Charged-Particle Multiplicities following Pion Absorption on ^{6}Li

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We have studied particle emission following π^+ absorption on ^{6}Li at $T_\pi = 150$ MeV by using a large-solid-angle detector. We find the absorption cross section leading to two or more energetic protons in the final state to be 98 ± 15 mb. We find that only about 65 mb can be explained as quasideuteron absorption.

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Although pion absorption amounts to 25%–50% of the total pion-nucleus cross section in the $\Delta(1232)$-resonance region,[1,2] it is still rather poorly measured and understood. Previous studies of absorption have concentrated in three main areas: (1) absorption of stopped π^-, (2) single-proton emission, and (3) two-proton or proton-neutron coincidence measurements.[2-6] There have been three published three-proton coincidence measurements[7-9] on ^{12}C and three measurements on ^{4}He involving three nucleons, either as *ppp* or *ppn*,[10,11] or with a deuteron in coincidence with a nucleon.[12]

Pion absorption on a single nucleon in a nucleus involves a large momentum transfer and consequently a small cross section,[13] only on the order of 1% of the total absorption. The next simplest mechanism is absorption on two nucleons. In principle, it could take place on either isospin-one or -zero nucleon pairs, but measurements[14-16] on ^{3}He indicate that absorption on $T=1$ pairs is about an order of magnitude less than on $T=0$ pairs. This fact is largely explained by the assumption that the absorption predominantly proceeds through a $\Delta(1232)$ intermediate state.[17] Absorption on $T=0$ nucleon pairs is usually referred to as quasideuteron absorption (QDA).

In recent years there has been increasing evidence that pion absorption has a significant component of three- (or more-) nucleon absorption. A rapidity analysis of single-proton spectra by McKeown *et al.*[18] was interpreted as showing that the mean number of nucleons participating in the absorption was three in ^{12}C and increased to about six in ^{181}Ta, with similar results for both π^+ and π^-. This result clearly disagrees with models which assumed that QDA was the dominant mechanism.

A direct measure of the fraction of the absorption cross section due to QDA has been attempted in a number of experiments.[3-6,19,20] These experiments, along with theoretical calculations,[21,22] indicated that the QDA was in the range of 40%–70% in nuclei heavier than carbon. The large range in the estimates is partially due to uncertainties in the estimates of the contributions of initial- and final-state interactions (ISI and FSI), which obscure the basic absorption mechanism. Corrections for multiple ISI and FSI are not expected to be very important in light nuclei.

In this Letter we present data for 150-MeV π^+ absorption on ^{6}Li. This nucleus is the lightest for which a solid target is available, and it has a well-defined shell structure which makes interpretation of the data less ambiguous than for heavier nuclei. Several measurements of pion absorption on ^{6}Li have already been made.[5,23-27] All involved the detection of two coplanar protons, with detectors of relatively small solid angle, except the experiment of Yakota *et al.*[5] which also detected neutrons. These experiments were done with pion energies below 76 MeV, well below the peak of the $\Delta(1232)$ resonance. This paper presents the first measurement in which two or three protons can be detected with good energy resolution independent of coplanarity, allowing an independent determination of three-body-like absorption.

The experiment was performed with a new large-solid-angle detector at the Clinton P. Anderson Meson Physics Facility (LAMPF), the BGO ball. The BGO ball consists of thirty phoswich detectors. Each detector has a 3-mm-thick plastic scintillator optically coupled to the front of a 5.6-cm-thick bismuth germanate crystal, with a 7.62-cm-diam photomultiplier tube mounted on the back. The anode signal from the phototube is time sliced to provide both ΔE (fast) and E (slow) signals for charged-particle (π, p, d, etc.) and neutral-particle (n,γ) identification. It was not possible to distinguish neutrons from photons. The crystals can stop up to 190-MeV protons and 90-MeV pions. The thirty detectors subtend $0.88\times 4\pi$ sr of solid angle, and cover scattering angles between 26° and 161°.

The pion beam had an average intensity of a few $\times 10^4$/sec, allowing individual pions to be counted. A 0.25-mm-thick plastic scintillator placed just before the target was used to define the beam. A coincidence of this detector with another scintillator upstream in the beam and any two of the BGO crystals was used as the event trigger.

