Three-nucleon pion absorption in carbon

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We have performed an experiment in which we have detected three protons in coincidence, following the absorption of positive pions in carbon. Data were collected with twelve plastic scintillator detectors, covering a fairly large region of the available phase space, at three incident pion kinetic energies: $T_\pi=130$, 180, and 228 MeV. Comparisons are made with phase space calculations which simulate quasifree three-nucleon and four-nucleon absorption mechanisms. The first of these provides an excellent description of the bulk of the data. Some of the observed events appear to come from quasideuteron absorption, followed by a final-state interaction of one of the outgoing protons. There is no evidence for absorption mechanisms involving more than three nucleons. Estimates are made for the contributions of the three-nucleon absorption mechanisms to the total pion absorption cross section. These are relatively small.

I. INTRODUCTION

The study of pion absorption in nuclei is interesting for many reasons. The reaction is one in which a pion disappears, and its rest mass energy is converted into the kinetic energy of the absorbing nucleons. This is a process which does not occur with more conventional projectiles, such as protons. More particularly, the pion absorption cross section in nuclei is relatively large, and because the absorption channel is coupled to others, such as the elastic and inelastic scattering channels, the former must be understood before we can claim to completely understand the latter. In fact, there has been mounting evidence over the last several years that we do not understand the process of pion absorption in nuclei, not only quantitatively, but even qualitatively. Thus, there is a possibility of observing some new effect. On the other hand, our lack of understanding may be due to the complexity of the various possible stages of the reaction, involving interactions between the particles directly involved in the absorption with the other particles present in the nucleus.

Absorption on a single nucleon is kinematically prohibited. The next simplest process one can envisage involves two nucleons. This mechanism has been clearly identified and studied extensively in the pion-deuteron system,[1] where kinematically complete experiments are easy to perform. Two-nucleon absorption has also been identified in heavier nuclei, from measurements of nucleon energy spectra, and the angular correlations between two nucleons, emitted after pion interactions. Many features of two-nucleon absorption in nuclei are similar to those of the elementary $\pi d \rightarrow pp$ process. For example, the angular dependence of the differential cross sections is the same. Also, the two absorbing nucleons are much more likely to be a neutron and a proton, rather than two neutrons or protons. For these reasons, two-nucleon pion absorption in nuclei has been commonly referred to as "quasideuteron" absorption. There have been several high resolution experiments performed recently,[2] which have provided some interesting detailed information about the quasideuteron absorption process. For example, the quasideuteron may be in a relative $l>1$ state with respect to the rest of the nucleus. This has consequences for the emitted nucleon angular distributions.

There have been other experiments however, which indicate that quasideuteron absorption is not the only active absorption mechanism, and perhaps not even the dominant one. For example, McKeown *et al.*,[3] in a single arm experiment, measured the energy distributions of protons emitted at particular angles. From a rapidity analysis of these data, they concluded that the average number of nucleons participating in pion absorption is ~ 3 in carbon, rising to ~ 5.5 in ^{181}Ta. Altman *et al.*,[4] in a two arm coincidence experiment, on carbon, measured the angular distribution of one emitted proton, when a second one was detected at a particular angle. They found that their measured angular distributions were well described by a sum of two Gaussians, one narrow, and the other wide. They attributed events in the narrow Gaussian to quasideuteron absorption, and found that after integration, these events amounted to only about 10% of the total pion absorption cross section. A similar experiment, with better energy resolution, was performed on nickel by Burger *et al.*[5] With a similar analysis, they concluded that only about 9% of the total absorption cross section could be accounted for with the quasideuteron mechanism, and further concluded that processes involving two nucleons were not the dominant absorption mechanisms. Even in a nucleus as light as ^{3}He, three-nucleon absorption events have been identified.[6–8] These events seem to fill the available three-body phase space uniformly, and make up some 25% of the total. There are indications from a single arm experiment[9] that in ^{4}He, only about 50% of the total absorption cross section can be attributed to quasideuteron absorption.

It must be noted that in experiments such as those of Refs. 4 and 5, the identification of absorption events as coming from the quasideuteron mechanism, as opposed to more complicated ones, is not entirely unambiguous. The range of validity of the two Gaussian decomposition, for example, has been questioned by Ritchie, Chant, and Roos.[10] Furthermore, there is the possibility that one or both of the nucleons from the quasideuteron absorption may undergo some kind of "final state interaction" (FSI) with the residual nucleus, and not be counted as having come from it. For example, an outgoing proton may undergo a charge exchange reaction, emerge as a neutron, and not be detected; or it may simply scatter and be deflected by an angle sufficiently large that it falls outside of the narrow Gaussian distribution. There have been estimates for the effect of FSI's made with "intranuclear cascade" (INC) calculations, based on Monte Carlo methods. These estimates range from factors of 2 (Ref. 11) to 3 (Ref. 12) or more. As a result, Refs. 4 and 5 claim upper limits of 25% and 50%, respectively, as the total contributions of the quasideuteron absorption process—as opposed to the uncorrected lower values quoted above. These values are still sufficiently small however, that the question of "what mechanism is responsible for the rest" is very interesting indeed.

One possibility, first raised by Masutani and Yazaki,[13] and then advanced by Ohta, Thies, and Lee,[14] is that an incident pion may first undergo an "initial state interaction" (ISI) in which it scatters from one nucleon in the nucleus, knocking it out in the process, before being absorbed by a quasideuteron. In an earlier experiment,[15] we had assumed that there would be a simple signature for such a process, and attempted to identify it by detecting three protons in coincidence following the interaction of 228 MeV π^+'s with carbon. No evidence for such a process could be found. It has been argued[16] that if pions did undergo ISI's, this would result in an asymmetry and shift of the narrow Gaussian distribution measured in experiments such as those of Refs. 4 and 5. One complicating factor, of course, is that when there are three emitted protons, there is no method of distinguishing the proton from the pion ISI, from those from the absorption, and the above argument only applies to the latter. In any case, the angular distributions observed in the two-body coincidence data do not appear asymmetric. In fact, Burger *et al.* have modeled ISI's, presumably incorporating the effect of indistinguishability mentioned above, and claim an upper limit of 30% for processes involving ISI's from their data. More recently, Silk[17] has argued that one should not expect to find evidence for the process we have described above. On the basis of the uncertainty principle, he claims that pions will be far off the mass shell after the first scattering, and will not leave the expected kinematic signatures, which assume on-shell pions in the intermediate state.

Apart from the lack of evidence for pion ISI's, it was difficult to draw definite conclusions from our previous experiment because of our rather incomplete coverage of the available phase space, and the lack of theoretical predictions with which to make comparison. Nevertheless, it seemed clear that in order to learn something about mechanisms involving more than two nucleons, it was important to perform experiments in which more than two nucleons were detected. One fact which did emerge from our previous experiment was that the three proton count rate was appreciable, and that further triple-coincidence experiments with relatively small counters were feasible. Thus, we have repeated our previous experiment with an improved set-up, which is described in Sec. II. The measured data from the two experiments are in good agreement. However, the estimate for the total three-nucleon absorption cross section at $T_\pi = 228$ MeV based on the data from the present experiment is less than half of that made in our earlier publication. The difference is due to the incorrect assumption about the isotropy of the proton angular distributions made in the earlier publication, and will be described in more detail in Sec. IV.

There have been several other experiments proposed recently[18] based on our experience. The fact that as large a phase space coverage as possible is considered important is reflected in the fact that plans are presently underway for the construction of two large detectors with nearly full 4π coverage: LADS at Schweizerisches Institut für Nuclearforschung (SIN) and CLASS at TRIUMF. Experiments have also been performed at LAMPF with a large solid angle detector composed of BGO crystals.[19] The only previous experiment which was able to detect more than two particles in the final state was that of Bellotti *et al.*,[20] which made use of a bubble chamber. That experiment suffered from poor statistics, and more importantly was performed at a time when our knowledge of pion absorption was even poorer than it is today, so that the analysis did not address the same questions which are currently being asked.

