PHYSICAL REVIEW C VOLUME 41, NUMBER 4 APRIL 1990

Composite particle emission following negative pion absorption on ^{12}C at $T_{\pi^-}=165$ MeV

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(Received 8 September 1989)

Double differential and total cross sections of the (π^-,pd), (π^-,dp), and (π^-,dd) reactions on ^{12}C were measured over a wide angular range at an incident pion kinetic energy of 165 MeV. The shape of the angular distributions of the differential cross sections of these reactions is in most cases similar to that of the ^{12}C$(\pi^-,pp)X$ reaction. These similarities seem to indicate a pickup mechanism in certain regions of phase space following three-nucleon absorption. Contributions from both three-nucleon absorption and two-step processes are found to be important for the above type of reactions.

In order to fully understand the pion-nucleus interactions one must first study and comprehend its various channels: elastic, inelastic, and reaction. Pion absorption in the nucleus dominates the reaction cross section at resonant energies even in fairly light nuclei and remains appreciable at energies up to the 1 GeV region. Thus it becomes very important to understand pion absorption.

This task is not easily accomplished. Pion absorption is a difficult process to study, both experimentally and theoretically, because in the absorption process the large energy deposited in the nucleus opens many reaction channels. In addition, pion absorption results are difficult to interpret due to the complexity of this process which may be divided into several subprocesses: (a) initial state interactions (ISI) of the incident pion with a nucleon; (b) proper absorption of the pion on a nucleon cluster and subsequent emission of nucleons or clusters (primaries); (c) final state interactions (FSI) between the primaries and other nucleons in the nucleus causing the emission of secondary nucleons; and perhaps even (d) evaporation of additional nucleons from the residual nucleus. These "evaporated" nucleons are beyond the detection capabilities of this experiment since they have energies ≤ 20 MeV (Ref. 1) which are below the threshold of detection.

A kinematical analysis of the results is helpful in providing some information on the absorption process. If, for example, there are no ISI or FSI, the nucleon pair which was involved in the proper absorption will share the full energy and momentum of the pion. In the presence of FSI, of one of the "primary" nucleons with a nucleon in the nucleus, some energy will be lost to the latter nucleon. ISI prior to the absorption complicates matters considerably since the pion loses an unknown amount of energy and momentum. This complication becomes more problematic at resonant energies where the pion can lose nearly a third of its total energy at the ISI stage[2] and then it equally distributes its remaining energy to the two "absorbing" nucleons thus leaving all three nucleons with similar energies. It is difficult to distinguish the signature of these three nucleons from that of a proper three-nucleon absorption (3NA) in which again all three nucleons may equally share the total pion energy.

The advantage of examining pion absorption with negative pions as a probe is the fact that the (π^-,pp) process is not dominated by the 2NA mechanism on a $T=0$ channel. This process can proceed via either 3NA on a $T=\frac{3}{2}$ channel or via a multistep process, such as 2NA in combination with ISI and/or FSI. More complicated processes such as 3NA+ISI/FSI or 4NA are also possible, but are expected to play an even smaller role because they involve a larger number of nucleons and processes with smaller cross sections. Since the $T=\frac{3}{2}$ channel is suppressed by the Pauli exclusion principle which requires the $T=\frac{3}{2}$ cluster to be in an $L\geq 1$ state with respect to the core, such investigations tend to emphasize ISI and FSI contributions fed mainly by the 2NA process.

There have been some experimental results reported in the past on composite particle emission from pion absorption using stopped pions.[3,4] The energy spectra of the detected particles from these experiments were successfully explained by a semiclassical multistep direct reaction model.[5,6] This model explained triton emission by using a multistep nucleonic cascade followed by a two-nucleon pickup near the surface. By comparing to experimental data, the authors of Ref. 5 also concluded that up to $\approx 13\%$ of the tritons produced by pion absorption on ^{12}C were primary tritons due to absorption on α clusters. In the case of the model being applied to deuteron emission,[6] the success in fitting the data shows evidence against stopped π^- absorption on clusters (other than nucleon pairs) leading to primary deuterons. The observed deuterons are claimed to be secondaries, modeled with general collisions of the nucleons inside the nucleus followed by a nucleon pickup in the surface as a last step.

