Measurement of three protons in coincidence following absorption of 228 MeV π^+ in carbon

R. Tacik, E. T. Boschitz, W. Gyles, W. List, and C. R. Ottermann
Kernforschungszentrum Karlsruhe, Institut für Kernphysik and Institut für Experimentelle Kernphysik der Universität Karlsruhe, D-7500 Karlsruhe, Federal Republic of Germany
(Received 19 April 1985)

We have measured energies and angular distributions of three protons detected in coincidence following absorption of 228 MeV π^+ in carbon. The counters used were arranged in a geometry that should have enabled observation of the two-step process of proton knockout followed by quasi-deuteron absorption of the recoil pion. The absence of high energy protons emitted in the backward direction provides strong evidence that such a two-step process does not contribute appreciably to the total absorption cross section, and suggests that in fact the pion may scatter several times before finally being absorbed on a quasi-deuteron.

I. INTRODUCTION

True absorption is one feature of pion-nucleus interactions which is not present with more conventional probes. Thus, the absorption process has been studied since the advent of pion beams in the 1960's. Several excellent reviews of this early work are available, for example in Refs. 1—4. There has been continued interest in the field following the opening of the meson factories in the 1970's. Despite the wealth of existing experimental data, however, a quantitative description of true pion absorption is not yet available. The reason for this must be attributed to the complexity of the absorption process, which can be considered in four stages:[5,6] (1) initial state interaction of the incoming pion; (2) absorption proper of the pion, accompanied by the emission of primary nucleons; (3) final state interactions of the primary nucleons, leading to emission of secondary nucleons; (4) evaporation of additional nucleons from the residual nucleus. (According to Ref. 5, the nucleons emitted during the evaporation stage have energies $\lesssim 20$ MeV, which is below our threshold in the present experiment.) A question which has aroused some debate recently is whether the main mechanism for the absorption proper is that of absorption on a p-n pair with the quantum numbers of a deuteron present in the nucleus, termed a quasi-deuteron, or whether more exotic processes such as absorption on heavier clusters or double-delta formation[7] play an important role.

In an experiment with stopped pions in carbon, Heusi *et al.*[8] find that the yield of primary nucleon pairs following absorption is 0.19 per π stop. Following the calculation of Chiang and Hüfner,[5] they estimate that there is only a 33% probability that both nucleons leave the nucleus without undergoing final state interactions. Thus, their lower limit for the contributions of the quasi-deuteron process to pion absorption is 0.58. This is in marked contrast to experiments with pions in flight. From a measurement of primary nucleons, Altman *et al.*[9] report that for 165 and 245 MeV π^+ absorbed in carbon, the fraction of the total absorption cross section due to the quasi-deuteron process is 0.09 and 0.11, respectively. They estimate that not more than 50% of the primary nucleons are lost due to final state interactions, and thus quote upper limits of 0.18 and 0.22 as the quasi-deuteron contribution to the total absorption cross section at the two energies.

The result of Ref. 9 appears to be in accord with the conclusions of McKeown *et al.*[10] From a complicated analysis of the momenta of protons emitted in a C(π,π'p) experiment, they find that an average of three nucleons participate in the absorption process. Girija and Koltun,[11] however, state that this result is based on neglecting initial state interactions, and can reproduce the data of Ref. 10 with only the quasi-deuteron mechanism for the absorption proper.

In a theoretical study of the two-nucleon mechanism of pion absorption, Ohta *et al.*[12] overestimate the cross sections of Ref. 9 by a factor of 4. They point out, however, that their method of calculation only accounts for direct absorption out of the elastic channel. Thus, their calculation does not include the effect of initial state interactions, which are certainly more important for the absorption of pions in flight than for stopped ones. Combining their analysis with the work of Masutani and Yazaki,[13] Ohta *et al.* suggest that a large fraction of the total absorption cross section could be from a two step inelastic process, that is, a (π,π'N) nucleon knockout followed by pion absorption.

Although Ohta *et al.* do not give a numerical estimate, Masutani and Yazaki calculate that at 226 MeV incident pion energy, the cross section for the two step process is equal to that for pure quasi-deuteron absorption; each accounting for 36% of the total absorption cross section. We feel that this suggestion deserves serious consideration, since it appears to be the only conventional mechanism for the involvement of more than two nucleons in the absorption process being proposed at this time.