The primary goal of the present experiment was to shed some light on the question of whether the dominant absorption process involves three, four, or more nucleons. The possibility of three is supported by the models of Refs. 13 and 14 mentioned above. Also, Oset *et al.*[21] have a model for direct many-nucleon absorption, and find that the contribution of three body is much larger than that of four body. In addition, there has been a model suggested[22] in which a π^+ is preferentially absorbed on a *pp* pair, in which case a third nucleon would of necessity have to become involved in order to conserve charge. The possibility of four is supported by a theoretical model[23] involving two Δ's. Also, the total absorption cross section on ^{3}He (near $T_\pi = 120$ MeV) is ~ 16 mb.[6] This is in rough agreement with what one would expect from considering the total cross section for the elementary $\pi d \rightarrow pp$ process, 12 mb,[24] and the total number of *np* pairs in ^{3}He. In ^{4}He however, the total absorption cross section jumps to 80 mb,[25] much more than can be accounted for simply from an increase in the number of *np* pairs. It is interesting to speculate whether this is related to the increased nuclear density of ^{4}He, or whether in fact it signals the opening of a new four-nucleon absorption channel. The involvement or more than four nucleons might indicate that the absorbed pion's rest mass energy was distributed evenly throughout the nucleus, in some sort of thermal equilibrium model.

Unfortunately, there are no theoretical calculations available which make detailed predictions of differential distributions which could be compared directly to our data. We hope the present results will stimulate theoretical interest. For the present, however, we have compared our data with phase space calculations. These are significantly more sophisticated than those presented in our previous publication, and are described in Sec. III. In some ways, a comparison with phase space is preferable to a comparison with the results of an INC calculation, at least initially. With INC programs, it is often difficult to disentangle purely kinematic effects from those due to various physical processes which are incorporated in the calculations.

Our initial hope was that after having addressed the question of how many nucleons were involved in the absorption, we would be able to isolate differences between the data and the phase space, and thus learn something about the details of the process. Our results are presented in Sec. IV. The data are in fact described remarkably well by the quasifree three-body phase space distributions. The phase space calculations are used to obtain estimates of the total three-nucleon absorption cross sections. A discussion of the results and conclusions are presented in Sec. V.

II. EXPERIMENTAL DETAILS

The experiment was performed with pions from the $\pi M1$ beamline at the Swiss Institute for Nuclear Research (SIN). A schematic diagram of the setup is given in Fig. 1. Twelve counters were used to detect emitted protons. These were of two types. Type (a) counters consisted of two plastic scintillators. The first of these was 20 cm wide, 70 cm high, and 0.5 cm thick, and was located at a distance of 188 cm from the scattering target. The second had the same area, but was 20 cm thick. Its front face was positioned 200 cm from the target. Both scintillators were equipped with two photomultipliers, one at each end. Type (b) counters consisted of two thin plastic scintillators. The first was 6 cm wide, 16 cm high, and 0.3 cm thick, and located 50 cm from the target. The second was 10 cm wide, 30 cm high, and 0.5 cm thick, and located 100 cm from the target. The signals from this second scintillator were read out with two photomultipliers, the first with only one. Because of the varying distances of the counters from the target, we have merely indicated the angular acceptances of the counters, rather than the detectors themselves, in Fig. 1. The exact angles at which the detectors were positioned are also indicated. Note that for convenience we have chosen to label the detector angles from 0° to 360°, as measured counterclockwise from the incident beam direction, in the scattering plane. Data were taken at three incident pion kinetic energies: 228, 180, and 130 MeV. At

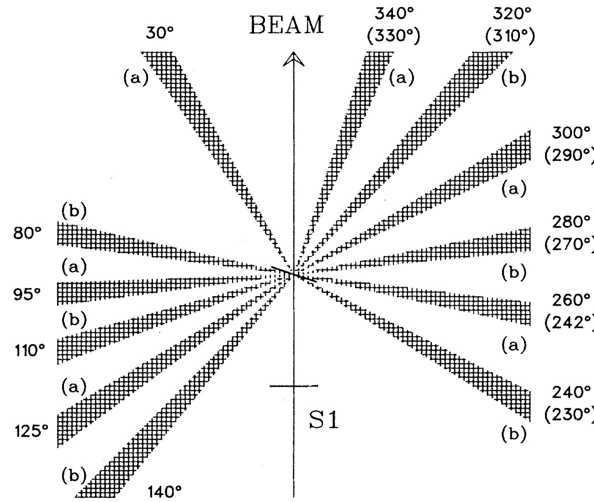

FIG. 1. Schematic diagram of the experimental setup. Shaded regions indicate the angular acceptance of the detectors in the scattering plane.

180 MeV data were also taken at a second angle setting for six of the twelve counters; the exact angles are given in parentheses in Fig. 1.

Signals from the two scintillators in each counter were put in coincidence. Then, these coincidence signals from all twelve counters were timed into a "multiplicity logic unit" (MLU).[26] The MLU was set so as to give an output only when signals were present on exactly three of the twelve inputs. This output signal was then put in coincidence with a BEAM signal, which set the timing. The output of this last coincidence was taken as the event trigger. It provided gates for the CAMAC analog-to-digital converters (ADC's) which were used to record pulse height information for each scintillator, and the start signals for the CAMAC TDC's which were used to record time of flight information, also for each scintillator. The MLU provides an additional output when the number of coincidence input signals is greater than three. This output was also put in coincidence with a BEAM signal, and could have provided a second event trigger. There were so few of these events however, that an analysis would not have been meaningful, and was not attempted.

The BEAM signal referred to above came from the coincidence rf$\cdot S1 \cdot \overline{S1}$, where rf represents the pickup of the SIN cyclotron frequency, and $\overline{S1}$ is the $S1$ counter signal triggered at a high level, used to reject protons coming down the beamline. The coincidence requirement with the rf is used to eliminate some muons and electrons coming down the beamline. The remainder, which is known from previous measurements to be less than a few percent, was ignored. The $S1$ counter itself consisted of five adjacent scintillator strips, each of which was 1 cm wide, 10 cm high, and 0.2 cm thick. The $S1$ signal referred to above was the electronic OR of the signals from the five individual strips. The BEAM signal was counted directly in order to determine the total number of incident pions. Typical incident pion fluxes were 10–15 MHz, but the maximum flux through any single $S1$ strip was limited to 5 MHz. At these relatively high incident rates, the total number of pions had to be corrected for multiples, since the in-beam scintillator will count only once per beam burst regardless of how many particles were actually present. The correction factor is given by $\epsilon = -\ln(1-\mu)/\mu$, where μ is the ratio of measured incident flux to the cyclotron rf (50 MHz). For consistency, the total number of incident pions was also monitored by a three element counter telescope (not shown in Fig. 1) which viewed the $S1$ counter from above.

The detected proton energies were determined from their times of flight, and corrected for losses in the scattering target. Our experimental timing resolution was approximately 0.5 ns [full width at half maximum (FWHM)]. This means that the uncertainty in the measured energy of a 100 MeV proton was approximately 4 MeV for the type (a) counters, and 7 MeV for the type (b) counters. For a 250 MeV proton, the uncertainties rise to 16 and 33 MeV. This is still fairly reasonable for the type (a) counters, but the type (b) counters are far from ideal, since the scintillator which set the timing was only 1.0 m from the target. The advantage of these counters, however, was that their two elements acted as a telescope, and thus they only accepted events which originated in the vicinity of the scattering target.

Target-out measurements were taken at all three incident pion energies. After a careful off-line analysis, the normalized target-out background contribution to the target-in foreground data was found to be only about 4%, and was subtracted from the foreground data.

