Photoproduction of η-Mesic ^{3}He

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The photoproduction of η-mesic ^{3}He has been investigated using the TAPS calorimeter at the Mainz Microtron accelerator facility MAMI. The total inclusive cross section for the reaction $\gamma^3\text{He} \rightarrow \eta X$ has been measured for photon energies from threshold to 820 MeV. The total and angular differential coherent η cross sections have been extracted up to energies of 745 MeV. A resonancelike structure just above the η production threshold with an isotropic angular distribution suggests the existence of a resonant quasibound state. This is supported by studies of a competing decay channel of such a quasibound η-mesic nucleus into $\pi^0 pX$. A binding energy of (-4.4 ± 4.2) MeV and a width of (25.6 ± 6.1) MeV is deduced for the quasibound η-mesic state in ^{3}He.

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It has long been discussed whether the attractive strong interaction among mesons and nucleons may lead to the existence of mesic nuclei. Deeply bound pionic states are known to exist due to the superposition of the attractive electromagnetic and repulsive strong interaction. In the case of the neutral η meson an attractive strong ηN interaction would allow for the formation of η-mesic nuclei. First predictions for such states were based on investigations of the η-nucleon scattering length $a_{\eta N}$. Its real part can be interpreted as a measure for the scattering of the initial particles while its imaginary part accounts for losses into other channels. First estimates of the ηN scattering length have been extracted from coupled channel analyses, performed by Bhalerao and Liu [1] in 1985. They found a scattering length $a_{\eta N}$ of $(0.27 + i0.22)$ fm. The corresponding phase shifts have positive values which indicate an attractive potential. Based on these calculations, Liu and Haider [2] claimed that bound states between the η and a nucleus should be possible for nuclei with mass number $A > 10$.

In 1992, Ueda [3] predicted the existence of a quasibound ηNN state with $I = 0$, $J = 1$. These theoretical studies have raised hopes of experimentally discovering quasibound states of η mesons in light nuclei. If they exist, one may expect them to be narrow in few-nucleon systems. The rapid slope of the near-threshold amplitude in $pd \rightarrow \eta^3\text{He}$ was interpreted by Wilkin [4] as an indirect evidence for the existence of η-mesic nuclei. A recent experiment [5] studied the possible photoproduction of η-mesic boron via the reaction $\gamma + {}^{12}\text{C} \rightarrow p + {}^{11}_{\eta}\text{B} \rightarrow \pi^+ + n + X$ with an intermediate $S_{11}(1535)$ resonance which decays into $\pi^+ n$. The correlated energies and momenta of pion and neutron have been used as a signature for the reaction channel.

Concerning the lightest nuclei, photoproduction experiments on the deuteron [6,7] and on ^{4}He [8] have shown modifications of the near-threshold behavior via a comparison with models based on an impulse approximation. Sibirtsev *et al.* [9] took final state interactions of the NN system as well as in the ηN system into account in their calculation of the quasifree η photoproduction off ^{2}H. The data were best reproduced for a scattering length $a_{\eta N} = (0.42 + i0.34)$ fm. Other analyses (e.g., [4,10–12]) of the scattering length yield varying results, especially for the real part of the scattering length. The η-^{3}He scattering length, extracted from photoproduction or hadroproduction, provides information on the possibility of a bound state of η and nucleus. In this Letter, the results for coherent η production off ^{3}He and the η-mesic decay channel into $\pi^0 pX$ are presented in terms of a possible photoproduction of η-mesic ^{3}He.

