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### **published in**

Default journal

1992

### **DOI (link to publisher)**

[10.1103/PhysRevC.46.R20](https://doi.org/10.1103/PhysRevC.46.R20)

### **document version**

Publisher's PDF, also known as Version of record

### [Link to publication in VU Research Portal](#)

### **citation for published version (APA)**

Bauer, T. S., Boberg, P., Breuer, H., de Laat, C. T. A. M., Geerling, F., Hamers, R., Hyman, S., Konijn, J., Lefevere, Y., Taal, A., van Dantzig, R., Visschers, J. L., & Ykema, R. (1992). Pion absorption followed by multinucleon emission. *Default journal*. <https://doi.org/10.1103/PhysRevC.46.R20>

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### Pion absorption followed by multinucleon emission

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(Received 5 November 1991)

Absorption of positive pions on  $^{16}\text{O}$  at 65 MeV has been measured with a large solid angle detector, covering also noncoplanar kinematics. Cross sections for reactions leading to little explored final states with three or four energetic nucleons ( $ppp$ ,  $pd$ , and  $ppd$ ) have been determined. These processes contribute about  $\frac{1}{3}$  to the total absorption cross section. Roughly  $\frac{1}{10}$  of all charged coincidence events involves the emission of a deuteron. Evidence for backward-peaked direct deuteron emission in the  $pd$  and  $ppd$  channels has been found.

PACS number(s): 25.80.Ls

Pion-nucleus interactions at energies below 300 MeV are dominated by the creation of an intermediate  $\Delta$ -nuclear state. In the pion absorption channel the deexcitation of such a state can occur through the emission of nucleons. At a pion energy of 65 MeV, well below the  $\Delta$  resonance, pion absorption contributes more than one-third to the total pion-nucleus reaction cross section [1], and couples to all other reaction channels. The strength of the simplest absorption mode, quasi-deuteron absorption (QDA), while still not well settled [1–6], does not exhaust the total absorption cross section. At pion energies above 115 MeV, this is even valid after correction for losses caused by final-state interactions (FSI), whereas at 65 MeV, QDA + FSI represents  $82 \pm 25\%$  of the total absorption cross section [7]. A sophisticated parameter-free model [8], based on the  $\Delta$ -hole formalism in conjunction with a two-nucleon absorption model, describes major aspects of inclusive  $(\pi^+, p)$  data for  $^{12}\text{C}$  up to a factor of 1.6. However, it fails to reproduce the total absorption cross section by a factor of 2 and the  $(\pi^+, pp)$  coincidence yield by about a factor of 4. Since absorption on one single bound nucleon is very unlikely [9], and two-nucleon absorption including FSI is apparently insufficient to describe the total absorption cross section, mechanisms involving more than two nucleons (hereafter called multinucleon) are needed to explain the data. The prediction by Oset, Futami, and Toki [10] that at low energies the two-nucleon absorption channel is nearly exhaustive, has not yet been tested experimentally.

Already bubble chamber data [11] showed the occurrence of multinucleon tracks. Yet, in recent experiments only modest contributions of multinucleon emission were observed [12–16]. For  $^{12}\text{C}$ , less than 5% of the absorption cross section at 130 MeV was found to result in direct three nucleon processes, and even less in the absorption on four nucleons [16]. These figures do not represent the total three or four nucleon yield, but only the direct processes after subtraction of two-step contributions. For  $^4\text{He}$ , contributions of 15% and 8% for three- and four-nucleon absorption, respectively, have been reported [17]. Thus the hypothesis that the missing absorption strength corresponds to multinucleon absorption has so far not been supported by direct experimental evidence. In fact, only for nuclei up to  $^4\text{He}$ , a more or less complete breakdown into different reaction channels has been accomplished. For heavier nuclei so far, most of the discussion has concentrated on the coincident emission of two or three nucleons only.

