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Direct (π^+,pd) cross sections for light nuclei

H. Yokota, S. Igarashi, K. Hama, T. Mori, T. Katsumi,* K. Nakayama,† K. Ichimaru, and R. Chiba
Department of Physics, Tokyo Institute of Technology, Ohokayama, Meguro-ku, Tokyo 152, Japan

K. Nakai and J. Chiba
National Laboratory for High Energy Physics, Oho, Tsukuba 305, Japan

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The angular distributions of the inclusive (π^+,pd) cross section were measured for ^{6}Li, ^{7}Li, and C at $T_\pi=70$, 130, and 165 MeV over a wide angular range. They were found very similar to that of the $\pi+{}^3\text{H}({}^3\text{He})\rightarrow N+{}^2\text{H}$ reaction in the low-momentum-transfer region, especially for Li isotopes. However, in the higher-momentum-transfer region, slight peaks which were not expected in the $\pi+{}^3\text{H}({}^3\text{He})\rightarrow N+{}^2\text{H}$ were observed.

Recently the inclusive and exclusive (π,Nd) cross sections have been measured to study the reaction mechanism for pion absorption by more than three nucleon systems in nuclei, where most of the energy and momentum brought by the incident pion were carried out by the outgoing nucleon and deuteron. However, the $\pi+{}^3\text{H}({}^3\text{He})\rightarrow N+{}^2\text{H}$ reaction process is not so well understood as the $\pi+{}^2\text{H}\rightarrow N+N$ reaction because the former is characterized by the large momentum mismatch between the incident pion and the outgoing nucleon of higher momentum than that in the latter case. The momentum transfer of the $\pi+{}^3\text{H}({}^3\text{He})\rightarrow N+{}^2\text{H}$ reaction at $T_\pi=165$ MeV ranges from 460 to 810 MeV/c according to the nucleon angle. The probability of finding high momentum protons in the p-d channel was recently determined by measuring the $^3\text{He}(e,e'p)^2\text{H}$ cross section[1] and found vanishingly small at the proton momentum larger than 450 MeV/c. Therefore, the one-step process should be strongly suppressed. In the two-step reaction model, the large momentum transfer is absorbed mainly by the pion absorption process on a strongly correlated two-nucleon system and by the large relative momentum between the pion-absorbing nucleon pair and the rest. The two-nucleon mechanisms dominate the cross section at forward angles and reproduce correctly the data, but deviate strongly at large angles, even in the resonance energy range. Laget and Lecolley[2] recently showed that the three-body meson exchange term (a genuine three-nucleon absorption process) is a good candidate for accounting for the discrepancy.

The characteristic angular distribution of the $\pi+{}^3\text{H}({}^3\text{He})\rightarrow N+{}^2\text{H}$ cross section has been used to study the possibility of a quasifree pion absorption on three-nucleon systems in nuclei. Recent data reported[3,4] on the exclusive (π^+,pd) cross section for ^{6}Li and ^{7}Li at $T_\pi=59.4$ MeV (Ref. 3) and for ^{4}He at $T_\pi=120$ MeV (Ref. 4) showed that the quasitriton model described fairly well the main features of the data: the shape of the momentum distribution of the spectator and the angular distribution of the (π,Nd) cross section.

However, when we compare the angular distribution of the (π,Nd) cross section with that of the $\pi+{}^3\text{H}({}^3\text{He})\rightarrow N+{}^2\text{H}$ reaction in more detail, an apparent difference in shape can be observed, especially for ^{4}He. The direct $^4\text{He}(\pi,Nd)$ cross section shows a flat behavior in the backward hemisphere and does not decrease so sharply as the $\pi+{}^3\text{H}({}^3\text{He})\rightarrow N+{}^2\text{H}$ cross section with the nucleon angle. The ratio of the cross section at 60° to that at 120° is 2.2 at $T_\pi=120$ MeV and is only one-fifth of the ratio for ^{3}He at $T_\pi=100$ MeV.[5] The ratio for ^{6}Li at $T_\pi=59.4$ MeV is also smaller than that for the $\pi^++{}^3\text{H}\rightarrow p+{}^2\text{H}$ reaction at $T_\pi=65.5$ MeV,[6] although the difference is not so significant as for ^{4}He. Therefore, it is important to measure the (π,Nd) cross section for light nuclei over an angular range as wide as possible.

