Helicity-dependent cross sections for the photoproduction of $\pi^0$ pairs from nucleons

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The double-polarization observable E and helicity-dependent cross sections $\sigma_{1/2}$, $\sigma_{3/2}$ have been measured for the photoproduction of $\pi^0$ pairs off quasi-free protons and neutrons at the Mainz MAMI accelerator with the Crystal Ball/TAPS setup. A circularly polarized photon beam was produced by bremsstrahlung from longitudinally polarized electrons and impinged on a longitudinally polarized deuterated butanol target. The reaction products were detected with an almost 4$\pi$ covering calorimeter. The results reveal for the first time the helicity- and isospin-dependent structure of the $\gamma N \rightarrow N^2\pi^0$ reaction. They are compared to predictions from reaction models in view of nucleon resonance contributions and also to a refit of one model that predicted results for the proton and for the neutron target. The comparison of the prediction and the refit demonstrate the large impact of the new data.

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Photoproduction of mesons is a powerful and versatile tool for the investigation of the nucleon excitation spectrum, which reflects the properties of the strong interaction in the non-perturbative regime. Reactions like $\gamma N \rightarrow N\pi, N\eta, N\omega, N\rho, N\sigma$ etc. have been studied in detail during the last two decades; however, single-meson production reactions are clearly biased against states that do not decay directly to the nucleon ground state. In the constituent quark model, higher-lying nucleon resonances may de-excite preferentially in two-step processes involving an intermediate excited state [1]. The restriction to single-meson production could thus exclude complete multiplets of quark-model states from observation.

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Cascade decays via intermediate states require the investigation of multiple-meson final states. The simplest cases are pseudoscalar (PS) meson pairs like $\pi\pi$ or $\pi\eta$. The reaction formalism and the sets of observables are discussed in [2, 3] and a field theoretic description of the process is given in [4]. For single-meson production, a ‘complete’ experiment, which allows the unique determination of the magnitudes and phases of all relevant amplitudes, requires the measurement of eight carefully chosen observables including single and double polarization observables as a function of two kinematic parameters (typically center-of-momentum (cm) energy and em-polar angle) [5]. Photoproduction of PS meson pairs requires the measurement of eight observables as a function of five kinematic parameters to determine just the magnitudes of the amplitudes, and 15 observables have to be measured to determine also their phases [2].

Such a complete experiment for meson pairs is unrealistic; however, limited data sets can give valuable insights. Three-body final states offer powerful analysis strategies that are not available for single-meson production. Invariant-mass distributions (e.g. the invariant mass of the intermediate state) of the particle pairs carry information about the decay chains. Polarization observables, which depend on the angle between reaction (photon - recoil nucleon) and production (meson - meson) plane, are easy to measure. They are robust against false instrumental asymmetries since they do not depend on azimuthal laboratory angles but only on the relative angle between the two planes.

Final states with neutral PS meson pairs are of special interest because non-resonant background terms are suppressed. Many recent efforts have been dedicated to the investigation of $\pi^0\pi^0$ and $\pi^0\eta$ pairs, however, with somewhat different results. Non-resonant background indeed seems to be small for $\pi\eta$-pairs. The results point to dominant contributions from the excitation of just a few isospin $I = 3/2$ $\Delta$ resonances up to invariant masses of $W \approx 2$ GeV (see Refs. [6–11]).

Surprisingly, photoproduction of neutral-pion pairs is less understood although it has been intensively studied experimentally. Measurements of unpolarized cross sections and several polarization observables for proton and quasi-free neutron targets from threshold throughout the second and third nucleon resonance region and above [1, 12–30] have been reported. However, there are several unresolved issues in the low-energy regime. Early data up to the second resonance region ($E_\gamma \approx 800$ MeV) [12, 13] for $\gamma p \rightarrow p\pi^0\pi^0$ were interpreted differently in models. Murphy and Laget [31] found a dominant contribution from the $N(1440)1/2^+$ $\rightarrow N\sigma \rightarrow N\pi^0\pi^0$ decay of the Roper resonance by emission of the $\sigma$ meson. This decay was negligible in the model of Gomez-Tejedor and Oset [32], which instead favored the $N(1520)3/2^- \rightarrow \Delta\pi^0 \rightarrow N\pi^0\pi^0$ decay. More precise invariant-mass distributions of the $\pi^0\pi^0$ and $\pi^0N$ pairs [15] and the helicity dependence of the cross section [20] demonstrated the importance of the sequential $N(1520)3/2^-$ decay. However, the GRAAL collaboration argued in Refs. [17, 21] again for a large $N(1440)1/2^+ \rightarrow \sigma N$ contribution.