An energy calibration was obtained from the $\pi^+ d \rightarrow 2p$ reaction with a CD_2 target. An energy resolution of 3% full width at half maximum was obtained at 215 MeV for events summed over all the counters in the ball, including contributions from the beam-energy spread and from energy loss and straggling in the target. The full data set for particle multiplicities following pion absorption on a range of nuclei from ^{6}Li to ^{208}Pb, and at $T_\pi = 50$–500 MeV, will be presented in later publications.

In Fig. 1 we present the summed proton-energy spectra for events in which two [Fig. 1(a)] or three [Fig. 1(b)] energetic protons ($T_p > 18$ MeV) were detected following π^+ absorption on ^{6}Li at $T_\pi = 150$ MeV. The two-proton spectrum is characterized by a peak at 280 MeV, and a second peak at 260 MeV, followed by a long tail extending to the detection threshold of 36 MeV. The three-proton spectrum is similar, except that it is missing the peak at 280 MeV.

^{6}Li is sufficiently small that all possible final reaction channels with two or more protons can be easily listed: $2p\,^4$He, $3pt$, $2pn\,^3$He, $2p2d$, $3pnd$, and $4p2n$. The Monte Carlo phase-space program FOWL,[28] along with certain assumptions about the interaction, was used to

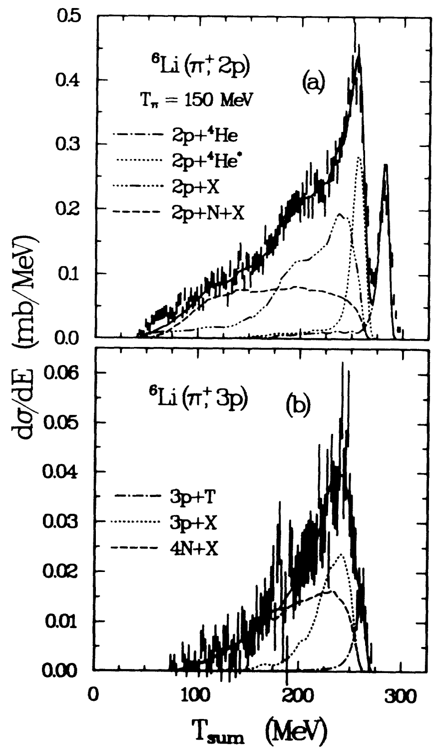

FIG. 1. (a) Summed charged-particle energy spectrum for events in which two energetic protons ($T_p > 18$ MeV) were detected following π^+ absorption with ^{6}Li at $T_\pi = 150$ MeV. (b) Summed charged-particle energy spectrum for events in which three energetic protons ($T_p > 18$ MeV) were detected following π^+ absorption with ^{6}Li at $T_\pi = 150$ MeV.

model the expected spectra in each of these channels. The calculated energies were smeared with the known energy resolution of the detector. In addition, we estimated the fraction undergoing nuclear reactions in the detector (up to 25% for 180-MeV protons), and assumed that an individual proton loses between 5 MeV and the full energy with equal probability. Some of these protons contribute to the long tails at lower energy seen in Fig. 1. The detector threshold of 18 MeV for protons was also included in the FOWL calculations. The shapes of the resulting spectra for the various final channels were then individually normalized to fit the observed $2p$ spectrum.

The $2p\,^4$He channel can have absorption that leaves the ^{4}He either in the ground state or in an excited state. We assume that the spectator ^{4}He has the momentum distribution observed in Ref. 27, and that all excitation energies between 20 and 30 MeV are equally probable. The calculated proton energy sums are shown as the two highest-energy curves in Fig. 1(a). We note that the energy carried by a ^{4}He of 300 MeV/c is only 12 MeV; thus the exact shape of the momentum distribution matters little in the energy sum, nor does the exact state of the ^{4}He*.

