PHOTOPRODUCTION OF MESONS OFF LIGHT NUCLEI — THE SEARCH FOR η-MESIC NUCLEI*

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Photoproduction of η mesons off light nuclei (d, ^{3}He, ^{7}Li) has been measured at the tagged photon beam of the Mainz MAMI accelerator with the combined Crystal Ball/TAPS detection system. Special attention was given to the threshold behavior of the reactions in view of possible indications for the formation of (quasi-) bound η-nucleus states, so-called η-mesic nuclei. A very strong threshold enhancement of coherent η photoproduction off ^{3}He was found and coherent η photoproduction off ^{7}Li was observed for the first time. Preliminary results will be discussed.

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1. Introduction

The interaction of mesons with nucleons and nuclei is a major source for our knowledge of the strong interaction. Elastic and inelastic reactions using secondary pion and kaon beams have revealed many details of the nucleon–meson potentials. However, secondary meson beams are only available for long-lived, preferentially charged mesons. Much less is known for short-lived mesons such as for example the η and η' mesons. Their interactions with nuclei can be studied only in indirect ways when the mesons are first produced in a nucleus from the interaction of some incident beam and then subsequently undergo final state interaction (FSI) in the same nucleus.

A very interesting question is, whether the properties of the strong interaction allow the formation of meson-nucleus bound states, which depend very sensitively on the strength of the interaction. Pionic atoms are well established and deeply bound pionic states have recently been studied by Geissel *et al.* [1, 2], yielding important results on the in-medium properties

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of the pion decay constant $f^{\star}_{\pi}$ [3], which are directly related to the predicted decrease of the chiral condensate in nuclear matter. In this case the superposition of the repulsive s-wave π^--nucleus interaction with the attractive Coulomb interaction gives rise to bound states. Neutral mesons, on the other hand, can form bound states only in the case of a sufficiently attractive strong meson–nucleus interaction. It is well known, that the pion–nucleus interaction for slow pions is weak and can certainly not produce bound states. The typical energy dependence can be extracted for example from the strength of the final state interaction. This is shown in Fig. 1 for the absorption properties of photon induced production of π^0 mesons. The production cross-sections as function of the atomic mass number A have been fitted with the simple Ansatz

$$\frac{d\sigma}{dT}(T) \propto A^{\alpha(T)}\,, \tag{1}$$

where α is the kinetic energy of the pions. A value of α close to unity corresponds to a cross-section scaling with the volume of the nucleus, *i.e.* with vanishing absorption (very weak FSI), while a value $\approx 2/3$ indicates surface proportionality corresponding to strong absorption. As expected, pions show strong FSI at kinetic energies large enough to excite the $\Delta(1232)$ nucleon resonance, but are almost undisturbed for energies below the Δ excitation threshold. The situation is completely different for η mesons, which show strong absorption for all kinetic energies measured so far. The reason is the overlap of the s-wave resonance $S_{11}(1535)$, which couples strongly to the $N\eta$-channel, with the production threshold. Eta-production in the threshold region is therefore completely dominated by this resonance [4].

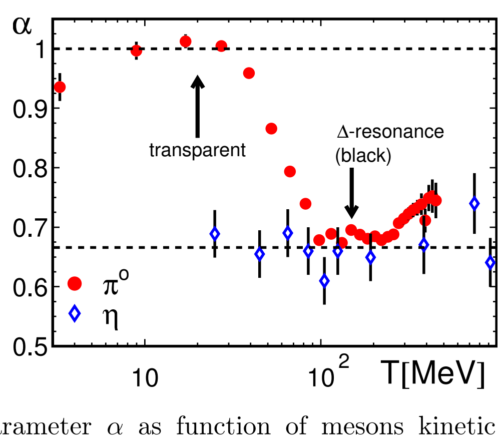

Fig. 1. Scaling parameter α as function of mesons kinetic energy for π^0 and η mesons.

