Large-Angle Charge-Exchange Scattering of Pions by ^{3}He at 200, 250, 275, and 290 MeV

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Differential cross sections for the reaction ^{3}He$(\pi^-, \pi^0)^3$H at energies of 200, 250, 275, and 290 MeV over the angular region $80° \lesssim \theta_{c.m.} \lesssim 150°$ are presented. Comparison is made with theoretical predictions based on Glauber theory and optical-potential calculations. Neither approach gives a satisfactory description of the data; in particular, the observed energy dependence is much smaller than the theoretical predictions.

Pion charge-exchange (CEX) scattering from nuclei has been studied for some time by means of decay measurements of the residual nucleus, which have provided information on the angle-integrated cross section (see the recent review articles[1,2]). The energy dependence of this total cross section has attracted particular interest. It has generally been found to be very small, and roughly flat around the energy of the (3, 3) resonance of the π-N interaction. Current scattering theories have had difficulty in reproducing this energy behavior. While there is an apparent need to include pion-nucleus distortion effects to reproduce the magnitude of the cross section, the strong pion absorption at resonant energies gives rise to a minimum in the predicted energy dependence; i.e., the effect of the (3, 3) resonance on absorption tends to dominate over the simple resonant behavior in the CEX transition amplitude. Various remedies for this erroneous energy dependence have been tried, and the inclusion of second-order effects seems to yield some improvement.[2,3]

Until now, there has been no conclusive theoretical account of the CEX scattering in complex nuclei, and data on the three-body nuclear system ^{3}He (or ^{3}H) have been desirable. The distortion effects should be smaller for this system and the theoretical difficulties should be much reduced, making detailed multiple-scattering and optical-model calculations[4-9] manageable. The predictions of current calculations have generally been put to a test by comparing with the extensive body of elastic-scattering data for these nuclei.[10] The amplitudes for pion elastic and CEX scattering from ^{3}He are simply related: The CEX amplitude is proportional to the difference between the π^+ and π^- elastic-scattering amplitudes. Data on all of these cross sections are thus needed to help put the current scattering theories and their approximations to further test. From an experimental point of view, the ^{3}He$(\pi^-, \pi^0)^3$H process presents the opportunity to detect the recoil triton, circumventing the problem of π^0 detection. We have exploited this technique in the present experiment, and in this Letter we report the first differential cross section of CEX scattering to a discrete final state.

The angular distributions were measured using the EPICS pion channel at LAMPF (the Clinton P. Anderson Meson Physics Facility) in the course of measurements of the (π^-, n) reaction on ^{3}He and ^{4}He.[11] Briefly, the beam used had a flux varying between 1 and 3×10^6 π^-/s. The target[12]

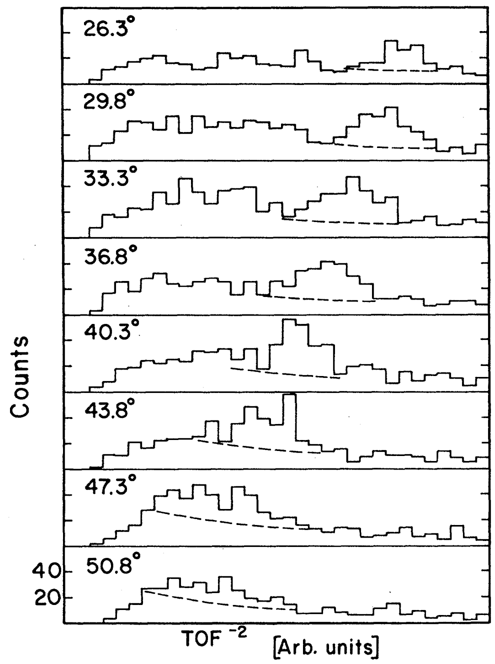

FIG. 1. Triton time-of-flight spectra obtained with the detector centered at $\theta_d = 38.5°$ in reactions $\pi^- + {}^3He$ at 290 MeV. Each spectrum corresponds to an angle of 3.5° across the detector. A background line is drawn below the peak of $^3He(\pi^-, \pi^0)^3H$.

