Pion Absorption on $T = 1$ Nucleon Pairs at $T_\pi = 70$ MeV

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Angular correlations of the ^{6,7}Li($\pi^\pm$,pn) cross sections were measured in a wide angular range at $T_\pi = 70$ MeV. The components of the two-nucleon absorption processes were extracted, and the angular distributions of the cross sections were obtained. Strong asymmetries about 90° were observed for the reactions ^{6,7}Li($\pi^\pm$,pn), and the cross sections were much larger than that of ^{3}He. These results show the importance of the σ_{11} component in pion absorption on $T = 1$ nucleon pairs for p-shell nuclei.

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The study of the pion-absorption process at the energy region of the (3,3) resonance is interesting because the behavior of isobars in the nuclear medium and the correlation between nucleons are sensitive to this process. Recent experimental and theoretical studies on s-shell nuclei[1,2] revealed that the (π^+,pp) reaction proceeds through the πNN-ΔN-NN dynamics, and the quasideuteron absorption process was found to be dominant from the measurements of the angular distribution of the ^{3}He(π^+,pp) cross section.[3] On the other hand, the (π^-,pn) reaction is strongly suppressed by a factor of more than 10 over a wide energy range of incident pions.[2-5] The S-wave ΔN component is forbidden for a $T = 1$ nucleon pair. Therefore, possible processes are pion absorption through the intermediate ΔN state with $L_{\Delta N} \geq 1$ and the intermediate N' isobar (a P_{11} πN interaction), and direct absorption processes such as the nucleon-pole mechanism πNN-NN-NN.[6]

For p-shell nuclei, the (π^+,pp) reaction has been also considered dominated by the quasideuteron process. Altman *et al.*[7] found that the angular distribution of the quasideuteron component had a shape similar to that of the $\pi^+ d$-pp reaction for C, even at relatively high incident pion energies where the multiple pion scattering before absorption was important. In a previous paper,[8] we reported on the study of pion absorption on $T = 1$ nucleon pairs from the (π^+,p), ($\pi^\pm$,pp), and ($\pi^\pm$,pn) reactions at $T_\pi = 65$ MeV. Analyzing the experimental results with the intranuclear-cascade (INC) model, we found that the absorption ratio R, the pion-absorption cross section for a pn nucleon pair divided by that for a pp or nn nucleon pair was about 4, and it was concluded that pion absorption on $T = 1$ ^3P nucleon pairs was important for the ($\pi^\pm$,pn) reaction, following the πNN-ΔN-NN dynamic theory.[1]

The angular distribution of the pion-absorption cross section for a $T = 1$ nucleon pair was measured for the first time by Moinester *et al.*[3] at $T_\pi = 65$ MeV for ^{3}He. They found that the angular distribution showed significant asymmetry about 90°, although the angular range of their observations was not very wide. The asymmetry was fairly well explained by the prediction of a two-intermediate-isobar model calculated by Silbar and Piasetzky.[9] Detailed studies of pion absorption on a $T = 1$ nucleon pair should make it possible to observe small effects in the πNN system that would otherwise be masked by the $L_{\Delta N} = 0$ intermediate state. The angular distribution of the ($\pi^\pm$,pn) cross section as well as the R value will give valuable information about the reaction process.

In this Letter, we present the results on pion absorption by Li isotopes at $T_\pi = 70$ MeV. Lithium is the lightest p-shell nuclei that has both S-wave and P-wave nucleon pairs. Therefore, we can discuss the contribution from higher ΔN partial waves by comparing the ($\pi^\pm$,pn) cross sections between Li and He. The angular distributions of the (π^+,pn) and ($\pi^\pm$,pn) coincident yields were obtained from angular-correlation measurements over a wide angular range. The comparison of the (π^+,pn) and (π^-,np) angular distributions is important, because the (π^-,np) reaction is the charge-symmetrical partner of the (π^+,pn) reaction. Moreover, the difference in the (π^+,pp) and ($\pi^\pm$,pn) yields between ^{6}Li and ^{7}Li will give information on the relation between the number of two-nucleon pairs and the coincident yields.