The next five listed channels are less sharp and are not distinguishable. We calculated their spectra by assuming that the momentum distributions of the two protons are determined by phase space and that the residual particles may be treated as spectators having only Fermi momenta. A spectator neutron or proton was assumed to have the momentum distribution found in Ref. 29, while the ^{2}H, ^{3}H, and ^{3}He had momentum distributions as discussed in Ref. 30. After being individually normalized, they were combined into the $2p+X$ curve of Fig. 1(a). The three-proton case in Fig. 1(b) was calculated similarly. The curve at the highest energy corresponds to the $3pt$ channel, and the next highest curve corresponds to the combination of the $3pnd$ and $4p2n$ channels with the three protons exhausting phase space (apart from Fermi momentum).

None of the calculated $2p$ distributions has a significant probability for an energy sum below 180 MeV, where there is still substantial yield in the observed spectra. However, we find that a suitable energy distribution can be obtained by assuming that the reaction energy has a phase-space distribution among three nucleons, but with one nucleon randomly undetected. The channels are thus $3pt$ with one proton unobserved, or $2pn\,^3$He with the neutron unobserved. No momentum restrictions were placed on the nucleons in these calculations. The corresponding curve is labeled $2p+N+X$ in Fig. 1(a), and it fits the shape of the lower end of the spectrum well. Such a strong three-nucleon contribution in detected two-nucleon channels was much less evident in earlier experiments at lower energies,[23-27] indicating either a strong energy dependence, a bias against this region due to the detection of only coplaner protons, or a combination of the two.

In the $3p$ case, about half of the cross section has an unobserved energy of more than 80 MeV and can be described by assuming four active nucleons in the final state. The curve labeled $4N+X$ was calculated from the $3pnd$ case, with no momentum restrictions placed on the four nucleons. The distribution of the $4p2n$ case is nearly identical. Only about 10% of the three-proton spectrum corresponds to $3pt$.

Further evidence that the low-energy region in the $2p$ spectrum follows a $3N+X$ phase-space distribution is provided in Fig. 2, which shows the angular distributions of proton energy spectra for $2p$ events gated on different regions of summed energy. The spectra for the region corresponding to ^{4}He and ^{4}He* in the final state ($240 < T_{\rm sum}$) follow the kinematics expected for QDA broadened by the Fermi momentum. However, at large missing energies ($0 < T_{\rm sum} < 180$), the distribution follows the Monte Carlo calculations of the $2pn\,^3$He phase space, illustrated by the solid curves.

We do not believe that the $2p$ low-energy distribution can be explained by a single ISI followed by QDA, or a QDA followed by a single FSI. In the case of a single ISI, for example, a pion knocks out either a proton or neutron and then undergoes a pure QDA. The recoil nucleon in a free πN scatter at 150 MeV can have a maximum energy of 80 MeV. Since the protons from QDA are roughly back to back, one expects either both or neither to be observed in our detector. Thus the energy sum should be within 80 MeV or so of 280 MeV, i.e., greater than 200 MeV. This energy overlaps the $2p+X$ region of the spectrum and is too high to explain the low-energy part. By similar but more complex arguments, we also conclude that the FSI contribution to the low-energy part of the spectrum is small. Soft FSI (potential scattering) can smear the proton angular correlation but cannot produce the observed low-energy tail.

