Measurement of the Gerasimov-Drell-Hearn Integrand for ^{2}H from 200 to 800 MeV

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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. The contribution to the Gerasimov-Drell-Hearn sum rule for the deuteron determined from the data is 407 ± 20(stat) ± 24(syst) μb for $200 < E_\gamma < 800$ MeV.

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Introduction.—Advances in polarized beam and target techniques over the last decade have provided the experimental means to check the well-known Gerasimov-Drell-Hearn (GDH) sum rule [1,2]. This sum rule links the anomalous magnetic moment κ of any particle having spin S and mass M to the helicity-dependent total photoabsorption cross section of circularly polarized photons on a longitudinally polarized target. It is written as

$$I_{\rm GDH} = \int_0^\infty \frac{\sigma_p(E_\gamma) - \sigma_a(E_\gamma)}{E_\gamma} dE_\gamma = \frac{4\pi^2 e^2}{M^2} \kappa^2 S, \quad (1)$$

where E_γ is the photon energy and σ_p and σ_a represent the total inclusive cross sections for the parallel and antiparallel alignment of the photon helicity and of the particle's spin. This relation rests upon basic physics principles (Lorentz and gauge invariance, crossing symmetry, unitarity) and an unsubtracted dispersion relation applied to the forward Compton amplitude. A measurement of the GDH integrand then represents a fundamental test of our knowledge of photonuclear interactions.

While the GDH sum rule gives similar results for the proton ($I_{\rm GDH}^p = 204$ μb) and the neutron ($I_{\rm GDH}^n = 233$ μb), a much smaller value is predicted for the deuteron ($I_{\rm GDH}^d = 0.65$ μb) due to the smallness of its anomalous magnetic moment ($\kappa_d = -0.143$ nuclear magneton units). This originates from an almost complete cancellation of the anomalous magnetic moments of the neutron and the proton, whose spins are parallel and predominantly aligned along the deuteron spin direction.

From the theoretical point of view, $I_{\rm GDH}^d$ is expected to be the result of a similar cancellation of contributions coming from different reaction mechanisms so that it tests the basic predictive ability of any model of the deuteron structure. In a recent model from Arenhövel, Fix, and Schwamb (AFS) [3] a strong anticorrelation between the $\vec{\gamma}\,\vec{d} \to pn$ process, which gives a large negative spin asymmetry immediately above the breakup threshold ($E_\gamma \sim$ 2.2 MeV), and the pion photoproduction reactions, which give a large positive contribution to $I_{\rm GDH}^d$ at $E_\gamma \gtrsim$ 140 MeV, is predicted. In this framework, the value $(I_{\rm GDH}^d)^{\rm AFS} = 25$ μb was obtained, a factor of $\simeq 40$ higher

than the I_{GDH}^d value so that experimental deuteron data are required to resolve these discrepancies and to map down the detailed behavior of the GDH integrand.

The first experimental check of the GDH sum rule for the proton was carried out jointly at the Mainz and Bonn tagged photon facilites, where I_{GDH}^p was experimentally evaluated in the photon energy range 200 MeV $< E_\gamma <$ 2.9 GeV [4–7]. The combination of this result with the theoretical predictions for the unmeasured energy ranges supports the validity of the GDH sum rule for the proton.

Since all existing sum rule predictions, based on γN data, are very sensitive to the $(I_{\text{GDH}}^p\text{-}I_{\text{GDH}}^n)$ difference (see, for instance, [5]), measurements for the neutron are needed to obtain a complete understanding of the γN interaction. In this case, a complication arises because of the need of nuclear (^{2}H or ^{3}H) targets and, by consequence, of a model dependent evaluation of the free neutron contribution.

The helicity-dependent total photoabsorption cross section on the deuteron has been measured at Bonn in the photon energy range $815 < E_\gamma < 1825$ MeV [8]. The value of I_{GDH}^n has also been derived in this energy region taking into account the deuteron d-state probability and neglecting other nuclear effects that play a relevant role at lower energies.

In this Letter we present the results of the first measurement of this observable into the region $200 < E_\gamma <$ 800 MeV, in which most of the contribution from the pion production processes is located. In addition, helicity-dependent semiexclusive $\gamma d \rightarrow NN\pi$ data up to $E_\gamma \simeq 430$ MeV will also be presented.

