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Pion scattering and absorption contributions to proton emission from pion-nucleus collisions at $T_\pi = 50$–295 MeV

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Proton spectra of ^{3,4}He($\pi^\pm$,p) and ^{27}Al($\pi^\pm$,p) have been measured at $\theta_p = 20°$ for $T_\pi = 50$, 100, 150, 200, and 250 MeV, and at $\theta_p = 20°$ and 40° for $T_\pi = 295$ MeV. A small contributor to these spectra is the exclusive pion absorption reaction for which the cross section of ^{4}He(π^+,p)^{3}He is reported. Major contributions are identified to come from quasifree $\pi N \to \pi p$ scattering and $\pi NN \to Np$ absorption for which cross sections are also reported. The quasifree cross sections are compared with those of the free reactions $\pi N \to \pi p$ and $\pi d \to pp$. We use these results to assess the contribution of quasifree reactions to the total reaction cross section. The comparison of the quasifree $\pi NN \to Np$ reaction relative to $\pi d \to pp$ is discussed in terms of differences in the attenuation and the dynamics of the reactions. This information is of interest for the phenomenological interpretation of complex reactions such as the two-nucleon absorption model of ^{3}He(π^-, n)^{2}H, ^{4}He(π^-, n)^{3}H, and ^{4}He(π^+, p)^{3}He in which $\pi d \to pp$ is assumed to be an elementary process. This experiment also provides information on the cross section of $\pi^- pp \to pn$ from which we determine the dependence of pion absorption on the isospin of the initial NN state.

[NUCLEAR REACTIONS ^{3,4}He($\pi^\pm$,p), ^{27}Al($\pi^\pm$,p) $E = 50$–295 MeV; measured $\sigma(E;E_p)$; $\theta = 20, 40°$.]

I. INTRODUCTION

The (π,p) reaction in nuclei offers a possibility of simultaneously studying two of the principal aspects of pion-nucleus interactions, namely, pion-nucleon scattering and pion absorption. The simplest of these processes are pion-nucleon single scattering and two-nucleon pion absorption, which can take place as quasifree processes in pion-nucleus collisions; i.e., quasifree $\pi N \to \pi p$ scattering (QFS) and quasifree $\pi NN \to Np$ absorption (QFA) reactions.

Information on the quasifree reactions can be used to gain insight into the principal interaction modes of pion-nucleus collisions. From the measured (π,p) spectra the relative importance of $\pi N \to \pi p$ pion scattering, $\pi NN \to Np$ pion absorption, and other more complicated multinucleon processes can be determined. From (π,p), one can also learn about the contribution of the quasifree cross sections to the total pion nucleus cross sections.[1,2] Information on the QFS and QFA reactions can also serve to better understand complex nuclear reactions such as the much studied exclusive pion absorption reaction $A(\pi,p)A-1$. In this case one resorts to externally determined input as much as possible because of the ambiguities relating to the nuclear wave functions at the large momentum transfer involved. Phenomenological models[3,4] have been applied for such (π,p) reactions in ^{3}He and ^{4}He, which specifically invokes the basic two-nucleon pion absorption mechanism using information on the $\pi NN \to Np$ cross section and the attenuation in the target nucleus. The combined use of QFS and QFA data offers a possibility of distinguishing between attenuation effects and dynamical initial state differences. Finally, the QFA reaction has attracted great interest in its own right because of the opportunity to measure the $\pi NN \to Np$ cross section for different initial NN states, i.e., as given by the free deuteron and the quasifree NN states in ^{3}He and ^{4}He.[5–7]

For ($\pi^\pm$,p) reactions in light nuclei, particularly ^{3}He and ^{4}He, the signature of the two-body kinematics of the quasifree reactions is particularly evident since the single particle momentum distributions of ^{3}He and ^{4}He are fairly narrow and the QFS and QFA reactions appear kinematically separated from each other in the (π,p) spectra. Furthermore, the number of spectator nucleons is small so the spectator interference does not become an overwhelming feature of the quasifree reactions, which is important in order not to compromise the means of distinguishing the quasifree reactions from other nonspecific multinucleon reactions. The (π,p) reactions in ^{3}He and ^{4}He present favorable conditions for identifying contributions of $\pi N \to \pi p$ and $\pi NN \to Np$. Having to detect only one exit particle makes it straightforward to extract cross sections for the QFS and QFA reactions for both π^- and π^+ over an extended range of incident energies including the (3,3) resonance region where the πN interaction depends crucially on the isospin. In this paper we report on results of cross section measurements for the $^4He(\pi^+,p)^3He$ and $^{3,4}He(\pi^\pm,p)$ reactions for forward proton angles at six incident energies between 50 and 300 MeV. The QFA part of these measurements has been discussed earlier,[5,6] and here we present all data emphasizing the interrelationship between information on quasifree scattering, quasifree absorption, and exclusive (π,p) pion absorption to discrete nuclear bound states.

II. EXPERIMENTAL

In this experiment, performed on the EPICS spectrometer at the Clinton P. Anderson Meson Physics Facility (LAMPF), we measured the doubly differential cross section $d^2\sigma/d\Omega\, dp$ for the nuclear $(\pi^\pm,p)$ reactions as a function of proton momentum (p_p) at $T_\pi = 50$, 100, 150, 200, and 250 MeV for $\theta_p = 20°$ and at $T_\pi = 295$ MeV for $\theta_p = 20°$ and 40°. Special attention was paid to utilizing an extended portion of the total spectrometer momentum bite. The spectrometer acceptance depends mainly on the deviation $[\delta = (p - p_0)/p_0]$ from the central momentum p_0 with a slight dependence on p_0 as field saturation is approached. The acceptance function was thus measured covering the practically useful δ range from -8% to $+12\%$. To obtain extended (π,p) spectra, the spectrometer field was changed in steps of 15%, which means that no portion of a measured proton spectrum had to be corrected by more than 50%. Composite (π,p) spectra consisted of two to six partial ones each of which was corrected for the measured acceptance function and normalized to the same accumulated pion beam flux. The beam was monitored by an ion chamber which gave the relative flux of π^+ or π^- at each incident energy. In order to relate the relative π^+ and π^- fluxes to each other, we measured $\pi^+ + p$ and $\pi^- + p$ elastic scattering at each energy using a CH_2 target. Differences in the amount of extraneous particles in the π^+ and π^- beams could thus be accounted for with the help of known $\pi^\pm p$ cross sections.[8] For the final normalization of measured $(\pi^\pm,p)$ yields in the target nuclei ^3He, ^4He, and ^{27}Al, and for determination of differential cross sections $d^2\sigma/d\Omega\, dp$, we relied on published cross sections[9] of the reaction $\pi^+ d \to pp$.

The cryostat for the liquid helium targets contained two cells ($15.2 \times 12.5 \times 2.5$ cm^3) for ^3He and ^4He which were kept at 1.5 K. The target thickness over the beam spot size used (6.2×11.0 cm^2) was determined from x-ray photographs; the effective ^3He and ^4He target densities were 311 and 574 mg/cm^2 ($< \pm 3\%$). The target cells had 25 mg/cm^2 thick aluminum windows. Spectra of $^{27}Al(\pi^\pm,p)$ were measured, with 200 and 1200 mg/cm thick targets, mainly for the purpose of subtracting the usually small admixture of $^{27}Al(\pi,p)$ in the spectra taken with the cryostat. A CD_2 target (194 mg/cm^2 thick) was used for measurement of $\pi d \to pp$ which allowed us to determine relative proton yields and cross sections (with the help of published cross sections[9] for the $\pi d \to pp$ reaction) for $^{3,4}He(\pi^\pm,p)$ and $^{27}Al(\pi^\pm,p)$.

The main objective of the present experiment was to measure (π,p) spectra in the kinematics region of two-nucleon pion absorption which meant detecting protons from the highest energies produced [corresponding to the reaction $A(\pi,p)A-1$ with the residual $A-1$ system left unexcited] down to approximately 50% of this value. The proton momentum for $^4He(\pi^+,p)^3He$ at $T_\pi = 295$ and $\theta = 20°$ is beyond the maximum momentum of the spectrometer ($P_0 = 785$ MeV/c) and subsequently we made complementary measurements at 40° for this energy. In a few cases, the $(\pi^\pm,p)$ measurements were extended all the way to the low momentum cutoff at about 350 MeV/c (where the range of protons becomes smaller than the detector thickness), which thus included the kinematical region of $\pi N \to \pi p$ scattering.

III. RESULTS

Our results on differential cross sections $d^2\sigma/d\Omega\, dp$ for the (π^+,p) and (π^-,p) reactions in ^3He, ^4He, and ^{27}Al con-

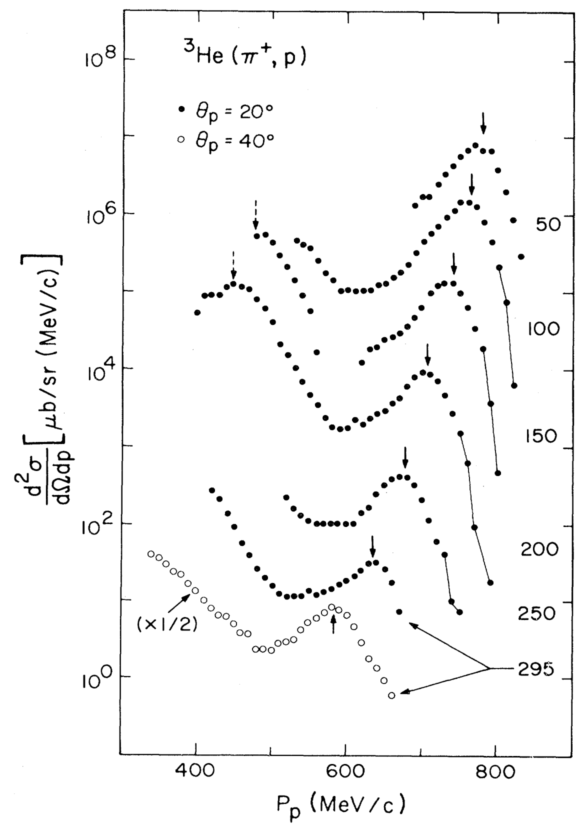

FIG. 1. The measured $^3He(\pi^+,p)$ spectra. The scales for the x and y axes refer to the 295 MeV spectrum and each spectrum of lower energies has been lifted one decade and translated 100 MeV/c to the right; for instance, the 50 MeV spectrum should be multiplied by 10^{-5} to read the cross section and translated -500 MeV/c to read the momentum. The arrows (solid and broken) indicate the computed positions for the QFA and QFS peaks.