The graphite target used had an areal density of 0.804 g/cm^2. It was placed at an angle of 20° relative to the incident beam direction. This means that several of the proton counters viewed the target at a steep angle. Because of energy losses in the target, only protons with kinetic energies greater than about 50 MeV reached these particular counters. Although the threshold in most other counters was significantly lower than this, during our analysis we imposed an energy cutoff of 50 MeV on all protons, in order to have a consistent data set.

Note that before taking actual triple coincidence data with the graphite target, we tested our setup by running with CH_2 and CD_2 targets. In these cases, the coincidence level of the MLU was set to two, and pairs of counters were set to angles corresponding to $\pi p \rightarrow \pi p$ or $\pi d \rightarrow pp$ kinematics. We measured differential cross sections for these reactions, and verified that our results were in reasonable agreement with published values. The CH_2 and CD_2 data was also used to provide an energy calibration for the time of flight measurements.

Two-dimensional histograms of time of flight versus pulse height were used to distinguish detected protons from pions and deuterons. The three particle types fall along different loci. The separation is quite clean except for the highest energy protons, which may be confused with lower energy pions.

III. PHASE SPACE CALCULATIONS

We believe it is important to describe our calculations in detail. The phase space for a "quasifree," as opposed to a "free" process, must somehow involve an estimate of the effect of the Fermi motion of the particle or particles involved. Such an estimate is not model independent, and the model should be described in order to avoid ambiguities.

In general one cannot calculate the phase space analytically for more than three particles in the final state, and therefore use must be made of numerical, Monte Carlo techniques. There are several standard phase space programs available, which makes use of efficient algorithms. For example, there is the CERN program GENBOD.[27] As input, this routine requires the number of particles in the final state, their masses, and the total center-of-mass energy available. As output, it provides the vector momenta of the outgoing particles, and a weighting factor which must be associated with that particular event. Any number of events may be generated in this way, and used to study distributions of interest. Note that actual experimental conditions may be simulated by placing the same constraints (such as counter acceptances, energy cutoffs, etc.) on these computer generated events as were imposed on the actual experimental data.

Our technique[28] for simulating the phase space for quasifree N nucleon absorption was the following. We would generate events (as described in principle above) with $(N+1)$ particles in the final state, where particles $1, \ldots, N$ were nucleons, and the $(N+1)$th was the residual nucleus. Rather than simply associating the free $(N+1)$ body weight (WT) with each event, however, we would use the product

$$\mathrm{WT} \times e^{-0.5(p_{N+1}/p_{\mathrm{Fermi}})^2}, \quad (1)$$

where p_{N+1} was the magnitude of the momentum of the residual nucleus. In order to determine what value to use for p_{Fermi}, we made use of our procedure to reproduce the width of the narrow Gaussian in the figure of Ref. 4, with p_{Fermi} as a free parameter. We found that a value of 170 MeV/c gave reasonable agreement. This narrow Gaussian is attributed to quasi-deuteron absorption. The Fermi momentum of the absorbing quasideuteron must somehow come from the momenta of the two individual nucleons, which may be expected to add quadratically. Thus, since $170 \simeq \sqrt{2} \times 120$, for the general case of quasifree N-nucleon absorption we used $p_{\mathrm{Fermi}} = \sqrt{N} \times 120$ MeV/c.

Note that in the description given above, it was assumed that the recoil nucleus has a fixed mass, that of its ground state. It is possible, however, or maybe even probable, that after absorption the residual nucleus will be left in an excited state. This effect can be easily incorporated in our approach by simply choosing a different mass for the residual nucleus for each event generated. For some calculations presented in the following section, the value of the mass was chosen at random from a uniform distribution.

For our purposes, the program GENBOD described above has two disadvantages. First, it generates events in their center of mass frame, whereas we wish to compare results in the lab frame. Second, it generates events distributed everywhere in space, whereas our detectors only covered a region within approximately ±10° of the scattering plane. Both these factors lead to inefficient use of computer time. We have overcome these problems by writing our own event generating program, based on the method described by Ruiz et al.[29] For the specific case of quasi-three-nucleon absorption, we proceed as follows. We start with the general expression for four-body phase space

$$R=\int \frac{d^3p_1}{E_1}\frac{d^3p_2}{E_2}\frac{d^3p_3}{E_3}\frac{d^3p_4}{E_4}\delta(E_T-E_1-E_2-E_3-E_4)\delta^3(\mathbf{p}_T-\mathbf{p}_1-\mathbf{p}_2-\mathbf{p}_3-\mathbf{p}_4)\ ,$$

where $\mathbf{p}_T$ is the incident pion momentum, and E_T is the total incident lab energy, $E_T=E_\pi^+=m_{^{12}\mathrm{C}}$.

One can use the δ functions to eliminate four of the twelve variables, and obtain an expression for the eightfold differential phase space. The choice of which variables to integrate over is completely arbitrary, but a particularly useful one for our purposes was p_3, θ_3, θ_4, and ϕ_4, in which case we have that

$$\frac{d^8R}{dp_1d\theta_1d\phi_1dp_2d\theta_2d\phi_2d\phi_3dp_4}=\frac{p_1^2\sin\phi_1p_2^2\sin\phi_2}{E_1E_2E_4|\sin\phi_4\sin(\theta_4-\theta_3)|}\ . \quad (2)$$

Note that for convenience, we have chosen a coordinate system in which the incident beam is along the $\hat{x}$ axis, and the $\hat{z}$ axis points vertically out of the scattering plane. θ is then the angle in the scattering plane, measured from the $\hat{x}$ axis counterclockwise towards the $\hat{y}$ axis, and runs from 0° to 360°. ϕ is measured down from the $\hat{z}$ axis, and runs from 0° to 180°.

In practice, for each event, we would choose the eight independent variables at random, each from a uniform distribution, between their minimum and maximum possible values. Then we would determine whether such an event satisfied energy and momentum conservation, by attempting to calculate the four dependent variables. If energy and momentum could not be satisfied, we would make another choice for the independent variables, and again attempt to calculate the dependent ones. Once we obtained an event which did satisfy energy and momentum conservation, its associated weight was calculated from Eq. (2).

This method has the advantage that the events are generated, and their associated weights evaluated, directly in the lab frame. Furthermore, rather than waste computer time by generating events which will obviously fall outside the experimental acceptance, and then rejecting them, one can limit the ranges over which some of the independent variables are chosen *a priori*. For example, rather than choosing the momenta p_1 and p_2 at random between 0 and p_{max}, one can choose them in the range from 310.4 MeV/c to p_{max}, and thus simulate the experimental kinetic energy cutoff of 50 MeV which has been applied to the data. The same applies to choice of angles. In order to verify that such a procedure does not distort the resulting distributions, we have compared results using both techniques, and found them to be identical. We have also compared the distributions generated with our technique with those generated with GENBOD, and again verified that the two were identical.

