$\pi^{\pm}$-induced multinucleon removal from ^{27}Al and ^{28}Si†

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γ-ray spectra were recorded following bombardment of ^{27}Al and ^{28}Si targets by 220 MeV π^- and 190 MeV π^+ beams. Residual nuclei were identified by their characteristic γ rays and cross sections for production of specific states of daughter nuclei were calculated. Results for $\Delta A > 2$ were found to be largely independent of the target and the charge state of the incident π. The resulting cross sections showed effects of binding energy and were in fair agreement with the results of an intranuclear cascade/evaporation calculation.

[NUCLEAR REACTIONS ^{27}Al($\pi^{\pm}$,$X\gamma$), ^{28}Si($\pi^{\pm}$,$X\gamma$); E_{π^-}=220 MeV; E_{π^+}=190 MeV; detected γ rays; Ge(Li); measured 90° σ for multinucleon removal.]

I. INTRODUCTION

Several recent experiments have studied prompt γ rays resulting from the interaction of pions,[1-6] protons,[7-10] and heavy ions[11] on nuclei to determine cross sections for the production of residual nuclei which are at least several nucleons removed from the target. It has generally been assumed that these nuclei result from a two-step process in which a pre-equilibrium phase is followed by evaporation. However, doubt has been cast on this interpretation by several experiments[12-14] which detected copious production of γ rays from nuclei corresponding to removal of one or more α particles from the target nucleus.

Since the experiment detects only the residual nuclei produced, the apparent strong production of α particle nuclei may not be due to direct interaction of the π with a pre-formed α cluster. There are two factors to which the experimental technique is insensitive that may cause the observed phenomena. Since the targets in which the effect is most pronounced are even-even, the α removal nuclei produced are also even-even. A larger fraction of γ decays in even-even nuclei cascade down through the first few excited states than in odd nuclei, biasing the experiment in favor of the detection of these nuclei. Further, there may be binding energy effects in the evaporation process which favor the production of even-even nuclei.

The present work involves a γ-ray study of π reactions on an even-even and an odd-even target nucleus located adjacently in the Periodic Table. Cross section measurements from these two targets to the same residual nucleus may then reveal the effects of γ-ray decay schemes and binding energy differences.

II. EXPERIMENT

The experiment was performed at SREL using the 220 MeV π^- and 190 MeV π^+ nominal energy beams. Information on the experimental technique, sample spectra, and a discussion of the data analysis have been published in several recent papers,[5,15] so only those factors pertaining to this particular experiment will be covered here. Isotopically unseparated targets of 13 g/cm^2 (π^- + ^{27}Al), 7 g/cm^2 (π^+ + ^{27}Al), 1.2 g/cm^2 (π^- + Si), and 9 g/cm^2 (π^+ + ^{28}Si) were used. γ rays in coincidence with a two scintillator beam telescope and in anticoincidence with a cup-shaped scintillator which surrounded the Ge(Li) detector to eliminate charged particle events were analyzed and stored in the first half of a gain-stabilized 4096 channel analyzer. Background and random contributions to the spectra were identified by recording off-time spectra in the second half of the analyzer. γ rays from ~ 0.3 to 6.4 MeV were detected with a typical resolution of ~ 4 keV. The efficiency of the Ge(Li) detector was 8% for $\pi^- + {}^{27}$Al and $\pi^+ + {}^{28}$Si and 20% for $\pi^+ + {}^{27}$Al and $\pi^- + {}^{28}$Si.

The measured cross sections which are reported in Table I have been corrected for feeding from higher energy states for which a cross section could be determined. Major contributions to the reported uncertainties were statistics, the energy dependent error in the relative efficiency, and the error in absolute efficiency normalization which was 15%. Cross sections for γ rays from (π, π') reactions are not reported because of contamination by secondary target neutron induced events. It should be noted that the results for $\pi^- + {}^{27}$Al have been previously published[5] and are included for comparison. Three cross sections which were reported as being doubtful in that paper have not been included in Table I.

The sum of all reported cross sections for each spectrum was within uncertainties ~ 240 mb, which is 40% of a typical reaction cross section obtained by a Kisslinger optical potential.[16] It becomes systematically more difficult to detect γ rays from the residual nuclei with $A \lesssim 18$. γ rays emitted by these lighter nuclei show a more pronounced Doppler-broadening making transitions from weakly excited states more difficult to detect. Because of the generally short lifetime of radioactive isotopes in this mass region, use of the off-beam radioactivity studies would not appreciably increase the available data.