Already in 1985 Bhalerao and Liu [5] performed coupled channel calculations for the $\pi N \to \pi N$, $\pi N \to \eta N$, and $\eta N \to \eta N$ reactions and found an attractive s-wave ηN interaction. Shortly later, Liu and Haider [6] pointed out, that for nuclei with $A > 10$ this interaction may lead to the formation of strongly bound η-nucleus systems which they termed η-mesic nuclei. Experimental evidence for 'heavy' η-mesic nuclei was *e.g.* searched for in $A(\pi^+,p)\eta(A-1)$ reactions [7], where it should manifest itself by a kinematic peak from the two-body $A(\pi^+,p)(A-1)_\eta$ process and in double pionic charge exchange reactions [8]. However, no conclusive evidence for the existence of η-mesic nuclei was reported from such experiments. Lebedev and Tryasuchev [9] have pointed out that photon induced reactions are advantageous for the search of η-mesic nuclei because they avoid initial state interaction effects. In contrast to hadronic induced reactions the photon can produce an η meson with *any* of the nucleons. Recently, Sokol *et al.* [10] claimed evidence for the formation of η-mesic nuclei with mass number $A = 11$ (carbon, beryllium) in the $\gamma+^{12}$C reaction via

$$\gamma + A \to N_1 + (A-1)_\eta \to N_1 + (N_2 + \pi) + (A-2)\,, \tag{2}$$

where the η meson is produced on the nucleon N_1, captured in the rest nucleus $(A-1)$, which subsequently decays by emission of a nucleon–pion pair.

During the last two decades the data basis for the ηN interaction was supplemented by new precise data in particular for η photoproduction from the proton [11–26], the deuteron [27–31], and He nuclei [32–34]. This has prompted several groups to carry out new analyses of the ηN interaction. Most of them find a real part of the ηN-scattering length a, which is considerably larger than the original value from the work of Bhalerao and Liu [5] ($a = 0.27 + i0.22$). The more recent results for the real part of the scattering length span the entire range from 0.2–1 and most cluster between 0.5–0.8 (see *e.g.* [35] and references therein). These larger values have prompted speculations about the existence of much lighter η-mesic nuclei than originally considered by Liu and Haider [6]. Light quasi-bound η-nucleus states 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 the expectation for phase space behavior. The threshold behavior of hadron induced η production reactions has been studied in detail, in particular, $pp \to pp\eta$ [36–38], $np \to d\eta$ [39, 40], $pd \to \eta^3$He [41], $dp \to \eta^3$He [42,43], $\vec{d}d \to \eta^4$He [44], and $pd \to pd\eta$ [45]. All reactions show more or less pronounced threshold enhancements.

If quasi-bound states do exist they should show up as threshold enhancements independently of the initial state of the reaction. Photoproduction of η mesons offers the advantage of a very well understood elementary reaction and rather clean experimental signals. In a previous experiment Pfeiffer *et al.* [34] searched for signatures of an η-mesic state for the ^{3}He system. Two different approaches were followed. Once a (quasi-) bound state has been formed it may decay above threshold via emission of the η meson, giving rise to the threshold enhancement of coherent η production. The η meson may also be re-captured by a nucleon, exciting it to the S_{11}-state which decays with a $\approx 50\%$ branching ratio to a nucleon–pion pair. This decay channel should result in a peak-like structure in the excitation function of nucleon–pion pairs, emitted back-to-back in the photon–^{3}He center-of-momentum (c.m.) system. Some indication for both effects has been reported by Pfeiffer *et al.* [34], however, at the limit of statistical significance.

The aim of the present experiments was, therefore, a large improvement of the statistical quality of the previous experiment, and in addition the study of it in a different nuclear system, namely ^{7}Li. The selection criterion for the nucleus is simple, due to the dominance of an iso-vector, spin-flip amplitude in the S_{11} excitation [46], and thus in threshold η photoproduction, only nuclei with isospin $I \neq 0$ and spin $J \neq 0$ can have non-negligible reaction rates for the coherent $\gamma A \rightarrow A\eta$ process.

