Coherent photoproduction of $\eta$-mesons off $^3$He - search for $\eta$-mesic nuclei

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Abstract

Coherent photoproduction of $\eta$-mesons off $^3$He, i.e. the reaction $\gamma^3\text{He} \rightarrow \eta^0\text{He}$, has been investigated in the near-threshold region. The experiment was performed at the Glasgow tagged photon facility of the Mainz MAMI accelerator with the combined Crystal Ball - TAPS detector. Angular distributions and the total cross section were measured using the $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ decay channels. The observed extremely sharp rise of the cross section at threshold and the behavior of the angular distributions are evidence for a strong $\eta^0$ final state interaction, pointing to the existence of a resonant state. The search for further evidence of this state in the excitation function of $\pi^0$-proton back-to-back emission in the $\gamma^3\text{He} \rightarrow \pi^0pX$ reaction revealed a very complicated structure of the background and could not support previous conclusions.

1. Introduction

The interaction of mesons with nuclei is a major source for our understanding of the strong interaction. For long-lived mesons, like charged pions or kaons, secondary beams can be used for detailed studies of elastic and inelastic reactions, revealing the relevant potentials. However, most mesons are short-lived so that their interaction with nucleons can only be studied in indirect ways, making use of final-state interactions (FSI). The general idea is to produce the mesons with some initial reaction in a nucleus and then study their interaction with the same nucleus.
It is much discussed whether the strong interaction allows the formation of quasi-bound meson-nucleus states. So far, all known meson-nucleus bound states involve at least partly the electromagnetic interaction. Pionic atoms are well established. More recently deeply bound pionic states have also been reported [1], but in this case the binding results from the superposition of the repulsive $s$-wave $\pi^-$-nucleus interaction with the attractive Coulomb force. Neutral mesons on the other hand could form quasi-bound states only via the strong interaction. The meson-nucleus interaction for slow pions is much too weak to produce quasi-bound states, but the situation may be different for $\eta, \eta'$, and $\omega$-mesons.

The case of $\eta$-mesons is special because the threshold region of $\eta$-production is dominated by an $s$-wave resonance [2,3], the $S_{11}(1535)$, which couples very strongly to $N\eta$ (branching ratio $\approx 50\%$ [4]). As a consequence FSI in nuclei are important; $\eta$-mesons are absorbed in nuclei with typical cross sections around 30 mb, basically independent of their kinetic energy $T$ over a wide range of $T$ from a few MeV to 1 GeV [5,6]. First hints for the possible existence of bound $\eta$-nucleus states came from the analysis of the $\eta N$ scattering length that characterizes the potential at low kinetic energies. Already in 1985 Bhalaero and Liu [7] reported an attractive $s$-wave $\eta N$ interaction from a coupled channel analysis of pion-induced reactions, yielding scattering lengths $a_{\eta N}$ with real parts between 0.27 fm and 0.28 fm and imaginary parts between 0.19 fm and 0.22 fm. Shortly afterwards, Liu and Haider [8] pointed out that this interaction might lead to the formation of quasi-bound $\eta$-nucleus states for $A > 10$. Experimental evidence for such ‘heavy’ $\eta$-mesic nuclei has been searched for in pion-induced reactions on nuclei in the oxygen region [9,10], but those experiments did not produce conclusive evidence. More recently, Sokol and co-workers [11,12] claimed evidence for the formation of $\eta$-mesic nuclei from bremsstrahlung-induced reactions on $^{12}$C

$$\gamma + ^{12}\text{C} \rightarrow p(n) + ^{11}\text{B}(^{11}\text{C}) \rightarrow \pi^+ + n + X \ ,$$

where the $n\pi^+$ pairs were detected in the final state. In this type of experiment, the $\eta$-meson is produced in quasi-free kinematics on a nucleon ($p,n$), which takes away the largest part of the momentum and the $\eta$ is almost at rest in the residual $A = 11$ nucleus. If a quasi-bound state is produced, the $\eta$-meson has a large chance to be re-captured by a nucleon into the $S_{11}$ excitation, which may then decay into a pion-nucleon back-to-back pair. Such pairs were searched for in the experiment, however, background from quasi-free pion production must be considered. Sokol and Pavlyuchenko [12] claim an enhancement above this background for certain kinematic conditions.