In analyzing the γ-ray spectra an attempt was made to locate γ transitions from the seven or eight lowest excited states of every possible residual nucleus. Generally, the absence of a cross section listed for a particular residual nucleus indicates no detectable γ transitions for that nucleus. (No cross sections could be determined for the first excited states of ^{23}Mg and ^{25}Al, which overlap within experimental energy resolution.)

TABLE I. Measured cross sections for 220 MeV π^- and 190 MeV π^+ on ^{27}Al and ^{28}Si.

Residual nucleus	$\pi^- + {}^{28}$Si (mb)	$\pi^+ + {}^{28}$Si (mb)	$\pi^- + {}^{27}$Al (mb)	$\pi^+ + {}^{27}$Al (mb)
^{27}Si	14 ± 3	6.9 ± 1.4		
^{26}Si	2.2 ± 1.4	0.3 ± 0.2		
^{27}Al	22 ± 4	26 ± 4		
^{26}Al	25 ± 5	22 ± 4	38 ± 5	29 ± 6
^{25}Al	2.6 ± 0.8			
^{26}Mg	17 ± 5	19 ± 3	46 ± 9	49 ± 8
^{25}Mg	15 ± 3	11 ± 2	19 ± 4	18 ± 3
^{24}Mg	28 ± 6	45 ± 8	34 ± 6	32 ± 7
^{22}Mg		0.8 ± 0.2		0.9 ± 0.3
^{25}Na				2.5 ± 0.8
^{23}Na	23 ± 4	17 ± 4	21 ± 4	21 ± 6
^{22}Na	4.9 ± 1.4	5.6 ± 1.2	3.6 ± 1.2	5.9 ± 1.4
^{21}Na	1.8 ± 0.5	2.8 ± 0.8	0.7 ± 0.3	2.0 ± 0.5
^{24}Ne	2.0 ± 0.5			2.6 ± 0.8
^{23}Ne	2.3 ± 0.8	1.1 ± 0.5		
^{22}Ne	11 ± 2	6.6 ± 1.2	16 ± 3	11 ± 2
^{21}Ne	20 ± 3	9.7 ± 2.2	13 ± 3	22 ± 4
^{20}Ne	11 ± 2	13 ± 3	15 ± 3	11 ± 2
^{19}Ne	2.1 ± 0.8	1.0 ± 0.4		2.2 ± 0.7
^{18}Ne			2.1 ± 0.5	
^{21}F	0.5 ± 0.2	0.7 ± 0.3		
^{20}F	1.6 ± 0.6	1.1 ± 0.4	3.3 ± 0.8	4.7 ± 1.2
^{19}F	4.3 ± 0.9	1.9 ± 0.5	5.4 ± 1.0	2.4 ± 0.7
^{18}F	3.0 ± 0.7	4.8 ± 1.0	3.9 ± 0.8	2.9 ± 0.6
^{18}O	0.8 ± 0.4			1.5 ± 0.4
^{17}O	1.8 ± 0.3	0.6 ± 0.2	3.9 ± 0.8	3.7 ± 0.9
^{16}O	6.0 ± 1.5	4.9 ± 1.8	7.3 ± 2.3	5.0 ± 1.4
^{15}O		2.6 ± 0.9		1.5 ± 0.6
^{16}N	2.1 ± 0.6	0.9 ± 0.6	3.2 ± 0.7	
^{15}N	1.7 ± 0.5	2.5 ± 1.0	2.0 ± 0.6	1.9 ± 0.7
^{12}C	10 ± 3[a]	8 ± 3[a]	12 ± 4[a]	7 ± 2[a]

[a]Cross section may be contaminated by π interactions in the scintillation counters.

III. RESULTS AND DISCUSSION

Table I lists the cross sections for production of residual nuclei obtained in the present experiment. A previous measurement[1] of γ rays from π reactions on these targets at 70 and 100 MeV detected fewer residual nuclei and found cross sections smaller by a factor of greater than 2. A later study[3] of 100 MeV π^+ on ^{27}Al found cross sections which were larger than those of Ref. 1 by almost a factor of 2 and comparable to the present results.