These theoretical results seem to agree with those of another theoretical model in which the deuteron spectrum is again calculated in a two-step model using a 2NA vertex.[7] The model uses pickup of a nucleon in the second step and the calculation is done in the partial wave formalism of the distorted wave Born approximation. The authors of this model claim that 2NA within a two-step process is adequate to describe deuteron emission and no cluster absorption is required. The fact that the emission cross sections are consistent with a nucleon pickup mechanism has been concurred by an in-flight pion experiment at LAMPF.[8]

Our data were obtained during a pion absorption experiment at the TRIUMF M11 medium energy pion channel. The energy response of the detectors was extracted via the $\pi^+ d \rightarrow pp$ reaction for various angle settings.[9] For this purpose, pions of 165 MeV kinetic energy struck a deuterated polyethylene $(CD_2)^k$ target.

The detection apparatus, having been described in detail elsewhere,[10] will be described only briefly here. The experimental apparatus consists of two arm assemblies labeled "Arm *A*" and "Arm *B*." Each arm uses a ΔE-E counter arrangement. Two multi-wire proportional chambers on each arm provide particle location on the X and Y planes. Both arm assemblies could rotate freely around a target-holder centerpost located along the vertical axis at the beam focus. The angular width of each arm is 20° and each arm could cover an angular range from 20° to 150°. The two arms are employed in a hardware coincidence together with a hodoscope[10] which is placed directly in front of the target (^{12}C with a density of 320 mg/cm^2) as a beam flux monitor. The beam was also independently monitored by a paddle counter placed approximately 50 cm in front of the target and by a pair of scintillators, located at the exit of the TRIUMF M11 channel at an 8° opening angle, which were counting, in coincidence, muons in the beam halo.

The reactions reported in this Rapid Communication are $^{12}\mathrm{C}(\pi^-,pd)X$, $^{12}\mathrm{C}(\pi^-,dp)X$, and $^{12}\mathrm{C}(\pi^-,dd)X$ which were investigated at 165 MeV incident pion kinetic energy. The notation in the brackets means that the first particle is fixed while the second is detected in the detector that scans the phase space. These reactions are compared to the (π^-,pp) reaction, some results of which have been reported previously in the literature.[11] The angular distributions for the cross section at eight different angles for Arm *A* were measured with Arm *B* scanning the opposite side of the beam. In this communication the angular distributions for three angles are reported, each a representative of a certain subset of the data. The solid curves shown in the Figs. 2–4 indicate the results of a Monte Carlo simulation of three-body phase space.[12]

The four-momenta of the three particles participating in the three-body phase space, were generated in their center-of-mass frame with each event being assigned the appropriate phase space weighting. The experimental conditions were simulated by a Lorentz transformation of the four momenta from the center-of-mass frame to the laboratory frame. The code uses as input the geometry of the detectors (size of each detector and distance from the target), their angles with respect to the beam and their energy thresholds. These inputs are used to simulate the acceptance of the detector apparatus. Three-body reactions are defined by entering the masses of the involved particles as well as the particle type, and the program is required to simulate the reactions with two of the particles being confined to the acceptance of the detectors and the third particle following phase space. This is a simple three-body calculation and does not include any nuclear effects such as Fermi motion or excitation of the residual nucleus. It should be noted that the particles in the phase space code which fall within the acceptance of our two detectors are either protons or deuterons, in order to simulate the actual experimental conditions. The third particle may be a proton, deuteron, or neutron. The code allows for recoil of the residual nucleus.