The topic gained much new interest after precise low-energy data for the photoproduction of $\eta$-mesons off the proton [2], deuteron [13–16] and helium nuclei [17,18] became available and refined model analyses of the scattering length were done by many groups (see [19] for a summary). The results for the imaginary part are rather stable, most

cluster between 0.2 fm and 0.3 fm. The real part, which determines the existence of quasi-bound states, is much less constrained. It runs all the way from a negative value of $-0.15$ fm to numbers close to and even above $+1$ fm. However, most of the more recent analyses prefer large values above 0.5 fm, which has raised controversial discussions about the possible existence of very light mesic nuclei and prompted theoretical studies of the $\eta$-interaction with $^2\text{H}$, $^3\text{H}$, $^3\text{He}$, and $^4\text{He}$ systems [20–29].

Experimental evidence for light $\eta$-mesic nuclei has mostly been searched for in the threshold behavior of $\eta$-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 dependence. Many different hadron induced reactions have been studied in view of such threshold effects. Already the measurement of pion induced $\eta$-production off $^3\text{He}$ in the reaction $\pi^- + ^3\text{He} \rightarrow \eta + t$ at LAMPF [30,31] revealed production cross sections significantly larger than DWIA predictions. Subsequently, different nucleon-nucleon and nucleon-deuteron reactions, in particular $pp \rightarrow pp\eta$ [32–34], $np \rightarrow d\eta$ [35,36], $pd \rightarrow \eta^3\text{He}$ [37], $dp \rightarrow \eta^3\text{He}$ [38–40], $dd \rightarrow \eta^4\text{He}$ [41], $d\bar{d} \rightarrow \eta^4\text{He}$ [42,43], and $pd \rightarrow pd\eta$ [44] have been studied. Interesting threshold effects have been found in most of them, but in particular the $pd \rightarrow \eta^3\text{He}$ [37] and $dp \rightarrow \eta^3\text{He}$ reactions [38–40] show an extremely steep rise at threshold, implying a very large $\eta^3\text{He}$ scattering length. Wilkin and collaborators [45] have argued from an analysis of the angular distributions that, not only the magnitude of the $s$-wave amplitude falls rapidly in the threshold region, but that its phase also varies strongly, which supports the idea of a quasi-bound or virtual $^3\text{He}$ state very close to the threshold.

If such states do exist, they should show up as threshold enhancements independently of the initial state of the reaction. Photoproduction of $\eta$-mesons from light nuclei is a very clean tool for the preparation of the $\eta$-nucleus final state with small relative momenta but, due to the much smaller electromagnetic cross sections, sensitive threshold measurements have been sparse until now. A particular problem is that the $\eta$-mesons have to be produced coherently off the target nuclei. As a consequence of the results from photoproduction of $\eta$-mesons off light nuclei, it is now well understood that the threshold production is dominated by an isovector spin-flip amplitude exciting the $S_{11}(1535)$ resonance (see [46] for a summary). Therefore, the coherent cross section is very small for the isoscalar deuteron and practically forbidden for the isoscalar-scalar $^4\text{He}$ nucleus, where only higher partial waves could contribute. Among the light targets only the ($I = 1/2, J = 1/2$) $^3\text{He}$ and $^4\text{He}$ nuclei have reasonably large cross sections for the $\gamma A \rightarrow A\eta$ reaction.

