# Multinucleon Removal in 220-MeV $\pi^-$ Reactions with $A \leqslant 51$ Nuclei*

V. G. Lind
*Utah State University, Logan, Utah 84322*

and

H. S. Plendl
*Florida State University, Tallahassee, Florida 32306*

and

H. O. Funsten and W. J. Kossler
*College of William and Mary, Williamsburg, Virginia 23185*

and

B. J. Lieb and W. F. Lankford
*George Mason University, Fairfax, Virginia 22030*

and

A. J. Buffa
*California State Polytechnic College, San Luis Obispo, California 93401*
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We have detected and identified prompt $\gamma$ rays from residual nuclei formed in 220-MeV $\pi^-$ reactions with C, F, O, Mg, Al, Si, S, Ca, and V. Cross sections for $2n+2p$ removal from the even-$A$, even-$Z=N$ targets are found to be comparable to inelastic cross sections; multiple-$(2n+2p)$-removal cross sections are also large. For the odd-$A$ target, $(n+2p)$- and $(2n+2p)$-removal cross sections are of the same order as inelastic cross sections. The results are compared with previously reported hadron-induced $\alpha$-particle—removal cross sections.

We have studied the interactions of negative pions in the $N_{33}$* resonance region with several light- and medium-mass nuclei. Prompt de-excitation $\gamma$ rays from residual nuclear levels were detected with a high-resolution Ge(Li) detector[1] to overcome some of the difficulties inherent in the use of currently available low-intensity, poor-resolution pion beams. The experiment was designed to measure neutron-to-proton knockout ratios. A striking feature of the spectra, however, was the appearance of strong lines from residual nuclei that can be formed by removal of one or several $\alpha$ particles or equivalent nucleons from even-$A$, even-$Z=N$ targets with yields comparable to inelastic scattering, while for odd-$A$ targets, $t$, $\alpha$, and $t+\alpha$ (or equivalent nucleon) removal lines were prominent.[2] We report here on an examination of this feature.

The work was performed with the 245-MeV $\pi^-$ beam from the Space Radiation Effects Laboratory synchrocyclotron. The beam intensity was $5\times10^5$ particles/sec, of which 80% were pions, the rest muons and electrons. We used isotopically unseparated targets (C, $H_2O$, LiF, Mg, Al, Si, S, Ca, and V), in which the pions lost ~50 MeV, so that the average $\pi^-$ energy was approximately 220 MeV. Events in a 40-$cm^3$ Ge(Li) detector (at 90° with respect to the beam) coincident with a beam telescope and anticoincident with a cup-shaped scintillator surrounding the Ge(Li) detector (to discriminate against charged particles) were energy analyzed and stored in the the first half of a 4096-channel analyzer. The overall resolution of the system was ~5 keV at 1 MeV. $\gamma$-ray spectra with reasonable statistics were obtained with the order of $10^{10}$ incident pions, at an average rate of about 100 counts/sec. These spectra included $\gamma$ rays from in-flight pion absorption, since coincidence with outgoing pions was not demanded. Background contributions to the spectra were identified by recording (in the second half of the analyzer) additional spectra consisting of events in the Ge(Li) detector that were delayed by ~50 nsec relative to beam-telescope events and by taking spectra with the target material removed.

A portion of the background-subtracted $\gamma$-ray spectra is shown in Fig. 1[3] for all targets except $H_2O$. Each spectrum has been renormalized to emphasize common as well as contrasting fea-

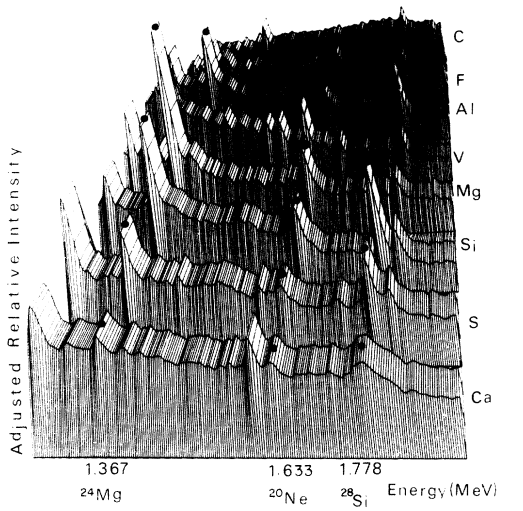


FIG. 1. A portion of the $\gamma$-ray spectra for all the targets except $H_2O$. The intensity scale is adjusted to illustrate common and contrasting features with peaks corresponding to about $10^5$ counts. The labeled lines are indicated with a solid circle as they appear in each target spectrum and illustrate the observed multiple-$\alpha$-removal effect.

tures among the spectra. Thus we have been able to identify common background lines as well as certain regularities such as the 1.635-MeV line of $^{20}$Ne or the 1.368-MeV line of $^{24}$Mg produced in each of the targets Ca, S, Si, Al, and Mg. Background lines included lines from Al, Fe, Ge, and Pb.

