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Helicity dependence of the total inclusive cross section on the deuteron

GDH and A2 Collaborations

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A measurement of the helicity dependence of the total inclusive photoabsorption cross section on the deuteron was carried out at MAMI (Mainz) in the energy range $200 < E_\gamma < 800$ MeV. The experiment used a 4π detection system, a circularly polarized tagged photon beam and a frozen spin target which provided longitudinally polarized deuterons. These new results are a significant improvement on the existing data and allow a detailed comparison with state-of-the-art calculations.

1. Introduction

In the past years, extensive experimental and theoretical research has been carried out on the study of the helicity dependence of photoinduced reactions on the proton and the deuteron above the pion production threshold (see, for instance, Ref. [1]). Thanks to the presence of interference terms among the different reaction amplitudes such data give more precise information on the elementary photon–nucleon interaction mechanisms than unpolarized data. In addition, the helicity dependent photonuclear observables provide an experimental test of the well-known Gerasimov–Drell–Hearn (GDH) sum rule [2,3]. This sum rule links the anomalous magnetic moment κ of a particle of spin S and mass M to the integral over the weighted spin asymmetry of the total absorption cross section of circularly polarized photons on a longitudinally polarized target:

$$\int_0^\infty \frac{\sigma_p - \sigma_a}{\nu} \mathrm{d}\nu = 4\pi^2\kappa^2 \frac{e^2}{M^2} S \tag{1}$$

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where ν is the photon energy and σ_p (σ_a) denotes the total absorption cross section for parallel (antiparallel) orientation of photon and particle spins. This relation gives a very important connection between ground state properties of a particle (rhs of Eq. (1)) and an integral property of its whole excitation spectrum (lhs of Eq. (1)), showing that the existence of a nonvanishing κ points directly to an internal dynamical structure of the considered particle.

The first measurement of the helicity dependent photon–deuteron interaction was made by our collaboration [4,5] using the tagged photon facilities of Mainz [6,7] and Bonn [8,9]. The aim was to study the behavior of the GDH integrand (lhs of Eq. (1)) for the deuteron and to extract information on the neutron. These data are however affected by quite large statistical errors which prevent a detailed comparison with the existing models of the photon–deuteron interaction.

We present in this Letter new data on the helicity dependent total inclusive photoabsorption cross section on deuterium from 200 to 800 MeV and helicity dependent semi-exclusive $\gamma d \to NN\pi$ data up to $E_\gamma \simeq 430$ MeV. These results improve the statistical precision of the data published in Ref. [5] by a factor of about 3 and allow to perform a detailed comparison with state-of-the-art predictions for the deuteron–photon interactions.

2. Experimental setup

The present data were obtained as a part of the GDH experiment at MAMI, Mainz.

Circularly polarized photons were obtained by bremsstrahlung of longitudinally polarized electrons having an average polarization of 75% [11]. The electron polarization was continuously measured using a Møller polarimeter [12] with an accuracy of 3%. Bremsstrahlung photons were tagged using the Glasgow–Mainz spectrometer with an energy resolution of about 2 MeV [13,14]. The tagging efficiency (probability of a photon passing through the collimation system given an electron hit in the spectrometer focal plane detector) was monitored throughout the experiment by an e^+e^- detector with an accuracy of 2%.

Longitudinally polarized deuterons were provided by a frozen-spin target [15] using deuterated butanol (C_4D_9OD) as target material. The use of a new doping material [16] led to a sizeable increase of the target polarization compared to Ref. [5]. Polarization values in excess of 70% were reached with a relaxation time of about 200 hours. The target polarization was monitored, with an accuracy of 1.6%, using NMR techniques.

Photoemitted hadrons were detected in the DAPHNE [17] detector, a large acceptance (94% of 4π) charged particle tracking device with cylindrical symmetry. It consists of three cylindrical multiwire proportional chambers (mwpcs) surrounded by a segmented ΔE–E–ΔE detector and by a double scintillator-lead sandwich allowing the detection of neutral pions with reasonable efficiency (typically between $\sim 15\%$ and $\sim 25\%$ when both π^0 decay photons are required to be detected in coincidence). All these sections cover the full azimuthal angular region and polar angles from 21° to 159°.