A direct, “genuine” multinucleon ( $N \geq 3$ ) absorption process, leading to the direct emission of more than two nucleons, is supposed to involve  $N$  nucleons in one reaction step. In contrast, two-step processes contain an “elementary” two-nucleon absorption process preceded by an initial-state interaction (ISI), or followed by a final-state interaction. Explicit two-step mechanisms have been reported [2,18], but the experimental distinction between direct and sequential mechanisms is in general difficult to make. In the latter case, one implicitly assumes that between two subsequent steps the particles are on the mass shell. In the distinction between “multi- $N$  absorption” and “two- $N$  absorption with ISI or FSI,” the question arises whether these ISI or FSI are part of the genuine absorption process or not. In a comparison to Monte Carlo simulations our data are consistent with a mixture of one-step three- and four-nucleon absorption processes but a sequential process cannot be excluded. We call a process in which  $N$  fast nucleons are emitted (excluding thereby slow evaporation products) an “ $N$ -nucleon emission process” (3NE, 4NE for  $N=3, 4$ ). We do not attempt to

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identify in any detail the underlying absorption mechanism. Specifically we do not separate the cross section into genuine three- or four-nucleon absorption processes and two-step mechanisms.

In this paper we report on a study on  $\pi^+$  absorption on  $^{16}\text{O}$  leading to coincidences of  $\geq 2$  charged particles using a large solid angle detector array covering 40% of  $4\pi$  sr (out-of-plane angle  $\beta$ ,  $-40^\circ < \beta < +40^\circ$ , in-plane angle  $\Theta$ ,  $20^\circ < |\Theta| < 160^\circ$ ). This setup samples a substantial part of the multinucleon phase space. Preliminary data have been presented elsewhere [19]. In the present paper we discuss three reaction channels involving  $\geq 3$  nucleons [ $(\pi^+, ppp)$ ,  $(\pi^+, pd)$ , and  $(\pi^+, ppd)$ ].

The experiment [20,21] was performed at the electron accelerator MEA of NIKHEF, using a secondary  $\pi^+$  beam of 65 MeV. Sixteen scintillator plastic telescopes of dimensions  $100 \times 18 \times 18 \text{ cm}^3$  ( $E$  detector) and  $102 \times 20 \times 1 \text{ cm}^3$  ( $\Delta E$  detector) were placed vertically around the target at distances of between 57 and 77 cm from the target. The energy resolution was slightly better than 10% for a 100-MeV proton. The horizontal detector width limited the angular resolution to about  $18^\circ$ . Particle identification was achieved by comparing energy and flight time for particles stopped in the  $\Delta E$  detector, and via the  $\Delta E$ - $E$  method for particles with a longer range. Three scintillators served to identify incoming pions by means of flight time. Heavy water ( $\text{D}_2\text{O}$ ) was contained in three mylar target cylinders of 7 mm diameter, each tagged by a scintillator. The  $\text{D}_2$  content served for energy calibration and for cross-section normalization [22]. The data have been corrected for mean-energy losses in the target, air, etc., and for background produced in materials other than  $^{16}\text{O}$ . Thresholds for the data analysis have been set to a kinetic energy at the center of the target of 25 MeV for protons (50 MeV for protons in  $pd$  events) and 50 MeV for deuterons.

To interpret the data, a Monte Carlo (MC) code [23] was used with an event generator which assumes that energy and momentum of the pion are absorbed by  $X$  nucleons ( $X=2,3,4\dots$ ), each moving independently with a Gaussian momentum probability distribution with variance  $k_F^2$ . The remainder of the nucleus acts as a spectator and carries an excitation energy  $E_X$  with uniform probability between 0 and 75 MeV (50 MeV for the  $pppN$  final state). These values correspond to the experimental cutoff. In the absence of any detailed experimental evidence for narrow structures, and since our energy resolution cannot resolve any discrete final states, a flat energy distribution has been chosen as the most simple one. The probability to find an ensemble of  $X$  independently moving nucleons with a combined momentum of  $k_c$  is given by

$$\rho(k_c) = \frac{k_c^2}{k_F^3 X (2\pi X)^{1/2}} \exp(-k_c^2/2k_F^2 X). \quad (1)$$

The value of  $k_F = 110 \text{ MeV}/c$ , in agreement with a mean value for the momentum distributions of  $s$ - and  $p$ -shell protons extracted from electron-scattering experiments [24], has been determined from a fit to the missing momentum spectrum of the  $^{16}\text{O}(\pi^+, pp)$  reaction for small missing energies, which is dominated by the QDA

mechanism [2,4]. The vector momenta of the  $X$  outgoing nucleons follow a phase-space distribution in the center-of-mass frame of the absorbing cluster. The MC simulation takes into account the full three-dimensional geometry of the setup as well as all thresholds and thus simulates the acceptance of our experiment.

