Helicity Dependence of $\gamma p \to N\pi$ below 450 MeV and Contribution to the Gerasimov-Drell-Hearn Sum Rule

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The helicity dependence of the single pion photoproduction on the proton has been measured in the energy range from 200 to 450 MeV for the first time. The experiment, performed at the Mainz microtron MAMI, used a 4π-detector system, a circularly polarized, tagged photon beam, and a frozen-spin target. The data obtained provide new information for multipole analyses of pion photoproduction and determine the main contributions to the Gerasimov-Drell-Hearn sum rule and the forward spin polarizability γ_0.

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I. Introduction.—A great deal of our knowledge about the properties of the nucleon and of its excited states has been obtained through reactions induced by real (or virtual) photons. In recent years, the improvements in polarized beam and target techniques have opened new possibilities for the investigation of the polarization degrees of freedom of the nucleon.

In the study of spin-dependent reactions on the nucleon, there is special interest in the experimental verification of the Gerasimov-Drell-Hearn (GDH) sum rule. This sum rule, derived in the 1960s by Gerasimov [1] and independently by Drell and Hearn [2], relates static properties of the nucleon, the anomalous magnetic moment (κ), the charge (e), and the mass (M), to the difference in the total photoabsorption cross sections for circularly polarized photons on longitudinally polarized nucleons. It is written as

$$\int_{\nu_0}^{\infty} \frac{\sigma_{3/2} - \sigma_{1/2}}{\nu}\, d\nu = \frac{\pi e^2}{2M^2}\,\kappa^2 = 204\ \mu\mathrm{b}\,, \quad (1)$$

where $\sigma_{3/2}$ and $\sigma_{1/2}$ are the photoabsorption cross sections for the total helicity states $3/2$ and $1/2$, respectively (parallel or antiparallel photon-nucleon spin configuration), ν_0 is the pion mass, and ν is the photon energy. The left-hand side of Eq. (1) is called the GDH integral.

In a similar way, the so-called forward spin polarizability γ_0 can be obtained:

$$\gamma_0 = -\frac{1}{4\pi^2}\int_{\nu_0}^{\infty} \frac{\sigma_{3/2} - \sigma_{1/2}}{\nu^3}\, d\nu\,. \quad (2)$$

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The GDH sum rule is based on basic physics principles (Lorentz and gauge invariance, unitarity, and causality) applied to the forward Compton scattering amplitude. The only questionable assumption made is that this amplitude becomes spin independent at infinite photon energies. Because of its fundamental character, this prediction provides an excellent test of the nucleon spin structure.

Because of the technical difficulty of a double-polarized experiment, the GDH sum rule has not been previously verified. Without any direct experimental results, some theoretical predictions for the GDH integral were made using multipole analyses of (mainly unpolarized) single pion photoproduction data, pion scattering data, and a crude model for double pion photoproduction [3–6]. Other multihadron processes have only recently been taken into account by the Regge approach of Ref. [7].

In the low energy region all models are quite consistent and predict that the dominant portion of the GDH integral is due to the excitation of the $\Delta(1232)$ resonance, but, apart from [7], they overestimate substantially the sum rule prediction (204 μb) for the proton. As has been shown in the analysis of Drechsel and Krein [8], small variations in the contributions of low lying multipoles can have a big influence on the sum rule value due to the energy weighting in the integral.

An experimental program has been started jointly at MAMI (Mainz: $m_\pi \leq E_\gamma \leq 800$ MeV) and ELSA (Bonn: 600 MeV $\leq E_\gamma \leq 3$ GeV) tagged photon facilities to perform an experimental test of the GDH sum rule on the nucleon [9]. In this paper the first results on the helicity dependence of the total cross section of the $\gamma p \rightarrow N\pi$ channels between 200 and 450 MeV obtained at Mainz are shown, together with the evaluated contribution to the GDH and forward spin polarizability integrals.

II. Experimental setup.—The experiment was carried out at the Glasgow-Mainz tagged photon facility of the MAMI accelerator in Mainz. Circularly polarized photons are produced by bremsstrahlung of longitudinally polarized electrons. A strained GaAs photocathode routinely delivered electrons with a degree of polarization of about 75% [10]. The electron polarization was monitored during the experiment with a precision of 3% by means of a Møller polarimeter. The polarization direction was flipped randomly every few seconds to minimize systematic effects. The photon polarization was evaluated according to Ref. [11].

The photon energy was determined by the tagging spectrometer which analyzes the momenta of the electrons which have radiated bremsstrahlung photons. This detection system is able to tag photons in the range from 50 to 800 MeV with a resolution of about 2 MeV [12].

The tagging efficiency was continuously monitored throughout the experiment by an e^+e^- pair detector that was installed downstream of the main hadron detector. The pair detector was regularly calibrated using a 100% efficient lead glass detector. By using this technique, the photon flux could be determined with a systematic uncertainty of 2% [13,14].