As will be discussed in the following section, we observed some peaks in our experimentally measured angular distributions which appeared to be due to two-nucleon absorption, followed by a final-state interaction of one of the outgoing nucleons. In order to model such a process in the context of our phase space calculations, we proceeded as follows. First, we would generate an event as described above. Then, we would calculate a weight to associate with this event which would simulate two nucleons absorption, in analogy with Eq. (1). For example, for absorption on particles 1 and 2, we have

$$\mathrm{WT}_{12}=\mathrm{WT}\times e^{-0.5(|\mathbf{p}_3+\mathbf{p}_4|/p_{\mathrm{Fermi}})^2}\ , \quad (3)$$

where WT is the value of the expression given in Eq. (2) for that particular event. p_{Fermi} in this case is taken to be $\sqrt{2}\times 120$ MeV/c. It is well known that in fact the differential cross section for the elementary $\pi d\rightarrow pp$ process is not isotropic, but given by

$$d\sigma(\theta^{jk}_{\mathrm{c.m.}})/d\Omega=\sum_{i=0,2,4}a_iP_i(\cos\theta^{jk}_{\mathrm{c.m.}})\ , \quad (4)$$

where $\theta^{jk}_{\mathrm{c.m.}}$ is the scattering angle of particle j or k in their center-of-mass frame. The coefficients a_i can be taken from existing results [24,30,31] for $\pi d\rightarrow pp$ scattering. The values we used are listed in Table I. We decided to incorporate this fact into our model, by modifying the two-nucleon weights we used. That is, we multiplied the WT_{jk}'s in Eq. (3) by $d\sigma(\theta^{jk}_{\mathrm{c.m.}})/d\Omega$, as given in Eq. (4). Next, in order to simulate a final-state interaction, we would evaluate an additional weight which had its maximum value when the two nucleons under consideration had zero relative momentum. This kind of prescription provided a good description of the final-state interactions between protons and neutrons in the $\pi d\rightarrow\pi pn$ reaction.[32] Specifically, for a FSI between particles 1 and 3, this additional weight was

$$\mathrm{WT}^{\mathrm{FSI}}_{13}=e^{-0.5(|\mathbf{p}_1-\mathbf{p}_3|/p_{\mathrm{Fermi}})^2}\ , \quad (5)$$

where now p_{Fermi} was 120 MeV/c. Thus, the full weight associated with each event was

TABLE I. Values of the coefficients a_i (see text) used for the three incident pion energies.

T_π (MeV)	a_0	a_2	a_4
130	1.94	2.02	−0.10
180	1.60	1.41	−0.33
228	0.75	0.60	−0.12

$$\mathrm{WT}_{12}\frac{d\sigma(\theta^{12}_{\mathrm{c.m.}})}{d\Omega}(\mathrm{WT}^{\mathrm{FSI}}_{13}+\mathrm{WT}^{\mathrm{FSI}}_{23})+\mathrm{WT}_{13}\frac{d\sigma(\theta^{13}_{\mathrm{c.m.}})}{d\Omega}(\mathrm{WT}^{\mathrm{FSI}}_{12}+\mathrm{WT}^{\mathrm{FSI}}_{23})+\mathrm{WT}_{23}\frac{d\sigma(\theta^{23}_{\mathrm{cm}})}{d\Omega}(\mathrm{WT}^{\mathrm{FSI}}_{12}+\mathrm{WT}^{\mathrm{FSI}}_{13}) .$$

In principle, one could apply the same technique to estimate the effects of FSI's in the case of three-body absorption. That is, one would generate events with five particles in the final state, and associate the following weight to simulate three-body absorption:

$$\mathrm{WT}_{123}=\mathrm{WT}\times e^{-0.5(|\mathbf{p}_4+\mathbf{p}_5|/p_{\mathrm{Fermi}})^2} .$$

This should result in distributions identical to those generated in the way that was described above, and it does. Then, one can proceed by multiplying this weight with additional ones similar to that in Eq. (5). There is some ambiguity at this point, because it isn't clear whether to allow for FSI's between any two particles, or only between each of the three protons coming from the absorption and the unobserved neutron. There is also the question of relative normalization. In any case, it was found that our data were well described by the three-body phase space without inclusion of this effect.

IV. RESULTS

The first question we wished to address in the analysis of our data was that of the number of nucleons involved in the absorption process. To do so we have compared the data with the three-body and four-body phase space calculations, and examined the agreement.

We start with a consideration of the measured angular distributions. Since we had twelve counters, there are in principle $(12\times11)/(2\times1)=66$ distinct angular distributions which could be plotted, in which the angles of two counters are held fixed, and the third varied. It is of course not feasible to present all of these, but a representative sample is given in Fig. 2. The data have been normalized, and are shown as an absolute triple differential cross section

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 d\Omega_3}=\frac{\text{yield}}{N_{\mathrm{inc}}N_{\mathrm{tgt}}\Delta\Omega_1\Delta\Omega_2\Delta\Omega_3} .$$

The statistical error bars are shown with each plotted point, but are usually smaller than the size of the points. Note that the values are averaged over the entire vertical acceptance of the counters used. The angles of the two counters held fixed are given in each subfigure. The incident pion energy for the distributions presented in Fig. 2 was 180 MeV, where, in some cases, we have data for two angle settings. The distributions at 228 and 130 MeV are identical in shape, but increased and reduced in magnitude, respectively. In the figure, the heavy solid line represents the results of the three-body phase space calculations, while the light solid line represents the four-body phase space. As described in the preceding section, the phase space calculations take the experimental detector geometry into account. The only free parameter in the calculations is an overall normalization factor. A single factor is used for all the three-body distributions shown in Fig. 2, and another for all the four-body distributions. There is no additional relative normalization factor between one subfigure and the next. The width of the three-body phase space distributions is due to the angular acceptance of the detectors, and the Fermi momentum of the absorbing nucleons. The width of the four-body phase space distributions is much greater, in part because of the large Fermi motion associated with the nucleons, but primarily because of the extra degree of freedom provided by the fourth undetected nucleon. It is quite evident that the three-body phase space distributions provide an excellent description of the experimental data, while the four-body distributions are too wide. This is true for all measured angular distributions, at each of the three incident pion energies. We have attempted to fit the data with an arbitrary sum of three- and four-body distributions. The best fit, however, was obtained with the three-body phase space alone. This is an indication that the contribution of any four-body absorption mechanism is significantly smaller than that of the three-body absorption.

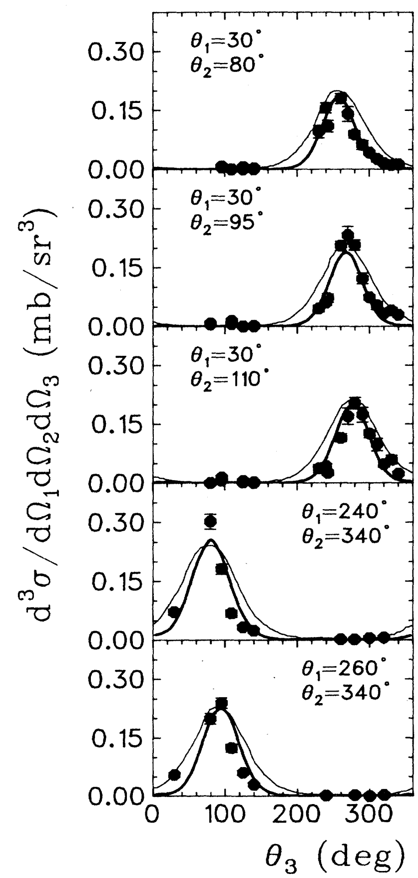

FIG. 2. Sample of measured $d^3\sigma/d\Omega_1 d\Omega_2 d\Omega_3$ distributions at $T_\pi=180$ MeV. Results of phase space calculations simulating quasifree three- and four-nucleon absorption are indicated by the heavy and light lines, respectively.

The phase space calculations also take the experimental energy threshold into account. That is, only those phase space events in which all three protons in the final state have kinetic energies greater than 50 MeV are considered. At an incident pion energy of 228 MeV, this condition is fulfilled by 47% of the three-body events and 22% of the four-body events. However, the total four-body phase space is larger than the three-body one. Thus, if there were an active four-body absorption mechanism of comparable importance to the three-body one there should be some evidence for it in the experimental data. There is none. Furthermore, the agreement between the three-body phase space distributions and the data is equally good at each of the three incident pion energies. The effect of the 50 MeV energy threshold is greater at $T_\pi=130$ MeV than at $T_\pi=228$ MeV. However, there is no evidence for any broadening of the measured angular distributions at 228 MeV relative to those measured at 130 MeV as one would expect if there were a significant contribution from a four-body absorption mechanism.

