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

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Pion-induced η-meson production populating a discrete nuclear state is observed for the first time in the reaction $\pi^- + {}^3\mathrm{He} \to \eta + t$. At 680 MeV/$c$ π^- momentum, this reaction is identified by measurement of the recoiling tritons. The measured cross sections are approximately 3 orders of magnitude greater than the $p+d \to \eta + {}^3\mathrm{He}$ and the $d+d \to \eta + {}^4\mathrm{He}$ cross sections. Distorted-wave impulse-approximation calculations underpredict the observed cross sections by a factor of 2–4.

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In recent years, the subject of the pion-nucleus interaction has been studied in great detail at several meson factories. In contrast, the η meson, which is a pseudoscalar meson classified in the same SU(3) octet as pions and kaons, has received little attention. There exists very little information on η-nucleon interaction, and almost nothing is known about η-nucleus interaction.[1]

It is instructive to compare the η meson with the more familiar π^0 meson. These two neutral mesons have identical quantum numbers of spin, parity, and C parity ($J^{PC}=0^{-+}$) and both decay electromagnetically with 2γ emission as the most dominant decay channel. The major difference is in the isospin ($I=1$ for π^0, $I=0$ for η). The SU(3) quark wave functions of η and π^0 are respectively $(u\bar{u}+d\bar{d}-2s\bar{s})/\sqrt{6}$ and $(u\bar{u}-d\bar{d})/\sqrt{2}$. The dominant quark content of η is the $s\bar{s}$ strange-quark pair, which accounts for the relatively large mass of η (~ 4 times heavier than π^0). A comparative study of the production and interaction of η and π^0 mesons in nuclei might reveal information on the production and interaction of an $s\bar{s}$ pair in nuclei.

In this Letter we report on the first observation of pion-induced η-meson production on a nuclear target, namely, the reaction ${}^3\mathrm{He}(\pi^-,\eta)t$. Existing data on the (π,η) reaction in nuclei are sparse and restricted to inclusive measurements with high-energy pion beams $[E(\pi) > 3$ GeV$]$.[2-6] The reaction ${}^3\mathrm{He}(\pi^-,\eta)t$ can be considered as a charge-exchange reaction similar to the reaction ${}^3\mathrm{He}(\pi^-,\pi^0)t$. However, unlike conventional charge-exchange reactions such as $(\pi^\pm,\pi^0)$ and (p,n), the (π^-,η) reaction involves two particles not belonging to the same isospin multiplet. The large mass difference between π^- and η implies a large momentum transfer in the (π^-,η) reaction, again distinct from conventional charge-exchange reactions. Therefore, the reaction mechanism and selectivity of the (π^-,η) reaction can be quite different from that of (π^-,π^0). It would be very informative to compare the reaction ${}^3\mathrm{He}(\pi^-,\eta)t$ with the well-studied reaction ${}^3\mathrm{He}(\pi^-,\pi^0)t$.[7,8]

The reaction ${}^3\mathrm{He}(\pi^-,\eta)t$ can also be regarded as coherent production of η mesons. As such, it provides information on the mechanism for coherent η-meson production and on the nature of the η-nucleus interaction, both of which are totally unknown at present.

The experiment was performed at the P^3 channel of the Clinton P. Anderson Meson Physics Facility (LAMPF). A 680-MeV/c π^- beam, with $\Delta p/p$ of 1.5% and a flux of 2×10^5/s, was incident upon a ${}^3\mathrm{He}$ cryogenic target.[9] The target cell, made of 2-mil-thick stainless steel, has a cylindrical shape with a 5-cm diameter. In order to identify the reaction ${}^3\mathrm{He}(\pi^-,\eta)t$, we detected the tritons emitted at forward angles by using the large-acceptance spectrometer (LAS),[10] which consists of two quadrupoles and one dipole. The dipole field was set for a central momentum of 783 MeV/c and the quadrupole fields were set near their maximum values to give a solid-angle acceptance of ~ 10 msr. Four sets of delay-line readout wire chambers were used to determine the trajectories and momenta of charged particles. Scintillators placed at the entrance and exit of the spectrometer provided time-of-flight (TOF) information.