The computer code SAMPO[4] was used to analyze the energy, intensity, shape, and statistical significance of the observed lines and to calculate the corresponding cross sections. Of the order of fifty lines per target were analyzed, and most of these were identified with previously observed transitions.[5] The cross sections were calculated assuming isotropic $\gamma$ emission with respect to the incident pion beam. Lines below 0.25 MeV and above 6.5 MeV could not be seen because of cutoffs in the electronics system. The lower limit for cross sections to be discernible was of the order of 0.1 mb in the O spectrum and of the order of 0.1 mb in the other spectra. Possible contributions to the spectra from target isotopes other than the most abundant one were estimated from the size of the inelastic scattering peaks for these isotopes and were found to be negligibly small. The cross sections were corrected for target $\gamma$-ray absorption, detector efficiency, background contributions, and, where appropriate, branching to lower levels. Feeding from higher levels was not corrected for in the cross sections reported here, so that the calculated cross sections represent the sum of all events (reactions and $\gamma$-ray de-excitations from higher levels) leading to the production of a particular excited level. The cross section for inelastic excitation of the 4.43-MeV $2^+$ state in $^{12}$C was determined to be 10.8 mb, in good agreement with a value of 9.5 mb calculated from the inelastic differential cross section that was measured by Binon *et al.* at 200 MeV.[6] The agreement indicates that contributions from secondary reactions are probably not more than 10% and hence do not seriously affect our results.

The cross sections for production of excited levels in residual nuclei that can be formed by single or multiple $2n+2p$ removal are shown in Table I for $^{16}$O, $^{24}$Mg, $^{27}$Al, $^{28}$Si, $^{32}$S, and $^{40}$Ca. Cross sections involving $n+2p$ or $2n+p$ removal are also given when observed; inelastic scattering as well as single-neutron-removal cross sections are given for comparison. Also shown are corresponding cross sections for 145-MeV proton-induced particle removal and inelastic scattering. These were measured by Clegg and collaborators[7,8] by detecting de-excitation $\gamma$ rays with low-resolution NaI detectors.

Single-proton-removal cross sections were generally within 50% of the single-neutron-removal cross sections. The neutron-to-proton removal ratios, other observed reactions, and an analysis of the Doppler broadening that was determined for many lines, will be reported elsewhere. These other reactions, which include multiple nucleon removal in combinations other than those we report here, are generally much weaker, but certain combinations do come within a factor of up to $\frac{1}{3}$ of the appropriately compared multiple-$\alpha$-decay cross sections.

For each residual nucleus, only the lowest $\gamma$-ray transition that was observed is reported in Table I. Cross sections corresponding to transitions from several additional low excited levels were determined for many of the other residual nuclei and were found to generally agree with known branching ratios.[5] Where strong disagreement existed, this was taken as evidence against the identification of that line solely with that particular level, and hence other possible assignments were looked for.

$\gamma$-ray transitions from the higher bound levels (usually few in number) for the "clustering" reactions reported herein were generally conspicuous-

TABLE I. Cross sections for the production of selected residual nucleus levels in $\pi^-$ and $p$ interactions with $A = 16-40$ nuclei. The 220-MeV $\pi^-$ data[a] and the 145-MeV $p$ data[b] are both for the lowest observed transition (usually the first to ground). Systematic errors in the absolute values of the $\pi^-$ data may be as high as 30% but the relative cross sections for a given target are good to 5%. For entries marked with an asterisk, the observed peak is ambiguous with another possible assignment; with a dash, looked for but not observed; with a question mark, result questionable.

| Target Nucleus | Projectile | Cross Section in mb for Target Minus Removed Equivalent Nucleons -0- | n | t | $^3$He | α | tα | 2α | 3α | 4α | 5α |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $^{40}$Ca | π | 45.9 | 32.1 | * | 21.7 | 137.9 | - | 114.8 | 66.1 | 36.2 | 27.4 |
| | p | <35* | | | | 37 | | <65* | | | <32* |
| $^{32}$S | π | 168.3* | 21.9 | - | 71.5 | 76.4 | - | 47.1 | 19.0 | | |
| | p | 39* | | | | 25 | | 7.9 | 9.4 | | |
| $^{28}$Si | π | 40.3 | 13.7 | - | 23.4 | 38.0 | ? | 21.6 | 5.9 | | |
| | p | 24.5 | 6.8 | | | 28.5 | | 18.5 | | | |
| $^{27}$Al | π | 34.9 | 12.4 | 47.5 | - | 29.9 | 10 | 6.9* | | | |
| | p | 11* | | 31 | | | 18 | | | | |
| $^{24}$Mg | π | 35 | 8.6 | - | 6.3 | 18.4 | | .5 | | | |
| | p | 36 | | | | 15 | | | | | |
| $^{16}$O | π | 12.5 | 2.9 | - | <1.4 | 16.8 | | | | | |

[a]This work.
[b]Refs. 7 and 8.

ly absent (except for O) within the experimental limits of 0.1 mb, which indicates that the reactions proceed preferentially to the lower excited levels and are not generally a consequence of preferential feeding from higher levels as one might expect. (Enhancement factors favoring $2^+$ first excited levels due to statistical feeding are estimated to be as large as 6 but such feeding is not detected.)