Another distribution we found useful to consider was the sum of components of the three proton momenta, especially that parallel to the incident beam (that is $\Sigma p_\parallel = p_{1\parallel}+p_{2\parallel}+p_{3\parallel}$). For the case of three-body absorption, one would expect this distribution to peak at the incident pion momentum, which is 340 MeV/c for an incident pion energy of 228 MeV. In the case of four-body absorption, one would expect the undetected fourth particle to carry off some momentum, and thus the four-body distribution should be broader than the three-body, and peak at some value smaller than 340 MeV/c. This is indeed what can be seen in Fig. 3, where the results of the three-body phase space are represented by the heavy solid line, and the four-body phase space by the light solid line. The histogram represents the data, which peak at the incident pion momentum, just as the three-body phase space. The same applies to the distributions at 180 and 130 MeV. Note that for the data, we have neglected the finite vertical size of our counters, and assumed all events to be exactly in the horizontal scattering plane. The phase space events were treated in the same way. We have also included our counters' finite horizontal acceptances, and the experimental energy threshold, in the phase space calculations. The apparent structure in the four-body phase space calculation must be an acceptance effect. The peak position and width of the measured distribution is relatively insensitive to the uncertainties in the time of flight calibrations used to determine the proton energies. Thus, this data provide another indication that the absorption mechanism responsible for producing our measured events involves three nucleons, and not four or more.

Some of our measured angular distributions appear to have peaks at angles where the three-body phase space is effectively zero. A sample of these, for $T_\pi=228$ MeV, is shown in Fig. 4. There are usually only one or two points associated with these "extraneous" peaks, but they are statistically significant. The events responsible for these peaks involve the emergence of one proton well separated from the two others, which emerge close together and usually impinge on adjacent counters. Furthermore, the magnitude of the "extraneous peaks" is greatest when the angles of the lone proton and one of the two which emerge together correspond to the kinematics of the free $\pi d\to pp$ reaction. In cases where the angles are far from $\pi d\to pp$ kinematics, such as those shown in Fig. 2, there

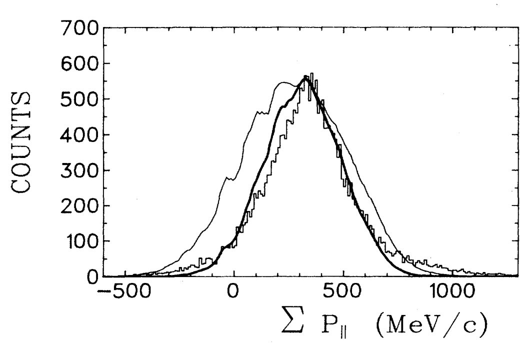

FIG. 3. Sum of the momentum components of the three detected protons, in the direction of the incident beam, at $T_\pi=228$ MeV. Results of phase space calculations simulating quasifree three- and four-nucleon absorption are indicated by the heavy and light lines, respectively.

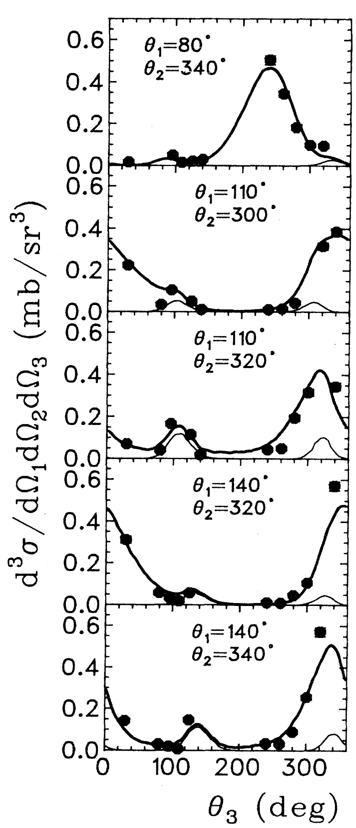

FIG. 4. Sample of measured $d^3\sigma/d\Omega_1 d\Omega_2 d\Omega_3$ distributions at $T_\pi=228$ MeV. The light lines indicate the result of calculations assuming the QDFSI mechanism (see text). The heavy lines include the calculations for the quasifree three-nucleon phase space.

TABLE II. List of detector angle combinations where events are better described by the QDFSI mechanism than by three-body phase space.

θ_1	θ_2	θ_3
30	240	260
30	260	280
300	79.5	95
300	95	110
300	110	125
300	125	140
320	79.5	95
320	95	110
320	110	125
320	125	140
340	79.5	95
340	95	110
340	110	125
340	125	140

is no indication of "extraneous" events. The two aforementioned facts suggest that the process giving rise to these "extraneous" events is that of quasideuteron absorption, followed by a final-state interaction of one of the outgoing protons. That is, the pion is absorbed on two nucleons, one of which emerges directly from the nucleus and hits one of our detectors. The other absorbing nucleon undergoes a soft final-state interaction, leading to the emergence of two protons which hit two different, usually adjacent, detectors. Since we will be referring to this process again, for convenience we will refer to it as QDFSI. To test whether in fact QDFSI is consistent with the data, we have constructed a model for it. This has been described in some detail in the previous section, and is represented by the light solid lines in Fig. 4. The heavy solid lines in this figure represent the sum of the results of the QDFSI calculations, and the standard quasifree three-body phase space calculation. The QDFSI calculations have been normalized relative to the three-body phase space by a simultaneous fit to a number of "extraneous" points, listed in Table II. The relative normalization factors are 0.409, 0.422, and 0.914 at $T_\pi = 228$, 180, and 130 MeV, respectively. Once this relative normalization factor has been fixed, there is only one overall normalization factor between the three-body phase space and the data. It is evident that there is excellent agreement between the data and the heavy solid line in Fig. 4.

At 180 and 130 MeV, the relative size of the peaks described by three-body phase space and those described by QDFSI changes. The former decrease in magnitude, while the latter remain approximately the same. This behavior is illustrated in Figs. 5 and 6. Again, there is only one overall normalization factor between the phase space and the data at each energy. In the case of 180 MeV, this is the same factor which was used in Fig. 2. It would be interesting to see whether the QDFSI peaks can be reproduced with an INC calculation. To date, there has been

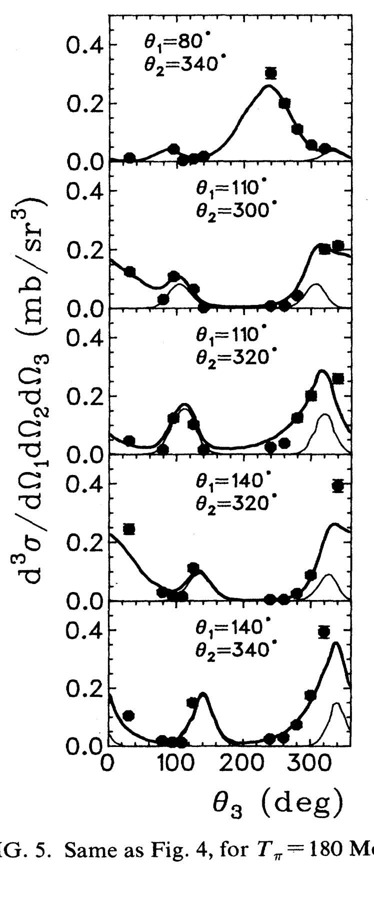

FIG. 5. Same as Fig. 4, for $T_\pi = 180$ MeV.

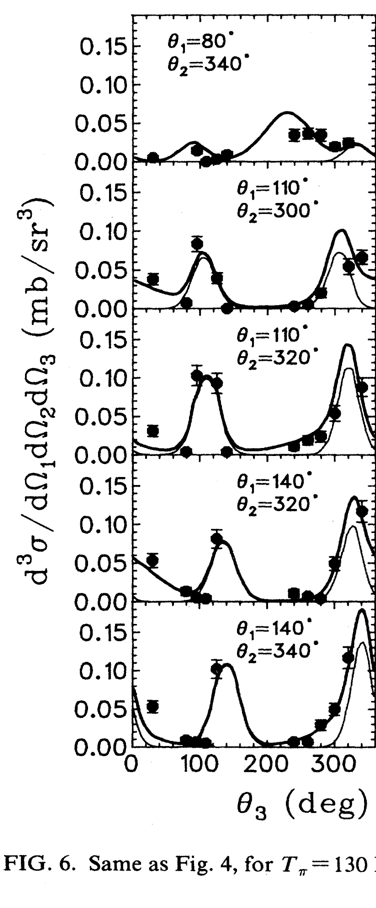

FIG. 6. Same as Fig. 4, for $T_\pi = 130$ MeV.

no data on the effect of FSI's with which INC calculations could be compared.

