Deuteron Compton scattering and electromagnetic polarizabilities of the nucleon

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Differential cross section of deuteron Compton scattering has been calculated using the Bonn NN-potential, a consistent set of meson-exchange currents and seagulls, and lowest- and higher-order electromagnetic polarizabilities of the nucleon. Estimates of the polarizabilities of the neutron are obtained from recent experimental data.

Photon scattering is a powerful tool for probing the structure of hadrons and nuclei. In particular, the electric and magnetic polarizabilities of the proton, $\alpha_p$ and $\beta_p$, have been successfully determined from data on low-energy $\gamma p$ scattering [1–3]. An extension of this method to the case of the neutron is of considerable interest. One of suggested ideas was to use (elastic) Compton scattering off deuterons. The latter process is not easy for measurements and interpretations. On the experimental side, one has to carefully separate elastic and inelastic channels. On the theoretical side, one has to separate effects caused by the proton’s and neutron’s structure from effects caused by the nuclear environment. Recently, a progress was made in solving both the problems. First data on low-energy $\gamma d$ scattering came from Urbana and Saskatoon [4,5] and several groups reported their calculations [6–11].

Two different approaches were applied in the quoted theoretical works. In [6–9], a phenomenological picture of a meson-mediated NN potential was used. It was assumed that the nucleons themselves are not modified. All binding effects were described by meson-exchange currents associated with the NN potential (and with excitation of the $\Delta$ isobar too) and by intermediate rescattering of nucleons between two acts of electromagnetic interaction.

In [10,11], a technique of effective field theories (EFT) was applied. In this approach, the very pion cloud which mediates the NN interaction affects properties of the nucleon (like the magnetic moment and polarizabilities), which therefore become dependent on the nuclear environment. An attractive feature of the EFT method is that the retardation effects, which are not inherent to the potential picture and which are especially large in the case of the pion exchange, are naturally included into the calculation. A big problem of EFT is, however, that an expansion over a small generic momentum $Q$ utilized there is not rapidly convergent. In order to extract polarizabilities of nucleons from $\gamma d$ scattering, it is not sufficient to calculate only the leading-order and next-to-leading order terms. Higher orders are not negligible at all (see a discussion

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in [9]). If so, numerous unknown parameters (low energy constants) of short-range interactions which always appear in higher orders make the strictness of the EFT illusive. In this situation the potential approach remains, in our opinion, more precise. Though model-dependent, it does not avoid facing the short-range dynamics, including resonance excitation, when relevant.

In our calculation [9], the nonrelativistic version of the Bonn one-boson-exchange-potential was used. Meson-exchange currents and seagulls were found via photon coupling to intermediate mesons and meson-baryon vertices. A special attention was paid to implementing effects of the meson-baryon form factors in a gauge-invariant way. Additional contributions due to Δ-isobar excitation and retardation effects in the pion propagator were also taken into account. The long-range pion exchange was found to almost saturate the meson-exchange currents and seagulls as seen in Compton scattering, whereas short-range contributions given by heavy mesons (ρ, ω, a₀, σ) and form factors almost cancel each other.

Photon interaction with free nucleons was described keeping leading-order relativistic corrections including the spin-orbit term and an additional spin-independent seagull of order \(1/M^3\). Apart from the dipole polarizabilities \(\alpha_N\) and \(\beta_N\) of the nucleon, higher-order polarizabilities (spin, quadrupole, and dispersion ones) have been taken into account as well. Their effect was estimated using predictions of dispersion relations [12,13]. It was found numerically important and giving a large positive shift in the extracted electric polarizability of the neutron of about \(+5 \times 10^{-4}\ \text{fm}^3\).

An accuracy of the theoretical calculation was checked through a comparison with the dispersion relation at forward angle. An agreement better than 3% (in the amplitude) was found at energies between 20 and 100 MeV.

\[\text{Figure 1. Differential cross section of } \gamma d \text{ scattering (CM). Solid lines: present results with } \alpha_N - \beta_N = 9 \times 10^{-4}\ \text{fm}^3. \text{ Dashed lines: Karakowski and Miller [8]. Dotted lines: Beane et al. [11]. Data are from Urbana [4] (49 MeV) and Saskatoon [5] (94 MeV).}\]

Compared with other recent calculations, our results at \(~100\ \text{MeV}\) disagree with those obtained in [8] (see Fig. 1). In part, this disagreement is caused by a different contribution we found from spin-orbit terms. We have a better agreement with the EFT predictions from [11], which however becomes worser at lower energies \(~50\ \text{MeV}\). We agree at 50 MeV with [8] and
stay just between predictions from [11] and [10]. The calculated differential cross section depends on the isoscalar (i.e., isospin-averaged) nucleon polarizabilities \( \alpha_N \) and \( \beta_N \) (see Fig. 2). Keeping all other parameters fixed, these polarizabilities can be extracted from comparison with the experimental data [4,5]. The result is

\[
\alpha_N + \beta_N \approx 17.1 \pm 1.6, \quad \alpha_N - \beta_N \approx 4.0 \pm 1.5 \quad \text{(in units of } 10^{-4} \text{ fm}^3),
\]

(1)

where (unknown) theoretical-model errors are not yet included. Jointly with experimental results for the proton’s electromagnetic polarizabilities, \( \alpha_p \approx 12 \pm 1 \) and \( \beta_p \approx 2 \pm 1 \) [3], this implies the following polarizabilities of the neutron:

\[
\alpha_n \approx 9 \pm 3, \quad \beta_n \approx 11 \pm 3.
\]

(2)

While the obtained electric polarizability of the neutron, \( \alpha_n \), resonably agrees with the proton’s polarizability \( \alpha_p \) and with dispersion-theoretical expectations (see, e.g., [13]), the magnetic polarizability \( \beta_n \) strongly deviates from \( \beta_p \) and from predictions of the dispersion theory which gives \( \beta_n \approx \beta_p \). Clearly, a further work must be done before any firm conclusion from deuteron Compton scattering can be derived concerning the neutron’s polarizabilities. In particular, of interest are evaluations of all \( 1/M^2 \) relativistic corrections, as well as calculations performed with modern high-quality NN potentials. More precise measurements of the differential cross section of \( \gamma d \) scattering at energies below pion photoproduction threshold would also be desirable.

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Figure 2: Differential cross section of \( \gamma d \) scattering (CM) at different isoscalar polarizabilities \( \alpha_N \) and \( \beta_N \). Solid line: \( \alpha_N + \beta_N = 14.6 \) (inferred from the Baldin sum rule) and \( \alpha_N - \beta_N = 9 \). Units are \( 10^{-4} \) fm\(^3\). Dashed-dotted lines show variations when \( \alpha_N - \beta_N \) is changed by \( \pm 3 \). Dotted line: \( \alpha_N = \beta_N = 0 \). Data are from Saskatoon [5].