Experimental setup.—The experimental setup has been described previously in detail [4,9,10] and only the main characteristics are given here. The experiment was carried out at the tagged photon facility [11,12] of the MAMI accelerator in Mainz. Circularly polarized photons were produced by bremsstrahlung of longitudinally polarized electrons [13]. The electron polarization (routinely about 75%) was monitored during the data taking by means of a Møller polarimeter. The photon energy was determined by the Glasgow-Mainz tagging spectrometer [11]. The tagging efficiency was monitored by an e^+e^- detector placed downstream of the main hadron detector [10].

Longitudinally polarized deuterons were provided by a frozen-spin deuterated butanol (C_4D_9OD) target [14]. The deuteron polarization was measured using NMR techniques and maximum polarization values of $\sim$35%, with relaxation times of $\simeq 200$ h were obtained.

Photoemitted hadrons were registered by the large acceptance ($\simeq 94\%$ of 4π sr) detector DAPHNE [15]. This is a charged particle tracking detector with cylindrical symmetry covering polar angles between 21° and 159° and the full azimuth. It consists of 3 cylindrical multiwire proportional chambers, surrounded by segmented plastic scintillator layers and by a double scintillator-absorber sandwich which allows the detection of neutral pions with reasonable ($\sim$15%–20%) efficiency.

Data analysis and unpolarized results.—An inclusive method of analysis has been developed to determine the total photoabsorption cross section. A detailed description of this method can be found in Refs. [5,10,16,17]; only general characteristics will be recalled here.

The large acceptance of DAPHNE enables a substantial fraction of σ_{tot} for the deuteron ($\sim$55% at 300 MeV; $\sim$80% at 700 MeV) to be accessed by counting numbers (N_{ch}) of charged hadrons final state.

Most of the remainder ($\sim$40% of σ_{tot} at 300 MeV; $\sim$15% at 700 MeV) can be deduced by measuring the number of π^0 events with no accompanying charged particle detected (N_{π^0}) and by using the π^0 detection efficiency ($\bar{\varepsilon}_{\pi^0}$) evaluated with a Monte Carlo computer model of DAPHNE [17]. Within the Mainz energy range, the π^0 detection efficiency ($\bar{\varepsilon}_{\pi^0}$) is always finite and nonzero for all emission angles and momenta. Thus the contribution of reactions with at least one final-state π^0 may be evaluated from the numbers of detected π^0, although a small correction ($\Delta N_{\pi^0\pi^0,\eta}$) has to be made since processes involving more than one π^0 in the final state are not included in the evaluation of $\bar{\varepsilon}_{\pi^0}$.

A model dependent extrapolation correction (Δ_{extr}) has then to be evaluated to obtain the remaining part of the total photoabsorption cross section ($\sim$5% of σ_{tot}) that produces events where all charged particles from the $\gamma d \rightarrow pn$, $NN\pi^\pm$, and $np\pi^+\pi^-$ reactions are emitted outside the detector acceptance.

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

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

For $E_\gamma > 200$ MeV, the region in which the data are presented here, the minimum proton momenta for $\gamma d \rightarrow pn$ and the minimum pion momenta for $NN\pi^\pm$ (due to the dominance of the quasifree processes on the single nucleons) are above the DAPHNE detection threshold.

For the pn case, the Δ_{extr} correction was evaluated from previously published DAPHNE data [18] while the angular (and momentum) extrapolations needed for the $NN\pi^\pm(\pi^\mp)$ processes were evaluated from the experimental spectra [10]. The combination of all different sources of systematic errors (see [5]) gives an overall systematic error of $\simeq \pm 4\%$ of σ_{tot}.

