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# Beam-helicity asymmetry $I^{\odot}$ in the photoproduction of $\pi^0$-pairs off the deuteron

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**Abstract.** Beam-helicity asymmetries have been measured at the MAMI accelerator in Mainz for the photoproduction of neutral pion pairs in the reactions $\gamma p \rightarrow p\pi^0\pi^0$ and $\gamma d \rightarrow (n)p\pi^0\pi^0$, $\gamma d \rightarrow (p)n\pi^0\pi^0$ off free protons and off quasi-free nucleons bound in the deuteron for incident photon energies up to 1.4 GeV. A circularly polarized photon beam was produced off a longitudinally polarized electron beam using bremsstrahlung processes. The photons were tagged with the Glasgow magnetic spectrometer. Decay photons from the $\pi^0$ mesons, recoil protons, and recoil neutrons were detected in the $4\pi$ covering detector system composed of the Crystal Ball and TAPS electromagnetic calorimeters. The free and quasi-free results are in almost perfect agreement. The measured asymmetries for reactions off protons and neutrons are very similar, in contrary to expectations. The results are compared to the predictions from the Two-Pion-MAID reaction model.

## 1 Introduction

Photoproduction of meson pairs off the nucleon has attracted a lot of interest during the last few years as a useful tool for the study of the excitation spectrum of the nucleon. In analogy to other composite systems, like atoms or atomic nuclei, the excitation spectrum must reflect the basic features of the underlying interaction, in this case the strong interaction described by Quantum Chromodynamics. Up till now the experimental results have been mainly interpreted with phenomenological quark models, since analytic or perturbative solutions of this field theory on the energy scale typical for excited states of the nucleon are missing. These quark models are based on different internal degrees of freedom (three equivalent constituent quarks, quark-diquark structures, additional collective modes) and different residual interactions of the quarks (gluon exchange, Goldstone boson exchange). Even though such models can only be used as a rough approximation of the complicated structure of the nucleon, a comparison to experiment should give them some guidance for the relevant properties of the interaction. However, so far this approach has had only limited success. Apart from problems with the ordering of some low lying states, already at moderate excitation energies the match in simple number counting between experiment and models is poor; many more states are predicted than have been observed.

During the last few years a lot of data covering the so-called second and third resonance regions have been collected with photon energies up to ≈1.5 GeV. Total cross sections and invariant-mass distributions of the $\pi\pi$- and the $\pi N$-pairs have been measured with the DAPHNE and TAPS detectors at the MAMI accelerator in Mainz [1–9], at GRAAL in Grenoble (also with linearly polarized photons) [10, 11], at ELSA in Bonn [9, 12], and with the CLAS detector at JLab (with electron beams) [13]. Recently polarization observables were also measured at the MAMI accelerator [14–16, 18].

However, despite these efforts, the interpretation of the data is still controversial even for double $\pi^0$ production at low excitation energies, where only a few well-known resonances contribute. Polarization observables are very sensitive to small reaction amplitudes via their interference terms with the leading multipoles [19–22].

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## 2 Results

### 2.1 The Beam Helicity Asymmetry

This single polarisation observable can be measured for three-body final states like $N\pi\pi$ with circularly polarized photons and unpolarized targets. It is defined by:

$$I^{\odot}(\Phi) = \frac{1}{P_\gamma}\frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{1}{P_\gamma}\frac{N^+ - N^-}{N^+ + N^-} \tag{1}$$

where $d\sigma^\pm$ are the differential cross sections for each of the two photon helicity states, and $P_\gamma$ is the degree of circular polarization of the photons. $\Phi$ is definded in the center-of-momentum (cm) system as the angle between the reaction plane, spanned by the incident photon and the outgoing recoil nucleon, and the production plane, spanned by the two pions [22].

Parity conservation imposes on the asymmetry the condition

$$I^{\odot}(\Phi) = -I^{\odot}(2\pi - \Phi) \tag{2}$$

and for identical mesons, like $\pi^0\pi^0$ pairs, when the numbering of the two pions is randomized, it must obey in addition

$$I^{\odot}(\Phi) = I^{\odot}(\Phi + \pi) \tag{3}$$

This relation does not apply, when the two pions are ordered by some kinematic condition, for example by $m(\pi^0_1, p) \geq m(\pi^0_2, p)$ where $m(\pi^0, p)$ are the invariant masses of the pion-proton pairs. For the extraction of $I^{\odot}(\Phi, \Theta_{\pi_1}, \Theta_{\pi_2}, ...)$ for fixed kinematic conditions the differential cross sections $d\sigma^\pm$ can be replaced by the respective count rates $N^\pm$, since all normalization factors cancel in the ratio. For a finite range of kinematics, the count rates must be weighted by the experimental detection efficiency.