For a more detailed description of the experimental apparatus, we refer to Refs. [7,10,18] and references therein.

3. Data analysis

The analysis procedure which was used to determine the total inclusive absorption cross section on the deuteron is not based on the identification of all possible partial reaction channels. A more global technique was developed to limit the systematic errors. Since the general principles of this method were fully described in Refs. [5,10,18] for the deuteron case, only their general characteristics will be recalled here.

A large fraction (from $\sim 50\%$ to $\sim 80\%$) of the total inclusive photoabsorption cross section (σ_{tot}) can be directly accessed by measuring the number of events with charged hadrons in the final state detected inside the DAPHNE acceptance (N_{ch}).

Most of the remainder is deduced by measuring the number of π^0 events with no accompanying charged particle detected (N_{π^0}) and by using the π^0 detection efficiency ($\bar{\varepsilon}_{\pi^0}$) evaluated with a GEANT-based simulation of DAPHNE which takes into account the full geometrical complexity of the setup and the electronic thresholds.

Due to the very poor photon energy resolution, the π^0 emission angles and energies cannot be measured by our apparatus and $\bar{\varepsilon}_{\pi^0}$ was evaluated as a function of E_γ only. However, thanks to the particular shape of the lead converters the photon detection efficiency is almost independent on their angular distributions and has a smooth dependence on their kinetic energy [12,19]. The validity of the algorithm developed for the estimation of $\bar{\varepsilon}_{\pi^0}$ in the total inclusive process on proton and deuteron and in some partial reaction channels on the proton was shown in Refs. [10,20–22]. The relative systematic error on $\bar{\varepsilon}_{\pi^0}$ is estimated to be $\pm 4\%$ [7].

Within the Mainz energy range, the π^0 detection efficiency is non-zero for all emission angles and momenta due to the angular acceptance of the DAPHNE detector. A small correction ($\Delta N_{\pi^0\pi^0,\eta}$) had to be made since processes involving more than one π^0 in the final state were not included in the evaluation of $\bar{\varepsilon}_{\pi^0}$. The maximal value of this correction is $\sim 5\%$ of $N_{\pi^0} \cdot (\bar{\varepsilon}_{\pi^0})^{-1}$.

A model dependent extrapolation correction (Δ_{extr}) was evaluated to obtain the remaining part (a few % of σ_{tot}) of the total inclusive photoabsorption cross section which produces events with all charged particles from the $\gamma d \to pn$, $NN\pi^\pm$ and $np\pi^+\pi^-$ reactions emitted outside the detector acceptance.

Using the notation above, σ_{tot} can then be written as:

$$\sigma_{tot} \propto N_{ch} + N_{\pi^0} \cdot (\bar{\varepsilon}_{\pi^0})^{-1} + \Delta_{extr} + \Delta N_{\pi^0\pi^0,\eta}. \tag{2}$$

N_{ch}, the term giving the more important contribution to σ_{tot}, has a relative systematic error of $\pm 1\%$, due to the uncertainties in mwpcs efficiency [10,23]. For this reason, the more important contribution to the overall systematic error stems from uncertainties in photon flux, target density and beam and target polarization. Detailed discussions of the systematic error evaluation for both the polarized and unpolarized cases can be found in Refs. [7,10]. In Refs. [5,10] comparisons of the results obtained with the previous unpolarized total inclusive cross section data are also shown.

In the analysis of the helicity dependent data, this method was used to evaluate the difference $\Delta\sigma_{tot} = (\sigma_p - \sigma_a)$ since in this case the unpolarized contributions from the spinless C and O nuclei present in the target vanish. In this case the evaluation of Δ_{extr} and $\Delta N_{\pi^0\pi^0}$ was performed using our previously measured data on the helicity dependence of all $\gamma p \to N\pi\pi$ channels [20,22,24] under the assumptions of (i) dominance of the quasi-free process on single nucleons and (ii) the helicity asymmetry outside the DAPHNE acceptance is the same as the measured one. The ΔN_η correction was evaluated assuming that only σ_a is present for the η channel [7].