The purpose of the present experiment is thus twofold. Since the advent of the meson factories, all experiments on pion absorption in flight have involved detecting either a single nucleon or a pair of nucleons in coincidence. In view of the debate on the number of nucleons involved in the process, and the disagreement between different calculations of the importance of final state interactions, we

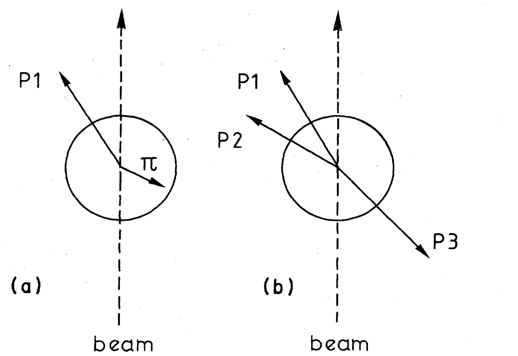

FIG. 1. Schematic illustration of the two step absorption process.

have measured the energies and angular distributions of three protons following absorption of 228 MeV π^+ on carbon. Furthermore, we have arranged our proton detectors in a geometry which would enable us to observe the two step process suggested in Ref. 12, should it occur. This process is illustrated schematically in Fig. 1: A positive pion impinges on a carbon nucleus, knocking out a proton (P1) in the forward direction. The recoiling pion is then absorbed on a quasi-deuteron, resulting in the emission of two more protons (P2 and P3). One might then expect that (a) the angular distribution of P3 (P2) for fixed P2 (P3) would peak at the angle corresponding to $\pi d \rightarrow pp$ kinematics for absorption of the recoil pion; (b) the shape of the integrated angular distributions of P2 and P3 would be similar to that measured for the $\pi d \rightarrow pp$ cross section, that is, peaked in the direction of the recoil pion; and (c) the energies of the three protons would be those given by the kinematics for the two step process. As we will point out in more detail in Sec. III, this implies a high energy (> 150 MeV) for P3.

II. EXPERIMENT

The experimental arrangement, as set up in the πM3 beam channel at SIN, is illustrated in Fig. 2. It consisted of 12 plastic scintillator telescopes. The relevant detector angles, distances, and dimensions are given in Table I. Both pulse height and time of flight information were recorded for each counter, the latter being used to determine the proton energies. The coincidence BEAM·P1·P2i·P3j, where Pk=Pka·Pkb, was taken as the event trigger. The BEAM definition was S1·S2·rf·$\overline{S2}$, where rf represents a pickup of the SIN cyclotron frequency, and $\overline{S2}$ is the S2 scintillator signal triggered at a high level, used to reject protons coming down the πM3 beam line. The beam rate, as defined above, was $\simeq$1.7 MHz, while the S2 singles rate was $\simeq$9.0 MHz.

Raw time to digital converter (TDC) spectra for counters P21 and P23 are shown in Fig. 3. The peaks labeled π in the two spectra are due to background events in which one pion was absorbed and produced two protons,

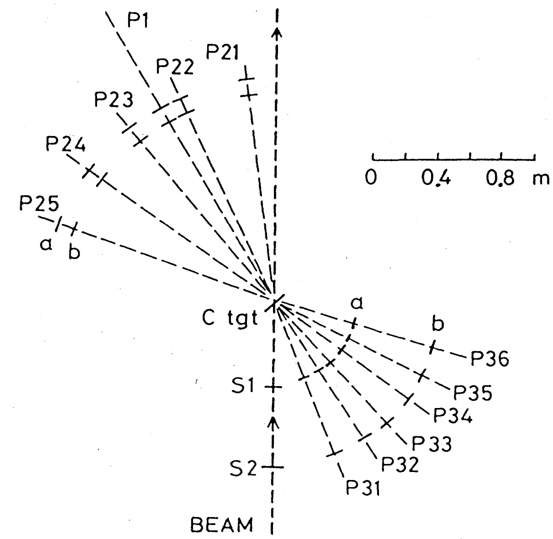

FIG. 2. Setup of the experimental apparatus.

and then a second pion, from the same or a subsequent beam burst, scattered elastically into the P1 or one of the P2 counters, thus creating a threefold coincidence. This identification is supported by the fact that the two peaks in each spectrum are separated by 20 ns, which is the

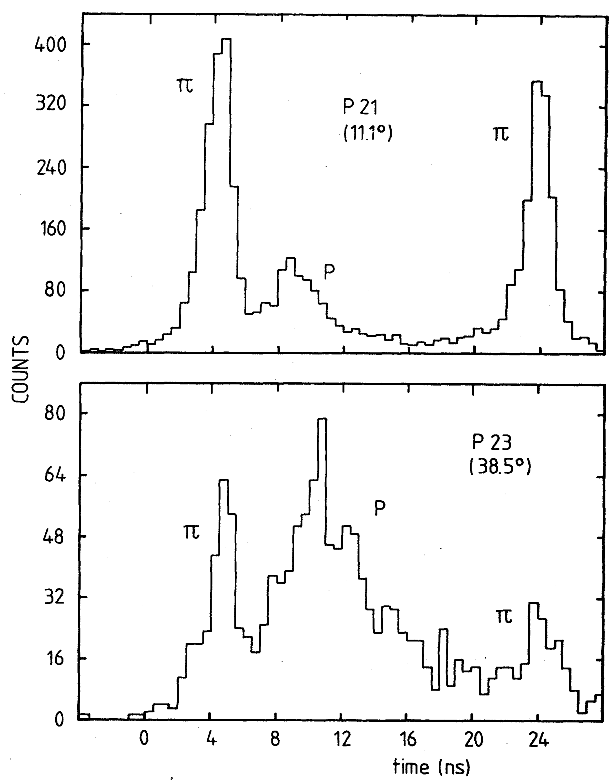

FIG. 3. Uncorrected TDC spectra for counters P21 and P23.