In a previous paper[7] we reported on the inclusive (π,d) and (π^+,pd) reaction for C and heavier nuclei over a wide angular range. The angular dependence of the (π^+,pd) cross section was similar to that of the $\pi^-+{}^3\text{He}\rightarrow n+{}^2\text{H}$ reaction, although it was strongly distorted by the short mean free path of outgoing deuterons and the contribution from other reaction process. In this paper we report on the (π^+,pd) reaction for ^{6}Li, ^{7}Li, and C at $T_\pi=70$, 130, and 165 MeV, comparing with the $\pi+{}^3\text{H}({}^3\text{He})\rightarrow N+{}^2\text{H}$ reaction over a wide range of the momentum transfer.

The experiment was performed at the $\pi\mu$ channel of the 12 GeV proton synchrotron at the National Laboratory for High Energy Physics (KEK). The experimental arrangement was the same as that described elsewhere.[8] Eight scintillator telescopes consisted of a large volume NE213 counter 8 in. diam × 7 in. deep and a plastic scintillator 5 mm thick, and were arranged in a reaction plane over an angular range from 20° to 160° in steps of 20°. At the other side of the reaction plane two layers of plastic scintillator were placed covering an angular range from 10° to 170° with an angular resolution of 10°. Analog and timing signals from all the elements were recorded on magnetic tape. ΔE and E signals from the NE213 telescope could serve to discriminate between π, p, d, and t. The thickness of the front and rear scintillator arrays was 5 and 15 mm, respectively. Therefore, the discrimination of protons from deuterons was possible for deuterons less than 70 MeV.

Angular correlations were obtained for coincident events between deuterons detected with the NE213 telescopes and protons with the plastic array for ^{6}Li, ^{7}Li, and C. The energy thresholds for protons and deuterons were 30 and 40 MeV, respectively. Typical examples are shown in Fig. 1 for ^{6}Li at $T_\pi = 130$ MeV. We can see that the angular correlations are composed of a narrow and a broad component similar to those of the (π^+,pp) reaction. At forward angles the relative amplitude of the narrow component to the broad one is much smaller than that for the (π^+,pp) reaction and the width of the narrow peak for ^{6}Li is larger by about 7° than that of the ^{6}Li(π^+,pp) reaction and is nearly equal to that of the ^{7}Li(π^+,pp) reaction. The peak angle for deuterons at forward angles is displaced by about 5° to a larger opening angle from that of the Li(π^+,pp) reaction according to the kinematics of the $\pi^+ + {}^3\mathrm{H} \rightarrow p + {}^2\mathrm{H}$ reaction, as we can see in Fig. 1. At $T_\pi = 70$ MeV, the difference in the peak angles between the two reactions is smaller (less than 2°) and we could not observe any appreciable displacement. The angular correlations were fitted with a sum of two Gaussians, and we obtained the coincidence yields for the narrow component of the inclusive (π^+,pd) reaction after correcting for the missing acceptance of typically 38%.

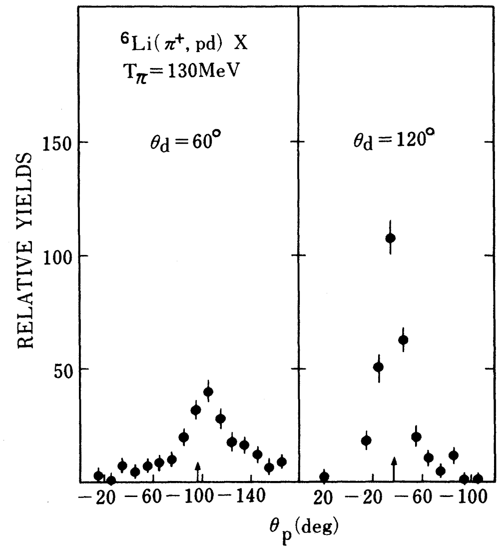

FIG. 1. Angular correlations for the ^{6}Li(π^+,pd) reaction at $T_\pi = 130$ MeV. The arrows indicate the angles corresponding to the narrow component of the (π^+,pp) reaction.

