PHOTOPRODUCTION OF MESONS FROM QUASIFREE NUCLEONS*

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Recent results for photoproduction reactions of quasi-free nucleons are discussed mainly in view of the electromagnetic excitations of the neutron which cannot be studied in other ways. Such experiments are necessary in order to study the isospin degree of freedom in electromagnetic nucleon resonance excitations. In particular, experiments with the Crystal Ball/TAPS setup at the Mainz MAMI accelerator and the Crystal Barrel/TAPS setup at the Bonn ELSA accelerator are discussed. Both experiments use electromagnetic calorimeters which cover almost the full solid angle and can detect and identify photons from the decay of neutral mesons, recoil protons and neutrons and partly also charged pions. The complications from the Fermi motion of the bound nucleons and final-state interactions of the final-state particles will be discussed. Examples for the impact of the new data comprising absolute cross sections and polarization observables for single- and multiple-meson production reactions are given.

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1. Introduction

Photoproduction of mesons has developed to a standard tool for the investigation of the nucleon excitation spectrum. Large progress has been made (see *e.g.* Ref. [1]) during the last two decades in experiment and also in the analysis methods (in particular, detailed coupled channel analyses). Experimental programs were running at several state-of-the-art experimental setups at modern electron accelerators (see *e.g.* [2, 3] for overviews). A part of this program is finished, however there are still certain aspects which have not yet been covered and are under intense investigation.

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Electromagnetic nucleon excitations are isospin-dependent. Consequently, the determination of the relevant amplitudes requires also measurements with neutron targets, which are experimentally more involved. Since there is no free neutron target, quasi-free neutrons bound in light nuclei, in particular the deuteron, have to be used. On the experimental side, this requires detector setups which, in addition to the final-state mesons, can also reliably detect and identify recoil nucleons, which is not trivial for neutrons. Also effects from the nuclear Fermi motion and final-state interaction effects (FSI) must be thoroughly considered (see Sec. 2). Previously, only a few absolute cross sections had been measured for the most basic reactions of quasi-free neutrons (like π^0-, η-production). The importance of such experiments is demonstrated in Fig. 1. The left-hand side of the figure shows the total cross section for the $\gamma p \to p\pi^0$ reaction for three well-known partial wave/coupled channel analyses. The right-hand side shows the predictions of the same analyses for the $\gamma n \to n\pi^0$ reaction based on all available data for $\gamma p \to p\pi^0$, $\gamma p \to n\pi^+$, and $\gamma n \to p\pi^-$. The results for $\gamma p \to p\pi^0$ agree very well. This is so because many experimental data exist for angular distributions and also for polarization observables. This data base forces the models to the same results.

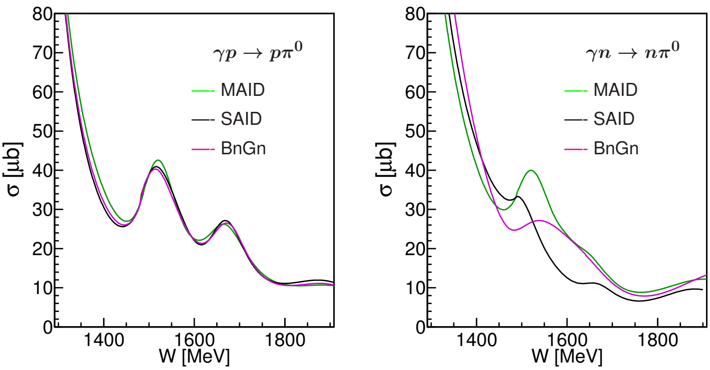

Fig. 1. Model results from the MAID [4], SAID [5], and BnGn [6] analysis for the total cross section of single π^0 photoproduction off the nucleon. Left-hand side: free proton target, right-hand side: free neutron target.