Figure 1(a) shows the spectrum of the sum of the kinetic energies of three coincident protons,  $T_{\text{sum}}$ . There are no counts above the kinematical limit (185 MeV) confirming the good background rejection. The cutoff between 80 and 100 MeV is caused by the acceptance of the apparatus. The steep rise at the kinematical limit agrees with 3NE simulations, whereas the assumption of a 4NE

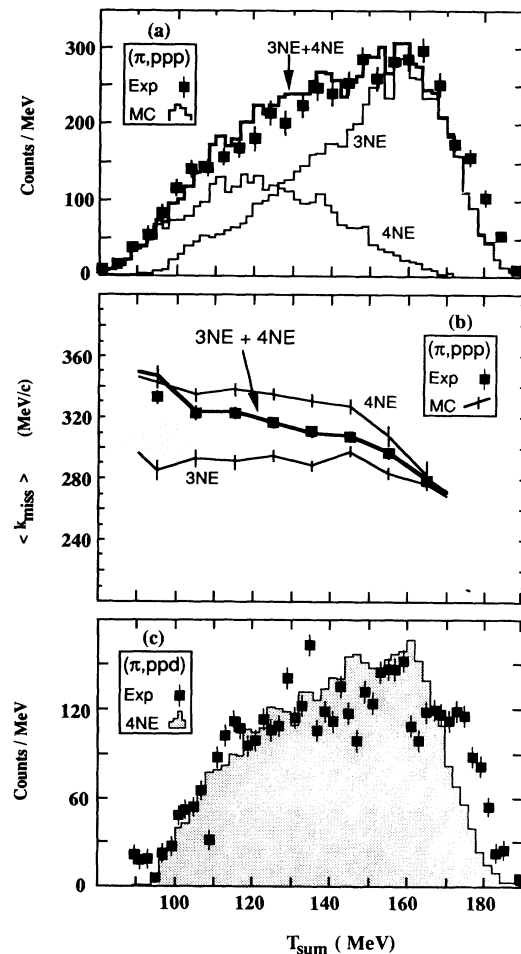


FIG. 1. (a) Spectrum of the summed kinetic energies of three protons,  $T_{\text{sum}}$ , emitted after absorption of  $\pi^+$  at 65 MeV on  $^{16}\text{O}$ . The background has been subtracted. Squares: experiment. Thin lines: MC simulations for 3NE and 4NE processes. Thick line: sum of 3NE and 4NE simulations. (b) Mean-missing momentum,  $k_{\text{miss}}$ , of the data in (a) as a function of  $T_{\text{sum}}$  (squares). The thin lines represent the simulations for pure 3NE and 4NE processes. The thick line gives the result for an incoherent sum of 3NE and 4NE simulations. (c) Spectrum of  $T_{\text{sum}}$  for two protons and one deuteron, emitted after absorption of  $\pi^+$  at 65 MeV on  $^{16}\text{O}$ . The background has been subtracted. Squares: experiment. Histogram and shaded area: MC simulation for 4NE processes.

process, including an undetected nucleon carrying away energy, leads to a more gradual rise.

Excitation energies of even several hundred MeV are small compared to the mass of the residual system ( $13 \text{ GeV}/c^2$ ) and will influence the momentum of the recoiling system only slightly. Therefore, the missing momentum,  $k_{\text{miss}}$ , is a better signature of the different processes than  $T_{\text{sum}}$ . Figure 2(a) shows good agreement between the experimental results and 3NE, in contrast to the 4NE simulation which exhibits a small but systematic deviation. However, for small  $T_{\text{sum}} \leq 120 \text{ MeV}$ , the region in which 4NE may play a dominant role [Fig. 1(a)], the experimental spectrum of  $k_{\text{miss}}$  is reproduced by the 4NE simulations [Fig. 2(b)]. A plot of the mean value of  $k_{\text{miss}}$  vs  $T_{\text{sum}}$  [Fig. 1(b)] confirms the presence of 4NE events. For decreasing  $T_{\text{sum}}$  the data exhibit a trend towards higher mean  $k_{\text{miss}}$  which is incompatible with the magnitude and the nearly constant behavior predicted by pure 3NE simulations, but which is compatible with a mixture of 3NE and 4NE processes. This dependency can be exploited to decompose the yield of three detected protons into components of 3 and of 4 emitted nucleons. The re-