Figure 2 shows the angular distributions of the (π^+,pd) cross section as a function of the deuteron angle in the laboratory system for the three targets. The angular distributions for Li isotopes are characterized by a strong peak at backward angles and the cross section depends weakly on the incident pion energy. For C, the peak at backward angles is not as strong as those for the Li isotopes; on the contrary, a slight peak at forward angle is

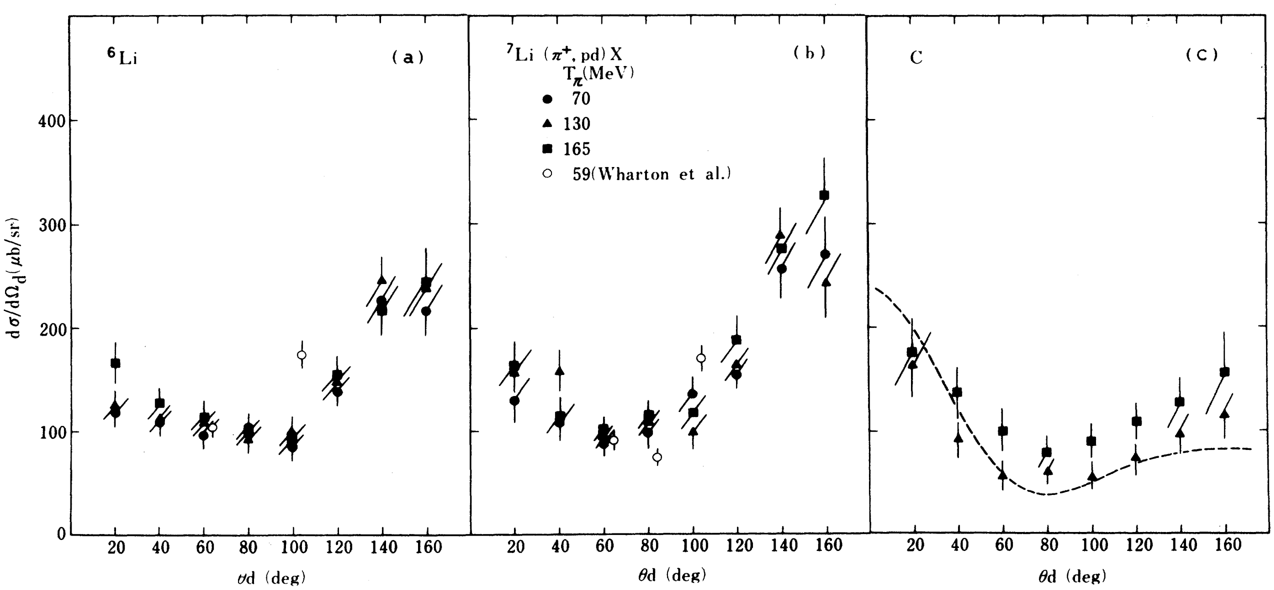

FIG. 2. Angular distributions of the direct (π^+,pd) cross section for ^{6}Li, ^{7}Li, and C at $T_\pi = 70$, 130, and 165 MeV. The dashed line in (c) shows the cross section for the $\pi^+ + d \rightarrow p + p$ reaction at 165 MeV.

more prominent. The cross sections for C seem to depend on the incident pion energy.

At backward angles the (π^+,pd) cross section contains a small amount of contaminations from the (π^+,dd) reaction because the scintillator arrays had difficulty in discriminating deuterons of more than 70 MeV from protons. The (π^+,dd) events should be due to pion absorption on ^{4}H clusters in nuclei or to the two-step process; the (π^+,pd) reaction followed by the neutron pickup reaction. The *d*-*d* coincidence yields from these processes should be considerably smaller because the four-nucleon *pnnn* correlation is not so strong as an α cluster, the direct ^{4}H absorption cross section will be suppressed, and the nucleon pickup probability is about 10% for light nuclei.[7] In fact, the (π^-,dd) yields with stopped pions were only 8% of the (π^-,nd) yields.[9] At forward angles most of the (π^+,dd) events could be rejected.