However, the results for $\gamma n \to n\pi^0$ disagree completely already for a trivial quantity like the total cross section, so that no partial wave analysis for this reaction trying to fix parameters of nucleon resonances can be reliable. On the first glance, this is surprising because the isospin structure of the reaction amplitudes is fixed by four equations involving the three independent components A^{IS} (isoscalar), A^{IV} (isovector), and A^{V3} (isospin changing) [7]. Consequently, the available data bases for the $p\pi^0$, $p\pi^-$, and $n\pi^+$ final state should also fix $n\pi^0$. They do not, because the data bases for this reactions are not ‘complete’ in a sense that they allow a unique determination of the amplitudes, and the contributions of non-resonant backgrounds to final states with charged and neutral pions are much different. Therefore, a measurement of the $n\pi^0$ final state (with minimal non-resonant background) is important.

The more recent experiments aim not only at a measurement of cross sections but also polarization observables for meson production off neutrons. Single and double polarization experiments (mainly polarized photon beams combined with polarized deuterated butanol targets) have moved into the focus. Here, the question arises how much the Fermi motion and FSI effects will influence polarization observables, in particular when intricate azimuthal distributions of reactions products have to be analyzed.

Furthermore, modern 4π calorimeters allow to study reactions like $\gamma d \rightarrow (p)n\pi^0\pi^0$ or $\gamma d \rightarrow (p)n\pi^0\eta$ (nucleon in brackets: undetected spectator). Reactions with meson pairs in the final state allow to study sequential decays of high-lying nucleon resonances via intermediate excited states. Such decays are expected for states which, in the quark model, have both oscillators excited and de-excite them in a two-step process so that they decouple from single-meson production. The analysis of final states with meson pairs is much more involved than single-meson production. While for single-meson production a unique determination of the magnitudes and phases of all amplitudes requires the measurement of eight carefully chosen observables as function of two kinematic parameters [8], photoproduction of pseudoscalar meson pairs requires already eight observables as a function of five kinematic parameters to determine just the magnitudes and 15 observables to fix also the phases [9]. It is obvious that no ‘complete’ experiments are possible in this case, but on the other hand, invariant mass distributions of the final-state particles and polarization observables which only occur for three-particle final states can give valuable information.

2. Complications from Fermi momenta and FSI

Measurements off quasi-free nucleons require the detection of the recoil nucleons. This is not a principle problem but complicates the experiments and reduces detection efficiencies for reactions off quasi-free neutrons typically by 1/3 since detection efficiencies of electromagnetic calorimeters for neutrons of reasonable energies are of the order of 30% compared to $\approx 95\%$ for recoil protons. In a brute force way, this can be solved by just longer beam times.

A more serious issue is the Fermi motion of the bound nucleons. Due to this, in particular sharp structures in excitation functions and angular distributions are smeared out as functions of incident photon energy. However, it is possible to reconstruct the total final-state energy W of the nucleon–meson system from the reaction kinematics taking into account the Fermi motion. The initial state — incident photon and nucleus at rest — is completely known. For photoproduction of neutral mesons also their three-momenta and invariant masses are known. For the recoil neutrons, often only the angles are known. Calorimeters do not directly measure their energies, and time-of-flight methods are mostly not possible because the target–detector distances are too small. This means that for a measurement with a deuterium target, four quantities are missing: the kinetic energy of the recoil 'participant' nucleon and the three-momentum of the 'spectator' nucleon. These quantities can be recovered from the four equations corresponding to energy and momentum conservation. For a deuteron target, the reconstruction is exact, although the experimental resolution for the measured momenta has to be considered. For heavier nuclei like, for example, He isotopes, the reconstruction is only approximate because the 'spectator' can be more complicated (can be a multi-nucleon system with relative momenta). However, even in this case, the reconstruction works quite well as it is demonstrated in Fig. 2. On the left-hand side total cross sections for η production in coincidence with recoil nucleons for a ^{2}H, ^{3}He, and a ^{4}He target are shown as a function of incident photon energy. On the right-hand side, the same data are shown as a function of total reconstructed energy W. The narrow structure in the neutron excitation function around 1 GeV photon energy (≈ 1.66 GeV in W) is completely smeared out as function of incident photon energy, but perfectly recovered by the kinematic reconstruction. This works equally well for all three targets although Fermi momenta are much larger for ^{4}He than for ^{2}H.