We see no evidence for any peaks or enhancements in our measured angular distributions, when θ_3 is separated from θ_1 or θ_2 (which are held fixed) by 90°. Such peaks were reported recently by Yokata *et al.*,[33] and attributed to proton hard FSI's following pion absorption on two nucleons. Their conclusion was largely based on the results of an INC calculation.

One might expect that the best way to distinguish between three- and four-body absorption would be to examine the distribution of the sum of the three detected proton kinetic energies. For the case of three-body absorption, one might expect this distribution to be sharply peaked, while for the case of four-body absorption, it should be much broader because the undetected fourth nucleon can carry away a significant amount of energy. When comparing our measured results, at $T_\pi=228$ and 180 MeV, with the phase space calculations, however, it was found that neither the quasifree three-body, nor the quasifree four-body provided a good description of the data. This was already observed in our earlier experiment.[15] From a consideration of the measured angular and momentum distributions, we have seen that the quasifree three-body phase space calculations provide an excellent description of the data. Why then does it not provide an equally good description of the measured energy distributions? It is evident that the situation is complicated by the fact that the residual ^{9}Be nucleus need not be left in its ground state, and may in fact carry significant amounts of energy as excitation. As pointed out in the previous section, we can model this effect within the context of our phase space calculations by choosing the mass of the residual nucleus at random from some given distribution for each phase space event generated, rather than keeping it fixed at its ground-state value. This procedure changes only the calculated energy distributions, and has little or no effect on the calculated momentum or angular distributions. Thus, our conclusion regarding the number of nucleons involved in the absorption process is unaffected.

In Fig. 7, the upper and lower histograms represent the data for the sum of any two of the three detected proton kinetic energies, at $T_\pi=228$ and 180 MeV, respectively. We present the sum of two rather than three because the former distributions are less sensitive to our rather poor energy resolution for higher energy protons. Also, these distributions may be of some interest for comparison with the results of two-arm coincidence experiments. Note that the lower limit of 100 MeV is a result of the 50 MeV threshold imposed on each individual counter. The light solid lines represent the results of quasifree three-body phase space calculations in which no allowance has been made for nuclear excitation. The heavy solid lines represent the same calculations, in which the nuclear excitation was assumed to be uniformly distributed. The average excitation values are 50 MeV and 30 MeV for $T_\pi=228$ and 180 MeV, respectively. The data for $T_\pi=130$ MeV, which is not shown, are adequately described by the quasifree three-body phase space without inclusion of nuclear excitation. It is not obvious what the

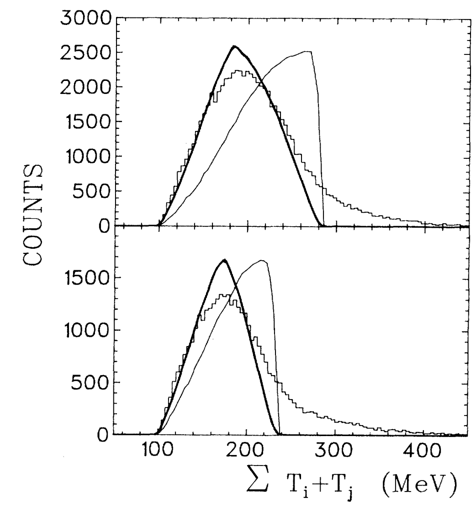

FIG. 7. Sum of two proton kinetic energies. The upper figure is for $T_\pi=228$ MeV, the lower for $T_\pi=180$ MeV. The light line is the result of the quasifree three-body phase space calculation, assuming the residual nucleus is left in its ground state. The heavy line includes the effect of nuclear excitation.

mechanism for producing the nuclear excitation may be. The average values of 50, 30, and 0 MeV at $T_\pi=228$, 180, and 130 MeV may at least exclude some possibilities: If the mechanism was simply absorption on three deeply bound nucleons, one might expect the average excitation energy to be the same for the three incident pion energies. If it was related to pion scattering prior to absorption, as was suggested in our previous publication, one might expect the average excitation be lowest at 180 MeV, where the pion mean-free path is shortest. The actual explanation may thus involve a combination of factors, including particle interactions before and after absorption, complicated by the nuclear structure of ^{12}C.

In Fig. 8, we present energy distributions of protons detected in some of our counters, integrated over all triple coincidences, at $T_\pi=228$ MeV. The solid lines represent the results of the quasifree three-body phase space calculations, including an average nuclear excitation of 50 MeV. As was the case for the angular distributions shown earlier, there is only one overall normalization factor for all the phase space distributions. The agreement between the phase space and the data is quite good, except maybe for the distributions at 340° and 30°, where there appears to be a bump in the data which is not reproduced by the phase space calculations. A similar effect was recently observed by Brückner *et al.*,[34] who measured the energy distribution of a proton detected at 8°, in coincidence with two others, detected over a fairly wide angular range, following pion interactions with carbon. Brückner *et al.* interpreted their bump as being due to a pion initial state interaction (quasielastic scattering) prior to quasideuteron absorption. That is the process we searched for in our first experiment. It may also be possible that when one of the three protons emitted after genuine three-nucleon absorption emerges at a forward angle, the residual nucleus is left with less excitation. This might have the effect of shifting the en-

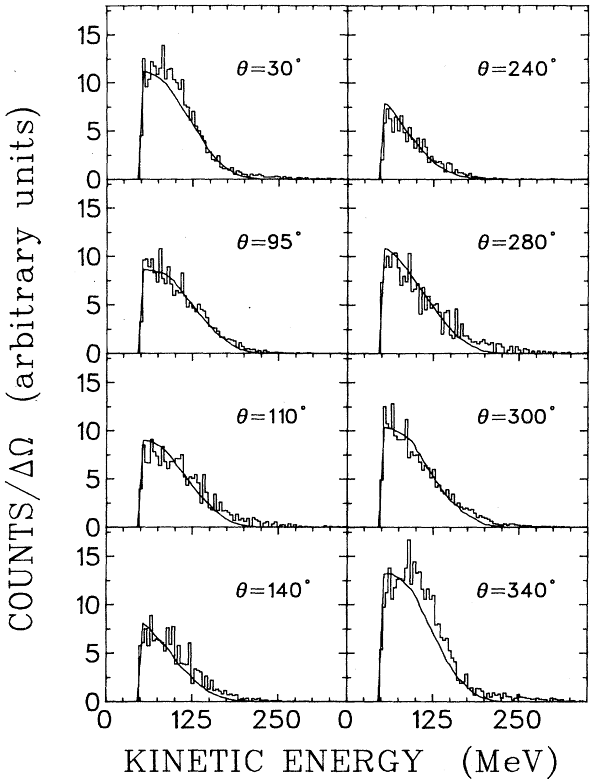

FIG. 8. Detected proton energy distributions, integrated over all triple coincidences, for several counters at $T_\pi=228$ MeV. The curves represent the results of quasifree three-body phase space calculations, including the effect of nuclear excitation.

ergies measured in the forward counters to higher values. In any case, the relative importance of whatever mechanism is responsible for producing the bump must be small, judging by the relative area of the bump above the phase space curve and the area below.