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 layout is shown in Fig. 1. Pion beam with contaminations of electrons (25%) and muons (5%) was focused on target counter of 30×30-mm^2 cross section. Positive- and negative-pion beams with a momentum resolution of 5% had an intensity of about

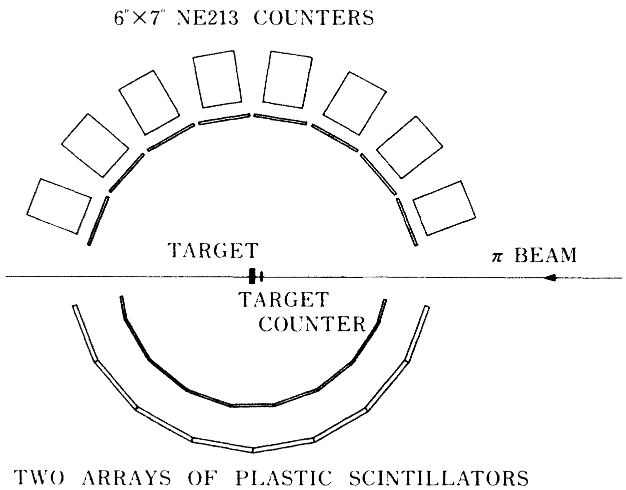

FIG. 1. Experimental setup for the coincidence experiment. The NE213 counters are coupled with R1250 photomultipliers.

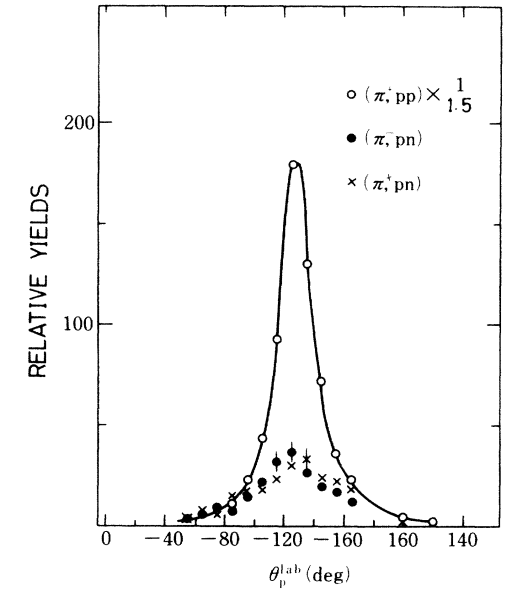

FIG. 2. Angular correlation of the (π^+,pp), (π^+,pn), and (π^-,pn) reactions for ^{7}Li, at a NE213 telescope angle of 40°. Sharp peaks are observed at the conjugate angle for the $\pi^+ d \rightarrow pp$ process.

10^5/spill at the target counter. Eight large-volume NE213 counters of 6 in. diam × 7 in. deep were placed at 60 cm from the target. They are arranged in the reaction plane, in an angular range from 20° to 160° in steps of 20°. A plastic scintillator 5 mm thick was placed in front of each NE213 counter as an anticounter for charged particles, and the two-dimensional ΔE-E plots for the NE213 telescopes served to distinguish protons from pions and deuterons. Discrimination of γ rays from neutrons could be carried out in 200 nsec, and a good n-γ separation was obtained in an energy range from 70-MeV down to 1-MeV electrons. The neutron detection efficiency was calculated with a Monte Carlo code originally written by Vervensky and modified by Higo.[10] At the other side of the reaction plane, two layers of plastic scintillators were arranged. They covered an angular range from 10° to 170° with an angular resolution of 10°. The thicknesses of scintillators for the front and rear arrays were 5 and 15 mm, respectively. Analog and timing signals from the two arrays were used for particle identification and energy determination of charged particles. Li targets were plates of isotopically enriched metal 40×40×15 mm^3 thick. They were contained in boxes made of thin stainless foil. An empty box was also prepared for the background measurement. A D_2O target was used for the calibration of analog and timing signals and for checking the detection efficiency for charged particles. Coincident signals between the target counter and counter telescope enabled data acquisition, and analog and timing signals from every scintillator were recorded on magnetic tape.