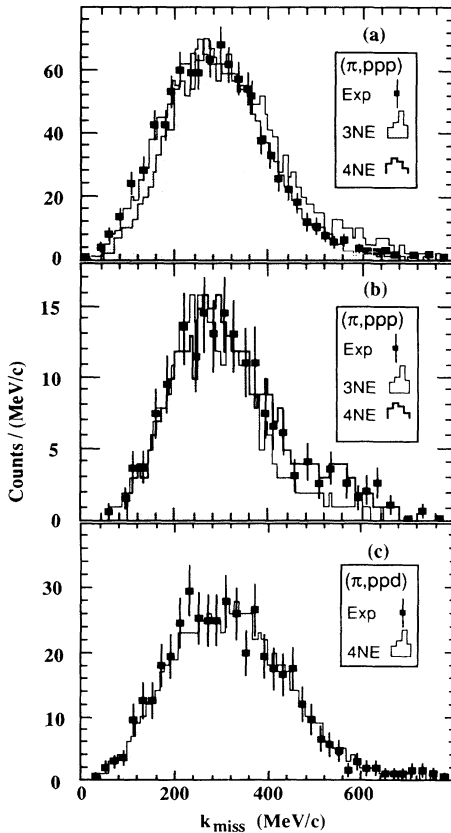


FIG. 2. (a) Spectrum of missing momentum,  $k_{\text{miss}}$ , for three-fold proton coincidences; experimental points are compared with MC simulations (shaded area: 3NE; solid line: 4NE). (b) As in (a) but only data with a summed energy,  $T_{\text{sum}}$ , below 120 MeV (squares) are compared with 3NE (shaded area) and 4NE (solid line) simulations. (c) Spectrum of  $k_{\text{miss}}$  for the  $ppd$  reaction; experimental points are compared to 4NE simulations (shaded area).

sults for the different contributions are given in Table I, and represented in Fig. 1(a) by the thick line. The presentation of the data in Figs. 1 and 2 does not allow for a separation of direct multinucleon absorption from two- $N$  absorption in a sequential process. However, we believe it is unlikely that ISI and FSI can account for the majority of  $ppp$  events both from 3NE and 4NE. Considering the 73 mb extracted for  $pp$ -2NE events, a cross section of 8 mb for  $ppp$ -3NE is compatible with 2NE accompanied by nucleon knockout. One cannot expect FSI, which requires one additional sequential step, to produce a  $ppp$ -4NE cross section (12 mb) even larger than the one for  $ppp$ -3NE (8 mb).

Deuteron emission after pion absorption has been reported previously (e.g., [11,25–27]), but usually is not discussed as a strong channel (e.g., [3,16]). In roughly  $\frac{1}{10}$  of all twofold, and in  $\frac{1}{3}$  of all threefold charged coincidences, we detected a deuteron. The two reaction channels  $(\pi^+, pd)$  and  $(\pi^+, ppd)$  contribute significantly to 3NE and 4NE (Table I). Figure 1(c) compares the energy spectrum for  $ppd$  events with the MC simulation. The discrepancy between data and MC simulation at high  $T_{\text{sum}}$  might indicate the preferential excitation of low-lying states in the residual  $^{12}\text{C}$  nucleus. Figure 2(c) shows the corresponding missing momentum distribution which is perfectly fitted by the MC simulation up to missing momenta as high as 600 MeV/c.

In the analysis of  $(\pi^+, pd)$  events, which was done in complete analogy to the analysis of  $(\pi^+, pp)$  events, the  $pd$  angular correlations have been determined [21]. For a given proton angle the widths of the angular correlations of  $pp$  and  $pd$  relative angles are almost identical, consistent with a two-body absorption process in which the angular correlation is smeared out by the Fermi (recoil) momentum of the residual nucleus. A striking feature, however, is the completely different angular dependence of the  $pd$  events as compared to the  $pp$  events. After integration over the angular correlation and division by the MC generated data, the angular distribution for  $pp$  events is dominated by the typical  $\cos^2\theta$  dependence known for quasi deuteron absorption. In contrast, the resulting angular distribution for  $pd$  events, shown in Fig. 3(a) in the center-of-mass system of the  $(\pi^+, pd)$  reaction, is asymmetric about  $90^\circ$  and has a pronounced maximum for protons at forward angles (and consequently for deuterons at backward angles). While the angular distribution for  $pd$  events might be compatible with a small rise for small deuteron angles, the deuteron angular distribution for  $ppd$  events increases monotonically with scattering angle, as can be seen in Fig. 3(b). In contrast, the  $ppp$  angular distribution is essentially flat.