The experiment was performed at the electron accelerator facility Mainz Microtron (MAMI) [13]. Photons were produced in a thin radiator foil and their energies were determined using the Glasgow tagged photon spectrometer [14]. The tagged photon energy range was 275–820 MeV with an energy resolution of ~2 MeV. The reaction products were detected in the TAPS photon spectrometer [15,16]. TAPS consisted of six blocks each with 62 hexagonally shaped BaF_2 scintillation detectors arranged in an 8×8 matrix and a forward wall with 138 BaF_2 detectors in an upright 11×14 arrangement. The length of the crystals is 250 mm (~12 radiation lengths) with an inner diameter of 59 mm plus a cylindrical end cap of 25 mm length (54 mm diameter). The crystals were read out by photomultipliers. The six blocks were located in a horizontal plane around the target point at angles of 153°, 104°, 55°, −54°, −103°, and −152° with respect to the beam axis at distances of 55–59 cm. The forward wall was positioned at 0° at a distance of 55 cm. The solid angle covered by this setup is around 40% of the full solid angle [17]. The target had an effective length of 115 mm and a diameter of 43 mm. It was filled with liquid ^{3}He. More detail can be found in [18].

For the identification of the η and π^0 mesons the double photon decay channel was used. The two photon invariant mass was calculated from the momenta of the measured photons. The experimental resolution is 21 MeV (FWHM) for π^0 detection and 60 MeV for the η meson. The identification of protons is achieved via the characteristic relation between deposited energy and time of flight, as well as pulse shape analysis [19]. The calibration of the proton energy was performed by calculating the missing mass for the reaction $\gamma^3\mathrm{He} \rightarrow \eta p d$. Energy losses of the protons and quenching effects in the detector have been corrected for such that the missing mass corresponds to that of the proton. Random coincidences in the tagging spectrometer have been taken into account by subtracting background events before and after the prompt time coincidence peak.

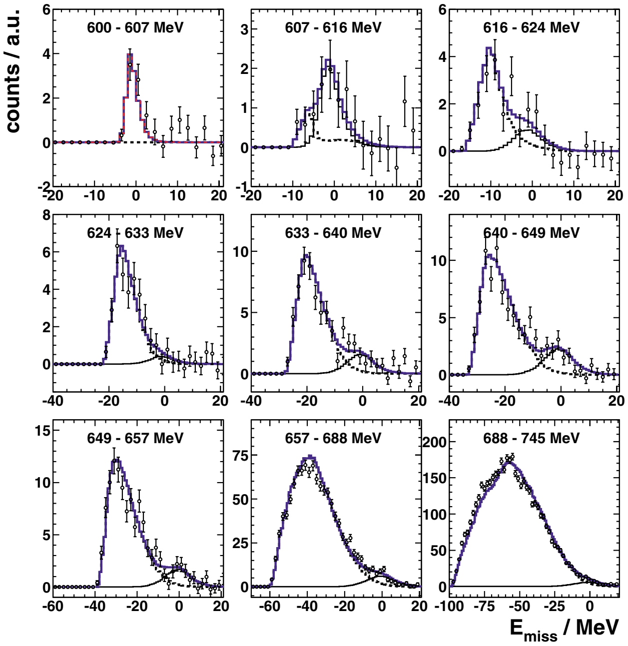

FIG. 1 (color online). Missing energy plots assuming coherent reaction kinematics in different regimes of the incoming photon energy. The simulations of the coherent reaction (thin solid lines) and the quasifree reaction (dashed lines) are adjusted to fit the data points. The thick solid lines show the sum of both simulations. At threshold (upper left plot, $E_\gamma =$ 600–606 MeV), the η production proceeds solely via the coherent process. In the other plots, the coherent cross section was derived from the ratio of the quasifree and coherent part (see text).

