Observation of a Quasifree Three-Nucleon-Absorption Mode of Pions in ^{4}He

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A kinematically complete experiment on ^{4}He$(\pi,dN)N$ absorption in flight reveals an absorption mechanism in ^{4}He with only one spectator nucleon. This adds to the evidence that modes beyond the two-nucleon mechanism contribute to the pion absorption process.

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Our picture of pion absorption in nuclei has been dominated for a long time by the idea that the genuine absorption act occurs solely on a two-nucleon pair. Investigations of pion absorption mechanisms beyond this quasifree nucleon-pair model have received strong impulses only recently. Direct evidence for three-nucleon-absorption processes has now been found in kinematically complete experiments on ^{3}He, where the emission of three highly energetic nucleons[1,2] and of *nd* pairs[2-4] has been observed. Various indirect signs have been reported that several nucleons may contribute to the absorption on more complex nuclei.[5] Also, an incident nucleon may induce a reaction on a three-nucleon subgroup as has been shown previously.[6]

It is, therefore, natural to search for the direct evidence that pion absorption in ^{4}He proceeds partially through a mechanism with a single nucleon as spectator. The *dNN* final channel is an especially attractive candidate for such an observation since coincident detection of deuterons and nucleons ensures the kinematical completeness of the measurement. This permits the unique identification of this mechanism. Moreover, in the case of a quasifree absorption on a three-nucleon subsystem the momentum distribution of the fourth nucleon is just the Fermi momentum distribution in ^{4}He which is well known and provides a unique possibility to identify the reaction mechanism.

Pion absorption on ^{4}He has been investigated so far mainly by single-arm experiments.[7] In such experiments, however, the above explained mechanism cannot be isolated from other contributions. In one experiment, *dn* coincidences induced by stopped negative pions in ^{4}He have been reported.[8] There, the data from different geometries have been combined for most of the results given. This introduces significant integration over variables and makes results more similar to single-arm experiments. The possibility of quasifree absorption on three nucleons has not been discussed there. Recently published results on pion absorption obtained in ^{4}He with a streamer chamber[9] do not include the *dNN* channel.

Our experiment has been conducted at the $\pi E1$ channel of the Swiss Institute for Nuclear Research (SIN). A pion beam of 220 MeV/*c* impinges upon a liquid-^{4}He target viewed by two spectrometers. One spectrometer for only charged particles is a total-absorption plastic scintillator hodoscope of twelve blocks, $170\times170\times300$ mm^3 each, arranged in an array of four columns × three rows. In front of the hodoscope there are two multiwire proportional chambers, consisting of three planes each, and a thin dE/dx scintillation counter. Charged-particle identification is based on time of flight versus pulse height measurement. The reconstruction of particle trajectories with multiwire proportional chambers is used to reject background by applying target cuts. The second spectrometer is a large-area (2×1.3 m^2) time-of-flight, position-sensitive plastic scintillation counter to identify and measure charged particles and neutrons. The efficiency for neutron detection is $\simeq 2\%$ at 100 MeV. Both spectrometers subtend a solid angle of $\simeq 0.2$ sr and have about 1° angular and $\simeq 5\%$ energy resolution for 100-MeV particles. The precise momentum determination allows also further background with use of missing mass technique for three-body final channels. More detailed information on the setup is available elsewhere.[10,11]

The data given here have been accumulated at different positions of the two spectrometers, all corresponding to the $d(\pi,NN)$ kinematics. These positions also cover the nearly identical laboratory angles for the ^{3}He(π^-,dn) kinematics. Hence coincidences of *dp*, *dn*, *pp*, and *pn* pairs have been measured. The different