There is no absolute way of normalizing the Monte Carlo phase space calculations to the measured angular distributions. Arbitrary normalization to the cross section at any angle setting, believed to be "purely" due to 3NA, runs the risk of overestimating the 3NA contribution at the other angles. This may occur if other processes have also contributed to the cross section at the angle setting where the normalization was made. The method used in this work in normalizing the phase space is to determine a common normalization factor for all angular settings, in such a way as to have minimum deviation from the lowest cross section (within error bars) for all angle settings simultaneously, and to never exceed the data in any of the angular settings. This method was accomplished by visually fitting the phase space curve to the lowest cross section for each angle setting in an iterative manner, until all distributions were fitted and none were exceeded by the phase space. The data cannot be exceeded, or even hoped to be entirely described by the phase space, since multistep processes also contribute to the cross section, a fact known from previous work[3,4,8,13,14] and observed in this work. This method of normalization has been cross-checked by comparing the momentum distribution of the third (unobserved) particle as calculated by phase space to the actual missing momentum distribution as determined from the experiment. Such an example is shown in Fig. 1, where the overlap in these two distributions, in each case, defines the normalization of the phase space to the cross section for this angle setting. The measured missing momentum is defined by the equation $\Delta\mathbf{p} = \mathbf{p}_\pi - \sum_{i=1}^{2} \mathbf{p}_i$, where $i = 1,2$ denotes the detected particles (protons or deuterons). The missing momentum distributions are composed of both 3NA and multistep processes, and hence the overlap discussed above describes the fraction of these distributions—and consequently the fraction of the cross section—due most likely to 3NA. The overlap fractions when multiplied by the cross sections yielded "normalization" points which acted only as a guide to the curve generated by phase space. The results of this method were identical to the other normalization method described above. An overall uncertainty of 20% has been estimated for the 3NA phase space normalization, which reflects the statistics of the missing momentum spectra, the sensitivity to the normalization value, and the exact proton and deuteron thresholds of 38 and 52 MeV, respectively. The normalization procedure was identical for all four processes (*pp*, *pd*, *dp*, and *dd*).

In Fig. 2, the angular distributions of the double-differential cross sections are shown for *pp*, *pd*, *dp*, and *dd* events in coincidence with Arm *A* fixed at 25° with

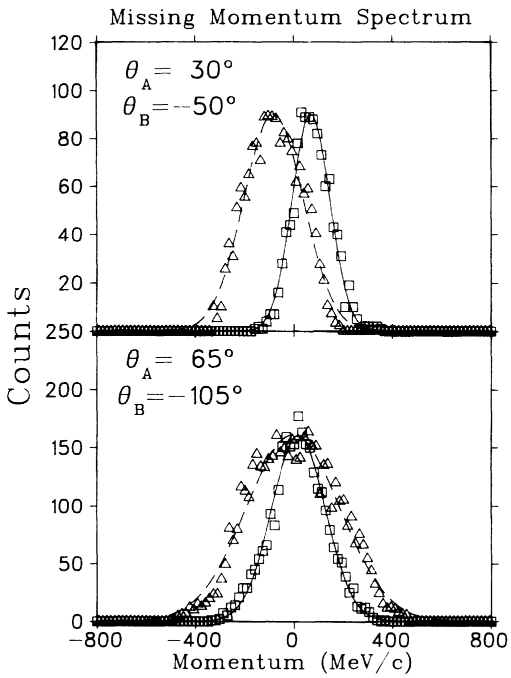

FIG. 1. Measured missing momentum (squares) and calculated third particle momentum (triangles) distributions exhibiting a specific overlap of 60% at the angle setting of (30°, −50°) and 100% at (65°, −105°). The distributions have been fitted by a Gaussian function and the results of these fits are shown as a solid line for the missing momentum and dashed line for the momentum distribution of the third particle as determined from phase space.

