Meson Photoproduction off the Deuteron and off ^{3}He

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Abstract. Photoproduction of mesons off the deuteron and ^{3}He nuclei has been studied at the tagged photon facilities of the Bonn ELSA accelerator and the Mainz MAMI accelerator with the Crystal Barrel/TAPS setup (Bonn) and the Crystal Ball/TAPS setup (Mainz). Meson photoproduction off the neutron has been investigated for different final states (π^o, $\pi^o\pi^o$, $\pi^o\pi^-$, η, η', $\eta\pi^o$). A surprising finding was a narrow structure in the $\gamma n \rightarrow n\eta$ excitation function, which is not seen in the proton case. Photoproduction off ^{3}He has provided further evidence for the formation of an η-mesic state.

Keywords: Photoproduction of Mesons, Nucleon Resonances, Photoproduction off Neutrons, η-mesic Nuclei
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INTRODUCTION

Photoproduction of mesons off light nuclei is motivated by two different subjects. It is the only way to learn about the isospin degree of freedom of the electromagnetic excitation of nucleon resonances. In particular, the deuteron is the most suited target to study photoproduction reactions off the neutron. The second topic is meson - nucleon interaction for short lived-mesons, which cannot be prepared as beams. A very interesting aspect in this field is the search for η-mesic nuclei: (quasi-)bound states formed of a light nucleus and an η-meson.

Photoproduction of mesons has become a prime tool for the investigation of the excitation spectrum of the nucleon [1, 2]), which is closely related to the properties of the strong interaction in the non-perturbative regime. The combination of modern electron accelerators in particular at Jlab, ELSA in Bonn, and MAMI in Mainz with up-to-date detector systems covering the full solid angle has driven this field over the last few years. Currently, worldwide it enters a new phase, where highly efficient polarized targets combined with linearly and circularly polarized photon beams allow the measurement of single and double polarization observables. This brings within reach the possibility of ‘complete’ experiments, allowing an (almost) model independent extraction of the partial wave amplitudes and a much more solid investigation of the excited nucleon states.

Thus we can expect progress for the most disputed questions in hadron physics like the ‘missing resonance’ problem, meaning that basically all models of the nucleon predict much more states than have been experimentally observed (see e.g. [3, 4]). At the same time, due to the progress in lattice gauge theory, recently the first ab initio calculations of the masses of the SU(3) ground state multiplets [5] became available, making a much closer connection between Quantum Chromo dynamics and the hadron spectrum, although calculations for the complex excitation scheme of the nucleon are still out of reach.

The real photon programs at the Bonn ELSA [6, 7] and Mainz MAMI [8] facilities cover a further aspect of nucleon structure, namely the iso-spin degree of freedom of the electromagnetic excitation of nucleon resonances. It is well-known already from total photoabsorption reactions [9] that the relative contributions of states to the photoexcitation of the proton and the neutron are quite different. Meson photoproduction off the neutron therefore may allow to study states that are only weakly excited on the proton. Furthermore quasi-free photoproduction off the neutron and coherent photoproduction off light nuclei are the only possibility to study the iso-spin composition of the electromagnetic excitations. This experimental program involves of course all the complications related to nuclear targets like the deuteron: the necessity of coincident detection of recoil nucleons, broadening of the excitation structures by nuclear Fermi motion, and final state interaction (FSI) effects. However, the detector facilities at ELSA and MAMI are very well suited to overcome the technical difficulties of such experiments. In particular, due to their photon and neutron detection capabilites, they allow the study of completely neutral final states like for example $\pi^o n$, ηn, $\eta' n$, $\pi^o\pi^o n$, $\pi^o\eta n$,... which are not accessible elsewhere.

Possible nuclear effects on the measured cross sections can be studied via a comparison of the respective reactions in coincidence with recoil protons to the free proton results [10, 11]. However, nuclear FSI-effects should not only be