For $\Delta A \geq 2$ the cross sections are relatively independent of the target and the charge state of the π, suggesting an evaporation process. Cross sections for $\Delta A < 2$ would be sensitive to the pre-evaporation phase of the reaction. In order to test this, we compared the results of Table I for $\Delta A \geq 2$ with the predictions of an intranuclear cascade/evaporation (INC/E) calculation by Harp *et al.*[17,18] This comparison is shown in Figs. 1, 2, and 3 for 200 MeV π^- on ^{27}Al and π^- and π^+ on ^{28}Si, respectively. Results for $\pi^+ + {}^{27}$Al were not available. In these figures the INC/E results are connected by a curve to guide the eye. The points plotted with error bars are the summed cross sections for each particular residual nucleus. Points plotted with a Δ will be discussed later.

A feature of the INC/E results for $\Delta A \gtrsim 2$ is the influence that binding energy has on the predicted cross sections. For a given Z there is a strong peak in σ at $N \approx Z$. Also the INC/E results for the

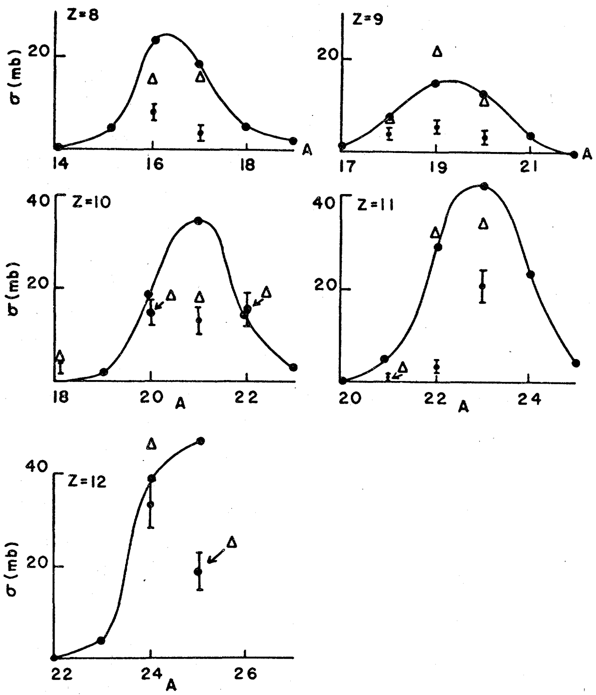

FIG. 1. The production cross sections for $\pi^- + {}^{27}\mathrm{Al}$ plotted for different values of residual nucleus Z. The continuous curve is the result of an intranuclear cascade/evaporation calculation (Refs. 17 and 18); the points with error bars are the summed experimental cross sections; and the "Δ" are the compensated cross sections discussed in the paper.

two targets and different charge states of the π are similar. This similarity has been observed in the present work.

A fraction of the production of each residual nucleus is missed by the γ-ray technique. This may result from either initial production of the residual nucleus in its ground state or γ excitation of states which do not feed the lowest excited states but are excited too weakly for their γ-ray transitions to be directly detected. Unfortunately, the fraction of "missed" cross section will vary with the γ-decay schemes of each residual nucleus. In even-even nuclei, transitions strongly feed the lowest 2^+ states, making it likely that a large fraction of the total cross section for an even-even nucleus is detected. Inspection of the γ-decay schemes of even-even nuclei in this mass region indicate that ~ 80% of states for which the γ-decay branching ratios are known feed the first excited state, either directly or indirectly. The corresponding fraction for non-even-even nuclei averages ~ 30% but ranges from 75% down to 15%.

Using a procedure discussed in detail in a previous paper[5] we have compensated the present