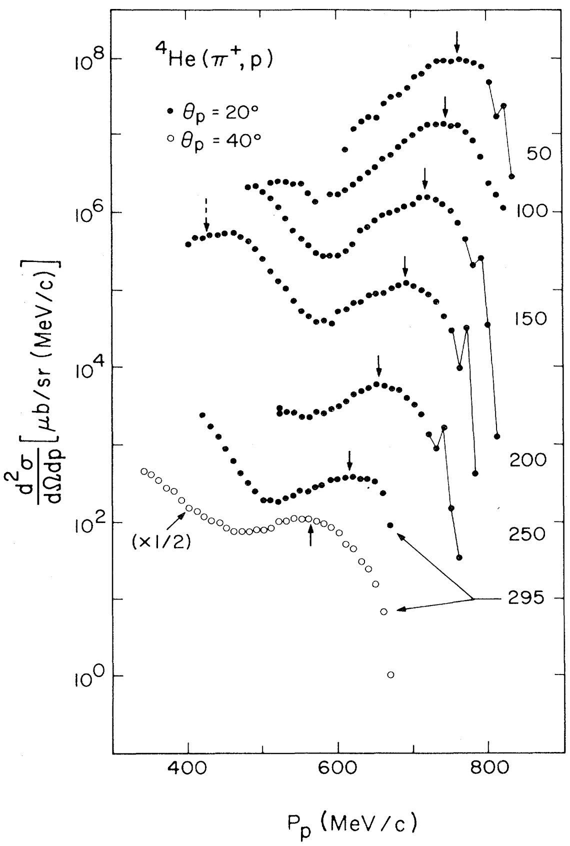

FIG. 2. The measured ^{4}He(π^+,p) spectra.

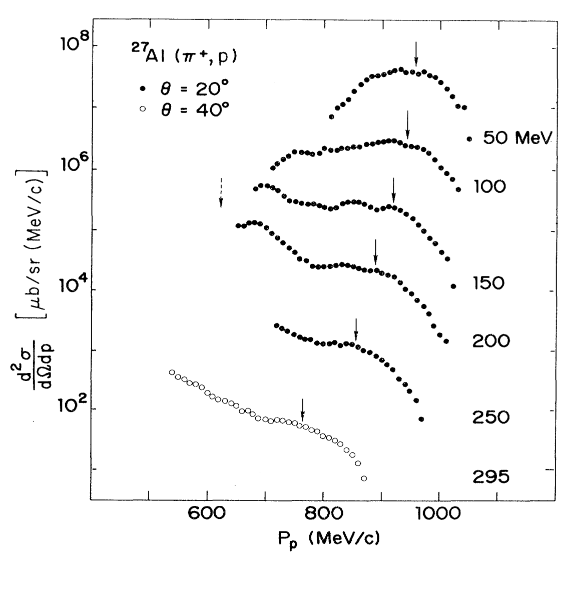

FIG. 3. The measured ^{27}Al(π^+,p) spectra.

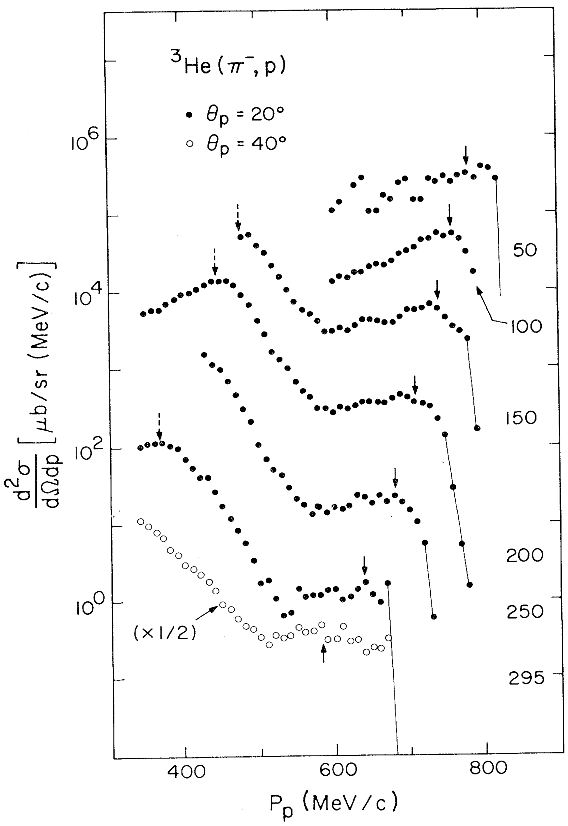

FIG. 4. The measured ^{3}He(π^-,p) spectra.

sist of spectra at $\theta_p=20°$ for $T_\pi=50$, 100, 150, 200, and 250 MeV and at $\theta_p=20°$ and 40° for $T_\pi=295$ MeV (Figs. 1–6). As for explaining the gross spectral features, there are two principal processes that can produce fast forward going protons, namely, proton knockout due to pion back scattering and proton ejection due to pion absorption. The maximum energy of pion scattering is determined by $A(\pi,\text{p})[(A-1)+\pi]$ with the pion at rest in the residual $A-1$ system. Therefore, pion absorption is a sole contributor to the uppermost 200–250 MeV/c of our (π,p) spectra.

The measured spectra show detailed features which suggest that further identification can be based on two-body kinematics. The momentum of the quasifree pion nucleon scattering (QFS) $\pi\text{N}\rightarrow\text{p}\pi$ can be calculated from the kinematics of the free scattering assuming that the nuclear proton (p_A) of the quasifree $\pi\text{p}_A\rightarrow\text{p}\pi$ scattering is stationary in the target and has the fictitious mass of $m_{\text{p}_A}=m_\text{p}-B$ to correct for the nuclear binding. As a value for B, we used the breakup energy for ^{3}He and ^{4}He, i.e., 7.7 and 28.3 MeV; for aluminum the breakup energy is not well defined and $B=30$ MeV was arbitrarily used to mark the arrows in Figs. 3 and 6. The calculated QFS momentum is found to locate the observed low-momentum peak quite well (Figs. 1–7). We can calculate the momentum of the quasifree two-nucleon pion absorption (QFA) in the same manner. This locates the maximum of the broad high momentum peak through the incident energies studied. Thus, significant portions of the

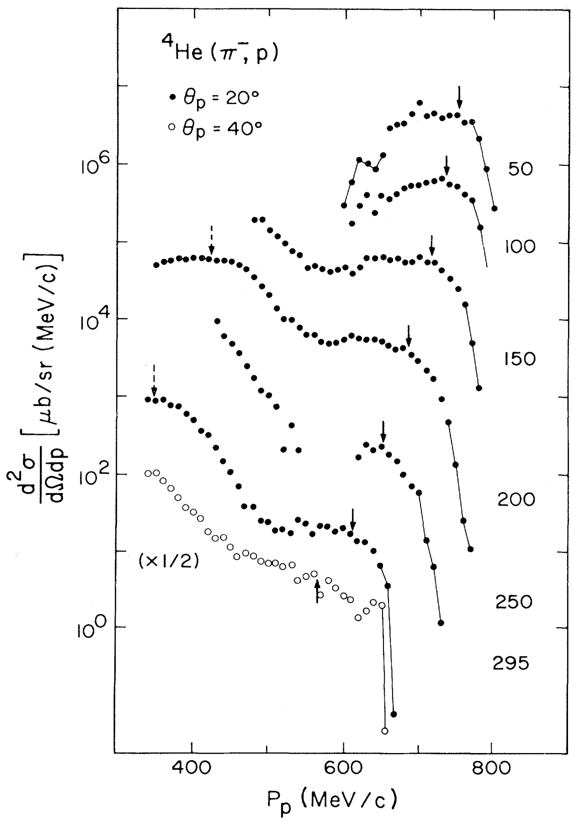

FIG. 5. The measured ^{4}He(π^-,p) spectra.

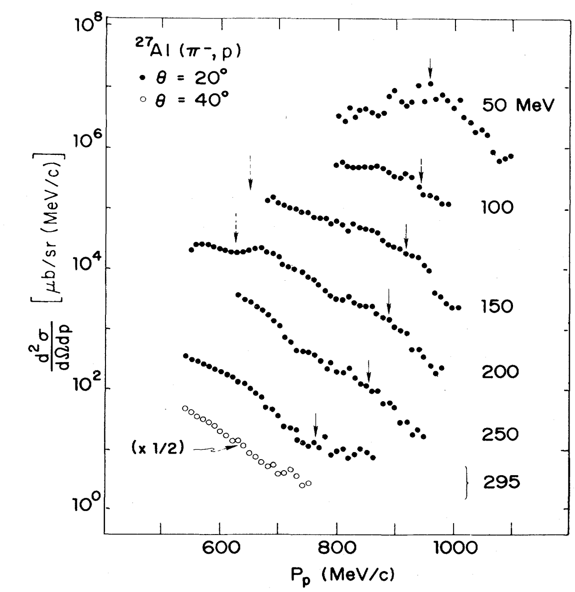

FIG. 6. The measured ^{27}Al(π^-,p) spectra.

pion scattering and pion absorption reactions appear in the form of corresponding quasifree processes. Finally, the only exclusive (π,p) reaction to a specific and bound nuclear state that we distinguish is ^{4}He(π^+,p)^{3}He. Although it is discernible in the spectra of Fig. 2, a well separated narrow peak is better observed in spectra of finer histogram divisions (see Fig. 8).

