Two neutral pion photoproduction off the proton between threshold and 800 MeV

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Abstract

The photoproduction of two neutral pions off the proton has been studied for incident photon energies between \( E_\gamma = 309 \text{ MeV} \) (threshold) and 792 MeV with the TAPS photon spectrometer at the Mainz Microtron MAMI. Both \( 3\gamma \)- and \( 4\gamma \)-events have been analysed in order to deduce the total \( p(\gamma, 2\pi)p \) cross section. The total cross section is less than 300 nb between threshold and \( \simeq 460 \text{ MeV} \), beyond which it starts to rise to a maximum value of about 11 \( \mu \text{b} \) at around 750 MeV. For the highest energies it starts to decrease again. The \( 4\gamma \)-sample has been used to reconstruct 2 neutral pions from the above reaction channel by an invariant mass and a missing mass analysis. After reconstruction of the unobserved proton, a Dalitz-plot of \( m^2_{\pi\pi} \) vs. \( m^2_{\pi p} \) has been obtained, which indicates that the decay chain includes the \( \Delta(1232) \)-resonance as an intermediate state.

1. Introduction

Meson photoproduction off the nucleon is one of the tools to obtain information about the structure of hadrons in the non-perturbative domain of QCD. For decades pion production has been used to study nucleon resonances via multipole analyses. Although the electromagnetic production promises a clean excitation with a well-known probe, the lack of high quality data prevented further advances in the field. This situation has changed with the advent of cw electron accelerators. Recently, experiments performed at the Mainz Microtron MAMI have produced total and differential cross sections for photoproduction of pions [1] and \( \eta \)-mesons [2] off the proton of unprecedented quality.

While single pion production is a powerful tool to study details of the \( \Delta \)-excitation [3], additional and more distinct channels are needed to disentangle the broad and overlapping resonances at higher excitation energies. One well known example is \( \eta \)-photoproduction, which is almost exclusively sensitive to the \( S_{11}(1535) N^* \)-resonance. Double pion production is a further promising channel, which might be used to study the Roper \( P_{11}(1440) \) resonance and the \( D_{13}(1520) \) resonance with its strong photon coupling. While the cross section for the channels with at least one charged pion is known to originate mostly from the \( \Delta n \)-Kroll-Rudermann term, double neutral pion photoproduction is not diluted by Born terms. In
addition due to isospin no contribution from \( \rho \)-decay is possible.

The first total cross section for the \( 2\pi^0 \)-photoproduction on the proton has been published by the DAPHNE-group at MAMI \([4]\). The DAPHNE experiment was based on the measurement of the recoil proton with good energy- and angular resolution, but it had only a limited photon detection capability. For this reason they were not able to obtain a \((\pi^0\pi^0)\)-cross section below \( E_\gamma \approx 450\) MeV and to get precise enough kinematical information about all final state particles to study the reaction in more detail.

Since TAPS is an electromagnetic calorimeter \([5]\) and the neutral pions are detected via their \( 2\gamma \)-decay with good energy and angular resolution, such restrictions do not apply for this measurement. If both neutral pions are identified, the unobserved proton can be reconstructed. This completely determines the reaction and allows to deduce additional observables, which can be used to investigate the reaction mechanism independent of model calculations.

In this paper, results from the first TAPS-measurements at MAMI for the reaction \( p(\gamma, 2\pi^0)p \) between threshold and 792 MeV are presented. In Section 2 the experimental setup is briefly described. Section 3 covers the data analysis and in Section 4 our results are presented and discussed by comparing them to calculations and previous data. Finally in Section 5 some conclusions are given.

2. Experimental setup

The experiment has been performed with the Glasgow-Mainz tagged photon facility of the A2 Collaboration \([6]\) at the Mainz Microtron MAMI \([7]\), using TAPS \([5]\) as a photon spectrometer. The setup is identical to the one described in \([2]\). We used an incident electron beam with an energy of 855 MeV, which allows to produce quasimonochromatic photons by means of bremsstrahlung tagging in the energy range up to 792 MeV and a flux of up to \( 10^8 \) photons per 2 MeV and per second. For most of the time, the tagged photon energy range was restricted to 660–792 MeV, because the main emphasis of the experiment was \( \eta \)-photoproduction. Only for about 20 hours the complete energy range was covered. The resulting poorer statistics was partly overcome by also analysing the \( 3\gamma \)-events in TAPS (see below). The liquid hydrogen target had a diameter of 4 cm and a length of 5 cm, corresponding to about \( 2 \times 10^{23} \) nuclei/cm\(^2\). As a photon spectrometer TAPS comprising 320 \( \text{BaF}_2 \)-detectors in 5 blocks of 8 \( \times \) 8 modules was used, each in a horizontal plane containing the target and mounted at polar angles of \( \pm 38^\circ, \pm 88^\circ, \) and \( +133^\circ \) and all at a distance of 55 cm from the target. All blocks except for the most backward one at \( 133^\circ \) were equipped with charged particle veto detectors (CPV) for each individual bariumfluoride detector.

3. Data analysis

The aim of the data analysis is to identify events from the reaction \( \gamma p \rightarrow \pi^0\pi^0p \rightarrow (4\gamma)p \); together with the luminosity (i.e. number of target nuclei times number of incident tagged photons per energy bin) and the detection and analysis efficiency (obtained from extensive Monte Carlo simulations, using the program package GEANT \([8]\)), their number determines the cross section.