The differences in the angular distributions of reaction channels with and without a deuteron strongly support the interpretation that the origin of  $pd$  and  $ppd$  events is not dominated by a FSI process in which a proton in a primary  $pp$  or  $ppp$  process picks up a neutron in a secondary step to form a deuteron. Such a process is expected to largely preserve the underlying primary angular distribution of  $pp$  or  $ppp$  events, respectively. While a certain fraction of the data may be due to such processes, the deuteron angular distributions indicate a strong direct

TABLE I. Cross sections  $\sigma_{\text{abs}}$  for pion absorption involving different numbers of nucleons in  $^{16}\text{O}$  at  $T_{\pi}=65$  MeV and their relative contribution to the total absorption cross section  $\sigma_{\text{abs}}^{\text{tot}}$  (estimated to be  $140 \pm 40$  mb from [29]) The quoted errors are a combination of the statistical error, the error in the normalization, and an estimate of the uncertainty introduced by the separation of the 3NE and 4NE processes.  $E_X$  is the excitation energy of the residual nucleus. The asterisks denote estimated values.

Label	Absorbing nucleons	Detected config.	$\sigma_{\text{abs}}$ (mb)	$E_X$ (MeV)	$\sigma_{\text{abs}}/\sigma_{\text{abs}}^{\text{tot}}$ (%)
3NE	$ppn$	$ppp$	$8 \pm 2$	0–75	$5.5 \pm 2$
3NE	$pnn$	$pd$	$7 \pm 1$	0–75	$5 \pm 2$
3NE	$pnn$	$ppn$	$8-16^*$	0–75	$5.5-11$
4NE	$pppN$	$ppp$	$8 \pm 3$	0–50	$5.5 \pm 3$
4NE	$pppN$	$ppp$	$4 \pm 2^*$	50–75	$3 \pm 2$
4NE	$ppnn$	$ppd$	$9 \pm 1$	0–75	$6.5 \pm 2$
Total:					
3NE+4NE			$48 \pm 6$	0–75	$34 \pm 11$
2NE	$pn$	$pp$	$73 \pm 7$	0–100	$55 \pm 5$

channel for the  $pd$  and  $ppd$  events. In fact, the distinctive shape of the angular distributions for these events is strongly reminiscent of those also found in the reactions  $^3\text{He}(\pi^-,n)d$  [13] and  $^7\text{Li}(\pi^+,pd)^4\text{He}_{\text{g.s.}}$  [28], which in these cases have been interpreted as a signature for a

direct process. The similarity of the angular distributions for the  $(\pi^+,pd)$  and  $(\pi^+,ppd)$  reactions make it possible that the  $ppd$  events could be the result of a  $pd$  reaction accompanied by a knockout of an additional proton in a FSI. The relatively large cross sections for  $ppd$  events, however, indicate that this cannot be the only production channel.

All extracted cross sections are compiled in Table I. The MC simulations provide an extrapolation into the unmeasured regions. The yield of three detected protons has been decomposed into contributions from 3NE and 4NE processes as described above. Due to the detection thresholds the values in Table I represent lower limits only. For a direct comparison of the  $(pppN)$  channel with the remaining reactions, the higher effective threshold introduced by the undetected nucleon  $N$  has to be considered and is estimated to be half the measured one, i.e.,  $4 \pm 2$  mb for excitation energies  $E_X$  between 50 and 75 MeV. Thus, 4NE [ $(\pi^+,pppN)$  and  $(\pi^+,ppd)$ ] contributes a total of 21 mb, or 15% of the total absorption cross section of 65-MeV pions on  $^{16}\text{O}$  estimated to be  $140 \pm 40$  mb [29]. The strength of the unmeasured  $ppn$  channel is estimated to at least equal the detected  $ppp$  strength ( $8 \pm 2$  mb). Experimental values twice as large as the  $ppp$  cross section have been reported [13]. This brings the contribution of the three-nucleon final states to some 15%–20% as well. These numbers are of the same order as those obtained by Steinacher *et al.* [17] for absorption on three and four nucleons, respectively, in  $^4\text{He}$ . Note that the 73 mb (Table I, [21,30]) we find for 2NE events includes cross section from events that do not agree with QDA kinematics.