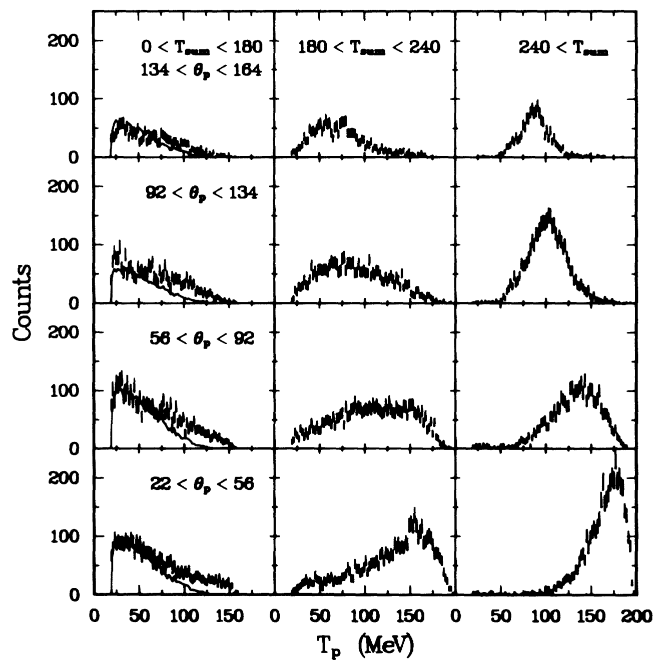

FIG. 2. Histograms of the energy distributions of protons from two-proton events with different cuts on the summed energy $T_{\rm sum}$ (columns), and for different scattering angles θ_p (rows). The solid lines for the column ($0 < T_{\rm sum} < 180$) are the result of $3N+X$ normalized to the data.

The measured cross sections, estimated counting-loss corrections, and full cross sections were extracted from the data on the basis of the phase-space calculations just described, and are presented in Table I. Corrections for reactions in the detector were discussed earlier. Corrections for the missing solid angle were determined by assuming that the protons have the same angular distribution as the $\pi^+d \rightarrow 2p$ reaction, for the channels containing a ^{4}He, or angular distributions given by the phase-space calculations, for the other channels. The corrections gave a good description of the width of the deuterium peak and the tail at lower energies for our $\pi^+d \rightarrow 2p$ calibration data, and yielded cross sections within 10% of the actual value. Since different runs on the same target had differences up to about 10%, we estimate the overall

TABLE I. Cross sections. These cross sections do not include contributions from protons whose energies are less than 18 MeV, the detector threshold.

Reaction channel	Fitted[a] (mb)	Correction Factors Interactions in detectors	Missing solid angle	Total[a] (mb)
$2p+{}^4\text{He}$	4.2	1.5	2.0	12.6
$2p+{}^4\text{He}^*$	5.4	1.5	2.0	16.2
$2p+X$	14.5	1.4	1.8	36.5
$2p+N+X$	12.2	1.2	1.4	20.5
$3p+{}^3\text{H}$	0.22	1.3	2.9	0.8
$3p+N+X$	2.40	1.3	2.9	9.1
$4p+X$	0.04	...	...	...
$p+d+X$	2.5	1.5	2.0	7.5
Sum[b]				98 ± 15

[a]Uncertainties in these quantities are dominated by the systematic error of $\pm15\%$. However, in the case of $2p+{}^4\text{He}^*$ and $2p+X$ the fitting error adds an additional 5-mb error to the total cross section.

[b]The sum is adjusted for double counting arising from the correction factors for missing solid angle.

systematic uncertainty on the total cross sections to be about 15%.

Using the $3p$ phase-space fit to the data where three protons are observed we estimate that $\simeq 3.9$ mb of the $2p+N+X$ cross section is due to three energetic protons in the final state where one is unobserved. This indicates that about $\frac{2}{3}$ of the cross section with three energetic nucleons in the final state is due to $2p+n+X$ and $\frac{1}{3}$ due to $3p+X$. A neutral of more than 20-MeV observed energy is seen in coincidence with two protons with summed energy less than 180 MeV in 10% of the events. This rate is consistent with every event containing a neutron, assuming an isotropic distribution of the neutrons and a detection efficiency of 20%. The ratio of $\sigma(ppp)/\sigma(ppn)$ of about one-half is consistent with the value for the three-nucleon absorption mode reported in Ref. 10. The estimated total cross section is 98 ± 15 mb. The value given in Ref. 1 for natural Li (93% ^{7}Li) with 165-MeV π^+ is 120 ± 20 mb and was attributed primarily to final states with two or more protons.

After making the full corrections, and, to avoid double counting, subtracting the 3.9 mb in the $2p$ spectrum that appears to be due to three-proton events, we find 63 mb which corresponds to either a "pure" QDA or a QDA with a single ISI or FSI. About 23 mb, or about one-quarter of the absorption cross section, corresponds to a region that appears to be due to absorption in which the pion energy is distributed statistically among three nucleons.

In conclusion, about one-third of the absorption cross section appears to be due to a process in which the reaction energy is shared amont three nucleons. The angular and energy distributions are not consistent with a single initial-state (final-state) interaction followed (preceded) by a simple quasideuteron absorption, although multiple interactions cannot be ruled out.

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