The $^3\text{He}$ system was previously investigated with photon-induced reactions by Pfeiffer et al. [47]. Possible evidence for the formation of a quasi-bound state was reported from the behavior of two different reactions. The coherent $\eta$-
photoproduction $\gamma^3\text{He} \rightarrow \eta^3\text{He}$ showed a strong threshold enhancement with angular distributions much more isotropic in the threshold region than expected from the nuclear form factor. These are indications for strong FSI effects. Furthermore, in an approach similar to the Sokol experiment [12], the excitation function for $\pi^0 - p$ pairs emitted back-to-back in the $\gamma^3\text{He}$ center-of-momentum (c.m.) system was investigated. The difference between the excitation functions for opening angles between 170° - 180° (almost back-to-back) and 150° - 170° (background from quasi-free pion production) showed a narrow peak around the $\eta$-production threshold. Such a peak is expected to arise when quasi-bound $\eta$-mesons are re-captured into a nuclear $^{3}\text{He}$ excitation with subsequent decay into the pion-nucleon channel. However, the statistical quality of the measurements was limited and it was pointed out by several authors [48,49] that the data do not prove the existence of a quasi-bound state.

The present experiment aimed at a measurement with significantly improved statistical quality and better control of systematic effects. This was achieved by using a detector system with much larger solid-angle coverage. Apart from counting statistics this is important for two aspects. It allows a measurement of not only the $\eta \rightarrow 2\gamma$ decays but also the $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ decay chain. Comparison of the two results helps to estimate systematic effects from the detection efficiency. Even more important, the coincident detection of recoil nucleons from non-coherent production processes becomes much more efficient and can be used to suppress this most important background.

2. Experiment and analysis

The experiment was performed at the tagged photon beam of the Mainz MAMI accelerator [50,51]. The electron beam of 1508 MeV was used to produce bremsstrahlung photons in a copper radiator of 10μm thickness, which were tagged with the upgraded Glasgow magnetic spectrometer [52–54] for photon energies from 0.45 GeV to 1.4 GeV. The typical bin width for the photon beam energy (4 MeV) is defined by the geometrical size of the plastic scintillators in the focal plane detector of the tagger. The intrinsic resolution of the magnetic spectrometer is better by more than an order of magnitude. The size of the tagged photon beam spot on the target was restricted by a 3 mm diameter collimator placed downstream from the radiator foil. The target was a mylar cylinder of 3.0 cm diameter and 5.08 cm length filled with liquid $^3\text{He}$ at a temperature of 2.6 K. The corresponding target density was 0.073 nuclei/barn.

The reaction products were detected with an electromagnetic calorimeter combining the Crystal Ball detector (CB) [55] made of 672 NaI crystals with 384 BaF$_2$ crystals from the TAPS detector [56,57], configured as a forward wall. The Crystal Ball was equipped with an additional Particle Identification Detector (PID) [58] for the identification of charged particles and all modules of the TAPS detector had individual plastic scintillators in front for the same purpose. The PID, in combination with the Crystal Ball, and the TAPS - TAPS-Veto system could be used for a $E - \Delta E$ analysis for the separation of different charged particles. 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 1.457 m downstream from the target, covered polar angles from $\pm$5° to 21°. This setup is similar to the one described in detail in [59]. The only difference is that, in the earlier setup, the TAPS forward wall consisted of 510 modules and was placed 1.75 m from the target.

For the present experiment the main trigger condition was a multiplicity of two separated hits in the combined CB/TAPS system and an integrated energy deposition of at least 300 MeV in the Crystal Ball. Details for the basis of the data analysis including calibration procedures, identification of photons and recoil nucleons and the absolute normalization of cross sections are discussed in [59]. Here, we will only outline the specific steps for the identification of coherent $\eta$-production. Results for quasi-free production of $\eta$-mesons off nucleons bound in $^3\text{He}$ in view of the structure recently observed for $\eta$-photoproduction off the neutron [60,61] will be reported elsewhere.