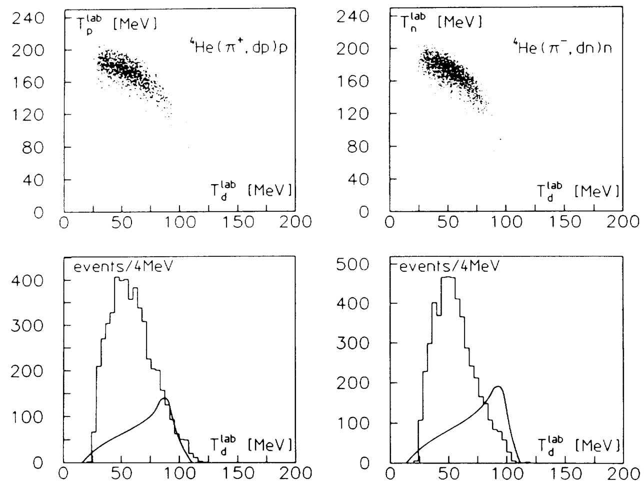

FIG. 1. Top: Dalitz plots for ^{4}He$(\pi^+,dp)p$ and ^{4}He$(\pi^-,dn)n$ for a pion momentum of 220 MeV/c. Bottom: Projections on the energy axis of the deuteron ($\theta_d = 113° \pm 15°$). The lines indicate the shape of the three-body phase space not normalized to the data.

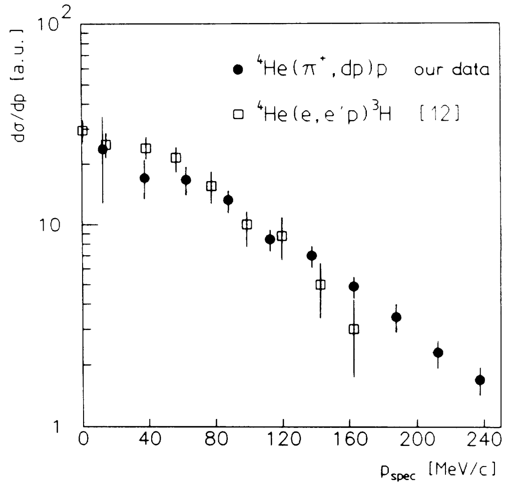

FIG. 2. Momentum distribution of the spectator nucleon, extracted from the reaction ^{4}He$(\pi^+,dp)p$. For comparison the momentum distribution from electron scattering in the reaction ^{4}He$(e,e'p)^3$H is also given. The errors shown are the statistical errors.

channels have been clearly separated by particle identification.

In the following, we focus our attention on deuteron-proton and deuteron-neutron events. In Fig. 1 the Dalitz plots for the ^{4}He$(\pi^+,dp)p$ and ^{4}He$(\pi^-,dn)n$ reactions and their projections on the deuteron energy axis are shown. The events are concentrated within the kinematically allowed region with only a small amount of background. In the projections large peaks are apparent at deuteron kinetic energies which correspond to a spectator nucleon being at rest. The shapes of the peaks can be explained by the Fermi motion. The smooth lines show the shape of the three-body phase space obtained by Monte Carlo simulation. It is obvious that the measured peaks are not caused by phase space. The material between the target and the scintillator and the electronics threshold define the deuteron threshold to be at 28 MeV. The sharpness of this threshold is not affected by the energy smearing ($\simeq 3$ MeV) caused by the finite target thickness. Hence, threshold effects cannot have simulated the observed peaks either. Figure 1 corresponds to a deuteron emission angle of 113° ± 15° relative to the beam direction. At smaller angles the peak becomes less intense as compared with other processes but is still clearly visible. Nevertheless our data show that the majority of the events are in the kinematical region of the quasifree three-nucleon absorption. Therefore, we may conclude that pion absorption on a three-nucleon subsystem plays a very important role for the dNN absorption channel.

