Pion Absorption in ^{3,4}He and πN Resonances

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The cross sections of ^{3,4}He$(\pi^-,n)^{2,3}$H have been measured at 285, 428, 525, and 575 MeV, extending the information on the energy dependence beyond the region previously known (50–300 MeV). The cross sections beyond the region of the Δ resonance are found to decrease less rapidly than that of the elementary $\pi d \rightarrow pp$ process. This energy dependence suggests that pion absorption in a nucleus is associated with $\pi + N$ (off-shell) scattering which includes $I=\frac{1}{2}$ πN resonances that are strongly suppressed in $\pi d \rightarrow pp$.

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The nuclear (π,N) reaction to discrete final states $A(\pi,N)A-1$ has mostly been studied at energies below 300 MeV, which is the energy range where the (3,3) Δ resonance is a dominant feature of the πN interaction. The (π,N) reaction reflects the energy variation of the Δ which can be qualitatively understood on the basis that the primary absorption mechanism consists of $\pi + N$ scattering preceding the pion annihilation. At higher energies, the data on $A(\pi,N)A-1$, $A>2$, are scarce and this absorption mechanism has yet to be tested for reactions other than $\pi d \rightarrow pp$. The $\pi d \rightarrow pp$ cross section manifests[1] resonances, one with a maximum just below 200 MeV due to the Δ resonance and another one at around $T_\pi \approx 1200$ MeV due to the next isobaric πN resonance.[2,3] In the intermediate energy range, there is a minimum thought to be due to the suppression of $I=\frac{1}{2}$ πN scattering in $\pi d \rightarrow pp$.[2] In this Letter we present new data on ^{3,4}He$(\pi^-,n)^{2,3}$H which extend the information on the exclusive pion absorption in nuclei of $A>2$ to the energy region above the (3,3) resonance.

The experiment was performed at the Clinton P. Anderson Meson Physics Facility (LAMPF) with use of the high-energy pion channel.[4] In the momentum range of interest, 400 to 700 MeV/c, this beam is relatively free from extraneous particles with an $e^- + \mu^-$ contamination of only a few percent that varies insignificantly with momentum. The beam intensity was monitored with an ion chamber downstream from the target. Liquid ^{3}He/^{4}He targets were used (51 and 91 mg/cm^2 thick) in the same cryostat as in an earlier low-energy experiment.[5] The general procedures and methods of that experiment were also followed as described elsewhere.[5] In short, the detector was a telescope of five plastic scintillators ($S1$–$S5$) of which $S1$–$S3$ provided time-of-flight and differential energy-loss information, $S4$ was the stopping counter for particles of interest, and $S5$ was a veto counter to reject particles (mostly pions) passing $S4$. Particle trajectories and positions were determined with two delay-line wire chambers located after $S1$ and before $S2$. The detector subtended a solid angle of 71 msr and 31° in the reaction plane. By rotating the detector around the target, angles between 25° and 150° were accessible. Protons, deuterons, and tritons could be identified and their energies measured over the ranges $T_p = 22$–150, $T_d = 34$–205, and $T_t = 37$–245 MeV. For incident energies of 285, 428, 525, and 575 MeV, deuteron and triton energy spectra were recorded in angular bins of 5°. Peaks corresponding to the two-body (π^-,n) reactions in ^{3}He and ^{4}He were seen rising from the continuum at the expected energies. The counts in these peaks minus a background determined from adjacent portions of the spectrum divided by the accumulated ion-chamber charge gave the (π^-,n) yield, from which (π^-,n) cross sections were determined by normalizing our 285-MeV data to those at 295 MeV of the previous experiment. The uncertainty in the cross-section scale is about ±15%, which must be added to the mainly statistical uncertainty in each differential-cross-section point.