TABLE I. Angles, dimensions, and distances from the scattering target of the counters used in the present experiment.

Counter	θ (deg)
P1	30.0
P21	11.1
P22	24.3
P23	38.5
P24	53.5
P25	69.1
P31	202.5
P32	212.5
P33	222.5
P34	232.5
P35	242.5
P36	252.5

Counter		Distance from target (cm)	Dimensions (mm) horizontal	vertical	thickness
P1	a	130	100	400	5
	b	134	100	420	5
P2	a	130	100	400	5
	b	134	100	420	5
P3	a	50	60	160	3
	b	100	100	300	5

period of the SIN cyclotron rf; by the fact that the peaks decrease in intensity with angle; and by an examination of the energy loss of the particles producing the peaks in the P1 or P2 counters. A scatter plot of this energy loss versus time of flight is shown for the P21 counter in Fig. 4. It illustrates how a relatively clean separation between the peaks can be made. It should be pointed out that since most particles do not stop in our scintillation counters, we cannot unambiguously differentiate between protons and deuterons with similar velocities. However, the energy spectrum of deuterons emitted after absorption of 137 MeV pions in carbon has been measured by Kosmach *et al.*,[14] who found the distribution to be peaked

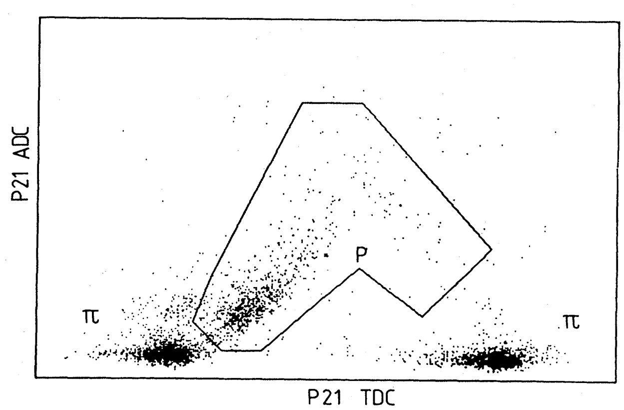

FIG. 4. Scatter plot of energy loss versus time of flight for the P21 counter.

at low (<20 MeV) energies. In the present experiment, good events consisted of only those particles which had a time of flight of less then 18.5 ns/m. This means that only deuterons with energies >31 MeV could have been accepted, and we do not expect these to be plentiful.

A raw TDC spectrum for the counter P35 is given in Fig. 5(a). Two peaks can be seen. The first corresponds in energy to protons from the $(\pi,\mathrm{pp})+(\pi,\pi)$ background reactions mentioned in the preceding paragraph. This peak disappears after one imposes the condition that only protons be in coincidence in the P1 and P2 counters, as can be seen in Fig. 5(b). For each combination of P1, P2i, and P3j counters, the TDC spectra can be integrated; and differential cross sections calculated from the standard formula

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 d\Omega_3}=\frac{N_{\mathrm{counts}}}{N_{\mathrm{incident}}N_{\mathrm{tgt}}\Delta\Omega_1\Delta\Omega_2\Delta\Omega_3}\ .$$

Our results are plotted as a function of P3 (P2) angle, for fixed P2 (P3) in Fig. 6 (7). The error bars shown reflect purely the statistical uncertainties. The solid curves are Gaussian fits to the data. The arrows indicate the positions in which one would expect the angular distributions to peak if they came from the two step process of nucleon knockout followed by pion absorption. The long- and short-dashed curves represent the results of phase space calculations to be discussed in the next section.

III. DISCUSSION

All Gaussians fit to the differential cross sections illustrated in Figs. 6 and 7 are $\simeq 60°$ wide, except for the dis-