The absorption cross section for a quasifree mechanism ^{4}He$(\pi,dN)N$ may be factorized as

$$d^5\sigma \simeq G(\theta)F(p_s)\Phi\, d\Omega_1\, d\Omega_2\, dp_s,$$

where $G(\theta)$ describes the absorption on the three-nucleon subsystem leading to particle emission at an angle θ relative to the pion momentum. $F(p_s)$ is the momentum distribution of the spectator nucleon and Φ is the phase-space factor calculated by Monte Carlo simulation. With use of this factorization the distribution $F(p_s)$ has been obtained from our data up to a constant factor by division of the measured recoil distribution by Φ. The result is shown in Fig. 2 together with that from the reaction ^{4}He$(e,e'p)^3$H.[12] A quasifree interaction requires $F(p_s)$ to be the same as the proton momentum distribution measured in $(e,e'p)$ experiments. The agreement in Fig. 2 is very good and provides a proof that the process is quasifree in the sense that the fourth nucleon behaves as a spectator.

The importance of this absorption mode can be seen by comparison with the standard two-nucleon absorption. Ratios of cross sections for various absorption channels are shown in Table I. They are obtained by integration of the differential cross sections over the re-

TABLE I. Ratios of quasifree differential absorption cross sections at a deuteron or proton emission angle of 113° ± 15° (laboratory system). The errors include both the statistical and systematic errors.

$$\frac{\sigma(\pi^+\,{}^4\mathrm{He} \rightarrow dp(p))}{\sigma(\pi^-\,{}^4\mathrm{He} \rightarrow dn(n))} = 1.1 \pm 0.2$$

$$\frac{\sigma(\pi^-\,{}^4\mathrm{He} \rightarrow dn(n))}{\sigma(\pi^-\,{}^4\mathrm{He} \rightarrow pn(nn))} = 1.6 \pm 0.3$$

$$\frac{\sigma(\pi^+\,{}^4\mathrm{He} \rightarrow dp(p))}{\sigma(\pi^+\,{}^4\mathrm{He} \rightarrow pp(pn))} = 0.16 \pm 0.03$$

spective quasifree peaks. Since the conjugate angles for the dN and the NN channels are identical within 3°, the two channels could be measured simultaneously. The spectator-momentum distribution determines the angular correlation. As the angular correlations have been found to differ very little[13] the geometrical detection efficiencies are the same within 20% for these two channels. The ratios of differential cross sections of the dN to NN channels at 113° are given in Table I. The table shows that the quasifree dN cross section is only an order of magnitude weaker than the quasifree absorption on a $T=0$ pair and surpasses the absorption on the $T=1$ pair. The ratios of the respective integrated cross sections are somewhat different as a result of the different angular distributions. The deviation, however, is less than a factor of 2.[13] Furthermore, the table shows that the cross sections for $^4\mathrm{He}(\pi^+,dp)p$ and $^4\mathrm{He}(\pi^-,dn)n$ are within 10% the same. Equal cross sections for π^+ and π^- were also found for the three-nucleon absorption in $^3\mathrm{He}$.[1,2]

The angular distribution for the quasifree $^4\mathrm{He}(\pi^-, dn)n$ cross section is given in Fig. 3. It shows a rather flat behavior in the backward hemisphere of the emitted neutron ($d\sigma/d\Omega=70\pm10$ μb/sr) and rises sharply by more than a factor of 2 in forward direction. There is a striking similarity with the angular distribution of the $^3\mathrm{He}(\pi^-,dn)$ absorption measured with the same apparatus[4] and previously observed by Källne *et al.*,[14] also shown in Fig. 3. This indicates that the absorption mechanism on the subgroup is similar to that on the analogous free nucleus.

Data reported recently on nucleon-deuteron coincidences resulting from π absorption in lithium isotopes[15,16] suggest also absorption on subsystems. In this case, however, the unobserved system of nucleons possesses higher complexity. Only for a smaller portion of the observed events (leading to discrete states of the residual nucleus) does the kinematical completeness exist and even these events are superimposed on a four- and more-body "background." Furthermore, one has to resort to cluster models to compare with the measured recoil-momentum distribution. Though less direct than the present results, these observations also support the conjecture of pion absorption on a three-nucleon subsystem. No similar analysis of (π,dN) data on $A>7$ nuclei has been reported so far. The most recent data[17] from C, Al, and Cu are presented in energy-integrated form only and therefore not kinematically complete.

