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(Received 9 January 1986)

Data for the reaction $^{58}\text{Ni}(\pi^+, 2p)$ at $T_\pi = 160$ MeV were obtained for a number of angle pairs. The resultant angular correlations for $T_1 + T_2 > 160$ MeV (guaranteed pion absorption) peak at a separation angle corresponding to absorption on a deuteron at rest. However, simple estimates of initial- and final-state scatterings suggest that less than 50% of the absorption cross section arises from absorption on nucleon pairs. The data show little evidence for scattering of pions before absorption on nucleon pairs.

PACS numbers: 25.80.Ls

The pion-absorption process has been the subject of numerous experimental and theoretical studies over the past few years. As yet the dominant reaction mechanisms for pion absorption on nuclei remain unclear. For example, a rapidity analysis¹ of inclusive (π^+, p) data suggests that for medium-mass nuclei approximately four nucleons participate in absorbing the energy and momentum of a resonance-energy pion. In addition, the authors of Ref. 1 argue that since the mean free path of a medium-energy nucleon is relatively long, multiple scattering should not account for the participation of significant numbers of nucleons. On the other hand, coincident protons from the reaction $^{12}\text{C}(\pi^+, 2p)$ at 165 and 245 MeV show an angular correlation peaking at angles corresponding to capture on an $n-p$ pair with low total momentum.² While such results show the occurrence of capture on nucleon pairs, the integrated cross section represents only about 10% of the total absorption cross section.³

Several open questions remain concerning pion absorption in nuclei: (1) What is the role of two-body absorption? (2) What is the importance⁴ of interactions preceding or following the absorption process? (3) What is the importance of actual multinucleon (> 2) processes in the absorption?

In an attempt to clarify these issues, we have investigated the reaction $^{58}\text{Ni}(\pi^+, 2p)$ at 160 MeV with moderately good energy resolution (residual-excitation-energy resolution ≤ 6 MeV). Although the angular distributions are not as detailed as those for ^{12}C

in Ref. 2, the improved energy resolution permits study of the proton angular and energy correlations as a function of missing mass, thus providing further insights into the reaction dynamics. We show initial results in this Letter. More detailed results and analysis are presented elsewhere.⁵

The experiment was carried out with a 160-MeV π^+ beam at the low-energy pion channel at the Clinton P. Anderson Meson Physics Facility (LAMPF). Reaction products from isotopically enriched ($> 95\%$) ^{58}Ni targets were detected by eight telescopes placed coplanar with the beam, covering an angular range of $\pm 30^\circ$ to $\pm 140^\circ$. Each telescope consisted of 0.16-cm-thick NE102 plastic ΔE detector, followed by a thin-entrance-window NaI(Tl) E detector with dimensions $7.6 \times 7.6 \times 12.5$ cm³. The solid angle subtended by each detector was typically 4.8 msr. A ΔE - E coincidence and the 12.5-cm thickness of the NaI crystal limited the dynamic range of the telescope to about 25–200 MeV, calibrated by means of the reaction $\pi^+ + d \rightarrow 2p$. Corrections were made for reactions of the protons in the target and detectors. The pion flux was monitored with an ionization chamber, calibrated by radiochemical methods using the known $^{12}\text{C}(\pi^+, X)^{11}\text{C}$ cross section.⁶ Relative uncertainties in the coincidence cross sections were dominated by uncertainties in detector acceptances and in the appropriate ΔE - E cut to identify protons (each typically $\sim 5\%$). Statistical uncertainties were considerably smaller. In addition there was an overall absolute normalization

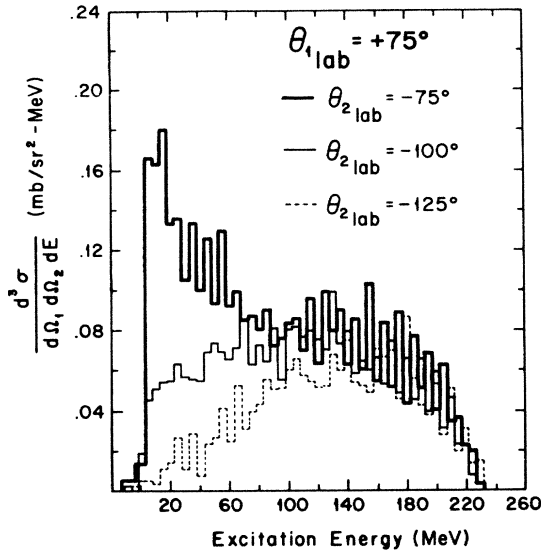


FIG. 1. Excitation-energy spectra for the reaction $^{58}\text{Ni}(\pi^+, 2p)$. Data are for the three angle pairs listed.

uncertainty of 7% in the product of beam flux and target thickness.