was liquid ^3He kept in a cell ($12.5\times12.5\times0.64$ cm^3) at a temperature of 1.4°K. The detector system consisted of three plastic scintillators and a wire chamber,[13] which were used to measure time of flight (TOF), energy loss [total (E) and differential (ΔE)], and angle (θ). The particle identification was made from the TOF-E and ΔE-E information. A peak was seen in the E and TOF spectra of tritons for a fintie angular bin. The peak position varied with θ and T_π in a way that was consistent with the kinematics of the process $^3He(\pi^-, \pi^0)^3H$. A sample of triton spectra is shown in Fig. 1 which were obtained in one detector setting with each angular bin being 3.5°. No corresponding peaks were seen with the ^4He target but only the structureless background from (mostly) $(\pi, \pi t)$ and (π, t) reactions in ^4He and the aluminum windows (80 mg/cm^2) of the target cell. A smooth background was thus subtracted when extracting the (π^-, π^0) cross section. This procedure was checked by doing two independent data reductions which gave consistent results. The absolute normalization of the cross sections was obtained by measuring π^--p elastic scattering, using a CH_2 target, and comparing to the data of Bussey *et al.*[14] The target thickness was checked by measuring π^+-^4He and π^+-^3He elastic scattering and comparing with existing data.[10] The resulting differential cross sections, for incident pion energies of 200, 250, 275, and 290 MeV, are shown in Fig. 1. The data are limited to the region of large angles because of the need for the recoil triton to have enough energy to leave the target with reasonably small energy loss in order to be detected. We estimate that the overall uncertainty in the cross-section normalization is less than ± 15%, plus the errors indicated on each point.

Our data cover a limited angular region around $\theta = 110°$, and in this particular region we do not see any strong angular dependence at any of the incident energies studied. The kinematic range of the experiment corresponds to a momentum transfer of $q = 450$–700 MeV/c, but the data show no distinct or simple q-dependent feature that can be related to the nuclear structure involved. In general, both the charge and spin form factors[12] of ^3He contribute to the CEX cross section, and in the momentum-transfer region of the experiment the form factors have both fallen two to three orders of magnitude from their values at small q. The charge form factor has a minimum at $q \approx 650$ MeV/c, which is near the upper limit covered by our data. The CEX cross section is found to be small, at the leval of 3–30 μb/sr, which is comparable to or just slightly smaller than the π^- elastic-scattering cross section from ^3He at $T_\pi = 208$ MeV at corresponding angles.[10] Elastic-scattering data on ^3He are not available for higher energies so we can only compare with the elastic-scattering cross section for ^4He, which decreases by a factor of 10 to 20 between 180 and 260 MeV. The CEX cross section, however, shows little or no energy dependence (Fig. 2) for any of the angles studied. Another CEX experiment has recently been performed,[15] which will extend the information on the energy dependence to lower energies, and more extensive measurements are currently being planned.[16]

Theoretical studies of pion CEX scattering on the nuclear three-body system have been carried out using the Glauber multiple-scattering formalism. Pion absorption effects[5] were found to be important, as were spin-flip effects,[6] in certain kinematical regions. Lohs and Mandelzweig[7] performed more detailed Glauber calculations of both a standard type and a modified form which incorporated pion-nucleus phase shifts rather than amplitudes. They also found the magnitude and shape of the predicted angular distributions

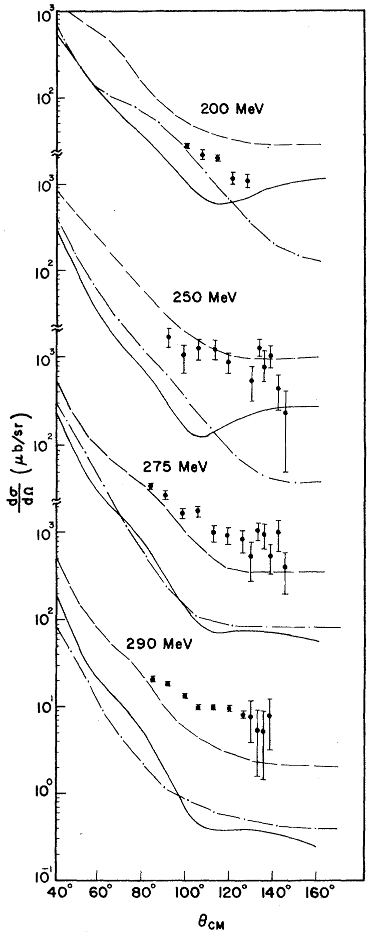

FIG. 2. Experimental values of the $^3He(\pi^-, \pi^0)^3H$ cross section as a function of the center-of-mass angle, with theoretical predictions. The solid curves are those of Landau (Ref. 9) and the remaining two are those of Lohs and Mandelzweig (Ref. 7). The dashed curve is the full Glauber calculation and the dot-dashed curve is the modified Glauber calculation including one spin flip.

to be sensitive both to the model used and to the form of the off-shell continuation of the pion-nucleon amplitude; their predictions for both the Glauber and modified Glauber calculations are shown in Fig. 2.