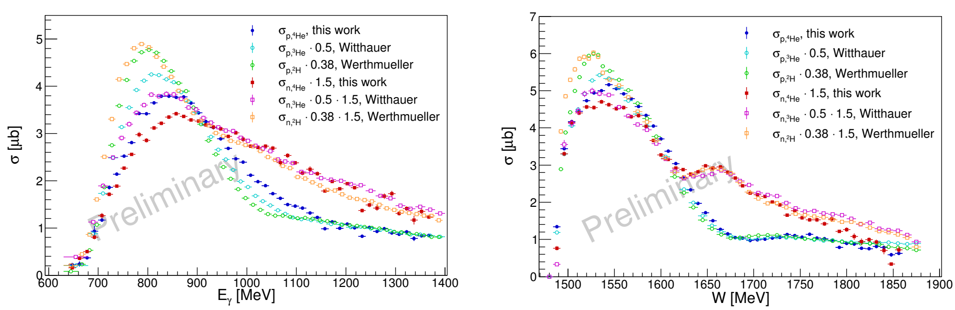

Fig. 2. Total cross section for photoproduction of η mesons off nucleons. Left-hand side: as a function of incident photon energy E_γ; right-hand side as a function of reconstructed final-state total energy W. Experimental results: deuteron target [10, 11], ^{3}He [12], ^{4}He [13] (preliminary). All cross sections per nucleon. Results for ^{4}He target absolutely normalized, for other targets with scaling factors to facilitate comparison of shapes. Factors 1.5 account for proton/neutron ratio measured with deuteron target, other factors phenomenological correction of differences in FSI.

The other complication is due to final-state interactions which modify the measured cross sections with respect to their free counter parts. Experimental results from the comparison of free and quasi-free proton data seem to indicate that these effects are much reaction dependent and also differ significantly for different observables. Some model results, in particular for single π^0 production are available [14, 15], but here, certainly further efforts are very desirable. An experimental observation is that for all reactions studied so far, FSI effects are much reduced for polarization observables in comparison to absolute cross sections. This could be some indication that, in general, FSI does not depend strongly on different polarization states so it often cancels in asymmetries. In practice, for most reactions investigated at ELSA and MAMI, FSI was corrected under the assumption that it is similar enough for quasi-free protons and neutrons so that the measured effects for the proton can be used to correct the neutron data. This is somewhat supported by the model calculations from [14]. In that case, significant differences between the proton and neutron case were only observed at extreme pion forward angles (where anyway no data is available).

3. Experimental setups

All experiments discussed in this paper were done at the ELSA facility in Bonn using the Crystal Barrel/TAPS detector or at the MAMI facility in Mainz using the Crystal Ball/TAPS detector. Both detector systems use large angle electromagnetic calorimeters with additional detectors for charged particle identification. The Crystal Barrel is composed of CsI crystals and the Crystal Ball of NaI(Tl) crystals. The TAPS component at both experiments uses identical hexagonally shaped BaF_2 crystals. Both facilities are equipped with magnetic spectrometers for the momentum analysis of the scattered electrons which have produced the bremsstrahlung photons in order to tag the photon energies. Both facilities have run with circularly (longitudinally polarized electrons) and linearly (coherent bremsstrahlung from diamond radiator) polarized photons and with longitudinally and transverse polarized solid butanol targets. More detailed descriptions can be found, *e.g.* in Ref. [16] (ELSA) and in [7, 11] (MAMI).

4. Results

In this chapter, only a short overview is given over the large body of material on this topic which became available during the last few years. We just summarize the experimental status for the main reactions and give the most relevant references.

4.1. Single π^0 photoproduction

Photoproduction of π^0 mesons is certainly one of the best studied meson production reactions for the proton target. However, as shown in Fig. 1, it was not at all understood for neutron targets. Already the measurement of absolute cross sections for the $\gamma n \to n\pi^0$ reaction has significantly altered the coupled channel model fits to this reaction [7, 17]. More detailed information came with the measurement of the helicity decomposition of the cross section, *i.e.* the split into the contributions from reactions with photon and nucleon spin parallel or antiparallel (double polarization observable E). Experimental results [18] and model predictions for recoil protons and recoil neutrons from a deuterated butanol target are compared in Fig. 3. In this case, FSI was substantial for absolute cross sections [7] (effects up to the 30% level measured for recoil protons) but negligible for the double polarization observable E [18].