An interesting suggestion has recently been put forward by Salcedo *et al.*[35] for distinguishing between the two step process of quasielastic scattering followed by quasideuteron absorption, and genuine three-body absorption. Consider a pion which interacts with one proton, and is then absorbed by two nucleons, "i" and "j." The quantity

$$M_{ij}^2=(T_i+T_j)^2-(\mathbf{p}_i+\mathbf{p}_j)^2\ ,$$

where T_i and T_j are the kinetic energies of the two nucleons, and $\mathbf{p}_i$ and $\mathbf{p}_j$ their vector momenta, plays the role of the invariant mass of the pion in the intermediate state. It should thus be sharply peaked at a value of m_π^2 in the case of quasielastic scattering prior to two-nucleon absorption, because the intermediate pion is then on-mass-shell. The distribution should be much broader in the case of genuine three-body absorption, because there the intermediate pion is off-mass-shell. The situation is complicated by the fact that one has no way of knowing with which of the three outgoing protons the pion interacted first, so one must calculate M_{ij}^2 three times for every event, using each of the three possible pairs. A plot

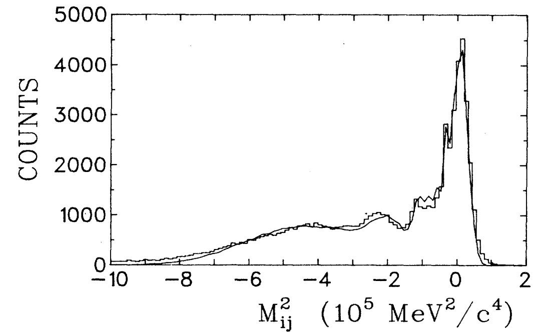

FIG. 9. Invariant mass of the intermediate pion (see text). The curve is the result of the quasifree three-body phase space calculation.

of M_{ij}^2 calculated from our data is shown as the histogram in Fig. 9. There is indeed a fairly sharp peak evident at $m_\pi^2=0.2\times10^5$ MeV^2, but the same peak is also present in the result of the quasifree three-body phase space calculation, which is represented by the line. There does not appear to be any enhancement in the data relative to the phase space calculation, and thus no evidence for the two step process of quasielastic scattering followed by quasideuteron absorption. The apparent structure in the data and the phase space is once again due to the finite acceptance of our counters.

It has been recently suggested[22] that a bound π^+pp state might play a role in pion absorption. If such were the case, one might expect to see some sort of bump in our data, corresponding to the bound π^+pp mass, when looking at a plot of the invariant mass of two of the three protons we have detected. In fact, we see no enhancements in the data, which are well described by the phase space calculations.

A final question of considerable interest is the total cross section for three proton emission. We could have tried to estimate this by fitting the peaks in our measured angular distributions, making some assumptions about out-of-plane extrapolations, and then integrating them. This was not practical because in fact the peak shape varies, and there are not always enough measured points for such fits to be meaningful, especially in the case of the QDFSI peaks. What we have done instead is make use of the excellent agreement between the data and the quasifree three-body phase space calculations and used them as a means of interpolating and extrapolating. The total

TABLE III. Estimate of the total cross sections for three proton emission, and their relation to the total pion absorption cross section.

	T_π	130	180	228
	σ_{abs} (mb)	170	180	121
σ (mb)	three-body	7.9	19.9	22.5
	QDFSI	1.6	1.4	0.4
σ/σ_{abs}	three-body	0.046	0.111	0.186
	QDFSI	0.009	0.008	0.003

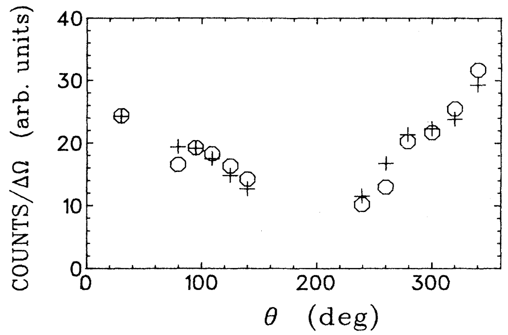

FIG. 10. The circles represent the total number of events detected in each of our twelve counters, integrated over all triple coincidences and proton energies, at $T_\pi=228$ MeV. The crosses represent the results of the quasi-free three-body phase space calculations.

cross section is given by

$$\sigma_{\text{tot}}=\frac{\text{yield}}{N_{\text{inc}}N_{tgt}}\frac{1}{F}\ ,$$

where yield is the total number of events we have detected, and F is the fraction of phase space events generated which actually hit our counters. In practice, we calculated F in three stages. First, determining the fraction of phase space events in which the three emitted protons were within $\pm10°$ of the horizontal scattering plane, and then determining what fraction of protons emitted within $\pm10°$ of the horizontal scattering plane hit our counters. Finally, we determined what fraction of events hitting our counters had all three protons with kinetic energies greater than 50 MeV. This was done separately for the QDFSI calculations, and the standard quasifree three-body phase space. The results are presented in Table III.

The circles in Fig. 10 represent the total number of events detected in each of our twelve counters, integrated over all triple coincidences and proton energies (i.e. $\sim d\sigma/d\Omega_p$ measured with our limited acceptance), at $T_\pi=228$ MeV, plotted as a function of detector angle. The crosses represent the results of the quasifree three-body phase space calculations. These take our limited acceptance and energy thresholds into account, and provide a reasonable description of the data. In our earlier $^{12}C(\pi,3p)$ experiment,[15] only those events in which one of the three detected protons hit a counter positioned at 30° were recorded. In order to obtain an estimate of the total three-nucleon absorption cross section from the earlier data, we had assumed that $d\sigma/d\Omega_p$ was isotropic, so that $\int(d\sigma/d\Omega_p)d\Omega_p=4\pi(d\sigma(30°)/d\Omega_p)$. It is evident from Fig. 10 that this assumption was incorrect, and led to too large an estimate. That is the reason the present estimate for the total three-nucleon absorption cross section at $T_\pi=228$ MeV of 22.5 mb is lower than the earlier one of 47 mb.

Using the data of Ashery *et al.*[36] for the total pion absorption cross sections, σ_{abs}, in Table III we also give the fraction of the total represented by our data. These are plotted as a function of incident pion energy in Fig. 11. We include the estimates of Brückner *et al.*[34] (25% at $T_\pi=289$ MeV), and Ransome[19] (3.4% at $T_\pi=110$ MeV), which agree well with ours. We disagree strongly with Bellotti *et al.*,[20] who estimated 29% at 130 MeV. Also in Fig. 11, we show the results of a theoretical calculation from Oset *et al.*,[21] and three calculated points from Masutani and Yazaki.[13] The two calculations appear to agree with each other, but are at least a factor of 2 higher than the data. One should keep in mind, however, that the calculation of Oset *et al.* appears to be for genuine three-body absorption, without regard to particle type. That is, they include absorption on *nnp* triplets, as well as on *ppn*, and we have measured only the latter. Experiments on ^{3}He (Refs. 6–8) indicate that the cross sections for the three-body absorption absorption processes $\pi^+(ppn)\rightarrow ppp$ and $\pi^-(ppn)\rightarrow nnp$ are comparable. It may thus not be unreasonable to assume that the cross sections for the three-body absorption process $\pi^+ppn\rightarrow ppp$ and $\pi^+nnp\rightarrow npp$ are comparable in carbon.

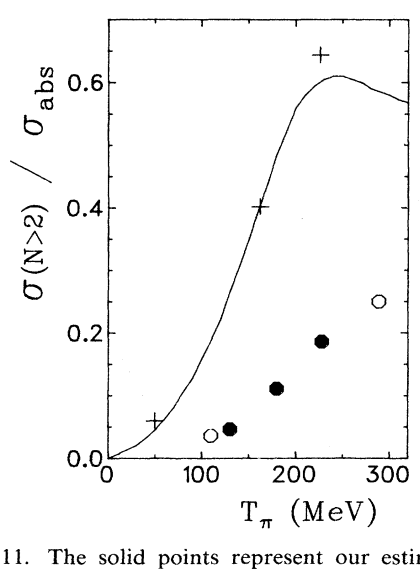

FIG. 11. The solid points represent our estimates for the fraction of the total absorption cross section due to three-nucleon absorption leading to three protons in the final state. The open points at 110 and 289 MeV represent the data of Refs. 19 and 34, respectively. The curve is the result of the theoretical calculation of Oset *et al.* (Ref. 21), while the crosses represent the calculation of Masutani and Yazaki (Ref. 31). Note that the calculations do not specify the isospin of the absorption nucleons and thus include processes leading to neutrons as well as protons in the final state.