For the even-$A$, even-$Z=N$ nuclei, both $\pi^-$- and proton-induced reaction cross sections leading to first excited states in $A-4$, $Z-2$ residual nuclei are seen to be comparable to inelastic scattering cross sections. Multiple $2n+2p$ or $\alpha$ removal also results in relatively large cross sections. A peculiarity, however, is the evidence for $1n+2p$ or $^3$He removal, but not (within experimental limits) for $2n+1p$ or triton removal. It should be noted that the cross sections for $\pi^-$-induced multiple $\alpha$ removal are seen to increase relative to single $\alpha$ removal in a consistent manner with increasing $A$.

For $^{27}$Al, the observed $\pi^-$-induced $(2n+2p)$-removal cross section is also large relative to inelastic scattering, but not as large as the $(2n+1p)$-removal cross section; cross sections for $4n+4p$ or $2\alpha$, and $4n+3p$ or $\alpha+t$ removal are also seen to be appreciable, while $(1n+2p)$-removal cross sections are not seen. The results for $^{19}$F and $^{51}$V (not shown in Table I) were similar. The removal of $2n+p$ from $^{51}$V leading to the first excited state of $^{48}$Ti is measured to be 95 mb, and the combined observed intensity for the transitions from the third and fourth levels to ground of $^{47}$Sc for $2n+2p$ removal is 115 mb. The two lower levels were very weakly populated.

Cross sections for a few of the $\gamma$-ray transitions following $\pi^-$ interactions with Si and $^{60}$Ni at 360 MeV average energy have recently been obtained by another group.[9] The cross sections at this energy, i.e., considerably above the $N_{33}$* resonance, are appreciably smaller, but multiple $\alpha$ removal has the same relative strength and increases with $A$ in the same way as near the resonance. Large $\gamma$-ray yields from residual nuclei formed by single and multiple $2n+2p$ removal from targets up to $^{93}$Nb have also been observed with stopped pions[10-13] and with stopped kaons.[14]

The results of the present work indicate that energetic pion interactions with nuclei generally result in decay products with single and multiple $\alpha$ particles removed. Interactions involving only one nucleon removal are generally not prevalent, even at an incident energy where the likelihood of $N_{33}$* formation and subsequent decay would appear to make them favored processes. The large amount of available excitation energy should also favor statistical evaporation of nucleons or nucleon clusters following excitation by $\pi^-$ absorption or inelastic scattering. The results, however, are in qualitative disagreement with this interpretation, since only some of the residual nuclei that would be expected to be formed have been observed; the apparent lack of $\gamma$-ray transitions from higher bound levels and the relative strength of $\alpha$ removal from odd-mass nuclei also speak against such a mechanism.

We made calculations with an evaporation code[15] that was adapted to pion-nucleus interactions with $^{40}$Ca.[16] The relative cross sections calculated with the assumption that either pion absorption or pion scattering with varying amounts of energy transfer resulted in compound-nucleus formation and subsequent $p$, $n$, and $\alpha$ evaporation are in gross disagreement with the observed ones. For example, single $n$ removal is unfavored, but so is single $\alpha$ compared to $\alpha+n$ removal. More detailed evaporation codes may eventually be capable of explaining these data, but at present it appears that these data are showing new nuclear phenomena related to clustering within the nucleus.

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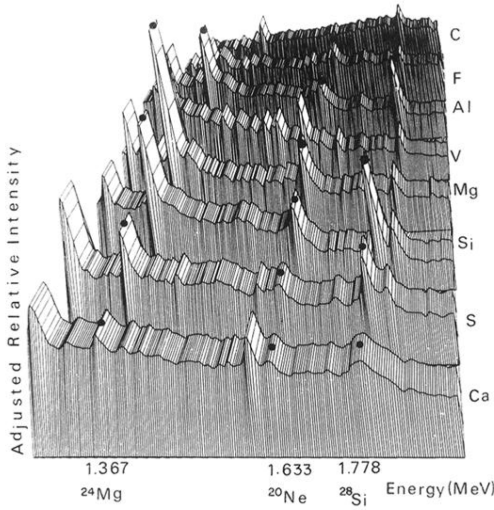


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