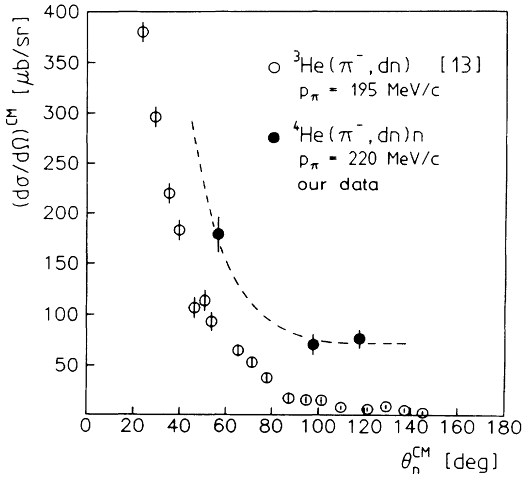

FIG. 3. Differential cross section as a function of the neutron c.m. angle for the quasifree process in the $^4\mathrm{He}(\pi^-,dn)n$ reaction as compared to the data of $^3\mathrm{He}(\pi^-,dn)$. The dashed line is a smooth curve through our data. The error bars contain the statistical and systematical errors.

In conclusion, we may summarize as follows. The emission of coincident deuteron-nucleon pairs following π absorption in $^4\mathrm{He}$ is consistent with the assumption of a quasifree absorption on a $3N$ subsystem. While the fourth nucleon acts as a spectator, the pion absorption mechanism in which the deuteron-nucleon pair receives the energy is not yet clear. There are attempts to describe the emission of composite particles following pion absorption by resorting to nucleon-nucleon interaction in the final state.[18] Only a detailed investigation, however, will show whether this concept is able to explain the data or whether additional mechanisms are needed. In this context the relation of this absorption mode with the recently discovered emission of three separate nucleons is very intriguing. Both of these three-nucleon emission channels deserve further study in particular since an explanation for a long-standing discrepancy between the measured total-absorption cross section and that of the quasifree $2N$ absorption mode[5] is still missing.

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[1] G. Backenstoss *et al.*, Phys. Rev. Lett. **55**, 2782 (1985).

[2] K. A. Aniol *et al.*, Phys. Rev. C **33**, 1714 (1986).

[3] D. Gotta *et al.*, Phys. Lett. **112B**, 129 (1982); G. Backenstoss *et al.*, Nucl. Phys. **A448**, 567 (1986).

[4] P. Salvisberg, diplomarbeit, University of Basel, 1985 (unpublished), and to be published.

[5] D. Ashery and J. P. Schiffer, Annu. Rev. Nucl. Part. Sci. **36**, 207 (1986).

[6] M. Furić *et al.*, Phys. Lett. **39B**, 629 (1972); J. Erö *et al.*, Nucl. Phys. **A386**, 484 (1982).

[7] J. Källne *et al.*, Phys. Lett. **97B**, 205 (1980).

[8] R. J. Barrett *et al.*, Nucl. Phys. **A216**, 145 (1973).

[9] F. Balestra *et al.*, Nuovo Cimento **92A**, 139 (1986).

[10] S. Cierjacks *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **238**, 354 (1985).

[11] T. Petković, dissertation, Zagreb University, 1986 (unpublished).

[12] V. A. Goldstein *et al.*, Nucl. Phys. **A355**, 333 (1981).

[13] G. Backenstoss *et al.*, to be published.

[14] J. Källne *et al.*, Phys. Rev. C **24**, 1102 (1981).

[15] M. Dörr *et al.*, Nucl. Phys. **A445**, 557 (1985).

[16] W. R. Wharton *et al.*, Phys. Rev. C **33**, 1435 (1986).

[17] H. Yokota *et al.*, Phys. Lett. B **175**, 23 (1986).

[18] H. W. Fearing, Phys. Rev. C **16**, 313 (1977); M. P. Locher and H. J. Weber, Nucl. Phys. **B76**, 400 (1974).