Two-dimensional energy spectra of *pp* and *pn* coincident events were obtained for every pair of telescopes. For *pp* coincident events at the conjugate angles, event plots were localized at the energies corresponding to the $\pi^+ d \rightarrow pp$ reaction. But for *pn* events, they were scattered broadly about the point determined by the two-nucleon absorption process, since the ^{6}Li(π,pn) reaction must involve at least one *s*-shell nucleon. The spectra were similar to those measured with stopped pions.[11] Therefore, events for the *pp* and *pn* angular correlations were defined with the condition that the two coincident nucleons had kinetic energies larger than 30 MeV. The uncertainty of the energy threshold was ±4 MeV. The yields from the accidental coincidences could be estimated from the two-dimensional time-of-flight spectra and were found to be negligibly small as a result of the continuous beam structure and the weak beam intensity. After subtracting the contribution from the empty target, the angular correlations for *pp* and *pn* coincidence events were obtained for eight NE213 counters, and an example at 40° for ^{7}Li is shown in Fig. 2. At the conjugate angle for the quasideuteron process, we can observe a sharp peak for the (π^+,pp) reaction superimposed on a broad component of small amplitude. Full widths at half maximum of the peak were 18° and 24° for ^{6}Li and ^{7}Li, respectively. These values are in good agreement with the results of the (π^-,nn) reaction with stopped pions.[11] The angular correlations of the $(\pi^\pm,pn)$ reactions also had clear peaks at the conjugate angles. The full widths at half maximum of the peak were larger than those of the (π^+,pp) reaction and were about 45° for both ^{6}Li and ^{7}Li. This value is again nearly equal to that for stopped pions. The broad component was as widely distributed as we could expect from the phase space for three- and four-nucleon breakup. After subtracting the broad component, the angular correlation was fitted to a two-dimensional Gaussian. Then, the yield for the two-nucleon absorption was corrected for missing acceptance for both the (π^+,pp) and $(\pi^\pm,pn)$ reactions.

The angular distributions in the *pd* center-of-mass system of the two-nucleon absorption cross section for the ^{6,7}Li(π^+,pp) and ^{6,7}Li$(\pi^\pm,pn)$ reactions over a wide angular range are shown in Fig. 3. The angles of the $(\pi^\pm,pn)$ cross sections are given for outgoing neutrons. The errors contain statistical and background subtraction uncertainties. The shape of the angular distributions for the (π^+,pp) is very similar to that of the π^+d-pp reaction for both ^{6}Li and ^{7}Li. In contrast, the shape for the (π,pn) reactions is clearly asymmetric about 90° for all four reactions. The coefficients of Legendre-polynomial fits are given in Table I and are compared with the results of pion absorption on ^{3}He and $n+p$ pion production. The sign of the A_1 term is negative for the (π^+,pn) reaction and positive for the (π^-,pn) reaction, and the absolute values of the ratios A_1/A_0 and A_2/A_0 are almost equal for the four $(\pi^\pm,pn)$ reactions.