2. Experimental setup

The experiments were done at the tagged photon beam of the Mainz MAMI accelerator [47, 48]. The electron beam of 1508 MeV energy was impinging on a copper radiator of 10μm thickness to produce bremsstrahl photons which were tagged with the Glasgow magnetic spectrometer [49] for photon energies between 0.45 GeV–1.4 GeV. The target was a capton cylinder of 4.3 cm diameter and 5.3 cm length filled with liquid ^{3}He at a temperature of 2.6 K. The target density was 0.07 nuclei/barn. The η mesons were identified via their $\eta \rightarrow 2\gamma$ and $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ decays. The decay photons were detected with an electromagnetic calorimeter combining the Crystal Ball [50] made of 672 NaI crystals with 384 BaF_2 crystals of the TAPS detector [51, 52] configured as a forward wall. The Ball was equipped with an additional inner detector (plastic scintillators) for charged particle identification via the $\Delta E - E$ method and all modules of the TAPS detector had individual plastic scintillators in front for the same purpose. Pictures and a schematic overview of the setup are shown in Fig. 2. The Crystal Ball covered the full azimuthal range for polar angles from 20° to 160°, corresponding to 93% of the full solid angle. The TAPS detector, mounted 1.07 m downstream from the target, covered polar angles from $\approx 2°$ to 21°.

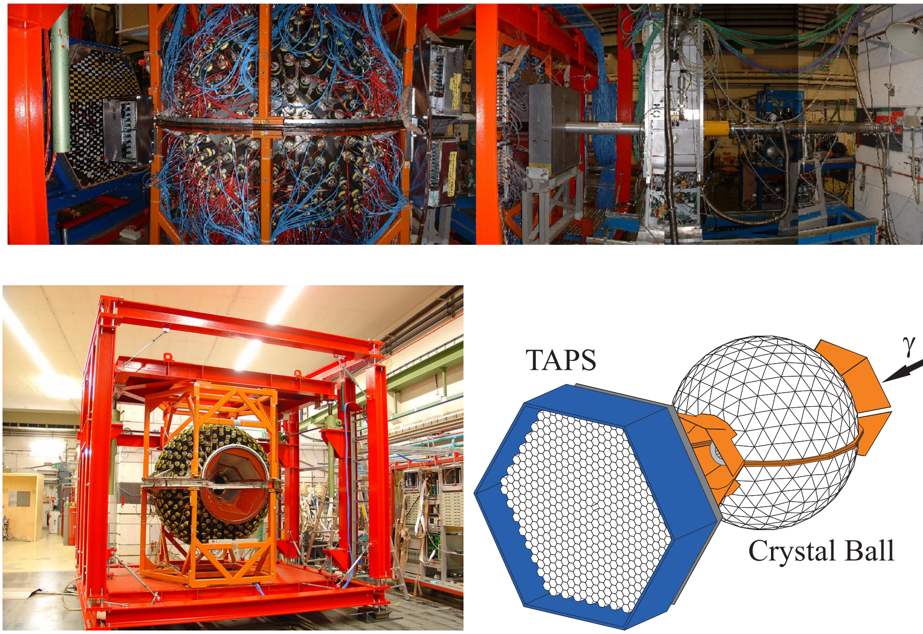

Fig. 2. Overview of the experimental setup. Upper part: beam coming from the right, Crystal Ball at the left of the picture, TAPS forward wall at the very left. Bottom part, left-hand side: Crystal Ball in setup phase, right-hand side: schematic drawing of the calorimeter.

3. Data analysis

Photoproduction of η mesons was analyzed via their 2γ- and 6γ-decay channels. For the analysis of the coherent process $\gamma^3\mathrm{He} \rightarrow \eta^3\mathrm{He}$ only events with exactly two (respectively six) photons and no further hit in the detector were accepted. This reduces the background from breakup reactions since events were the participant nucleon is detected are suppressed. The η mesons were identified with a standard invariant mass analysis for the two photon decay. Residual background under the η-peak was subtracted by a fit of the simulated line shape and a background polynomial. In the case of $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ decay, the six photons were first combined via a χ^2 test to three pairs which are the best solution for three π^0 invariant masses. A cut between 110 MeV–150 MeV was made on these invariant masses. Subsequently, the six photon invariant mass was constructed, which in this case is an almost background free η invariant mass peak (the cross-section for triple π^0 production not related to η-decays is very small in the interesting range of incident photon energies).

