Coherent η-Meson Production in the Reaction $\pi^- + {}^3\mathrm{He} \to \eta + t$

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The reaction $\pi^- + {}^3\mathrm{He} \to \eta + t$ has been observed by detecting $\eta \to 2\gamma$ decays. The observed forward-angle cross sections vary from ~ 100 μb/sr at 680 MeV/c to ~ 2 μb/sr at 590 MeV/c. Distorted-wave impulse-approximation calculations reproduce the shape but underestimate the magnitude of the observed cross sections. These cross sections are approximately 100 times larger than those for the reaction $p + d \to \eta + {}^3\mathrm{He}$ measured at similar η center-of-mass energies.

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The pion-nucleus interaction has been extensively studied at the meson factories. To obtain a global picture of the meson-nucleus interaction, it is clearly desirable to also study the interaction between other heavier mesons and nuclei. In particular, interest in the physics of η mesons has grown significantly in recent years. For example, the observation[1] of an unexpectedly large cross section for the $p + d \to \eta + {}^3\mathrm{He}$ reaction near threshold energy suggests the possibility[2] of building a tagged-η facility for measuring rare decay modes of the η. This observation also generates considerable interest in investigating the mechanisms responsible for η production in nuclei[3] and in understanding the nature of the η-nucleus interaction.[4]

η mesons can be produced with pion and photon beams as well as with proton beams. In particular, the $\pi^- + p \to \eta + n$ reaction has been extensively studied. A recent coupled-channel analysis[5] of this reaction in the framework of an isobar model suggests an attractive ηN interaction with a scattering length of $0.28 + 0.19i$ fm. This analysis led to the prediction[6] of the existence of η bound states in nuclei. However, an experiment[7] to search for such narrow η-nuclear bound states failed to show positive evidence, suggesting that the widths of these η-nuclear states are significantly broader than predicted.[6]

In this Letter, we report the measurement of the $\pi^- + {}^3\mathrm{He} \to \eta + t$ reaction at several beam momenta near threshold energy. Like the $p + d \to \eta + {}^3\mathrm{He}$ reaction, the $\pi^- + {}^3\mathrm{He} \to \eta + t$ reaction involves coherent production of the η meson in a mass-3 system. The behavior of production near threshold energy will be compared for these two reactions. These data are also expected to provide information on the mechanism of pion-induced η production in nuclei, and on the nature of the η-nucleus interaction at low energies. In particular, the $\pi^- + {}^3\mathrm{He} \to \eta + t$ cross sections can be compared with predictions using the $\pi N \to \eta N$ amplitudes of Ref. 5.

The $\pi^- + {}^3\mathrm{He} \to \eta + t$ reaction can be observed by detecting the $\eta \to 2\gamma$ decay. This reaction was observed[8] for the first time in a recent experiment by detecting the recoil tritons corresponding to backward center-of-mass (c.m.) angle η production. The present experiment covers the forward-c.m.-angle region at several beam energies and complements the previous measurement. These measurements also represent the first attempt to measure the (π,η) reaction on nuclear targets with sufficiently good energy resolution to identify transitions to discrete nuclear states. Previous experiments, performed at much higher beam energies, had relatively poor energy resolution and could study only the inclusive (π,η) reaction on nuclei.[9,10]

The experiment was performed at the High Energy Pion Channel (P^3) at the Clinton P. Anderson Meson Facility (LAMPF). Pion beams of 680, 650, 620, 600, and 590 MeV/c were incident on a cryogenic ^{3}He target.[11] The pion flux, measured by placing a sampling grid scintillator[12] (SGS) in the beam downstream of the target, varied from 4.0×10^5 π^-/s at 680 MeV/c to 4.5×10^6 π^-/s at 590 MeV/c. The SGS is able to measure relatively high beam flux. It is composed of small pellets of scintillator implanted uniformly in a slab of lucite so that only 0.85% of the beam is sampled. The SGS used in this experiment is similar to the one designed by Holley, Schnurmacher, and Zingher.[13]