The integrated cross sections for the ^{6}Li(π^+,pp) and ^{7}Li(π^+,pp) reactions were 20.2 ± 0.6 and 17.5 ± 0.5 mb, and larger than the free $\pi^+d\to pp$ cross section by factors of 2.6 and 2.2, respectively. The ratio of the (π^+,pp) cross section for ^{7}Li to that for ^{6}Li is 0.86 ± 0.05. If we assume that ^{7}Li is composed of an α particle and a t particle, and ^{6}Li of an α particle and a deuteron, then the ratio of numbers of *pn* nucleon pairs with deuteron quantum number will be 4.5/4. Therefore, the experimental ratio is attenuated by a factor of 0.76. For the (π^-,pn) reaction, the ratio of the observed cross section was 0.68 ± 0.10, and the numbers of *pp* nucleon pairs should be identical for ^{7}Li and ^{6}Li, for both *S*-wave and *P*-wave nucleon pairs. Therefore, the attenuation factor is 0.68. Similarly, the ratio of the (π^+,pn) cross sections was 1.5 ± 0.2, and the ratio of the number of *nn* nucleon pairs is expected to be about 2, for both *S*-wave and *P*-wave nucleon pairs. The experimental ratio is therefore attenuated by a factor of 0.75. These attenuation factors are in good agreement among the three reactions. The small difference in the factors between the (π^-,pn) and the (π^+,pn) reactions may be attributed to stronger distortion of π^- in ^{7}Li. The cross sections for the direct two-nucleon absorption process depend on the mean free path of pions and two outgoing nucleons, and the density distribution of the nuclear medium. These effects can be taken into consideration in the INC model.[8] The INC results for the ratios of the total reaction, the (π^+,p) and the (π^+,pp) cross sections, are 1.05, 0.97, and 0.83, respectively.

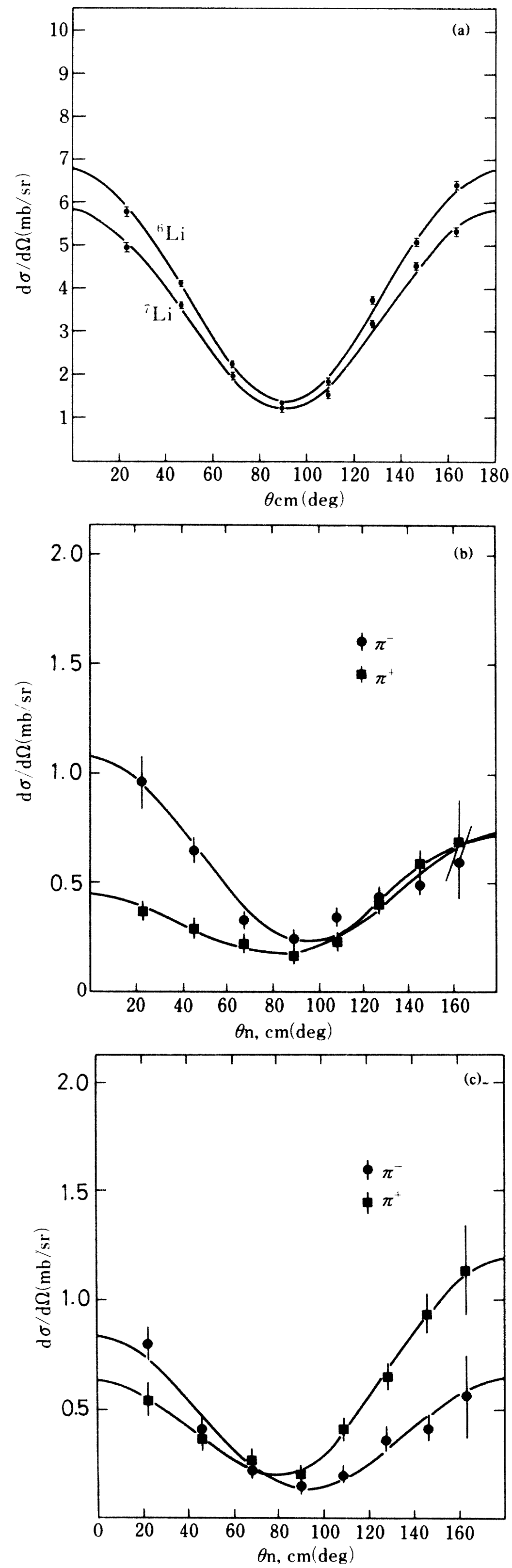

FIG. 3. Angular distributions of the differential cross sections for the two-nucleon absorption process on (a) *pn* pairs in ^{6,7}Li, (b) *pp* and *nn* pairs in ^{6}Li, and (c) *pp* and *nn* pairs in ^{7}Li. Solid lines are Legendre-polynomial fits to the data.