In Fig. 1(a), the values of σ_{tot} obtained with an unpolarized liquid deuterium target prior to the main, polarized-target experiment, are compared to previous results [10,19]. While a good agreement can be clearly seen with [10], a systematic difference between the present data and those from [19] is present at $E_\gamma \sim 260$ MeV and $E_\gamma \sim 400$ MeV. The reason of this discrepancy, as shown in [10], is very probably due to a problem of the data from [19] which, for the ^{1}H nucleus and $E_\gamma \lesssim$ 450 MeV, are not in agreement with the sum of the measured cross sections for the $\gamma p \rightarrow N\pi$ channels, that are
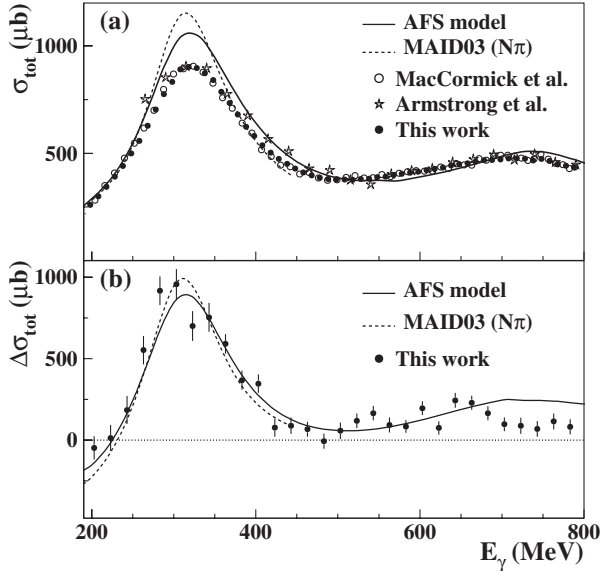
FIG. 1.   The unpolarized (a) and the helicity dependent (b) total inclusive photoabsorption cross section on ^{2}H obtained in this work (full circles) are compared to previous unpolarized results [10] (open circles), [19] (stars) and to the predictions of the nuclear AFS model [3]. The predicted sum of all free $N\pi$ channels from the MAID [20,21] analysis is also shown up to $E_\gamma = 450$ MeV. Only statistical errors are shown.

effectively the only involved reactions in this energy region.

In the same figure, our data are also compared to the sum of all free $\gamma N \to N\pi$ unpolarized total cross sections predicted by the MAID analysis (up to $E_\gamma = 450$ MeV) and to the results of the AFS model [3]. In the latter framework the photodisintegration process is treated with a realistic retarded potential while the elementary amplitudes for $\gamma N \to N\pi(\eta)$ (taken from MAID [20,21]) and for $\gamma N \to N\pi\pi$ (taken from an effective Lagrangian model [22]) are modified to take into account the final-state interactions.

A clear discrepancy between the AFS model and the experimental results can be seen, especially in the Δ-resonance region. This feature could be due either to the elementary amplitudes used as input or to the approximations made inside the model itself. The examination of the exclusive, partial reaction channels is required to resolve this problem.

Using the present analysis method, the total unpolarized cross section (σ_π) for the semiexclusive channels, (i) $\gamma d \to \pi^\pm NN$ and (ii) $\gamma d \to \pi^0 X(X = pn$ or $d)$, were evaluated up to $E_\gamma \simeq 430$ MeV, a region where the contributions of the $\gamma d \to \pi\pi NN$ channels can be neglected.

The yield from (i) was evaluated by subtracting from N_{ch} the yield coming from the $\gamma d \to pn$ and $\gamma d \to \pi^0 pn$ channels. Both reactions were identified by using the extended $\Delta E - E$ technique described in [23] to select events with a proton detected in the final state. Events from

(ii) were obtained by adding to $N_{\pi^0}(\bar{\varepsilon}_{\pi^0})^{-1}$ the fraction of events from the $\gamma d \to \pi^0 pn$ channel which had a proton detected inside the DAPHNE acceptance.

In Fig. 2(a) the obtained total unpolarized cross sections (σ_π) for (i) and (ii) are shown together with the corresponding predictions of the AFS model and with previously published results [24] for reaction (ii). These two sets of data agree within the quoted systematic errors ($\pm 5\%$ of σ_π for the present data). Both processes are overestimated by the model and discrepancies are bigger for reaction (ii) in the Δ-resonance region.

In the analysis of the helicity-dependent data, the inclusive method [Eq. (2)] was used to evaluate the difference $\Delta\sigma_{tot} = \sigma_p - \sigma_a$ since in this case the unpolarized contributions from the target C and O nuclei vanish.

However, a different method of evaluating Δ_{extr} was necessary in this case, which is outlined as follows: (1) the AFS model [3] was used for the pn channel as it reproduces our experimental $\vec{\gamma}\vec{d} \to pn$ data obtained with an independent analysis [25] reasonably well, (2) MAID was used to predict the $NN\pi^\pm$ channels as it reproduces previous DAPHNE helicity-dependent measurements of $\vec{\gamma}\vec{p} \to N\pi$ [9,26] reasonably well, (3) our polarized $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$ data [27,28] were used to predict the $np\pi^+\pi^-$ channel. The helicity asymmetry $[2\Delta\sigma/(\sigma_{unpol})]$ was assumed to be the same, inside and outside the DAPHNE acceptance.