The η mesons were detected using the LAMPF π^0 spectrometer[14] in a two-post configuration. The two arms of the spectrometer measured the energies and conversion points of the two high-energy photons from the $\eta \to 2\gamma$ decay. The distance from the target to the front of the first photon converter was set at 50 cm. The opening angle (ψ) between the two arms of the spectrometer was set at a variety of angles ($150° \geq \psi \geq 116.6°$) in order to detect η mesons produced at a range of beam momenta. Since the η mesons produced in this experiment have relatively low kinetic energies, the pair of photons from the $\eta \to 2\gamma$ decay give a unique signature due to their high energies and large opening angle. Figure 1 shows the resulting invariant mass of the two photons, $M = 2\sin(\psi/2)(E_1E_2)^{1/2}$, for incident momenta of 680 and 590 MeV/c. E_1 and E_2 are the energies of the two photons. The η mesons are clearly identified by the peak centered around 550 MeV in this invariant-mass spectrum. The continuum background in the mass plot is attributed mainly to two random photons, each emitted from a separate π^0 meson. Details on the detection of η mesons with the LAMPF π^0 spectrometer have been published elsewhere.[15]

After selecting the η events by their invariant mass, the η kinetic energies are calculated using the expression

$$T = \frac{M_\eta}{\sin(\psi/2)(1-X^2)^{1/2}} - M_\eta, \qquad (1)$$

where $X = (E_1 - E_2)/(E_1 + E_2)$ and M_η is the mass of η.

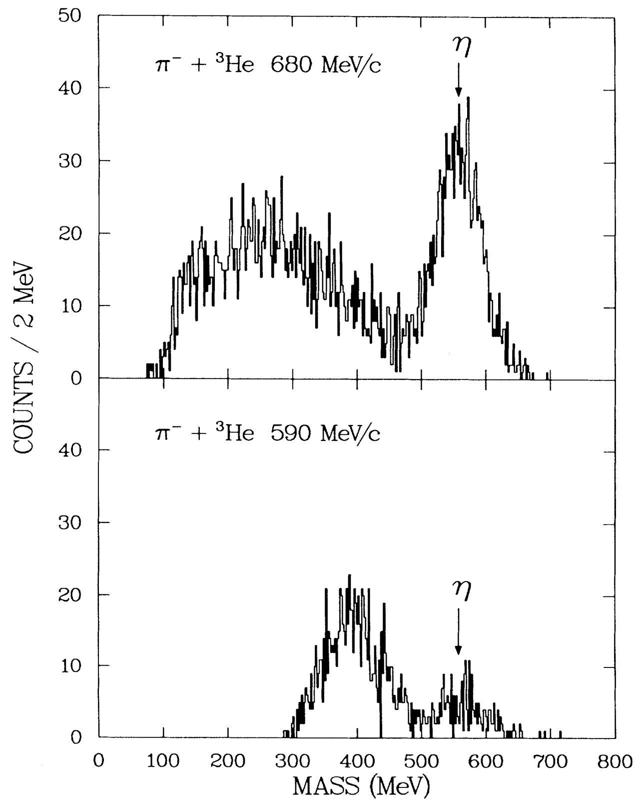

FIG. 1. Invariant-mass spectra of the two photons detected in the $\pi^- + {}^3$He reaction at 680 and 590 MeV/c. A higher photon-energy threshold was applied in the measurement at 590 MeV/c.

The expected energy resolution is obtained from a Monte Carlo simulation[14] which includes the effects of the beam momentum spread, the finite target thickness, the position resolution of the converters, and the intrinsic energy resolution of the lead-glass shower detectors. The expected energy resolution varies from $\sigma = 6$ MeV at 590 MeV/c to $\sigma = 10$ MeV at 680 MeV/c, with the dominant contribution coming from the effects of finite target thickness (5 cm) which cause an uncertainty in the determination of the opening angle.

