New Pion-Absorption Modes Observed from Triple Coincidences in ^{4}He

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The first triple-coincidence data resulting from pion absorption in ^{4}He are reported. The existence of a three-nucleon absorption component in the four-nucleon channel is established. A four-nucleon phase-space-like contribution and nucleon-nucleon final-state interactions are also identified.

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In the last few years there has appeared increasing evidence[1,2] for new pion-absorption modes which are beyond the scope of the two-nucleon (2N) absorption approach. It has been known for some time[1] that the 2N processes by far do not exhaust the total absorption cross section. One part of the missing cross section certainly is located in channels with composite-particle emission or in kinematical regions characterized by small nucleon-nucleon relative momenta, i.e., regions of "soft" final-state interaction. Another part may be contained in sequential processes,[3] where the 2N absorption is combined with scattering or charge exchange before or after the genuine absorption. The states between the different steps are near the mass shell. Thus the final state will reflect in its kinematical signature the different steps involved. The most exciting part of the missing cross sections, however, is expected to show up in processes in which the pion interacts in the genuine absorption process with more nucleons. Such a reaction type will not be confined to specific parts of the phase space, but will cover it entirely.

Because of the experimental difficulties only very few measurements on noncollinear multinucleon emission have been reported so far. The lightest possible target, ^{3}He, has the advantage that the emission of three separate nucleons can be completely determined kinematically in a twofold coincidence experiment. With this target the reactions $(\pi^+,pp)p$ and $(\pi^-,pn)n$ have been studied.[4-6] Large parts of the available three-body phase space have been examined with the result that for 3N absorption the corresponding matrix element is constant[4] within experimental uncertainty. Aside from considerations about the small number of available nucleons, this latter result is a strong argument against a sequential character of the observed process.

Historically, the first indications for absorption followed by multinucleon emission came from experiments with poor statistics, performed with a bubble chamber[7] and a streamer chamber.[8] Later, counter experiments from ^{12}C with threefold coincidences with better statistical accuracy were reported. In this case the kinematical completeness for the many particles in the final state could not be achieved. In one experiment,[9] no conclusion about a specific reaction mechanism was drawn, whereas in the other experiment[10] there was an indication of a sequential mechanism. Recent measurements on ^{6}Li (Ref. 11) may also indicate the influence of sequential mechanisms.

The experiments on multinucleon absorption in ^{3}He have shown that an unambiguous interpretation of the data in terms of reaction mechanisms is possible only in an exclusive experiment, allowing one to determine any relevant kinematical quantity. In order to investigate the importance of reaction mechanisms involving more than two nucleons, we have chosen ^{4}He as the target. This enables us to study the participation of up to four nucleons, while the kinematics is determined completely by a threefold coincidence measurement. In addition, this type of measurement has the advantage that the momentum range of the fourth, undetected particle is not limited by thresholds. We will show later that the data are most sensitive to the observed reaction mechanisms in the kinematical regions, where the momentum of one of the emitted nucleons is very small.

The experiment was conducted at the Swiss Institute for Nuclear Research [SIN, now the Paul Scherrer Institute (PSI)]. A positive pion beam with 220-MeV/c momentum impinged upon a liquid ^{4}He target. The triple-coincidence system included a charged-particle total-absorption scintillator hodoscope (detector 1) and two time-of-flight detectors for neutrons and charged particles (detectors 2 and 3). The total-absorption plas-

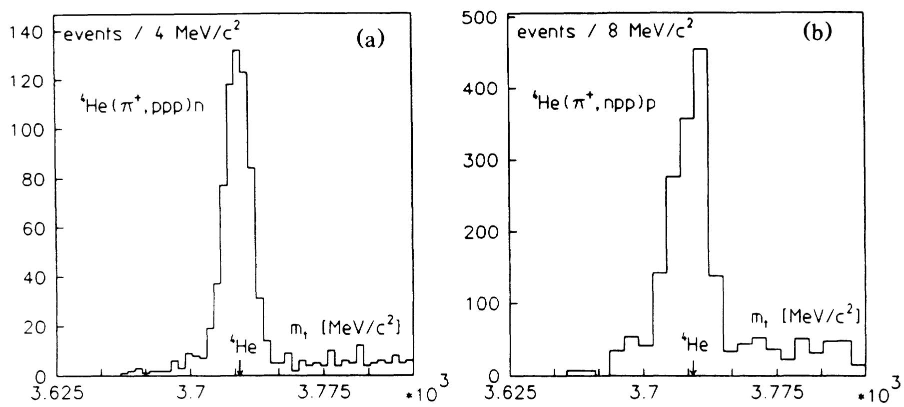

FIG. 1. (a) Reconstructed mass spectrum of the target nucleus (m_t) for ^{4}He(π^+,ppp)n at a pion momentum of 220 MeV/c. (b) Reconstructed mass spectrum of the target nucleus (m_t) for ^{4}He(π^+,npp)p with the number of events corrected for neutron detection efficiency.