The asymmetries have been analyzed in two different ways, for a randomized numbering of the two pions and ordered with the condition $m(\pi^0_1, p) \geq m(\pi^0_2, p)$. The first analysis was only used for a comparison to the previous results from [23,24] for the free proton. The agreement between the two measurements is excellent and shows that the analysis is working reliably. As a fit for the asymmetries the sine-series

$$I^{\odot}(\Phi) = \sum_{n=1}^{\infty} A_n \sin(n\Phi). \tag{4}$$

was used. When using the second analysis (kinematically ordered $\pi$'s) also the odd-coefficients of the series may contribute, yielding more information about the reaction mechanism can be gained.

### 2.2 Quasifree Results With Ordered Pions

In Fig. 1 we show the results for $I^{\odot}(\Phi)$ for different ranges of $W = \sqrt{s}$, where the two pions were ordered according to $m(\pi^0_1, p) \geq m(\pi^0_2, p)$. The comparison of the asymmetries for the free and quasi-free proton do not reveal significant discrepancies, demonstrating that the removal of effects from nuclear Fermi motion via the kinematic reconstruction works excellently. Thus the neutron asymmetries measured this way can be taken as a good approximation of free-neutron data and be compared to corresponding model results. Against all expectations the quasi-free neutron and proton results are almost identical for the two isospin channels. This is in particular surprising for the third resonance region, where reaction models predict for proton and neutron contributions from different resonances. Additionally we have analyzed the asymmetries for different ranges of the polar angles $\Theta^\star_{\pi\pi}$ in the photon-nucleon cm-system, where $\Theta^\star_{\pi\pi}$ is the direction of a hypothetical parent particle of the two pions. The $A_3$ and $A_4$ coefficients are in general small but at least for the central angles significantly different from zero. $A_1$ and $A_2$ are large, vary quite strongly with $W$ and $\Theta^\star_{\pi\pi}$ and are again similar for proton and neutron for central and backward angles. The largest differences occur for $A_2$ at forward angles. Most problematic for the model is again $A_1$ at backward angles and $A_2$ for the neutron.

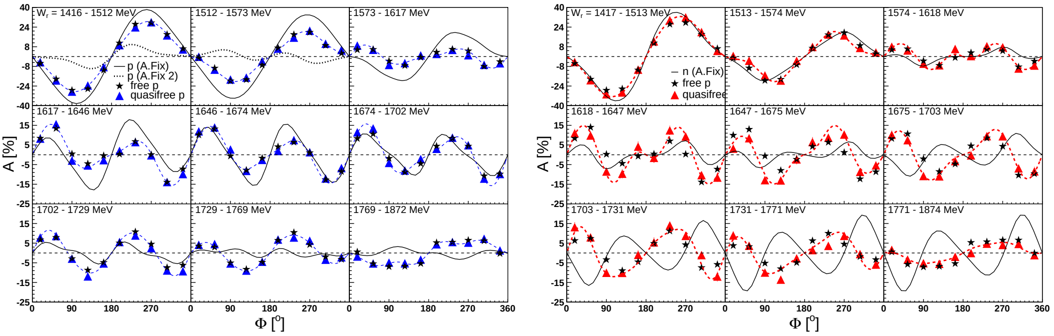


**Fig. 1.** Preliminary results for $I^{\odot}(\Phi)$ for different ranges of $W = \sqrt{s}$.
Left hand side: (black) stars: free proton, (blue) triangles: quasi-free proton, dashed (blue) curves: fits to quasi-free proton data with Eq. 4, (black) solid curves: model results from [20]. (black) dotted curves (only for lowest $W$ ranges): model results from [17].
Righ hand side: (black) stars: free proton, (red) triangles: quasi-free neutron, dashed (red) curves: fits to neutron data with Eq. 4, solid (black) curves: model results from [20].

## 3 Summary And Conclusion

Precise results have been measured for the beam-helicity asymmetries in the production of $\pi^0$-pairs of free protons from a hydrogen target and quasi-free protons and neutrons from a deuterium target with a circularly polarized photon beam. The asymmetries are sizable and the results for free and quasi-free protons are in excellent agreement when the kinematics of the quasi-free reaction is completely reconstructed. A surprising similarity between the asymmetries for the proton and neutron target are observed. The apparent discrepancies to model predictions should give important input for the further improvement of the reaction models and the extraction of nucleon resonance contributions from this reaction channel. In addition differential beam-helicity asymmetries have been measured. They confirm the similarity for the proton and neutron asymmetries.

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