Figure 2 shows the ^{3}He(π^-,η) spectra measured at 650 and 620 MeV/c. Both the exclusive reaction, $\pi^- + {}^3\mathrm{He} \to \eta + t$, and the continuum reaction, $\pi^- + {}^3\mathrm{He} \to \eta + t^*$, contribute to the observed spectra. At 620-MeV/c incident momentum the exclusive transition is clearly observed as a peak at zero excitation energy (E_x). At 650 MeV/c, the exclusive ground-state transition is less well separated from the continuum transition. Nevertheless, the spectrum shows a large excess of counts near zero excitation energy. In order to verify that these counts indeed correspond to the ground-state transition, we have also measured the cross sections for the ^{3}He(π^+,η) reaction with identical settings of the spectrometer. These spectra are also shown in Fig. 2. Since the ^{3}He(π^+,η) reaction can only lead to three-

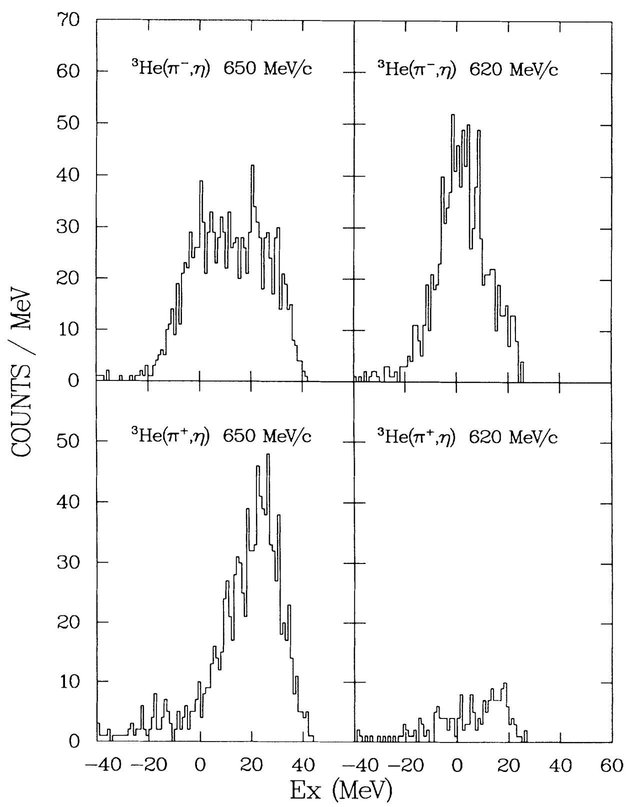

FIG. 2. Excitation-energy spectra for $(\pi^\pm,\eta)$ reactions on ^{3}He measured at 650 and 620 MeV/c. $E_x = 0$ corresponds to the $\pi^- + {}^3\mathrm{He} \to \eta + t$ transition.

proton continuum states, a comparison between the $^3He(\pi^+,\eta)$ and the $^3He(\pi^-,\eta)$ spectra indicates the presence of strength from the $\pi^- + {}^3He \rightarrow \eta + t$ transition. It is also interesting to note that at 590 MeV/c the beam energy is only 4 MeV above the $\pi^- + {}^3He \rightarrow \eta + t$ threshold and is below the threshold for exciting continuum states. Therefore the η peak observed at 590 MeV/c (Fig. 1) can only come from the $\pi^- + {}^3He \rightarrow \eta + t$ reaction.

The differential cross sections for the $\pi^- + {}^3He \rightarrow \eta + t$ reaction are shown in Fig. 3 for five beam energies. The error bars include uncertainties in the beam flux, the acceptance of the spectrometer, the separation of the ground state from the continuum states, and the statistics. Figure 3 shows that the cross sections at forward angles vary from ~ 100 μb/sr at 680 MeV/c to ~ 2 μb/sr at 590 MeV/c, a drop of approximately a factor of 50 over the $\sim$100-MeV/c momentum range studied. Figure 3 also shows that the differential cross sections become nearly isotropic as the beam momentum approaches the absolute threshold. This is consistent with contributions from S wave only just above threshold energies.

