determining the electromagnetic polarizabilities is quasi-free Compton scattering from the neutron bound in the deuteron. It has been shown that the useful range of incident photon energies is limited by the behavior of the differential cross section. Below the π-production threshold a precise determination of $\bar{\alpha}_n$ is hardly possible. At photon energies between 200 MeV and 300 MeV the triple differential cross section and the photon asymmetry show sufficient sensitivity to $\bar{\alpha}_n$ for achieving good precision. An accuracy of 5% and 10% is needed for the differential cross section and the asymmetry Σ, respectively, to arrive at $\Delta\bar{\alpha}_n^{exp} = \pm 2$.

In order to reduce the theoretical uncertainties from rescattering and MEC effects, although they are expected to be very small, a simultaneous measurement on the bound proton is highly desirable. By comparing the results of quasi-free Compton scattering from the proton with the recently measured free Compton scattering cross sections [49] the influence of these effects can be studied in detail. The most significant theoretical uncertainties stem from multipole analyses of single pion photoproduction on the nucleon and can be reduced only if one has new and more accurate experimental data on pion photoproduction. At present, the uncertainties mentioned may lead to $\Delta\bar{\alpha}_n^{th} = \pm 2$ when extracting the neutron polarizability from data on the differential cross section of the reaction (16) but only to $\Delta\bar{\alpha}_n^{th} = \pm 0.5$ if $\bar{\alpha}_n^{exp}$ is extracted from the data on the asymmetry Σ.

Experimental efforts to investigate reaction (16) are already underway at LEGS [50] and SAL [51]. A further experiment has been approved at MAMI [52].

The authors are indebted to A.I. L'vov for supplying them with the nucleon Compton scattering amplitudes calculated with different multipole analyses of single pion photoproduction on the nucleon and many useful discussions. One of the authors (M.I.L.) highly appreciates the hospitality of II. Physikalisches Institut der Universität Göttingen where part of the work was done. The work was supported by Deutsche Forschungsgemeinschaft (Grant # Schu-222 and # 438 113/173) and by Fundamental Research Foundation of Belarus (Grant # F94-072).

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