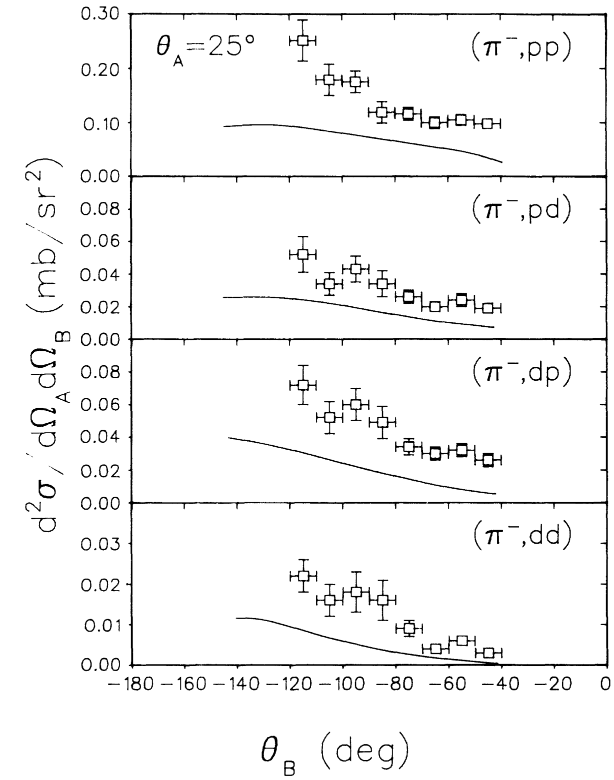

FIG. 2. Double-differential cross section of the $^{12}C(\pi^-,pp)X$, $^{12}C(\pi^-,pd)X$, $^{12}C(\pi^-,dp)X$, and $^{12}C(\pi^-,dd)X$ reactions at 165 MeV incident pion kinetic energy, plotted in 10° steps, for Arm A placed at 25°. The solid curve indicates the three-nucleon phase space.

respect to the incident pion beam. For each type of coincidence the cross sections were extracted in an independent and absolute fashion. A common feature of these distributions is the general trend to follow three-body phase space with the third nucleon going undetected. Although the phase space accounts for the general features of angular distributions it does not account for all of the observed strength. This suggests the presence of two-step processes which must be uncorrelated (one detected particle is produced in the first step, while the other must come from the second step) since these processes do not contribute to the shape of the angular distributions in the form of an enhancement which is a characteristic of correlated processes.

To contrast with the $\theta_A = 25°$ angular distributions we also present the $\theta_A = 125°$ distributions for the same reactions, in Fig. 3. Here the differences between the various channels are more pronounced. In the pp distribution significant deviations from phase space are observed for angles larger than $\theta_B = -90°$, where almost none of the strength is accounted for by three-body absorption. These deviations from 3NA might be attributed to correlated two-step processes, but more investigation needs to take place before any definite conclusions may be reached. Deviations from the three-body phase in the off-conjugate regions have also been seen in positive pion absorption on ^{3}He,[13] although these authors did not comment on what process was responsible for these deviations. Similar evidence has been observed in the results of two more experiments, at TRIUMF (Ref. 14) and at LAMPF (Ref. 15).

Recently, results from KEK on light nuclei at $T_{\pi^\pm} = 65$ (Ref. 16) and $T_{\pi^+} = 165$ MeV (Ref. 17) have been reported. Comparisons for carbon at 65 MeV incident π^+ and π^- energies reveal that the (π^+,d) and (π^+,p) distributions are very similar. Furthermore, the ratio of $\sigma(\pi^+,d)/\sigma(\pi^-,d)$ was consistent with unity. These measurements are results of single-arm (inclusive) experiments and cannot, in principle, be directly compared with our $(\pi^\pm,dp)$ results. However, a meaningful comparison can be made due to the fact that the only other competing processes that are significant, the $(\pi^\pm,dd)$, have very small contributions compared to their corresponding dp channels as determined in this work and quoted below. The ratio of the total (integrated) cross section that follows 3NA phase space for the (π^+,dp) and (π^-,dp) reactions, in this work, was also consistent with unity, while the ratio of the yields of these reactions, as measured in the $d^2\sigma/d\Omega^2$ distributions, was consistent with a ratio of five.[18] This was true over the entire range of the angular distributions even far away from the $\pi^+ t \rightarrow dp$ quasitriton kinematics. This change in behavior from 65 to 165 MeV may indicate the increasing importance of multistep processes—that manifest themselves as deviations from phase space—with increasing energy, while the underlying 3NA cross section appears to have the same energy dependence for both the π^+ and π^- induced reactions.