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viewed as a complication. They allow detailed investigations of the meson - nucleon interaction. Such interactions have also largely contributed to our understanding of the strong force. In the case of long-lived mesons like charged pions or kaons, secondary beams can be prepared. However, the interaction of short-lived mesons with nuclei is only accessible in this indirect way. Of particular interest is the η-meson. The η-N interaction at small momenta is strong since it is dominated by the s-wave nucleon resonance $S_{11}(1535)$, which has a large coupling to the Nη-channel [12]. Therefore it has been intensively and controversially discussed in the literature whether in contrast to pions η-mesons might form (quasi-)bound states with atomic nuclei. The first suggestion for $A > 10$ nuclei goes back to Liu and Haider [13]. Even lighter quasi-bound η-nucleus systems have been sought in experiments investigating the threshold behavior of hadron induced η-production reactions. The idea is, that quasi-bound states in the vicinity of the production threshold will give rise to an enhancement of the cross section relative to phase space behavior. Results were reported for $pp \rightarrow pp\eta$ [14, 15, 16], $np \rightarrow d\eta$ [17, 18], $pd \rightarrow \eta^3$He [19], $dp \rightarrow \eta^3$He [20, 21], $\vec{d}d \rightarrow \eta^4$He [22], and $pd \rightarrow pd\eta$ [23]. More or less pronounced effects have been found in most reactions, in particular the measurement of $dp \rightarrow \eta^3$He by Mersmann et al. [21] shows an extremely sharp rise of the production cross section at threshold. If these effects are related to (quasi-)bound states, they should show up independently of the initial state of the reaction. Threshold photoproduction of η-mesons from light nuclei (deuteron, helium isotopes) was also investigated [24, 25] and again threshold enhancements were observed. The most promising signal so far was found in the $^3He(\gamma,\eta)^3He$ reaction [25], although the statistical significance was weak. Here, we report preliminary results from a follow-up experiment with much better statistical quality.

EXPERIMENTS

The experiments were done at the Bonn ELSA and Mainz MAMI facilities. At both electron accelerators tagged photon beams are produced by the bremsstrahlung method. Maximum beam energies are 3.2 GeV at ELSA and 1.5 GeV at MAMI. Circularly polarized photon beams have been prepared via the use of longitudinally polarized electron beams, while linearly polarized photon beams were obtained with coherent bremsstrahlung from diamond radiators. The liquid deuterium and Helium targets (typically 5 - 10 cm long) were unpolarized.

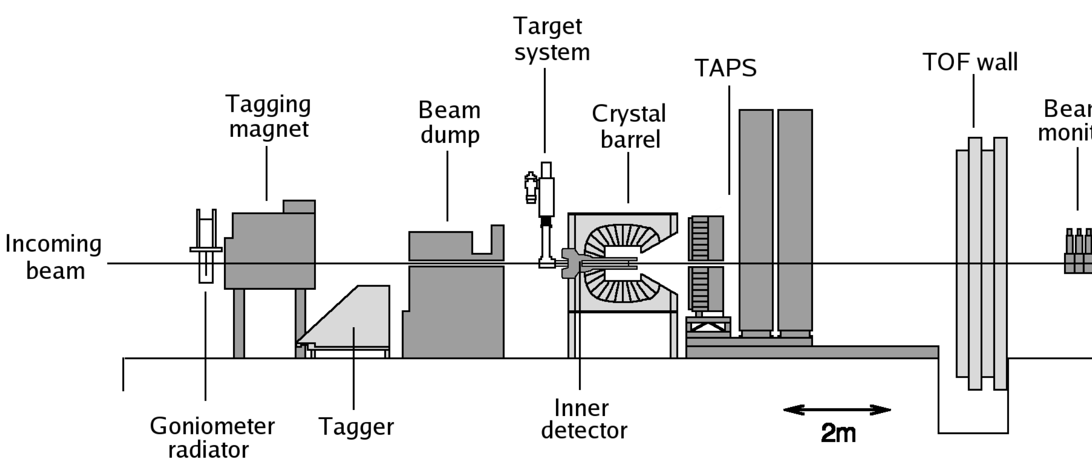

FIGURE 1. Overview of the experimental setup at the Bonn ELSA-accelerator.

The setup at ELSA combined the Crystal Barrel detector [26] (1290 CsI crystals covering the full azimuthal angle for polar angles between 30° and 168°) with the TAPS detector [27, 28] (528 BaF_2 crystals mounted as hexagonal forward wall covering polar angles down to 4.5°). Both detectors are equipped with additional scintillators for charged particle identification, TAPS with plastic detectors in front of each module, the Barrel with a scintillating fiber detector [29] around the target. A schematic view of the arrangement is shown in Fig. (1), more details can be found in [30].

