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HELICITY STRUCTURE OF PION PHOTOPRODUCTION AND THE GDH SUM RULE*

H.-J. Arends

Institut für Kernphysik, Universität Mainz
J.-J. Becherweg 45, D-55099 Mainz, Germany

for the GDH- and A2- Collaborations

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First measurements of pion photoproduction using circularly polarized photons on longitudinally polarized protons were carried out at MAMI (Mainz) in the energy range $E_\gamma = 140$–800 MeV. Preliminary results of the helicity dependence of the total inclusive photoabsorption cross section in the full energy range and of the partial reaction channels $\gamma p \rightarrow p\pi^0$ and $\gamma p \rightarrow n\pi^+$ in the Δ region are now available. These data provide new input for multipole analyses and determine the main contribution to the Gerasimov–Drell–Hearn (GDH) integral and the forward spin polarizability γ_0.

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1. Introduction

The helicity dependent total cross sections for the absorption of real photons on nucleons, $\sigma_{3/2}$ and $\sigma_{1/2}$, corresponding to parallel or antiparallel relative spin configurations, respectively, are related to the anomalous magnetic moment κ of the nucleon via the Gerasimov–Drell–Hearn (GDH) sum rule [1]:

$$\int_{m_\pi}^{\infty} \frac{\sigma_{3/2} - \sigma_{1/2}}{\nu} d\nu = \frac{\pi e^2}{2M^2}\kappa^2 = 204\mu\mathrm{b}\,. \tag{1.1}$$

This sum rule connects the static properties of the nucleon (M, e, κ) with the dynamics of the excitation spectrum from pion threshold to infinity.

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In a similar way, the forward spin polarizability γ_0, a structure constant of the nucleon still unmeasured, can be obtained as:

$$\gamma_0 = -\frac{1}{4\pi^2} \int_{m_\pi}^{\infty} \frac{\sigma_{3/2} - \sigma_{1/2}}{\nu^3} d\nu. \tag{1.2}$$

The GDH sum rule is based on very general physics principles (low-energy theorems, optical theorem, unsubtracted dispersion relation) applied to the forward Compton scattering amplitude. Due to its fundamental character this prediction, formulated in the 1960's, deserves a verification which has needed technical developments that only recently have taken place.

Some estimates of the GDH sum rule have been made using multipole analyses of the existing single pion photoproduction data (mainly from unpolarized experiments) and a simple model for the contribution of double pion photoproduction processes [2]. These estimates were incompatible with the GDH sum rule prediction, giving significantly higher values for the proton but much lower ones for the neutron [2–6]. However, the present lack of direct experimental data on the double polarization observables prevents to draw any definitive conclusions about any violation of the GDH sum rule.

Apart from the GDH sum rule, another important motivation to study the helicity structure of single and double pion photoproduction lies in the fact that it provides completely new and up to now inaccessible information on partial wave amplitudes. The inclusion of this new observable into multipole analyses will allow to access small resonance amplitudes and help to separate them from the dominating ones and from the nonresonant background.

The aim of the GDH collaboration is to provide an extensive data set of helicity dependent cross sections for all the partial reaction channels both on the proton and on the neutron at the electron accelerators MAMI (Mainz) ($m_\pi \leq \mathrm{E}_\gamma \leq 800$ MeV) and ELSA (Bonn) ($\mathrm{E}_\gamma \leq 3$ GeV). In 1998 the data taking on the proton was completed in Mainz. In the following, preliminary results from this experiment will be presented and discussed.

2. Experimental setup

The experiment was carried out at the tagged photon facility of MAMI. Circularly polarized photons were produced by bremsstrahlung of longitudinally polarized electrons. The source of polarized electrons, based on the photoeffect on strained GaAs crystals, delivered routinely electrons with a degree of polarization of about 75% or higher. The degree of polarization was continuously measured during the whole experiment by Møller scattering in a magnetized vacuflux foil. Both electrons were detected in coincidence in the tagging spectrometer. A dedicated trigger ensured that the sum of the electron energies matched the beam energy.

Polarized nucleons were available in the frozen spin target [7] that was built and operated by the groups of Bonn, Bochum and Nagoya. The system consists of a horizontal dilution refrigerator and a superconducting polarization magnet, which was used in the polarization phase together with a microwave system for dynamical nuclear polarization (DNP). During the measurement the polarization was maintained in the "frozen spin" mode at temperatures of about 50 mK by an internal superconducting coil (B$\simeq$ 0.4 T) which is integrated into the dilution refrigerator. The target material was butanol (C_4H_9OH). At 2.5 T maximum polarization values close to 90% were obtained for the protons with a typical relaxation time in the "frozen spin" mode of about 200 hours. The holding field was homogeneous enough to allow for continuous NMR monitoring of the target polarization during the experiment.