The inclusive η cross section was deduced from the rate of η events divided by the number of target nuclei per cm^2, the photon flux, the branching ratio of η into 2γ, and the detection and analysis efficiency. These efficiencies were determined by Monte Carlo simulations using the GEANT3 code. The photon flux was measured by counting the number of scattered electrons in the tagger. The missing energy, E_{miss}, for the coherent reaction $\gamma^3\mathrm{He} \rightarrow \eta^3\mathrm{He}$ was obtained by subtracting the calculated η energy from two-body kinematics from the measured η energy in the η-^{3}He center of momentum (CM) system. Coherent events should be centered at $E_{\mathrm{miss}} = 0$ MeV while breakup events are distributed at negative values of the missing energy. The fraction of coherent η production (thin solid lines in Fig. 1) and quasifree η production (dashed lines) was obtained by fitting simulations for both production mechanisms to the experimental data. The simulation for the quasifree production includes the elementary production cross section on the proton folded with the Fermi momentum distribution. The resulting coherent η cross section is plotted in Fig. 2. The peaklike behavior of the near-threshold cross section can be interpreted as a first sign for a modified η production process. To investigate this behavior further, the angular distribution for the two energy ranges 600–625 and 625–745 MeV are plotted in the lower part of Fig. 2. While the latter distribution agrees with the expected angular dependence $[d\sigma/d\Omega \sim F^2(q^2)]$, the distribution at threshold is unexpectedly isotropic. Here, $F^2(q^2)$ is the ^{3}He form factor depending on the momentum transfer q. The observations are consistent with the assumption of an η-mesic nucleus which isotropically decays into the coherent η channel.

There are different theoretical efforts for describing the experimental data. A plane wave impulse approximation calculation by Kamalov and Tiator [20,21] does not deal with final state interaction (FSI) effects (dotted lines in Fig. 2). FSI effects are explicitly taken into account in the calculations of Shevchenko and collaborators [22,23] The model employs the finite rank approximation which excludes virtual excitations of the nucleus during the interaction with the η meson. The calculation is performed in such a way as to reproduce the real part of the scattering length to be 0.75 fm (dashed and dot-dashed lines in Fig. 2). A third calculation has been performed by Fix and Arenhövel [24]. In contrast to the assumptions of Shevchenko which neglect target excitations, a two-body quasiparticle separation is applied to the η-$3N$ problem. The analysis obtains values for the η-^{3}He scattering length that do not allow a bound state of η and nucleus.

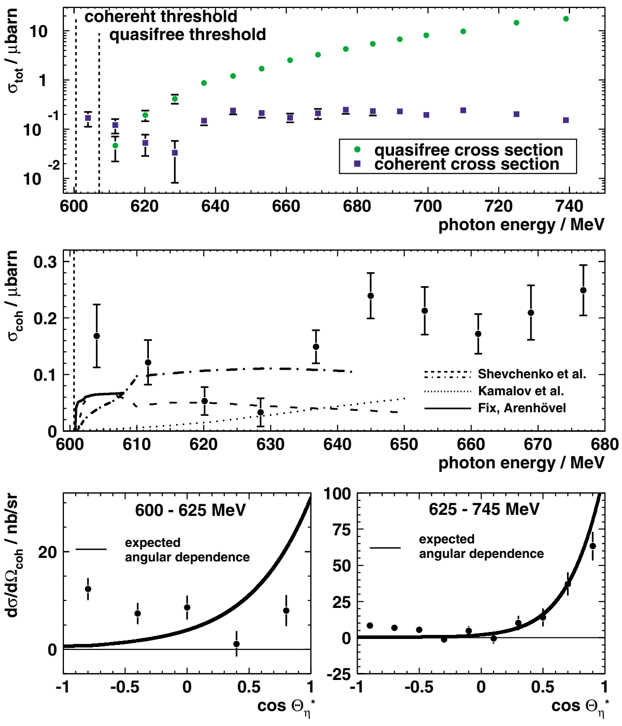

FIG. 2 (color online). Total cross sections for coherent and quasifree η production off ^{3}He and angular distributions in the γ-^{3}He CM system. The error bars contain statistical and systematic uncertainties. The curves in the angular differential plots show the calculated coherent η cross section according to $d\sigma/d\Omega \sim F^2(q^2)$ scaled to the measured data. Calculations of the coherent cross section are compared to the data.

However, the existence of a virtual pole near threshold is claimed, implying a quasiresonance with positive binding energy that modifies the threshold behavior of the coherent cross section. The cross section shows a sharp cusp effect at threshold but stays a factor of 2 below the measured data (solid lines in Fig. 2).