A. Pion scattering

On the high momentum side of the QFS peak, the (π,p) cross section is seen to decrease with a nearly exponential slope. We interpret this slope as reflecting the nuclear momentum (P_A) distribution of the knocked out nucleon which decreases monotonically as P_A departs from the maximum at $P_A=0$. The slope extends approximately to the kinematical limit for (π,p) scattering (cf. Fig. 7). Unfortunately, our measurements do not cover the whole QFS peak, but, from the high momentum slope measured, we can estimate the width of the QFS peak and also the cross section for $\pi N \rightarrow \pi p$. From Gaussian slope fits to the data (assuming that the QFS peak is centered at the expected position) we determine widths (FWHM) of $=90\pm15$ and 135 ± 20 MeV/c for ^{3}He and ^{4}He, respectively. From widths of 120 and 200 MeV/c for the single particle momentum distributions in ^{3}He and ^{4}He (taken from Refs. 10 and 11), we calculate the expected widths to be 88 and 146 MeV/c, respectively, for the QFS peaks. These values refer to quasifree (π,p) scattering at $\theta_p=20°$ with insignificant variation over the incident energy range of $T_\pi=150$ to 295 MeV; at $\theta_p=40°$ and $T_\pi=295$ MeV we observe widths of 200 and 230 MeV/c compared to the expected values of 140 and 210 MeV/c. From these fits we also determined ($\pi^\pm$,p) QFS cross sections with the results shown in Table I. The errors shown represent the uncertainty in fitting the peak in the spectra but do not account for how valid the Gaussian peak shape assumption is. There is an additional uncertainty of $\pm15\%$ in the overall normalization. The ratio of the π^+ to π^- QFS cross sections at a given energy can be determined with somewhat better accuracy (Table II).

B. Inclusive pion absorption

The (π^+,p) spectra of ^{3,4}He show a broad high momentum peak which we ascribe to the QFA process (Figs. 1, 2, 4, and 5). The width of this peak is found to be about 54 and 100 MeV/c in the spectra of ^{3}He(π^+,p) and ^{4}He(π^+,p), respectively, at $T_\pi=200$ MeV. It is clear that a Fermi motion of the NN pair (relative to the remaining $A-2$ nucleus in the target nucleus) will contribute to the QFA peak width. The full width of the observed peaks for ^{3}He and ^{4}He corresponds to a Fermi momentum of ±60 and ±120 MeV, respectively. The NN pair of the $\pi^+ NN \rightarrow pN$ process is essentially a quasideuteron since the pn $T=0$ pair dominates. These values for the nuclear quasideuteron momentum are close to the values for the mentioned single particle momentum in ^{3}He and ^{4}He. It is thus reasonable to ascribe most of the width of the peak to the nuclear two-nucleon motion and it is consistent with interpreting the observed peak as due to the QFA reaction. It is interesting to note, however, that more detailed information on the ^{3}He structure has become available from the (e,e'p) experiment of Jans *et al.*[11] They find

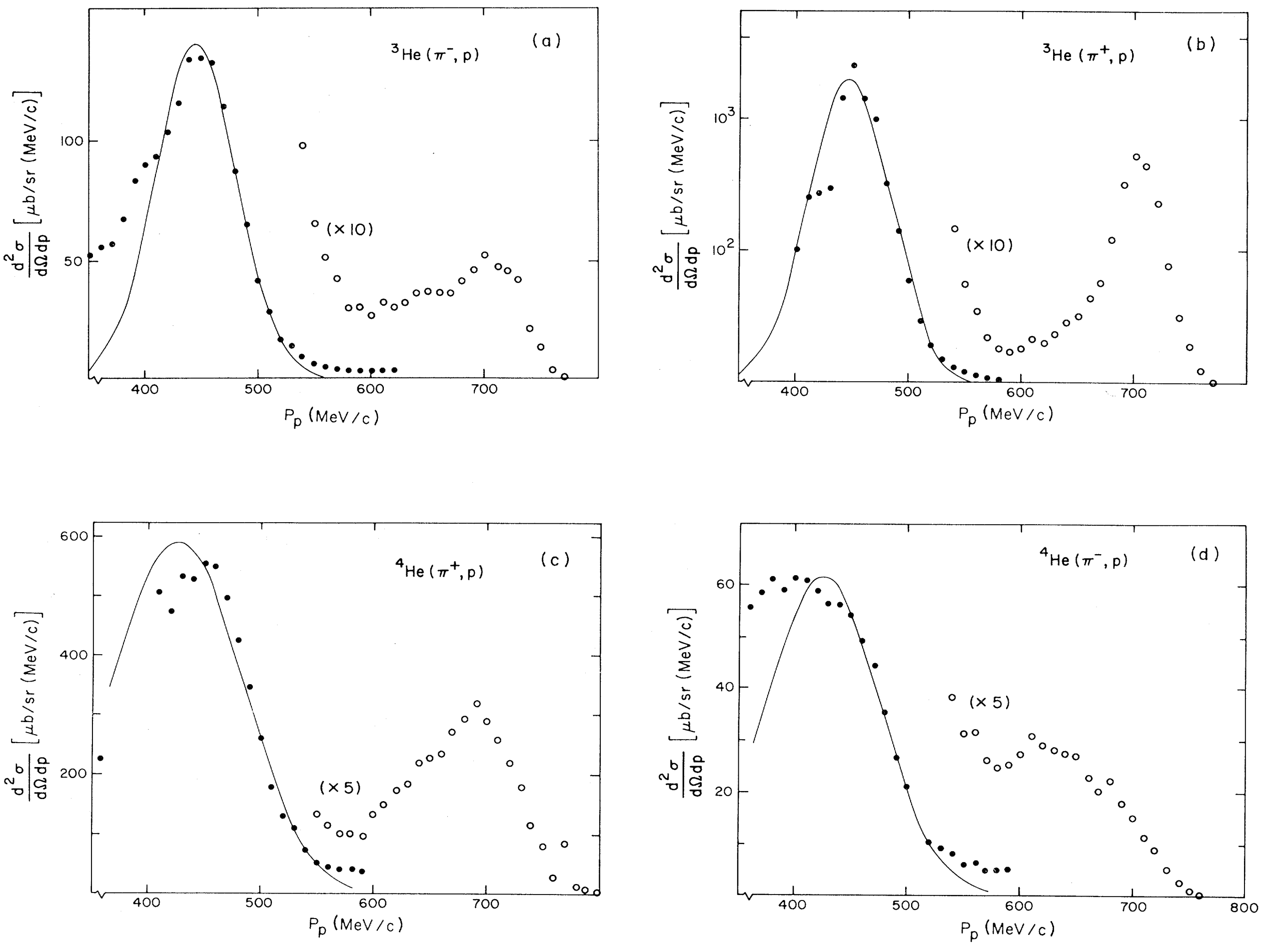

FIG. 7. The measured spectra at $T_\pi=200$ MeV and $\theta=20°$ for ^{3}He(π^+,p), ^{3}He(π^-,p), ^{4}He(π^+,p), and ^{4}He(π^-,p) [(a)—(d)]. The curve shown is the fitted Gaussian shape to the QFS peak.

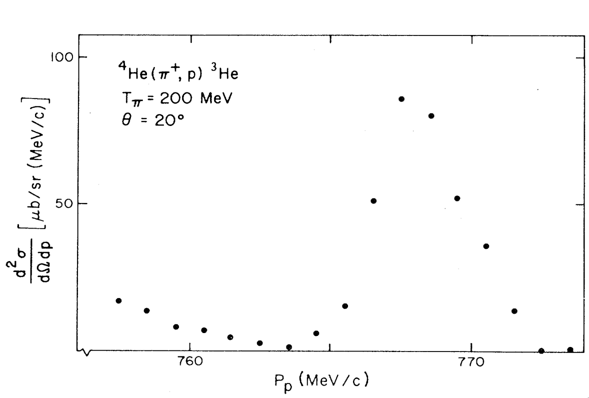

FIG. 8. Detail of the ^{4}He(π^+,p) spectrum at $T_\pi=200$ MeV and $\theta_p=20°$ showing the peak due to ^{4}He(π^+,p)^{3}He.

that the ^{3}He→pd momentum distribution is narrower than that for ^{3}He→p[pn]; the corresponding widths would be approximately ±45 and ±63 MeV/c. Our QFA data suggest that the $T=0$ NN (quasideuteron) motion in ^{3}He have a broader momentum distribution than that of ^{3}He→pd measured in the (e,e′p) experiment. Cross sections were determined by integrating the high momentum portion of the (π^+,p) spectra with the lower bound of integration set at the minimum about 120 MeV/c below the center momentum. Although the weak ^{4}He(π^+,p)^{3}He contribution is of no practical importance in this context it was not included all the same. We thus obtain a (π^+,p) cross section that can be associated with the QFA π^+NN→Np reaction. The results are given in Table III as the (π^+,p) yield in ^{3}He, ^{4}He, and ^{27}Al relative to ^{2}H. The uncertainty in these values is estimated to be ±7% for (π^+,p) in ^{3,4}He and ±10% for (π^-,p); for (π^+,p) and (π^-,p) in ^{27}Al, the errors are ±15% and ±20%. Cross sections can be obtained by multiplying relative yields and known π^+d→pp cross sections (also given in Table III).