The results are shown in Fig. 1 in the form of differential cross sections versus the c.m. angle of the neutron. The angular distributions are forward-peaked with a relatively sharp drop for $\theta \lesssim 70°$ followed by a flatter region. The total variation is about a factor of 10 over the measured angular range $\theta \approx 20°-120°$ corresponding to a momentum-transfer range of $q \approx 0.5-1$ GeV/c $\{q = |[(A-1)/A]P_{-\pi} - P_{-n}|$ in the c.m. frame$\}$. We note that the (π^-, n) cross section decreases more slowly with increasing q at higher energies than is typical at lower energies. Actually, our (π^-, n) cross section at large θ is found to be several orders of magnitude larger than expected from the rate of change with q if that rate were extrapolated from the region of lower q values or taken from the analogous (p,d) reaction.[6]

These cross sections can be compared to specific models based on the assumption of a two-nucleon absorption mechanism. We use the results of Fearing[7] where the cross section is expressed as the product of a form factor, $F^2(K)$ with $K \sim [(A-2)/(A-1)]q$, and the measured $d\sigma/d\Omega$ of $\pi d \to pp$. $F(K)$ is essentially the Fourier transform in momentum transfer K of the threefold product of the wave functions of the initial nucleus, the quasideuteron, and the final nucleus. Fearing also includes in $F(K)$ factors to account for the distortions of incoming and outgoing waves, thereby including, for example, the effects of $\pi + N$ scattering preceding the absorption. The prediction tends to fall below the data at large angles for $T_\pi = 285$ and 428 MeV, which is contrary to the situation at lower energies. The enhancement of the cross section at large angles (and large q) might indicate that the form factor, which determines the dependence of the cross section on the nuclear dynamics, has a plateau in this q region. It is also possible that at these higher energies, other reaction mechanisms may contribute as θ increases.

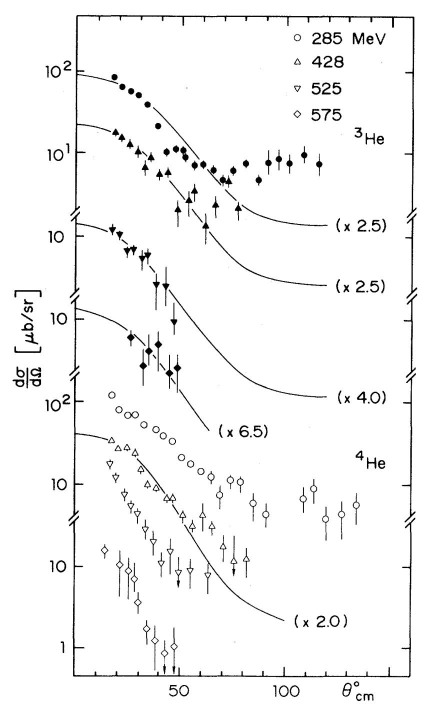

FIG. 1. Results on differential cross sections for $\pi^- + {}^3\text{He} \to n + d$ and $\pi^- + {}^4\text{He} \to n + t$ at 285, 428, 525, and 575 MeV. The solid curves are calculations multiplied with the factors indicated.

We also note that the predicted cross section has to be normalized (see Fig. 1) to match the data. The normalization follows a monotonic trend in energy beginning with a factor of 2 at $T_\pi = 200$ MeV and reaching a factor of 6.5 at 575 MeV; i.e., the predicted cross section falls off with energy faster than the data. It is not immediately clear whether this indicates a shortcoming in the approximations used in the model or is due to an inappropriate choice of reaction mechanisms.

In order to study the energy dependence alone, we integrated the differential cross section over the region $0° \leq \theta \leq 90°$ to obtain σ_F, using the measured values along with an extrapolation outside the measured range where needed. At 525 and 575 MeV, we assumed the same angular shape as observed for lower energies and increased the error on σ_F appropriately. The results are shown in Fig. 2 together with data at $T = 50-295$ MeV from the forerunner[5] of the present experiment and some other experiments[8] at $T > 300$ MeV. Also shown is the total cross section of $\pi d \to pp$ $[\sigma_F(\pi d \to pp) = \frac{1}{2}\sigma_{tot}]$. All three reactions exhibit a maximum in the region of the (3,3) πN resonance and, except for the factor of about 16 by which the $\pi d \to pp$ cross section is divided, show a remarkable similarity of energy dependence, well into the region of the minimum.