The correction applied to the averaged π^0 efficiency, arising from neglecting the $N\eta$ channels, was evaluated
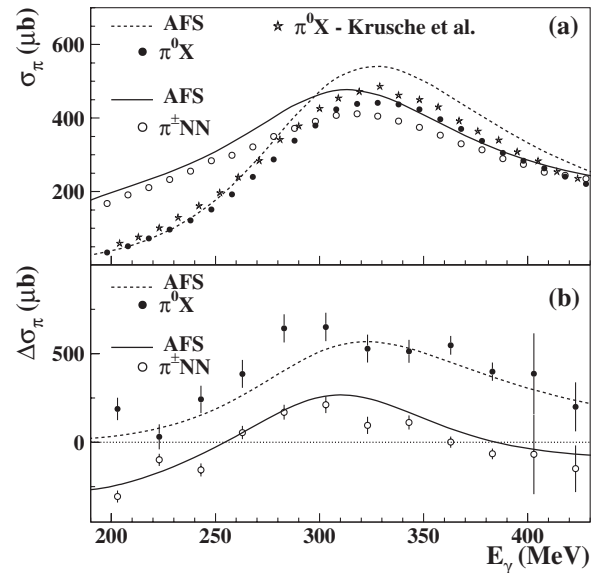

FIG. 2.   The unpolarized (a) and helicity-dependent (b) total cross section for the semiexclusive channels (i) $\gamma d \to \pi^\pm NN$ (open circles) and (ii) $\gamma d \to \pi^0 X(X = pn$ or $d)$ (closed circles) are compared to the corresponding predictions of the AFS model in the Δ-resonance region. In (a) our data for (ii) are also compared to previous results [24] (stars). Only statistical errors are shown.

assuming a helicity asymmetry of -0.97, following the calculation of Refs. [20,21]. The correction factor for the $N\pi^0\pi^0$ channel was obtained using our published helicity-dependent data for this reaction [29].

For all these last contributions, a systematic error of $\pm 50\%$ of the evaluated corrections is assumed. This gives a maximum relative systematic error on $\Delta\sigma_{tot}$ of $\sim 2\%$. Taking also into account the uncertainties in the beam and target polarization values, the overall systematic error on $\Delta\sigma_{tot}$ obtained by summing in quadrature all contributions (see [5]) is estimated to be $\sim 6\%$ of the measured values.

Polarized results and conclusions.—The analysis procedure described above results in the total cross section difference $\Delta\sigma_{tot}$ depicted in Fig. 1(b) [17]. In the same figure, our data are compared to the AFS [3] and the free $N\pi$ MAID [20,21] predictions.

The AFS model reproduces these experimental data better than in the unpolarized case, although it overestimates our data at the higher photon energies ($E_\gamma \gtrsim 700$ MeV), where the experimental behavior is also quite different from the one measured on the proton [5] in the same energy region. A similar difference is shown in Ref. [24] between the unpolarized $\gamma d \to \pi^0 np$ and $\gamma p \to \pi^0 p$ processes. This could be due to sizeable differences in the $N\pi(\pi)$ excitation mechanisms of the proton and the neutron in the region of the $D_{13}(1520)$ resonance.

The free $N\pi$ MAID analysis agrees surprisingly well with the present data in the Δ-resonance region, possibly indicative that effects related to composite nuclear structure are not strongly helicity dependent and their net effect is then reduced in the $\Delta\sigma$ case.

In Fig. 2(b) the total helicity-dependent cross section difference, $\Delta\sigma_\pi = (\sigma_{\pi,a} - \sigma_{\pi,p})$, for the (i) $\pi^\pm NN$ and (ii) $\pi^0 X$ channels is shown. The overall relative systematic error on $\Delta\sigma_\pi$ is $\sim 4\%$ for (i) and $\sim 6\%$ for (ii). In the same figure are also shown the AFS predictions in the Δ-resonance region which, in both cases, fairly well reproduce the experimental data.

Figure 3 displays the experimental running GDH integral (from a lower limit of 200 MeV to an upper limit which constitutes the running variable) obtained from the present data in combination with the high energy data of Ref. [8] and compares to the AFS predictions.

The measured value of the GDH integral between 200 and 800 MeV amounts to $407 \pm 20(\text{stat}) \pm 24(\text{syst})$ μb, while the value up to 1.8 GeV is $440 \pm 21(\text{stat}) \pm 25(\text{syst})$ μb. This value is consistent, within the quoted uncertainties, with the predictions of AFS even if this model slightly underestimates the polarized data in the Δ-resonance region and overestimates the Mainz and Bonn data for photon energies above ~ 700 MeV.