Theoretical studies of the $\pi^- + {}^3He \rightarrow \eta + t$ reaction have been performed in the framework of the distorted-wave impulse approximation (DWIA). The $\pi N \rightarrow \eta N$ and $\eta N \rightarrow \eta N$ amplitudes used in the DWIA calculations were obtained from Ref. 5, where an off-shell model was used to describe the $\pi^- p \rightarrow \eta n$ reaction near threshold energy. In this model, the $\pi^- p \rightarrow \eta n$ reaction proceeds through the formation of N^* isobars. The resulting off-shell amplitudes are required to describe the $\pi^- + {}^3He \rightarrow \eta + t$ reaction at energies below the free threshold. The nuclear form factors for ^3He and t were taken from electron-scattering experiments.[11,16]

The results of the DWIA calculations are shown in Fig. 3. Two different sets of the $\pi N \rightarrow \eta N$, $\eta N \rightarrow \eta N$ amplitudes, based on two different πN phase shifts,[17,18] were used in these calculations. While the shape of the angular distributions is quite well reproduced by the DWIA calculations, the absolute magnitude is under-predicted by a factor of 1.5–1.6. This situation is similar to what has been observed previously in the $\pi^- + {}^3He \rightarrow \eta + t$ reaction at back angles, where the DWIA

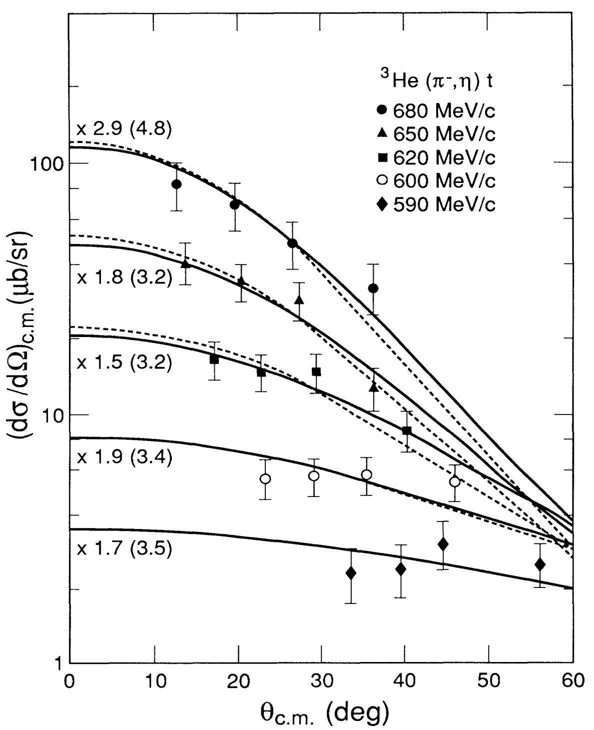

FIG. 3. Angular distributions of the cross section for the $\pi^- + {}^3He \rightarrow \eta + t$ transitions. Solid (dashed) curves represent DWIA predictions using (π,η) amplitudes deduced from the πN phase shifts of Ref. 17 (Ref. 18). The calculations have been renormalized by the factors shown next to the curves in order to match the absolute magnitude of the cross sections. The numbers in parentheses are for the dashed curves.

