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A narrow structure in the excitation function of η -photoproduction off the neutron

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The photoproduction of η -mesons off nucleons bound in ^2H and ^3He has been measured in coincidence with recoil protons and recoil neutrons for incident photon energies from threshold up to 1.4 GeV. The experiments were performed at the Mainz MAMI accelerator, using the Glasgow tagged photon facility. Decay photons from the $\eta \rightarrow 2\gamma$ and $\eta \rightarrow 3\pi^0$ decays and the recoil nucleons were detected with an almost 4π electromagnetic calorimeter combining the Crystal Ball and TAPS detectors. The data from both targets are of excellent statistical quality and show a narrow structure in the excitation function of $\gamma n \rightarrow n\eta$. The results from the two measurements are consistent taking into account the expected effects from nuclear Fermi motion. The best estimates for position and intrinsic width of the structure are $W = (1670 \pm 5)$ MeV and $\Gamma = (30 \pm 15)$ MeV. For the first time precise results for the angular dependence of this structure have been extracted.

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Photo- and electroproduction of mesons has become a primary tool for the investigation of the excitation spectrum of the nucleon [1–4]. So far, most efforts have been devoted to the excitation spectrum of the proton, simply because free neutron targets are not available. However, since the electromagnetic excitations are isospin dependent, such measurements are indispensable. Experiments therefore have to make use of quasi-free neutrons bound in light nuclei, in particular in the deuteron. The specific problems of using quasi-free neutron targets have been studied in detail during the last few years [5–8].

An exciting result was a narrow structure in the excitation function of η -photoproduction off the neutron, which

was first reported from the GRAAL experiment in Grenoble [9] and subsequently seen in measurements at ELSA in Bonn [5, 6], and at LNS in Sendai [10]. The study of η -photoproduction off the neutron was motivated by several unresolved issues. Prior to the above mentioned experiments, η -photoproduction off the deuteron (or other light nuclear targets) had been studied with incident photon energies below 1 GeV [11–15]. There, it is dominated by the excitation of the $S_{11}(1535)$ resonance [16, 17] (see [1] for a summary). However, reaction models like the η -MAID model [18] predicted a rapid change of the neutron/proton cross section ratio at higher incident-photon energies. The electromagnetic excitation of the

$D_{15}(1675)$ state is Moorhouse suppressed [19] for the proton and expected to contribute much more strongly for the neutron. Related structures should correspond to typical parameters of nucleon resonances in the 1.5 GeV - 2 GeV mass range, i.e. to widths greater than 100 MeV. There were also predictions for a narrow structure related to the conjectured baryon anti-decuplet [20]. Taking together the results from [20,21,22] the non-strange P_{11} -like member of the anti-decuplet should be electromagnetically excited more strongly on the neutron, should have a large decay branching ratio to $N\eta$, an invariant mass around 1.7 GeV, and a width of a few tens of MeV. Surprisingly, all experiments which tried to identify a corresponding structure in the $\gamma n \rightarrow n\eta$ reaction reported a positive result [5, 6, 9, 10]. Recently, evidence for this structure was also claimed for the $\gamma n \rightarrow n\gamma'$ reaction [24]. The Review of Particle Physics [23] lists the results as tentative evidence for a one-star isospin $I = 1/2$ nucleon resonance close to 1.68 GeV with narrow width and otherwise unknown properties.

There are two issues that need urgent clarification: how robust is the experimental evidence for this narrow structure and, if it is confirmed, what is its nature? The present Letter reports results from high statistics measurements of quasi-free η -photoproduction off nucleons bound in the deuteron and in ^3He nuclei, which establish the structure beyond any doubt and reveal its angular distribution. The experiments were performed at the tagged photon beam [26] of the Mainz MAMI accelerator [25] with liquid deuterium and liquid ^3He targets. For the deuterium three different beam times with varying parameters for the target (length between 3.02 cm and 4.72 cm; surface densities 0.147 - 0.230 nuclei/barn) and different trigger conditions were analyzed. For the helium measurement the target length (surface density) was 5.08 cm (0.073 nuclei/barn). Electron beam energies were between 1508 MeV and 1557 MeV.

The decay photons from the η -mesons and the recoil nucleons from quasi-free production reactions were detected with an electromagnetic calorimeter, combining the Crystal Ball (CB) [27] and TAPS [28] detectors in a setup covering almost the full solid angle ($\approx 98\%$ of 4π). Charged-particle identification was provided by additional scintillation detectors around the target (PID) [29] and in front of the TAPS wall (CPV). More details are given in Ref. [30].