TABLE I. Results on the differential cross section (in units of mb/sr) of quasifree $\pi^+N \rightarrow \pi p$ and $\pi^- p \rightarrow \pi^- p$ scattering at $\theta_p = 20°$, and the ratio (R) of measured to calculated cross sections.

	$\pi^+ + ^3$He		$\pi^+ + ^4$He		$\pi^- + ^3$He		$\pi^- + ^4$He	
T_π	$d\sigma/d\Omega$	R	$d\sigma/d\Omega$	R	$d\sigma/d\Omega$	R	$d\sigma/d\Omega$	R
100	9± 3	0.11	9± 6	0.10				
150	51± 8	0.26	39± 7	0.18	5.0±0.6	0.42	3.0±0.7	0.25
200	111±11	0.73	85± 8	0.50	12.5±1.2	0.79	7.9±0.8	0.50
250					12.7±1.9	1.20	11.4±2.2	1.08
295	54±11	1.43	65±13	1.62	12.0±1.2	1.74	10.2±1.0	1.48
295[a]	27± 5	1.28	45±11	1.88	7.4±1.1	1.90	10.9±2.2	2.80

[a]$\theta_p = 40°$ while $\theta_p = 20°$ for all other cases.

The (π^-,p) spectra have less distinct features than those of (π^+,p). Still, evidence of QFA contributions can be found in the ^{3,4}He(π^-,p) spectra showing a maximum at the expected momentum for QFA. The clearest example of a QFA peak in the (π^-,p) spectra is seen for ^{3}He at $T_\pi = 100$ MeV (Fig. 9). The shapes of the (π^-,p) and (π^+,p) spectra differ, however, in this region. First a remark about the spectra at 50 MeV (Figs. 1 and 4). Here we can notice that the (π^-,p) spectrum does not show the same decrease for momenta above the QFA peak momentum. This might indicate contributions from ^{3}He(π,p)[nn] where the nn pair is subject to strong final state interactions (FSI) at low relative energy. This cross section can be estimated to be about 30% of the entire integrated yield of the QFA region or 0.3 mb/sr. A comparison can be made with the (π^+,p) reaction in ^{4}He where a bound nuclear state can be reached. At $T_\pi = 50$ MeV, the cross section of ^{4}He(π^+,p)^{3}He amounts to 0.26 mb/sr or 1.5% of the QFA yield. We thus find that the ^{3}He(π^-,p)[nn] and ^{4}He(π^+,p)^{3}He cross sections are of the same magnitude. The cross section of ^{4}He(π^+,p)^{3}He decreases relative to that of the QFA $\pi NN \rightarrow Np$ process with increasing pion energy (because of increasing momentum transfer) and the same should be expected also for the ^{3}He(π^-,p)[nn] reaction. Therefore, FSI effects should not interfere significantly with QFA cross sections evaluated for energies of $T_\pi \geq 100$ MeV. In general, however, the spectral differences between (π^+,p) and (π^-,p) must arise due to other causes. One possibility is that there are dynamical differences between the nuclear NN pairs contributing to the π^- and π^+ absorption reactions. The shape differences could also signal that the (π^-,p) spectrum in the QFA region is composed of contributions from several reactions, i.e., the QFA process plus what we can call background reactions. The background reactions are of concern in extracting the QFA cross section. It was determined in the same way for (π^-,p) and (π^+,p) (the results for both reactions are given in Table III), but since (π^-,p) is a weaker channel, background reactions could be relatively more important than for (π^+,p). Therefore it is important to make estimates of the background effects.

The background reactions must involve three or more nucleons and they are thus (partially) distinguishable from the $\pi NN \rightarrow Np$ absorption on the basis of kinematics. Since these reactions are likely to be kinematically shifted to the low momentum side of the QFA peak (as discussed below), minimum background interference would occur around the maximum of the QFA peak. A comparison of (π^+,p) and (π^-,p) spectra for ^{3}He and ^{4}He at the QFA maximum shows (π^-,p) to (π^+,p) ratios that are 20% to 40% smaller than the ratios determined by the integrated cross sections.[6] These values give some indication of the level of background contributions we have to reckon with. It is of interest, however, to obtain direct estimates of the magnitude of the (π^-,p) pion absorption due to non-QFA processes and to determine how much the strongest background reactions might contribute to the cross section in the QFA region.

We first consider the case of a true multinucleon pion absorption in which the proton momentum distribution can be represented by the corresponding phase space. The three-body phase space for $\pi NNN \rightarrow NNp$ was calculated and normalized to the cross section measured in the intermediate momentum region (Fig. 9). In this way we can determine the maximum contribution of three-body pion absorption to our (π^-,p) spectra. For the case $T_\pi = 100$ MeV, we find that this (maximum) background subtraction would reduce the QFA cross section by 20% and 50% for ^{3}He and ^{4}He, respectively. In the case of ^{4}He, one should in principle consider both three-body and four-body absorption and the effective phase space distribution would depend on knowing the relative contribu-

TABLE II. Results on the cross section ratio of π^+ to π^- quasifree scattering compared with computed ratios.

T_π	^{3}He		^{4}He	
(MeV)	Measured	Calculated	Measured	Calculated
150	9.8±1.0	16.5	12.5±2.5	18.5
200	8.4±0.5	9.6	10.9±1.1	10.6
250	4.3±1.3	6.5		7.1
295	5.6±0.9	5.4	7.7±1.2	5.9
295[a]	3.9±0.5	5.5	4.8±1.0	6.1

[a]$\theta_p = 40°$.

TABLE III. Results on yields of quasifree $\pi NN \to Np$ absorption at $\theta_p = 20°$ expressed relative to the reaction $\pi^+ d \to pp$. The bottom line shows the expected yields. The last column gives the cross section (in the laboratory frame) for (π^+,p) in deuterium for detecting either of the two exit protons (taken from Ref. 9).

T_π	π^+ ^{3}He	π^+ ^{4}He	π^+ ^{27}Al	π^- ($\times 10^{-2}$) ^{3}He	π^- ($\times 10^{-2}$) ^{4}He	π^- ($\times 10^{-2}$) ^{27}Al	$\pi^+ d \to pp$ $dr/d\Omega$ (mb/sr)
50	1.9	3.9	25	11	19	330	2.43
100	2.2	3.5	12	12	18	120	4.53
150	2.0	3.8	9	16	20	90	4.85
200	2.1	4.4	13	16	22	80	2.95
250	2.2	5.0	15	18	25	150	1.49
295	2.8	5.1		19	27	140	0.87
295[a]	2.5	5.4	19	19	30		0.50
Theory	1.63	3.38		13	13		

[a] $\theta_p = 40°$.

tions; the 50% reduction would then represent an upper limit for multibody pion absorption in ^{4}He. For the ^{3}He(π^-,p) spectra, we performed the background subtraction at other energies as well and found that the smallest reduction of the QFA cross section occurs at 100 MeV (20%) and the highest at 200 MeV (45%). The ratio of the π^+ to π^- multibody absorption cross sections is between five and ten as judged from the measured cross section in the minimum region of both the ^{3}He and ^{4}He spectra. For the ^{3,4}He(π^+,p) spectra, however, the contributions of three-body phase space to the QFA cross section is quite small; i.e., the upper limit is estimated to be 10%. We note in this context that although the three-body phase space correction tends to make the shape of the (π^+,p) and (π^-,p) spectra more similar in the region of the QFA peak, the (π^-,p) peak generally remains broader than that of (π^+,p).

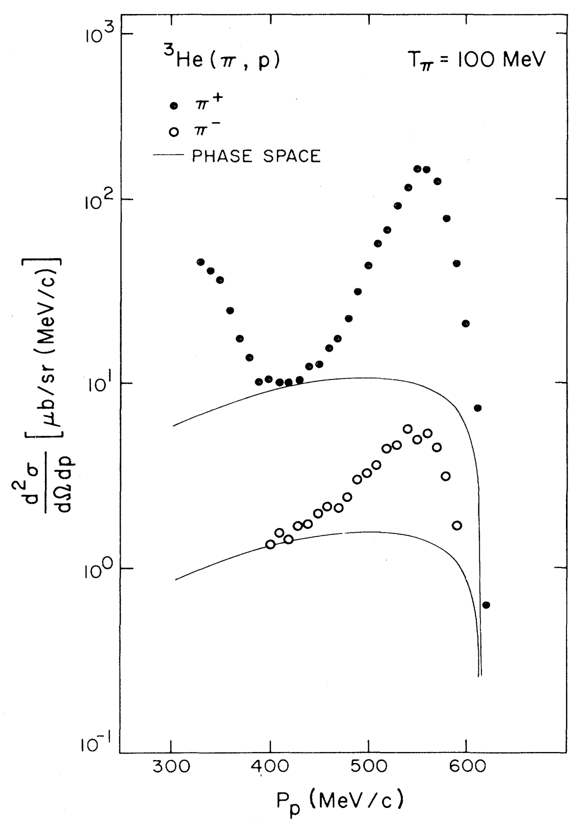

FIG. 9. The spectra at $T_\pi = 100$ MeV and $\theta = 20°$ of ^{3}He(π^+,p) and ^{3}He(π^-,p) compared with the phase space curves for the reaction $\pi^+ + {}^3\text{He} \to ppp$ and $\pi^- + {}^3\text{He} \to nnp$.

There is no obvious reason why the multinucleon absorption mechanism should be stronger than the two-nucleon absorption mechanism accompanied by interactions with spectator nucleons. Of particular interest are interactions that can enhance the (π^-,p) absorption cross section. As an example we consider the (π^-,p) reaction consisting of a $\pi^- pn \to nn$ two-nucleon absorption followed by $np \to pn$ single charge exchange scattering (QFA-SCE) in the exit channel. Here we shall attempt an estimate of this contribution to pion absorption in the QFA region using the data on QFS.