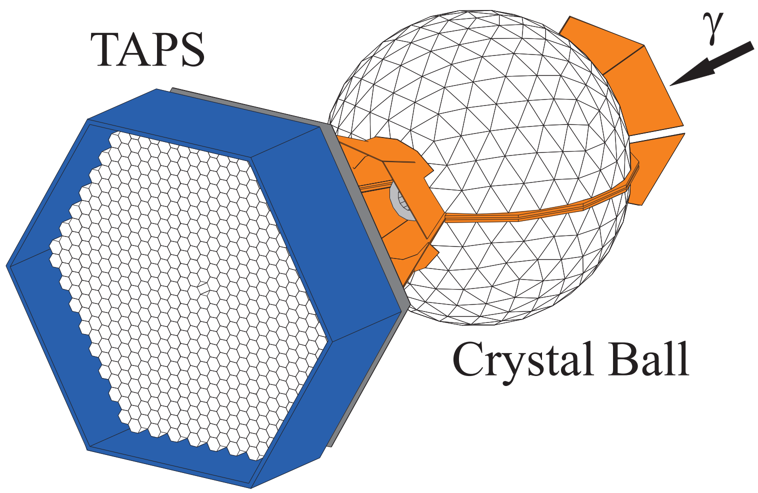

FIGURE 2. Combined Crystal Ball and TAPS detector at MAMI.

At the tagged photon beam [31] of MAMI the Crystal Ball detector [32] was operated together with TAPS. TAPS was again configured as a forward wall, covering polar angles below 20^o. The Crystal Ball, consisting of 672 NaI crystals, covered polar angles between 20^o - 160^o. A detector for charged particle identification was placed in the ball around the target. A schematic view of the setup is shown in Fig. (2). Both setups allow the detection of photons as well as recoil nucleons and deuterons. For the identification of the different particles, information from the charged particle detectors, time-of-flight-versus-energy measurements, as well as a pulse-shape analysis for the BaF_2 crystals were combined. Standard invariant mass (decay photons from neutral mesons), missing mass, and missing energy techniques were used for the identification of the different reaction channels.

RESULTS

Quasi-free photoproduction of mesons off bound nucleons

Quasi-free photoproduction off the bound neutron has been investigated for many different reaction channels. Here, we will give only a few examples of recent results for the η, η', $\pi^o\pi^o$, and $\pi^o\pi^-$ channel.

In all cases we have also studied the respective reactions off the quasi-free proton bound in the same nucleus for control of the nuclear effects. Furthermore, for all channels discussed here, contributions from coherent reaction mechanisms have been found to be very small, negligible compared to their quasi-free counterparts. This means, that it is possible to control systematic uncertainties related to the detection of the recoil nucleons (the neutron is of course the most critical case) in a simple way. Always three different sets of cross sections have been obtained. For the inclusive cross section σ_{inc} all events where the meson(s) of the respective channel were identified (and production of additional mesons was excluded e.g. via missing mass analysis) were included. For the other two sets coincident detection of a recoil proton σ_p or a recoil neutron σ_n was required. These cross sections must then be related in the deuteron case via:

$$\sigma_{inc} = \sigma_p + \sigma_n + \sigma_d \qquad (1)$$

where the coherent cross section σ_d is negligible. Thus we can measure σ_n directly via detection of recoil neutrons or indirectly as difference $\sigma_{inc} - \sigma_p$. The first involves the neutron detection efficiency, the second the completely different proton detection efficiency. In all cases good agreement was found.

Very interesting results have been obtained for the η-channel. Photoproduction of η-mesons off the free proton has been studied in detail [33]-[46] from the production threshold at ≈707 MeV up to incident photon energies of 2.8 GeV. Since in the threshold region this reaction is completely dominated by the $S_{11}(1535)$ excitation [12] it plays a similar role for this this resonance as pion production for the $\Delta(1232)$: it allows an almost background free study of this state. Detailed analyses of angular distributions and polarization observables at higher incident photon energies have revealed weak contributions from higher lying resonances (see e.g. [47]). The isospin degree of freedom was also studied in this energy range via quasi-free and coherent η-photoproduction off the deuteron [48]-[51] and He-isotopes [52, 25]. In summary, the neutron/proton cross section ratio for the $S_{11}(1535)$ is close to 2/3, and the electromagnetic excitation of this resonance is dominantly of iso-vector nature [1].