tic scintillator was divided into twelve hodoscope components and subtended a solid angle of 0.2 sr. Two multiwire-proportional-chamber systems with a total of six planes were located in front of the scintillation blocks. The charged-particle trajectories were also intercepted with a thin dE/dx scintillation counter in front of the multiwire proportional chambers. For background rejection, the reaction vertex was checked through a ray-tracing technique with use of the multiwire-proportional-chamber coordinates. The time-of-flight detectors were large-area position-sensitive plastic scintillators designed for subnanosecond timing. They subtended solid angles of 0.075 and 0.09 sr with an energy resolution around 5% for 100-MeV nucleons. The efficiency for neutron detection was energy dependent, being 12% at 100 MeV. Thin anticoincidence counters in front of the time-of-flight scintillators served to identify the neutrons. Charged-particle identification for all three detectors was performed off-line, imposing cuts upon the pulse-height versus time-of-flight information. The positions of the detectors relative to the beam direction were 72°, 240°, and 305° for the centers of detectors 1, 2, and 3, respectively. All three detectors were at beam height. More detailed information on the setup is available elsewhere.[12,13]

By exploiting the constraint of our measurement, the target mass for each event can be reconstructed. Target-mass spectra for the ppp coincidences and for the npp coincidences are shown in Figs. 1(a) and in 1(b), corrected for neutron detection efficiency. Only events consistent with a ^{4}He mass are processed further.

Final results for triple coincidences, corrected for neutron detection efficiency, are shown in Fig. 2 for ^{4}He(π^+,ppp)n and in Fig. 3 for ^{4}He(π^+,npp)p. The histograms show the data as a function of the momentum of the undetected nucleon.

Both figures are dominated by a peak centered around 100 MeV/c. The shapes of the spectra in the region of this peak can be explained by a quasifree three-nucleon (Q3N) mechanism. In this mode the unobserved nucleon spectates, while the absorption takes place on the other three nucleons. The momentum of the fourth nucleon is, therefore, determined by the momentum distribution of that nucleon within the ^{4}He nucleus. A Monte Carlo simulation for our geometry was made by the weighting of the four-body phase space with the nucleon momentum distribution as obtained by (e,$e'p$).[14] This simulation reproduces the data very well in the region of 0–200 MeV/c.

The choice of off-conjugate positions mentioned before strongly suppressed contributions from 2N absorption with the coincident detection of a spectator nucleon. In

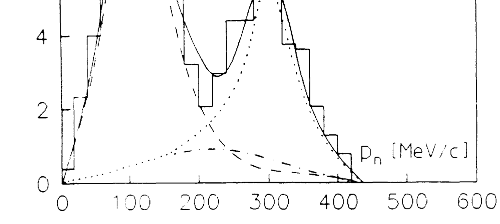

FIG. 2. Differential cross section as a function of the momentum p_n of the undetected neutron for ^{4}He(π^+,ppp)n. Histogram: our data; dashed line: Q3N simulation; dotted line: 4N+FSI$_{pn}$ simulation; dash-dotted line: continuation of the 4N simulation without the FSI$_{pn}$ enhancement; solid line: sum of the Q3N and the 4N+FSI$_{pn}$ simulations.

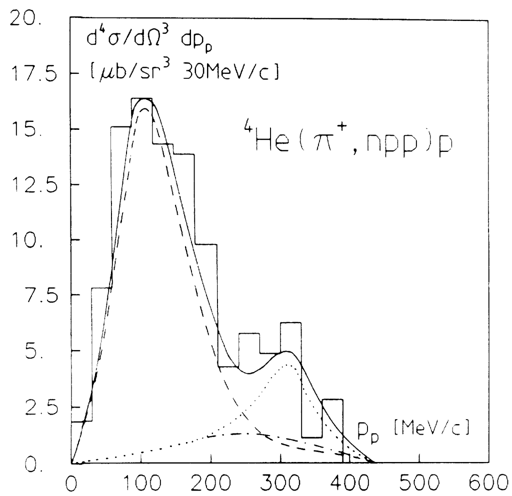

FIG. 3. Differential cross section as a function of the momentum p_p of the undetected proton for ^{4}He$(\pi^+,npp)p$, corrected for neutron detection efficiency. Histogram: our data; dashed line: Q3N simulation; dotted line: 4N+FSI$_{pp}$ simulation; dash-dotted line: continuation of the 4N simulation without the FSI$_{pp}$ enhancement; solid line: sum of the Q3N and the 4N+FSI$_{pp}$ simulations.

addition the thresholds of counters 2 and 3 were chosen to be sufficiently high (about 40 MeV) that contribution from 2N absorption can be neglected in the following.

For a four-nucleon absorption model (4N), in which all nucleons participate according to phase space, the Monte Carlo simulation exhibits a broad bump around 200 MeV/c. This is not supported by our data in Figs. 2 and 3. Obviously, 4N dynamics does not dominate in our geometry.

The high-momentum (300 MeV/c) peak of Fig. 2 is characterized by a small relative momentum between the proton in detector 1 and the unobserved neutron. Therefore, the peak is identified as a "soft" final-state-interaction (FSI) effect between the proton and the fourth nucleon, as described, e.g., by the Watson-Migdal approach.[15] Such an assignment is strengthened by the fact that the corresponding peak in Fig. 3 is barely visible. This is to be expected from the well known relationship between n-p and p-p FSI, as the latter is significantly weaker due to Coulomb repulsion.