As shown in [5], the same analysis method also allows the evaluation of the total helicity dependent cross section ($\Delta\sigma_\pi$) for the semi-exclusive channels, (i) $\gamma d \to \pi^\pm NN$ and (ii) $\gamma d \to \pi^0 X$ ($X = pn$ or d) up to $E_\gamma \simeq 430$ MeV, a region where the contributions of the $\gamma d \to \pi\pi NN$ channels can be neglected.

4. Results and comments

The analysis procedure described above results in the helicity dependent total inclusive cross section $\Delta\sigma_{tot}$ depicted in Fig. 1(a) in comparison to our previous results [5] and to the predictions of two state-of-the art models [25,26].

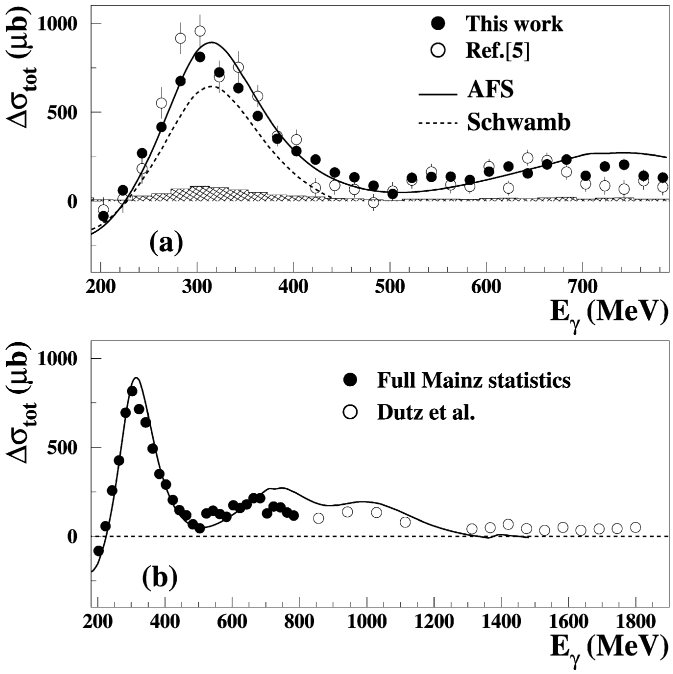

Fig. 1. (a) The helicity dependent total inclusive photoabsorption cross section obtained in this work (full circles) compared to previous results [5] (open circles) and to theoretical predictions of AFS [25] and Schwamb [26]. The hatched band shows the experimental systematic uncertainties. (b) The sum of all helicity dependent total inclusive data obtained at Mainz (full circles), our previous results from Bonn [4] (open circles) and the predictions of the AFS [25] model.

Within the Arenhövel, Fix, Schwamb (AFS) framework [25], the reactions $\gamma d \to pn, \pi^0 d$ are treated in a coupled NN–$N\Delta$ approach but using different parameterizations for the interactions and currents in both reactions. The remaining channels are treated in terms of a diagrammatic approach by embedding the elementary amplitudes for $\gamma N \to N\pi(\eta)$ (taken from MAID [27,28]) and for $\gamma N \to N\pi\pi$ (taken from an effective Lagrangian model [29]) into the deuteron reaction. In addition final state interactions are incorporated in a perturbative manner.

In an alternative approach of Schwamb [26], special emphasis is devoted to a unified and consistent description of all contributing reactions, a feature which is missing in the AFS model. This is performed in the framework of a retarded coupled NN–$N\Delta$ approach with a partially nonperturbative treatment of the πNN dynamics. Gauge invariance and unitarity is fulfilled in leading order in all considered channels ($\gamma d \to pn, \pi^0 d, \pi NN$). As an advantage, this leads to the incorporation of two-body pion production operators that were usually treated at most on a perturbative level. A typical prototype of such a mechanism is depicted in Fig. 2. The interaction in the intermediate state, after photon absorption, but before pion emission, is treated in terms of a full off-shell scattering amplitude. Usually, as in the AFS model, this amplitude is approximated by a one-pion exchange (OPEP) mechanism in the Born approximation. Due to the strong $NN \to N\Delta$-interaction, this simplification appears to be questionable, at least in the Δ region. In the approach of Schwamb, this shortcoming has been overcome with a nonperturbative treatment in terms of a coupled NN–$N\Delta$ approach. Within this framework, the on-shell limit of the above mentioned scattering amplitude can be tested using the NN scattering process above the pion-production threshold. This comparison gives satisfactory agreement with the phase shifts and inelasticities in the $^1D_2$ and $^3F_3$ channels, where the $N\Delta$ dynamics is most prominent. In addition, all model parameters are determined exclusively by π–N and elastic NN scattering data and no adjustment has been made to reproduce the existing photoinduced data. However, the practical implementation of these important conceptual features resulted in a simplified elementary pion production operator. No perfect agreement with the existing γd data can therefore be expected and additional theoretical work is in progress to improve this situation.