The neutron/proton cross section ratio at higher incident photon energies (above E_γ= 900 MeV) is interesting since models (for different reasons) predicted a significant rise. The Eta-MAID analysis [47] of the proton data found a large $N\eta$-branching ratio of the $D_{15}(1675)$, which, since its electromagnetic excitation on the proton is suppressed, would result in a much larger contribution for the neutron. Kaiser and collaborators [53, 54], treating the $S_{11}(1535)$ as a dynamically generated $K\Sigma$ quasi-bound state, predicted a strong rise of the cross section ratio with increasing energy. Finally, in the framework of the chiral soliton model [55] a state with the same properties is predicted, which would be the P_{11}-state of the anti-decuplet of pentaquarks. The measurement of quasi-free η-photoproduction off the deuteron at ELSA [11] indeed found a strong energy dependence of the neutron/proton cross section ratio with a narrow structure around incident photon energies of 1 GeV. This structure has also been seen in the GRAAL experiment [56] and at Tohoku-LNS [57], however, its nature is still unknown and very different suggestions are discussed in the literature [58, 59].

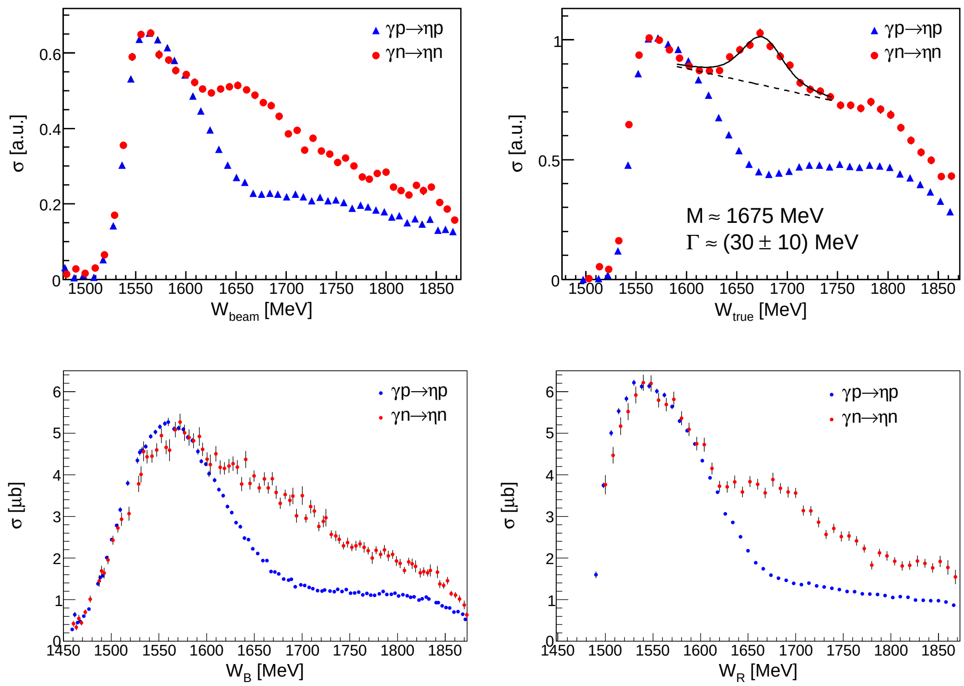

FIGURE 3. Very preliminary results for quasi-free excitation functions measured at MAMI. Not finally corrected for analysis cuts and detection efficiency. Upper row: deuterium target, bottom part: ^{3}He target. Left hand side: W calculated from beam energy, Right hand side: W from final state invariant mass.

We have recently re-measured this reaction with much better statistical quality at the MAMI accelerator with a deuteron target and also with a ^{3}He target (the latter experiment was motivated by the search for η-mesic nuclei, see below). Very preliminary results are shown in Fig. (3). The excitation functions have been constructed in two different ways: at the left hand side of the picture the total cm energy W is calculated from the incident photon energy, at the right hand side as invariant mass of the η-neutron final state system. The letter removes the broadening of the structure due to Fermi motion, but is limited by the experimental resolution for the neutron four-vector. The significance of the structure is beyond any doubts for both targets and a fit of a Breit-Wigner (BW) resonance curve folded with the simulated experimental resolution to the deuteron data yields a width of the unfolded BW of 30$\pm$10 MeV, in agreement with the GRAAL and Tohoku results.