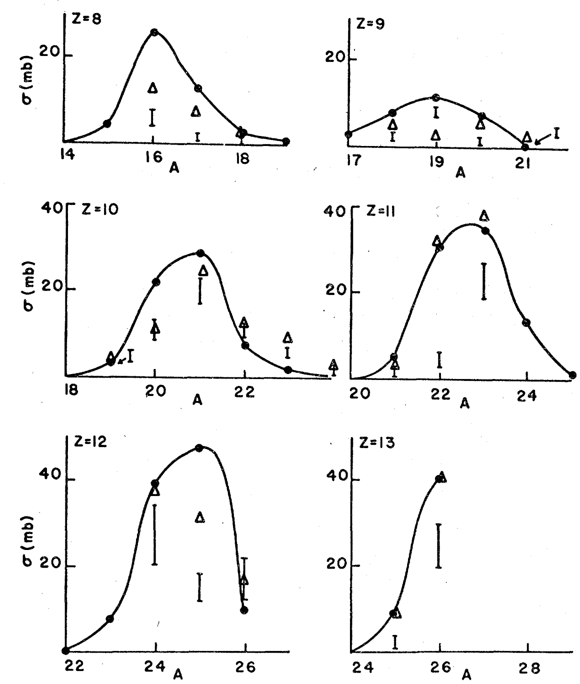

FIG. 2. The production cross sections for $\pi^- + {}^{28}\mathrm{Si}$. (See explanation for Fig. 1.)

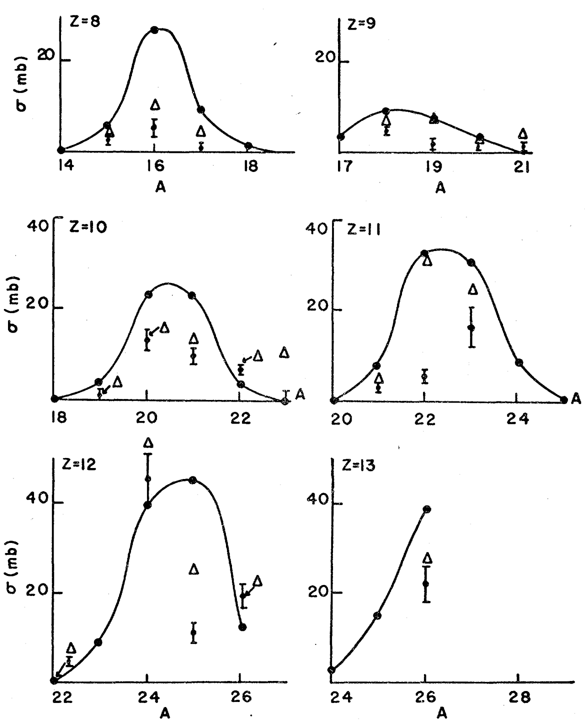

FIG. 3. The production cross sections for $\pi^+ + {}^{28}\mathrm{Si}$. (See explanation for Fig. 1.)

cross sections for the effects of variation in feeding. This compensation is performed by dividing the value of the measured ith state cross section (not corrected for feeding from higher energy states) by the fraction of the total production of that nucleus which decays through the ith state. Calculation of this fraction used available γ-ray feeding information and assumes a statistical $2J + 1$ initial population of all states. The resultant "compensated" cross section should then be equal to the total production cross section for that nucleus. The compensated cross sections calculated for all detected states of a residual nucleus should be equal to each other. This is not always the case, which may be due to the fact that the compensated cross sections calculated for the higher energy states detected involve a generally small cross section and a very large compensation. Clearly compensated cross sections calculated for the lowest excited states of a given nucleus should be most reliable.

The additional points Δ plotted in Figs. 1–3 are compensated cross sections calculated for the lowest excited state detected for each residual nucleus. Generally there is better agreement with the INC/E results than was found for the summed cross sections.

Effects of multiple α removal may be examined by comparing summed cross sections for residual nuclei produced by α removal from ^{28}Si (^{24}Mg, ^{20}Ne, ^{16}O, and ^{12}C) with those produced by α removal from ^{27}Al (^{23}Na, ^{19}F, and ^{15}N). The former make up 23% of the $\pi^- + {}^{28}$Si cross sections and 33% of the $\pi^+ + {}^{28}$Si cross sections whereas the latter make up only 11% of the $\pi^- + {}^{27}$Al cross sections and 12% for the $\pi^+ + {}^{27}$Al. Cross sections for ^{24}Mg, ^{20}Ne, ^{16}O, and ^{12}C which result from α removal from ^{28}Si are 27% of $\pi^- + {}^{27}$Al and 23% of $\pi^+ + {}^{27}$Al cross sections. This again shows the target independence of these results and suggests that the process may not involve cluster effects.

The average number of nucleons removed $\langle \Delta A \rangle$ was ~ 5 for π^- on ^{28}Si and ~ 4.3 for π^- on ^{27}Al. The predictions of the INC/E code were ~ 5.9 and ~ 5.7, respectively. This is reasonable agreement considering the difficulty in detecting γ rays for $A \lesssim 18$.

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