More precise cross-section data from the CBELSA/TAPS experiment [22, 23] covering a larger energy range were analyzed with the Bonn-Gatchina (BnGa) coupled channel model. A dominant contribution from the broad $\Delta(1700)3/2^-$ state was suggested from threshold up to the third resonance bump. The contribution from the $N(1520)3/2^-$ was significant, and the one from the Roper resonance was small but required to derive new parameters for this state. Further results from CBELSA/TAPS, including polarization observables, [29, 30] have been used to extract properties of several higher lying states. However, this analysis also suggested a somewhat modified picture for the low-energy resonance structure with a much stronger contribution of the $N(1680)5/2^+$ state. Results from the Crystal Ball/TAPS experiment [25, 26] have been analyzed with the Mainz MAID isobar model [33] and also with a partial-wave expansion of the amplitudes. The latter found evidence for an unexpectedly large contribution of the $3/2^-$ partial wave in the threshold range.

The only data available so far for the $\pi^0\pi^0$ final state are cross sections from the GRAAL [21] and Crystal Ball/TAPS [28] experiment and the polarization observable $T^0$ (circularly polarized beam, unpolarized target) [27] also from Crystal Ball/TAPS.

In this Letter we report results from a precise measurement of the double-polarization observable $E$ and helicity-dependent cross sections $\sigma_{1/2}$ and $\sigma_{3/2}$ for $\pi^0\pi^0$ pairs off protons and neutrons at the Mainz MAMI accelerator [34]. In the formalism for pseudoscalar meson pairs given in [2] this observable would be $P^0_{\pi^0\pi^0}$. The definition is identical to the one for the observable $E$ in single meson production. For a circularly polarized photon beam and a longitudinally polarized target, two different relative spin orientations, parallel or antiparallel, corresponding to the cross sections $\sigma_{3/2}$ ($\uparrow\uparrow$) and $\sigma_{1/2}$ ($\uparrow\downarrow$) are possible. They are related to the asymmetry $E$ by

$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{\sigma_{1/2} - \sigma_{3/2}}{2\sigma_0},$$

where $\sigma_0$ is the unpolarized cross section.

The helicity dependence of the cross section allows contributions from nucleon resonances with spin $J = 1/2$ (contribution only to $\sigma_{1/2}$) and $J \geq 3/2$ to be disentangled.

The experimental setup and the analysis procedures are described in Refs. [10, 35–37] (most details are given in Ref. [36]) for other reaction channels ($N\eta$, $N\pi^0$, and $N\eta\pi^0$). A more detailed description of the present experiment and analysis will be given in a longer journal paper. Longitudinally polarized electron beams ($e^-$ energy 1558 MeV) with polarization degrees between 83 and 85% produced circularly polarized bremsstrahlung photons. The energy-dependent polarization $P_\phi$ of the
with $x = E_\gamma/E_{e-}$. The photons were energy tagged with the Glasgow magnetic spectrometer \cite{39}. The longitudinally polarized target contained solid deuterated butanol. The deuterons had polarization degrees between 55 and 62%. The polarization of the nucleons bound in the deuteron ($P_D$) was smaller due to the $d$-wave component of the deuteron wave function ($\approx 6\%$). The carbon and oxygen nuclei were unpolarized.

The reaction products, i.e., the four photons from the $\pi^0$ decays and a recoil proton or recoil neutron, were detected with an electromagnetic calorimeter covering almost the full solid angle. It was composed of the Crystal Ball (CB) \cite{40} and TAPS \cite{41} detectors. The CB covered polar angles from 20° to 160°, while TAPS was used as a forward wall for polar angles between $\approx 5^\circ$ and $\approx 21^\circ$. The target was placed in the center of the CB and TAPS was mounted 1.457 m downstream of the target. For the identification of charged particles, the target was surrounded by a particle identification detector (PID) \cite{42} and plastic scintillators for charged particle identification (CPD) were installed in front of the BaF$_2$ crystals of the TAPS forward wall. The trigger was based on a twofold coincidence between different segments of the calorimeter. For this purpose, the CB was logically subdivided into 42 clusters of 16 adjacent crystals and TAPS into six triangular sectors. In addition, an energy deposition (analog sum of the energy signals) of 250 MeV in the CB detector was required.

The identification of the $p\pi^0\pi^0$ and $n\pi^0\pi^0$ final states was done as in Ref. \cite{28}. Photon, proton, and neutron candidates were identified using the energy deposition in the calorimeter, a $\Delta E - E$ analysis combining PID and CB, the response of the CPD, pulse-shape (PS), and time-of-flight (ToF) versus energy analysis for TAPS. The best combination of the four (for $p\pi^0\pi^0$) or five (for $n\pi^0\pi^0$) neutral hits to two $\pi^0$ mesons was determined with a $\chi^2$ analysis of the invariant masses of all possible pairs. Only the ‘best’ combinations were accumulated in a two-dimensional invariant-mass spectrum of the two pions. The reaction identification was completed with a condition on coplanarity of the three particles and a missing-mass analysis eliminating background from higher multiplicity final states with particles that escaped detection; for example, from the $\eta \rightarrow 3\pi^0$ decay. Effects from nuclear Fermi motion were removed with a kinematic reconstruction of the final state of the reaction as discussed in \cite{43}. The invariant mass $W$ of the $N_p\pi^0\pi^0$ ($N_p =$ participant nucleon) system was determined from the incident-photon energy, the four momenta of the two pions, and the polar angle of the recoil nucleon.