As a further example we show preliminary results for quasi-free η' production off the neutron in Fig. 4. Also for this reaction we find excellent agreement between the quasi-free proton cross section as compared to free proton data. The neutron data, extracted either from the detection of recoil neutrons or as difference of inclusive and proton data, are consistent with each other and there is a clear difference between proton and neutron excitation functions, indicating different resonance contributions.

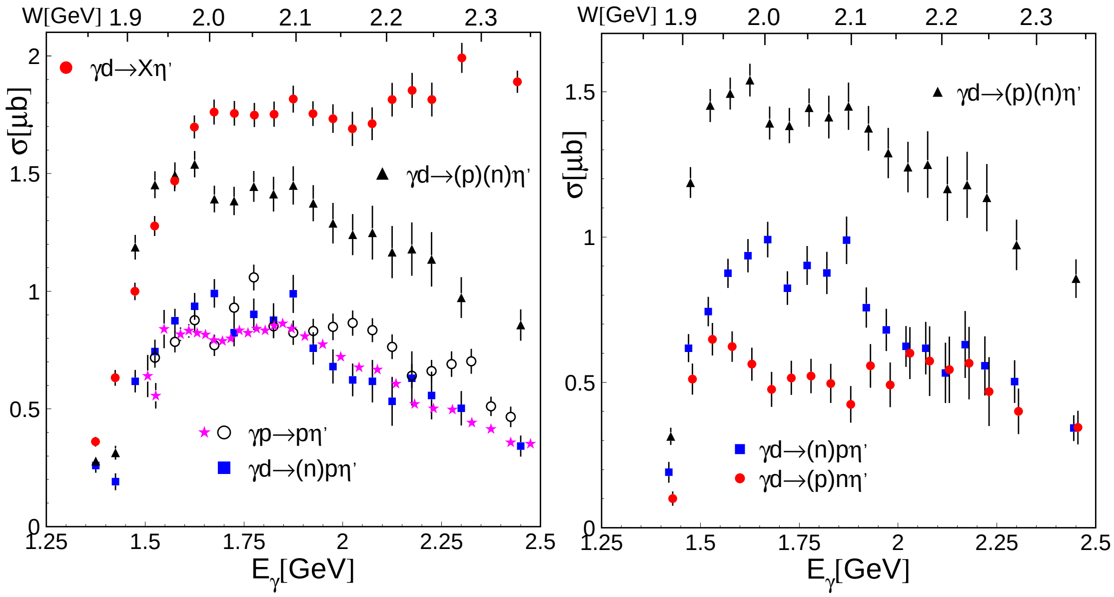

FIGURE 4. Preliminary results for quasi-free photoproduction of η'-mesons off the deuteron. Left hand side: Total inclusive cross section (including e.g. $\eta'\pi$ final states), inclusive single η', and quasi-free proton compared to free proton (circles: [46], stars: [45]). Right hand side: quasi-free proton compared to quasi-free neutron.

Finally, we will discuss one example involving polarization observables for the neutron target. Double pion is an important tool to search for and study resonances that do not decay directly to the nucleon ground state but to higher lying excited states. Total cross sections, invariant mass distributions, and some polarization observables have been measured at MAMI in Mainz [60]-[71], at GRAAL in Grenoble [72, 73], at JLab [74, 75], and at ELSA in Bonn [76, 77].

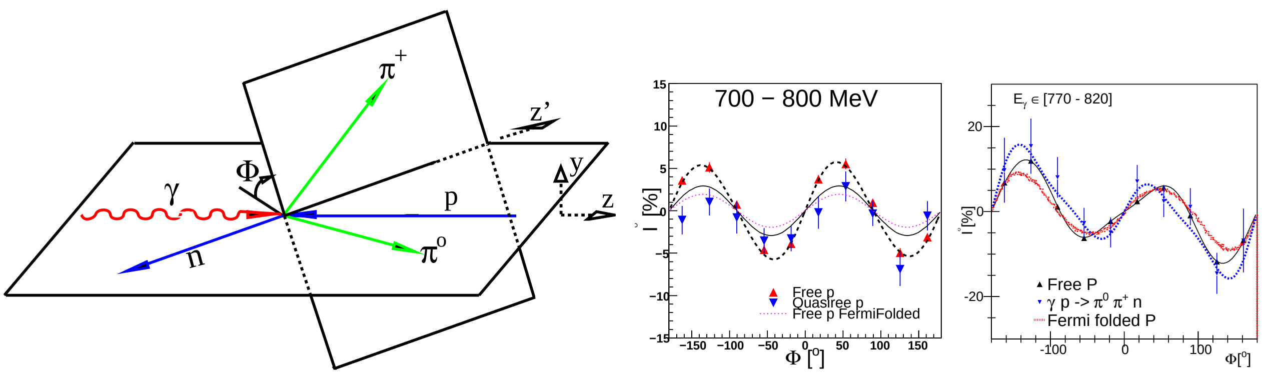

FIGURE 5. Left hand side: definition of the angle Φ, center: comparison of asymmetries for free and quasi-free production of $\pi^o\pi^o$-pairs off the proton, right hand side: same for $\pi^o\pi^+$.