The next important step is then the separation of the coherent events from residual background from breakup reactions were a nucleon is removed from the helium nucleus but not detected. This was done using a missing energy analysis which compares the kinetic c.m. energies of the η mesons extracted directly from the measured decay photons with the ones calculated from the incident photon energy under the assumption of coherent

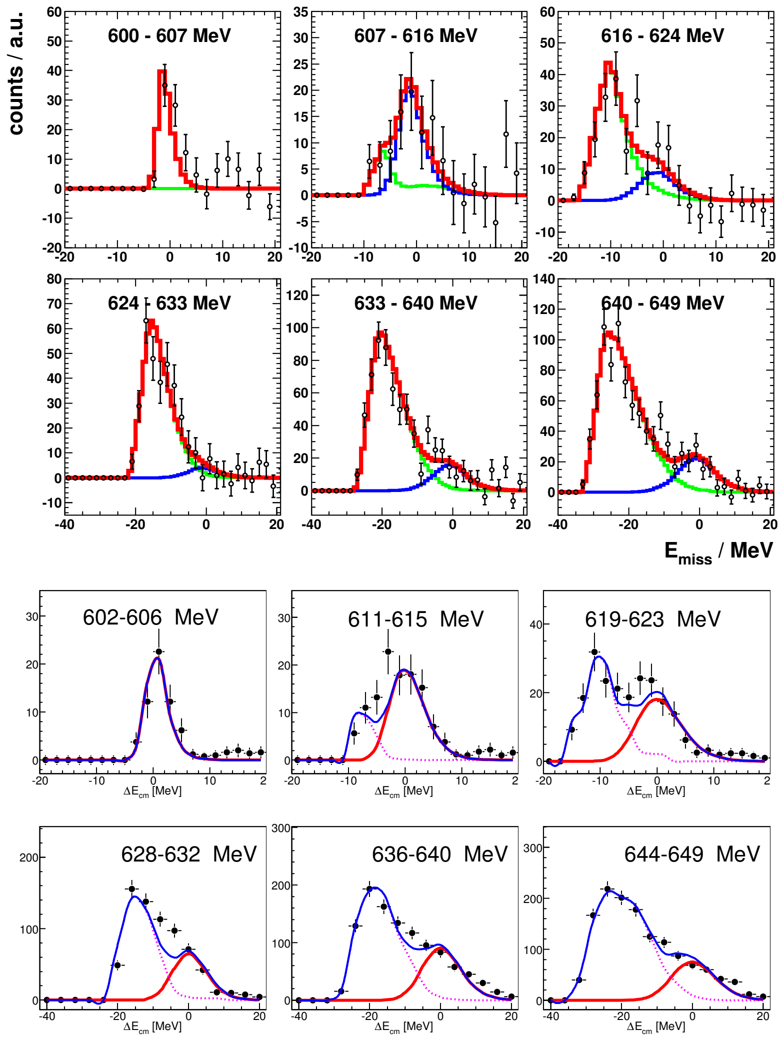

Fig. 3. Missing energy spectra. Upper part: results from the previous experiment [34], bottom part: present experiment. In both cases for the $\eta \to 2\gamma$ decay. Lines: simulated line shapes of coherent signal (centered around $\Delta E = 0$), breakup background (at negative missing energies) and sum of both.

kinematics. The result is a peak around zero for coherent events and some background structure at negative missing energies for breakup events. The shape of both contributions has been generated with Monte Carlo simulations using the GEANT4 package [53]. This analysis was done independently for each bin of incident photon energy and c.m. polar angle of the η mesons. The result of this analysis is compared in Fig. 3 to the results of the previous experiment by Pfeiffer *et al.* [34]. Due to the large angle coverage of the present experiment not only the statistical quality of the coherent signal is much improved. In addition, the relative contribution from background events from breakup reactions is much reduced due to the detection of the recoil nucleons. As in the previous experiment, the first energy bin between coherent and breakup threshold shows a clean single of coherent production, in good agreement with the simulated line shape. An identical analysis was done for the six-photon channel and for the ^{7}Li nucleus.

4. Results

Preliminary results for the extracted total cross-sections are summarized in Fig. 4. The results from the two- and six-photon decays of the η mesons are in quite good agreement. Both excitation functions show an extremely steep rise at coherent threshold, which cannot be resolved with the incident photon energy resolution of 4 MeV defined by the width of the tagger focal plane detectors. This result is very similar to the observation in the hadron induced reaction $pd \to \eta^3$He studied by Mersmann *et al.* [43]. The independence of this effect on the initial state clearly demonstrates its origin from