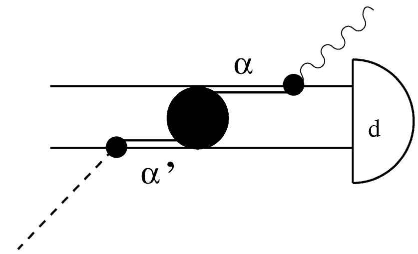

Fig. 2. Example for a two-body pion photoproduction operator. The large black circle denotes a full-offshell scattering amplitude.

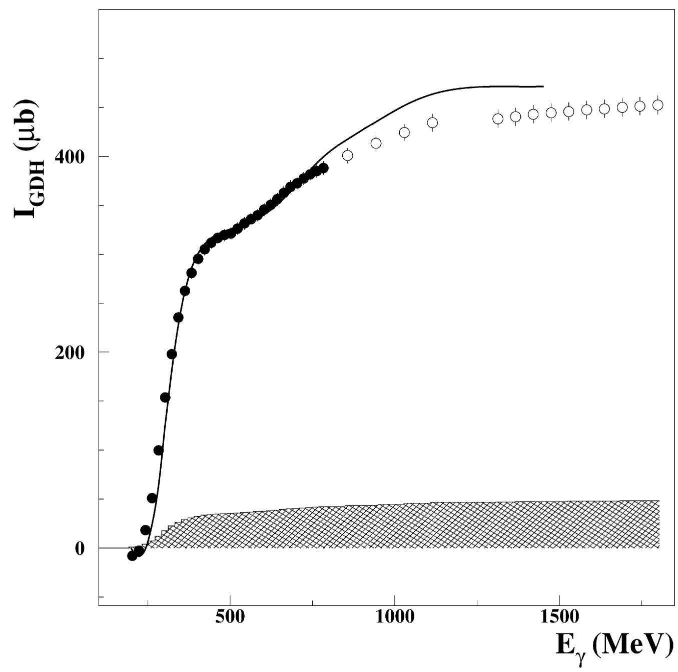

Fig. 3. The running GDH integral for the deuteron obtained with the present data (full circles) and with the data from [4] (open circles) compared to the predictions of the AFS model. The hatched band shows the systematic uncertainties, obtained by linearly adding the errors of each individual bin.

While our two sets of experimental data agree within the quoted errors, neither model reproduces the data in the Δ-resonance region, with a difference which is more pronounced for the unified description of Schwamb.

In Fig. 1(b) the overall sum of the Mainz data is shown together with our previously published high energy data from Bonn [4]. Above 700 MeV the AFS model clearly overestimates our data. This feature is probably due to a poor treatment of the double pion photoproduction channels which certainly needs further improvement. Fig. 3 shows the dependence of the experimental running integral

$$I_{\rm exp} = \int_{\nu_0}^{E_\gamma} \frac{\Delta\sigma}{\nu} {\rm d}\nu, \tag{3}$$

on the upper integration limit E_γ. In Eq. (3) ν_0 is the lowest measured photon energy value (200 MeV). The measured value of $I_{\rm exp}$ between 200 and 800 MeV amounts to $388 \pm 7({\rm stat}) \pm 21({\rm sys})$ μb, while the value up to 1.8 GeV is $452 \pm 9({\rm stat}) \pm 24({\rm sys})$ μb.