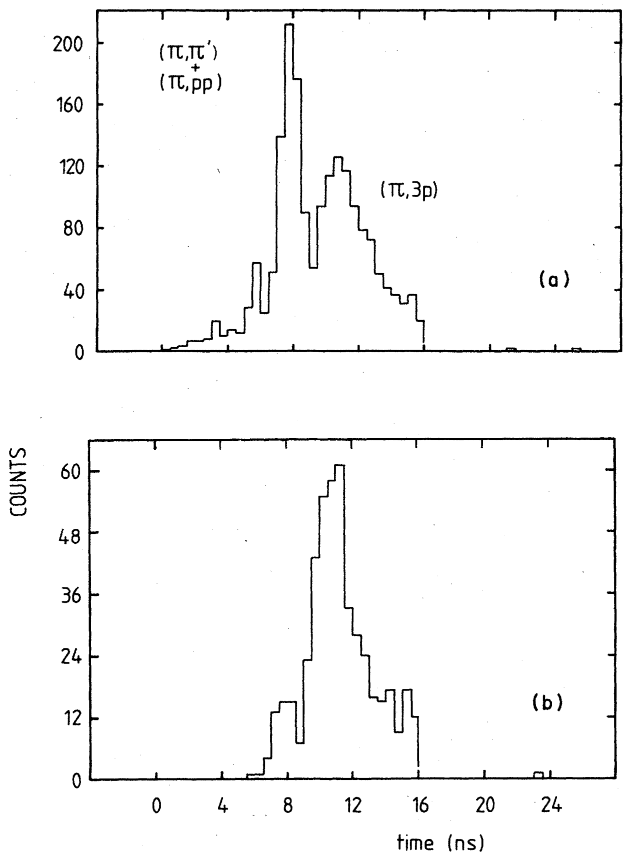

FIG. 5. TD spectra for counter P35; (a) uncorrected; (b) with the requirement that there be a coincidence with protons in the P1 and P2 counters.

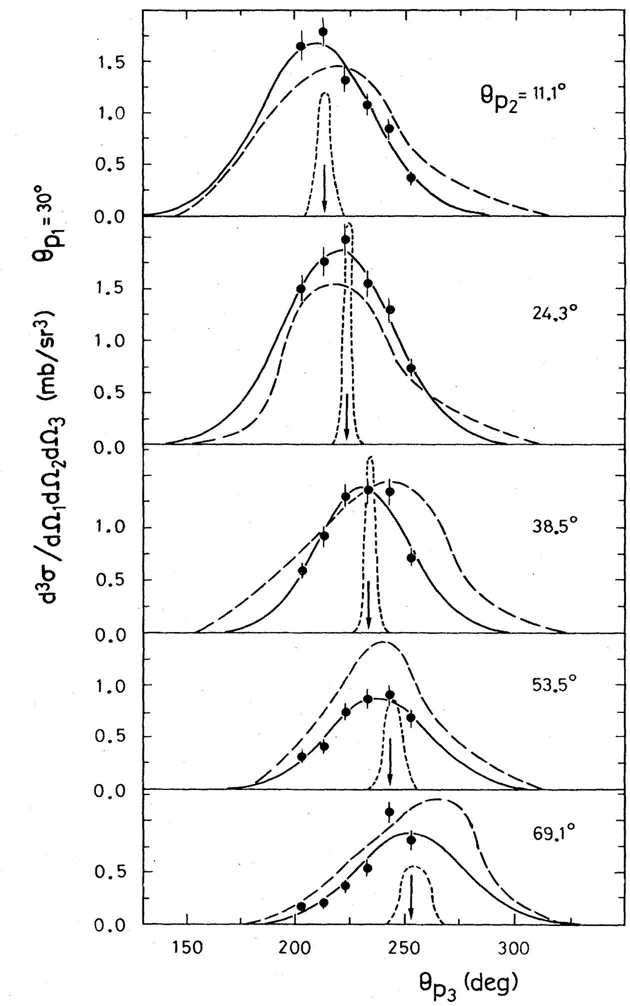

FIG. 6. Angular distribution of measured differential cross sections for fixed P1 and P2 angles. The arrows indicate the expected peak positions from the two step process. The solid curves are Gaussian fits to the data. The long-dashed and short-dashed curves represent phase space calculations assuming quasi-four-body and quasi-three-body absorption mechanisms, respectively. Note that the phase space calculations do not include the effects of Fermi motion.

tributions at fixed P35 and P36, which are best fit with Gaussians $\simeq$100° wide. It can be seen that the measured differential cross sections do indeed peak at the positions one would expect if they came from the two step process of nucleon knockout followed by pion absorption. The exceptions are the distributions for fixed P34, P35, and P36 (at 232.5, 242.5, and 252.5 deg). These are important to note, since they are the angles closest to the direction of the recoiling pion. If one expected the present integrated angular distributions to be similar in shape to those of the $\pi d \rightarrow pp$ reaction and to be peaked in the direction of the absorbed pion, these three distributions would be where one would expect the signal for the two step process to be strongest, that is, the peaking to be sharpest. It may be argued that the angular distributions should be broadened due to the Fermi momentum of the nucleons involved in the absorption, but it would seem peculiar that this smearing effect was most significant just at those angles where one would expect to see the clearest peaks.