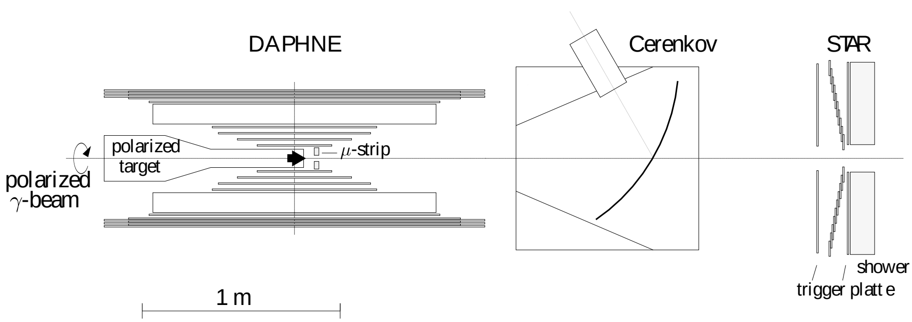

Fig. 1. Schematic side view of the experimental setup of the GDH experiment in Mainz.

The photon induced reaction products were registered by means of the large acceptance detector DAPHNE [8], built by CEA Saclay and INFN–Sezione di Pavia, which was complemented by forward detectors to increase the solid angle acceptance (see Fig. 1). DAPHNE is mainly a charged particle tracking detector with cylindrical symmetry. It consists of 3 coaxial multi-wire proportional chambers with cathode readout, surrounded by 16 segments of $\Delta E - E - \Delta E$ plastic scintillator telescopes and by a double scintillator-converter sandwich which allows the detection of neutral pions with a useful efficiency. The silicon microstrip detector MIDAS [9] covers the angular range down to 7 degrees, the aerogel Čerenkov counter serves for online suppression of electrons and positrons, extreme forward angles are covered by the annular ring detector STAR [10] and a lead-scintillator sandwich counter.

3. Data analysis

Charged particles stopped inside DAPHNE were identified and their kinetic energies determined by a maximum likelihood method using all energy losses in the DAPHNE scintillator layers.

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. The excellent agreement found between the old and present data for the total unpolarized cross sections for $\gamma p \to n\pi^+$ and for $\gamma p \to p\pi^0$ proves that the detector response is well under control. These data are well described by both the phenomenological multipole analysis SAID [4] and the dispersion theoretical analysis HDT [12].

As an example for the helicity dependent signal from the polarized butanol target, Fig. 2 shows missing energy distributions for protons emitted at $E_\gamma < 400$ MeV and detected in DAPHNE, under the hypothesis that they originate from the π^0 production on a free proton. Events from the free proton can be seen as a clear peak at zero missing energy on a broad background coming from quasifree pion production and quasideuteron processes from carbon and oxygen. Since these nuclei are not polarized, the corresponding contributions are the same for both helicity states, and vanish in the difference, as is clearly demonstrated in the lower spectrum of Fig. 2.

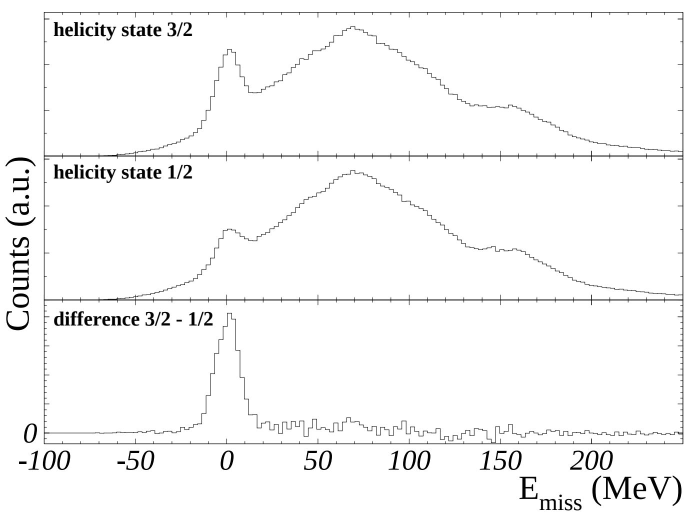

Fig. 2. Missing energy spectra for protons detected in DAPHNE assuming the reaction $p(\gamma,p)\pi^0$.