The probability for final state SCE scattering can be assumed to be proportional to the number of target protons available for SCE (allowing only one interaction) and some general proportionality factor (C). The $\pi^- pn \to nn$ reaction is analogous to $\pi^+ pn \to pp$, which is essentially the same as the measured QFA (π^+,p) cross section. The combined contribution to the (π^-,p) QFA cross section, i.e., QFA + QFA-SCE, would then be

$$\sigma(\pi^-,p) = \sigma(\pi^- pp \to pn) + C\sigma(\pi^+,p) \quad (1)$$

which means that

$$\sigma(\pi^- pp \to pn) = \sigma(\pi^-,p)\left[\frac{1 - C\sigma(\pi^+,p)}{\sigma(\pi^-,p)}\right]. \quad (2)$$

Since the

$$\frac{\sigma(\pi^+,p)}{\sigma(\pi^-,p)}$$

ratios are large, of the order of 10 or 20 for ^{3}He or ^{4}He (see Table III), SCE effects can be important for the (π^-,p) absorption even for rather small values of C. In order to estimate C, we observe that SCE effects might also show up for QFS. In the quasifree scattering, SCE rescat-

TABLE IV. The differential cross section of $^4He(\pi^+,p)^3He$ at $\theta_p=20°$ in the laboratory frame.

T_π (MeV)	$\frac{d\sigma}{d\Omega}$ (mb/sr) Present experiment	Ref. 13
50	0.26±0.04	0.08±0.03
100	0.29±0.04	0.17±0.03
150	0.29±0.04	0.28±0.06
200	0.34±0.05	0.28±0.05
250	0.18±0.03	0.17±0.03

tering can enhance the (π^-,p) scattering cross section through $\pi^-n\to n\pi^-$ elastic scattering followed by $np\to pn$ SCE scattering, i.e.,

$$\sigma(\pi^-,p)=\sigma(\pi^-p\to p\pi^-)+C\sigma(\pi^+p\to p\pi^+) \quad (3)$$

for ^3He. We can thus determine C from

$$C\simeq[\sigma(\pi^-,p)-\sigma(\pi^-p\to p\pi^-)]/\sigma(\pi^+p\to p\pi^+) \quad (4)$$

for ^3He; for ^4He it would be half this value (since two protons are available for SCE scattering in the exit channel). As we shall discuss later, the measured QFS cross section of (π^-,p) relative to (π^+,p) is within 10% of the expected value as estimated on the basis of the free cross sections[12] $\sigma(\pi^-p\to p\pi^-)$, $\sigma(\pi^+p\to p\pi^+)$, and $\sigma(\pi^+n\to p\pi^0)$. Since (π^+,p) scattering is about ten times stronger than (π^-,p) scattering, we obtain $C<0.01$. If this value is applied to pion absorption [Eq. (3)], we estimate that the QFA-SCE contributions are at the most 20% or 30% of the $^3He(\pi^-,p)$ or $^4He(\pi^-,p)$ cross sections in the QFA region.

C. $^4He(\pi^+,p)^3He$ reaction

Cross sections of $^4He(\pi^+,p)^3He$ were extracted from our spectra at $\theta=20°$ and at $T_\pi=50$, 100, 150, 200, and 250 MeV. The results are shown in Table IV compared with previous ones[13]; the uncertainty in the cross section scale is estimated to be ±10% relative to the cross sections of $\pi d\to pp$ which were used for normalizing $^4He(\pi^+,p)^3He$.

IV. DISCUSSION

A. Quasifree scattering

The (π^+,p) reaction is obtained through elastic π^++p scattering as well as through single charge exchange (SCE) $\pi^+n\to p\pi^0$ scattering while (π^-,p) is fed only through elastic scattering. The elementary cross sections of free $\pi+N$ scattering[12] at the kinematics of the measured (π,p) reaction and the number of target nucleons provide an impulse approximation (IA) framework for discussing the cross sections of quasifree (π,p) scattering. Results on the ratio (R) between measured to calculated IA cross sections are given in Table I.

The ratio R for ^3He and ^4He is found to increase systematically with incident energy. It is difficult to explain this behavior unless one assumes a combination of two causes. The very low R value $(R=0.1-0.4)$ for the lowest energies suggests attenuation of the (π,p) reaction, possibly due to pN final state interactions in the exit channel. The pN scattering cross section is known[14] to increase rapidly with decreasing momentum in the region $p<400$ MeV/c so that the (π,p) reaction for $T_\pi<200$ MeV would be exposed to an increased probability for being removed from the QFS channel due to pN final state interactions. For the highest energy ($T_\pi=295$ MeV), the measured cross sections of $^{3,4}He(\pi,p)$ exceed the IA limit by up to a factor of 2. Such an enhancement might arise if the local (off-shell) $\pi+N$ energy is lower than the laboratory energy. The cross section difference for free πN scattering at $T_\pi=180$ and 295 MeV is about a factor of 4, which would be an upper limit for this kind of enhancement. The on-resonance πN interaction (corresponding to $\pi N\to\Delta$) can take place given a nuclear (off-shell) momentum of about 120 MeV/c which is the recoil momentum P_{A-1} of the reaction $\pi+A\to\Delta+A-1$ at $T_\pi=295$ MeV and $\theta_\Delta=\theta_p=20°$. The single particle momentum distributions of ^3He and ^4He peak at $P=0$ MeV/c and decrease by a half at $P=120$ MeV/c. The net enhancement is thus a tradeoff between the form factor q dependence and the energy dependence of the πN scattering.

Another remark of interest in this context is the phase space difference between the quasifree $\pi N\to p\pi$ scattering and the quasifree reaction $\pi N\to\Delta$ where the Δ subsequently decays, i.e., $\pi N\to\Delta\to p\pi$. This difference should depend on detecting the forward going heavy particle in $\pi p\to p\pi$ rather than the back scattered pion. A comparison between QFS cross sections measured in (π,p) and (π,π') at the conjugate angles would reflect kinematical effects of the type mentioned (manifesting intermediate Δ production) besides possible differences between πN and pN final state interactions.

At $T_\pi=200$ MeV we find that the QFS cross sections are smaller than the IA estimates for both ^3He and ^4He; i.e., the ratios are $R=0.76$ and 0.50. The off-shell scattering effects should be small at this energy so R values less than unity are attributable to attenuation effects. The R values are found to be the same for (π^+,p) and (π^-,p) in ^4He while there is a small difference for ^3He, $R=0.73$ and 0.79, respectively. The attenuation can arise from spectator nucleon interactions which can remove reactions from the quasifree channel in different ways; for instance, through nucleon-nucleon final state interaction, shadowing in the incident channel, and pion interaction with two or more nucleons simultaneously. The systematics of these data seem to tell us that increasing the number of strong (Δ-resonance) $\pi+N$ scatterings decreases the QFS cross section. This is the situation we encounter for $^3He(\pi^-,p)$ compared to $^3He(\pi^+,p)$, where (π^-,p) is less attenuated (due to π^-+n scattering) than (π^+,p), where strong π^++p rescattering can occur twice. The fact that R is 1.6 times smaller for ^4He than for ^3He could reflect greater spectator interference for ^4He, due to difference in size and binding energy.

It is interesting to compare our QFS (π,p) data with results on QFS (π,π') backscattering. An experiment on $^3He(\pi^-,\pi^0)$ scattering[15] at $T_\pi=200$ MeV gave an R value of about 0.5 with an estimated uncertainty of ±20%. Other measurements[16,17] have been done on $^{3,4}He(\pi,\pi')$, the most recent one by Whitney *et al.*[17] gives R values of 0.61 and 0.42 (with an uncertainty of about ±10%) for ^3He and ^4He at $T_\pi=200$ MeV. The pion angle was

$\theta_\pi = 120°$ which corresponds to $\theta_p \approx 22°$. The ratios for (π,π') are thus 20—30% lower than for (π,p). The uncertainty in our R values at $T_\pi = 200$ MeV is about $\pm 15\%$ so that the observed difference is just outside one standard deviation of each measurement. Lower R values for (π,π) than for (π,p) could be ascribed to attenuation effects suggesting that the exit pion is more likely to suffer interaction with the spectator nucleon than the exit proton of the (π,p) reaction. It can also be noted that the R value for (π,π') increases between $T_\pi = 200$ and 295 MeV but not as much as we observe for (π,p). We have already suggested that this difference could in part be of kinematical origin. Thus there seem to be differences between (π,π) and (π,p) quasifree scattering which should be compared with cascade model calculations in order to quantitively estimate the importance of nucleon-nucleon and pion-nucleon final state interactions.

B. Quasifree (π,p) absorption

The $\pi^+ d \rightarrow pp$ reaction is well known experimentally and to some extent also theoretically. It can serve as a reference to discuss the nuclear pion absorption reactions, in particular, the two-nucleon absorption part $\pi^+ NN \rightarrow Np$ of the nuclear (π^+,p) absorption, which preferentially takes place on the quasideuteron pn state. (Below we shall come back to the question of the relative importance of different πNN states including both π^+ and π^- absorption.) For the lightest elements ^{2}H, ^{3}He, and ^{4}He, we find that the QFA (π^+,p) cross section seems to scale approximately as the number of target pn pairs; i.e., 1:2:4, respectively, for ^{2}H, ^{3}He, and ^{4}He. The (π^+,p) absorption in ^{27}Al, however, is only some eight times stronger than in ^{2}H and hence far weaker than the total number of pn pairs in ^{27}Al. A difference between the lightest elements and ^{27}Al is that much fewer pn pairs in ^{27}Al are in the ^3S, $T=0$ state (quasideutrons) and not all nucleons are neighboring each other to form effective pairs for pion absorption. Both a dependence on the state of the pn pair and a limited reaction volume for $\pi NN \rightarrow Np$ absorption would be factors determining the effective number of target pairs for $\pi NN \rightarrow Np$ absorption. For nuclei in the mass region $A > 12$, it is known[2] that the total nuclear pion absorption cross section (of which the $\pi NN \rightarrow Np$ reaction is part) increases as $A^{0.6}$. It thus seems that the scaling to the total number of nucleon pairs observed for the (π^+,p) cross section for the few-body systems does not persist for nuclei of increasing A.