It should be noted that in all references to the two step process thus far, we have spoken of the knockout proton hitting the counter P1, and the two protons from quasideuteron absorption hitting the counters P2 and P3. In fact, the roles of counters P1 and P2 could be interchanged. Perhaps surprisingly, the kinematics for these two processes are such that the angles one would expect the differential cross sections to peak at remain unchanged. The angle of the recoiling pion does change though, and it may be argued that this somehow causes the smearing of the P34, P35, and P36 distributions, and that the lack of strong peaking there may not be good evidence against the two step process.

In order to see whether the measured angular distributions could also be consistent with other absorption processes, we have used the CERN Library program GENBOD (Ref. 15) to generate phase space distributions assuming several different models for the absorption mechanism.

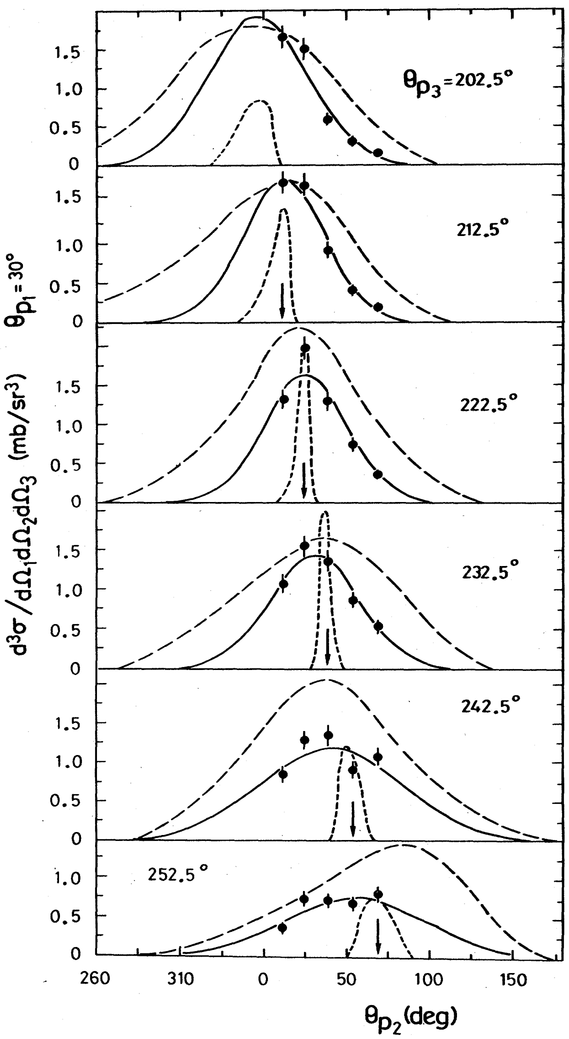

FIG. 7. Same as Fig. 6 for fixed P1 and P3.

One possibility investigated was that of "quasi-three-body" absorption, i.e., with kinematics similar to those for the free $\pi^+\ {}^3\mathrm{He}\rightarrow ppp$ reaction. The results are shown as the short-dashed curves in Figs. 6 and 7. We see that the distributions are quite narrow, and peak at the same angles as those expected from the two step process. Another possibility was that of "quasi-four-body" absorption, i.e., with kinematics similar to those for the free $\pi^+\ {}^4\mathrm{He}\rightarrow pppn$ reaction. These are shown as the long-dashed curves in Figs. 6 and 7. One notes that these distributions also peak at about the same angles as those expected from the two step process. They are considerably broader than the quasi-three-body distributions; for the case of the fixed P3 counters (Fig. 7) even broader than the experimentally measured distributions.

We must emphasize that in the phase space calculations, we have taken into account the finite sizes of our detectors, the energy losses of the outgoing protons in the carbon target, and the experimental energy thresholds. We have not, however, taken into account the effect of Fermi motion of the absorbing ^{3}He and ^{4}He clusters, whose effect should be to broaden the angular distributions plotted in Figs. 6 and 7, without affecting the peak positions. We note that a phase space calculation assuming the pion's energy to be shared among more than four nucleons in the carbon nucleus, in a process such as $\pi^+\ {}^{12}\mathrm{C}\rightarrow pppn\alpha\alpha$, for example, results in a flat angular distribution. From this, and the fact that in some cases the quasi-four-body distributions are already too broad, one would tend to conclude that the relatively narrow widths of the measured angular distributions indicate that the absorption must occur on fewer than four nucleons.

