THE ABSORPTION OF π^- AT REST ON COMPLEX NUCLEI^{*)}

H.D. Engelhardt, C.W. Lewis^{†)} and H. Ullrich

CERN, Geneva, Switzerland
Institut für Experimentelle Kernphysik der Universität
und des Kernforschungszentrums Karlsruhe, Germany

ABSTRACT

The energy, width, and intensity of prompt nuclear γ -rays following capture of π^- at rest by ^9Be , ^{10}B , ^{16}O , ^{19}F , ^{31}P , Ca, and ^{93}Nb were measured with a Ge(Li) detector. In most cases it was possible to identify the final nucleus from the energy of the observed γ -ray. Using the measured Doppler-broadening of γ -rays from short-lived states, the vector sum momentum distribution of the emitted nucleons was calculated. From the measured γ -ray intensities, isotopic yields were deduced corresponding to the removal of from 1 to 12 nucleons. The average number of removed nucleons changes from 3.0 to 5.5 as the target varies from ^{16}O to ^{40}Ca . A comparison was made with data from both spallation reactions and multi-nucleon pick-up reactions.

Keywords:

E NUCLEAR REACTIONS ^9Be , ^{10}B , O, ^{19}F , ^{31}P , Ca, ^{93}Nb (π^- , γ), $E = 0$ MeV; measured E_γ , Doppler broadening, transition yields; deduced yields of single and multi-nucleon removal; deduced recoil momenta. ^{10}B enriched target.

Geneva - 14 August 1975

(To be submitted to Nuclear Physics)

^{*)} Work supported in part by the Bundesministerium für Forschung und Technologie of the Federal Republic of Germany.

^{†)} Present address: U.S. EPA, Research Triangle Park, North Carolina 27711, USA.

1. INTRODUCTION

Beginning several years ago a series of results has been published in which the interaction of pions with nuclei have been investigated by means of the prompt nuclear γ -rays that are emitted. These have included measurements both of pion absorption at rest¹⁻⁵⁾ and interaction of pions at non-zero kinetic energies⁶⁻⁹⁾. Such experiments, which have used Ge(Li) spectrometers for the γ -ray energy measurement, enjoy a number of advantages: a) technical simplicity; b) excellent energy resolution (several keV) which allows final states in the residual nuclei to be resolved and identified; c) possibility of surveying the relative importance of all reaction channels simultaneously; and d) ease of obtaining the angle-integrated cross-section (or absolute yield, in the case of pion absorption at rest) for excitation of a particular final state, relative to measurements based on the detection of emitted nucleons. At the same time the γ -ray technique is of course not without liabilities: reactions that lead directly to ground or long-lived excited states are unobservable, and it is impossible to learn the sequence or type of emitted particles which precede the formation of the final γ -ray emitting state.

Our measurements reported here deal only with pion absorption at rest. With such a restriction the interpretation is in principle simplified: the initial quantum state is reasonably well known from mesic atom experiments¹⁰⁾ and the reaction type is unambiguous. In contrast, none of the measurements done with energetic pions⁶⁻⁹⁾ have even been able to separate absorption processes from those in which the pion survives the nuclear interaction. An unusual feature of the high-energy pion bombardments is the apparent enhancement of γ -ray yields in residual nuclei corresponding to integral numbers of "alpha particles" (i.e. their nucleon equivalent) removed from the target nucleus^{6,7)}. It is thus, for example, of interest to look for such a feature in pion absorption at rest where the experimental conditions are better defined.

Following the description of the experimental equipment and procedure, measured γ -ray yields per absorbed pion are given for a series of target nuclei from ^9Be to ^{93}Nb . In addition, recoil momentum distributions are calculated from the Doppler broadening of a number of the observed γ -ray lines. Finally, the results are discussed both in terms of "direct" mechanisms (i.e. the possibility that absorption occurs on multi-nucleon "clusters"), and from a "spallation" point of view. The former interpretation is based on the combination of nuclear structure and pion-specific considerations. In contrast the latter explores the extent to which pions resemble any other hadron, in terms of the isotopic distribution of residual nuclei which results from their interaction with nuclei.

The present work gives complete results for the nuclei studied, in contrast to earlier papers, which have dealt only with selected transitions^{3,4}). In any case of inconsistency the present results and conclusions supercede those in the earlier reports.

2. EXPERIMENTAL METHOD

2.1 Apparatus and procedure

The measurements were performed with negative pion beams from the CERN Synchro-cyclotron. The bulk of the measurements were done at the muon channel ($E_{\pi} = 125$ MeV) although the low-energy pion (LEP) channel ($E_{\pi} = 80$ MeV) was also used. Target materials in which the pions were stopped in different experiments included isotopically separated ^{10}B , and natural Be, H_2O , LiF, P, Ca, and Nb.

In reaching the target, the pions traversed a conventional beam telescope consisting of (in order) two 10 mm thick plastic scintillators (counters 1 and 2), an energy degrader, and a 3 mm thick scintillator (counter 3) in contact with the target. An additional scintillator (counter 4) was in contact with the target on its downstream side. The over-all length of the beam telescope was typically about 80 cm. Counters 1-3 had areas of 10×10 cm², while counter 4 was 15×15 cm². The degrader material was either carbon or aluminium, depending on which target was under study, and the length was adjusted to cause the maximum number of pions to be brought to rest in the target. This adjustment was done by the usual range-curve technique in which the (1, 2, 3, 4) rate -- corresponding to stopped-pion logic -- was maximized. The effective target thickness in the direction of the pion beam was nominally 5 g/cm² for measurements at the muon channel and 3 g/cm² for the LEP channel. These numbers reflect the better energy resolution of the LEP channel compared with the muon channel -- 12 MeV versus 30 MeV (FWHM) -- as determined by the width of the pion peak in a range-curve measurement with a thin target. For the LEP measurements, the target plus counters 3 and 4 were inclined at 45° to the beam direction in order to minimize target self-absorption of the emitted γ -rays, which were detected at 90° to the beam axis.

The γ -ray detector was one of several 40 cm³ Ge(Li) spectrometers that were used during the course of the experiments, having an energy resolution, under beam conditions, which was typically 6 keV (FWHM) at 2.6 MeV. The typical distance from the target centre to the front face of the detector was 14 cm. A 10 mm thick scintillator (counter 5) covering the front face was used in anticoincidence to veto the effects of charged particles from the target reaching the detector. Except for the front face the detector was shielded with lead on all sides.

In order to measure the prompt γ -ray energy spectrum resulting from π^- absorption at rest, a Ge(Li) timing pulse and a (1, 2, 3, 4, 5) signal were required to be in fast coincidence (50 nsec), which opened the gate of a multichannel pulse-height analyser and allowed the associated Ge(Li) energy pulse to be recorded. Some special tests were also performed with modified electronics, as described in later sections. The counting rates for the numbers of pion stops, singles γ -rays, and γ -ray coincidences were typically of order 10^5 , 10^3 , and 10^2 per second,

respectively, so that problems of accidentals and detector resolution deterioration due to count rate were minimal.

The energy calibration of each Ge(Li) detector was done approximately with radioactive sources and then more precisely by the self-consistency of known energies of the more easily recognizable lines in the measured spectra themselves. An accuracy of ± 1 keV for γ -rays with energies up to 6 MeV was thus achieved. The absolute yield of each measured γ -ray line (the number of emitted γ -rays per stopped pion) was determined by normalizing to muonic X-ray yields by a method described in the Appendix.

2.2 Background

2.2.1 General

In the following discussions, "background" should be understood to have a very broad meaning, i.e. any line appearing in a γ -ray energy spectrum that is not the direct result of pion absorption at rest on a nucleus of the target. This background is composed of two parts, one characteristic of the particular target used, and the other unrelated to the target, as discussed below.

2.2.2 Target unrelated

This component is very easy to distinguish, as it is the set of lines that are common to all the measurements. Table 1 lists the most intense lines of this set. The particular lines and intensities will of course depend on the types of materials used near the Ge(Li) detector, and on geometrical factors.

2.2.3 Target related

The possibilities which can in principle contribute to this type of background are: a) pion absorption in flight; b) inelastic scattering or reactions of pions (and also of muons and electrons present as beam contaminations) in which the interacting particle is emitted at a large angle and thus simulates stopped-pion logic; c) muon absorption at rest; and d) secondary reactions in the target induced by the emission products of pion absorption at rest.

Discussing these possibilities in order, we first note that for (a) and (b) unreasonably large cross-sections would be required if the measured γ -ray yields had appreciable contributions from pion interactions in flight. Taking as an example pions coming to rest in a $5 \text{ g/cm}^2 \text{ H}_2\text{O}$ target, in order to simulate a yield of 1% per stopped pion an average cross-section exceeding 100 mb is necessary. Since this is for only one reaction channel, and since the average energy of the pions incident on the front face of the target is only about 20 MeV, such a value is inconsistent with pion total cross-sections at low energy. Concerning the effects of muon and electron contamination of the beam, both range-curve and

time-of-flight measurements showed that their fluxes were indeed comparable with that of the pions, but cross-sections of 100 mb size are equally unreasonable for particles that do not have a strong interaction. It should be noted, however, that the electrons are not entirely harmless, since the bremsstrahlung they produce probably makes an important contribution to the continuous background present in all the γ -ray spectra.

The origin of (c) is the relatively poor momentum resolution of the beam which causes a small part of the low-momentum tail of the muon flux to be brought to rest when the pion stop rate is maximized. Typically about 6% of the measured number of stops are actually due to muons, as could be determined from the measured yields of muonic X-rays (see ^{31}P discussion). In any case the resulting γ -rays are delayed and hence are effectively eliminated by the fast coincidence requirement.

The most important of the secondary reactions referred to in (d) are of course those due to neutrons. Their cross-sections for inelastic scattering are often large enough to cause appreciable excitation of states of the target nuclei. Indeed it is estimated that this is the dominant source of such γ -ray transitions which are visible in most of the spectra. On the other hand, it is expected that neutron interactions do not contribute significantly to the production of γ -rays from nuclei lighter than the target. The simplest evidence for such an assumption is the presence of γ -ray lines from nuclei that are one proton lighter than the target together with the complete absence of one neutron removal lines. If such lines were produced by neutron interactions, then on average the two nuclei would be produced with approximately the same probability. In contrast it is impossible to remove one neutron by π^- absorption, consistent with observation.

Finally, we note that the effective γ -ray yield per stop for processes (a), (b), and (d) is target thickness dependent, whereas for pion absorption at rest this quantity is independent of thickness. Most of the targets used were measured for both 3 and 5 g/cm² thicknesses, and the relative γ -ray yields in corresponding measurements were found to be approximately the same, except for target γ -rays from inelastic scattering, whose yield dependence on target thickness was qualitatively correct (see ^{31}P discussion).