An observable which has recently moved into the focus is the beam-helicity asymmetry, which is measured in photoproduction of meson pairs with circularly polarized photons alone (no target, no recoil polarization). Due to parity conservation, this asymmetry does not exist for the two-body final states of single meson production, but appears for three-body final states, depending on the angle Φ between reaction and production planes (see Fig. 5). Models predict a large sensitivity of this observable to the details of the reactions [78]-[81]. However, it came as a surprise, that its first measurements [75, 71] for double pion production contradicts almost all available model predictions. At Mainz we have started to investigate this observable also for reactions on the neutron. Preliminary results are promising in so far, as the results obtained for quasi-free production off the bound proton are in quite good agreement with the free proton results (see Fig.5). Very preliminary results for the quasi-free neutron (not shown) indicate similar asymmetries for proton/neutron targets for the $\pi^o\pi^o$ channel but significantly different behavior for the mixed charge channel.

Coherent photoproduction of η-mesons off ^{3}He - search for η-mesic nuclei

Due to their quantum numbers (spin J=1/2, isospin I=1/2) ^{3}He and ^{3}H are the only light nuclei where the iso-vector part of the E_{0+} spin-flip amplitude, which dominates threshold η-photoproduction via the $S_{11}(1535)$ excitation, contributes significantly to the coherent reaction. Therefore, the cross section of the coherent reaction, used as entrance channel for the formation of (quasi-)bound η-states, is much larger than for example for the deuteron or ^{4}He. Due to the technical and safety problems related to the use of radioactive tritium targets, so far only the ^{3}He system was investigated. The first experiment with the TAPS detector at MAMI [25] found indeed some indication for the existence of an η-mesic state. The cross section of coherent η-production showed a strong threshold enhancement. The excitation function of $p\pi^o$ back-to-back pairs in the photon-helium cm-system, which may arise from the $S_{11} \rightarrow N\pi$ decay after re-capture of the quasi-bound η by a proton, showed a peak around the η-production threshold. However, both effects suffered from poor statistical quality of the data. The experiment has now been repeated with the much larger acceptance of the new 4π detector setup. First, preliminary results confirm the earlier findings. As an example the excitation function for coherent η-production is shown in Fig. (6). Events from the coherent reaction have been selected via a missing energy analysis using the constraints from the two-body kinematics of the final state. Very similar to the results from the hadron induced reaction [21], the cross section rises abruptly at the coherent production threshold. Within the first 4 MeV above threshold it reaches roughly 50 % of its maximum value, which is strong evidence for a resonance-like threshold enhancement. The peak-like structure in the excitation function of $p\pi^o$-pairs (not shown here) has also been confirmed with much better statistical significance.

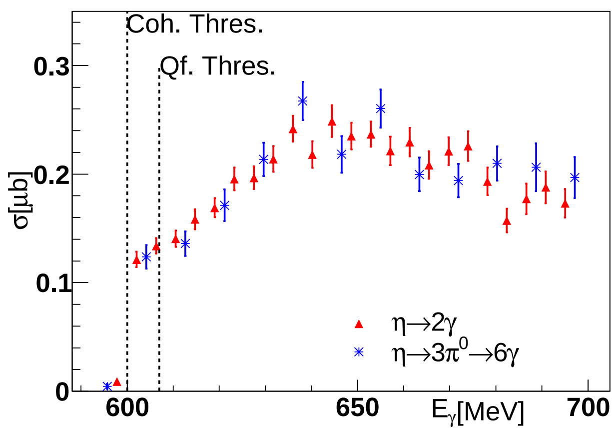

FIGURE 6. Very preliminary excitation functions for the reaction γ^3He$\rightarrow^3$Heη for the $\eta \rightarrow 2\gamma$ and $\eta \rightarrow 3\pi^o$ decays.

