Evidence for a Direct Three-Nucleon Pion-Absorption Process

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Evidence for a three-nucleon absorption mechanism has been observed in ^{3}He for positive and negative pions of 220 MeV/c. The effect shows pure phase-space behavior with integrated cross sections of 3.9 ± 0.5 mb for π^+ and 3.7 ± 0.6 mb for π^- absorption.

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Pion absorption in nuclei has been described in various review articles.[1,2] At present a general consensus seems to exist that this complicated process can be subdivided into several steps: (1) initial-state interaction of the incoming pion, (2) the genuine absorption involving a defined number n of nucleons, (3) final-state interaction of the emitted nucleons, and, for completeness, (4) evaporation. The present paper is concerned with step (2), the absorption proper. Since the importance of all other steps relative to (2) is expected to increase with the nuclear mass A, we investigate the light nucleus ^{3}He, which offers also the unique possibility to determine a three-nucleon final state kinematically completely by measuring only two nucleons in coincidence. The kinematical completeness, however, is required to identify the different reaction mechanisms unambiguously.

Up to now, it has been generally believed that the number of nucleons involved in the genuine absorption process is predominantly $n=2$. Processes with $n=1$ are known to be on a level of 10^{-3},[3] and those with $n>2$ are still rather speculative. Examples of theoretical approaches for $n>2$ are the α-cluster–pole model[4] and the double-Δ mechanism.[5] Indirect experimental evidence has been discussed on the basis of deexcitation γ's following pion absorption[6] and of rapidity plots of single-arm spectra.[7] Another hint for $n>2$ is given by events with more than two prongs, as observed in early emulsion and bubble-chamber studies.[8] Furthermore, the cross sections for the two-nucleon absorption processes, as measured by the emission of back-to-back nucleon pairs,[9] are considerably smaller ($\lesssim 50\%$) than the total absorption cross sections as derived from transmission experiments. However, all these experiments did not seem to provide conclusive evidence for $n>2$, mainly because of the unknown contributions of steps (1), (3), and (4).

A special class of absorption processes involving more than two nucleons is characterized by the collinearity of the emitted particles. An example is the back-to-back pair emission where one or both members of the pair are composite particles such as d, t, ^{3}He, ^{4}He,. . . .[10,11] This again could be explained by step (2) having either $n>2$, or $n=2$ followed by step (3). At least for stopped pions it could be shown that the latter possibility does not provide an adequate explanation as long as independence of the two steps is assumed.[11] Coherent mechanisms can possibly explain these processes, as is also suggested from inverse reactions.[12] Though this class of events is also present in ^{3}He appearing as deuteron emission or events with two nucleons with small relative momentum (classical final-state interactions),[13,14] we will not deal with it here. In contrast we will show evidence for a completely different reaction mechanism involving three nucleons. It is not restricted to special phase-space regions but covers the whole available phase space uniformly without structure.

The measurements were performed at the πE1 channel of the Swiss Institute for Nuclear Research ring accelerator within the scope of a more extensive program to study pion absorption in ^{3}He. Details about the target and the two-arm spectrometer can be found elsewhere.[15,16] The momenta of pp and pn pairs emerging from a 0.5-g/cm^2 liquid target were measured by a 2-m-long position-sensitive time-of-flight (TOF) counter and a total-absorbing plastic-scintillator hodoscope (E counter) preceded by two multiwire proportional chambers. Particle identification was made by thin scintillators in front of both counters and time-of-flight and pulse-height measurements. Both counters could be rotated around the target covering relative angles of 60° horizontally and 40° vertically in each position.

In order to determine absolute cross sections, considerable effort was devoted to measure the number of pions hitting the target and to eliminate events from the target surroundings. The pion flux was determined by two methods, measurement of a TOF-selected telescope rate and the β^+ activity of pion-activated ^{11}C. Both methods agreed for the fluxes used (10^6–10^7 s^{-1}) within 5%. The chamber information was used to trace back the events and select those originating from the target. Less than 3% of the incoming pions hit the target frame. Since the momenta of two nucleons from the three-nucleon final state are determined, the measurement is kinematically overdetermined containing one constraint. This constraint is used for further background reduction as illustrated in Fig. 1 which shows the reconstructed-mass distribution of the target nucleus. It is dominated by a peak at the ^3He mass, superimposed on a small and flat background. The number of good events is determined by fitting a Gaussian function to the ^3He peak and subtracting the flat background. This could be attributed to the target walls by target-empty measurements to 60–80% depending on the counter configuration.