The relative strengths of the different mechanisms we see in our spectra are determined by the following procedure: In the Watson-Migdal model, only an already existing amplitude in the appropriate kinematic region contributes to the enhancement (FSI peak). When weighting both the Q3N and 4N mechanisms, we find that the Q3N strength in the FSI region does not contribute significantly. The FSI peak is therefore, in effect, described as an enhancement of 4N only. In our simulation we have used standard values for the parameters of the effective-range approximation. The optimal fit to the full spectrum of Fig. 2 is obtained by our adding incoherently the contributions of Q3N and 4N+FSI amplitudes with relative strengths 0.65 and 0.35, respectively. The corresponding numbers for the npp coincidences (Fig. 3) are 0.8 and 0.2. We obtain then for our geometry the following differential cross sections: $d^3\sigma_{ppp}^{\rm Q3N}/d\Omega^3 = 56 \pm 8$ μb/sr^3, $d^3\sigma_{npp}^{\rm Q3N}/d\Omega^3 = 80 \pm 16$ μb/sr^3. These numbers are corrected for the thresholds in our detectors.

In order to obtain integrated cross sections we need to extrapolate from our limited geometry to the full solid angle. For this procedure, the same assumptions were made as for the simulations described above. That means that in the Q3N case a phase-space distribution is taken, modified by imposing on one nucleon the measured[14] Fermi-momentum distribution in ^{4}He (dashed lines in Figs. 2 and 3). For the integrated cross section of quasifree three-nucleon absorption with a neutron or a proton as spectator, we obtain $\sigma_{ppp}^{\rm Q3N} = 2.1 \pm 0.5$ mb, $\sigma_{npp}^{\rm Q3N} = 4.4 \pm 1.3$ mb.

For the determination of the integrated cross section in the 4N case, we need to extract that part of the measured 4N cross section which behaves according to the phase-space factor. FSI, however, is concentrated in a small part of the phase space. We have, therefore, determined for the ppp coincidences (Fig. 2) in our geometry the ratio of 4N without and with FSI included as 4N/(4N+FSI)=0.22 by Monte Carlo simulation. For the extrapolation to the full solid angle in the 4N case, we have assumed a pure phase-space-type distribution and obtain for the integrated cross section (FSI excluded) $\sigma^{\rm 4N} = 0.5 \pm 0.15$ mb.

Our data are obviously dominated by the new quasifree three-nucleon mechanism, whose contribution is clearly separated and identified; three nucleons share the energy released by the absorbed pion. The mechanism generalizes the already observed three-nucleon absorption mode[4,5] found for the ^{3}He target. It is also similar to the recently reported one-nucleon-spectator mechanism responsible for nucleon-deuteron coincidences[16] in the case of the ^{4}He target. In both cases the momentum distribution of one nucleon is governed by the Fermi distribution.

Our Q3N integrated cross section can be compared with the integrated cross section for free three-nucleon absorption in ^{3}He with $p_\pi = 220$ MeV/c (Ref. 4): $\sigma_{(\pi^+,pp)p}^{\rm 3N} = 3.9 \pm 0.5$ mb and $\sigma_{(\pi^-,pn)n}^{\rm 3N} = 3.7 \pm 0.6$ mb. The Q3N cross sections in ^{4}He are smaller than expected by our simply scaling the number of nucleons. It should be mentioned, however, that distortion effects may result in a reduction of the cross sections. In contrast to the ^{3}He results, we see in ^{4}He a dependence on the isospin in the final state, as the pure $I = \frac{3}{2}$ channel $\sigma_{ppp}^{\rm Q3N}$ is by a factor of 2 weaker than $\sigma_{npp}^{\rm Q3N}$, which is a mixture of $I = \frac{1}{2}$ and $I = \frac{3}{2}$.

The 4N contribution to the total-absorption cross section is an order of magnitude smaller than that of Q3N. A possible model for 4N absorption has been proposed, resorting to a double-Δ mechanism.[17] No kinematical signature is predicted there. A strong deviation from phase-space behavior, however, is not expected as at our energy the two intermediate Δ's must be quite far off shell. The proposal that a 4N mechanism might explain the difference between the 2N absorption and the total-absorption cross section[18] is not supported by our estimates of the 4N part. Also, the authors of Ref. 17 themselves expect a double-Δ mechanism to contribute significantly only at higher energies. Our experimental result that the absorption on three nucleons is stronger than that on four nucleons, is, however, in agreement with a nuclear-matter calculation.[19]

In conclusion, direct observation is made of a new pion-absorption mode on a three-nucleon subgroup freeing all of them. This generalizes the already observed three-nucleon mode on the ^{3}He nucleus.[4] Because of our special geometry we see both a strong signal from *p-n* FSI and a weaker one from *p-p* FSI. In addition, we also find a four-nucleon absorption mode, the contribution of which is, however, substantially weaker.

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