This is perhaps a surprising result. It is expected that pion absorption by the deuteron should have energy dependence which is quite different from that of the (π, N) process in any other nucleus. In the deuteron, the absorption can proceed without help from high-momentum components of the nuclear wave function, whereas, whatever reaction mechanism is adduced to estimate the ab-

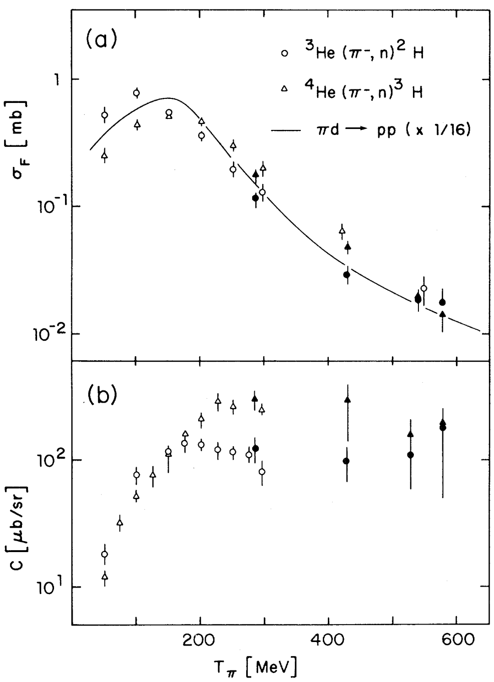

FIG. 2. (a) Results on σ_F from the present experiment and other experiments (open symbols) (Refs. 5 and 8). The solid line represents the measured total cross section (Ref. 1) for $\pi d \to pp$ divided by a factor of 16. (b) The energy dependence of the reactions $\pi^- + {}^3\mathrm{He} \to n + d$ and $\pi^- + {}^4\mathrm{He} \to n + t$ represented by the parameter C. The data for $T < 295$ are from Ref. 5.

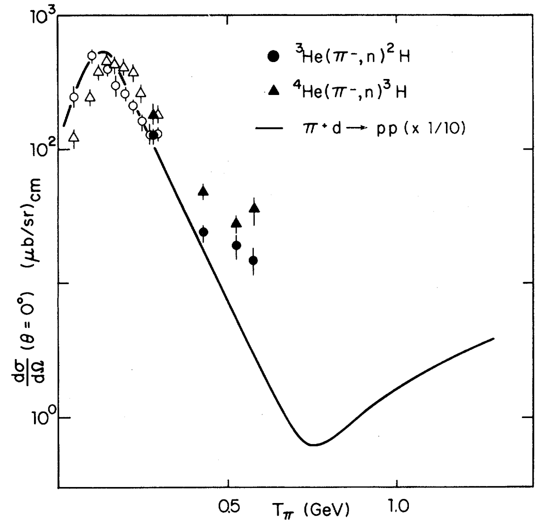

FIG. 3. The differential cross section of ${}^3\mathrm{He}(\pi^-, n)^2\mathrm{H}$ and ${}^4\mathrm{He}(\pi^-, n)^3\mathrm{H}$ at $\theta = 0°$ compared with $\pi d \to pp$ represented by the solid line (Ref. 1). Open symbols are data from Ref. 5.

sorption by a more complex nucleus, the high-momentum components of the nuclear wave function will be important. The form factor that enters the cross section as a result generally decreases with increasing momentum transfer which, if it acted alone, would lead to smaller cross sections at higher energies.

In order to study the apparent suppression of the expected q dependence, and to unfold the suppression factor from the observed cross section, we fit the data in the forward-angle region $\theta \leq 70°$ with the approximate form

$$d\sigma/d\Omega = C(T)\exp[-(Q-q)/\lambda].$$

Here, the forward-angle falloff in the angular distributions is associated with the form factor's q dependence. The energy dependence is represented by the normalization $C(T)$ used to fit the cross section at each energy keeping the slope constant fixed at its fitted value $\lambda = 48$ MeV/c and the offset parameter set to $Q = 500$ MeV/c. In Fig. 2(b), one then observes that there is no clear indication of a decrease in $C(T)$ as the energy is increased beyond the region of the (3,3) resonance while the $\pi d \to pp$ cross section over the same energy range decreases more than a factor of 20 from its maximum at $T_\pi \approx 150$ MeV. Although this is a larger difference than the discrepancy between the ${}^{3,4}\mathrm{He}(\pi^-, n)^{2,3}\mathrm{H}$ data and the prediction based on the quasideuteron model, it is a difference in the same direction. Separated from its q dependence in this approximate way, the (π, N) process in ${}^{3,4}\mathrm{He}$ appears to persist more strongly at high energy than it does in ${}^2\mathrm{H}$.