Because of thresholds and finite dimensions of the counters, each configuration of the apparatus covers a limited part of the total five-dimensional phase space. Figure 2 shows a projection of data on the horizontal laboratory angle of particle 2 with the center of the E counter for particle 1 kept constant at 117°. Data from four positions of the TOF counter were combined. Figure 2 shows a pronounced peak around $\theta = 36°$ which is attributed to quasifree absorption on a nucleon pair ($2N$ absorption). The shape of the peak is well understood by the Fermi momentum of the absorbing pair, i.e., the known momentum of the undetected third nucleon. Correspondingly, the cross section is expected to vanish at angles far away from the maximum. This is obviously not the case. Instead the measured distribution levels off at a nearly constant value about 2 orders of magnitude below the peak value. Also shown in Fig. 2 is a Monte Carlo simulation of the three-nucleon decay on the assumption of a constant matrix element, i.e., that the transition amplitude depends only on the $3N$ phase space. The simulation fits well the shape of the measured distribution outside the $2N$ peak.

It is obvious from Fig. 2 that experimental information about the three-body absorption ($3N$ absorption) should preferentially come from phase-space regions far away from the $2N$ peak. Therefore, measurements have been performed at various counter configurations outside the $2N$ peak. In this way also the classical final-state interaction region which corresponds to 180° in the c.m. system has been omitted.

Figure 3 shows a survey of all counter configurations used for the present experiment. The laboratory angle accepted by the E counter is displayed versus that angle for the TOF counter. The $2N$ region is shown by a hatched band indicating its FWHM. It can be seen that configurations 1, 2, and 5 are far away from this band and hence not affected by the $2N$ process, whereas configurations 3 and 7 are nearly touching the band. In the latter cases only parts of the available acceptance have been utilized as indicated with the rectangles shown for each configuration. Configuration 4 and some others not shown in the figure served for reference measurements in the $2N$ region. Figure 3 illustrates that information from rather distant parts of the total phase space has been collected in order to reduce uncertainites in the integrated cross section. Because of the symmetry with respect to nucleon interchange, actually a large part of the phase space is covered.

The results obtained for all counter configurations are summarized in Table I. In order to derive cross sections the counter acceptance for the $3N$ channel has been determined for each setting. The numbers given in the table resulted from a Monte Carlo simulation

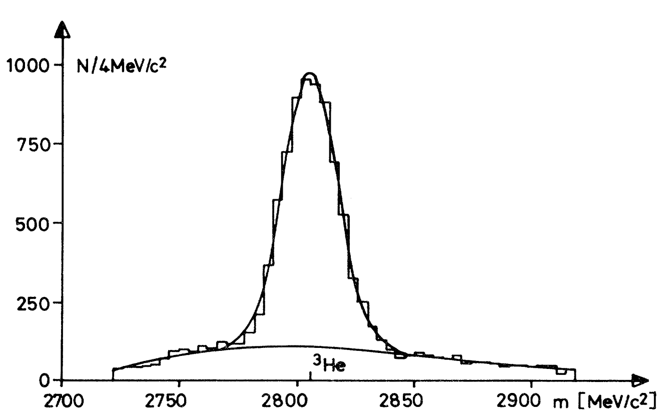

FIG. 1. Reconstructed mass of the target nucleus fitted by a Gaussian; configuration 1, π^+.

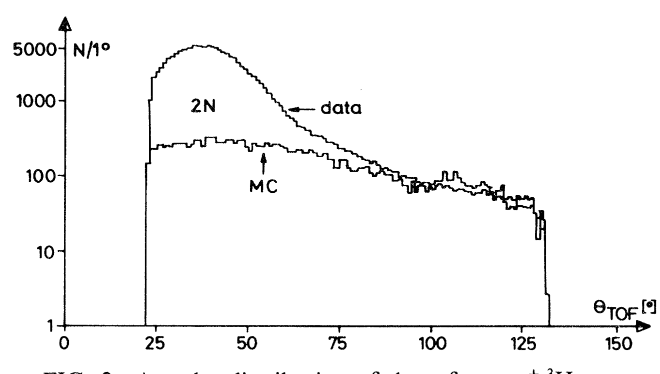

FIG. 2. Angular distribution of the p from $\pi^+ {}^3He \rightarrow ppp$ in the TOF counter; E counter at 117° ± 14°; configurations 1–4 of Fig. 3. Data, measured distribution; MC, three-body phase-space simulation.

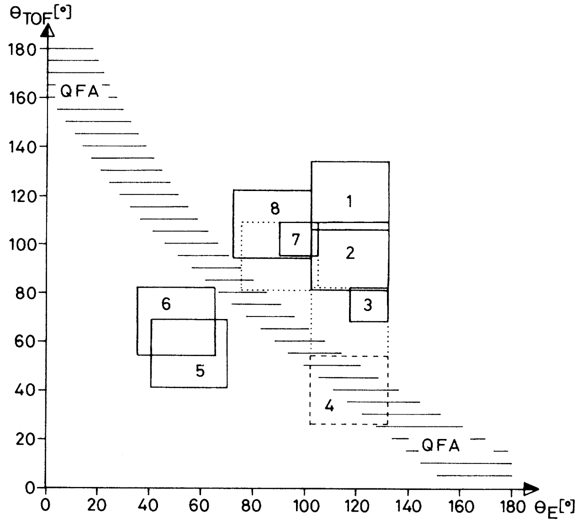

FIG. 3. Counter configurations used in the measurements (lab angles). QFA, quasifree $2N$ absorption.