Coherent photoproduction of meson pairs

As discussed above, coherent η-photoproduction off spin/iso-spin zero nuclei like ^{4}He is negligible (so far only upper limits have been derived [52]). However, the situation can be much favorable when production of the η is accompanied by a π^o-meson. Recent measurements of photoproduction of $\pi^o\eta$ off the proton have indicated for the threshold region a dominant contribution from the decay chain $D_{33}(1700) \rightarrow \eta P_{33}(1232) \rightarrow N\pi\eta$ [41],[82]-[86]. Since this reaction chain starts with an isospin I=3/2 Δ-resonance, the electromagnetic coupling is identical for protons and neutrons, thus there can be no cancellation between proton and neutron amplitudes. Furthermore, when the resonance is excited by an electromagnetic dipole photon ($E1$), the spin of the nucleon needs not to be flipped (the η-meson is emitted in s-wave, while the $l = 1$ pion from the $\Delta(1232)$-decay carries away the photon spin). Therefore, coherent photoproduction of $\pi^o\eta$-pairs is by far not so strongly suppressed for most light nuclei as single η-photoproduction.

Very recently, we have for the first time identified this reaction for the deuteron (ELSA) and also for ^{3}He (MAMI). Identification is much easier for the deuteron, since recoil deuterons can be identified in TAPS via time-of-flight-versus-energy spectra (helium isotopes are stopped before they reach the detector). The analysis for He was based on the reaction kinematics (missing mass spectra). First, very preliminary results for the deuteron case are shown in Fig. 7.

The observed total cross section is comparably large, on the order of 100 nb, i.e. more than on order of magnitude larger than for coherent single η-photoproduction off the deuteron (although for the latter the elementary cross section off the free nucleon is larger by a factor of $\approx$4 and the suppression due to the deuteron from factor is smaller). The coherent cross section reaches a comparable level as single η-production off ^{3}He (cf. Fig. 6) and is predicted to be even larger for ^{4}He. Study of coherent production of light nuclei can be used as a spin/iso-spin filter for the production amplitude and thus allows an even more detailed investigation of the different resonance contributions. Furthermore, it might provide a new tool for the study of η-mesic nuclei in particular for the ^{4}He case. Kinematic energy distributions of the η and π^o mesons off deuterium are summarized in Fig.7. Close to threshold the η-mesons have small kinetic energies, which are needed for the formation of bound states (the π^o kinetic energies mostly correspond to the decay of the Δ(1232), so they do not change much with incident photon energy).

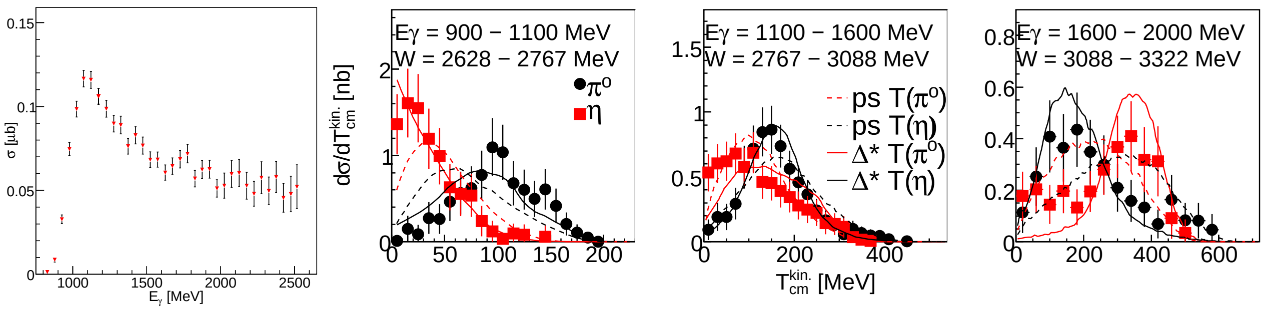

FIGURE 7. Left hand side: total cross section for $\gamma d \rightarrow \pi^o \eta d$. Other plots: kinetic energy distributions of the π^o and η mesons for different bins of incident photon energies. Dashed curves: phase space simulations, solid curves: simulations of the $\gamma d \rightarrow d^\star(\Delta^\star) \rightarrow d^\star(\Delta(1232))\eta \rightarrow d\pi^o\eta$ reaction chain (very preliminary results).

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