Now let us turn our attention to the energies of the detected protons. Note that a complete presentation of our data would consist of at least ninety energy spectra (i.e., three counters at a time, under $5\times6=30$ different coincidence conditions). It does not seem feasible to include all of this information here. We present instead, in Figs. 8 and 9, the distributions of the energies measured in the individual P2 and P3 counters, irrespective of which P3 or P2 counter they were in coincidence with. One can see that the general trend is for the mean energy detected in one of the P2 counters to decrease with increasing angle, while the mean energy detected in the P3 counters is

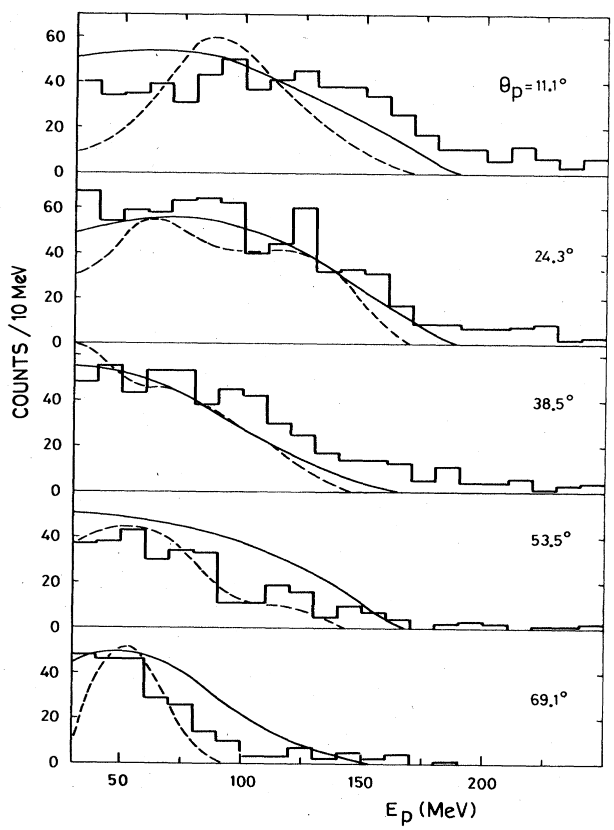

FIG. 8. Distribution of proton kinetic energies measured with the P2 counters. The solid and dashed curves represent phase space calculations assuming quasi-four-body and quasi-three-body absorption mechanisms, respectively.

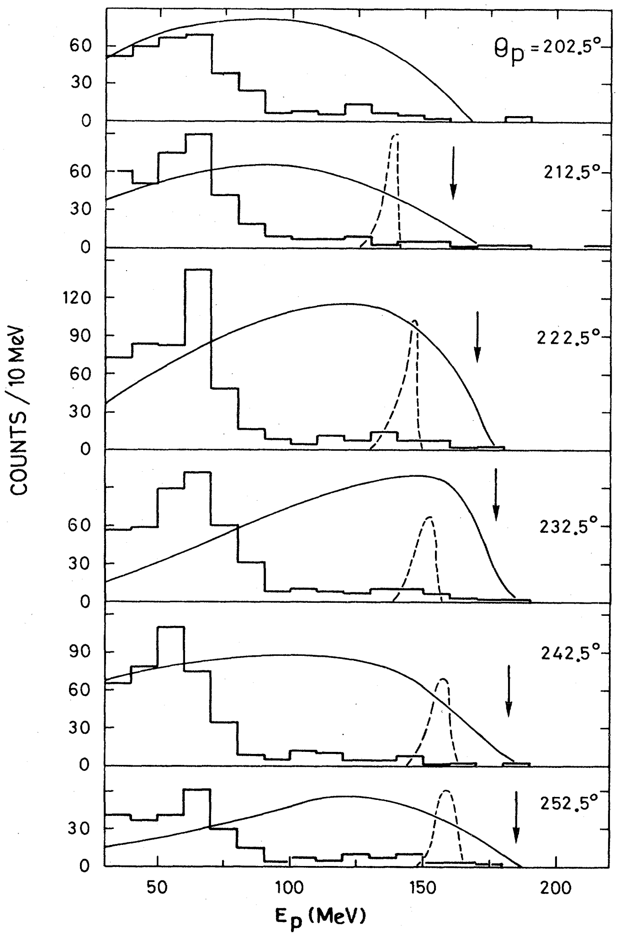

FIG. 9. Same as Fig. 8 for P3 counters. The arrows indicate the proton energies expected from the two step process.

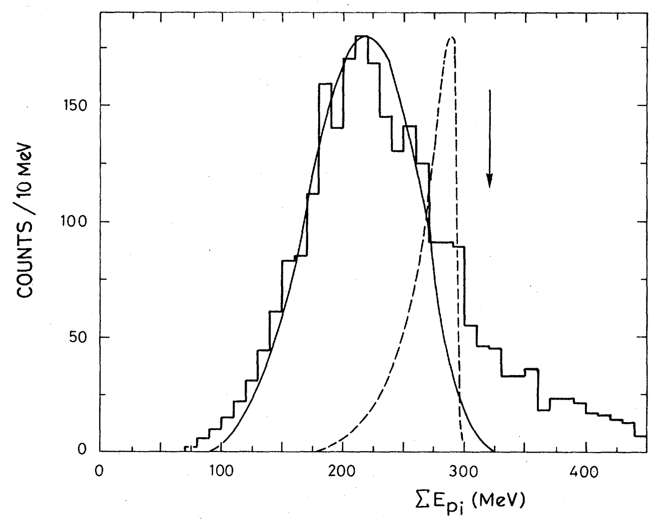

FIG. 10. Distribution of the sum of the three detected proton kinetic energies. The arrow indicates the location of the peak expected from the quasi-three-body reaction; the dashed curve represents a phase space calculation assuming the quasi-four-body absorption mechanism; the solid curve assuming the reaction $\pi^+ {}^{12}C \rightarrow pppn\alpha\alpha$.