In Fig. 1 are presented typical residual-excitation-energy spectra for $^{58}\text{Ni}(\pi^+, 2p)$ at an angle pair corresponding to capture on a deuteron at rest ($\theta_1 = +75^\circ$, $\theta_2 = -75^\circ$, referred to as a quasideuteron angle pair), and two other θ_2 angles, 25° and 50° away from this condition. At the quasideuteron angle the low-excitation-energy region (≤ 50 MeV excitation) shows a clear peak which disappears fairly rapidly for angles away from this angle. This region is expected to arise primarily from absorption on $(f_{7/2})^2$ or $(f_{7/2}, 2s-1d)$ nucleon pairs. As the excitation energy increases the spectra show little angular dependence. Results for other angle pairs are qualitatively similar.

These spectra suggest that capture on nucleon pairs may dominate for the outermost shells, but that the more tightly bound inner orbitals play little role in the direct two-body process. The relatively flat angular dependence of the higher-excitation-energy regions suggests more complicated reaction mechanisms.

The data were integrated with use of energy cuts of $T_1 + T_2 \geq 230$ MeV (cut I, first 50 MeV of the excitation in ^{56}Co), $T_1 + T_2 \geq 160$ MeV (cut II, still guaranteed absorption of the pion), and $T_1, T_2 \geq 25$ MeV (cut III, all detected events) to produce angular correlations $d^2\sigma/d\Omega_1 d\Omega_2$. Results for $\theta_1^{\text{lab}} = +75^\circ$ ($\theta_1 = +90^\circ$ in the π - NN center-of-momentum frame) are shown in Fig. 2. The correlations for cut I peak strongly at the quasideuteron angle, as in the case² of ^{12}C . As expected from the spectra shown in Fig. 1, the angular correlations broaden as the excitation energy increases.

In order to make a comparison with Ref. 2, as well

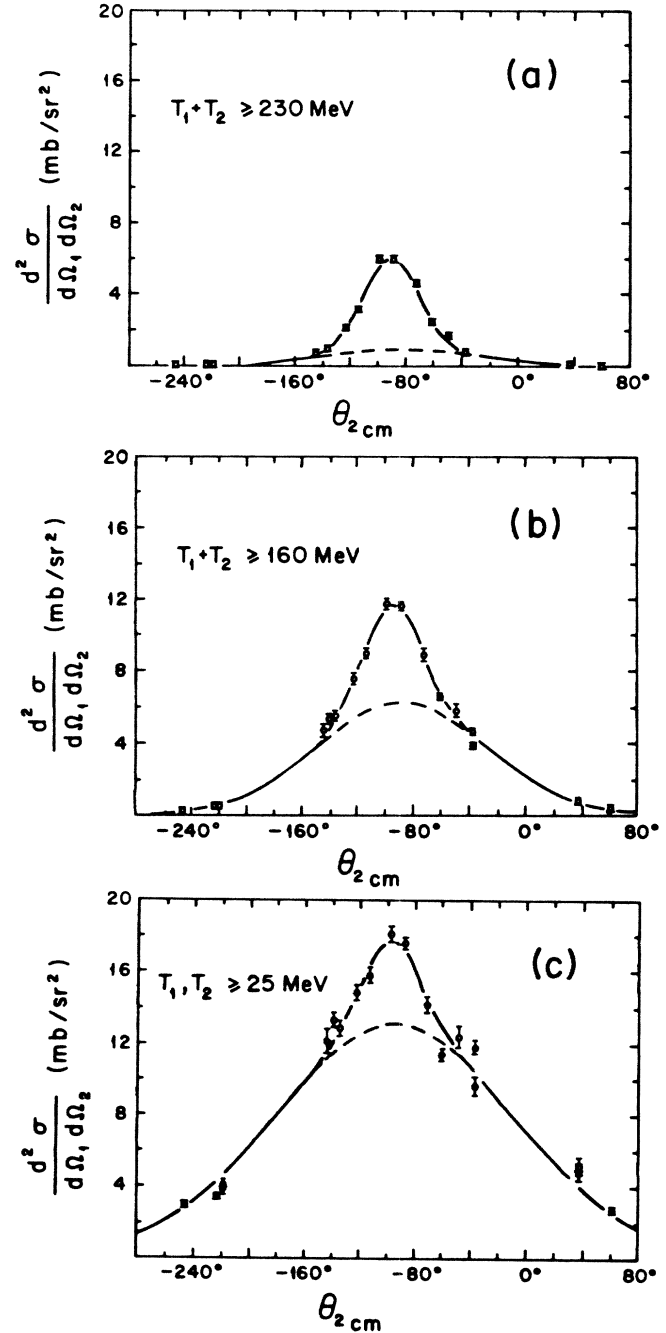


FIG. 2. Angular correlations for $\theta_1 = +90^\circ$ data, in the πd c.m. frame, for (a) energy cut I, (b) energy cut II, and (c) energy cut III.