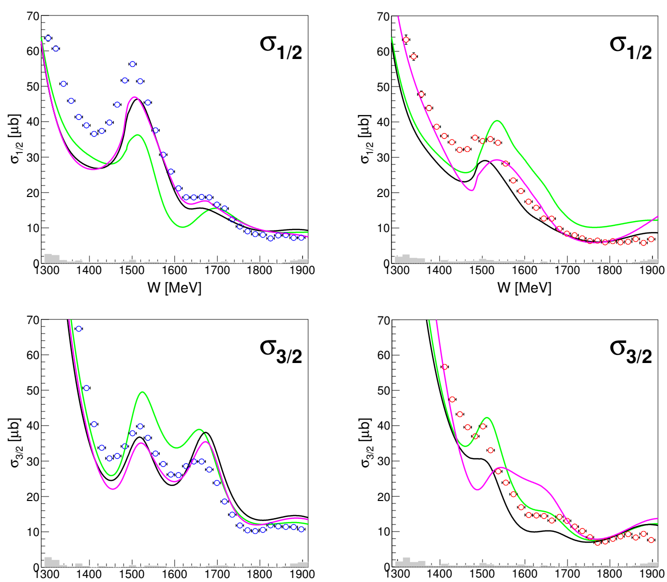

Fig. 3. (Color online) Total helicity-dependent cross sections for $\gamma N \to N\pi^0$. Symbols: experimental results [18], light gray/green curves: MAID [4], black SAID [5], gray/magenta BnGa [6]. From left to right: $\gamma p \to p\pi^0$ $\sigma_{1/2}$, $\gamma n \to n\pi^0$ $\sigma_{1/2}$, $\gamma p \to p\pi^0$ $\sigma_{3/2}$, $\gamma n \to n\pi^0$ $\sigma_{3/2}$.

4.2. Photoproduction of η and η' mesons

Photoproduction of η mesons at low incident photon energies is completely dominated by the $S_{11}(1535)$ resonance [19, 20]. Early experiments with deuteron targets revealed the absolute value and the relative sign of the isoscalar and isovector electromagnetic couplings of this state [21–23]. At higher incident photon energies (around ≈ 1 GeV) an unexpected narrow structure has been observed in the excitation function of the $\gamma n \rightarrow n\eta$ reaction (see Fig. 2) [10–12, 24–27]. The nature of this structure is still not finally understood. First measurements of the helicity dependence of the cross section [16, 28] with circularly polarized beam and longitudinally polarized target have shown that this structure appears only in the $\sigma_{1/2}$ part of the cross section. Consequently, if it is due to nucleon resonance excitations, S_{11} and/or P_{11} resonances must be involved. FSI effects are much less pronounced than for π^0 production. This is plausible for the dominant S_{11} excitation because it involves a nucleon spin-flip. The spin configuration of the nucleon final state is different from the deuteron which reduces nucleon–nucleon FSI.

Only absolute cross sections have been measured so far for the photoproduction of η' mesons off quasi-free nucleons from a deuterium target [29]. The cross section is largely reduced with respect to the proton case. FSI effects are found to be small as in the η case. Photoproduction off heavier nuclei has been used to extract parameters of the η' nucleus potential. An overview over photoproduction of η and η' mesons off the free nucleon and light and heavy nuclei is given in [3].