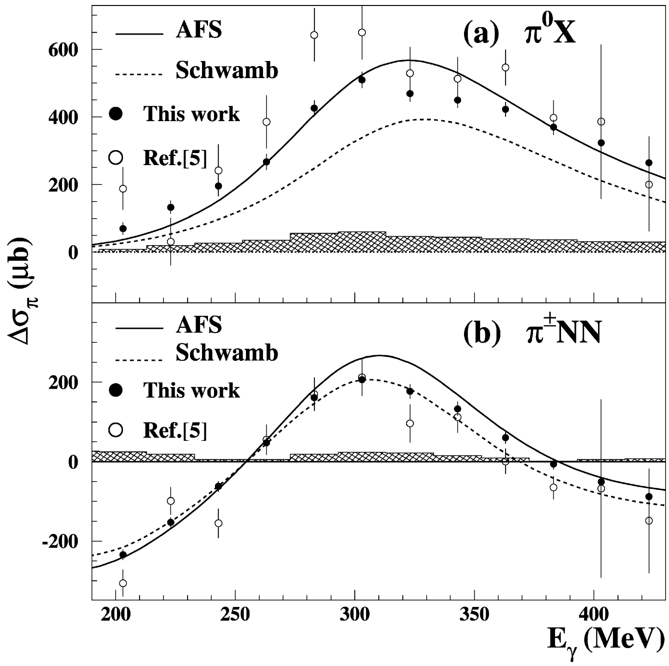

Fig. 4. The helicity dependent total cross section for the semi-exclusive channels (a) $\gamma d \to \pi^0 X$ ($X = pn$ or d) and (b) $\gamma d \to \pi^{\pm} NN$ (full circles) compared to our previous results [5] (open circles) and to the corresponding model predictions in the Δ-resonance region. The hatched bands show the systematic uncertainties.

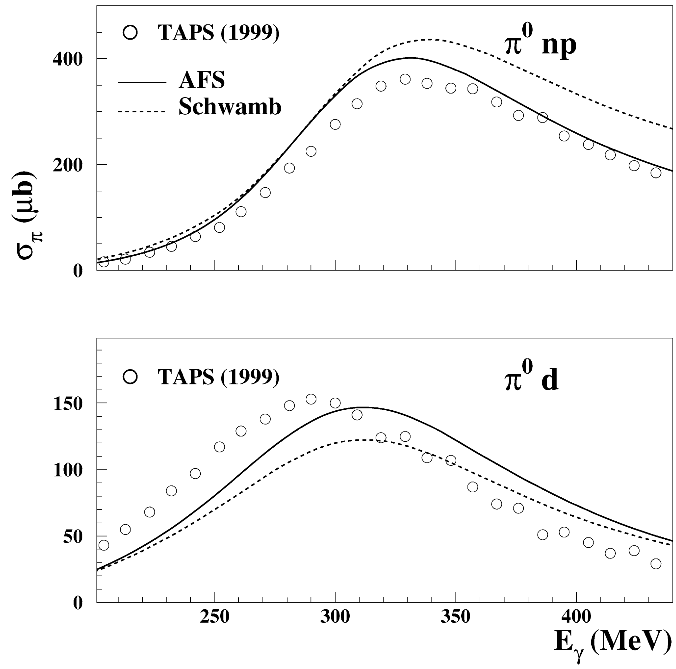

Fig. 5. The unpolarized total cross section data for the (a) $\gamma d \to \pi^0 pn$ and (b) $\gamma d \to \pi^0 d$ partial channels from [31] compared to the model predictions.

