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About methods of measuring the electromagnetic polarizabilities of the neutron

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The electric and magnetic polarizabilities α and β are fundamental properties of the nucleon, familiar from classical physics. They describe the response of the nucleon's charge and magnetization to an external electromagnetic field. A deformation of the system's ground state caused by an incoming electromagnetic wave and encoded into electromagnetic polarizabilities of the system contributes to radiation of outgoing photons.

The absence of a free dense neutron target makes it impossible to measure the neutron polarizabilities in free neutron Compton scattering experiments. There are two different methods to investigate the electric polarizability of the neutron: 1) scattering of low energy neutrons in the Coulomb field of heavy nuclei; 2) free or quasi-free Compton scattering from the deuteron bound in the deuteron. The history of studies along the first method is summarized in Ref. [1]. The latest in a series of experiments have been carried out at Oak Ridge [2] and Munich [3] leading, respectively, to the following values

$$\alpha_n = 12.6 \pm 1.5 \pm 2.0, \;\; \alpha_n = 0.6 \pm 5.0, \tag{1}$$

in units of $10^{-4}\,\mathrm{fm}^3$ which are used for the polarizabilities throughout the paper. While the Munich result [3] has a large error, the Oak Ridge result [2] is of very high precision. However, this high precision has been questioned by a number of researchers active in the field of neutron scattering [4]. Their conclusion is that the Oak Ridge result [2] possibly might be quoted as $7 \le \alpha_n \le 19$. Furthermore, it should be noted that electromagnetic scattering of neutrons in a Coulomb field does not constrain the magnetic polarizability β_n.

Another option for measurements of the neutron polarizabilities provides elastic scattering of real photons on the neutrons. Let us consider particular examples forward and backward nucleon Compton scattering. The corresponding spin averaged amplitudes at sufficiently low photon energies ω have the forms [5]

$$T(\omega,0) = -\frac{Z^2e^2}{M_N}\mathbf{e}\cdot\mathbf{e}'^* + 4\pi(\alpha+\beta)\omega^2\mathbf{e}\cdot\mathbf{e}'^* + O(\omega^3), \tag{2}$$

$$T(\omega,180^0) = -\frac{Z^2e^2}{M_N}\mathbf{e}\cdot\mathbf{e}'^* + 4\pi(\alpha-\beta)\omega^2\mathbf{e}\cdot\mathbf{e}'^* + O(\omega^3), \tag{3}$$

where Z and M_N is the charge ($Z_p = 1$ and $Z_n = 0$) and mass of the nucleon, respectively, $\mathbf{e}$ and $\mathbf{e}'$ being the polarizations of the initial and final photons. Observables which are measured in experiments on nucleon Compton scattering (e.g., the differential cross section) are proportional to quadratic combinations of the scattering amplitude T. Therefore, such experiments allow one to extract the nucleon polarizabilities.

An inspection of Eqs. (2) and (3) shows that the amplitude at forward and backward angles T depends on the sum and the difference of the polarizabilities, respectively. The sum of the polarizabilities is usually obtained in an indirect way making the use of Baldin sum rule predictions [6]. This sum rule relates the sum $\alpha_N + \beta_N$ with the integral over the photoabsorption cross section $\sigma_N(\omega)$:

$$\alpha_N + \beta_N = \frac{1}{2\pi^2}\int_{\omega_0}^{\infty} \frac{\sigma_N(\omega)}{\omega^2}\, d\omega. \tag{4}$$

In Eq. (4) ω_0 is photoabsorption threshold. Due to the factor ω^{-2} in the integrand, this integral converges very rapidly and it can be evaluated rather reliably. A recent reevaluation of this sum rule [7]

РЕПОЗИТОРИЙ ГГУ ИМЕНИ Ф. СКОРИНЫ

gives quite precise values for the sum of the nucleon polarizabilities

$$\alpha_p + \beta_p = 14.0 \pm 0.3, \quad \alpha_n + \beta_n = 15.2 \pm 0.5. \tag{5}$$

Therefore, in order to have α_N and β_N separately, one needs to measure the difference of the polarizabilities and, as it follows from Eq. (3), this can be done by measurements of observables in nucleon Compton scattering at backward angles.

Of course, experimental studies of neutron Compton scattering and a further extraction of the neutron polarizabilities are much more difficult than those for the proton. Actual measurements of γn-scattering are forced to have a deal with neutrons bound in nuclei and hence to take into account effects of the nuclear environment. To minimize theoretical uncertainties in the interpretation of experimental data, preference should be given to the use of the deuteron as a “neutron target”. Depending on the final np-state, two reactions, $\gamma d \to \gamma' np$ and $\gamma d \to \gamma' d'$, can be considered.