roughly constant with angle. In Fig. 9, the arrows indicate the energies that protons arising from the two step process should have. The dashed curves represent the proton energies from quasi-three-body absorption, while the solid curves show the distributions that would arise from quasi-four-body absorption. In Fig. 8, the dashed and solid curves have the same meanings, and we can see that both provide an adequate description of the data. In Fig. 9, however, for the backward P3 counters, one notes immediately that the distributions of the measured proton energies are limited to much smaller energies than those predicted by any of the two step, quasi-three-body, or quasi-four-body mechanisms.

In fact, the measured energy distributions resemble most closely those from quasi-deuteron absorption of a forward going low energy ($\lesssim$40 MeV) pion. Thus, the following mechanism suggests itself: namely, that the incoming pion scatters several ($\geq$2) times, losing its kinetic energy to several nucleons, one of which we observe, before finally being absorbed on a quasi-deuteron, and producing the additional two observed protons.

In Fig. 10 we show the distribution of the sum of the three detected proton kinetic energies. The arrow indicates the total energy one would expect the three protons to have if they came from a quasi-three-body absorption. The dashed curve is the result of assuming quasi-four-body absorption. The solid curve represents the spectrum of the sum of the three proton kinetic energies from the $\pi^+ {}^{12}C \rightarrow pppn\alpha\alpha$ reaction. We see that this curve best describes the measured distribution. This is consistent with the mechanism proposed in the preceding paragraph. That is, that the pion's kinetic energy is shared among several nucleons, only one of which we observe; and that the absorption proper occurs on a quasi-deuteron, leading to the measured narrow angular distributions.

It is not immediately clear why such a mechanism should be favored over the simpler two step process we originally described. Masutani and Yazaki calculate that at 226 MeV, a three step process should be lower than pure quasi-deuteron absorption, or a two step process, by a factor of $\frac{17}{42}$. They also calculate, however, that at low incident pion energies absorption should be almost purely due to the quasi-deuteron mechanism. Actually, there is evidence from an experiment at TRIUMF,[16] involving the ${}^3He(\pi^{\pm},NN)N$ reactions at 65 and 85 MeV, that indicates that even at these low energies, and with such a light target, pure quasi-deuteron absorption accounts for only about half of the total events.

Perhaps the best way to evaluate whether the present results require a reevaluation of our present understanding, or are merely a reflection of the complexity of the absorption process, would be to compare our results with a full cascade calculation. Such a calculation is presently being performed,[17] and preliminary indications are that it does indeed describe the essential features of our data. We note that an additional test might be to study the reaction $(\pi,\pi pp)$, which, to the best of our knowledge, has not been thoroughly investigated to date. There is some evidence for this reaction in the present data. Unfortunately, we are not able to extract reliable cross sections.

We note that none of the energy spectra in Fig. 9 contain a peak corresponding to protons from the direct quasi-deuteron absorption of a 228 MeV pion. This seems to be an indication that the process of quasi-deuteron absorption followed by some sort of final state interaction of the forward going proton does not contribute significantly to the cross section for three proton emission.

In order to make an estimate of the total cross section for the process of three proton emission following pion absorption, we can integrate the Gaussian functions used to fit the differential cross sections presented in Figs. 6 and 7. Assuming that the distributions in the vertical plane are of the same shape as those measured in the horizontal plane, we find that the average value of

$$\int (d^3\sigma/d\Omega_1 d\Omega_2 d\Omega_3)d\Omega_3$$

is 1.8 ± 0.2 mb/sr^2, for fixed P1, irrespective of the angle of P2. Furthermore, the average value of

$$\int (d^3\sigma/d\Omega_1 d\Omega_2 d\Omega_3)d\Omega_2$$

is also 1.8 ± 0.2 mb/sr^2, for fixed P1, irrespective of the angle of P3. In other words, given that we have detected one proton at 30°, and a second proton at some other angle, the integral of the distribution of the third proton is 1.8 ± 0.2 mb/sr^2, irrespective of the angle the second proton was detected at. Since there are no constraints due to energy-momentum conservation on this second proton,

$$\int (d^3\sigma/d\Omega_1 d\Omega_2 d\Omega_3)d\Omega_2 d\Omega_3 = 4\pi(1.8\pm0.2) \text{ mb/sr} .$$

If we now assume that the distribution is also isotropic with respect to the first proton, one obtains

$$\sigma_{\text{tot}} \simeq 4\pi\times4\pi\times(1.8\pm0.2)/6 = 47\pm5 \text{ mb} .$$

The factor of 6 is due to the indistinguishability of the three outgoing protons. From an interpolation of the data of Ref. 18, we have that σ_{abs} for 228 MeV π^+'s is $\simeq 121$ mb. Thus, three proton emission accounts for $\simeq 39\pm5$ % of the total absorption cross section.