3. RESULTS

3.1 Gamma-ray yields

3.1.1 Summary

The observed γ -rays and their yields are given in Tables 2-6. For each table the target nucleus is specified in column 1. The γ -ray energy region over which the measuring system was sensitive is given in column 2. The observed γ -ray energies listed in column 8 are accurate to about 1 keV, except in cases of severe Doppler broadening. The % yield of each γ -ray (number of emitted γ -rays per 100 absorbed pions) corrected for target self-absorption, and detector geometry and efficiency, is given in column 9. The error given for the yields includes only the estimated error in the detector relative efficiency and the uncertainty in the γ -ray peak area. Additional systematic errors may be as large as 20%. For targets in the form of compounds (LiF and H₂O) the listed yields have been corrected for the fraction of pions absorbed only by the nucleus of column 1, so that in effect the yields are for pions absorbed in a target of the pure element. The assumed origin of each γ -ray is indicated in columns 3 and 4. The branching ratio for the decay of the initial state by means of the transition given in column 4 is listed in column 5. The spin, parity, and lifetime of the initial state are given in columns 6 and 7. All information in columns 3-7 has been taken from refs. 11, except for the few cases indicated by alphabetical superscripts, for which more accurate information has recently been published. Each entry in the last column represents a sum of the yields for direct excitation of all excited states in the specified residual nucleus. Each is calculated from the appropriate yields in column 9, combined according to the known decay scheme of each nucleus. For several cases it was impossible to assign the observed γ -ray to a unique residual nucleus. In each such case the different possibilities are shown, linked by a common numerical superscript. Such ambiguities of course have the consequence that the corresponding isotopic yields are no longer unique but instead cover a range of possible values. In the following the experimental conditions and problems specific to each target are individually discussed.

3.1.2 Beryllium-9

No prompt γ -rays, except for the background lines seen with all targets, were observed when pions were stopped in a solid beryllium target of 2.6 g/cm² effective thickness. Since there are several γ -rays that can result from the decay of excited states in nuclei lighter than ⁹Be, and would be seen in the energy range covered by the detector, the null result is not a trivial observation. In particular the 478 keV ⁷Li γ -ray, corresponding to a (π^- , nn) reaction, is not seen. A practical consequence of the lack of γ -rays from this target is that it provided a convenient means to assess the target-unrelated background with other targets.

3.1.3 Boron-10

This measurement used an isotopically separated (99%) ^{10}B metallic powder target of 5.2 g/cm^2 effective thickness. The experiment was done under unfavourable beam-sharing conditions which resulted in a pion flux an order of magnitude smaller, and relative muon and electron fluxes significantly higher, than in all other measurements. One of the motivations of the experiment was to search for high-energy γ -rays from ^8Be . Accordingly the detector energy range was extended to 17 MeV. As seen in Table 2 however, the only transition which could be unambiguously established was that corresponding to the first excited state (477 keV) in ^7Li . The upper limit for excitation of the analogue state (429 keV) in ^7Be was 0.2% per stopped pion.

3.1.4 Oxygen-16

Prompt γ -rays from π^- absorption at rest in ^{16}O have been previously measured by Kossler et al.²⁾. We considered a remeasurement to be worth while under improved experimental conditions. In particular, the availability of a better quality pion beam allowed the use of a water target of 3 g/cm^2 effective thickness and 160 cm^3 volume, which were a factor 5 and at least two orders of magnitude smaller than the respective dimensions used in ref. 2. Such a decrease reduces uncertainties related to background as discussed in subsect. 2.2, and uncertainties in absolute yield determination, due to smaller γ -ray self-absorption effects and a better estimate of the true number of pion stops. In addition, aluminium instead of carbon was used for the pion energy degrader.

The prompt γ -ray spectrum obtained is shown in Fig. 1, from which the γ -ray yields given in Table 2 were derived. Since about 99% of all pions captured by an H_2O molecule are ultimately absorbed by the oxygen nucleus¹²⁾, the presence of hydrogen in the target has negligible influence.

The ^{12}C and ^{10}B γ -ray yields require special comment. Both can easily be confused with background lines associated with carbon in the telescope scintillators, the processes being inelastic scattering and the $^{12}\text{C}(\pi^-, \text{nn})^{10}\text{B}$ reaction¹³⁾, respectively. To eliminate this ambiguity (present in ref. 2) the water target was replaced by a beryllium target of the same stopping power and irradiated by the same total pion flux, i.e. two successive measurements under identical conditions. Since neither γ -ray can result from the beryllium target, and since the neutron spectra from the two targets should be similar in shape and intensity per pion absorption, the intensities of these γ -rays in the beryllium spectrum directly give the background contributions which must be subtracted from the water spectrum yields. The yields given in Table 2 have been corrected for backgrounds in this way.

In general the relative yields measured in the present experiment are similar to those given in ref. 2. However, the absolute yields from the present experiment are systematically higher by a factor of order three. A possible explanation for this discrepancy lies in the difficulty of accurately determining the true number of pion stops. For very thick targets pion out-scattering can cause this number to be overestimated, so that γ -ray yields per pion stop will be underestimated. In the Appendix details are given of the method we have used to determine our γ -ray absolute yields, based on a comparison with muonic X-ray yields, which largely avoids the stop number uncertainty.

The ^{14}N lines 1632 and 2313 keV, and the ^{12}C line all show appreciable Doppler broadening. The recoil momentum distributions which can be obtained from the broadening are discussed in subsec. 3.2. The properties of the ^{12}C line have been discussed earlier³⁾.

3.1.5 Fluorine-19

The prompt γ -ray spectrum resulting from pions stopped in a lithium fluoride powder target of 5 g/cm^2 effective thickness is shown in Fig. 2. A carbon pion energy degrader was used. The γ -ray yields given in Table 3 have been corrected so that they represent the number of γ -rays emitted per 100 pions absorbed in fluorine nuclei. To obtain the correction factor one must know the fluorine/lithium capture ratio in lithium fluoride. Since the ratio has not been measured for pions, the corresponding measurement¹⁴⁾ for muons, 3.6 ± 0.4 , has been used. Such an equality is commonly assumed and has been experimentally verified, for example, in CaO ¹⁵⁾. Accordingly the observed yields per pion stop have been multiplied by the factor $4.6/3.6$, resulting in the yields shown.

To verify that the observed 4440 keV ^{12}C γ -ray was not due to background, two short runs were made successively with a lithium fluoride and a beryllium target, using an aluminium energy degrader. By a comparison similar to that done with ^{16}O , the background contribution was found to be unimportant.

It should be noted that γ -rays from ^{17}N , which would result from the reaction (π^-, np) on ^{19}F , are not observed. Such γ -rays were carefully searched for using recent, more accurate, data¹⁶⁾ on the energies, branching ratios, and lifetimes of ^{17}N excited states, but without success.

3.1.6 Phosphorus-31

Gamma-ray yields from pions absorbed at rest in ^{31}P are given in Table 4. These results were obtained with a red phosphorus powder target of 5 g/cm^2 effective thickness and a carbon pion energy degrader. The spectrum from which the yields were obtained has been shown in ref. 4. The yields have been corrected for background by means of comparison with a background spectrum. The background

spectrum itself was obtained by increasing the length of the degrader so that the pions were stopped in front of the target, and then measuring the γ -ray spectrum in coincidence with the logical condition (1, 2, $\bar{3}$). The background correction was most significant for the two ^{27}Al lines.

Phosphorus was the lightest target nucleus in this study for which serious problems arose in deciding between alternative transition assignments based on the observed γ -ray energy alone. In several cases, in which choices differed by about 1 keV or less, other arguments were used to reject competitors. Transition possibilities that were considered but rejected were as follows:

- 1) 584 keV: ^{22}Na (583 - 0). The lifetime of this state is 350 nsec so that the observed intensity of this radiation would be strongly suppressed by the 50 nsec experimental resolving time.
- 2) 1273 keV: ^{22}Ne (1275 - 0). The ^{22}Ne state has a lifetime of 5 psec, which would allow virtually no Doppler broadening to occur, since the slowing down time is about 1 psec¹⁷⁾. The observed broadening, although small, is more consistent with the 0.4 psec lifetime of the ^{29}Si state. In addition, the ^{29}Si choice involves the first excited state of a residual nucleus which is expected in general to be strongly excited via the (π^-, nn) reaction.
- 3) 1266 keV: ^{30}P (1973 - 709). This state also has a 41% branch to ground, which is not observed, nor is the 709 keV line. The yield of the 1266 keV γ -ray showed a 40% decrease when the target volume was reduced by about a factor of 5. Even though this comparison was done under quite different conditions (different detectors, geometry, and beam line) it is thought to be quite accurate since the nearby 1273 keV line, whose yield should not show any variation with thickness, could be used as a calibration. The yield decrease is consistent with a secondary effect, in particular, with inelastic scattering in the target of neutrons originating from pion absorption processes.
- 4) 1368 keV: ^{22}Na (1952 - 583). The lifetime of this state is only 9 fsec, which would allow the full Doppler broadening to occur, assuming the state is directly populated. The amount observed is very small however, and is more consistent with the 1.8 psec lifetime of ^{24}Mg .
- 5) 1779 keV: ^{26}Mg (3588 - 1809). The observed Doppler broadening is inconsistent with the long lifetime (7 psec) of this state.
- 6) 2029 keV: ^{31}P (3295 - 1266). This state can also decay by emitting a 1061 keV γ -ray with a 19% branching ratio. A 0.15% upper limit for the yield of this γ -ray implies that the ^{31}P contribution to the 2029 keV yield is less than 0.6%, so that the dominant part is due to ^{29}Si .

- 7) 1015 keV: ^{28}Al (1014 - 0). This choice is possible only if the observed 985 keV line also originates from the decay of the same state in ^{28}Al . The 985 keV line, however, can also be identified with a first excited state to ground transition in ^{27}Mg . In spite of this ambiguity at most 25% of the observed 1015 keV intensity can be accounted for by the ^{28}Al transition, based on the known branching ratios for the 1014 keV ^{28}Al state, and the observed intensities of the 985 and 1015 keV lines.

The γ -ray of energy 2236 keV is consistent with a transition in either ^{30}Si or ^{31}P , on the basis of both energy and Doppler broadening. Considerable additional effort was spent in attempting to determine which identification is more likely. However, none of the experiments performed, which included target thickness variation, using (1, 2, 3, +4) telescope logic, and comparison with stopped muons, was able to uniquely assign the γ -ray to one or the other of the transitions. It is interesting to note that a delayed γ -ray spectrum (which selected γ -rays emitted during a 1 μsec interval beginning 80 nsec after the 1, 2, 3, $\bar{4}$ signal) measured with stopped muons showed this γ -ray to be the most strongly excited line present, presumably from ^{30}Si , owing to a (μ^-, n) reaction. In the stopped pion measurement the muon contamination of the pion beam was approximately 5/79, based on the observed μ - ^{31}P (2p-1s) yield (5%) and the known yield per stopped muon (79%) for this transition¹⁸⁾. However, the muon contribution to the 2236 keV line in the prompt stopped pion measurement was less than 10% of the observed intensity. Independently of muonic X-ray considerations, this conclusion was based on examination of a delayed spectrum taken simultaneously with the normal prompt spectrum using stopped pions, and taking into account the lifetime¹⁹⁾ for muonic absorption in ^{31}P .