A suggestion to exploit the reaction $\gamma d \to \gamma' np$ in the neutron quasi-free kinematic region in order to study Compton scattering off the neutron was made in Ref. [8]. An idea of this method is rather simple. One can estimate from the values of the deuteron binding energy, $E_b = 2.224$ MeV, and the nucleon mass, $M_N \simeq 939$ MeV, that the characteristic momenta of the nucleons in the deuteron are about 50 MeV/c, i.e. the nucleons are practically at rest inside the deuteron.

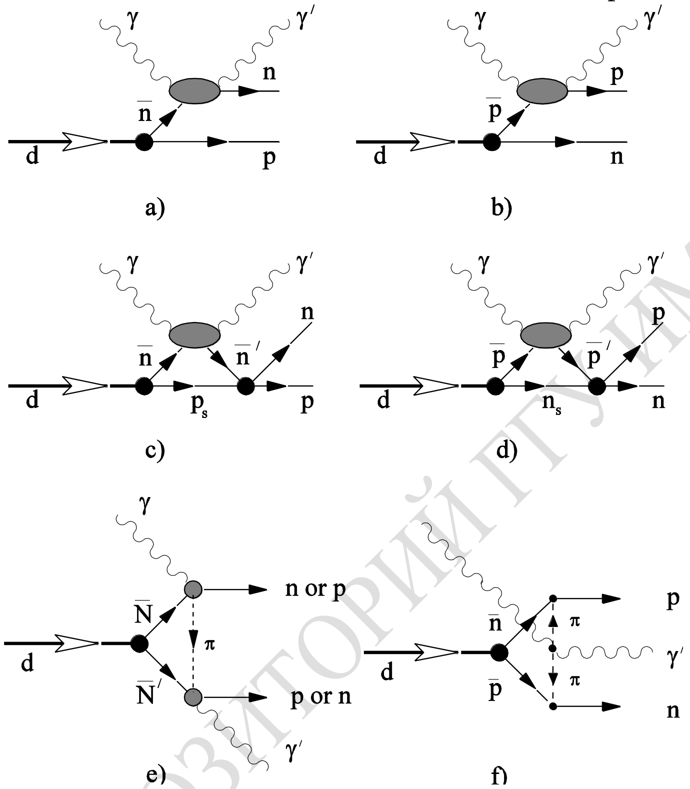

Fig. 1. Main graphs contributing to the reaction $\gamma d \to \gamma' np$.

Let us suppose that after photon scattering off the deuteron, we observe in the final state the neutron with high momentum and the proton with low momentum. Such a situation means that probably the photon was scattered by the neutron rather them by the proton. The corresponding mechanisms are depicted in Fig. 1*a*. However, there are other mechanisms which have to be taken into account. Diagrams *a* and *b* in Fig. 1 correspond to the case when the final nucleons after photon scattering spread as a plane wave. But the situation is possible when these nucleons interact with each other in the final state (see diagrams *c* and *d* in Fig. 1). One more mechanism giving rise to the reaction amplitude is shown in diagrams *e* and *f* in Fig. 1. It is often referred to as meson-exchange seagulls (MES).

It should be kept in mind that at energies below pion photoproduction threshold, the differential cross section of the reaction $\gamma d \to \gamma' np$ is practically independent of the value of α_n if this value lies between 0 and 10 [8]. That is why it was proposed in Ref. [8] to use the method at the photon energies above 200 MeV. The method has been realized in a series of experiments at MAMI-B [9,10] and at SAL [11]. The values for the neutron polarizabilities found in those experiments with the use of the theoretical model [8] are in agreement with each other being different, however, in the size of the quoted errors. The most accurate values have been reported in Ref. [10]

$$\alpha_n = 12.5 \pm 1.8(\text{stat})^{+1.1}_{-0.6}(\text{syst}) \pm 1.1(\text{model}), \tag{6}$$

$$\beta_n = 2.7 \mp 1.8(\text{stat})^{+0.6}_{-1.1}(\text{syst}) \mp 1.1(\text{model}). \tag{7}$$

The anticorrelated errors in Eqs. (6) and (7) are due to the application of the sum rule result (5). In view of the model errors containing in Eqs. (6) and (7), a confirmation of these values is of great importance.

РЕПОЗИТОРИЙ ГГУ ИМЕНИ Ф. СКОРИНЫ

Elastic (Compton) scattering by the deuteron provides a further method for determining the electromagnetic polarizabilities of the neutron. The presence of the proton next to the neutron and the coherence of the proton and neutron contributions makes two advantages. First, the $O(\omega^2)$ contribution of the neutron polarizabilities to the scattering amplitude can interfere with the $O(1)$ contribution from proton Thomson scattering (first term in the right hand sides of Eqs. (2) and (3)), so that a sensitivity of the differential cross section with respect to the polarizabilities is enhanced. Of course, only the isospin averaged nucleon polarizabilities, $\alpha_N = (\alpha_p + \alpha_n)/2$ and $\beta_N = (\beta_p + \beta_n)/2$, can be measured with this method. But that is not a major problem since the proton values are quite accurate. Second, the largest contribution to the spin polarizabilities of nucleons which comes from the *t*-channel π^0-exchange does not contribute to γd-scattering at all (due to isospin), so that $O(\omega^4)$ corrections, which are not small for individual nucleons, especially for the neutron, are more suppressed in the considered case. Nevertheless, various binding corrections, including meson-exchange currents (MEC) and MES, are rather important and have to be introduced and carefully evaluated.