In regions of phase space where the three-body absorp-

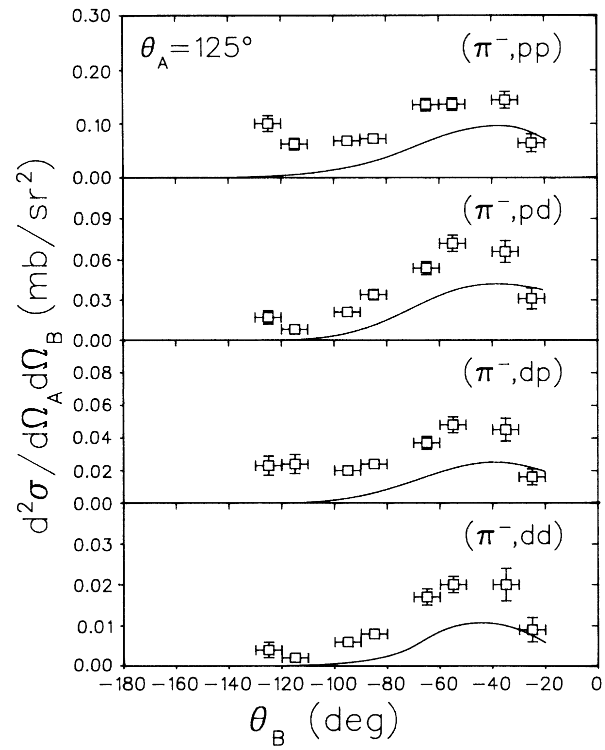

FIG. 3. Same as in Fig. 1 with Arm A placed at 125°.

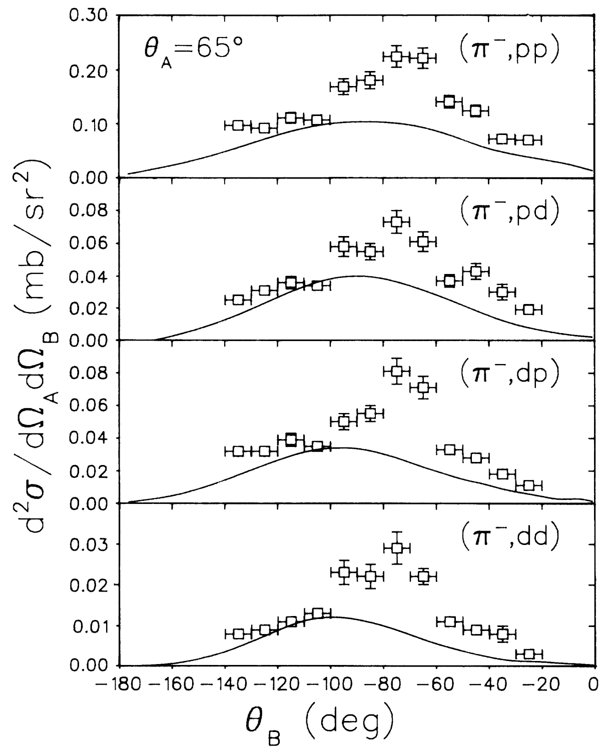

FIG. 4. Same as in Fig. 1 with Arm A placed at 65°.