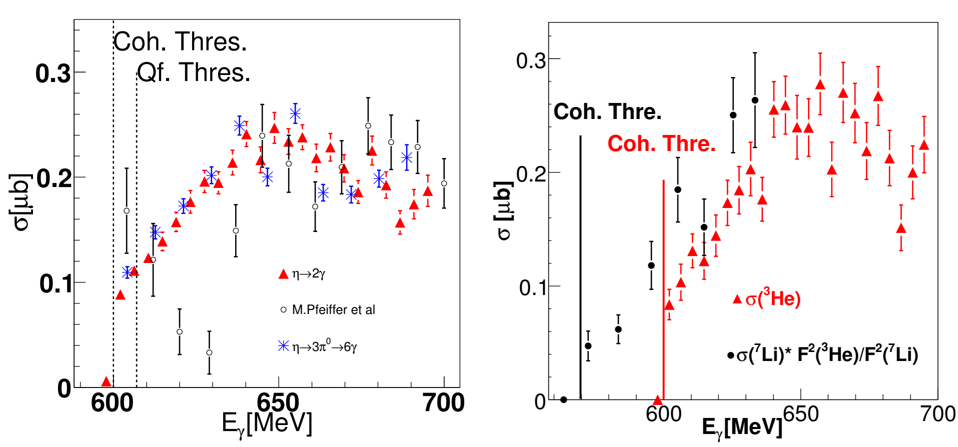

Fig. 4. Left: total cross-section for coherent η production off ^{3}He from the two η-decay channels compared to the previous result from Pfeiffer *et al.* [34]. Right-hand side: comparison of $\gamma^3\text{He} \to \eta^3\text{He}$ to $\gamma^7\text{Li} \to \eta^7\text{Li}$ scaled by the ratio of the nuclear form factors. All results preliminary.

final state properties and is thus an indication towards the existence of a (quasi-) bound state. The data are in reasonable agreement with the previous results [34] except in the energy region from 620–630 MeV. Inspection of the missing energy spectra shows, that the previous experiment within its low statistics and the presence of the large background structure was consistent with a null result, while the present data show a clear and statistically significant coherent contribution in this range.

The right-hand side of the figure shows a comparison of the total cross-sections for coherent production off ^{3}He and ^{7}Li. The latter is scaled up by the ratio of the form factors of the nuclei which differs by roughly one order of magnitude so that the Li cross-sections are of the order of only a few ten nb. This is the first positive signal for coherent η photoproduction for any nucleus with mass beyond $A = 3$. The fact that after correction for the nuclear form factor the cross-sections for the two nuclei are very similar is not surprising. Coherent production for spin-/isospin-independent reactions like π^0 photoproduction in the Δ range scales with the atomic mass numbers. However, since in η photoproduction the isovector, spin-flip component is dominant, for both nuclei the largest contributions comes from the single unpaired nucleon. This is the $s_{1/2}$ neutron for ^{3}He and the $p_{3/2}$ proton for ^{7}Li. Also the Li-data show a steep rise at coherent threshold, however, less pronounced than in the helium case.

Angular distributions for the coherent reaction off ^{3}He are summarized in Fig. 5. Since the elementary reactions of η photoproduction off the nucleon are not much angular dependent in the energy range of interest one expects that the main angular dependence arises from the nuclear form factor $F^2(q^2)$.

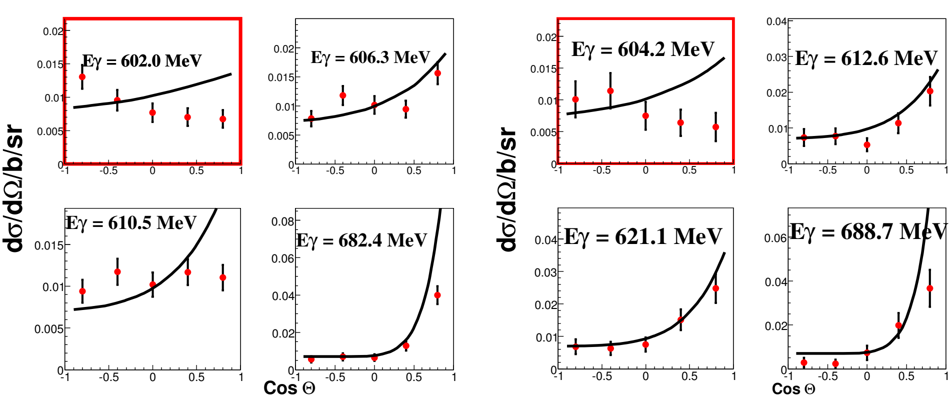

Fig. 5. Angular distributions for $\gamma^3\mathrm{He} \rightarrow \eta^3\mathrm{He}$. Left-hand side: two-photon channel, right-hand side: six-photon decay. The curves show the behavior expected from the nuclear form factor. All results preliminary.