The separation of photons, protons, and neutrons in the TAPS detector used the signals from the plastic scintillators, a time-of-flight (ToF) versus energy analysis, and a pulse-shape analysis (PSA) for the BaF_2 modules. In the CB, the PID allowed photons and neutrons to be separated from charged particles and protons to be distinguished from charged pions using a $\Delta E - E$ analysis. More details are given in [31]. Photons and neutrons could not be distinguished in the CB. Neutral CB hits were taken as candidates for both. Events with η -mesons in coincidence with either recoil protons or recoil neutrons were analyzed. The reaction identification

used standard invariant and missing mass techniques and coplanarity between the η -meson and the recoil nucleon, as in [6]. For both nuclei η -mesons were identified from their $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ decays. For events with three ($\eta \rightarrow 2\gamma$ decay) or seven ($\eta \rightarrow 3\pi^0$ decay) neutral hits, a χ^2 test on the invariant mass of photon pairs, compared to the η -mass or to three π^0 invariant masses was used to identify the most probable assignment of the neutron candidate. For hits in TAPS those candidates had also to pass the PSA and ToF-versus-energy filters.

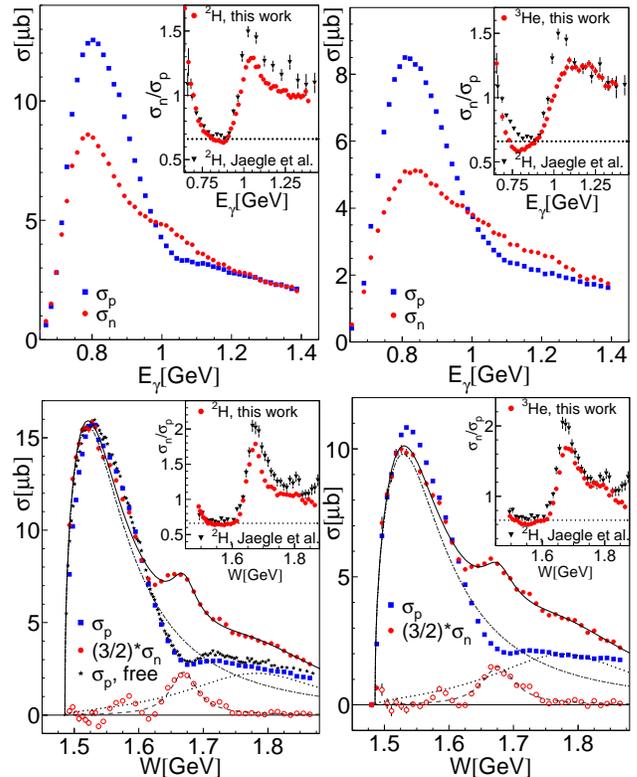


FIG. 1: Top: Total cross sections σ_p (coincident protons, blue squares) and σ_n (coincident neutrons, red circles) as function of incident photon energy E_γ . Left-hand side: deuterium target. Right-hand side: helium target. Bottom: same as function of reconstructed ηN invariant mass W . Black stars: results for free proton [32]. The open red circles are present data after subtraction of the fitted S_{11} and background components. Curves: fit results for S_{11} resonance (dash-dotted), background (dotted), narrow structure (dashed), and full fit (solid). Inserts for all figures: σ_n/σ_p ratio from present work (red circles) and from Ref. [6] (black triangles).

Total cross sections as function of incident photon energy are shown in Fig. 1, upper part. They have been averaged over the two η -decay modes. For both nuclei the σ_n/σ_p ratio shows a rapid rise around 1 GeV. As expected, the structure has a slow rise for the ^3He target due to the larger Fermi momenta.

The effects of Fermi motion can be removed when instead of the incident photon energy, the invariant mass W of the nucleon - meson pair in the final state is used. In case of the three-body $n\eta$ final state for the deuteron, W

can be reconstructed from the measured four-momentum of the η -meson, the energy of the incident photon, and the direction of the recoil nucleon [6]. For the reaction $\gamma^3\text{He} \rightarrow \eta X$, reconstruction is only possible under the assumption of vanishing relative momentum between the two spectator nucleons. This approximation may result in a poorer resolution for the reconstruction of W , however, the effect does not appear to be large. The results of this analysis are summarized in the bottom part of Fig. 1. The proton data measured with the deuterium target are compared to the cross section for the free $\gamma p \rightarrow p\eta$ reaction from Ref. [32]. The agreement is excellent, and demonstrates the validity of the reconstruction method.