3.1.7 Calcium

The prompt γ -ray spectrum obtained at the muon channel with a natural calcium pellet target of 4.5 g/cm^2 effective thickness, using a carbon energy degrader for the pions, is shown in Fig. 3. The resulting γ -ray yields are given in Table 5. A measurement at the LEP channel with a 2.8 g/cm^2 CaO powder target gave similar relative yields. In the following, transition identifications which were considered but rejected are discussed, along with the few cases that could not be decided without ambiguity.

- 1) 671 keV: ^{38}Cl (671 - 0). The lifetime of this state is 716 msec so that the resulting transition is entirely excluded by the 50 nsec experimental resolving time.
- 2) 771 keV: ^{40}K (800 - 30). In principle this state could be excited by pion radiative capture or a secondary (n, p) reaction. However, since none of the other spectra showed any evidence for either of these reactions, the more likely origin of the γ -ray is ^{38}Ar (4710 - 3937). This is also consistent with the presence of a 3937 keV line from the subsequent de-excitation.
- 3) 1267 keV: ^{31}P (1266 - 0) and ^{39}Ar (1267 - 0). The energies of these two transitions are indistinguishable, and the lifetime of the ^{39}Ar state has not been measured. The lifetime however has been predicted²⁸⁾ to be 1.5 psec (or twice this value, depending on the assumptions made), which, if confirmed, suggests that the narrow component of the line shape is mainly due to ^{39}Ar while the broadened remainder is from ^{31}P .
- 4) 1727 keV: ^{37}Cl (1727 - 0). At the same energy there is a peak due to background, however with a yield smaller than the observed one. The ^{37}Cl (1727 - 0) transition should show Doppler broadening, its lifetime being 187 fsec. The observed line is however narrow, only its foot is broadened. An accurate yield for the ^{37}Cl (1727 - 0) transition could therefore not be obtained.
- 5) 1991 keV: ^{33}Cl (1990 - 0). The lack of any Doppler broadening for this line is inconsistent with the 70 fsec lifetime corresponding to ^{33}Cl , but agrees with the 1.47 nsec lifetime associated with ^{35}S (1991 - 0).
- 6) 2208 keV: ^{38}Ca (2206 - 0) and ^{27}Al (2209 - 0). The ^{38}Ca choice is very improbable, since it cannot result from a π^- absorption process, and there is no evidence in any of the other spectra for two-neutron knockout due to secondary reactions in the target. A 2209 keV ^{27}Al peak appears in all spectra as a background line, but it is always Doppler-broadened in contrast to the sharp peak seen at 2208 keV in Fig. 3. Thus the dominant origin of the line is attributed to ^{36}Ar (4178 - 1970). This choice is consistent with the long lifetime ($> 3 \text{ psec}$) of the 4178 keV ^{36}Ar state and the observed yield of the

subsequent ^{36}Ar (1970 - 0) transition. However, about 20% of the total intensity of the 2208 keV line is assumed to come from the transition ^{40}K (3100 - 892), and this division of intensity is indicated in Table 5. This is required by the observation of a peak corresponding to ^{40}K (3100 - 0). From the yield and branching ratio of the latter transition, the yield of the other branch could be calculated.

- 7) 2229 keV: ^{32}P (2230 - 0) and ^{40}K (2261 - 30). After subtraction of the relatively narrow peaks at 2208 keV and 2233 keV, and correcting for the presence of the 2209 keV ^{27}Al background line, there remains a broad symmetric peak whose centre is 2229 keV. Neither the ^{32}P nor the ^{40}K transition can contribute a significant portion of the intensity of this peak since the excited state for both cases has another decay branch, but neither is observed in the spectrum of Fig. 3. No such argument can be used to exclude the ^{34}Cl (2376 - 146) transition, but since the lifetime for the ^{34}Cl state is unknown, it is impossible to judge whether the observed large Doppler broadening is consistent with this choice. Consequently the most probable origin of the 2229 keV peak is either ^{32}S (2230 - 0) or ^{32}S (4459 - 2230). The peculiar accident that both the energies of these two transitions and the corresponding lifetime are experimentally indistinguishable causes the isotopic yield for ^{32}S to be uncertain by a factor of two.
- 8) 2233 keV: ^{30}Si (2236 - 0). This choice has been rejected in favour of ^{31}P (2234 - 0) on the basis of the better agreement with energy.

3.1.8 Niobium-93

Table 6 shows the γ -ray yields from negative pions absorbed at rest in a ^{93}Nb metallic target of 5 g/cm² effective thickness, using a pion beam at the muon channel and a carbon pion degrader. The spectrum is shown in Fig. 4. Some difficulties arose because of the high level density of the residual nuclei and the partly missing information about exact energies, electromagnetic decay probabilities and life-times of the levels in question. In the cases of unresolved ambiguity, different possible assignments for the same γ -ray energy are included in the table under the same subscript, using corrections identical to those for the ^{40}Ca table. Transition probabilities that were considered but rejected, or included as alternatives and which therefore need a comment, are the following:

- 1) 448 keV: ^{92}Zr (1383 - 934). This possibility was considered, but cannot explain the measured yield because the (934 - 0) transition is only observed with a yield of 0.8%, whereas the 449 keV γ -ray shows a yield of 3.2%. Therefore at most 25% of the observed γ -ray intensity may be due to the (1383 - 934) transition in ^{92}Zr .

2) 524 keV: ^{83}Kr (562 - 41^{isomer}). This state in ^{83}Kr decays with about 70% to the 41 keV state - an isomer with 1.9 h half-life - and with 30% to the 9 keV state. The (562 - 9) keV transition should then be observed with a yield of 0.5%, but it was not seen.

3) 540 keV: ^{86}Rb (1027 - 488). The non-observation of a sufficiently strong 488 keV γ -line rules out this possibility, the 488 keV state not being an isomer.

^{85}Sr (769 - 231). The absence of a (769 - 0) transition, which should show a comparable branching ratio resulting in a yield of 1.6% rules out this assignment.

0.5% of the yield of the 540 keV γ -ray is due to background.

4) 560 keV: ^{81}Br (836 - 276). The (836 - 0) transition with a branching ratio of 29% is not seen above background.

^{90}Zr (2748 - 2186). The 560 keV γ -ray is observed with a yield of 1.9%, whereas the 2186 keV γ -ray shows a yield of 0.6%. Therefore only a small fraction, if any, can be due to ^{90}Zr .

5) 660 keV: ^{84}Sr (1453 - 793). The (793 - 0) transition in ^{84}Sr has been observed with a yield of 3.6%. There is, however, a second cascade from the 176 keV to the 793 keV state, which could be unambiguously identified and which has a yield of 3.7%. The (1453 - 793) transition is therefore excluded.

^{93}Nb (1605 - 950). This possibility was excluded, as other known transitions from the 1605 keV state have not been observed.

6) 751 keV: ^{85}Kr (1050 - 305). This attribution is very unlikely, because of an energy difference of 6 keV.

7) 778 keV: ^{90}Y (777 - 0). This transition cannot be strictly excluded, however, part (1%) of the 778 keV γ -ray must be unambiguously attributed to the (777 - 0) keV transition in ^{82}Kr , the ^{82}Kr (1821 - 777) keV transition being observed with a 1% yield.

8) 792 keV: ^{87}Y (792 - 0). Energy and level scheme considerations do not exclude this transition. The 792 keV γ -ray is, however, unambiguously attributed to the (792 - 0) transition in ^{84}S , because the 976 keV γ -ray attributed to the ^{84}Sr (1767 - 792) transition has been observed with a similar yield.

9) 948 keV: ^{93}Zr (947 - 0). This transition cannot be strictly excluded. The line was however attributed to ^{93}Nb , because three cascade transitions (1335 - 950, 1491 - 950, and 2003 - 950) in ^{93}Nb are observed with consistent yields.

- 10) 1022 keV: ^{86}Rb (1026 - 0). There is a large branching ratio for ^{86}Rb (1026 - 488); the resulting γ -ray of 538 is at the same energy as a background peak, and the 488 keV transition is statistically not assured.
- 11) 1056 keV: ^{93}Nb (2003 - 950). From energy and level scheme considerations this transition cannot be ruled out as the 950 keV γ -ray is observed with a compatible yield. However, three more transitions feeding the 950 keV level have been identified and exhaust already the yield of the 950 keV transition. The 1056 keV γ -ray can also be attributed to the ^{88}Zr (1058 - 0) transition and this is considered to be more likely.
- 12) 1128 keV: ^{85}Sr (1354 - 231). This transition has a branching ratio of 75%, the remainder being equally distributed among transitions giving γ -rays of 1354 keV and 550 keV, which are not observed in the spectrum. However, the expected yields are at the limit of observation (0.1%).

The 1127 keV γ -ray has a yield of 1.6%; 0.2% is due to background from ^{26}Mg , at most 0.8% is attributed to the ^{92}Zr (2067 - 935) transition, the ^{92}Zr (935 - 0) transition being observed with a yield of 0.8%; the remainder of 0.6% should be due to ^{85}Sr .

- 13) 1657 keV: ^{91}Y (2207 - 555). This transition can explain only part of the yield, as other observable branchings are only weakly seen. The ^{89}Y (2566 - 909) transition is considered to explain most or all of the yield of the 1657 keV γ -ray, the 909 keV level being an isomer of 16 sec lifetime.

^{82}Kr (2427 - 776). This is excluded because the 2427 keV state should also decay to the 1475 keV state, whose decay was not observed.

- 14) 2187 keV: ^{91}Zr (2189 - 0). This transition cannot be excluded, although the 2189 keV state is the seventh excited state of ^{91}Zr .

^{93}Zr (2457 - 267). This transition cannot be ruled out by level scheme considerations, but it was found unlikely for a ^{93}Zr residual nucleus to be produced by radiative capture. Also (n, p) reactions cannot explain the observed yield, considering the cross-sections and the number of neutrons produced in the target.