Identification of tritons was achieved on the basis of the momentum and TOF information. The spectrometer was set at $\theta_{\mathrm{lab}}=5°$ and 10° to measure the (π^-,t) reaction on the ${}^3\mathrm{He}$ target. The acceptance of the LAS and the efficiency of the wire chambers were checked by our detecting the reaction $p(\pi^-,p)\pi^-$. This measurement was made on a CH_2 target with the conditions of the

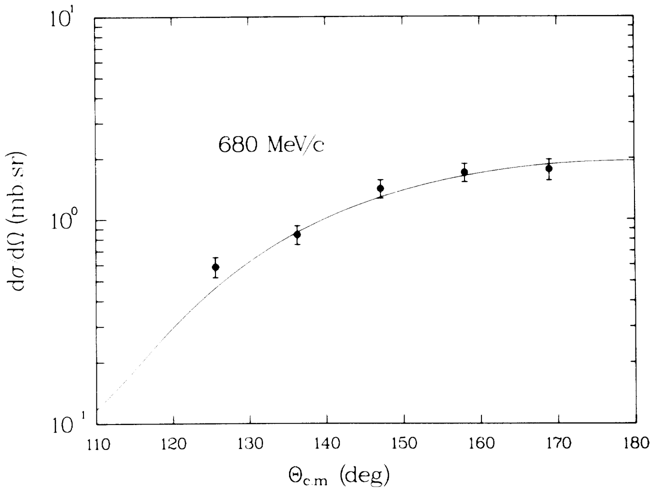

FIG. 1. Angular distribution for the reaction $p(\pi^-,\pi^-)p$ measured with the LAS by detection of the recoiling protons. The solid curve is the prediction of the phase-shift solution in Ref. 11.

LAS identical to the $^3He(\pi^-,t)$ measurements. Figure 1 shows the $p(\pi^-,p)\pi^-$ cross sections from this experiment and those from the phase-shift solution of Arndt and Roper.[11] The good agreement between them indicates that the characteristics of the LAS detection system are well understood.

Figure 2(a) shows the time of flight versus momentum for the measurement of the 680-MeV/c π^- beam on the ^3He target at $\theta_{lab}=10°$. The tritons are clearly separated from the deuterons. The momentum spectrum of tritons is shown as the solid curve in Fig. 2(b). The arrow in Fig. 2(b) indicates the expected location of tritons emitted in the reaction $^3He(\pi^-,t)\eta$. Since some of the detected tritons originate from the reaction of the π^- with the stainless-steel target cell, separate measurements on a stainless-steel dummy target with an equivalent amount of pions were made. The (π^-,t) spectrum on the dummy target, shown as the dashed curve in Fig. 2(b), exhibits a shape which falls off at higher triton momenta, similar to other pion-induced particle-emission spectra.[12]

Figure 3 shows the $^3He(\pi^-,t)$ energy spectra resulting from the subtraction of the dummy target spectra. In both spectra, a peak is observed at the location corresponding to the binary reaction $^3He(\pi^-,t)\eta$. The width of these peaks is ~ 15 MeV, consistent with an energy resolution attributed mainly to the beam momentum spread, the energy loss of tritons in the ^3He target, and the multiple scattering of tritons in the spectrometer. In addition to the $^3He(\pi^-,t)\eta$ peak, a continuum background is also observed. The origin of this continuum is believed to be from the multipion-production reactions $^3He(\pi^-,t)\pi\pi$ and $^3He(\pi^-,t)\pi\pi\pi$. The $^3He(\pi^-,t)\pi^0$ binary peak is situated far outside the momentum acceptance of the spectrometer. The dashed lines in Fig. 3 represent our estimate of the continuum background under the $^3He(\pi^-,t)\eta$ peak. This estimate is made by our assuming a smooth shape for the multipion-production spectra.