The first-order optical model has also been used to calculate elastic and CEX scattering on ^{3}He. The predictions of Mach[8] indicate a sensitivity both to nuclear-structure details and to the little-known off-shell behavior of the π-N amplitudes. The calculation of Landau[9] was based on a theoretical momentum-space optical potential with realistic nuclear form factors of a π-N t matrix with finite range. Cross sections for ^{4}He were calculated as well. The overall agreement with the experimental ^{4}He elastic and total cross sections is rather good over the entire region of the resonance, as is the agreement with the ^{3}He elastic data. The CEX predictions of this calculation are shown in Fig. 2.

As can be seen, none of these predictions gives a satisfactory account of the CEX over the full energy range. At any fixed angle, the data do not vary by more than a factor of 2 in cross section between 200 and 290 MeV, whereas the predictions shown have a much greater variation (Fig. 2). The predictions of the Glauber calculation of Lohs and Mandelzweig lie closest to the data, but any apparent agreement may be fortuitous because of the nature of the Glauber approximation. Its application to pion-nucleus scattering in general is known to be doubtful, because its validity depends on a forward peaking of both the pion-nucleus and pion-nucleon amplitudes, which is not a characteristic of the latter. The prediction of elastic scattering on ^{3}He at large angles is also poor.[7] The modified Glauber calculation attempts to circumvent this shortcoming but this remedy, which the authors describe as "*ad hoc*," seems to worsen the disagreement with our CEX data.

The poor agreement between Landau's calculation and our data is perhaps a little more surprising, in view of its success in reproducing the large body of elastic-scattering data for ^{3}He and ^{4}He. We observe, however, that for higher energies (say $T_\pi \gtrsim 200$ MeV), the large-angle region ($\theta > 90°$) has not been stringently tested because of the lack of high-quality data. One is then inclined to conclude that some important piece of physics is left out in the first-order optical model which indicates the need to include, for instance, second-order effects involving true pion absorption and reemission.

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Phenomenology of Inclusive Fast-Nucleon Spectra in Weak, Electromagnetic, and Strong Nuclear Processes

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The spectrum of fast backward nucleons emitted in nucleon-nucleus scattering is correlated with the inclusive fast-neutron spectra from μ capture and radiative π capture by using a universal, phenomenological nuclear recoil function. Agreement with experiment, where available, is good.

Fast nucleons emitted by complex nuclei in muon capture,[1] in radiative pion capture,[2] and at back angles in high-energy nucleon-nucleus collisions[3] have as their common origin the cooperative effect of the nucleus. Such fast particles cannot be emitted in the corresponding processes on free nucleons, nor can the nuclear motion of a Fermi-gas model account for such energetic nucleon emission. In this Letter we give a unified, phenomenological description of these processes that accounts for the observed inclusive spectral shapes and rates. We relate the processes by assuming that the back-angle nucleon-nucleus reaction is direct and can be written[4] as the product of a nucleon-nucleon amplitude at the appropriate momentum transfer times a function that characterizes the ability of the target to absorb that momentum and produce the observed nucleon. We further assume that the "nuclear recoil function" so defined is a rapidly falling exponential function of momentum carried by the nuclear debris and is therefore dominated by the minimum possible value of that momentum. For muon and radiative pion capture we assume factorization into the appropriate elementary amplitude for capture on a single nucleon, times this same nuclear recoil function. Since we account for shapes and approximately for rates even though the minimum momentum carried by the target debris can vary by more than an order of magnitude between the hadron scattering and capture experiments, this picture greatly extends the range of applicability of the phenomenology.[3,4]

Consider the reaction $1+2\rightarrow 1'+3'$ [Fig 1(a)] in which 1 and 1′ are the target nucleus A and the (excited) recoiling nuclear debris $(A-1)^*$; 2 is the initial p, π^-, or μ^-; 2′ is a nucleon, photon, or neutrino, respectively; and 3′ is the detected nucleon. 1′ and 2′ are undetected in the inclusive process. We assume that the invariant transition amplitude,[5] T, for all three processes can be expressed in factorized form so that

$$|T|^2 = \mathfrak{A}|\mathcal{T}|^2 F_A(k^2) M_A M_{A-1}/M^2, \tag{1}$$

where $\mathfrak{A}$ is the effective target nucleon number. It is equal to A for the strong process and is some effective Z for the weak and electromagnetic captures. The M, M_A, and M_{A-1} are the nucleon and nuclear masses. $\mathcal{T}$ is the amplitude for the elementary process $2+a\rightarrow 2'+b$ [Fig. 1(b)], a and b being virtual nucleons. Nucleon b may or may not interact with the "spectator" nucleus; these effects are hidden in the function $F_A(k^2)$.[6] The inclusive differential cross section is then