V. SUMMARY AND CONCLUSIONS

We have performed an experiment in which we have detected three protons in coincidence, following the absorption of positive pions in carbon. Data were collected with twelve plastic scintillator detectors, covering a fairly large region of the available phase space, at three incident pion energies: $T_\pi=130$, 180, and 228 MeV. Comparisons were made with phase space calculations which simulated quasifree three- and four-nucleon absorption mechanisms. The three-nucleon phase space calculation provided an excellent description of most of our measured angular distributions, at all three incident pion energies, while the four-nucleon phase space results gave results which were too broad. The same was true for a comparison with the measured distribution of the sum of components of the three detected proton momenta in the direction of the incident beam. On the basis of these facts we conclude that the absorption mechanism giving rise to the great majority of our events involves only three nucleons, and not four or more. One must keep in mind that our relatively high energy threshold of 50 MeV for each detected proton may tend to bias the measurement against events with more particles in the final state, especially at $T_\pi = 130$ MeV. However, the fact that there is no change in the measured peak shapes between $T_\pi = 130$ MeV and $T_\pi = 228$ MeV, and the fact that the best description of the measured angular distributions is provided by the three-body phase space distributions alone, and not by a sum of three- and four-body distributions, even at $T_\pi = 228$ MeV, leads us to conclude that any possible four-nucleon absorption mechanism must be significantly less important than one involving three nucleons.

A small fraction of our events, which were not well described by the quasifree three-body phase space, were successfully described with a model simulating quasifree two-nucleon absorption, followed by a final-state interaction of one of the outgoing protons. Although these data may be of some interest as a possible calibration for judging how well various INC calculations handle proton final-state interactions, their contribution to the total pion absorption cross section is quite small.

Unlike our angular and momentum distributions, our measured energy distributions at $T_\pi = 228$ and 180 MeV were not well described by the quasifree three-body phase space calculations until the possibility of leaving the residual nucleus in an excited state was taken into account. Models in which the residual nucleus was left with an average of 50 and 30 MeV excitation energy at $T_\pi = 228$ and 180 MeV, respectively, did provide a good description of the data. There is some indication of a bump in the inclusive energy distributions of the two counters which were at the most forward angles. This may be due to a process involving a pion quasielastic scattering prior to two-nucleon absorption. But, judging by the size of the bump, the contribution of such a process to the total absorption cross section must be quite small.

We have made use of the excellent agreement between the data and the results of the quasifree three-body phase space calculations to make an estimate for the fraction of the total absorption which is represented by the three-nucleon absorption process. This is 4.6% at $T_\pi = 130$ MeV, 11.1% at $T_\pi = 180$ MeV, and 18.6% at $T_\pi = 228$ MeV. We do not know the relative probabilities for π^+ absorption on a *ppn* triplet, compared to absorption on *pnn* or *nnn*, since we have only measured the first of these. It would seem that investigating the other possibilities is the next obvious thing to do. We have shown that a lot of information can be obtained with a relatively simple counter setup, so that perhaps there is no need to wait for the completion of the large 4π detectors which are currently being built. In any case, if we assume that the absorption cross sections for the various possible triplets are roughly comparable, then our estimates for the total three-nucleon absorption cross section would be in fairly good agreement with the calculation of Oset *et al.*[21] Whether or not his agreement is merely fortuitous must depend on a comparison of the theory with various differential distributions, and not just the total cross sections. The fact that our data appear to fill the total available three-body phase uniformly should make such a comparison much easier, since a comparison of the theory with the three-body phase space will be almost equivalent to a comparison with the data themselves.

Although the fact that our data is well described by the three-body phase space allows us to conclude that the dominant process giving rise to our observed events involves three nucleons, and not four or more, it does not unfortunately provide us with any information on the detailed nature of the three-nucleon absorption mechanism. There would appear to be two possibilities. Either there is one particular mechanism, which happens to have a constant matrix element, or there are many competing mechanisms, each with its own dependence on angles, etc., which on average conspire to produce a constant matrix element. The observation of genuine three-body absorption events has also been reported from experiments on ^{3}He.[6-8] These events also seem to fill the total available phase space uniformly, so it may not be unreasonable to assume that the same process is responsible for both. If so, then it might seem more likely to assume that a single mechanism with a constant matrix element is at play, since it is hard to envisage the possibility of many competing mechanisms in a nucleus as simple as ^{3}He.

This brings us to the final problem of decomposing the total absorption cross section according to the various mechanisms involved. Even if we assume that the cross section for absorption on *ppn*, *pnn*, and *nnn* triplets are all comparable, this means that at $T_\pi = 180$ MeV, for example, the contribution of three-body absorption to the total is only $3 \times 11\% = 33\%$. Our data indicate that the contribution of four-body absorption is small. Altman *et al.*[4] quote an upper limit of 25% for the contribution of quasideuteron absorption, based on their two-Gaussian decomposition, and integration of the narrow Gaussian. This leaves some 42% unaccounted for. There have been absorption processes observed which produce deuterons in the final state. It is not clear, however, whether the deuterons are actual participants in the absorption process, or merely a result of final-state interactions of the nucleons which do participate. In any case, there is no evidence to suggest that mechanisms involving deuterons contribute as much as 42% to the total. One is thus forced to conclude that Altman *et al.* underestimate the contribution of two-nucleon absorption. We are not in a position to say whether the problem lies in the data themselves, or in the method of analysis.

Gibbs and Kaufmann[37] claim that in fact they can account for approximately 70% of the total absorption cross section in ^{12}C with only the two-nucleon absorption mechanism. This would agree well with our present conclusions. Their statement is based on the results of an INC calculation, in which special attention was paid to providing a good description of effects such as those arising from Fermi motion, nucleon binding, pion scattering before absorption, and nucleon scattering after absorption. Although their treatment of nucleon final-state interactions has been criticized, Gibbs and Kaufmann are able to reproduce the experimentally observed angular distribution. Furthermore, Girija and Koltun[38] claim that the rapidity data of McKeown *et al.*[3] is also consistent with a two-nucleon absorption mechanism, when effects of multiple scattering before absorption are taken properly into account. It might be interesting to repeat the experiment of Altman *et al.* on carbon, with good energy resolution, and analyze it in the light of the present discussion. In fact, this has been done recently at TRIUMF,[39] and preliminary indications[40] are that the final conclusions will not be dissimilar to those presented here.

Our conclusions are also consistent with recent results from SIN on pion absorption on ^{4}He.[41] The authors of Ref. 41 estimate that at $T_\pi = 121$ MeV, four-body absorption mechanisms are an order of magnitude less important than those involving three nucleons, and that the latter account for less than 8% of the total absorption cross section.[25] It has been reported[6] that at $T_\pi = 120$ MeV three-body absorption accounts for some 25% of the total absorption cross section on ^{3}He. In absolute terms, however, the reported three-body cross section on ^{3}He is ~ 4 mb, which is smaller than the ~ 8 mb we estimate for carbon at 130 MeV. Thus, the two values are not incompatible, especially in view of the fact that there may be some selectivity of the reaction requiring the nucleons in the absorption *ppn* triplet in carbon to be in some particular angular momentum state.

It is probably safe to say that although there are still several open questions, we are making progress in our understanding of pion absorption in nuclei.

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