4. Preliminary results and discussion

4.1. Single pion production

The total cross section difference $\sigma_{3/2} - \sigma_{1/2}$ was extracted for the $p\pi^0$ channel from threshold up to 450 MeV and for $n\pi^+$ from 200 MeV up to 450 MeV [11].

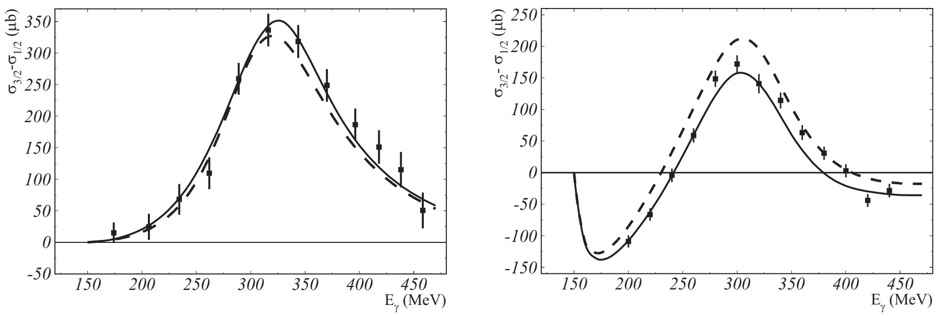

Fig. 3. Difference $\sigma_{3/2} - \sigma_{1/2}$ for $\gamma p \to p\pi^0$ (left) and $\gamma p \to n\pi^+$ (right)

These data (see Fig. 3) represent about 50% of the total available statistics taken with DAPHNE only, the analysis of the forward particles detected in MIDAS is still in progress. The relatively bigger statistical uncertainty associated to the $p\pi^0$ channel is due the low efficiency for the detection of pure π^0 events. The errors shown are statistical only, the systematic error is about 6%. For $\vec{\gamma}\vec{p} \to p\pi^0$ strong positive values are found in the full energy range due to the dominant contribution of the M_{1+} multipole. The difference for $\vec{\gamma}\vec{p} \to n\pi^+$, however, clearly starts out negative at low energies, due to the E_{0+} multipole and turns positive at about 240 MeV. This behaviour is also seen in the multipole analyses. For $p\pi^0$, the data are well described by SAID whereas HDT slightly overestimates them near the Δ peak. However, there is a larger difference between SAID and HDT in the $n\pi^+$ channel, which has its origin in the more complex multipole composition of this channel in combination with the higher sensitivity of the helicity dependent cross sections to small amplitudes due to interference terms. HDT is in excellent agreement with our data below the peak of the Δ resonance while SAID is better above it.

Fig. 4 shows the result of the Mainz Unitary Isobar Model (UIM) [13] with the electric quadrupole amplitude ($E_{1+}^{3/2}/M_{1+}^{3/2} = 2.5\%$) switched on and off. This is a clear example for the sensitivity of the helicity difference to small multipole amplitudes.

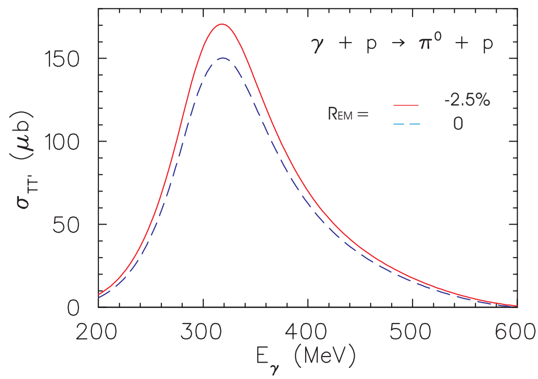

Fig. 4. Difference $\sigma_{TT'} = 1/2(\sigma_{3/2} - \sigma_{1/2})$ for $\gamma p \rightarrow p\pi^0$ from UIM with E_{1+}/M_{1+}=0 and -2.5%, see text.

4.2. Double pion production

For the three double pion production channels there are very preliminary results in the DAPHNE acceptance available, the analysis is going on. On the theoretical side, no official results for helicity dependent cross sections exist yet, but the work in progress by the Valencia [14] and Mainz/Gent [15] groups are very encouraging.