4.3. Photoproduction of pion pairs

Photoproduction of pion pairs has been intensively studied during the last decade, in particular for $\pi^0\pi^0$ pairs off free protons (see [30–36] and references therein). The isospin dependence of this reaction was investigated with the measurement of absolute cross sections [37] and also with polarization observables [38, 39]. In Ref. [39], the polarization observable $I^{\odot}$ is explored which contributes only to reactions with at least two mesons in the final states. This asymmetry is measured with a circularly polarized beam and an unpolarized target as a function of the azimuthal angle between the reaction plane (spanned by photon and recoil nucleon) and the production plane (spanned by the mesons). It was found that after a complete kinematical reconstruction of the final state, FSI effects for protons are negligible, in contrast to absolute cross section which showed effects on the 20% level. In contrast to model predictions, the observed asymmetries are very similar for recoil protons and neutrons. The helicity dependence of the cross section was also measured. Preliminary results for $\sigma_{1/2}$ and $\sigma_{3/2}$ are shown in Fig. 4. The advantage of $2\pi^0$ production is that non-resonant terms are much suppressed. However, the production of mixed charged pion pairs is also very interesting because in this channel, the ρ meson can contribute. Results for the polarization observable $I^{\odot}$ have been published in [40]. Again, FSI effects seem to be negligible. The results are similar for recoil protons and neutrons in the second resonance region but differ a lot at higher incident photon energies. Measurements at MAMI of absolute cross sections for free proton targets and quasi-free nucleons from deuterium and ^{4}He targets as well as the helicity decomposition for reactions on quasi-free nucleons bound in deuterium are under analysis.

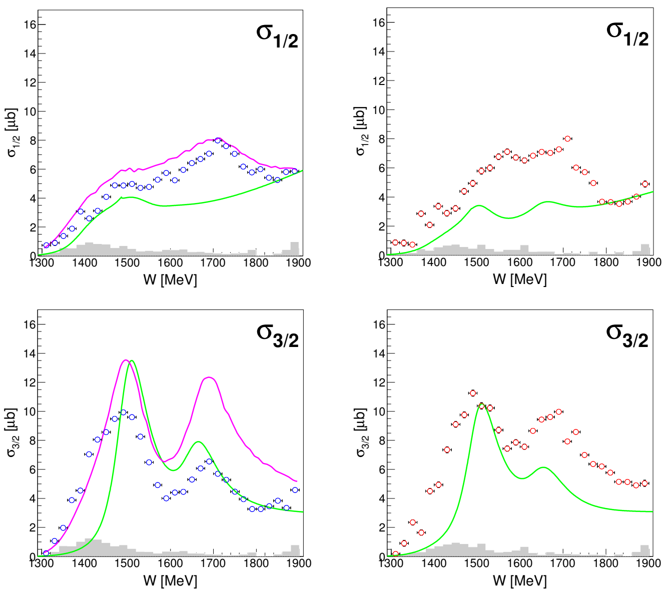

Fig. 4. (Color online) Preliminary results for $\sigma_{1/2}$, $\sigma_{3/2}$ for $\gamma N \rightarrow N\pi^0\pi^0$ [38]. Notation as in Fig. 3.

4.4. Photoproduction of $\pi\eta$ pairs

Photoproduction of $\eta\pi$ pairs is experimentally more involved than pion pairs, but surprisingly this reaction is already much better understood by reaction models than the production of pion pairs. This is mainly due to the dominance of just a few Δ resonances, in particular the $D_{33}(1700)$, as initial states. They decay by η emission to the $\Delta(1232)$ with subsequent decay to $N\pi$. Other decay channels have also been identified but are much less important. Results for the $\gamma p \rightarrow p\pi^0\eta$ are given in [41–49]. The isospin decomposition of this reaction was studied with measurements of the unpolarized cross sections off nucleons bound in deuterium for the $\pi^0\eta$ and $\pi^\pm\eta$ final states [50, 51]. The cross-section ratios for the different recoil nucleons and also for the different meson final states were found in perfect agreement with the assumption of a $\gamma N \rightarrow \Delta \rightarrow \Delta(1232)\eta \rightarrow N\pi\eta$ reaction chain. Also the double polarization observable E and the helicity-dependent cross sections $\sigma_{1/2}$, $\sigma_{3/2}$ have been measured for all isospin combinations [52]. The two helicity components contribute equally which is also in agreement with the dominant excitations of the $D_{33}(1700)$ and the $D_{33}(1940)$ which have both equal electromagnetic excitation amplitudes $A_{1/2}$ and $A_{3/2}$ [53].

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