The analysis was based on the $\eta \rightarrow \gamma \gamma$ and $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ decay channels. The measurement of both channels allowed an additional control of systematic uncertainties. Events were analyzed with either two or six photon candidates and no further hit in the detector system. The latter condition reduces the incoherent background since events with recoil nucleons were suppressed. For the two-photon decay, $\eta$-mesons were identified with a standard invariant-mass analysis. Residual background under the $\eta$-peak was subtracted by fitting the spectra with simulated line shapes and a background polynomial. This procedure was applied individually for each combination of incident photon energy and meson c.m.-polar angle. For the six photon decay, the photons were first combined via a $\chi^2$-test to three pairs, which were the best solution for three $\pi^0$ invariant masses. A cut between 110 MeV - 150 MeV was made on these invariant masses. Subsequently, the six-photon invariant mass was constructed. The corresponding spectra were basically background free under the $\eta$-peak (direct triple-$\pi^0$ production has a very small cross section in the energy range of interest).

The most important step in the analysis is the separation of the coherent reaction from breakup where nucleons are removed from the nucleus. Since the $^3\text{He}$ recoil nuclei cannot be detected (they are mostly stopped in the target) only the overdetermined reaction kinematics can be used. The kinetic energy of the $\eta$-mesons in the $\gamma^3\text{He}$ c.m.-system is fixed not only by the incident photon energy but also from the measured laboratory energy and polar angle of the meson. The difference, the missing energy $\Delta E$, is shown for both data samples in Fig. 1 and compared to the simulated line shapes of the coherent and breakup reactions. The simulations were done with the Geant4 program package [62],
taking into account all details of the target and detector setup. The simulation of the coherent part is straightforward due to the two-body final-state kinematics. In case of the breakup part, the momentum distribution of the bound nucleons has to be considered, and this was taken from the work of McCarthy, Sick, and Whitney [63]. Several final states, such as $pd$, $np$ with different participant - spectator combinations, contribute. Good agreement between data and simulations was achieved, at all the incident photon energies investigated, with three different reaction components: the coherent process, the breakup process with a quasi-free participant nucleon, and the breakup process where the recoil is taken by a ‘participant’ deuteron.

The relative contributions of these processes have been determined by fitting the data with a superposition of their line shapes (cf Fig. 1). Since in principle the detection efficiency for the different components can be different for the $\eta \to 2\gamma$ and $\eta \to 6\gamma$ decays, no constraints relating the two channels were imposed on the fits. As a consequence, for some energy bins the fitted relative contributions of the breakup processes are different for the two decay channels, but the fit of the coherent contribution is quite stable. This is so because the breakup background makes almost no contribution at positive missing energies, so that the coherent contribution is only weakly dependent on the exact shape of the background. The lowest range of photon energies (600 MeV < $E_\gamma$ < 608 MeV) lies between the kinematical thresholds of coherent and breakup reactions. Consequently, only the coherent reaction can contribute. In fact, a clean signal at zero missing energy is seen, which agrees with the simulated coherent signal shape. At even lower photon energies, the spectra show no signal above statistical noise.

The count rates are roughly a factor of 2.75 larger for the $\eta \to 2\gamma$ data than for the $\eta \to 3\pi^0 \to 6\gamma$ data (note the different scales for the left and right parts of Fig. 1), which is due to the respective detection efficiencies ($\approx 80\%$ for $2\gamma$, $\approx 35\%$ for $6\gamma$) and decay branching ratios ($b_{2\gamma} = (39.31 \pm 0.20)\%$, $b_{6\gamma} = (32.57 \pm 0.23)\%$). Absolutely normalized total and differential cross sections for both decay channels have been extracted from the yields, the target density, the decay branching ratios [4], the simulated detection efficiency, electron beam flux measured in the focal-plane detector of the tagging spectrometer, and the tagging efficiency $\varepsilon_{\text{tag}}$, i.e. the number of correlated photons that pass through the collimator. The latter was measured in special low-intensity runs with a lead-glass detector in the photon beam (see [59] for details) and ranged from 60% to 75%. For the systematic uncertainties we estimate 10% for the overall normalization including target density (measurement of target temperature and possible deformation of the cold target cell, $\approx 7\% - 8\%$), photon flux (measurement of tagging efficiency and electron flux, $< 5\%$) and decay branching ratios (almost negligible $< 1\%$). For the reaction dependent simulations of the detection efficiency, $5\%$ uncertainties are estimated. Finally, the energy dependent uncertainty for the reaction identification (in particular the separation in the missing energy spectra) ranges from $2\%$ at threshold to $20\%$ at the highest incident photon energies.