4.3. Total cross section

Using an inclusive analysis method, based on the detection of charged hadrons (p, $\pi^{\pm}$) and neutral pions, the helicity difference of the total photoabsorption cross sections $\sigma_{3/2} - \sigma_{1/2}$ from 200 to 800 MeV has been determined, see Fig. 5.
This difference starts out negative due to the $E_{0+}^{n\pi^+}$ multipole and has, as expected, a strong positive contribution due to the M_{1+} multipole. Above the Δ resonance peak a sizeable contribution of the double pion photoproduction processes can clearly be seen. The curves shown for comparison are from SAID [4] (solution SM99K) and from HDT [12] which both include the single pion production processes only.

Although the data available up to now are still preliminary, we can use them to determine the contribution to the integrals of Eqs. (1.1) and (1.2).

The integration of our data from 200 to 800 MeV yields $(228 \pm 6)\mu$b and determines the dominant contribution to the GDH integral, see Fig. 6.

The missing low energy contribution below 200 MeV according to HDT is -27μb, the high energy contribution above 800 MeV given by single pion photoproduction according to SAID is 25μb.

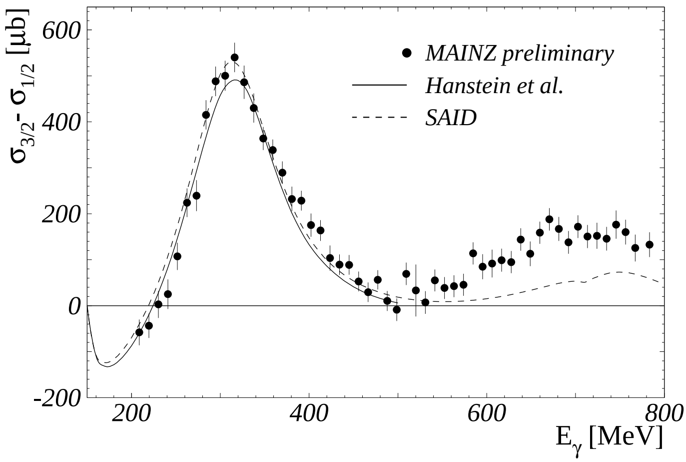

Fig. 5. Difference of helicity dependent total cross sections $\sigma_{3/2} - \sigma_{1/2}$ on the proton compared to model predictions.

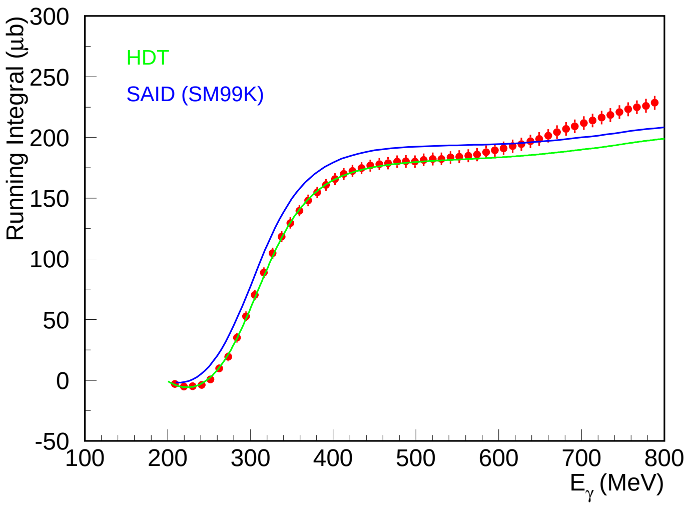

Fig. 6. GDH integral starting at 200 MeV as a function of the upper integration limit.

The integration of our data according to eq. 1.2 in the energy range from 200 to 800 MeV yields $(-1.68 \pm .07) \times 10^{-4}$ fm^4. Due to the strong energy weighting ($\propto \nu^{-3}$) the high energy single pion and double pion processes are expected to contribute very little to the spin polarizability. HDT yields 1.0×10^{-4} fm^4 for the missing contribution below 200 MeV resulting in a preliminary value for γ_0 of about $(-.7 \pm .07) \times 10^{-4}$ fm^4. This value is significantly smaller than the values extracted from SAID [3] $(-1.34 \times 10^{-4}$ fm$^4)$

and the result from chiral perturbation theory [16] (-1.5×10^{-4} fm^4). It is in better agreement with a recent dispersion theoretical result of Ref. [17] ($-.80 \times 10^{-4}$ fm^4).

5. Outlook

The analysis of the data taken at MAMI on the proton will be carried on. The measurements on the proton will be extended to higher energies at ELSA (Bonn) during the second half of 2000. In the next phase of the GDH experiment, data on polarized ^{2}H and ^{3}He targets will be taken at MAMI in 2002.

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