as for convenience in integrating the cross sections, we have fitted the angular correlations for the different cuts with the sum of two Gaussian distributions, one narrow and one broad. The fits for $\theta_1^{\text{c.m.}} = 90^\circ$ are also shown in Fig. 2. It is seen immediately that the area of the narrow Gaussian is nearly independent of the energy cut, while the broad-Gaussian area increases dramatically as the energy cut is relaxed. The total

cross sections associated with the narrow and broad Gaussians can be estimated by use of the following procedure. We assume the same angular correlation out of plane as in plane (evidence for the validity of this assumption is presented in Ref. 2), and integrate the narrow Gaussian to extract a cross section $d\sigma(\theta_1)/d\Omega_1$. Adequate angular coverage was available for distributions around only three values of θ_1^{lab} (30° , 75° , and 130°). Although limited, the data for these three angles are consistent with the free $\pi^+ + d \rightarrow 2p$ angular distribution. Assuming this angular variation to extrapolate our data, we obtain the total cross sections σ_{nar} (integrated over θ_1) listed in Table I. For the broad Gaussian, $d\sigma(\theta_1)/d\Omega_1$ was found to be independent of θ_1 for all energy cuts. Therefore, the total cross sections σ_{brd} were obtained by multiplying $d\sigma(\theta_1)/d\Omega_1$ by 2π . The fraction of the total absorption cross section that each cut represents is also presented.

An important question is what physical processes are represented by the narrow and broad Gaussian distributions. In Ref. 2, the corresponding narrow Gaussian for $^{12}\text{C}(\pi^+, pp)$ was assumed to consist of direct two-nucleon absorption events. Scattering of the final-state protons was estimated to reduce the observed two-nucleon events by about a factor of 2, leading to a total two-nucleon absorption cross section of 20% of the total absorption cross section. It has been suggested⁷⁻⁹ that some pure two-nucleon absorption events for ^{12}C might have appeared in the broad Gaussian, but this would in any case leave most of the absorption cross section unaccounted for. It has also been suggested by Girija and Koltun⁴ that quasifree pion scattering preceding pion absorption on a two-nucleon system may be a very important process, although this conjecture has been disputed by Schiffer.¹⁰

From our ^{58}Ni data alone, evidence for the validity of the two-Gaussian approach is provided by the independence of energy cut of the narrow-Gaussian area, by the agreement of the narrow-Gaussian angular

distribution with that for the reaction $\pi^+ d \rightarrow pp$, and by the flatness of the broad-Gaussian angular distribution. We have carried out Monte Carlo calculations to estimate the effects of Fermi motion of the nucleons, scattering of the pion before absorption, and final-state interactions of the emitted protons. The calculations used reasonable momentum distributions for the nucleons and "deuterons" in the nucleus and free $\pi^+ N$ and $\pi^+ d \rightarrow pp$ cross sections to describe the energy and angular dependence of the processes. It should be emphasized that these calculations are expected to yield information only on the *shape* of the angular correlation. The results are the following: (1) Absorption of the π^+ on $n-p$ pairs, with a pair momentum described by a Gaussian distribution of width 300 MeV/c, is sufficient to describe the position and width of the narrow Gaussian (Fig. 3). (2) For $\theta_1^{\text{lab}} = +75^\circ$, the effect of $\pi^+ - N$ scattering before absorption would be to produce an asymmetry and possible shift of the angular-correlation peak (Fig. 3). (3) Such an asymmetry may be indicated by our data, but it is small; this suggests that fewer than $\sim 30\%$ of the pions scatter before being absorbed on $n-p$ pairs, a rather striking observation in itself.

We therefore conclude that the narrow Gaussian component does correspond to direct absorption on two-nucleon pairs with minimal final-state interactions. The chief effect of final-state interactions is to remove events from the narrow Gaussian distributions placing them in the broad Gaussian. With a proton mean free path of 5 fm, final-state interactions would reduce the narrow-Gaussian area in Ni by a factor of 3 to 4. This estimate is confirmed by distorted-wave impulse-approximation calculations. Thus, direct two-nucleon absorption, even with initial- and final-state interactions, would seem to account for $< 50\%$ of the total absorption cross section for π^+ 's on ^{58}Ni .

Factorized quasideuteron distorted-wave impulse-approximation calculations¹¹ were compared to the direct two-nucleon absorption data (cut I). The in-

TABLE I. Summary of the (π^+, pp) cross sections for the narrow (nar) and broad (brd) Gaussian components. The energy cuts are described in the text. Comparison is made to the total absorption cross section σ_{abs} for 165-MeV π^+ on ^{56}Fe , 577 ± 89 mb (see Ref. 3). The listed uncertainties include those associated with the fitting procedure as well as the relative and absolute uncertainties described in the text. Since the sum of the narrow and broad Gaussians is better determined than each Gaussian alone, the listed uncertainties for $\sigma_{\text{nar}} + \sigma_{\text{brd}}$ might be considered to be conservative. However, an uncertainty of $\sim 7\%$ is included to reflect our assumptions about the shapes of the angular distributions (see text).