3.2 Doppler broadening results

3.2.1 Method

The Doppler broadening of γ -rays in these experiments can be analysed to give the distribution in recoil momenta (which comes from the π^- absorption process) of the residual nucleus from which the γ -ray is emitted. The method was first developed²⁾ for situations in which the γ -ray emission lifetime is infinitely short, but the analysis has since been generalized¹⁷⁾ so that cases with lifetimes

as long as the slowing down time of the recoil nucleus (typically of order 1 psec) can be evaluated. In Ref. 17 two methods of analysis are given. The first method is exact but requires precise knowledge of the Doppler-broadened γ -ray line shape. The second is approximate and less ambitious in its goal: the general form of a one-parameter momentum distribution is assumed, and the parameter is determined from gross features of the measured line shape.

For the analysis of the present measurements the second method has been used since the statistical accuracy and dispersion (keV/channel) were generally insufficient for employing the exact approach. The form of the recoil momentum distribution was taken as

$$\frac{dN}{dK} \propto K^2 \exp(-K^2/K_{\max}^2).$$

The value of momentum K for which dN/dK has its maximum is $K = K_{\max}$. This form is a "natural" one since, in the case of an infinitely short lifetime, it produces a γ -ray line shape that is Gaussian. The value of $K_{\max}$ is then determined from the full width at half maximum (FWHM) of the measured γ -ray line shape (corrected for detector resolution) by the expression

$$K_{\max} = \frac{Mc}{A(\alpha/\tau, K_n)} \cdot \frac{\text{FWHM}}{E_\gamma}$$

Here M is the mass of the recoil nucleus and E_γ is the nominal γ -ray energy. The attenuation function A depends on the ratio α/τ , where α is the electronic slowing down time of the recoil and τ is the mean lifetime for γ -ray emission, and on the nuclear stopping parameter K_n . Formulae for α and K_n and graphs of A are given in Ref. 17.

3.2.2 Recoil momentum distributions

The resulting values of $K_{\max}$ obtained from the measured line shapes are given in Table 7. The errors in these values have been estimated from the listed errors in α , K_n and FWHM. In general, limitations of the theory from which α is calculated introduce an uncertainty of about 20% in its value¹⁷⁾. In addition, for the ^{31}P powder target, uncertainty in the microscopic density further increased the error in α , since α is inversely proportional to this density. In the case of the H_2O target however, the values of α could be calculated more accurately using a compilation of semi-empirical heavy ion stopping powers²²⁾. The errors in the values of K_n have been estimated at 30%¹⁷⁾.

The values of FWHM and related errors were obtained from the γ -ray peaks using a Gaussian peak-fitting computer program. In order to keep errors in $K_{\max}$ values within reasonable limits, only those cases were analysed for which both

$\alpha/\tau > 1$, and $\text{FWHM} > \text{twice the intrinsic detector resolution}$. (For small α/τ the non-Doppler broadened part of the line shape becomes dominant and the separation of the two line shape components, which is necessary for the analysis, becomes impractical. In addition, a Gaussian is a poor approximation to the broadened part of the line shape in these cases.)

3.2.3 Magnetic substate alignment effect

The theory with which the momentum distributions have been calculated rests on the assumption that the direction in which the γ -ray is emitted is uncorrelated with the direction of motion of the excited nucleus from which the γ -ray emission occurs. This is equivalent to assuming that the magnetic substates of the nuclear excited state are equally populated. That this may not necessarily be true has been speculated previously²⁾, but there have been no experimental tests. The 2313 and 1632 keV γ -rays in ^{14}N , which are produced from absorption on ^{16}O , can be used however to investigate this in the following way.

From the yields and branching ratios given in Table 2 it is apparent that most of the 2313 keV intensity is the result of a cascade following the 1632 keV decay of the 3945 keV excited state, with the direct excitation of the 2313 keV state small in comparison with that of the 3945 keV state. Since the first γ -ray emission is very fast -- on the average less than 1% (i.e. α/τ) of the original momentum is lost before the 2313 keV state is reached -- the recoil momentum distributions which are measured by the two γ -rays should be virtually identical. As the 2313 γ -ray results from the decay of a spin 0 state, it can only have an isotropic distribution. Thus if the same momentum distribution is determined from each γ -ray, this would indicate that the 1632 keV γ -ray has a correlation which is also isotropic -- which in principle it need not be, since it originates from a state of spin 1. In fact the calculated values of K_{max} for the two γ -rays, as given in Table 7 do agree within their error limits of about 5%. In contrast it has been shown¹⁷⁾ that K_{max} for the 1632 keV γ -ray would appear to be greater or less than that for the isotropic case, by more than 30%, as the population of the $m = 0$ substate varies from 0 to 100%, respectively. The present measurement gives a population of the $m = 0$ state of $(27 \pm 7)\%$, compared with 33.3% for the isotropic case. Figure 5 shows the experimental data on which these conclusions are based. The 1632 keV line shape has been measured previously by Kossler et al.²⁾. If their result is expressed in terms of K_{max} their value is 140 MeV/c compared with 130 ± 5 MeV/c from the present measurement.

4. DISCUSSION

4.1 Average features

All transitions identified in the present work are compiled in Tables 2-6. The data show a large variety of residual nuclei, produced by the removal of up to 12 nucleons. From the summed information from these tables some average features of pion absorption reactions become apparent.

- 1) The average number of removed nucleons per reaction lies between 3 and 6, the number of protons and of neutrons being about equal (see Table 8). The number is observed to increase monotonically with the target mass. Reactions in which the particle emission leads to the ground state of the respective residual nucleus could not be observed with the present method and are therefore not contained in these numbers. Although the amount of ground-state transitions might be appreciable, they are not expected to change the average features much, as the excitation energies of the observable states are small compared with the pion mass. From the average number of removed nucleons, assuming they are emitted separately and with a binding energy of 8 MeV/nucleon, the total released kinetic energy on the average can be shown to be about 100 MeV per absorption.
- 2) The probability to remove a certain number of nucleons per reaction has its maximum at two nucleons (see Fig. 6). For numbers in excess of two the probability decreases slowly, but is of comparable size.

The observed probability distribution agrees with current theories of pion absorption on a NN pair in so far as the maximum is at two nucleons. The large probability for larger numbers of nucleons is initially surprising. There are, however, several possibilities to make the observed distribution still compatible with the 2N picture: a) the two originally emitted nucleons can knock out additional nucleons on their way out of the nucleus; b) deep-lying two-hole states originating from the 2N absorption can be filled in Auger-like reactions; and finally c) evaporation processes are possible if the excitation involves larger parts of the nucleus. Such mechanisms are thus expected to mask the original pion interaction to a large degree.

4.2 Spallation reaction comparison

To estimate the amount of such masking a comparison of our data with spallation reactions is of interest. We have done such a comparison, using Rudstam's empirical four-parameter formula²³⁾ for the yields:

$$\sigma(Z,A) = \exp [PA - Q - R (Z - SA)^2] ,$$

where Z and A are the atomic number and the mass of the residual nucleus. The values for the parameters P , Q , R , and S given by Rudstam fit a large number of various spallation data throughout the periodic table, for projectiles ranging from protons to alpha particles and with energies from 200 MeV to 20 GeV. The formula corresponds to an exponential A -dependence and a Gaussian Z -distribution. We consider the A -dependence first: as the formula does not contain the mass of the target nucleus, we can replace A by the difference ($A_{\text{target}} - A_{\text{res.nucl.}}$), i.e. the number of nucleons removed, and add up the data for all target nuclei. This has been done in Fig. 6 using the isotopic yields from Tables 2-5. The results for Nb have not been included because of the relatively large number of unidentified or ambiguous lines. On the logarithmic representation the formula predicts a straight line, and in fact the measurements can be fitted by a straight line with the slope $P = 0.14$ for nucleon numbers from 2 to about 8. In the Rudstam formalism the slope should be a function of only the energy of the projectile. The value $P = 0.14$ corresponds to an energy of about 500 MeV, whereas the pion rest energy of 140 MeV corresponds to a value $P = 0.43 \pm 0.13$. The latter with its error limits is in disagreement with the data. We should, however, bear in mind that Rudstam determined the parameters mainly with proton-induced reactions. In view of the differences in the first step of pion- and proton-induced reactions -- the pion is absorbed and deposits its total energy in the nucleus, whereas the proton can be inelastically scattered and delivers only part of its kinetic energy -- the observed discrepancies are not unreasonable.

Figure 7 shows the Z -dependence of our data, again added for all target nuclei except Nb. The value for S has been taken to be 0.486 as given by Rudstam. The parameter R depends on the mass region of residual nuclei and should be about 2.8 for our data. A Gaussian with this parameter is in fair agreement with our data. A least squares fit to our data gives $R = 3.7$.

In comparing our data in Figs. 6 and 7, we should keep in mind the small sample size represented by the data from this experiment. Because of this, a comparison with more refined computer calculations²⁴⁾ seems to be of limited use at present. The conclusion which can be drawn so far is that our results do show similarities with spallation reactions and cannot exclude an initial $(\pi^-, 2N)$ process as a first step of a more complex reaction. But on the other hand neither could this comparison exclude contributions from initial pion interactions with heavier clusters.

4.3 Direct reaction comparisons

4.3.1 One-nucleon removal

Pion absorption leading to the emission of a single nucleon is expected to be strongly suppressed owing to the small probability that a nucleon will have a

Fermi momentum as large as that corresponding to 140 MeV kinetic energy. Measurements of the analogous reaction $(\pi^+, p)^{25)}$ showed indeed small cross-sections for ^9Be and ^{16}O as targets. These measurements have been restricted to the ground state of the residual nucleus, and very little is known about transitions into higher states. A possible mechanism for such reactions could be a 2N reaction with one of the two nucleons subsequently captured by the residual nucleus. The final states produced in this way are expected to be of a more complicated configuration than just one hole, i.e. two hole - one particle.

Another possible reaction that results in the removal of one nucleon is radiative pion capture. In the case of π^- absorption at rest, only protons can be removed, the contribution of the reaction being about 2% of the total absorption rate. The states produced by radiative capture should have one-hole configurations.

Tables 2-6 show that several cases of one proton removal have been observed. In order to decide by which reaction they have been produced, comparisons with μ -capture experiments and photo-induced reactions have been made. These two reaction types are related to radiative capture via the theory of giant resonance analogue states and should lead to the same final states in the respective residual nuclei. Comparisons have also been made with 1N transfer and knock-out reactions as well as with calculations about one-hole strengths.

The result of these comparisons is the following: a) for the target nuclei ^{16}O and ^{40}Ca the observed final states are not the same as with μ -capture and photo-induced reactions and do not show large one-hole strengths. The best example is the 6323 keV $3/2^-$ state in ^{15}N , which is well known to contain most of the one-hole strength of the $P_{3/2}$ shell and which is strongly populated by μ -capture, photo-reactions, $(d, ^3\text{He})$ and (t, α) reactions, but is not observed in the present work. Conversely, the 5270 keV ^{15}N $5/2^+$ state which is excited certainly does not have a simple one-hole configuration; b) for the target nuclei ^{19}F and ^{31}P , however, our results show strong similarities with the analogous reactions mentioned above. Whether this is fortuitous and due to the fact that for the corresponding residual nuclei the one-hole strength is spread over a large number of states cannot be decided.