The change in the A dependence of the absorption cross section can be localized as taking place between ^{4}He and ^{6}Li. The (π^+,p) cross section for ^{6}Li, which is mostly due to $\pi^+ np \rightarrow pp$, has been found[18] to be only slightly (about 20% at $\theta_p = 20°$) larger than in ^{4}He(π,p) while the number of pn pairs is 2.25 times larger. Obvious differences between the ^{4}He and ^{6}Li nuclei are the larger size of ^{6}Li and the presence of pn pairs in other than $L=0$ states. This suggests to us that the effective reaction volume of $\pi NN \rightarrow Np$ is smaller than the size of ^{6}Li and/or that the $L \neq 0$ pn states are not as effective in absorbing pions as is the $L=0$ pn state of which ^{3}He and ^{4}He mostly consist. It therefore seems that further comparisons between ^{3,4}He(π,p) and ^{6}Li(π,p), which require more complete data for ^{6}Li, could help identify the crucial nuclear conditions affecting the $\pi NN \rightarrow Np$ reaction.

For a detailed analysis of (π^+,p) and in order to include (π^-,p) it is necessary to consider the isospin state of the initial NN pair in $\pi NN \rightarrow Np$. This can be explicitly carried out for ^{3}He and ^{4}He for which it is reasonable to assume that the ground state configurations are $1s^3$ and $1s^4$. The number of $T=1$ pp pairs is one for both ^{3}He and ^{4}He with one nn pair in ^{4}He. There are two, respectively, four pn pairs in ^{3}He and ^{4}He which are divided into $T=0$ and $T=1$ states in the ratio 3:1. We further consider only resonance energies so that the Δ dominates the πN interaction assuming the reaction mechanism to be $\pi NN \rightarrow \Delta N \rightarrow Np$. We can thus calculate[6] the $\pi^+ pn \rightarrow pp$ yields for $T=0$ and $T=1$ states and the $\pi^- pp \rightarrow pn$ yield shown in Table III. Note that the (π,p) yields are expressed relative to that of $\pi^+ d \rightarrow pp$ and refer to detecting either of the two protons of (π^+,p) in direct correspondence to the experimental situation; for (π^-,p) the relative cross section of $\pi^- pp \rightarrow np$ is twice the value quoted for the relative yield. These theoretical relative yields can now be compared with the measured average QFA yields (see Table III) in the energy range $T_\pi = 150$—250 MeV.

The (n^+,p) absorption. For π^+ absorption in ^{3,4}He we find that the experimental values are some 30% higher than the theoretical ones. This is essentially a difference between quasideuterons and the free deuteron since absorption on the np $T=0$ initial state dominates (π^+,p). The results suggest that the pion absorption is sensitive to the initial state NN wave function and that there are dynamical differences between the πNN interaction in ^{3,4}He and ^{2}H. The dynamical enhancement of the $\pi NN \rightarrow Np$ cross section for ^{3,4}He compared to ^{2}H is likely to be larger than the observed difference in yields because of attenuation of the $\pi NN \rightarrow Np$ reaction in ^{3,4}He. For the purpose of illustration we can use the same factors (0.84 and 0.55) by which the QFS (π,p) cross sections in ^{3}He and ^{4}He were found to be reduced relative to the estimates based on free πN scattering. The (π^+,p) reactions in ^{3}He and ^{4}He would then be dynamically enhanced by factors of 1.5 and 2.3, respectively, relative to $\pi^+ d \rightarrow pp$; we assume that there is no attenuation for reactions in ^{2}H. These factors would then be indicative of dynamical πNN differences between the free deuteron and the quasideuteron states in ^{3}He and ^{4}He. The dynamical difference between ^{2}H and ^{4}He has been calculated[19] and predicted to enhance the absorption rate by a factor of 2 for low πNN energies where S wave scattering dominates.

The (π^-,p) absorption. The $(\pi^- p)$ absorption is a much weaker reaction channel than (π^+,p) with the theoretical relative yield of 0.13 in ^{3,4}He. Experimentally, we determine (integrated) QFA yields of about 0.16 and 0.21 for ^{3}He and ^{4}He in the energy range $T_\pi = 150$—250 MeV. These yields are larger than the theoretical one and the difference could be attributed to background contributions. As before, we can use phase space to estimate the upper limit estimates for the background, which leads to lower limits for (π^-,p) QFA yields of 0.09 and 0.10 for ^{3}He and ^{4}He in the energy range $T_\pi = 150$—250 MeV. The ^{3}He(π^-,p) spectrum at $T_\pi = 100$ MeV deserves special attention since it has a shape most suggestive of a dominant QFA contribution and because it is the (π^-,p) spectrum most similar to (π^+,p). For this case, which we judge to be the one least affected by background contributions, we determine the relative QFA yield to lie in a narrow range of 0.10—0.12. We thus find that, after applying corrections for maximum estimated background contributions, we obtain (π^-,p) QFA yields at the level of 70% of the calculated $\pi^- pp \rightarrow pn$ yield. The ratios of the QFA yields for (π^+,p) to (π^-,p) in the energy range $T_\pi = 150$—250 MeV are found to be 14 and 20 for ^{3}He and ^{4}He, or 23 and 40 with maximum correction for background interference. The theoretical ratios are 13 and 26.

Comparisons can be made with results from a recent measurement[7] of the coincidence rates of (π^+,pp) and (π^-,pn) in ^{3,4}He at angle settings of θ_{pp} or θ_{pn} corresponding to the kinematics for quasifree two-nucleon absorption. Some angle settings were also chosen in order to study nonquasifree background contributions. The cross section ratio of

$$\frac{\sigma(\pi^+ pn \rightarrow pp)}{\sigma(\pi^- pp \rightarrow pn)}$$

was determined to be about 100:1 for ^{3}He at $T_\pi = 165$ MeV and $\theta_p = 55°$. The fractional background levels were found to be similar for π^+ and π^-. Since this ratio is corrected for the presence of two protons in the exit channel for π^+ it corresponds to a proton *yield* ratio of 200:1. This measurement gives a $\pi^- pp \rightarrow pn$ yield in ^{3}He at $\theta = 55°$ and $T_\pi = 167$ MeV which is about ten times smaller than our (π^-,p) yield at $\theta = 20°$ in the energy range $T_\pi = 100$—200 MeV. This difference seems surprisingly large to be attributable to angular dependence and we shall therefore assess some alternative causes.

We first test the hypothetical explanation[7] of dominant background contributions in the QFA region of (π^-,p) single spectra. From the coincidence experiment the (π^+,pp) and (π^-,pn) cross sections outside the quasifree kinematics region are found to be in the approximate ratio of 1:8 relative to the cross section at the quasifree kinematics setting. This background measurement could be compared to our background estimate based on the three-body phase space, which was determined to be at the 5% to 10% level of the QFA cross section for ^{3}He(π^+,p) in the energy range $T = 100$—200 MeV. If we were to identify this background with the one measured in the coincidence experiment, and using the result of the coincidence experiment that the fractional background levels are the same for (π^+,p) and (π^-,p), we would expect the background interference to be comparable for the (π^+,p) and (π^-,p) spectra in our case, too. However, a 5% to 10% background contribution to our QFA (π^-,p) cross sections is an insignificant correction in view of the observed difference of a factor of 10.

Next we therefore discuss a background reaction which kinematically resembles the QFA process. The QFA-SCE reaction would be kinematically similar to QFA because the $np \rightarrow pn$ cross section is forward peaked as we have discussed in Sec. III B. This contribution would be proportional to the $np \rightarrow pn$ cross section over the angular acceptance of the measurement. By accounting for differences in acceptance we can compare our data with those of the coincidence experiment. In the coincidence experiment the angular acceptance is set by the second counter and is estimated to be $\Delta\theta \sim 10°$. We, however, discriminate on the basis of recoil momentum loss in the reaction, so that reactions outside, say, $\Delta p = 30$ MeV/c, would be kinematically separable from our QFA cross sections. This would correspond to an angular acceptance of $\Delta\theta \leq 20°$. We thus estimate that the QFA-SCE background reaction would appear some five times stronger in our spectra than in the coincidence measurement within the kinematics of the QFA reaction. This difference in backgrounds, however, cannot explain the factor of 10 difference in the QFA cross sections even if the coincidence cross section consisted of nothing but background.

The above discussion suggests that background contributions cannot provide a reasonable explanation for the difference between the (π,p) and (π,Np) experiments with regard to π^- and π^+ absorption. The observed difference must therefore be considered a genuine effect and might be ascribed to different angular dependences of the $\pi^+ pn \rightarrow pp$ and $\pi^- pp \rightarrow np$ reactions. One should also further investigate final state interactions in the nuclear $\pi^+ pn \rightarrow pp$ and $\pi^- pp \rightarrow np$ reactions and their probability for removing intensity from the quasifree channel of two-nucleon pion absorption.