In order to achieve this, one first has to identify coincident photons from the decay of the 2 neutral pions. Thanks to the properties of the bariumfluoride scintillators (good timing resolution of less than 1 ns, pulse shape discrimination \([5]\)) and the CPV detectors this can be done in a very reliable and efficient way. Single \( \pi^0 \) events are rejected by requiring at least 3 photons per event. The relative timing of all photons is used to suppress events in which not every photon is originating from the target, for example a two-photon event from \( \pi^0 \rightarrow \gamma \gamma \), in which one \( \gamma \) scatters from one into a second detector. Most of these events are identified due to the late arrival of the third photon. All remaining \( 3\gamma \)-events for incident energies below 707 MeV which contain a photon pair in the \( \pi^0 \) invariant mass range are taken as \( 2\pi^0 \)-events. True \( 3\gamma \) background events from the decay of the \( \eta \)-meson into \( 3\pi^0 \) can only be avoided by restricting the energy of the incident photon to below the threshold energy of \( E_\gamma = 707.9\) MeV \([2]\). In order to obtain the \( 2\pi^0 \)-cross section above the \( \eta \)-threshold, we used \( 4\gamma \)-events and a missing mass analysis (see below). Finally, as usual in every tagging experiment, we eliminate accidental coincidences by a scaled subtraction of events out-
Fig. 1. (a) Two-dimensional invariant mass plot of two-photon combinations in 4γ-events (3 entries per event). The two neutral pion events are located at the intersection of the two pion bands. The histograms show projections of the event distributions on the mγγ-axes. (b) Missing mass for two neutral pion events. The peak at zero missing mass results from the reaction \( p(\gamma, 2\pi^0) p \), while the structure at positive missing mass is due to \( \eta \to \pi^0 \pi^0 \pi^0 \) decays, in which one of the neutral pions is missing the detector. This can easily be verified by requiring that the incident photon has an energy below the \( \eta \)-threshold of \( E_\gamma = 707.9 \) MeV, in which case the broad structure disappears (see Fig. 1b). Events inside the window \(-60 \text{ MeV} < \text{missing mass} < +60 \text{ MeV}\) are considered background free \( p(\gamma, 2\pi^0) p \)-events; for those we reconstruct the four-momentum of the not-detected recoil proton, using the four momenta of the incident photon and the two neutral pions.

4. Results and discussion

In Fig. 2 the results of our measurements for the total cross section of the reaction \( p(\gamma, 2\pi^0) p \) are plotted as a function of the incident photon energy together with the results obtained by DAPHNE [4]. The results of the 3γ- and the 4γ-analysis agree within the errors (only statistical errors are shown) with exception of one data point obtained from the 4γ-analysis at \( E_\gamma = 510 \) MeV. Both the DAPHNE- and the TAPS-data show a peak structure at \( E_\gamma \approx 710 \) MeV with a maximum cross section of about 1 \( \mu \)b. The 2\( \pi^0 \) data of this work are very small between threshold and approximately 460 MeV at a level of \( \leq 300 \) nb. Beyond that the cross section smoothly rises to the maximum. The cross section measured by DAPHNE only agrees with the present one for \( E_\gamma \geq 600 \) MeV. In the low energy part the DAPHNE data are definitely higher than the results of this work.

There are two calculations available for this reaction [9,10]; both calculations start from a similar set of Feynman-diagrams – much less than in the case of the two other isospin channels, because the photon...
does not couple directly to the neutral pion – but the results are strikingly different. While Tejedor and Oset [9] nearly reproduce the shape of the measured cross section, Murphy and Laget [10] predict too small a peak cross section and too large a width. More surprisingly, Tejedor and Oset attribute the major contribution to the excitation of the $D_{13}(1520)$ resonance and its subsequent decay via the intermediate $\Delta(1232)$ state, while in the Murphy and Laget calculation the main part of the cross section is due to the excitation of the $P_{11}(1440)$ Roper-resonance and a decay of two correlated neutral pions in a relative s-state into the ground state of the nucleon.

In order to investigate the reaction mechanism experimentally, additional information has been used for the high energy part ($E_\gamma = 660$–792 MeV). Fig. 3 shows the Dalitz-plot for those events, in which 2 neutral pions have been identified as due to $p(\gamma, 2\pi^0)p$, and the proton has been reconstructed (see above); more specifically $m^2(\pi^0\pi^0)$ vs. $m^2(p\pi^0\pi^0)$ is shown corrected for the detection efficiency in TAPS. Also shown are the two projections onto the axes and the adjusted expectation for pure phase space production. In spite of the rather limited statistics it is obvious that we observe a peak in $m^2(p\pi^0\pi^0)$ due to the intermediate $\Delta$-resonance. Together with the peak structure in the total cross section at $E_\gamma \approx 710$ MeV (corresponding to $\sqrt{s} \approx 1490$ MeV), this indicates that the reaction proceeds dominantly via the chain $\gamma p \rightarrow D_{13}(1520) \rightarrow \Delta(1232)\pi^0 \rightarrow p\pi^0\pi^0$. This interpretation is also corroborated by the calculation of Ref. [9].

5. Summary and conclusions

Double neutral pion photoproduction from the proton has been measured between threshold and 800 MeV, exploiting the decay of neutral pions into two photons. The total cross section has been determined and a Dalitz-plot of $m^2(\pi^0\pi^0)$ vs. $m^2(p\pi^0\pi^0)$ has been obtained. From the results of our measurement the following conclusion can be drawn: In the second resonance region (550–800 MeV), the reaction mechanism involves excitation of a high lying nucleon resonance presumably the $D_{13}(1520)$-resonance, which has a large photon coupling and subsequent decay via the intermediate $\Delta(1232)$-resonance. Clearly this first exploratory experiment was hampered by low statistics, particularly close to threshold. Further experiments have already been performed [11] or are being prepared [12], which will improve the statistical precision significantly in the near future.
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References