Earlier measurements of the η production off ^{3}He [25,26] in a different initial state—the proton induced reaction on the deuteron—showed a similar energy dependence when dividing the different phase space factors out and thus comparing the average amplitude as a function of the η momentum in the CM frame (Fig. 3). Only the two data points between 0.6 and 0.8 fm^{-1} seem to be significantly lower in the photoproduction data compared to the proton induced case. Also shown in Fig. 3 is an optical model fit to the data below 0.5 fm^{-1}.

Additional information about a possible η-mesic state can be deduced by studying another decay channel for an η-mesic nucleus. The quasibound system will decay into η-^{3}He for energies above the η production threshold. Since the phase space is limited, the momentum of the decaying η meson will preferentially be low, and hence there is a high probability for the η to be captured by a nucleon into an $S_{11}(1535)$ resonance. This resonance has some 50% branching ratio into ηN but also roughly the same probability to decay into πN. The advantage of the latter decay mode is that the η meson is acting as an intermediate particle only. Only the lighter π meson is emitted in the final state. Hence the reaction can also take place below the η production threshold. Below threshold, the decay into η-^{3}He is not possible and the decay proceeds exclusively into the πN channel.

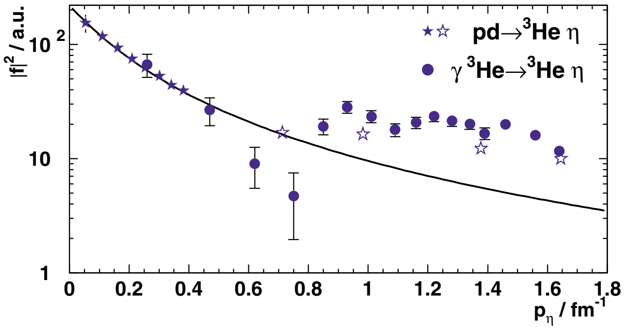

FIG. 3 (color online). Average amplitude squared as a function of the CM η momentum for the proton induced reaction (full stars [25], empty stars [26]) compared to the photoproduction data. The normalization of the data sets is arbitrary. The solid curve is an optical model fit of the near-threshold data (figure adapted from [26]).

The signature for the decay of an η-mesic nucleus into πN is given by correlated pairs of π^0 and p. With a low momentum η in the intermediate state, the decaying S_{11} will also be at low momentum. Thus, the relative angle of π^0 and proton has to be near 180° in the γ-^{3}He CM system. The triangles in the left panel of Fig. 4 show the excitation function for relative angles between 170° and 180° as a function of $W = \sqrt{2E_\gamma m_{^3\mathrm{He}} + m^2_{^3\mathrm{He}}} - m_d - B_{^3\mathrm{He}}$. Here, the total CM energy is reduced by the mass m_d of the residual nucleus and the ^{3}He binding energy of $B_{^3\mathrm{He}} = -5.5$ MeV [the η-^{3}He binding energy for a structure at resonance mass W_R would then be given as $B_\eta = W_R - (m_\eta + m_p)$]. The reaction channel is dominated by the quasifree π^0 production. This background channel is determined by subtracting the scaled $\pi^0 p$ excitation function for relative opening angles of 150° to 170°. A remaining structure just below the production threshold for η mesons may indicate the formation for an η-mesic ^{3}He nucleus. Its peak position is $W_R = 1483$ MeV (± 5 MeV) with a width $\Gamma = 39$ MeV (± 21 MeV). The experimental resolution is given by the tagger spectrometer resolution of about 2 MeV. The statistical significance of the structure $\sigma = [S/\sqrt{(\Delta S)^2 + (\Delta \mathrm{BG})^2}]$ (S is the number of signal counts and BG the corresponding background under the peak) is $\sim 3.5\sigma$. Figure 5 shows a comparison of both decay channels with a simultaneous fit of both channels. The result, $W_R = 1481.2$ MeV (± 4.2 MeV) and $\Gamma = 25.3$ MeV (± 6.1 MeV), is consistent with the results given in Fig. 4 but reduces the error bars on the extracted parameters. The different phase space factors for the two decay channels were taken into account by assuming a single intermediate