How can we explain the angular distribution of the inclusive (π^+,pd) cross section? The narrow component includes only events with a low recoil momentum, so that the contribution from the two-step process associated with pion absorption on low total momentum nucleon pairs should be excluded. However, the angular distributions still have a significant peak at forward angles which cannot be expected in the $\pi+{}^3\mathrm{H}({}^3\mathrm{He})\rightarrow N+{}^2\mathrm{H}$ reaction. Figure 3 shows the ratio of the double-differential cross section $(d^2\sigma/d\Omega_1 d\Omega_2)$ between the (π^+,pd) and the (π^+,pp) reactions at the peak angle in each angular correlation for ^{6}Li and ^{7}Li, at $T_\pi=70$ MeV. The ratios for ^{6}Li are smaller than those for ^{7}Li, because the average total momentum of the pion-absorbing pair in ^{6}Li is smaller than that for ^{7}Li, and the momentum of the three nucleons concerned in the (π^+,pd) reaction is almost equal between the two nuclei. The angular distributions of the ratio show that the ratios at backward angles are larger than those at forward angles by a factor of 2, and the ratios are nearly constant in the two angular regions. The drastic change of the ratio at 80° indicates that the (π^+,pd) cross section is strongly asymmetric at about 90°. The constant ratio between 20° and 80° signifies the existence of a process which has an angular dependence similar to that of the (π^+,pp) reaction.

The exclusive Li(π^+,pd) cross section at 59.4 MeV measured by Wharton *et al.*[3] was given in a limited angular range (from 60° to 100°) and as a function of outgoing proton angle. As they estimated the single-differential cross section from a triple-differential cross section at the conjugate angle assuming a *T* matrix based on the quasitriton model, we can estimate approximately the single-differential cross section for deuterons using the kinematic factor for a deuteron from the $\pi^+ + {}^3\mathrm{H}\rightarrow p+{}^2\mathrm{H}$ reaction. The sums of the cross section for the ground state and for the excited-state or resonance-state transitions are given in Fig. 2 for ^{6}Li and ^{7}Li. They are in fairly good agreement with the result at $T_\pi=70$ MeV, except for a value at $\theta_p=60°$ for ^{6}Li.

The $\pi^+ + {}^3\mathrm{H}\rightarrow p+{}^2\mathrm{H}$ cross section has not been measured over the wide angular range. Therefore, we refer to the $\pi^- + {}^3\mathrm{He}\rightarrow n+{}^2\mathrm{H}$ cross section measured by Källne *et al.*[5] covering the kinematic region $T_\pi=50$–300 MeV and $\theta_n=20°$–$150°$. The main feature of the present Li(π^+,pd) cross section might be explained by the $\pi+{}^3\mathrm{H}({}^3\mathrm{He})\rightarrow N+{}^2\mathrm{H}$ process because the cross section is remarkably similar to the $\pi^- + {}^3\mathrm{He}\rightarrow n+{}^2\mathrm{H}$ cross section at $T_\pi=150$ MeV over a wide angular range

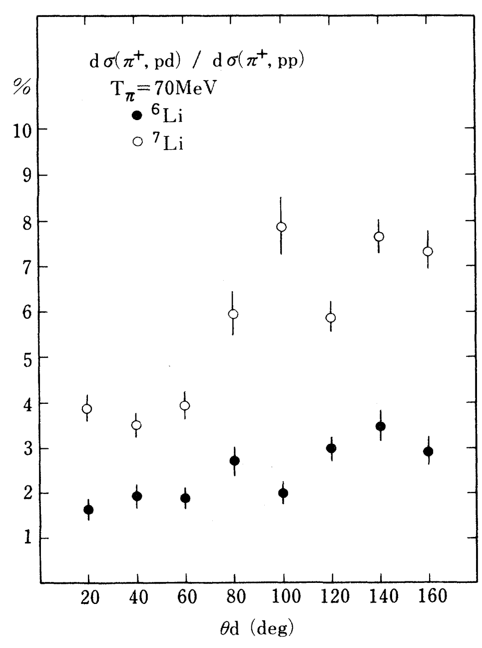

FIG. 3. Angular distributions of the yields ratio between the (π^+,pd) and (π^+,pp) reactions at the peak angle, for ^{6}Li and ^{7}Li at 70 MeV.