A butanol (C_4H_9OH), frozen-spin target [15] provided the polarized protons. The system consisted of a horizontal dilution refrigerator and a superconducting magnet ($\simeq$2.5 T), used in the polarization phase, together with a microwave system for dynamic nuclear polarization. During the measurement the polarization was maintained in the frozen-spin mode at a temperature of about 50 mK and a magnetic field of 0.4 T, supplied by a small superconducting holding coil inside the cryostat. A maximum polarization close to 90% and relaxation times in the frozen-spin mode of about 200 h have been regularly achieved. The target length of 2 cm gave a total thickness of $N_t \simeq 9 \times 10^{22}$ protons cm^{-2}. The target polarization was measured, using NMR techniques, with an absolute precision of 1.6%.

Photoemitted hadrons were registered in a detector system covering almost the full solid angle. This system was based on the large angular acceptance $(21^\circ \leq \vartheta \leq 159^\circ; 0^\circ \leq \varphi \leq 360^\circ)$ detector DAPHNE [16] complemented by additional detectors to increase the acceptance into the forward angular region. DAPHNE is a charged particle tracking detector consisting of three cylindrical multiwire proportional chambers, surrounded by segmented $\Delta E - E - \Delta E$ plastic scintillator layers and by a scintillator-absorber sandwich, allowing the detection of neutral pions with reasonable efficiency. The additional forward detectors were the silicon microstrip detector MIDAS [17] $(7^\circ \leq \vartheta \leq 16^\circ)$, an aerogel Čerenkov counter to suppress electromagnetic background, and the annular ring detector STAR [18], followed by a forward scintillator-lead sandwich counter $(2^\circ \leq \vartheta \leq 5^\circ)$.

III. Data analysis.—In this paper, data recorded only by the DAPHNE detector will be presented. The identification methods for hadrons have been described in detail previously [13,14] and only the main characteristics will be given here.

Charged particles stopped inside the detector were identified using the range method described in [19]. Its most important feature is the simultaneous use of all of the charged particle energy losses in the DAPHNE scintillator layers to discriminate between protons and $\pi^\pm$ and to determine their kinetic energies. This method can be applied for particles stopped inside the detector. In the considered E_γ range ($E_\gamma < 450$ MeV) all recoil protons from π^0 production are stopped within DAPHNE, and only photoemitted π^+'s may have enough energy to escape the detector.

In the case of the $p\pi^0$ final state, when the proton was not detected by DAPHNE, the π^0 was used as a signature for this channel. The π^0 was identified by requiring a coincidence between the two photons resulting from its decay. Since a fraction of these photons are detected inside our apparatus for all π^0 energies and angles, no angular or momentum extrapolation was needed for this channel.

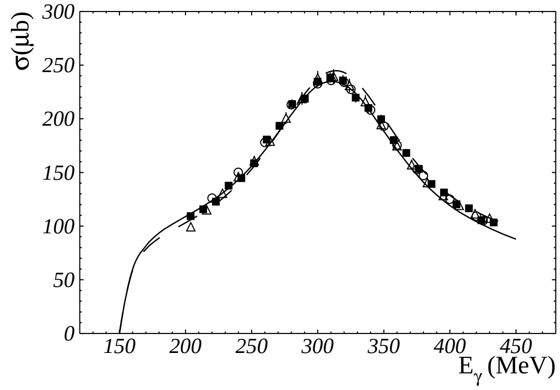

FIG. 1. Unpolarized total cross section for $\gamma p \rightarrow n\pi^+$ measured on a pure hydrogen target (solid squares) in comparison to Ref. [13] (Δ), Ref. [21] ($\bigcirc$), and to the analyses of HDT [20] (solid line) and SAID [22] (dashed line).

The absolute π^0 detection efficiency ϵ_{π^0} varied between 15% and 20% and was evaluated using a GEANT based simulation.

The situation is different for the $n\pi^+$ channel since DAPHNE was not used to detect neutrons alone. For $E_\gamma > 200$ MeV, the region where the data will be presented for this reaction, the lower π^+ momentum limit was above the detection threshold applied during the analysis and only angular extrapolation was necessary. About 95% of the total cross section could then be measured directly. The extrapolation into the unobserved region was made using the calculation of Hanstein *et al.* (HDT) [20]. Since the total correction is of the order of 5% only, the corresponding systematic error is assumed to be less than 2%.