There is only one case where the recoil momentum distribution for 1p removal could be determined via Doppler broadening. This case is the 2236 keV state in ^{30}Si with a K_{max} of 100 ± 30 MeV/c as given in Table 7. A corresponding (π^+, p) reaction -- regardless whether it is a true one-nucleon reaction or a degenerated two-nucleon process -- should have a discrete momentum of about 500 MeV/c, which is not in agreement with the observed line shape in the γ -spectrum. Therefore

one must conclude, that this very case is a radiative capture reaction. [One should be reminded however that an alternative identification for this line is a transition in the target nucleus itself (Table 4)].

In spite of this observation, however, we believe that on average most of the one-proton removal reactions observed in the present work are produced by de-generated two-nucleon processes. This is based on the results obtained for ^{16}O and ^{40}Ca , where the simpler and better known properties of these closed-shell nuclei allowed conclusions via the configurations of the final states.

4.3.2 Two-nucleon removal

With one nucleon removal being kinematically suppressed, the pion interaction with two nucleons is expected to be the most frequent first step in any reaction induced by pion absorption. If a reaction is observed which results in the emission of two nucleons one naturally interprets this as a direct one step reaction (rather than a one nucleon emission process followed by the sequential emission of a second nucleon). Among all possible reactions two nucleon removal is thus expected to carry the most information about the first step of the pion interaction. Consequently the study of the final states produced by this reaction type is very promising and can probably reveal selection rules.

From the direct, i.e. quasifree, mechanism it follows that the final states should have simple two-hole configuration (relative to the target nucleus). There is in principle the possibility that the outgoing nucleons may scatter inelastically with the residual nucleus and hence produce more complicated configurations, but this mechanism is expected to have a smaller likelihood in the region of nuclei studied here. Taking into account γ -ray cascades one can extract from Tables 2-6 the yields to states which are directly populated by the emission of two nucleons. They are given in Table 9.

One typical advantage of the γ -method is the knowledge of the quantum numbers of the final states. Examination of Table 9 shows a) for all observed cases of $n + p$ removal the quantum numbers are compatible with the initial state of the $n + p$ system having $(J^\pi, T) = (1^+, 0)$, i.e. like a free deuteron; and b) for $p + p$ removal only the case of the 4^- state in ^{38}Ar would be inconsistent with the two protons (necessarily coupled to $T = 1$) being in an S-state relative to each other. The 4^- state in ^{38}Ar , however, is a special case, as it can also be populated by a cascade transition from the 5^- , 4585 keV state in ^{38}Ar (the branching ratio to the 4^- state is 90% but the decay could not be observed, as the energy of the corresponding γ -ray was below the detector threshold). Assuming such a cascade, there is no remaining inconsistency with the S-state hypothesis.

Unfortunately no case of two analogue states, produced by np and 2p removal, respectively, was observed, and not even a case where one of a known pair of analogue states was observed with the yield of the second one being consistent with zero within error limits. Hence no direct information about the ratio of np to 2p removal yields could be obtained. We only mention that according to our data there seems to be a tendency for this ratio to decrease with increasing mass of the target nucleus.

The 2N removal reactions can in principle be compared with 2N transfer reactions such as (d, α) which lead to the same residual nuclei. As far as equivalent measurements could be found, similarities are visible. It should however be pointed out that for the pion-induced reactions there exist less *a priori* restrictions. For instance the removed np pair has not necessarily the quantum numbers of the deuteron. Regarding theoretical predictions, the only comprehensive calculations of coefficients of fractional parentage (CFP) are restricted to the 1p shell²⁶⁾. In comparing these calculations with the present ^{16}O target data, we should note that the 3945 keV state in ^{14}N , which has by far the largest yield, also has a large CFP. However, another state in ^{14}N (2313 keV) also has a large CFP, but is very little excited. This indicates the influence of factors which are specific for the pion interaction. Such factors have been expected and partly taken into account in calculations. Kopaleishvili²⁷⁾ has calculated the excitation spectrum in ^{14}N produced by π^- absorption from S and P orbits for various ranges of recoil momenta, but the agreement with our data is generally poor.

4.3.3 "Alpha" removal

A striking feature of the data given in Tables 2-6 is the presence of γ -rays from residual nuclei that have two protons and two neutrons less than the target. The yields of such γ -rays are among the highest seen (typically, comparable with two nucleon, and an order of magnitude larger than one neutron-three proton, or one proton-three neutron removal) and occur without any obvious preference for the evenness or oddness of the target nucleus. In view of increasing theoretical interest²⁹⁾ in the possibility of alpha-particle cluster-absorption of pions in nuclei, it is natural to consider the experimental results from this point of view. In such a model, in analogy with the one- and two-nucleon removals previously discussed, an important influence in determining whether a particular excited state $(A-4, Z-2)^*$ will be observed is its parentage in the ground state of the target nucleus, i.e. the spectroscopic factor for the decomposition $(A, Z) \text{ g.s.} \rightarrow \alpha + (A-4, Z-2)^*$. In the following we consider the available spectroscopic information, as determined both from theoretical nuclear structure studies and experimental "alpha transfer" reactions, and compare with the specific excited states observed in the present work. Such a comparison of course totally ignores the influence of possible selection rules in pion-alpha cluster absorption, of which virtually nothing is known at present.

There is a variety of shell model studies which agree that the ^{16}O ground state has a large alpha-particle spectroscopic factor. Further there is general agreement that its alpha-width relative to the first excited state of ^{12}C is even larger than relative to the ground state, by a factor of order five³⁰⁾. The alpha-pickup reactions (τ , ^7Be) and (d , ^6Li) on ^{16}O measured at 30³¹⁾ and 19.5 MeV³²⁾, respectively, are at least qualitatively consistent with this as they both show larger cross-sections to the first excited state than to the ground state. Our observation of a strong ^{12}C first excited state de-excitation γ -ray is thus reasonable in the context of an alpha cluster pion absorption model. It has also been shown³⁾ that the Doppler broadening of the γ -ray can be interpreted to yield a momentum distribution for the alpha cluster within ^{16}O which is similar to that found in (p , $p\alpha$) knockout measurements³³⁾.

A small value of binding energy for a specific cluster of nucleons in a nucleus is often used as an argument for the reality of such a preformed cluster. It is thus of interest to note that the binding energy of an alpha particle in ^{19}F is only 4.01 MeV. Experimentally, the results of the (τ , ^7Be) and (d , ^6Li) reactions^{31, 32)} on ^{19}F are similar: the ground, first + second (unresolved), and third excited states of ^{15}N are clearly seen. In a measurement of the photodisintegration of ^{19}F Thomas et al.³⁴⁾ observed an unexpectedly strong γ -ray from the first excited state of ^{15}N , and, using the evidence of Refs. 31 and 32, suggested that it should be interpreted as a nuclear structure effect. The same γ -ray is strongly seen in the present work.

For the target ^{31}P there seems to be no conventional alpha transfer data available. The photodisintegration of ^{31}P shows a strong production of the second excited state of ^{27}Al and a yield to the first excited state nearly five times weaker³⁴⁾. It is interesting to note that these observations are mirrored in the present work. Since the mechanism for such a photodisintegration is not understood, it is difficult to know how much importance should be placed on the similarity of the two experiments (for the ^{19}F as well as the ^{31}P target).

Martin et al.³⁵⁾ have measured the (d , ^6Li) reaction on ^{40}Ca at 28 MeV bombarding energy. Their results show prominent excitations of the ground (0^+), first excited (2^+), and (probably) the third excited (4^+) states in ^{36}Ar , although the latter was not resolved from two other nearby states. This $0^+-2^+-4^+$ set is thought to be well-described by $(d_{3/2})^{-4}$ configurations. A zero-range DWBA analysis of the angular distributions gave relative spectroscopic factors for these states in the ratio 0.54: 1.15: 1.90, i.e., values not vastly different from one another. The (τ , ^7Be) reaction on ^{40}Ca seems to excite the ground and first excited states of ^{36}Ar with similar strength, although only the ground state was analyzed³¹⁾. Possibly other states are excited but could not be distinguished

from the background. The present γ -ray measurements show excitation of the first excited (2^+) state in ^{36}Ar , and probably the 3^- state at 4178 keV. The lack of excitation of the 4^+ state is perhaps not surprising on the general ground that high angular momentum states are not usually excited due to the relatively small amount of angular momentum that can be delivered to the target nucleus in pion absorption at rest.

In general, for the few cases that can be directly compared, the same excited states in the residual nuclei ($A-4$, $Z-2$) which are seen in the pion absorption measurements are also seen in alpha transfer reactions (except for the 3^- ^{40}Ca state). Additional states are frequently seen with the latter however, suggesting a greater selectivity in the case of excitation by pion absorption.

4.3.4 Multi-alpha removal

The only unambiguous observation of a residual nucleus which was lighter than the target nucleus by an integral number $n > 1$ of equivalent alpha particles was in the case of pion absorption on ^{31}P leading to the first excited state of ^{23}Na . One other case of 2-alpha removal is very likely (^{40}Ca target) but the ^{32}S identification of the γ -ray line in question is not unique. The general paucity of multi-alpha removal in these measurements is in contrast to published results from π^- interactions with nuclei near⁷⁾ or above⁶⁾ the (3,3) resonance, in which large cross-sections for multi-alpha removal were observed -- up to 5-alpha for a Ca target. In this respect the present results are more similar to those obtained with 70 MeV π^+ and π^- incident on ^{28}Si and ^{27}Al in which multi-alpha removal was not observed⁸⁾ and on ^{31}P ⁴⁾, where only 1α and 2α removal has been found. In this context, it is interesting to note that recent measurements based on the direct detection of emitted charged particles³⁶⁾ showed no spectacularly high yield for α -particles from pion induced reactions at 70 MeV incident energy. Finally, (p,X γ) experiments³⁷⁾ on Ca at 230 and 600 MeV incident proton energies show multi-alpha removal lines in the γ -spectra similar to those obtained with fast pions. All these results taken together strongly suggest that multi-alpha phenomena are mainly influenced by the amount of available energy, and have little to do with the type of projectile.

5. CONCLUSION

The interaction of stopped negative pions with complex nuclei has been studied through the "window" of γ -ray transitions from excited states in the residual nuclei. This method allows the simultaneous observation of many -- even unexpected -- reaction channels and the results obtained exhibit several new and interesting features. The removal of up to 12 nucleons was observed, which demonstrates the complexity of the entire process.