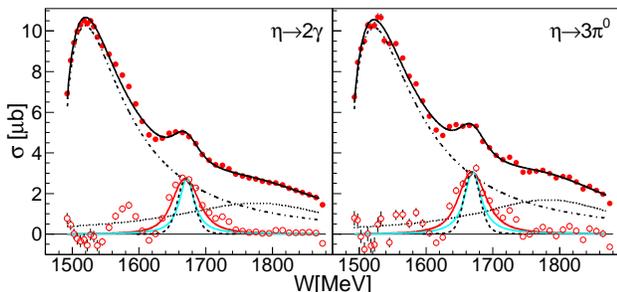


FIG. 2: Excitation functions for $\gamma n \rightarrow n\eta$ from the deuteron target. Left-hand side from $\eta \rightarrow 2\gamma$ decay, right-hand side from $\eta \rightarrow 6\gamma$ decay. Solid curve and dashed curves: fit components like in Fig. 1. Open symbols: data with background fit subtracted (scaled up by factor of 2). Curves at bottom: experimental resolution dashed (black), fitted signal (red), intrinsic signal shape (light blue) (see text).

The structure in the neutron excitation functions is much more pronounced than for the Fermi smeared results as function of E_γ shown in Fig. 1, top. The peak in the σ_n/σ_p ratio appears at the same position for the results from both nuclei and agrees also with the previous deuteron data [6]. The data have been fitted with the ansatz from Ref. [6], using a Breit-Wigner (BW) curve with energy dependent width for the $S_{11}(1535)$ state (dash-dotted curves in Fig. 1), and two further Breit-Wigner curves, one as a phenomenological parameterization of all background contributions (dotted curve) and one for the narrow structure (dashed curve). Note that the small structure below 1.6 GeV in the difference spectrum of data and background fit is an artifact because the simple ansatz for the fit curve does not exactly reproduce the lineshape in the high energy tail of the S_{11} resonance peak. The fitted BW parameters of the narrow structure from the present experiments and from Jaegle et al. [6] are compared in Table I. They are in good agreement but represent only upper limits for the width of the structure which includes the contribution from the experimental resolution for W .

The results from the deuterium target, which have smaller systematic uncertainties due to the simple three-body final state, were analyzed in more detail. Excitation functions for the $\eta \rightarrow 2\gamma$ and $\eta \rightarrow 6\gamma$ decays are

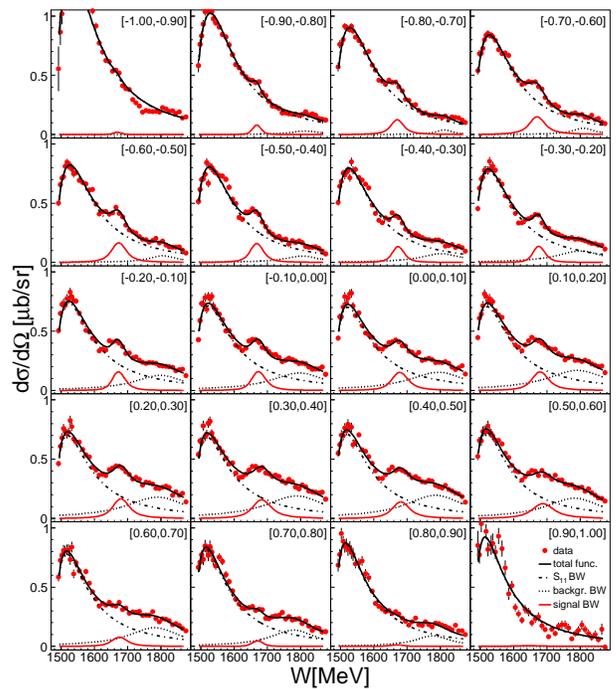


FIG. 3: Excitation functions for $\gamma n \rightarrow n\eta$ for different ranges of $\cos(\Theta_n^*)$ measured with the deuteron target. The fit curves are as in Fig. 1.