In order to extract the value of the GDH integral for the free neutron from I_{exp}, one may assume that in the measured energy region (from $E_\gamma = 200$ MeV to $E_\gamma = 1.8$ GeV) the incoherent, quasi-free meson production processes dominate, resulting in an incoherent sum

$$I_{\text{exp}} \approx I_p^{\text{GDH}} + I_n^{\text{GDH}} \tag{4}$$

of the proton and neutron contributions to the deuteron data. Taking for I_p^{GDH} the measured value $(255 \pm 5 \pm 12)$ between [0.2–1.8 GeV] [8], we get for I_n^{GDH}[0.2–1.8 GeV] a value of 197 μb which has to be compared to the GDH sum rule prediction for the neutron (233 μb). Of course, we are aware that this estimate is quite crude. First of all, the low ($E_\gamma < 200$ MeV) and very high ($E_\gamma > 1.8$ GeV) energy regions are missing in our data. Furthermore, besides incoherent meson production, also the $\gamma d \to \pi^0 d$ and the $\gamma d \to pn$ channels contribute to I_{exp}. These reactions cannot, even approximatively, be treated in the quasi-free picture. However, their contributions to I_{exp} beyond $E_\gamma = 200$ MeV are expected to be considerably smaller than the ones from incoherent pion production [25]. In addition, reactions on the deuteron are affected by its internal nuclear dynamics, resulting in effects due to (i) the d-state deuteron component, which reduces the effective nucleon polarization compared to the free case by about 10% (see, for instance, Ref. [30]); (ii) two-body meson production; and (iii) final-state interactions (FSI). Therefore, a measurement of the helicity dependence constitutes an important test of our present understanding of nuclear dynamics. Despite these complications, our rough estimate of I_n^{GDH}[0.2–1.8 GeV] can be considered as an indication that the value for the GDH integral of the free neutron should be, as expected, of the same order of magnitude as the one for the proton.

In order to pin down the source of the discrepancies between model predictions and our experimental data, partial channel separation needs to be performed. In Fig. 4 the total helicity dependent cross section difference, $\Delta\sigma_\pi = (\sigma_{\pi,a} - \sigma_{\pi,p})$, for the (a) $\pi^0 X$ and (b) $\pi^{\pm} NN$ channels is shown in comparison to our previous results [5] and to the corresponding predictions. Although our previous $\pi^0 X$ data points are somewhat higher than the new ones, these two sets of data are consistent between each other within the quoted statistical and systematic uncertainties.

The unified approach of Schwamb fairly well reproduces the $\pi^{\pm} NN$ channel (Fig. 4(b)), while considerably underestimating the $\pi^0 X$ channel (Fig. 4(a)). On the other hand, the AFS model overestimates both partial channels around the Δ resonance peak region.

Both models fail to predict the measured shape of the $\pi^0 X$ channel (Fig. 4(a)), for which the nuclear effects are more important than in the $\pi^{\pm} NN$ case. As shown for instance in Ref. [25], the values of $\Delta\sigma_\pi$ in the Δ resonance region for the $\pi^0 pn$ channel are reduced by about 40% when FSI are added to the pure quasi-free mechanisms. Compared to this, there is only a few% effect for the $\pi^{\pm} NN$ channels.

Even the unpolarized total cross sections for both the $\pi^0 np$ and the $\pi^0 d$ channels are not well reproduced by the theory as shown in Fig. 5, where the previously published data from the TAPS Collaboration [31] are compared to the model predictions. For the $\pi^0 d$ channel, both calculations show a shift of the cross section towards higher energies. This can be traced back to the spectator-on-shell approach [32] which was used for the determination of the invariant energy of the important $\gamma N \to \Delta \to \pi N$-amplitude. The failure of this choice, which is dictated by basic principles (time-ordered perturbation theory), presently constitutes a serious theoretical problem.

5. Conclusion

The helicity dependence of the total inclusive photoabsorption cross section on the deuteron has been measured with high accuracy at MAMI (Mainz) in the energy region $200 < E_\gamma < 800$ MeV. The combination of all available helicity dependent data allow an estimate of the GDH sum rule value on the deuteron from 0.2 to 1.8 GeV but, due to nuclear effects, only a very rough estimate of the neutron GDH sum rule value. Nevertheless, these data constitute a stringent test of our present understanding of nuclear dynamics. Available state-of-the-art calculations are not able to describe in a satisfactory manner the helicity dependence of both the total inclusive photoabsorption cross section and the πX channels in the Δ resonance region. This fact strongly motivates further theoretical and experimental research in the field. In particular, additional helicity dependent data on the different partial reaction channels on the deuteron are needed to clarify the situation. Such experiments are presently planned at the MAMI accelerator in Mainz.

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