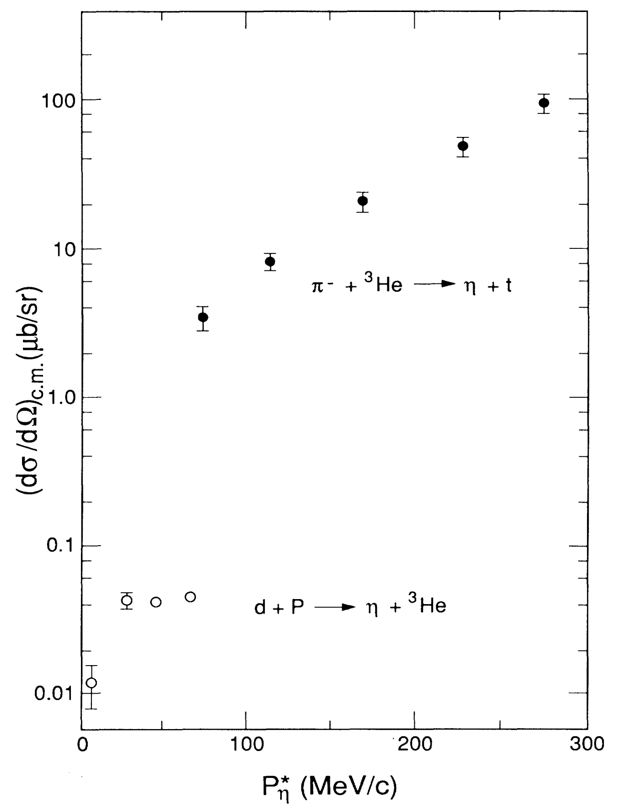

FIG. 4. Cross sections for the $\pi^- + {}^3He \rightarrow \eta + t$ reaction at $\Theta = 0°$ plotted as a function of η c.m. momenta (P_η^*). The cross sections were obtained by extrapolating the data to 0° using the DWIA fits shown in Fig. 3. The forward-angle data from Ref. 1 for the $d + p \rightarrow \eta + {}^3He$ reaction are also shown for comparison.

underpredicts the cross sections by a factor of 2–4. It is worth noting that the two sets of amplitudes, which give equally good descriptions of the $\pi^- p \to \eta n$ data, predict magnitudes for the $\pi^- + {}^3\mathrm{He} \to \eta + t$ cross sections which differ by a factor of 2. The amplitudes deduced from the πN phase shifts of Ref. 17 give better agreement with the data than those of Ref. 18. The present result suggests that the mechanisms for (π,η) reactions on nuclei below the free threshold are more complicated than those considered in the first-order DWIA theory. In particular, collective effects, similar to those observed[19] in π^0 production below the free threshold, may lead to significantly enhanced cross sections at these energies. The importance of three-body mechanisms for explaining the $p+d \to \eta + {}^3\mathrm{He}$ reaction, as discussed in Ref. 3, should also be examined.

It is of interest to compare the threshold behavior of the $\pi^- + {}^3\mathrm{He} \to \eta + t$ reaction with that of $p+d \to \eta + {}^3\mathrm{He}$. Figure 4 shows the forward-angle cross sections for these two reactions as a function of η c.m. momenta. While the cross sections for the (π,η) reaction increase monotonically with beam energy, the (p,η) cross sections start to level off at $P_\eta^* \simeq 30$ MeV/c. At comparable P_η^* momentum, the (π,η) cross section is ~ 100 times greater than that for (p,η).

In summary, we have observed the $\pi^- + {}^3\mathrm{He} \to \eta + t$ reaction at several beam momenta near threshold. The $\pi^- + {}^3\mathrm{He} \to \eta + t$ cross section is ~ 100 times greater than the $p+d \to \eta + {}^3\mathrm{He}$ cross section at comparable η c.m. momentum. DWIA calculations significantly underpredict the observed cross sections. This discrepancy suggests that the DWIA is an inadequate description of the (π,η) reaction below the free production threshold but may also indicate the inadequacy of the η production amplitudes used in these DWIA calculations. Further theoretical studies beyond the simple DWIA calculations discussed here are needed in order to better understand the mechanisms of the (π,η) reaction on nuclei.

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