Additional double polarization data, currently under analysis, have been collected by our collaboration on exclusive partial reaction channels in the pion production region. A direct measurement of I_{GDH}^d from the breakup
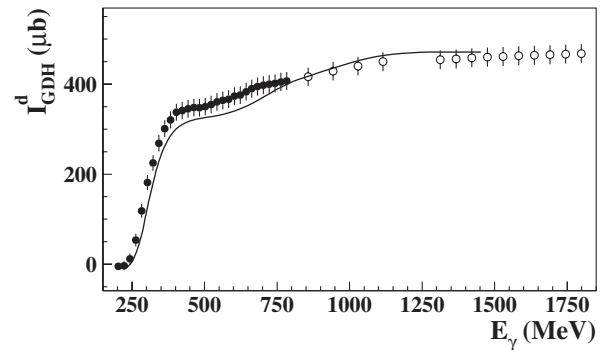

FIG. 3. The running GDH integral for the deuteron obtained with the present data (closed circles) and with the data from [8] (open circles) is compared to the predictions of the AFS model. Only statistical errors are shown.

threshold region up to the pion production region is also planned at the newly upgraded HIγS facility of the TUNL laboratory (Durham NC, USA) [30].

All these new data will then provide a much deeper insight into both the full GDH sum rule for the deuteron and the elementary mechanisms of the γd interaction.

Improved theoretical descriptions of these mechanisms are also needed for a reliable evaluation of the free γn contribution within the presently measured energy range.

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[1] S. B. Gerasimov, Sov. J. Nucl. Phys. **2**, 598 (1965).
[2] S. D. Drell and A. C. Hearn, Phys. Rev. Lett. **16**, 908 (1966).
[3] H. Arenhöevel, A. Fix, and M. Schwamb, Phys. Rev. Lett. **93**, 202301 (2004).
[4] J. Ahrens et al., Phys. Rev. Lett. **84**, 5950 (2000).
[5] J. Ahrens et al., Phys. Rev. Lett. **87**, 022003 (2001).
[6] H. Dutz et al., Phys. Rev. Lett. **91**, 192001 (2003).
[7] H. Dutz et al., Phys. Rev. Lett. **93**, 032003 (2004).
[8] H. Dutz et al., Phys. Rev. Lett. **94**, 162001 (2005).
[9] J. Ahrens et al., Eur. Phys. J. A **21**, 323 (2004).
[10] M. MacCormick et al., Phys. Rev. C **53**, 41 (1996).

[11] G. Anthony *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **301**, 230 (1991).

[12] S. Hall *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **368**, 698 (1996).

[13] K. Aulenbacher *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **391**, 498 (1997).

[14] C. Bradtke *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **436**, 430 (1999).

[15] G. Audit *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **301**, 473 (1991).

[16] M. MacCormick *et al.*, Phys. Rev. C **55**, 1033 (1997).

[17] T. Rostomyan, Ph.D. thesis, University of Gent, 2005.

[18] R. Crawford *et al.*, Nucl. Phys. **A603**, 303 (1996).

[19] T. Armstrong *et al.*, Phys. Rev. D **5**, 1640 (1972).

[20] D. Drechsel *et al.*, Nucl. Phys. **A645**, 145 (1999).

[21] D. Drechsel, S. S. Kamalov, and L. Tiator, Phys. Rev. D **63**, 114010 (2001).

[22] A. Fix and H. Arenhoevel, Eur. Phys. J. A **25**, 115 (2005).

[23] A. Braghieri *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **343**, 623 (1994).

[24] B. Krusche *et al.*, Eur. Phys. J. A **6**, 309 (1999).

[25] O. Jahn, Ph.D. thesis, University of Mainz, 2005.

[26] J. Ahrens *et al.*, Phys. Rev. C **74**, 045204 (2006).

[27] H. Holvoet, Ph.D. thesis, University of Gent (2001).

[28] M. Lang, Ph.D. thesis, University of Mainz, 2004.

[29] J. Ahrens *et al.*, Phys. Lett. B **624**, 173 (2005).

[30] H. R. Weller, in *Proceedings of the 3rd International Symposium on the GDH Sum Rule and its Extensions* (World Scientific, Singapore, 2004), p. 269.