applying the actual geometry and energy thresholds (E, 20 MeV; TOF, 33 and 16 meV for p and n, respectively) and assuming a constant matrix element. This was verified by comparison with the data for energy and angular projections of different kinematical regions. Figure 2 may serve as an example for the angles outside the $2N$ region. For a given configuration this acceptance factor is different for pp and pn pairs because of symmetries for particle interchange and the neutron detection efficiency which enters here as a mean value. The number of events as obtained by use of the kinematical constraint (Fig. 1) divided by the pion flux and the acceptance factor determines the $3N$ cross section. The errors also listed originate from counting statistics and uncertainties in determining acceptances, counting efficiencies, and subtractions of unwanted contributions. The data are in remarkably good agreement with each other, justifying again the assumption of constancy within the total phase space. A mean value of 3.9 ± 0.5 mb for π^+ and 3.7 ± 0.6 mb for π^- has been obtained. The common errors of target thickness and pion flux have been included.

We have observed nonzero cross sections for pion absorption in ^{3}He in various phase-space regions outside the domain of quasifree $2N$ absorption and of the classical final-state interaction. In contrast to these known processes the observed new process shows no structure. The data can be well fitted by Monte Carlo simulations assuming a matrix element which is constant throughout the whole phase space. Thus, the newly observed process shows the most simple behavior. The fact that σ_{3N}^+ and σ_{3N}^- agree within the experimental error suggests that in both cases the final state has the same isospin ($I=\frac{3}{2}$).

Comparing integrated cross sections we note that the observed $3N$ cross section amounts to about 25% of the $2N$ cross section for nucleon pairs with $I=0$ and

TABLE I. $3N$ cross sections of π^+ and π^- for the configurations indicated in Fig. 3. θ_E, θ_{TOF}: central angle of detectors E and TOF in the lab system; N_π: total number of incoming pions; α: acceptance; ϵ_n: neutron detection efficiency (energy dependent).

Config.	θ_E (deg)	θ_{TOF} (deg)	$10^{-10} N_\pi$	$10^3\,\alpha$	ϵ_n (%)	Events	σ_{3N} (mb)
1	117	120	4.00	0.35		5200	3.9 ± 0.6
2	117	95	3.20	1.02		11 150	3.7 ± 0.4
3	117	68	2.40	0.42		3550	3.8 ± 0.6
4	117	40	0.39	2.97		69 800	69.0[a]
5	55	55	1.82	1.84		12 600	4.2 ± 0.5
6	50	68	0.91	2.11		4930	4.0 ± 0.5
7	90	95	2.33	0.40		3200	3.8 ± 0.5
8	87	108	2.00	3.55		17 890	3.7 ± 0.5
							$\bar{\sigma}_{3N}^+ = 3.9 \pm 0.5$ mb
1	117	120	20.8	0.15	12.2	1490	4.1 ± 0.6
2	117	95	10.5	0.38	12.4	1600	3.5 ± 0.6
3	117	68	9.5	0.15	12.6	700	4.3 ± 0.6
4	117	40	12.5	1.02	12.7	12 200	14.7[a]
						2500	3.6 ± 1.5[b]
5	55	55	10.1	0.66	12.6	2500	3.4 ± 0.5
							$\bar{\sigma}_{3N}^- = 3.7 \pm 0.6$ mb

[a]Only for comparison the $3N$ acceptance is applied to the $2N$ and final-state interaction regions.

[b]Number of $3N$ events after subtraction of $2N$ and final-state interaction events; cross section not entering the final result.

about four times that for $I=1$. Hence the $3N$ reaction forms an important part of the total absorption which cannot be neglected. The possibilities of comparing our results with other experimental data are rather limited. Only from the pioneering bubble-chamber study of Bellotti, Cavalli, and Mattenzzi[8] can an integrated $3N$ cross section for 130-MeV π^+ on ^{12}C of about 60 mb be deduced. The kinematically complete experiments[13–15,17,18] on ^3He were mainly concerned so far with the $2N$ absorption on pairs with different isospin and restricted to the corresponding phase-space regions. Possible three-nucleon absorption was mentioned, mainly as an assumed flat background to the $2N$ structures in the energy spectra of detected nucleons.[14,17,18] Neither a systematic research nor numbers for cross sections have been published which could be compared.

The situation is better for the absorption of stopped pions on ^3He where the measurement integrates automatically over all variables except two. Hence the complete results can be presented in a single Dalitz plot. From the number of events outside the regions of the known mechanisms a possible $3N$ contribution of less than 10% can be derived.[13] This result indicates an energy dependence of the $3N$ process even stronger than that for the $I=0$ $2N$-process and may suggest a multi-Δ mechanism.

A recent calculation by Oset, Futami, and Toki[19] is in agreement with the observed energy dependence.

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