tion is equally spanned as for $\theta_p=\theta_d=65°$, the angular correlations of all four processes (*pp*, *pd*, *dp*, and *dd*) are very similar and peaked, as shown in Fig. 4. The significance of the (π^-,pp) enhancement has been discussed in Ref. 11. Similar behavior has been reported for the (π^+,pp) and (π^+,pd) reactions at 65 MeV,[16] only there $\sigma(\pi^+,pp)/\sigma(\pi^+,pd)\approx 40$ instead of a ratio of $\sigma(\pi^-,pp)/\sigma(\pi^-,pd)\approx 3$, that was observed in this work. Unlike the case for π^+ at 65 MeV, however, the *pp*:*pd*:*dp*:*dd* cross section ratios for the π^- process at 165 MeV are fairly independent of angle. The ratios do not depend upon angle even at angle configurations where the three-body phase space accounts for nearly all of the cross section. It is interesting to note that the behavior of these ratios differs from that in the π^+ case as reported in Ref. 16, where the ratio of $\sigma(\pi^+,pd)/\sigma(\pi^+,pp)$ exhibits a rather pronounced angular dependence. This difference may be explained by the fact that in the π^+ case the dominant process is absorption on a three-nucleon cluster with two-step processes modifying the angular distribution.[16] In this work, the flat angular dependence of these ratios may be explained by a pickup process in which the basic reaction mechanism is that which leads to the *pp* channel with the other three channels resulting from the pickup of one (*pd*,*dp*) or two (*dd*) protons or neutrons. This conclusion is consistent with the claims of Refs. 3–8 described above.

By integrating the cross section under the normalized phase space we obtain a total cross section for pion absorption in the $T=\frac{3}{2}$ channel of $\sigma_{\rm tot}^{\rm 3NA}=4.90\pm0.98$ mb. The cross sections for the *pd*, *dp*, and *dd* channels, respectively, were measured as 3.63 ± 0.73, 3.11 ± 0.62, and 0.40 ± 0.10 mb. In addition, the ratios of the $(\pi^-,{\rm NN})$ double-differential cross sections to the phase space were calculated in the angular range between $-140°$ and $-30°$. Assuming that these ratios will not change appreciably by extending the measurements to 0° and $-180°$, we have deduced the total cross section for the four reactions by using the $\sigma_{\rm tot}^{\rm 3NA}$ cross sections. Hence, for the *pp*, *pd*, *dp*, and *dd* reactions we have, respectively, 8.09 ± 1.63, 5.48 ± 1.11, $5.63\ \pm1.11$, and 0.77 ± 0.19 mb.

The total emission cross section for π^- absorption leading to the emission of a proton and a deuteron (*pd* or *dp* channels) is substantial as compared to the *pp* channel, in contrast to the π^+ case where the *pp* to *pd* cross section ratio is 25 to 1.[18] This is most likely related to the fact that the (π^-,pp) reaction can proceed only via either a $T=\frac{3}{2}$ cluster absorption or two-step processes. The (π^-,pd) reaction, on the other hand, can proceed via $\pi^-(ppp)\rightarrow ppn$ plus a pickup reaction by either the proton or the neutron leading to a deuteron. In addition, it can also proceed via two-step processes such as $\pi^-pp\rightarrow pn$, $np\rightarrow d$ (pickup) and $\pi^-(ppn)\rightarrow pnn$, $np\rightarrow d$ (pickup). As a result, the (π^-,pd) cross section is almost as large as that of the *pp* channel mainly because the latter is restricted to fewer available channels and is also suppressed by the Pauli exclusion principle.

In conclusion, we have measured the differential and total cross sections for the π^- absorption on ^{12}C leading to charged particle emission and determined that "pure" 3NA absorption accounts for a substantial fraction of the observed strength, as seen in Figs. 2–4. The total cross section for absorption leading to emission of at least one deuteron is almost the same as the total cross section leading to two protons unlike the π^+ absorption reaction. Composite particle emission following π^- absorption is consistent with FSI in the form of pick-up reactions.

We would like to thank Dr. D. L. Humphrey and Dr. P. Weber for many useful discussions, Dr. P. Trelle and Dr. E. L. Mathie for assisting during the experiment, and C. Jillings and B. Elrich for assisting in the analysis. This project was supported in part by grants from the Natural Sciences and Engineering Research Council of Canada. The generous assistance of Dr. E. W. Vogt, Director of TRIUMF, is also gratefully acknowledged.

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