Although theoretical studies of deuteron Compton scattering began many years ago, only recently a very reliable model has been built in Ref. [7]. The model takes into account the so-called resonance contributions, MEC and MES. The corresponding diagrams are displayed in Figs. 2 to 4. The realistic Bonn one-boson-exchange picture of NN-interactions was used to built the deuteron wave function and the NN-scattering amplitude.

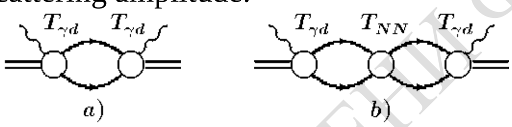

Fig. 2. The resonance contributions. Shown are terms without (*a*) and with NN-rescattering in the intermediate state (*b*).

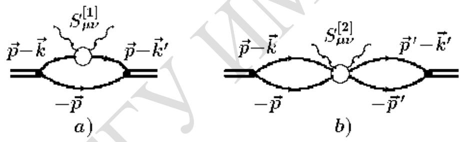

Fig. 3. The one-body (*a*) and two-body (*b*) seagull amplitudes of γd-scattering.

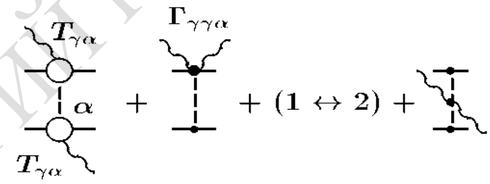

Fig. 4. The diagrammatic representation of the two-body seagull $S^{[2]}$. The symbol α stands for different types of mesons. $T_{\gamma\alpha}$ means the meson photoproduction amplitude.

Using tagged photons with energies of 49 and 69 MeV the Illinois group [12] obtained the first data on the differential cross section which were precise enough to reveal the effect from the nucleon polarizabilities. Later on, the SAL group [13] measured the differential cross section at about 94 MeV of the incident photon energy and backward angles. A bulk of new experimental data has been recently provided in an experiment at MAX-lab [14]. If all these data are fitted using the theoretical model [7], the following ”global average” is inferred

$$\alpha_N + \beta_N = 16.7 \pm 1.6, \quad \alpha_N - \beta_N = 4.8 \pm 2.0, \tag{8}$$

with $\chi^2/N_{\text{dof}} = 38/(29-2)$. Using the most recent global average $\alpha_p - \beta_p = 10.5 \pm 0.9(\text{stat}+\text{syst}) \pm 0.7(\text{model})$ [15] and the Baldin sum rule predictions (5), one obtains

$$\alpha_n = 7.2 \pm 2.1, \quad \beta_n = 8.1 \pm 2.1. \tag{9}$$

Here both statistical and systematic errors are combined together, the latter being taken into account through a rescaling of measured cross sections within their normalization uncertainties. As to the model uncertainty in the derived values, we estimate them as about ± 3.0.

РЕПОЗИТОРИЙ ГГУ ИМЕНИ Ф. СКОРИНЫ

Combining the values extracted from the quasi-free neutron data (6) and (7) with these obtained in the deuteron Compton scattering (9), the PDG group has reported the presently most reliable values for the neutron polarizabilities [15]:

$$\alpha_n = 11.4 \pm 1.5, \quad \beta_n = 3.7 \pm 2.0. \qquad (10)$$

Therefore, proposed in Refs. [7,8] methods to measure the neutron polarizabilities in the reactions $\gamma d \to \gamma' np$ and $\gamma d \to \gamma' d'$ have allowed one to extract the values of the neutron polarizabilities with much better accuracy in comparison with that achieved in neutron scattering experiments for more than 50 years of measurements. We hope that approved experiments in Darmchtadt (Germany) and at MAX-lab on measurements of the differential cross section of the reaction $\gamma d \to \gamma' d'$ will provide further improvement of the accuracy for values of the neutron polarizabilities.

Abstract. Possible methods to measure the neutron electromagnetic polarizabilities are discussed. Elastic and inelastic Compton scattering off the deuteron as more promising ones are considered in some detail. Recent experiments based on the use of these methods have allowed one to obtain the most accurate value for the electric polarizability of the neutron, $\alpha_n = (11.6 \pm 1.5) \times 10^{-4}$ fm^3, and for first time to measure its magnetic polarizability, $\beta_n = (3.7 \pm 2.0) \times 10^{-4}$ fm^3.

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