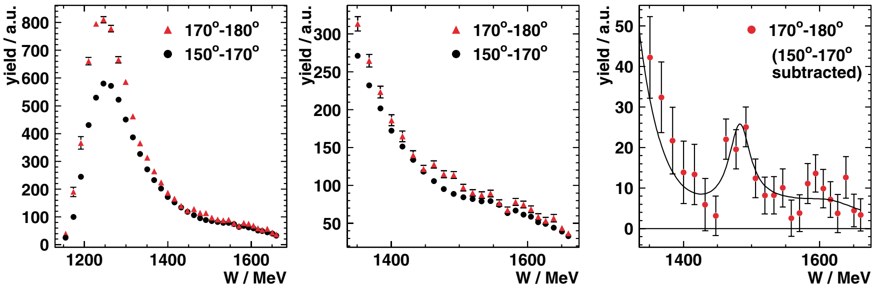

FIG. 4 (color online). Left and center panels: Excitation function of the π^0-proton production for opening angles of 170°–180° (triangles) compared to opening angles of 150°–170° (circles) in the γ-^{3}He center of momentum system. Right panel: Difference of both distributions with a Breit-Wigner distribution plus background fitted to the data.

$S_{11}(1535)$ resonance neglecting multiscattering processes. The fit function is a Breit-Wigner distribution $f_{\rm BW}(W) = [\frac{1}{4}\Gamma^2/(W - W_R)^2 + \frac{1}{4}\Gamma^2]$ folded with the corresponding phase space factors

$$B_{\pi,\eta}(W) = b_{\pi,\eta} \times \sqrt{\frac{[W^2 - (m_p - m_{\pi,\eta})^2][W^2 - (m_p + m_{\pi,\eta})^2]}{4W^2}}.$$

Here, $b_{\pi,\eta}$ are constants that fix the partial widths for the decay of the S_{11} into π and η to 75 MeV at the pole mass of 1535 MeV, respectively. Further, m_p is the proton mass and $m_{\pi,\eta}$ are the meson masses.

In summary, we have investigated the photoproduction of η-mesic ^{3}He by studying two possible decay channels: the coherent η production and the decay into $\pi^0 p$. Both decay channels show indications for photoproduction of η-mesic ^{3}He. In the η channel, a resonancelike behavior of the coherent cross section associated with an isotropic angular distribution in the threshold regime is observed. In contrast, a strong forward peaking is expected for coherent η production from form factor considerations. In the $\pi^0 p$ channel, correlated π^0-proton pairs with relative angles near 180° in the CM system have been observed that give rise to a peaklike structure at energies slightly below the η production threshold. The extracted resonance parameters [binding energy = (-4.4 ± 4.2) MeV, full width = (25.6 ± 6.1) MeV] are consistent with expectations for η-mesic nuclei.

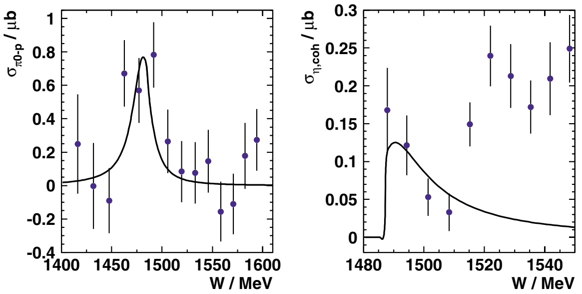

FIG. 5 (color online). Comparison of the decay channels of an η-mesic nucleus together with a simultaneous fit. The resonance position is at 1481.2 MeV ± 4.2 MeV with a full width of (25.3 ± 6.1) MeV.

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