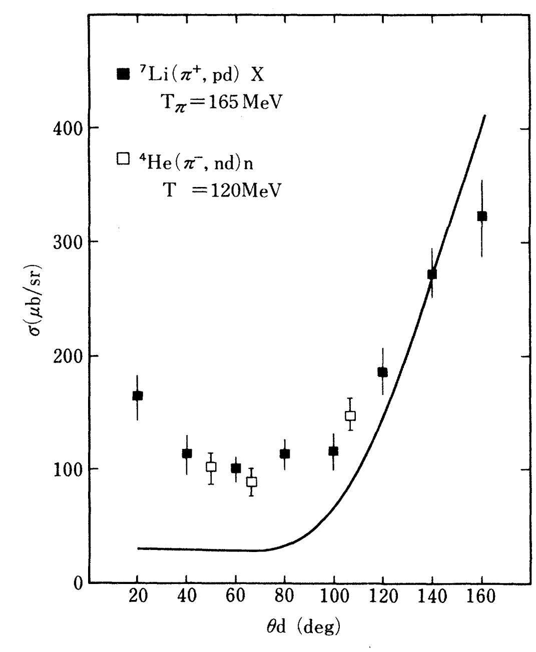

FIG. 4. The ^{7}Li (π^+,pd) cross section at 165 MeV was compared with the ^{4}He(π,Nd) data at 120 MeV (Ref. 4). The solid line shows the ^{3}He(π^-,nd) data at 150 MeV (Ref. 5) multiplied by a factor of 1.63.

$\theta_d = 100°-160°$, as we can see in Fig. 4, where the ^{3}He data were multiplied by a factor of 1.63 and normalized to the ^{7}Li data at $\theta_d = 140°$, and were shown with a solid line. The present values for large angles are possibly underestimated, because of the relatively high energy threshold for deuterons, by about 15% and 30% at 120° and 140°, respectively, considering from the Daliz plots for the ^{4}He($\pi^+ pd$) reaction.[4] However, the (π^+,pd) cross section is weakly dependent on T_π between 70 and 165 MeV, in agreement with the ^{3}He data.

As we mentioned above, an enhancement of the (π,Nd) cross section at the large momentum transfer was also signified for ^{4}He at 120 MeV.[4] The ^{4}He data as a function of deuteron angle are included in Fig. 4. It is in good agreement with the present Li results. Therefore, the enhancement at large momentum transfer is possibly common for nuclei heavier than ^{4}He.

The mechanism of pion absorption with the emission of coincident nucleon and deuteron is not yet clear. In a simple two-step process for the $\pi + {}^3\mathrm{H}({}^3\mathrm{He}) \rightarrow N + {}^2\mathrm{H}$ reaction,[10] the relative momentum required between a pion-absorbing nucleon pair and a nucleon to be picked up increases rapidly from 250 to 400 MeV/c with the nucleon angle. The momentum is much larger than the Fermi momentum in light nuclei. Consequently, the two-step process with low recoil momentum requires strongly correlated three-nucleon systems. However, for nuclei heavier than ^{4}He the three nucleons need not be always strongly correlated, although the relative and total momenta of the residual nuclei should be a little higher than those expected from the quasifree absorption model. Possible explanations for the enhancement in the cross section at large momentum transfer are (a) the three-body meson exchange process[2] which should be enhanced in nuclei of higher density, (b) the higher probability for finding both high total momentum pion-absorbing nucleon pairs and high momentum nucleons to be picked up, and (c) more complex processes such as the Δ-hole model. The present data should be helpful in distinguishing these possibilities through detailed theoretical studies of the nuclear wave function and reaction process.

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*Present address: IBM Japan Ltd., Kawasaki-shi, Kanagawa 210, Japan.

†Present address: Toshiba Corp., Kawasaki-shi, Kanagawa 210, Japan.

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