For the analysis of the excitation function of $\pi^0$-p back-to-back pairs in the $\gamma$-$^3$He c.m.-system, Monte Carlo simulations were done for the signal and the background coming from quasi-free production of $\pi^0$ mesons. For the signal, the decay of bound $S_{11}$ resonances into $N\pi$ was modelled with a momentum distribution corresponding to the nuclear Fermi-motion. These simulations were used to select the kinematical conditions best suited for the signal. In the spectra of the pion-proton opening angle, signal events appear roughly between $150^\circ - 180^\circ$, while the background is distributed between $100^\circ$ and $180^\circ$.
3. Results

3.1. Coherent photoproduction of $\eta$-mesons off $^3\text{He}$

The total cross section data for coherent $\eta$-production from the two $\eta$ decay branches is compared to model predictions [64–66] in Fig. 2. The agreement between the two data sets is quite good, but none of the existing models reproduce the data, even when their systematic uncertainties (shown as shaded band in the figure) are considered. The most prominent feature of the data is the extremely sharp rise at threshold. Here one should note that the binning of the data (4 MeV for the $2\gamma$-channel, 8 MeV for the $6\gamma$-channel) is very large compared to the energy resolution of the magnetic tagging spectrometer (roughly 200 keV).

![Graph](image_url)

Fig. 2. Total cross section for the $^3\text{He} \rightarrow \eta^3\text{He}$ reaction from $\eta \rightarrow 2\gamma$ and $\eta \rightarrow 6\gamma$ decays. The shaded band at the bottom indicates the systematic uncertainty. The two vertical lines indicate coherent and breakup threshold. Theory curves: (blue) dotted and dashed from Shevchenko et al. [66] for two different versions of elastic $\eta N$ breakup threshold. Theory curves: (blue) dotted and dashed from systematic uncertainty. The two vertical lines indicate coherent and elastic $\eta$ and $\eta$ from the two decay branches is compared to model predictions [64–66] in Fig. 2. The agreement between the two data sets is quite good, but none of the existing models reproduce the data, even when their systematic uncertainties (shown as shaded band in the figure) are considered. The most prominent feature of the data is the extremely sharp rise at threshold. Here one should note that the binning of the data (4 MeV for the $2\gamma$-channel, 8 MeV for the $6\gamma$-channel) is very large compared to the energy resolution of the magnetic tagging spectrometer (roughly 200 keV).

The work by Tiator, Bennhold and Kamalov [64] is based on a coupled-channel analysis of pion- and photon-induced pion- and eta-production off the nucleon, which parameterizes the resonance contributions with an isobar model and the background terms with effective Lagrangians. For the coherent production off $^3\text{He}$, realistic nuclear wave functions were used, but the model was based on the plane-wave impulse approximation (PWIA). The result strongly underestimates the magnitude of the measured cross section and does not reproduce the energy dependence.

Fix and Arenhövel [65] have modelled coherent $\eta$-photoproduction off $^3\text{He}$ and $^3\text{H}$ in PWIA, in a distorted-wave impulse approximation (DWIA), using an optical potential, and in a full four-body scattering model. They find strong FSI effects, which amplify the threshold cross section for the full four-body model with respect to PWIA and DWIA (which give similar results). Nevertheless their cross section underestimates the data by roughly a factor of two.

Shevchenko and collaborators [66] have also calculated coherent $\eta$-production off the three-nucleon system in a microscopic few-body description. They find a strong dependence of the result on the elastic $\eta N$ rescattering, which is not sufficiently constrained by experiment. Two examples for different FSI modelling are shown in Fig. 2. They exhibit strong threshold effects, but do not reproduce the measurements above the breakup threshold.