C. ^{4}He$(\pi^+,p)^3$He reaction

Information on the cross section of ^{4}He$(\pi^+,p)^3$He, or the related ^{4}He$(\pi^-,n)^3$H and ^{3}He$(p,\pi^+)^4$He reactions, exist from previous experiments[13,20,21] at incident pion energies (or equivalent proton energies) in the range $T_\pi = 12$—575 MeV; detailed balance was used to make the transformation from (p,π) to (π,p). We have used these data to determine the energy dependence at $\theta_p = 20°$. Our experiment overlaps in energy with the measurements of Ref. 13 and good agreement is found at $T_\pi = 150$, 200, and 250 MeV while there is a clear difference of two standard deviations at 50 MeV. Using the present value at 50 MeV and averages at other energies of overlapping data in Fig. 10, we find that the cross section at $\theta_p = 20°$ varies very little with energy between 10 and 200 MeV but falls off quite sharply above 200 MeV. The energy dependence of the ^{4}He$(\pi^+,p)^3$He cross section at fixed angle can be compared with that of $\pi d \rightarrow pp$. To be noted is that the $\pi d \rightarrow pp$ cross section has a maximum at about 260 MeV and a minimum at about 10 MeV. These two features have been taken as indications of p-wave and s-wave pion-scattering in pion absorption.[22] The minimum in $\pi d \rightarrow pp$ and that indicated in ^{4}He$(\pi,p)^3$He, at a somewhat higher energy of $T_\pi \gtrsim 30$ MeV, might be of the same origin and hence provide an indication of the relative strength of s and p wave scattering of (π,p) in ^{2}H and ^{4}He.

An important contribution to the energy variation of the ^{4}He$(\pi,p)^3$He cross section at fixed angle is the nuclear form factor dependence $F(q)$. The form factor decreases as the momentum transfer q increases, i.e., as T increases. An empirical fit[13] to $F(q)$ is $F(q) = e^{(Q-q)/\lambda}$, where $\lambda = 48$ MeV/c, $q = |\frac{3}{4}p_\pi - p_p|$ in the center-of-mass system, and $Q = 400$ MeV/c. Over the energy range 10—575 MeV, q changes from 400 to 620 MeV/c for ^{4}He$(\pi^+,p)^3$He at $\theta = 20°$. This means that $F(q)$ varies two orders of magnitude and this variation should be considered before comparison to the cross section of $\pi d \rightarrow pp$ which has no corresponding *nuclear* form factor dependence. As an attempt at correcting for some of the form factor dependence in ^{4}He$(\pi,p)^3$He, we have divided $d\sigma/d\Omega$ $(\theta = 20°)$

by $F[q(\theta=20°)]$. The thus obtained reduced cross section for ^{4}He(π,p)^{3}He can now be compared with the cross section of πd$\rightarrow$ pp (see Fig. 10) as a means of detecting the differences in energy dependence between ^{4}He(π,p)^{3}He and πd$\rightarrow$ pp.

Inasmuch as the πd$\rightarrow$ pp reaction is a viable subprocess for interpreting the ^{4}He(π,p)^{3}He reaction (for instance within the framework of the Ruderman model[3,4]), direct comparison can be made with the cross section of the QFA reaction. From the data on QFA yields (Table III) we have determined that the effective number of quasideuterons is 1.2 to 1.7 times the theoretical number for ^{3}He and 1.0 to 1.5 times that for ^{4}He. This number includes both the dynamical difference between pion absorption on a free and a quasifree deuteron and the difference in attenuation for (π,p) reactions in ^{2}H and ^{3}He or ^{4}He. These data provide information for the normalization of calculations in the framework of the Ruderman model[3]

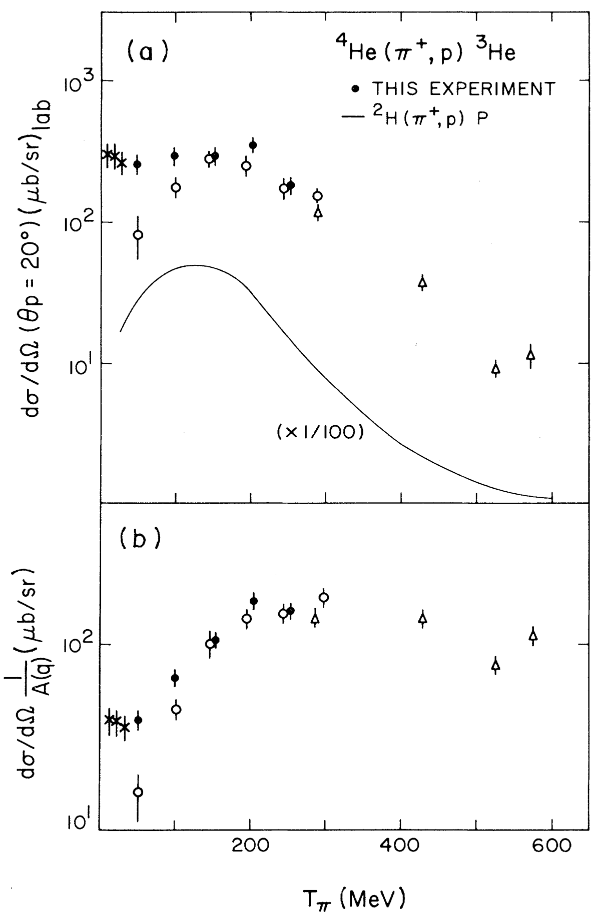

FIG. 10. (a) The differential cross section of ^{4}He(π,p)^{3}He at $\theta=20°$ (lab) at energies between $T_\pi=12$ and 575 MeV as measured in the present experiment compared with other results. (Refs. 13 and 21). Also shown is the cross section of π^+d$\rightarrow$*pp* taken from Ref. 9. (b) The reduced cross section (obtained as described in the text) for ^{4}He(π^+,p)^{3}He.

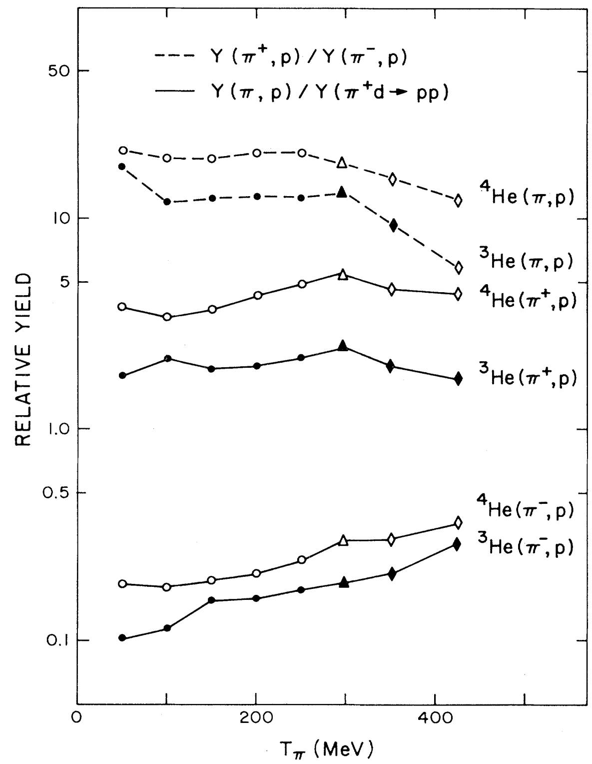

FIG. 11. The yields of (π^+,p) and (π^-,p) in the QFA region for ^{3}He and ^{4}He expressed relative to π^+d$\rightarrow$pp. The QFA yield ratios (π^+,p)/(π^-,p) are also shown. The data at $T_\pi=350$ and 425 MeV are from Ref. 25.

where the incorporation of attenuation cannot be done rigorously. A direct comparison can be made with the calculations of Fearing[8,23] for ^{3}He(π^-,n)^{2}H and ^{4}He(π^+,p)^{3}He. He estimates the attenuation factor at $T_\pi=200$ MeV to be about 0.2 compared to the factor of 0.7 we find on the basis of the QFS data. The effective number of quasifree deuterons determined from the QFA yields would allow a direct normalization of the theoretical cross sections, and comparison with calculations could also help distinguish between dynamical and attenuation effects. Another observation to be made is that the cross section ratio of ^{4}He(π^-,p) to π^+d$\rightarrow$ pp shows a relatively small variation over the energy range 50 to 300 MeV (Fig. 11). This is in marked contrast to the large difference in energy dependence between the reduced cross section of ^{4}He(π^+,p)^{3}He and the cross section of π^+d$\rightarrow$ pp (Fig. 10). Given this particular reaction model, it is thus obvious from this comparison that the quasideuteron absorption is altered relative to πd$\rightarrow$ pp due to, for instance, final state interactions in ^{4}He(π,p)^{3}He, or due to contributions from configurations of the ^{4}He ground state other than the $T=0$ quasideuteron.[20]

D. Total reaction cross section

The total (angular integrated) $\pi+{}^4$He cross section has been measured in other experiments[2] as well as the separate components[1,24,25] due to pion elastic and inelastic scattering and pion absorption. Although our measurements refer only to one angle, it may still be compared with total cross sections since the ^{3,4}He(π^+,p) spectra are principally caused by quasifree reactions. The quasifree reactions can be assumed to have an angular dependence similar to the corresponding free reaction, and the differential cross sections of the free $\pi+$N scattering and πN$\rightarrow$ np absorption reactions are known. Therefore, it is possible to obtain estimates for total cross sections from our (π,p) spectra. A comparison of these with measured values should indicate the validity of the angular dependence assumption and the overall importance of quasifree reactions in the global picture of the total reaction cross section.