The asymmetry $E$ (Eq. (1)) can be directly derived from the measured count rates $N_{1/2}, N_{3/2}$ for the two spin configurations

$$E = \frac{B \left( N_{1/2} - N_{3/2} \right)}{P_T} .$$

Many systematic effects cancel in this ratio. However, the background count rate $N_B$ from nucleons bound in the unpolarized carbon and oxygen nuclei of the butanol molecules drops out only in the numerator but contributes to the denominator. This count rate was determined with a measurement using a special carbon-foam target that had the same geometry and the same density of the heavy nuclei as the butanol target. The subtraction of the unpolarized background required that the count rates from both targets were normalized to the incident photon flux. Asymmetries determined this way are labeled analysis (1). Alternatively, one can replace the denominator of Eq. (3) by $2\sigma_0$, where $\sigma_0$ is the unpolarized cross section measured with a liquid deuterium target. In this analysis (2) absolutely normalized cross sections must be also used in the numerator. They were determined from the measured yields, photon fluxes,
the target density, and the experimental detection efficiency constructed with Monte Carlo simulations using the Geant4 package [44]. The small differences between the two analyses observed in some energy regions indicate typical systematic uncertainties and were included in the estimates for systematic errors.

The helicity-dependent cross sections \( \sigma_{1/2} \) and \( \sigma_{3/2} \) were then derived from

\[
\sigma_{1/2} = \sigma_0 \cdot (1 + E), \quad \sigma_{3/2} = \sigma_0 \cdot (1 - E) .
\]

The unpolarized cross sections \( \sigma_0 \) were taken from [28]. For the \( p\pi^0\pi^0 \) final state, the measurement with a liquid hydrogen target was used. For the \( n\pi^0\pi^0 \) final state, the results measured with a liquid deuterium target were used after correction for final-state interactions (FSI) under the assumption that they are similar for reactions with bound protons and neutrons [28]. The leading FSI effects on the magnitude of cross sections, which are substantial (order of 20%), were thus removed. Only residual FSI effects, which are different for the \((\uparrow\uparrow), (\uparrow\downarrow)\) spin configurations or for quasifree proton and neutron targets, could not be corrected; however, these are assumed to be small. Under this assumption, the experimental data are compared to model results for free nucleons.

The most important results are summarized in Figs. 1-4. In the upper row (a) of Fig. 1, the results for \( E \) from analyses (1), (2) are compared. There is almost no systematic deviation between the two analyses, which demonstrates that the treatment of the unpolarized background is well under control. For the following three rows (b)-(d) the two analyses have been averaged. In contrast to systematic uncertainties, statistical uncertainties are highly correlated between the two analyses because they are dominated by the numerator of the asymmetry, which is identical for both analyses. Therefore the mean of the statistical uncertainties of the two analyses (instead of standard error propagation) was used for the final results. At invariant masses below 1.5 GeV the results for \( E, \sigma_{1/2}, \sigma_{3/2} \) for the quasifree proton are compared to free-proton results from Ref. [20]. They agree within sta-
tistical fluctuations, which demonstrates that FSI effects, at least in this regime, have been removed. However, the present results are statistically more precise. No previous results for the neutron target at any energy are available.

Differential spectra are shown in Figs. 2,3,4 for angular distributions and the invariant meson-nucleon and meson-meson distributions. The angle \( \theta_{2\pi} \) is the polar angle of the combined two-pion system in the overall cm frame (i.e., within experimental resolution back-to-back with the recoil nucleon). The invariant-mass distributions of the pion-nucleon system are mostly sensitive to contributing intermediate resonances and the pion-pion invariant masses carry the signal from contributions such as \( N^* \rightarrow N\sigma \) involving the \( f_0(500) \) meson [47].

The experimental data are compared to the results from two models for this reaction, the BnGa model [22] and the MAID model [33]. The first is for double-pion production still restricted to the proton target. However, this coupled-channel analysis also fits many other reaction channels for the proton and also some (for example this coupled-channel analysis also fits many other reactions). The results demonstrate that the contributions of different nucleon resonances is very important input for reaction models that try to identify the contributions of different nucleon resonances to the reaction process. The results demonstrate that the BnGa coupled-channel model is already in reasonable agreement with the main body of the proton data, although the \( \sigma_{1/2} \) component in the third resonance region is significantly overestimated. The MAID model fit had to be completely redone to accommodate the new data and it now describes these data and also data for other observables much better. Altogether, the new data significantly improve the data base for \( \pi^0\pi^0 \) production in both isospin channels. However, there are still features of the data that are not adequately reflected by model fits and need further investigation (e.g., the structures in the \( \pi^0\pi^0 \) invariant-mass distributions for the neutron target at largest \( W \), in particular for \( \sigma_{1/2} \)).

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