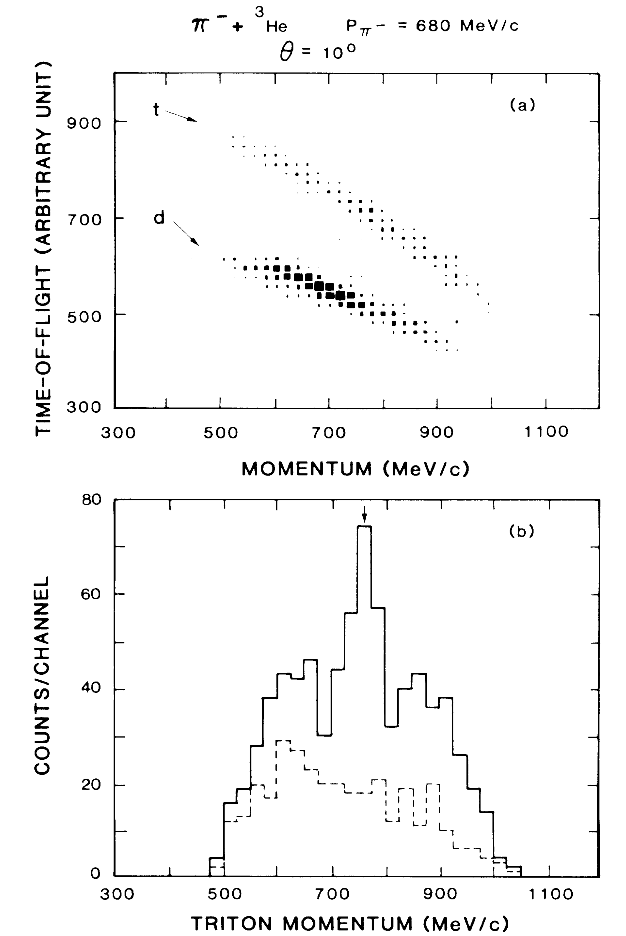

FIG. 2. (a) Separation between the triton group and the deuteron group as shown in the momentum-vs-TOF plot. (b) The triton spectra for the (π^-,t) reaction on ^3He and dummy targets, shown as the solid and dashed curves, respectively.

Figure 4 shows the cross sections of the reaction $^3He(\pi^-,\eta)t$ measured in this experiment. Although recoil tritons were detected at forward laboratory angles, these angles correspond to backward center-of-mass angles in the reaction $^3He(\pi^-,\eta)t$. The momentum transfer at these angles is very large (~ 800 MeV/c). It is remarkable that the observed cross sections are rather sizable (0.82 ± 0.19 μb/sr at $\theta_{c.m.}=149.1°$ and 1.01 ± 0.30 μb/sr at $\theta_{c.m.}=164.7°$) despite the unfavorable momentum transfer and the fact that the beam momentum is already below the threshold for $p(\pi^-,\eta)n$ (686 MeV/c). These results are to be compared with the proton-induced η-meson production reaction $p+d\rightarrow {}^3He+\eta$, where the cross sections at backward

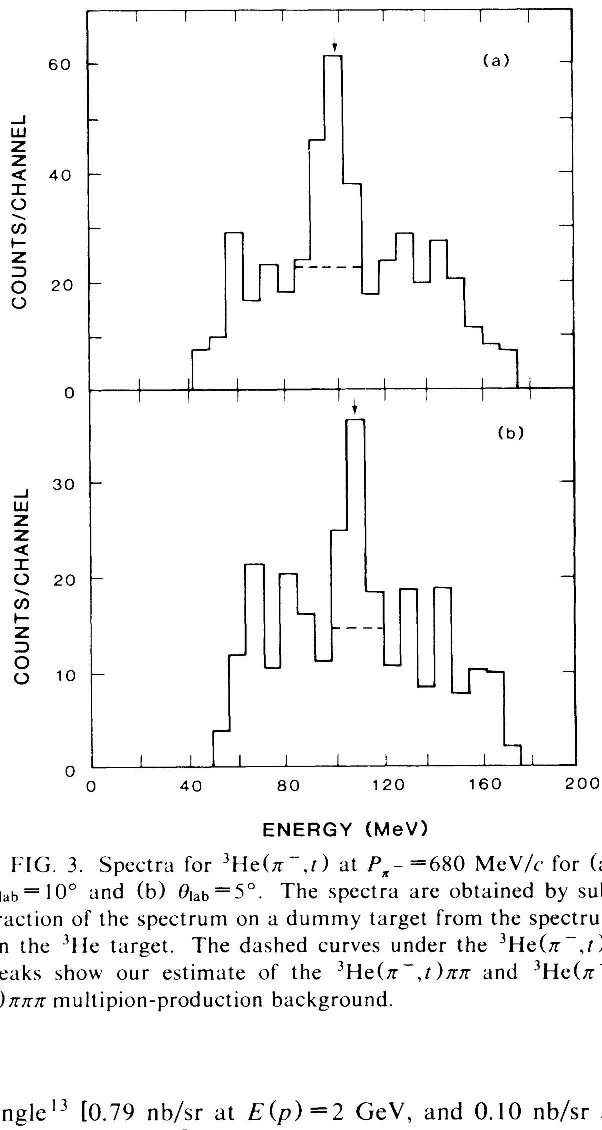

FIG. 3. Spectra for $^3He(\pi^-,t)$ at $P_{\pi^-}=680$ MeV/c for (a) $\theta_{lab}=10°$ and (b) $\theta_{lab}=5°$. The spectra are obtained by subtraction of the spectrum on a dummy target from the spectrum on the ^3He target. The dashed curves under the $^3He(\pi^-,t)\eta$ peaks show our estimate of the $^3He(\pi^-,t)\pi\pi$ and $^3He(\pi^-,t)\pi\pi\pi$ multipion-production background.