Prior to the main experiment, data for detector calibration and for testing the analysis methods were taken with the same apparatus using an unpolarized pure liquid hydrogen target. In Fig. 1, the total unpolarized cross section for $\gamma p \rightarrow n\pi^+$ is compared to previously published data [13,21] and to the SAID [22] and HDT [20] multipole analysis results. This cross section is well described

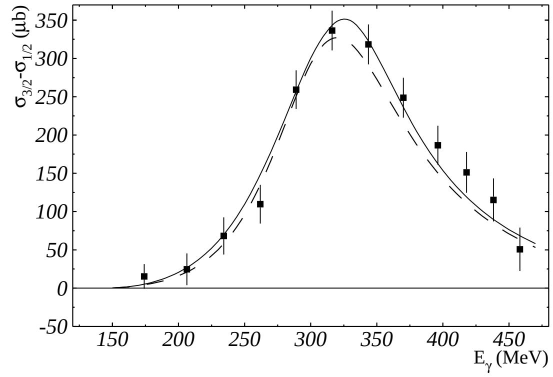

FIG. 3. Difference of the total cross sections for $\vec{\gamma}\vec{p} \rightarrow p\pi^0$ for the helicity states $3/2$ and $1/2$ as a function of energy, in comparison to the SAID and HDT multipole predictions (symbols as in Fig. 1).

by both multipole analyses, and the excellent agreement found between the old and present data strongly suggests that the detector response is well under control. The same quantitative agreement was found for $\gamma p \rightarrow p\pi^0$.

In the analysis of the data taken using the butanol target, the background contribution of the reactions produced on C and O nuclei could not be fully separated event-by-event from the polarized H contribution. However, this background, coming from spinless nuclei, is not polarization dependent and cancels when the difference between events in the $3/2$ and $1/2$ states is taken. As an example, Fig. 2 shows this difference in E_{miss} (missing energy) obtained from events with a photoemission proton in the Δ region. E_{miss} is the difference between the measured proton kinetic energy and the proton kinetic energy evaluated (using E_γ and the polar emission angle) under the assumption that the proton originated from a π^0 production process on hydrogen. Missing energy distributions are shown for both helicity states and for their difference. The region outside the peak at $E_{\text{miss}} = 0$ corresponds to quasifree reactions on C and O nuclei and has a yield consistent with zero in the difference spectrum.

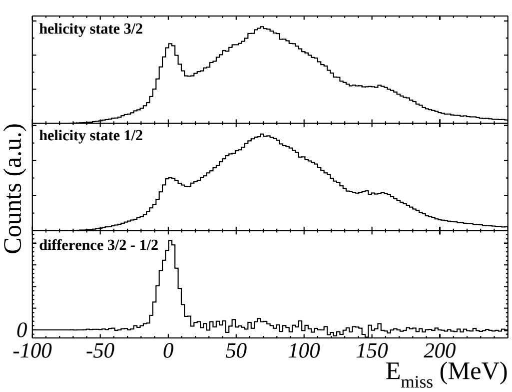

FIG. 2. Missing energy spectra for the reaction $\vec{\gamma}\vec{p} \rightarrow p\pi^0$ under the assumption that the proton originated from a reaction on a free proton. The spectra are shown for both helicity states and their difference.

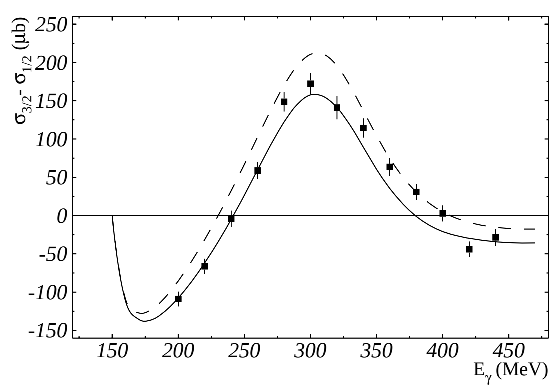

FIG. 4. Difference of the total cross sections for $\vec{\gamma}\vec{p} \rightarrow n\pi^+$ for the helicity states $3/2$ and $1/2$ as a function of energy, in comparison to the SAID and HDT multipole predictions (symbols as in Fig. 1).

TABLE I. Results from the present experiment and multipole predictions for the GDH integral (in μb) in the energy range from 200 to 450 MeV.

	Experiment	SAID	HDT
$\pi^0 p$	144 ± 7	132.0	143.6
$\pi^+ n$	32 ± 3	55.0	26.4
total	176 ± 8	187.0	170.0

IV. Results and discussion.—By using the methods described above, the total cross section difference $\sigma_{3/2} - \sigma_{1/2}$ was extracted as a function of the primary photon energy from threshold up to 450 MeV for the $p\pi^0$ channel [23] (Fig. 3) and from 200 MeV up to 450 MeV for $n\pi^+$ [24] (Fig. 4). These data represent about 80% of the total available statistics below 350 MeV and 50% above. The relatively bigger statistical uncertainty associated with the $p\pi^0$ channel is due to the low efficiency of the detection of pure π^0 events. Their contribution to this channel ranges from 100% at threshold to $\simeq$30% at $E_\gamma = 400$ MeV.