![Graph](image_url)

Fig. 3. Total cross section for $^3\text{He} \rightarrow \eta^3\text{He}$ (averaged over $2\gamma$ and $3\pi^0$ decays) (red dots) compared to previous data [47] (green triangles). Solid (dashed) curves: PWIA with realistic (isotropic) angular distribution for $\gamma n \rightarrow \eta \pi$ (see text). The present data are binned in the same way as the angular distributions in Fig. 4 (bin width $\approx 8$ MeV). Insert: ratio of measured and PWIA cross sections.

The average of the two data sets is compared to the previous result from Pfeiffer et al. [47] in Fig. 3. The two data sets are in reasonable agreement (within uncertainties) except for two points around 620 MeV. Here, one should note that, in this range, the systematic uncertainty in the previous data was large because the coherent signal had to be extracted by fitting a small coherent contribution in the missing energy spectra, which were dominated by the quasi-free reaction. The quasi-free contribution is less important at lower incident photon energies, and is better separated from the coherent component at higher incident photon energies. The present experiment profited in this range from the almost 4$\pi$ coverage of the detector, which allowed some suppression of the quasi-free background by the detection of associated recoil nucleons.

Also shown in this figure are the results from a simple PWIA model. It uses the effective photon energy $E_{\gamma}^{\text{eff}}(E_{\gamma}, x)$ given by

$$E_{\gamma}^{\text{eff}} = \frac{s_{\text{eff}} - m_N^2}{2m_N}, \quad s_{\text{eff}} = (P_\gamma + P_N)^2,$$

(2)
where $E_\gamma$ is the laboratory energy of the incident photon and $\Theta_\eta^*$ is the polar angle of the $\eta$ meson in the photon-nucleus c.m. system with $x = \cos(\Theta_\eta^*)$. The effective photon energy corresponds to the $s_{\text{eff}}$ of the incident photon (four-momentum $P_\gamma$) and a nucleon (four-momentum $P_N$) with three-momentum $p_N$ from the nucleon motion inside the nucleus. The nucleon momentum is related in the factorization approximation to the momentum $q$ transferred to the nucleus by [67]:

$$p_N = - \frac{A-1}{2A} q = - \frac{1}{3} q,$$

where all momenta are in the laboratory system.

The coherent cross section is then composed of three factors:

$$\frac{d\sigma_{\text{PWIA}}}{d\Omega}(E_\gamma, x) = \left( \frac{g_\eta(q_\eta^*)}{k_\eta^*(q_\eta^*)} \right) \cdot \frac{d\sigma_{\text{elem}}}{d\Omega} \cdot \frac{F_\gamma^2(q^2)}{F_p^2(q^2)} \cdot \frac{1}{d\Omega}$$

the elementary cross section $d\sigma_{\text{elem}}/d\Omega$, a kinematical factor, and the nuclear form factor for point-like nucleons. The kinematical factor accounts for the change of phase-space between the different c.m. systems and is derived from the photon and $\eta$ three-momenta in the photon-nucleon ($k_\eta^*(q_\eta^*)$, $q_\eta^*$), and photon-nucleus ($k_\gamma^*(q_\gamma^*)$, $q_\gamma^*$) c.m. systems. The nuclear form-factor $F_\gamma^2(q^2)$ was taken from [63]. It includes the spatial distribution of the charge (respectively magnetic moment) of the nucleon, while here the distribution of point-like nucleons is relevant. We have therefore used the ratio of the nuclear form factor $F_\gamma^2(q^2)$ and the nucleon dipole form factor $F_p(q^2)$ to approximate the distribution of point-like nucleons in the $^3$He nucleus.