While the "classical" (π^- , 2N)-reaction in fact showed the highest yields it was however much less dominant than expected. For this reaction channel all observed cases are consistent with the two nucleons removed being in an s-state relative to each other. Removed np-pairs are consistent with the deuteron quantum numbers ($J^\pi = 1^+$, $T = 0$).

Even within the simple picture of pion absorption on two nucleons, the additional removal of more nucleons in sequential processes is expected in some cases, due to intranuclear cascades, nuclear Auger effects, evaporation etc. The observed yields for multinucleon removal as a function of the number of removed nucleons are not in contradiction with this picture: the yields decrease slowly with increasing number of nucleons; within the accuracy of our measurements there is no other peak in this curve apart from the peak at $N = 2$. (A peak at $N = 4$, for instance, could have been considered as an indication of a reaction channel involving 4 nucleons in the initial step.) A comparison made between our data and results from proton- and alpha induced spallation reactions show rather strong similarities.

The γ -ray method allows the determination of recoil momentum distributions via Doppler broadening, in cases where the lifetime of the respective final state is short enough. Each distribution obtained in this way can be characterised by a value of momentum $K_{\max}$ for which the distribution has its maximum. For a given target nucleus there is some tendency for the resulting $K_{\max}$ values to increase with the number of removed nucleons. Such a behaviour is compatible with the γ -ray emitting state having been reached by a process of sequential particle emission.

Multi-alpha removal was found to be much less pronounced, compared with published results from similar measurements with pions at higher energies. The removal of one alpha particle was observed in most cases and comparisons were made with results from alpha transfer reactions like (d , ^6Li) and (τ , ^7Be). The comparisons show strong similarities in the population of certain final states in the residual nuclei. While this observation seems to support an alpha cluster absorption mechanism, it cannot however strictly exclude sequential processes, and hence cannot prove the presence of cluster absorption.

Table captions

- Table 1 Principal target-unrelated background lines.
- Table 2 Prompt γ -ray transition yields and isotopic yields of the reactions induced by stopped π^- on ^9Be , ^{10}B and ^{16}O .
- Table 3 Prompt γ -ray transition yields and isotopic yields of the reaction $^{19}\text{F} + \pi^-$.
- Table 4 Prompt γ -ray transition yields and isotopic yields of the reaction $^{31}\text{P} + \pi^-$.
- Table 5 Prompt γ -ray transition yields and isotopic yields of the reaction $^{40}\text{Ca} + \pi^-$.
- Table 6 Prompt γ -ray transition yields and isotopic yields of the reaction $^{93}\text{Nb} + \pi^-$.
- Table 7 Recoil momentum distribution results from Doppler-broadened line shapes.
- Table 8 Average numbers of removed nucleons.
- Table 9 Yields of states in residual nuclei directly populated by the emission of two nucleons.

Table 1

Energy (keV)	Yield/stop (%)	Identification
197	0.4	^{19}F
414	0.6	^{10}B
440	0.2	^{23}Na
511	25	β^+
537	0.6	^{206}Pb
565-585	4.0	$^{207}\text{Pb}(570)$ $^{208}\text{Pb}(583)$
590-630	10	$^{74}\text{Ge}(596)$ $^{74}\text{Ge}(609)$
693	1.2	^{72}Ge
717	1.8	^{10}B
803	2.6	^{206}Pb
829-851	7.0	$^{72}\text{Ge}(834)$ $^{27}\text{Al}(844)$
898	0.7	^{207}Pb
984	0.4	^{27}Mg , ^{28}Al
1014	1.1	^{27}Al
1040-1070	2.0	$^{70}\text{Ge}(1041)$
1200-1238	1.4	$^{19}\text{F}(1235)$ $^{56}\text{Fe}(1238)$
1369	0.2	^{24}Mg
1434	0.7	^{10}B
1593	0.9	$^{208}\text{Pb}(2615\text{DE})$
1690-1770	1.5	$^{207}\text{Pb}(1770)$
1809	0.9	^{26}Mg
2209	1.0	^{27}Al
2615	2.7	^{208}Pb

Table 2

Target nucleus	Energy range (keV)	Residual isotope	Transition (keV)	Branch (%)	J^π	τ (psec)	Measured energy (keV)	Transition yield (%)	Isotopic yield (%)
^9Be	300-6000	-	-	-		-	-	-	-
^{10}B	100-17000	^7Li	477 $\rightarrow$ 0	100	$1/2^-$		478	1.7 ± 0.4	1.7
^{16}O	300-8000	^{16}O	6131 $\rightarrow$ 0	100	3^-	24	6133	1.7 ± 0.29	1.7
		^{15}N	5270 $\rightarrow$ 0	100	$5/2^+$	2.9	5268	0.5 ± 0.16	0.5
		^{14}N	2313 $\rightarrow$ 0	100	0^+	8.5×10^{-2}	2314	5.3 ± 0.64	6.4
			3945 $\rightarrow$ 2313	96	1^+	4.5×10^{-3}	1634	4.8 ± 0.86	
			5106 $\rightarrow$ 0	80	2^-	12	5106	0.7 ± 0.15	
			5106 $\rightarrow$ 2313	20	2^-	12	2794	0.2 ± 0.05	
		^{14}C	6728 $\rightarrow$ 0	93	3^-	97	(6728)	$0.2^{+0}_{-0.2}$	<0.2
		^{13}C	3684 $\rightarrow$ 0	100	$3/2^-$	1.5×10^{-3}	3682	1.9 ± 1.0	2.9
			3854 $\rightarrow$ 0	62	$5/2^+$	11	3853	1.0 ± 0.25	
		^{12}C	4439 $\rightarrow$ 0	100	2^+	5.6×10^{-2}	4436	4.0 ± 1.3	4.0
		^{10}B	717 $\rightarrow$ 0	100	3^+	1.01×10^3	717	1.3 ± 0.26	1.3

Table 3

Target nucleus	Energy range (keV)	Residual isotope	Transition (keV)	Branch (%)	J^π	τ (psec)	Measured energy (keV)	Transition yield (%)	Isotopic yield (%)
^{19}F	400-7000	^{19}F	1346→110	97	$5/2^-$	4.8	1235	0.5 ± 0.10	2.3
			1554→197	95	$3/2^+$	4.4×10^{-3}	1354	1.7 ± 0.24	
		^{18}O	1982→0	100	2^+	3.8	1980	1.4 ± 0.20	1.4
		^{17}O	871→0	100	$1/2^+$	260	870	1.3 ± 0.15	1.3
		^{16}O	6131→0	100	3^-	24	6131	1.9 ± 0.33	1.9
		^{15}N	5270→0	100	$5/2^+$	2.9	5270	2.3 ± 0.32	2.3
		^{14}N	5106→0	80	2^-	12	5106	0.4 ± 0.10	0.4
		^{14}C	6728→0	93	3^-	97	6730	0.5 ± 0.10	0.5
		^{13}C	3684→0	100	$3/2^-$	1.5×10^{-3}	3684	0.6 ± 0.11	0.9
			3854→0	62	$5/2^+$	11	3854	0.9 ± 0.15	
		^{12}C	4439→0	100	2^+	5.6×10^{-2}	4442	2.1 ± 0.80	2.1

Table 4

Target nucleus	Energy range (keV)	Residual isotope	Transition (keV)	Branch (%)	J^π	τ (psec)	Measured energy (keV)	Transition yield (%)	Isotopic yield (%)
^{31}P	100-7000	$\pi^- \text{ } ^{31}\text{P}$	3d $\rightarrow$ 2p				118	(a)	
			4d $\rightarrow$ 2p				158	(a)	
			5d $\rightarrow$ 2p				176	(a)	
			6d $\rightarrow$ 2p				186	(a)	
		$\mu^- \text{ } ^{31}\text{P}$	2p $\rightarrow$ 1s				457	5 ± 0.52	
			3p $\rightarrow$ 1s				545	0.5 ± 0.06	
		^{31}P	1266 $\rightarrow$ 0	100	$3/2^+$	0.74	1266	4.5 ± 0.50	4.5-8.2
			2234 $\rightarrow$ 0	100	$5/2^+$	0.40	2236 ¹⁾	3.5 ± 0.41	
			3295 $\rightarrow$ 1266	81	$5/2^+$	0.14	2029 ²⁾	$<0.6 \pm 0.08$	
		^{30}Si	2236 $\rightarrow$ 0	100	2^+	0.34	2236 ¹⁾	3.5 ± 0.41	0-3.5
		^{29}Si	1273 $\rightarrow$ 0	100	$3/2^+$	0.40	1273	3.4 ± 0.40	5.0-5.6
			2028 $\rightarrow$ 0	95	$5/2^+$	0.41	2029 ²⁾	2.0 ± 0.28	
			3067 $\rightarrow$ 1273	82	$5/2^+$	0.02	1795	1.0 ± 0.18	
		^{29}Al	1398 $\rightarrow$ 0 ^{b)}	100	$1/2^+$	6.5 ^{b)}	1399	0.3 ± 0.05	0.3
		^{28}Al	1014 $\rightarrow$ 31	63	3^+	0.13	985 ³⁾	0.9 ± 0.14	0-1.4
			1014 $\rightarrow$ 0	37	3^+	0.13	1015 ⁴⁾	$<0.5 \pm 0.06$	
		^{28}Si	1779 $\rightarrow$ 0	100	2^+	0.68	1779	5.0 ± 0.63	5.0
		^{27}Al	844 $\rightarrow$ 0	100	$1/2^+$	44	844	0.4 ± 0.05	1.9-2.4
			1014 $\rightarrow$ 0	97	$3/2^+$	1.9	1015 ⁴⁾	2.0 ± 0.23	
		^{27}Mg	985 $\rightarrow$ 0	100	$3/2^+$	1.4	985 ³⁾	0.9 ± 0.14	0-0.9
		^{26}Al	417 $\rightarrow$ 0	100	3^+	1.8×10^3	<417	0.6 ± 0.07	0.6
		^{26}Mg	1809 $\rightarrow$ 0	100	2^+	0.40	1808	4.0 ± 0.47	4.3
			2938 $\rightarrow$ 1809	90	2^+	0.08	1129	2.7 ± 0.35	
			585 $\rightarrow$ 0	100	$1/2^+$	4.9×10^3	584	2.0 ± 0.30	2.8
		^{25}Mg	975 $\rightarrow$ 0	51	$3/2^+$	14	975	0.8 ± 0.13	
			975 $\rightarrow$ 585	49	$3/2^+$	14	391	0.6 ± 0.08	
		^{24}Mg	1369 $\rightarrow$ 0	100	2^+	1.8	1368	2.9 ± 0.32	2.9
		^{23}Na	440 $\rightarrow$ 0	100	$5/2^+$	1.6	440	3.0 ± 0.31	3.0
		^{21}Ne	351 $\rightarrow$ 0	100	$5/2^+$	20	352	1.1 ± 0.12	1.1

a) Yield poorly determined due to low energy

b) Ref. 20.