Energy cut	σ_{nar} (mb)	$(d\sigma/d\Omega)_{\text{brd}}$ (mb/sr)	σ_{brd} (mb)	$\sigma_{\text{nar}} + \sigma_{\text{brd}}$ (mb)	$\sigma_{\text{nar}}/\sigma_{\text{abs}}$ (%)
I	41 ± 5	2.6 ± 0.5	16.6 ± 3.0	58 ± 6	7.0 ± 1.3
II	55 ± 8	26.8 ± 3.5	168 ± 22	223 ± 23	9.5 ± 2.0
III	53 ± 14	88 ± 9	555 ± 58	608 ± 60	9.2 ± 2.8

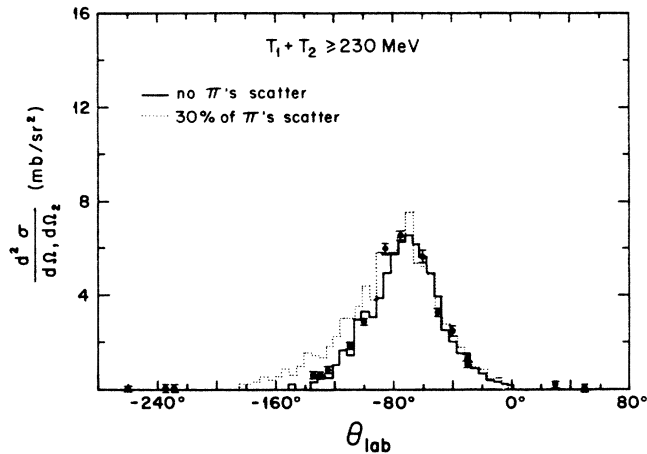


FIG. 3. Comparison of the $\theta^{\text{lab}} = +75^\circ$ angular-correlation data, using energy cut I, with the calculated correlation from a Gaussian-momentum-distribution (width = 350 MeV/c) nucleon pair. The histograms refer to different amounts of scattering of the pions before absorption.

clusion of all $f_{7/2}$ contributions with zero oscillator quanta in the n - p relative motion produced an angular correlation a factor of 3 too narrow and a factor of 50 too small. With regard to the width, it is interesting to note that the width measured for ^{58}Ni ($\sim 45^\circ$) is greater than that measured for ^{12}C ($\sim 35^\circ$). Any quasideuteron calculations based solely on components with zero oscillator quanta in the relative motion will predict the opposite change. Thus, at a minimum, this comparison indicates the need for the inclusion of many other n - p configurations using a more sophisticated model.¹²

Given that much of the absorption process does not seem to involve two-nucleon absorption, the nature of the broad Gaussian component is of considerable interest. It is noteworthy that the broad Gaussian is peaked at the two-nucleon correlation angle, indicating that some signature of a two-nucleon absorption process remains. Some events of this nature would of course simply arise from final-state interactions of the protons, as discussed above.

As seen in Table I, the sum of narrow and broad Gaussians can account for all of the total absorption cross section. If we postulate approximate cancellation of the effects of increased cross section due to yield below our energy thresholds, and decreased cross section due to higher (> 2) multiplicity of emitted particles, this agreement with the total absorption cross section is probably reasonable. This is consistent with our observation of very few coincidences for the emission of other charged particles such as deuterons and

tritons. It should be remarked that the data of Ref. 2 do not appear able to account for all of the π^+ - ^{12}C total absorption cross section, even considering the different energy cuts on the outgoing protons.

From the present results and analysis we conclude the following concerning in-flight pion absorption on ^{58}Ni : (1) The $(\pi^+, 2p)$ reaction can account for the entirety of the total absorption cross section. (2) The angular correlation, for the low-excitation-energy region of the residual nucleus, peaks strongly at the quasideuteron angle pair, indicating dominance of a two-nucleon mechanism. However, the two-nucleon process appears not to be the overall dominant absorption mechanism, even including initial- and final-state interactions. (3) The flatness of most of the angular and residual energy distributions suggests significant contributions from more complicated processes. (4) Distorted-wave impulse-approximation calculations in a quasideuteron model are unsatisfactory and indicate the need to include higher principal quantum numbers in the n - p relative-motion wave function.

We thank the Los Alamos National Laboratory staff for their help during the experiment. This work was supported in part by the Department of Energy and by the National Science Foundation.

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