As demonstrated in the figure, this is the case except for the immediate vicinity of the threshold. This is a further indication that FSI effects are dominating in this region.

A further signal for the formation of a (quasi-) bound state discussed by Pfeiffer *et al.* [34] was a narrow peak around the η production threshold in the excitation function of π^0–proton back-to-back pairs in the photon-^{3}He c.m. system. The kinematics for the decay of a (quasi-) bound state via re-capture of the η by a nucleon and subsequent decay of the $S_{11}(1535)$ into a pion–nucleon pair has been simulated. Events from the data have been selected in a way to maximize the ratio of this signal with respect to quasi-free π^0 production. The excitation functions are shown in Fig. 6. Following the same procedure as in [34] by subtracting properly scaled excitation functions for opening angles between 150°–165° from the data for 165°–180° indeed reproduces the narrow structure discussed in [34]. However, the new data of much better statistical quality covering a larger incident photon energy range clearly show the appearance of two structures in this excitation functions arising from the third and second resonance region in quasi-free π^0 photoproduction. These structures move in incident photon energy as function of the selected opening angle between the π^0 and the proton, which is a trivial kinematic effect. Unfortunately, the subtraction of the excitation functions of the expected signal bin and the background bin accidentally generates an artificial structure right at the η-threshold.

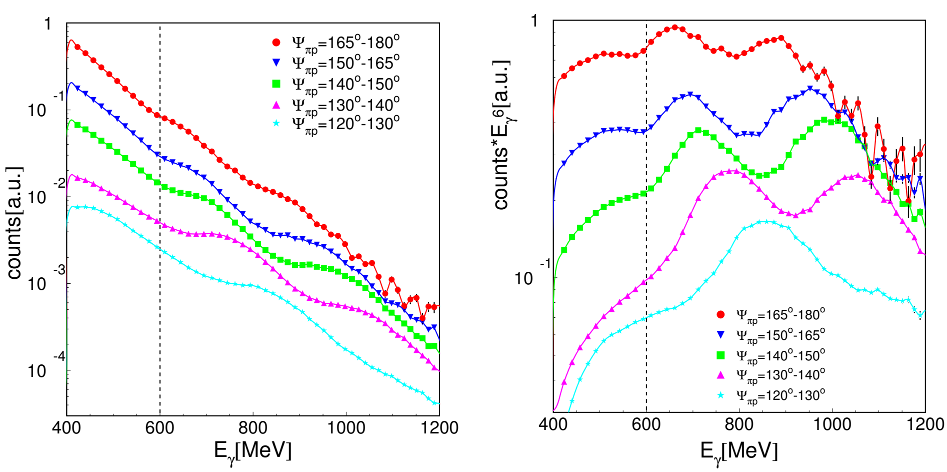

Fig. 6. Excitation functions of π^0–proton pairs with different opening angles ψ in the photon–^{3}He c.m. frame. Left-hand side: excitation functions, right-hand side: multiplied with E_γ^6 to remove the overall energy dependence.

5. Conclusions

Coherent photoproduction of η mesons has been studied in the threshold region for ^{3}He and ^{7}Li nuclei. The results for ^{3}He are much improved in terms of statistical quality with respect to a previous measurement [34] and confirm the extremely steep, almost step-like rise of the excitation function at the coherent threshold which is evidence for strong final state interaction. Together with the results from the hadron induced reaction $pd \rightarrow \eta^3$He [43], which show a similar behavior, this supports the formation of a (quasi-) bound η-nucleus state. The angular distributions also show the previously observed deviation from the expected form factor dependence in the threshold region. A similar measurement for ^{7}Li produced the first ever data for coherent η photoproduction off a nucleus beyond the $A = 3$ mass range and show also a strong threshold enhancement also less pronounced than for ^{3}He. The previously observed [34] threshold structure in the π^0–p back-to-back emission excitation function exists, but is most likely an artefact from quasi-free π^0 production.

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