Table 5

Target nucleus	Energy range (keV)	Residual isotope	Transition (keV)	Branch (%)	J ^π	τ (psec)	Measured energy (keV)	Transition yield (%)	Isotopic yield (%)
Ca	400-7000	μ-Ca	2p+1s				785	5.7 ± 0.60	
		⁴⁰ Ca	3737+0	100	3 ⁻	61	3737	0.8 ± 0.14	0.8
		⁴⁰ K	800+30	100	2 ⁻	0.47	771 ¹⁾	0.6 ± 0.15	0-1.0
			3100+892	45		0.1	2208 ³⁾	0.2 ± 0.05	
			3100+0	55		0.1	3103	0.2 ± 0.05	
		³⁹ K	2814+0	100	7/2 ⁻ (5/2 ⁻)	72	2814	0.3 ± 0.08	0.3
		³⁹ Ar	1267+0	100	3/2 ⁻		1267 ²⁾	1.9 ± 0.40	0-1.9
		³⁸ K	2646 ^{a)} +0	100		>12 ^{a)}	2645 ⁴⁾	0.3 ± 0.07	0-0.3
		³⁸ Ar	4480+3810	100	4 ⁻	2	671	1.2 ± 0.17	1.9-2.2
			4710+3937	100	0 ⁺		771 ¹⁾	0.6 ± 0.15	
			3810+2168	100	3 ⁻	0.08	1643	0.6 ± 0.10	
			2168+0	100	2 ⁺	0.53	2167	1.6 ± 0.20	
			3937+0	94	2 ⁺	0.05	3937	0.3 ± 0.10	
		³⁷ Ar	1410+0	100	1/2 ⁺	1.0	1409	0.7 ± 0.15	4.0
			1611+0	100	7/2 ⁻	6300	1611	3.3 ± 0.40	
		³⁶ Ar	1970+0	100	2 ⁺	0.42	1970	1.9 ± 0.40	1.9
			4178+1970	94	3 ⁻	>3	2208 ³⁾	0.7 ± 0.20	
		³⁵ Cl	2646+0	91	7/2 ⁺	0.25	2645 ⁴⁾	0.3 ± 0.07	1.2-1.5
			3163+0	90	7/2 ⁻	50	3164	1.1 ± 0.16	
		³⁵ S	1991+0	100	(5/2 ⁻ , 7/2 ⁻)	1470	1991	0.4 ± 0.12	0.4
		³⁴ Cl	2376+146	100	4 ⁺		2229 ⁵⁾	5.5 ± 1.00	0-5.5
		³⁴ S	2127+0	100	2 ⁺	0.41	2128	1.6 ± 0.36	1.6
		³³ S	1966+0	100	5/2 ⁺	0.16	1964	2.4 ± 0.60	2.8
			2934+0	43	7/2 ⁻	41	2935	0.4 ± 0.10	
			2934+1966	57	7/2 ⁻	41	968	0.5 ± 0.10	
		³² S	2230+0	100	2 ⁺	0.23	2229 ⁵⁾	5.5 ± 1.00	2.8-5.5
			4459+2230	100	4 ⁺	0.19	2229 ⁵⁾	2.7 ± 0.50	
		³² P	1755+78	96	3 ⁺	0.47	1675	0.3 ± 0.10	0.3
		³¹ P	1266+0	100	3/2 ⁺	0.74	1267 ²⁾	1.9 ± 0.40	0.7-2.6
			2234+0	100	5/2 ⁺	0.40	2233	0.7 ± 0.30	

a) Ref. 21.

Table 6

Target nucleus	Energy range (keV)	Residual isotope	Transition (keV)	Branch (%)	J^π	τ (psec)	Measured energy (keV)	Transition yield (%)	Isotopic yield (%)
^{93}Nb	300-6000	$\pi\text{-}^{93}\text{Nb}$	4f $\rightarrow$ 3d				308	30 ± 3.10	
		^{93}Nb	686 $\rightarrow$ 29	100	$1/2^-$		660	2.2 ± 0.26	9.5
			744 $\rightarrow$ 0	100	$7/2^+$		743	3.7 ± 0.42	
			950 $\rightarrow$ 0	100	$13/2^+$		948	3.6 ± 0.37	
			1335 $\rightarrow$ 950	100	$17/2^+$		386	1.2 ± 0.18	
			1491 $\rightarrow$ 950	100			540	1.1 ± 0.17	
			2003 $\rightarrow$ 950	100			1056 ¹⁾	3.5 ± 0.50	
		$\mu\text{-}^{93}\text{Nb}$	2p $_{1/2} \rightarrow$ 1s $_{1/2}$				2605	0.8 ± 0.10	
			2p $_{3/2} \rightarrow$ 1s $_{1/2}$				2628	1.9 ± 0.22	
		^{92}Zr	934 $\rightarrow$ 0	100	2^+		933	0.8 ± 0.14	0.8
			1383 $\rightarrow$ 934				448 ²⁾	$\leq 0.8 \pm 0.12$	
			2067 $\rightarrow$ 934	100	2^+		1128 ³⁾	$\leq 0.8 \pm 0.12$	
		^{91}Zr	2170 $\rightarrow$ 0	100	11/2		2170	0.5 ± 0.09	0.5-1.1
			2189 $\rightarrow$ 0	100			2187 ⁴⁾	0.6 ± 0.10	
		^{91}Y	1305 $\rightarrow$ 556	85	5/2		751	1.3 ± 0.22	5.6-6.9
			1580 $\rightarrow$ 556	95	5/2		1022	3.9 ± 0.43	
			2207 $\rightarrow$ 556	30	$5/2^-$		1657 ⁷⁾	1.1 ± 0.19	
		^{90}Zr	2186 $\rightarrow$ 0	99	2^+	0.13	2187 ⁴⁾	0.6 ± 0.10	0-0.6
			2748 $\rightarrow$ 2186	100	3^-		560 ⁵⁾	0.6 ± 0.09	
		^{90}Y	777 $\rightarrow$ 0	80	2^+		778 ⁶⁾	1.8 ± 0.25	0-2.3
		^{89}Y	2566 $\rightarrow$ 909	100	11/2		1657 ⁷⁾	1.1 ± 0.43	0.7-1.1
		^{88}Zr	1058 $\rightarrow$ 0	100	2^+		1056 ¹⁾	3.5 ± 0.50	2.2-3.5
		^{87}Rb	403 $\rightarrow$ 0	100	$5/2^-$	0.1	401	2.7 ± 0.35	2.7
		^{87}Kr	529 $\rightarrow$ 0	100	$1/2^+$		524	1.4 ± 0.16	1.4
		^{86}Rb	557 $\rightarrow$ 0	100	6^-		560 ⁵⁾	1.9 ± 0.30	1.3-1.9
		^{85}Sr	1354 $\rightarrow$ 231	75			1128 ³⁾	1.4 ± 0.20	0.6-1.4
		^{84}Sr	792 $\rightarrow$ 0	100	2^+		792	3.6 ± 0.42	3.6
			1767 $\rightarrow$ 792	100			976	3.7 ± 0.60	
		^{82}Kr	777 $\rightarrow$ 0	100	2^+	6.9	778 ⁶⁾	1.0 ± 0.15	1-2.8
			1821 $\rightarrow$ 777	100			1039	1.0 ± 0.12	
		^{81}Kr	640 $\rightarrow$ 190	100			448 ²⁾	3.2 ± 0.40	2.4-3.2

APPENDIX

ABSOLUTE YIELD DETERMINATION

The absolute yields of the pionic-induced γ -ray lines were determined by comparison with muonic x-rays, using the following method. Six sheets of Ta (0.16 g/cm^2 per sheet) were interleaved between the layers of the original LiF, P, Ca and Nb targets. For the H_2O target a grid of 10 equally spaced Pb sheets (0.28 g/cm^2 per sheet) was immersed in the water volume. Each of the resulting sandwich targets was placed in the same geometrical orientation as used in the pionic measurements, and then irradiated with a beam of stopped muons. The beam line parameters were adjusted to select muons from "backward" decaying pions, resulting in a muon beam that was essentially free of any charged particle contamination. For each observed muonic x-ray of energy E a point on the detector efficiency curve could be found from the relation

$$\epsilon(E) = \frac{k(E)N_x(E)}{N_\mu Y_x(E)} \quad (\text{A1})$$

where N_x is the number of detected x-rays from element A, Y_x is the number of x-rays produced per muonic capture in A, and N_μ is the total number of muons captured by A. The resulting efficiency curve includes target self-absorption effects, which were slightly larger for the muonic measurements because of the presence of the Ta or Pb sheets. Consequently the quantity $k > 1$ corrects the efficiency so as to be appropriate for the pionic measurements. Typically $k \approx 1.1$ so that a relatively crude calculation could be made to determine its value at each x-ray energy.

The total number of stops in a target was determined from the number of electronic stop signals, (1234), reduced by the number of simulated stops due to "background", as judged from the appearance of the complete range curve. (This prescription was of course applied to pion as well as muon beam measurements.) To determine N_μ the fraction of muons stopped in each of the two components A and B of each target must be known. This was calculated from the relation

$$N_{\mu B}/N_{\mu A} = (t_A/R_B)(m_B/m_A) \quad (\text{A2})$$

where m_A and m_B are the total thicknesses (g/cm^2) of the two components of the target. The quantity t_A is the thickness (g/cm^2) of one sheet of Ta or Pb, while R_B is the range in material B of a muon whose range in A is t_A . For the combinations of materials used the magnitudes of the ratios t_A/R_B lay in the range 1.3-2.2. For any particular combination this ratio was very insensitive to t_A , for hypothetical choices of t_A in the vicinity of its actual value.

The values Y_x of the absolute x-ray yields which were used are listed in Table A1. In the case of Ta, De Wit et al.³⁸⁾ have measured relative intensities of the components within several of the x-ray multiplets. These relative intensities for the dominant components were combined with absolute values for the total multiplet yield (2p-1s, 3d-2p, etc.) as calculated with a cascade program originally due to Hufner. Details of the program version actually employed are given in Ref. 39, in which also very good agreement is shown between careful absolute yield measurements and cascade calculations for muonic Tl. In the case of Pb yields of individual transitions were calculated from the same program. Relative yields for many transitions in muonic Pb have been measured by Anderson et al.⁴⁰⁾ and it was satisfying to note that the cascade calculations were in good agreement with these measurements. The agreement is in fact better than with an alternative calculation with which the measurements were compared in Ref. 40.