The errors shown are statistical only. The systematic errors contain contributions from charged particle identification (2.5%), photon flux normalization (2%), photon polarization (3%), target polarization (1.6%), and π^0 detection efficiency (4%) or π^+ extrapolation (2%), respectively. Adding these errors in quadrature leads to a probable total systematic error of about 6%.

For $\vec{\gamma}\vec{p} \rightarrow p\pi^0$, strong positive cross section difference values are found in the full energy range due to the dominant contribution of the M_{1+} multipole. The difference for $\vec{\gamma}\vec{p} \rightarrow n\pi^+$, however, clearly starts out negative at low energies, due to the E_{0+} multipole and turns positive at about 240 MeV. This behavior is also seen in the multipole analyses.

In the difference of the helicity-dependent cross sections for $p\pi^0$, SAID and HDT are consistent with each other but there is a slight underestimation, in the SAID analysis, of the experimental results. There is a more noticeable difference in the $n\pi^+$ channel between SAID and HDT. The latter analysis is in better agreement with our data below the peak of the Δ resonance, while the former is better above it.

In the energy range under consideration these two channels represent the total photoabsorption cross section. The extraction of the total cross section difference allows direct determination of the contribution in the energy range investigated to the GDH integral and the forward spin polarizability. The integration was separately performed for each measured data point, assuming a constant $(\sigma_{3/2} - \sigma_{1/2})$ difference in the corresponding photon energy bin. The values thus obtained, summed up from 200 to 450 MeV, are listed in Tables I and II in comparison with the results of the SAID [22] and HDT [20] multipole analyses. In both cases, the HDT predictions are closer to the experimental integral values, mainly because of the better agreement with our data for the $n\pi^+$ channel below the peak of the Δ resonance.

TABLE II. Results from the present experiment and multipole predictions for the forward spin polarizability integral (in 10^{-4} fm^4) in the energy range from 200 to 450 MeV.

	Experiment	SAID	HDT
$\pi^0 p$	-1.45 ± 0.09	-1.34	-1.48
$\pi^+ n$	-0.23 ± 0.04	-0.54	-0.19
total	-1.68 ± 0.1	-1.88	-1.67

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[1] S. B. Gerasimov, Sov. J. Nucl. Phys. **2**, 430 (1966).
[2] S. D. Drell and A. C. Hearn, Phys. Rev. Lett. **16**, 908 (1966).
[3] I. Karliner, Phys. Rev. D **7**, 2717 (1973).
[4] R. L. Workman and R. A. Arndt, Phys. Rev. D **45**, 1789 (1992).
[5] V. Burkert and Z. Li, Phys. Rev. D **47**, 46 (1993).
[6] A. M. Sandorfi *et al.*, Phys. Rev. D **50**, R6681 (1994).
[7] N. Bianchi and E. Thomas, Phys. Lett. B **450**, 439 (1999).
[8] D. Drechsel and G. Krein, Phys. Rev. D **58**, 116009 (1998).
[9] J. Ahrens *et al.*, Mainz MAMI Proposal A2/2-95; G. Anton *et al.*, Bonn ELSA Proposal, 1992.
[10] K. Aulenbacher *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **391**, 498 (1997).
[11] H. Olsen and L. C. Maximon, Phys. Rev. **114**, 887 (1959).
[12] I. Anthony *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **301**, 230 (1991); S. J. Hall *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **368**, 698 (1996).
[13] M. MacCormick *et al.*, Phys. Rev. C **53**, 41 (1996).
[14] R. Crawford *et al.*, Nucl. Phys. **A603**, 303 (1996).
[15] C. Bradtke *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **436**, 430 (1999).
[16] G. Audit *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **301**, 473 (1991).
[17] S. Altieri *et al.*, INFN Report TC-98/30, 1998; S. Altieri *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A (to be published).
[18] M. Sauer *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **378**, 143 (1996).
[19] A. Braghieri *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **343**, 623 (1994).

[20] O. Hanstein *et al.*, Nucl. Phys. **A632**, 561 (1999).
[21] H. Genzel, P. Joos, and W. Pfeil, in *Photoproduction of Elementary Particles*, edited by H. Schopper, Landolt-Börnstein, New series, Group 1, Vol. 8 (Springer-Verlag, Berlin, 1973).
[22] R. A. Arndt *et al.*, Phys. Rev. C **53**, 430 (1996) (solution SM99K).
[23] B. Seitz, Ph.D. thesis, Cuvillier Verlag, Göttingen, 1999.
[24] I. Preobrajenski, Ph.D. thesis, Mainz (to be published).