Previous pion absorption coincidence experiments have been performed with coplanar setups, whereas final states with more than three particles are not restricted to coplanar momentum vectors and are, therefore, suppressed by such setups. The angular acceptance alone of our apparatus for uncorrelated threefold coincidences is  $6\% \text{ of } 64\pi^3$ , roughly 500 times the acceptance of the apparatus used in a previous threefold coincidence experimental [16]. In addition, the geometry of our apparatus samples a larger fraction of the available phase space, depending

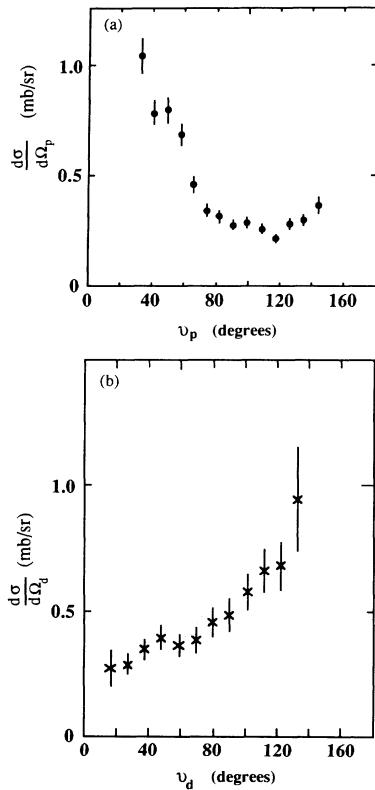


FIG. 3. (a) Differential cross section for the reaction  $^{16}\text{O}(\pi^+,pd)$  as a function of center-of-mass angle. (b) Differential cross section of a deuteron in coincidence with a proton pair, as a function of the deuteron angle for  $E_x < 25$  MeV. The experimental data in (a) and (b) have both been divided by the Monte Carlo phase space results.

on the reaction. Taking into account  $73 \pm 7$  mb (55% of the total absorption cross section) detected in two-nucleon final states (Table I), we identify a total of  $121^{+13}_0$  mb,  $85^{+11}_8\%$  of the total absorption cross section on  $^{16}\text{O}$ . For the mean number of participating nucleons in the process of pion absorption on  $^{16}\text{O}$  we obtain a value of  $2.5^{+1.0}_{-0.5}$ , slightly smaller than the value found at higher energies by McKeown *et al.* [31].

In conclusion, we have shown that even at this low pion energy a considerable fraction of the total pion absorption cross section on  $^{16}\text{O}$ , namely,  $\frac{1}{3}$ , leads to the emission of 3 and 4 nucleons. Some additional 3NE and 4NE absorption strength may be present below the energy thresholds. The emission of deuterons occurs for some 10% of the total absorption cross section. The angular distribution for  $(\pi^+, pd)$  events is similar to the one for the "elementary"  $^3\text{He}(\pi^-, nd)$  process, indicating direct pion absorption on a tritonlike configuration in  $^{16}\text{O}$ . This channel alone rep-

resents 5% of the total absorption cross section at 65 MeV. According to our analysis, each of the channels  $ppp$ ,  $pd$ ,  $pppN$ , and  $ppd$ , represents between 5% and 8% of the total absorption cross section. The relative strength of especially the 4NE emission channel, which is roughly as strong as the 3NE emission channel, cannot be explained by a sequential model in which a two-nucleon absorption process is preceded or followed by another interaction. Thus direct multinucleon emission represents a fraction of the total absorption cross section considerably higher than previously found in experiments.

We are indebted to E. W. A. Lingeman and J. M. Bailey for their contributions to the installation of the experimental setup. Financial support by the Dutch Foundations FOM and NWO and by the U.S. National Science Foundation is gratefully acknowledged.