shown separately in Fig. 2. For these data the experimental resolution has been determined with a Monte Carlo simulation. The event generator produced the phase-space decay of a resonance at the position of the observed structure with zero intrinsic width (δ -function). The events were tracked through the detector system using the Geant4 [33] code and analyzed in the same way as the experimental data. The results are shown as black, dashed curves in Fig. 2, which have a width (FWHM) of ≈ 27 MeV, reflecting the experimental energy and angular resolution. Subsequently, the phenomenological fits described above were repeated but now the BW curve for the narrow structure was numerically folded with the experimental resolution. The result for the BW curve should then represent the intrinsic width of the structure (solid, light blue curves in Fig. 2). The results of this analysis are also shown in Table I. The position of the structure is not influenced by the resolution. Also the signal strength (which is proportional to the square root of the integral of the peak) is similar for the two analyses. But the widths are decreased to values around 30 MeV.

For the ^3He data the contribution of the experimental resolution to the effective width is not exactly known due to the approximations made in the kinematic reconstruction. In Table I we quote a value obtained under the assumption that the resolution would be the same as for deuterium, i.e. the relative momentum of the spectator nucleons is negligible (which results in an upper limit for the width).

Finally, for the deuteron results, the dependence on

TABLE I: Fitted BW parameters (see text for description of fit ansatz and Figs. 1 (bottom) and 2 for fit curves) of narrow structure. W_R and Γ : position and width. Electromagnetic coupling $A_{1/2}^n$ extracted under the assumption of an s-wave resonance. Values for width in brackets: fit with BW curve, without brackets: BW folded with experimental resolution. *) the intrinsic width for ${}^3\text{He}$ is calculated assuming the experimental resolution is the same as for the deuteron. For Ref. [6] (a) corresponds to the parameters given in the reference (analysis with cut on the spectator momentum) and (b) to an analysis without this cut.

	W_R [MeV]	Γ [MeV]	$\sqrt{b_\eta} A_{1/2}^n$ [$10^{-3}\text{GeV}^{-1/2}$]
${}^2\text{H}$, 2γ & 6γ	1670 ± 1	29 ± 3 (50 ± 2)	12.3 ± 0.8
${}^2\text{H}$, 2γ	1670 ± 1	27 ± 3 (50 ± 3)	12.1 ± 0.8
${}^2\text{H}$, 6γ	1669 ± 1	30 ± 5 (49 ± 4)	12.9 ± 0.8
${}^3\text{He}$ 2γ & 6γ	1675 ± 2	$46\pm 8^{*})$ (62 ± 8)	11.9 ± 1.2
best estimate	1670 ± 5	30 ± 15	12.3 ± 0.8
${}^2\text{H}$ [6] ^(a)	1663 ± 3	(25 ± 11)	12.2 ± 3
${}^2\text{H}$ [6] ^(b)	1673 ± 4	(54 ± 16)	16 ± 3

the η polar angle in the center-of-momentum frame was analyzed. The results are summarized in Fig. 3, where excitation functions are shown for narrow bins of $\cos(\Theta_\eta^*)$. The strength of the structure is similar for a large range of polar angles, but it disappears towards extreme forward and backward angles. The results for the ${}^3\text{He}$ measurement (not shown) behave similarly.

In conclusion, the present results demonstrate beyond

any doubt the existence of a narrow structure in the excitation function of $\gamma n \rightarrow n\eta$. We estimate a position of $W = (1670\pm 5)$ MeV and an intrinsic width of $\Gamma = (30\pm 15)$ MeV. These values are not statistically weighted averages of the entries from Table I but reflect the range of observed variations, taking into account that the ${}^3\text{He}$ results for the width are only upper limits. The central value reflects the deuteron results and the uncertainties have been enlarged so that also the ${}^3\text{He}$ results fall within the range. When treated like an s-wave resonance the corresponding coupling strength $\sqrt{b_\eta} A_{1/2}^n$ is approximately $(12.3\pm 0.8) 10^{-3} \text{GeV}^{-1/2}$. If the structure actually corresponds to a nucleon resonance, it would have very unusual properties, but also other suggestions like the strangeness threshold effects discussed in [34] or interference terms between different resonances [35–37] have been put forward. The precise results for the angular distribution of $\gamma n \rightarrow n\eta$ will allow stringent tests of models. Measurements of further observables, exploiting polarization degrees of freedom, are already under way.

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