angle[13] [0.79 nb/sr at $E(p)=2$ GeV, and 0.10 nb/sr at $E(p)=3.74$ GeV] are more than 3 orders of magnitude lower than those of the reaction $\pi^- + {}^3He \rightarrow \eta + t$. A recent measurement of the reaction $d+d \rightarrow {}^4He+\eta$,[14] at 1.95 GeV deuteron kinetic energy, gives a c.m. cross section of 0.25 ± 0.10 nb/sr for η's produced at $\theta_{c.m.}=146°$. It is also interesting to compare the $^3He(\pi^-,\eta)t$ with the reaction $^3He(\pi^-,\pi^0)t$ which has been measured at several beam energies. The back-angle ($\theta_{c.m.} \simeq 140°$) cross section[7] for the reaction $^3He(\pi^-,\pi^0)t$ measured at 406 MeV/c is $\simeq 8$ μb/sr, about a factor of 10 larger than the $^3He(\pi^-,\eta)t$ cross sections measured in this experiment. One would expect this factor to be significantly larger, since the $p(\pi^-,\pi^0)n$ cross section at 406 MeV/c is $\simeq 20$ mb while the Fermi-averaged $p(\pi^-,\eta)n$ cross section at 680 MeV/c is calculated by us to be $\simeq 1$ mb. Furthermore, the momentum mismatch in the reaction $^3He(\pi^-,\eta)t$ is more severe than in the reaction $^3He(\pi^-,\pi^0)t$. Therefore, it appears that the observed

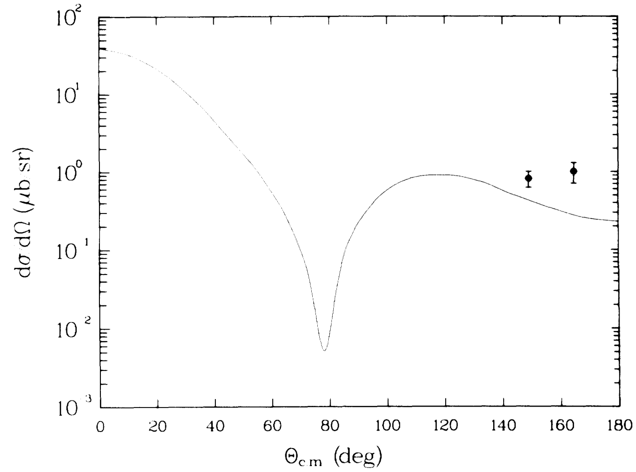

FIG. 4. Cross sections for the reaction $^3He(\pi^-,\eta)t$ measured at $P_{\pi^-}=680$ MeV/c. The solid curve is a prediction of DWIA calculations as described in the text.

$^3He(\pi,\eta)t$ cross sections are larger than expected from simple considerations.

Theoretical studies on the reaction $^3He(\pi^-,\eta)t$ have been carried out by use 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 an off-shell model[15] in which reactions proceed by the formation of N^* isobars. The parameters in the off-shell model were determined from the πN phase shift alone and the existing $\pi^- p \rightarrow \eta n$ cross sections near threshold energies were well described by this model. The nuclear form factors of ^3He and triton were taken from electron-scattering experiments. The result of the DWIA calculation is shown as the solid curve in Fig. 4. The DWIA predicts a diffractive shape for the angular distribution which has a minimum near $\theta \simeq 80°$. The observed cross sections at the backward angles are greater than the prediction by a factor of 2–4. The disagreement between the experimental data and the DWIA prediction calls for further theoretical studies on the mechanisms of the (π^-,η) reaction on nuclei. In particular, the modification of N^* resonances in the nuclear medium and other dynamics of pion and eta propagation inside a nucleus have been ignored in the first-order DWIA calculations.

In summary, we report the first observation of the (π^-,η) reaction on a nuclear target populating a discrete final state. The observed cross sections are many orders of magnitude larger than the proton-induced η-meson production reaction $p+d \rightarrow {}^3He+\eta$. DWIA calculations underpredict the experimental cross sections by more than a factor of 2. The observation of the reaction $^3He(\pi^-,\eta)t$ shows that the isobaric analog state is excited in this unconventional "charge-exchange" reaction despite the unfavorable momentum transfer.

Further experimental studies on the (π,η) reaction over wider ranges of angle, energy, and target mass are under way and should shed more light on the mechanisms of the (π,η) reaction on nuclear targets, and provide more information on the interaction of the η meson and the N^* resonances in nuclei. It would also be interesting to study the production of other massive mesons (ρ, ω, σ, η', etc.) in nuclei with energetic pion beams.

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