Since $\eta$-photoproduction in this energy range is almost only due to the $S_{11}$ excitation, the dominant electromagnetic multipole is the $E_3$ spin-flip. Neglecting small contributions from other multipoles and higher components in the $^3$He wave function, only the unpaired neutron contributes to coherent production because a spin-flip of a proton is Pauli-blocked. Therefore, we use for the elementary cross section the experimental results for the $\gamma n \rightarrow n\eta$ reaction from [60,61]. Since the angular dependence up to the $S_{11}$ peak is almost isotropic, one can approximate the c.m. differential cross section by:

$$\frac{d\sigma_{\text{elem}}}{d\Omega}(E_\gamma^{\text{eff}}, x) = \sigma_n(E_\gamma^{\text{eff}})/4\pi,$$

where the total neutron cross section $\sigma_n$ is parameterized as a Breit-Wigner curve with an energy dependent width using the numerical values from [61] ($W=1546$ MeV, $\Gamma=176$ MeV, $A_{11/2}^n=90 \times 10^{-3}$ GeV$^{-1/2}$, $b_\eta=0.5$, $b_\gamma=0.4$, $b_\pi=0.1$). Variation of the parameters within their uncertainties changes the predictions for the coherent cross section typically on the 10% level.

The results from the PWIA model are compared to the data in Figs. 3 and 4. They are shown for the approximation of Eq. 5 assuming isotropic angular distributions for the elementary $\gamma n \rightarrow n\eta$ reaction, and also for realistic angular distributions taken from [61]. The difference is, as expected, negligible. Despite the simplicity of the model, the predicted cross section agrees with experiment within statistical and systematic uncertainties for the highest incident photon energies. In the threshold region it is in excellent agreement with the PWIA calculation by Fix and Arenhövel. However, in this region it underestimates the data by nearly one order of magnitude, which is evidence for strong FSI effects at threshold.

The behavior of the angular distributions of the PWIA model with isotropic angular distributions for $\gamma n \rightarrow n\eta$, solid curves with realistic angular distributions, dotted curves: folded with experimental resolution. (see text).
ble for the strong forward peaking. At high incident photon energies the data show the same tendency, though the rise to forward angles is not as steep as in the model. This indicates significant FSI effects even for those energies, since the more trivial approximations in the PWIA model cannot explain this discrepancy. The use of realistic angular distributions for the elementary cross section instead of Eq. 5 (dashed curves in Fig. 4) has basically no impact. The use of more realistic nuclear wave functions instead of the simplified scalar form factor in Eq. 4 leads only to comparatively small changes [65]. Finally, the experimental angular resolution is only responsible for minor effects. This is demonstrated by the dotted curves in Fig. 4, which have been folded with the detector response.

Towards the threshold, the measured angular distributions become almost isotropic. Between coherent and breakup threshold, they develop a rise to backward angles, together with the disagreement in the absolute scale while in PWIA the form factor still causes a forward peak-breakup threshold, they develop a rise to backward angles, to forward angles is not as steep as in the model. This indicates significant FSI effects even for those energies, since the more trivial approximations in the PWIA model cannot explain this discrepancy. The use of realistic angular distributions for the elementary cross section instead of Eq. 5 (dashed curves in Fig. 4) has basically no impact. The use of more realistic nuclear wave functions instead of the simplified scalar form factor in Eq. 4 leads only to comparatively small changes [65]. Finally, the experimental angular resolution is only responsible for minor effects. This is demonstrated by the dotted curves in Fig. 4, which have been folded with the detector response.