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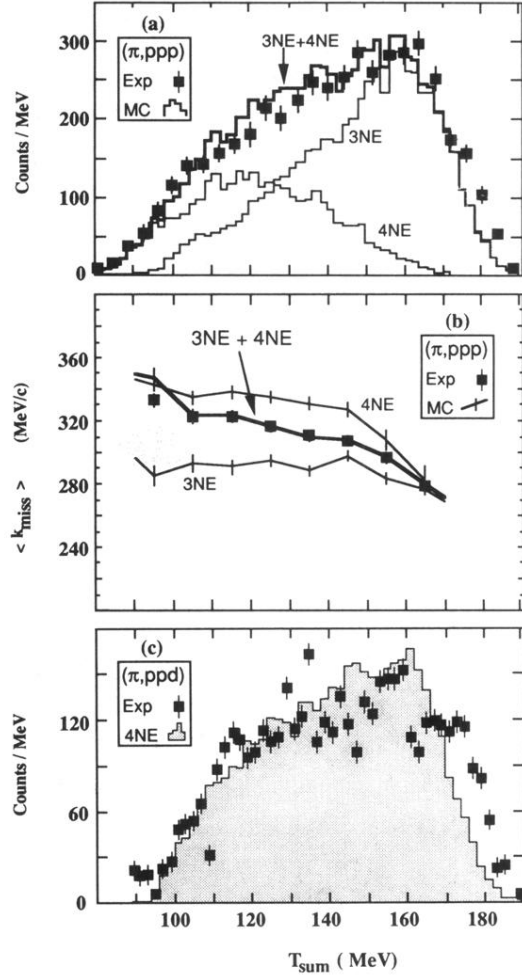


FIG. 1. (a) Spectrum of the summed kinetic energies of three protons,  $T_{\text{sum}}$ , emitted after absorption of  $\pi^+$  at 65 MeV on  ${}^{16}\text{O}$ . The background has been subtracted. Squares: experiment. Thin lines: MC simulations for 3NE and 4NE processes. Thick line: sum of 3NE and 4NE simulations. (b) Mean-missing momentum,  $k_{\text{miss}}$ , of the data in (a) as a function of  $T_{\text{sum}}$  (squares). The thin lines represent the simulations for pure 3NE and 4NE processes. The thick line gives the result for an incoherent sum of 3NE and 4NE simulations. (c) Spectrum of  $T_{\text{sum}}$  for two protons and one deuteron, emitted after absorption of  $\pi^+$  at 65 MeV on  ${}^{16}\text{O}$ . The background has been subtracted. Squares: experiment. Histogram and shaded area: MC simulation for 4NE processes.

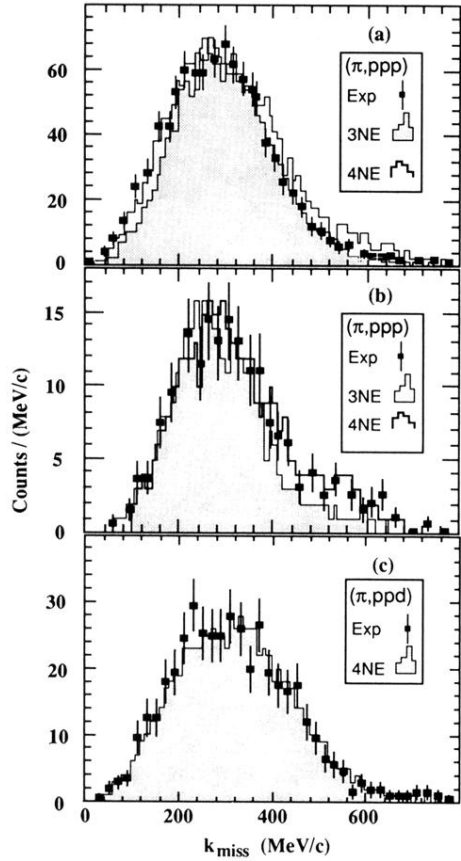


FIG. 2. (a) Spectrum of missing momentum,  $k_{\text{miss}}$ , for three-fold proton coincidences; experimental points are compared with MC simulations (shaded area: 3NE; solid line: 4NE). (b) As in (a) but only data with a summed energy,  $T_{\text{sum}}$ , below 120 MeV (squares) are compared with 3NE (shaded area) and 4NE (solid line) simulations. (c) Spectrum of  $k_{\text{miss}}$  for the  $ppd$  reaction; experimental points are compared to 4NE simulations (shaded area).