TABLE I. Coefficients A_0, A_1, and A_2 of Legendre-polynomial fits shown in Fig. 3, and the ratios A_1/A_0 and A_2/A_0 for the ^{6,7}Li(π^+,pp), (π^+,pn), and (π^-,pn) cross sections at $T_\pi = 70$ MeV. They are compared with the results from the ^{3}He(π^-,pn) reaction (Ref. 3) and the $np \rightarrow \pi^- pp$ reaction (Ref. 13).

Reaction	A_0 (mb)	A_1 (mb)	A_2 (mb)	A_1/A_0	A_2/A_0
^{6}Li(π^+,pp)	3.22 ± 0.08		3.56 ± 0.23		
^{7}Li(π^+,pp)	2.78 ± 0.07		3.02 ± 0.14		
^{6}Li(π^+,pn)	0.31 ± 0.02	-0.14 ± 0.02	0.27 ± 0.03	-0.45 ± 0.09	0.88 ± 0.14
^{7}Li(π^+,pn)	0.46 ± 0.03	-0.28 ± 0.04	0.45 ± 0.04	-0.61 ± 0.12	0.97 ± 0.16
^{6}Li(π^-,pn)	0.45 ± 0.03	0.17 ± 0.03	0.43 ± 0.05	0.38 ± 0.08	0.95 ± 0.15
^{7}Li(π^-,pn)	0.34 ± 0.02	0.11 ± 0.02	0.40 ± 0.04	0.31 ± 0.05	1.19 ± 0.18
^{3}He(π^-,pn)	0.067 ± 0.004	0.048 ± 0.009	0.099 ± 0.009	0.72 ± 0.14	1.48 ± 0.22
$n+p \rightarrow \pi^- pp$	1.26 ± 0.06	0.73 ± 0.05	0.59 ± 0.06	0.58 ± 0.08	0.47 ± 0.07

These values reproduce fairly well the present (π^+,pp) ratio and the ratio of the inclusive (π^+,p) cross sections (1.05 ± 0.02).[12] Full details of the calculation and the inclusive measurement will be published elsewhere.[12] From the inclusive and coincidence measurements of pion absorption on lithium isotopes, we conclude that for very light nuclei the cross section for each two-nucleon process at low T_π is approximately proportional to the number of nucleon pairs in the nucleus needed for that process.

The π^-/π^+ ratio of the total ^{6}Li(π,pn) cross section is much larger than 1 (1.45 ± 0.12). The Coulomb effects in the initial and final states are 5% and 15%, respectively, using the same charge-dependent parameters adopted by Köhler.[13] The reason for the rest (20%) is not evident, but we might expect a genuine effect in pion absorption on complex nuclei, reported by Navon *et al.*[14]

The angular distribution of the ^{6}Li(π^-,pn) cross section is similar to that of the ^{3}He(π^-,pn) reaction, although A_1/A_0 and A_2/A_0 ratios are smaller for ^{6}Li. However, the total cross section of the direct (π^-,pn) reaction for ^{6}Li is larger by a factor of 6.7 than that for ^{3}He. This factor is much larger than the ratio of the number of pp nucleon pairs between ^{6}Li and ^{3}He, and the ratio $\sigma(\pi^+,pp)/\sigma(\pi^+,pn)$ for ^{6}Li is nearly equal to that for C at $T_\pi = 65$ MeV.[8] The microscopic study of the Δ-nucleus potential by Lee and Ohta[1] is based on the two-nucleon data and predicted large contributions of the ΔN partial waves $^3P_{0,3}$ and $^5P_{1,2}$ as well as $^5S_2$. Their calculation predicts the R value to be as small as 4 for ^{6}Li.

It will be interesting to compare the present results with the $np \rightarrow \pi^\pm NN$ cross section at T_n corresponding to the two-nucleon pion absorption at $T_\pi = 70$ MeV. The angular distribution of pions has been measured at $T_n = 400$ MeV[15] and 409 MeV.[16] They showed significant asymmetry about 90° and the signs of the A_1 terms were in agreement with the present results. These facts again indicate an appreciable nonresonant, isoscalar contribution to the reaction.

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