3.2. Excitation function of \( \pi^0 - p \) back-to-back pairs

The excitation function of \( \pi^0 \)-proton pairs for different ranges of their opening angle in the \( \gamma - 3\text{He} \) c.m. system was analyzed in a manner similar to that of Pfeiffer et al. [47]. The idea was, that when \( \eta \)-mesons are produced on an \( \eta \)-\( 3\text{He} \) resonant state, overlapping with the coherent production threshold, those produced at photon energies below the threshold are off-shell and cannot be emitted without violating energy conservation. They can, however, be captured by a nucleon which is then excited to the \( S_{11} \)-resonance. Since this resonance has a \( \approx 50\% \) decay branching ratio into \( N \pi \), the expected signal would be pion-nucleon pairs emitted back-to-back in the \( \gamma - 3\text{He} \) c.m. system. The results are shown in Fig. 5. The figure shows the difference of the excitation functions for opening angles from 165° - 180° (back-to-back range taking into account effects of Fermi motion) and the data from 150° - 165°. These ranges were optimized with Monte Carlo simulations of signal and background and are slightly different from those used by Pfeiffer et al. (170°-180° and 160°-170°), but this is a minor effect. The result shows the peak at the coherent \( \eta \) threshold that had been observed previously, but now with much higher statistical significance. However, the data also show some structure at higher incident photon energies which was not previously seen because the earlier experiment covered only incident photon energies up to 800 MeV. The much higher statistical quality of the new data allowed a detailed analysis of these structures. This is summarized in the insert of Fig. 5.

It shows the excitation functions for different ranges of opening angle, when the overall energy dependence of the data (\( \propto E_{\gamma}^{-6} \)) is removed. The broad, peak-like structures are due to the second and third resonance regions of the nucleon. The position of these signals shifts to higher incident photon energies for smaller opening angles. This is a purely kinematical effect; small opening angles correspond to decays of nucleon resonances moving forward in the photon-nucleus c.m. system. Therefore, for a given mass \( M_R = W \) of the resonance, small opening angles correspond to large incident photon energies (and nucleon Fermi momenta parallel to the photon momentum). Unfortunately, subtraction of the normalized excitation functions for the 165° - 180° and 150° - 165° opening-angle ranges produces a narrow peak exactly at the \( \eta \)-production threshold. This peak does, however, not originate from a special structure in the back-to-back data, but it is due to the subtraction of the shifted low energy tails of the second resonance region in single pion production.

Here, we have only presented the results from an analysis similar to the previous work by Pfeiffer et al. [47]. The much better statistical quality of the present data allows also more refined analyses with additional cuts to enhance the signal-to-background ratio. For this purpose we have done detailed Monte Carlo simulations of the kinematical correlations for the signal and the background from quasi-free pion production and analyzed the excitation functions with optimized cuts. However, also with these analyses no structures that could be uniquely related to the decay of an \( \eta \)-mesic state into \( N \pi \) could be identified. The \( \pi^0 - p \) background before very specific cuts is at least three orders of magnitude larger than any expected signal from an \( \eta \)-mesic state. In consequence, it seems to be impossible to identify in this reaction channel a small signal from the decay of bound \( S_{11} \) resonances on top of these complicated background structures, even when the signal exists.
4. Summary and conclusions

Coherent photoproduction of $\eta$-mesons off $^3$He has been measured with much improved statistical quality compared to the pilot experiment of Pfeiffer et al. [47]. The total cross section rises sharply between the coherent and breakup thresholds. Compared to a PWIA, which is in fair agreement with the data in the $S_{11}$ peak, the threshold values are enhanced by nearly one order of magnitude. This is very different e.g. from the behavior of coherent $\eta$ photoproduction off the deuteron, which is in reasonable agreement with PWIA [15]. The angular distributions at threshold are almost isotropic, and are unlike the forward peaked distributions expected to result from the form factor behavior. This result is similar to that previously observed for the hadron induced reactions $pd \rightarrow \eta^0^3$He [37] and $dp \rightarrow \eta^3$He [38–40]. This independence from the initial state is strong evidence for dominant $\eta$-nucleus interaction effects, related to a resonant state in the vicinity of the $\eta$ production threshold.

The excitation function of $\pi^0 \rightarrow p$ back-to-back pairs was investigated as an independent signal for the formation of a quasi-bound or virtual $\eta$-nucleus state, as originally suggested in the work by Sokol et al. [11,12]. A peak-like structure at the $\eta$-production threshold had been observed in a previous measurement of photoproduction from $^3$He by Pfeiffer et al. [47]. This signal was reproduced with much improved statistical significance, but it could be attributed to an artifact arising from the complicated background structure of quasi-free pion production.

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