We choose the spectrum of ^{4}He(π^+p) at $\theta=20°$ and $T_\pi=200$ MeV as an illustration. The total cross section at $\pi+{}^4$He at $T_\pi=200$ MeV has been determined[1,2] to be 310 mb and the three components of elastic, inelastic, and absorption cross sections have individually been determined to be 100, 200, and 40 mb. From our ^{4}He(π,p) spectrum we find that the QFS is reduced by a factor of 0.54 relative to the free π^+p$\rightarrow$ pπ^+ and π^+n$\rightarrow$ pπ reactions. Assuming the same reduction for all angles one obtains an inelastic $\pi+{}^4$He cross section of $0.54\times2\times\frac{11}{9}=1.34$ times the sum of the free π^+p$\rightarrow$ pπ^+ and π^+n$\rightarrow$ pπ, i.e., 250 mb; the factor of $\frac{11}{9}$ is included to correct for the π^+n elastic scattering that is not detected in (π^+,p). This estimate refers to single $\pi+$N scattering. It should be noted that for small angles (say $\theta<45°$), QFS may not be the dominant part of $\pi+$N single scattering because of Pauli blocking of the recoiling nucleon, which sets in for low momentum transfers. On the other hand, when inelastic scattering is thus blocked, the single $\pi+$n scattering can still proceed through the $\pi+{}^4$He elastic scattering. The single scattering cross section can therefore be compared (cf. Ref. 15) to the sum of the measured inelastic and elastic cross sections, which is 300 mb. An estimate for the pion double scattering in $\pi+{}^4$He can be obtained by multiplying the cross section of the double charge exchange reaction ^{4}He(π^+,π^-), which has been measured[26] to be 400$\pm$60 μb, by a factor of 31; the factor of 31 acounts for the difference in sequential, elementary πN elastic and charge exchange scattering cross sections in the 3,3 channel contributing to π^+N$\rightarrow$ pπ^+ QFS and (π^+,π^-) double charge exchange scattering. We thus obtain the estimate of 13 mb for the (π^+,p) double scattering cross section; i.e., double pion scattering occurs at the 5% level of single scattering. The two-nucleon pion absorption cross sections can be estimated to be 33 mb using the relative yield in Table III and the known total πd$\rightarrow$ pp cross section[9] of 7.55 mb. In comparison, the exclusive pion absorption reaction, ^{4}He(π,p)^{3}He, carries[13] a very small cross section (0.54 mb).

The single scattering and pion absorption cross sections (our estimated sum is 284 mb) are part of the total $\pi+{}^4$He cross section (measured[1,2] to be 310 mb). The difference between our summed cross section and the total cross section would be due to reactions that escape detection in our (π,p) spectra. Excluded from our summed cross section are processes that are removed from the quasifree channels because of proton-nucleon scattering in the exit channel. Furthermore, true $\pi+2$N scatterings (to be distinguished from sequential single scatterings) or true three- or four-nucleon pion absorption would also not be part of our summed cross section. Our estimate for this difference suggests that the latter cross sections are small. More extended measurements are needed to obtain quantitative results and a comparison of both (π,p) and (π,π') cross sections with total cross sections could be particularly fruitful in illuminating the role of pion and proton nuclear interactions.

V. CONCLUSIONS

We have reported on measurements of the ($\pi^\pm$,p) reactions in ^{3,4}He and ^{27}Al and presented cross sections on $\pi+$ N quasifree scattering (QFS), quasifree two-nucleon pion absorption (QFA), and the reaction ^{4}He(π,p)^{3}He. We find that the (π^+,p) spectra are dominated by QFS and QFA and we estimate that a large part (>90%) of the total $\pi+{}^4$He cross section is attributable to $\pi+$ N single scattering plus two-nucleon pion absorption. The nuclear $\pi+$ N scattering is found to be attenuated relative to free $\pi+$ N scattering and more so for ^{4}He than for ^{3}He. At the highest energy, $T_\pi=295$ MeV, we observe an enhancement of the QFS cross section which is ascribed to scattering at a πN energy closest to the resonance energy as is possible by using nonstationary target nucleons (requiring single particle momenta in the range $p\lesssim120$ MeV/c).

A comparison between our (π,p) results for QFS and the (π,π) results of other experiments shows differences which can be related to the nuclear attenuation in the exit channel and differences between proton and pion rescattering effects in the exit channel. The QFA (π^+,p) reactions in ^{3}He and ^{4}He are found to be stronger relative to πd$\rightarrow$pp scaling by the number of quasideuterons available in the target. This enhancement is further accentuated if the attenuation as measured by QFS is taken into account. We find that π^+pn$\rightarrow$pp in ^{3}He and ^{4}He is dynamically enhanced over πd$\rightarrow$pp by factors of about 1.5 and 2.0, which would be attributable to the NN state dynamics rather than to the πNN interaction since the relationship between (π^+,p) in ^{2}He, ^{3}He, and ^{4}He is found to be insensitive to pion energy. This view is also consistent with calculations for low energy pions which predict the π^+np$\rightarrow$pp yield in ^{4}He to be lower than that for ^{3}He because of wave function differences. Our (π^-,p) spectra indicate that the π^-pp$\rightarrow$np reaction in ^{3}He or ^{4}He is factors of 12 to 35 or 20 to 60 weaker than the (π^+,p) yields of π^+pn$\rightarrow$pp as compared to yield ratios of 13:1 or 26:1 expected from isospin consideration. Our π^+ and π^- absorption ratios are smaller than those of a recent coincidence measurement at $\theta_p=55°$ which might indicate an angular dependence in this ratio rather than a general, strong suppression of two-nucleon pion absorption on $T=1$ NN pairs at pion-nucleon resonance energies as suggested by the coincidence data. The new results on ^{4}He(π^+,p)^{3}He indicate larger cross sections at $T_\pi=50$ MeV than previous ^{4}He(π^-,p)^{3}He data suggesting a rather weak variation with energy in the range $T_\pi\approx10$—200 MeV in contrast to the rapid decrease towards higher energies. The effect of the πN resonance on the ^{3}He(π,p)^{3}He reaction can still be seen in the form of a maximum if the nuclear form factor dependence is accounted for.

We demonstrate the application of experimental information on the basic pion-nucleon interactions (scattering and absorption) to interpret poorly known complex nuclear pion reactions. The (π,p) attenuation factor deduced from the QFS data and the dynamical enhancement factor obtained from the QFA data provide information for the normalization of calculations based on phenomenological two-nucleon models for $^4He(\pi^+,p)^3He$ [or $^4He(\pi^-,n)^3He$] and $^3He(\pi^-,n)^2H$. The rather constant ratio of QFA to $\pi d \rightarrow pp$ observed over the wide energy range 50 to 500 MeV suggests that $\pi d \rightarrow pp$ should be adequate for use in two-nucleon reaction models so long as the main contributions can be assumed to come from $T=0$ NN pairs. The combined use of information on the basic nuclear reactions QFS and QFA along with complex reactions can provide insight into specific nuclear reactions such as $A(\pi,p)A-1$, as well as into the balance between scattering and absorption in the global picture of pion-nucleon interactions.

[1]M. Hirata, F. Lenz, and K. Yazaki, Ann. Phys. (N.Y.) 108, 116 (1977).
[2]D. Ashery *et al.*, Phys. Rev. C 23, 2173 (1981).
[3]M. Ruderman, Phys. Rev. 87, 383 (1952).
[4]H. W. Fearing, Phys. Rev. C 16, 313 (1977).
[5]J. Källne *et al.*, Phys. Lett. 97B, 205 (1980).
[6]J. Källne *et al.*, J. Phys. G 1, L287 (1981).
[7]D. Ashery *et al.*, Phys. Rev. Lett. 47, 895 (1981).
[8]P. J. Bussey *et al.*, Nucl. Phys. B58, 363 (1973).
[9]J. Hoftiezer *et al.*, Phys. Lett. 100B, 462 (1981); B. G. Ritchie *et al.*, Phys. Rev. C 24, 552 (1981).
[10]R. Frascaria *et al.*, Nucl. Phys. A178, 307 (1971); W. H. T. Van Oers *et al.*, Phys. Rev. C 25, 390 (1982).
[11]R. I. Jibuti and R. Ya. Kezerashvili, Phys. Lett. 57B, 433 (1975); J. S. McCarthy, I. Sick, R. R. Whitney, and M. R. Yearin, Phys. Rev. C 13, 712 (1976); and E. Jans *et al.*, Phys. Rev. Lett. 49, 974 (1982).
[12]G. Hohler, F. Kaiser, R. Koch, and E. Pietrinen, *Handbook of Pion-Nucleon Scattering* (Fachinformationszentrum, Karlsruhe, Federal Republic of Germany).
[13]J. Källne, J. E. Bolger, M. J. Devereaux, and S. L. Verbeck, Phys. Rev. C 24, 1102 (1981).
[14]B. D. Dieterle, in *Nucleon-Nucleon Interactions—1977 (Vancouver),* Proceedingss of the Second International Conference on Nucleon-Nucleon Interactions, AIP Conf. Proc. No. 41, edited by H. Fearing, D. Measday, and A. Strathdee (AIP, New York, 1978), p. 35.
[15]M. D. Cooper *et al.*, Phys. Rev. C 25, 438 (1982).
[16]S. M. Levenson *et al.*, Phys. Rev. Lett. 47, 479 (1981).
[17]R. R. Whitney *et al.* (unpublished).
[18]J. Källne *et al.*, Phys. Rev. C 21, 2681 (1980).
[19]B. F. Bertsch and D. O. Riska, Phys. Rev. C 18, 317 (1978).
[20]L. Orphanos *et al.*, Phys. Rev. Lett. 46, 1562 (1981).
[21]N. Willis *et al.*, J. Phys. G 7, 195 (1981).
[22]B. Goplen, W. R. Gibbs, and L. E. Lomon, Phys. Rev. Lett. 32, 1012 (1974).
[23]J. H. Alexander and H. W. Fearing, in *Meson-Nuclear Physics—1976 (Carnegie-Mellon Conference),* Proceedings of the International Topical Conference on Meson-Nuclear Physics, AIP Conf. Proc. No. 33, edited by P. D. Barnes, R. A. E. Eisenstein, and L. S. Kisslinger (AIP, New York, 1976), p. 468.
[24]F. Binon *et al.*, Nucl. Phys. A298, 499 (1978).
[25]J. Källne *et al.*, Phys. Rev. Lett. 45, 517 (1980); Phys. Lett. 103B, 13 (1981).
[26]A. W. Stetz *et al.*, Phys. Rev. Lett. 47, 782 (1981).