Alternatively, we can make an estimate for the total cross section by making use of the Monte Carlo phase space program in the following way: First, we assume that the absorption mechanism is the quasi-four-body one discussed above. Although this assumption is not consistent with the observed proton energy distributions, it does provide a reasonably good description of the measured angular distributions. We then use the Monte Carlo simulation to estimate the fraction of the total cross section which would produce an event within our experimental acceptance. This procedure results in a value of 60 ± 6 mb, where the error reflects the statistical uncertainties of both the Monte Carlo calculation and the experimental data.

This value is in good agreement with the one obtained by integrating the fitted Gaussians. Both of these are in agreement with that estimated from the results of a bubble chamber experiment by Bellotti *et al.*[19] They interpreted their observed three proton events as being due to pion absorption on an alpha cluster present in the carbon nucleus. They did not, however, examine the distribution of the protons' energies as a function of angle, which in the present case is in disagreement with the quasi-four-body mechanism.

It is evident that there are considerable insights to be gained regarding pion-nucleus interactions by studying three particle coincidences. It would be interesting to pursue these investigations at different energies and on different targets.

ACKNOWLEDGMENTS

We wish to thank Dr. G. R. Smith and Dr. R. R. Johnson for their help in preliminary stages of this experiment; Dr. K. Junker for discussions regarding analytic phase space calculations, and the staff of SIN for their support. This work was supported in part by the Bundesminsterium für Forschung und Technologie of the Federal Republic of Germany.

[1]D. S. Koltun, Adv. Nucl. Phys. **3**, 71 (1969).
[2]T. I. Kopaleishvili, Part. Nucl. **2**, 87 (1973).
[3]J. Hüfner, Phys. Rep. **21C**, 1 (1975).
[4]V. S. Buttsev, Fiz. Elem. Chastits At. Yadra **11**, 900 (1980) [Sov. J. Part. Nucl. **11**, 358 (1980)].
[5]H. C. Chiang and J. Hüfner, Nucl. Phys. **A352**, 442 (1981).
[6]Q. Ingram, Nucl. Phys. **A374**, 319c (1982).
[7]G. E. Brown, H. Toki, W. Weise, and A. Wirzba, Phys. Lett. **B118**, 39 (1982); B. Schwesinger, A. Wirzba, and G. E. Brown, *ibid.* **B132**, 269 (1983).
[8]P. Heusi, H. P. Isaak, H. S. Pruys, R. Engfer, E. A. Hermes, T. Kozlowski, U. Sennhauser, and H. K. Walter, Nucl. Phys. **A407**, 429 (1983).
[9]A. Altman, E. Piasetzky, J. Lichtenstadt, A. I. Yavin, D. Ashery, R. J. Powers, W. Bertl, L. Felawka, H. K. Walter, R. G. Winter, and J. v. d. Pluym, Phys. Rev. Lett. **50**, 1187 (1983).
[10]R. D. Mckeown, S. J. Sanders, J. P. Schiffer, H. E. Jackson, M. Paul, J. R. Specht, E. J. Stephenson, R. P. Redwine, and R. E. Segel, Phys. Rev. Lett. **44**, 1033 (1980).
[11]V. Girija and D. S. Koltun, Phys. Rev. Lett. **52**, 1397 (1984).
[12]K. Ohta, M. Thies, and T.-S. H. Lee, Ann. Phys. (N.Y) (to be published).
[13]K. Masutani and K. Yazaki, Nucl. Phys. **A407**, 309 (1983).
[14]V. F. Kosmach, A. A. Kotov, and V. L. Ostroumov, Yad. Fiz. **8**, 32 (1968) [Sov. J. Nucl. Phys. **8**, 18 (1969)].
[15]F. James, CERN Computer Centre Program Library, W515, 1975.
[16]K. A. Aniol, A. Altman, R. R. Johnson, H. W. Roser, R. Tacik, U. Wienands, D. Ashery, J. Alster, M. A. Moinester, D. R. Gill, and J. Vincent (unpublished).
[17]E. Piasetzky, private communication.
[18]D. Ashery, I. Navon, G. Azuelos, H. K. Walter, H. J. Pfeiffer, and F. W. Schleputz, Phys. Rev. C **23**, 2173 (1981).
[19]E. Bellotti, D. Cavalli, and C. Matteuzzi, Nuovo Cimento **18A**, 75 (1973).