Two checks of the efficiency values derived from Eq. A1 were made. In the first, calibrated sources of ^{137}Cs , ^{22}Na and ^{88}Y were placed in the centre of one of the targets and counted. While this only approximates the actual extended nature of the "source" under beam conditions, the resulting points nonetheless agreed within about 15% with the previous efficiency curve. A second check was provided by the circumstance that for the P-Ta, Ca-Ta and Nb-Ta targets x-rays from both target components could be measured. There were no apparent inconsistencies between efficiency values based on either of the two components.

Several advantages of this method of absolute yield determination can be noted. The muonic x-ray energies span most of the useful energy range of the detector. Gamma ray attenuation effects, averaged over the target volume and folded with the beam profile, are automatically accounted for. From Eq. A1 it is apparent that the absolute yield of a pionic-induced gamma ray will be proportional to the ratio of muonic to pionic stops, so that counter telescope inefficiencies and geometrical effects tend to cancel.

Table A1

Muonic X-ray yields used in detector efficiency calibration

Nucleus	X-ray energy (keV)	Transition	Y_X (X-rays/ μ -capture)	Reference
Pb	5974	$2p_{3/2} \rightarrow 1s_{1/2}$	0.64	a, b
Pb	2644	$3d_{3/2} \rightarrow 2p_{1/2}$	0.30	a, b
Pb	2502	$3d_{5/2} \rightarrow 2p_{3/2}$	0.53	a, b
Pb	972	$4f_{5/2} \rightarrow 3d_{3/2}$	0.32	a, b
Pb	938	$4f_{7/2} \rightarrow 3d_{5/2}$	0.45	a, b
Ta	5129 - 5137	$(2p \rightarrow 1s)^e$	0.37	a, c
Ta	2155 - 2173	$(3d \rightarrow 2p)^e$	0.27	a, c
Ta	1978 - 2026	$(3d \rightarrow 2p)^e$	0.28	a, c
Ta	742 + 766	$4f \rightarrow 3d$	0.76	a, c
Nb	2609 + 2630	$2p \rightarrow 1s$	0.88	a
Nb	665 + 687	$3d \rightarrow 2p$	0.72	a
Ca	784	$2p \rightarrow 1s$	0.84	d
P	457	$2p \rightarrow 1s$	0.79	d

a) Cascade calculation

b) Ref. 40

c) Ref. 38

d) Ref. 18

e) Only the range of x-ray energies listed in column 2 are included.

REFERENCES

- 1) G. Poelz, H. Schmitt, L. Tauscher, G. Backenstoss, S. Charalambus, H. Daniel and H. Koch, Z. Physik 227 (1969) 311.
- 2) W.J. Kossler, H.O. Funsten, B.A. MacDonald and W.F. Lankford, Phys. Rev. C 4 (1971) 1551.
- 3) C.W. Lewis, H. Ullrich, H.D. Engelhardt and E.T. Boschitz, Phys. Letters 47B (1973) 339.
- 4) H. Ullrich, E.T. Boschitz, H.D. Engelhardt and C.W. Lewis, Phys. Rev. Letters 33 (1974) 433.
- 5) E.T. Boschitz, G. Bradley, H.D. Engelhardt, C.W. Lewis and H. Ullrich, GFK Ext. Rep. 3/72-8 (1972);
H.D. Engelhardt, Thèse ès Sciences, ISN-T-74-02, Grenoble-1 Univ. (1974).
- 6) H.E. Jackson, L. Meyer-Schützmeister, T.P. Wangler, R.P. Redwine, R.E. Segel, J. Tonn and J.P. Schiffer, Phys. Rev. Letters 31 (1973) 1353.
- 7) V.G. Lind, H.S. Plendl, H.O. Funsten, W.J. Kossler, B.J. Lieb, W.F. Lankford and A.J. Buffa, Phys. Rev. Letters 32 (1974) 479.
- 8) D. Ashery, M. Zaider, Y. Shamaï, S. Cochavi, M.A. Moinester, A.I. Yavin and J. Alster, Phys. Rev. Letters 32 (1974) 943.
- 9) B.J. Lieb and H.O. Funsten, Phys. Rev. C 10 (1974) 1753;
B.J. Lieb, H.S. Plendl, H.O. Funsten, W.J. Kossler and C.E. Stronach, Phys. Rev. Letters 34 (1975) 965.
- 10) G. Backenstoss, Ann. Rev. Nucl. Sci. 20 (1970) 467.
- 11) F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. A114 (1968) 1;
F. Ajzenberg-Selove, Nucl. Phys. A152 (1970) 1;
F. Ajzenberg-Selove, Nucl. Phys. A166 (1971) 1;
F. Ajzenberg-Selove, Nucl. Phys. A190 (1972) 1;
P.M. Endt and C. Van der Leun, Nucl. Phys. A214 (1973) 1;
F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. A227 (1974) 1;
Nuclear level schemes from A = 45 through A = 257 (from Nuclear Data Sheets),
(Ed. by Nuclear Data Group, Tennessee, USA) (Academic Press, New York and London 1973).
- 12) J.A. Bisterlich, K.M. Crowe, A.S.L. Parsons, D. Skarek and P. Truöl, Phys. Rev. C 5 (1972) 1867.
- 13) H.O. Funsten, W.J. Kossler and C.E. Stronach, Bull. Am. Phys. Soc. 17 (1972) 464.
- 14) V.G. Zinov, A.D. Konin and A.I. Mukhin, Sov. J. Nucl. Phys. 2 (1966) 613.
- 15) C.W. Lewis, E.T. Boschitz, D. Engelhardt and H. Ullrich, Bull. Am. Phys. Soc. 19 (1974) 592.
- 16) D.W.O. Rogers, J.A. Becker, T.K. Alexander, N. Anyas-Weiss, T.A. Belote, S.P. Dolan, N.A. Jelley and W.L. Randolph, Nucl. Phys. A226 (1974) 424;
D.W.O. Rogers, N. Anyas-Weiss, J.A. Becker, T.A. Belote, S.P. Dolan and W.L. Randolph, Nucl. Phys. A226 (1974) 445.
- 17) C.W. Lewis, Nucl. Instr. and Meth. 123 (1975) 289.

- 18) L.E. Temple, Lawrence Berkeley Laboratory report LBL-781 (1972) 46.
- 19) M. Eckhause, R.T. Siegal and E. Welsh, Nucl. Phys. 81 (1966) 575.
- 20) F.A. Beck, T. Byrski, G. Costa and P. Engelstein, Nucl. Phys. A218 (1974) 213.
- 21) H. Hasper and P.B. Smith, Phys. Rev. C 8 (1973) 2240.
- 22) L.C. Northcliffe and R.F. Schilling, Nucl. Data Tables 7 (1970) 233.
- 23) G. Rudstam, Z. Naturforschg. 21A (1966) 1027.
- 24) G.D. Harp, K. Chen, G. Friedlander, Z. Fraenkel and J.M. Miller, Phys. Rev. C 8 (1973) 581;
H.W. Bertini, Phys. Rev. C 6 (1972) 631.
- 25) J. Amato, R.L. Burman, R. Macek, J. Oostens and W. Shlaer, Phys. Rev. C 9 (1974) 501.
- 26) S. Cohen and D. Kurath, Nucl. Phys. A141 (1970) 145.
- 27) T.J. Kopaleishvili, J.Z. Machabeli and M.S. Chachkhunashvili, Sov. J. Nucl. Phys. 15 (1972) 629.
- 28) D.H. Gloeckner, R.D. Lawson and F.J.D. Serduke, Phys. Rev. C 7 (1973) 1913.
- 29) J. Hüfner, L. Tauscher and C. Wilkin, Nucl. Phys. A231 (1974) 455;
V.M. Kolybasov and V.A. Tsepov, Sov. J. Nucl. Phys. 14 (1972) 418.
- 30) I. Rotter, Nucl. Phys. A122 (1968) 567;
D. Kurath, Phys. Rev. C 7 (1973) 1390.
- 31) C. Détraz, H.H. Duham and H. Hafner, Nucl. Phys. A147 (1970) 488.
- 32) H.H. Gutbrod, H. Yoshida and R. Bock, Nucl. Phys. A165 (1971) 240.
- 33) S.L. Kannenberg, Ph.D. dissertation, Northeastern University (1968).
- 34) B.J. Thomas, A. Buchnea, J.D. Irish and K.G. McNeill, Can. J. Phys. 50 (1972) 3085.
- 35) P. Martin, J.B. Viano, J.M. Loiseaux and Y. Le Chalony, Nucl. Phys. A212 (1973) 304.
- 36) A. Doron, J. Julien, M.A. Moinester, A. Palmer, A.I. Yavin, Phys. Rev. Letters 34 (1975) 485.
- 37) O. Artun, Y. Cassagnou, R. Legrain, N. Lisbonna, L. Roussel, J.P. Alard, A. Baldit, J.P. Costilhes, J. Fargeix, G. Roche and J.C. Tamain, Preprint Saclay DPN (1975).
- 38) S.A. De Wit, G. Backenstoss, C. Daum and J.C. Sens, Nucl. Phys. 87 (1967) 657.
- 39) H. Backe, R. Engfer, U. Jahnke, E. Kankleit, R.M. Pierce, C. Petitjean, L. Schellenberg, H. Schneuwly, W.U. Schröder, H.K. Walter and A. Zehnder, Nucl. Phys. A189 (1972) 472.
- 40) H.L. Anderson, C.K. Hargrove, E.P. Hincks, J.D. McAndrew, R.J. McKee, R.D. Barton and D. Kessler, Phys. Rev. 187 (1969) 1565.

Figure captions

- Fig. 1 : Prompt γ -ray spectrum of the reaction $\text{H}_2\text{O} + \pi^-$ at rest.
- Fig. 2 : Prompt γ -ray spectrum of the reaction $\text{LiF} + \pi^-$ at rest.
- Fig. 3 : Prompt γ -ray spectrum of the reaction $\text{Ca} + \pi^-$ at rest.
- Fig. 4 : Prompt γ -ray spectrum of the reaction $^{93}\text{Nb} + \pi^-$ at rest.
- Fig. 5 : Selected portions of the prompt γ -ray energy spectrum resulting from π^- absorption at rest in an H_2O target. The solid line is a computer fit of a Gaussian plus linear background function to the experimental points. The experimental points which lie above the top of the 2313 keV peak are due to unshifted 2313 keV γ -rays which are preceded by the slow transition ^{14}N (5106-2313). The intrinsic detector resolution is given by the non-Doppler broadened width of the 1593 keV ^{208}Pb double escape peak.
- Fig. 6 : Yields as a function of the number of removed nucleons of this experiment compared to data from spallation reactions [23].
- Fig. 7 : Z-dependence of nucleon removal of this experiment compared to spallation data [23].

64810

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7