The cause of this difference in energy dependence might be related to the reaction mechanisms. It is interesting to note that the $\pi + N$ off-shell scattering amplitudes that can contribute to pion absorption in ${}^2\mathrm{H}$ and ${}^{3,4}\mathrm{He}$ are quite different. The $I = 0$ state of the deuteron discriminates against $\pi^+ + n$ $I = \frac{3}{2}$ scattering contributions to $\pi^+ d \to pp$ (or against $\pi^- + p$ in $\pi^- d \to nn$) because it suppresses $I = \frac{1}{2}$ pion-nucleon scattering.[2] The $I = \frac{1}{2}$ πN resonances which should be most clearly manifested around 700 MeV thus have a weight of only $\frac{1}{16}$ in $\pi d \to pp$. This offers a natural explanation of the observed minimum in the $\pi d \to pp$ cross section.[1] This minimum is illustrated in Fig. 3, which shows $d\sigma/d\Omega$ at $\theta = 0°$ for both the $\pi d \to pp$ and the ${}^{3,4}\mathrm{He}(\pi, n)^{2,3}\mathrm{H}$ reactions (the latter derived by extrapolation of the data in Fig. 1). There is a clear tendancy for the two cross sections to diverge as the energy increases. In ${}^{3,4}\mathrm{He}$, there are $I = 1$ NN pairs which allow (π^-, n) pion absorption initiated by a $\pi^- + p$ scattering both in the $I = \frac{1}{2}$ and $\frac{3}{2}$ isospin states. The ratio between $I = \frac{1}{2}$ and $\frac{3}{2}$ resonances is estimated to be 1:4 for $\pi^- pn \to nn$ ($I_{pn} = 1$), compared to 1:16 for $\pi^- d \to nn$. It seems clear that the $I = \frac{1}{2}$ πN resonances would contribute more in ^{3,4}He$(\pi^-, n)^{2,3}$H than in $\pi^- d \to nn$ with the result that the minimum would be shallower in ^{3,4}He than in ^{2}H. In order to assess quantitatively these isospin effects in nuclear pion absorption, calculations are needed that take into account contributions from absorption on $I = 0$ as well as $I = 1$ NN states including the possible complications due to interfering amplitudes.

In conclusion, this paper has presented new data on nuclear pion absorption above the (3,3) resonance region. The energy dependence is found to be different from that of $\pi d \to pp$ when the nuclear form factor dependence is taken out. We suggest that this observation indicates the importance of $\pi + N$ (off-shell) scattering in the absorption process where the selective formation of intermediate $I = \frac{1}{2}$ and $I = \frac{3}{2}$ πN resonances depends on the isospin of the initial nucleon state involved. Calculations should be attempted on these (π, N) reactions in ^{3,4}He to assess the role of $I = \frac{1}{2}$ and $I = \frac{3}{2}$ πN resonances in nuclear pion absorption which would help clarify the elusive question of the reaction mechanism.

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Selective Population of High-*j* Orbitals in Er Nuclei by Heavy-Ion-Induced Transfer

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Selective population of high-j and high-K states in ^{167,169,171}Er nuclei has been observed in heavy-ion—induced single-neutron—transfer reactions. γ rays in coincidence with outgoing particles have been used to aid in level assignments and several previously unobserved high-j states have been identified.

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The backbending phenomenon and high-spin isomers are two examples of the unique role played by high-spin single-particle states in the structure of nuclei. Identification of these states with the (d,p) reaction can be made only in isolated cases since the reaction mechanism strongly favors low spin states.[1] The location of high-j neutron hole states has been extensively studied with the selective $(^3\text{He},\alpha)$ pickup reaction,[2] while the inverse reaction leading to particle states has been rarely studied. In this Letter we report the use of two heavy-ion—induced stripping reactions to selectively populate high-spin particle states in deformed nuclei, specifically in ^{167,169,171}Er. In addition to populating known low-lying levels, several other high-spin states, not observed in an earlier (d,p) study,[3] have been identified. These results demonstrate that heavy-ion—induced transfer reactions can play an important role as a spectroscopic tool to locate high-spin single-par-

