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Reaction cross section studies with ^{28}Si ions

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The fusion-evaporation products in the ^{28}Si-induced reactions on ^{27}Al at 65–81 MeV have been studied by detecting γ rays from the residual nuclei. Cross sections for two- and three-particle removal from the initial compound nucleus ^{55}Co are found to dominate. High spin states in the product nuclei have been investigated. Experimental reaction cross sections are compared with compound nucleus evaporation calculations.

[NUCLEAR REACTION ^{27}Al(^{28}Si, $\chi\gamma$), E = 65, 72, 77, and 81 MeV; measured $\sigma(E_\gamma, E)$ and $\gamma\gamma$ coincidence. Deduced reaction cross sections.]

I. INTRODUCTION

The present work is part of a program to study heavy ion reaction cross sections using ^{28}Si beams, and we present now the results for the ^{27}Al(^{28}Si, $xn, yp, z\alpha\gamma$) reactions. Except for our initial publication,[1] no use of ^{28}Si beams for in-beam γ-ray experiments has been reported in the literature. We are planning a series of investigations of fp-shell nuclei, and this initial work has been a good means of studying the reaction mechanisms and establishing the facility for ^{28}Si induced in-beam spectroscopy at this laboratory.

Because the deexcitations of heavy ion reaction products proceed mainly by high-spin cascades, we are able to study high-spin states in the residual nuclei. The γ-ray yields due to transitions to the ground states are good measures of the reaction cross sections. Considerable interest[2] has recently been directed to cross sections of reactions involving bombardment of fp-shell nuclei with beams of π, K, p, ^{3}He, and ^{6}Li. In the present work we have identified the products from the initial compound nucleus ^{55}Co by means of γ-ray singles and $\gamma\gamma$ coincidence measurements in order to study reaction cross sections.

II. EXPERIMENTAL PROCEDURE

Targets of ^{27}Al were bombarded with ^{28}Si ions which had been extracted from the inverted sputter source and accelerated by the Florida State University Super FN tandem Van de Graaff Accelerator to energies of 65–81 MeV. Singles γ-ray spectra were measured at 90° to the beam direction using a Ge(Li) detector with resolution ~2.8 keV [full width at half maximum (FWHM)] at 1332 keV. A typical thick-target spectrum is shown in Fig. 1, in which some of the peaks are labeled with energies in keV. No appreciable contamination of the Al target was observable. Energy and efficiency calibrations were accomplished using National Bureau of Standards mixed radioactive sources in separate runs. The $\gamma\gamma$ coincidence measurements used two Ge(Li) detectors on either side of and 90° to the beam line. The timing resolution was ~14 ns (FWHM). Thin targets of 350 μg/cm^2 ^{27}Al evaporated onto thick Ta backings were used in the measurements of excitation curves.

III. RESULTS

Using the measured values of the energies and intensities of the γ rays (see Table I), energy

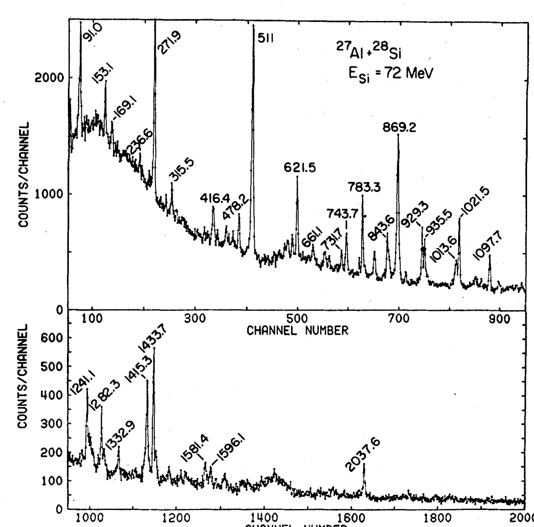

FIG. 1. γ-ray spectrum observed from the ^{27}Al + ^{28}Si reactions at 72 MeV using a thick Al target.

TABLE I. Present results for the ^{27}Al + ^{28}Si reaction.

E_γ (keV) (±0.6)	I_γ	Assignment	E_γ^{lit} (keV)
91.0	53	^{49}Cr(β^+)^{49}V	90.65±0.02
153.1	11	^{49}Cr(β^+)^{49}V	152.94±0.02
169.1	11	^{52}Mn	168.8 ±0.3
236.6	6	(^{51}Mn	237.40±0.15)
243.3	3	a	
262.0	4	a	
271.9	103	^{49}Cr	271.4 ±0.3
301.5	4	a	
315.5	18	^{51}Cr	315.6 ±0.2
326.4	3	a	
416.4	24	(^{26}Al	416.9 ±0.3)
426.9	14	^{52}Cr	427.3 ±0.5
447.4	12	^{52}Mn	447.0 ±0.5
453.8	4	^{52}Mn	453.6 ±0.5
463.9	6	^{49}V	463 ±1
478.2	21	^{49}Cr	478.7 ±0.3
590.5	9	^{52}Cr	591.0 ±0.5
598.0	22	a	
609.8	22	^{50}Cr	609.9 ±0.5
621.5	64	^{52}Mn	621.5 ±1.0
661.1	14	^{50}Cr	661.8 ±0.5
690.6	14	^{49}Cr	689 ±1
701.1	7	a	
731.7	17	^{52}Mn	731.5 ±0.5
743.7	63	^{52}Cr (^{53}Fe	744.2 ±0.1 741.1 ±0.1)
775.4	16	^{51}Cr	755.4 ±0.2
783.3	99	^{50}Cr (+^{52}Cr	783.3 ±0.2 782 ±1)
812.3	60	^{49}Cr	810.7 ±0.5
843.6	50	(^{27}Al	843.76±0.03)
848.2	29	^{52}Cr ^{52}Fe	847 ±1 849.0 ±1.5

E_γ (keV) (±0.6)	I_γ	Assignment	E_γ^{lit} (keV)
869.2	270	^{52}Mn	869.3 ±0.5
889.0	8	a	
929.3	64	^{52}Mn	928.7 ±1.0
935.5	53	^{52}Cr (+^{49}Cr	935.5 ±0.2 936.8 ±0.3)
941.5	13	a	
1013.6	59	(^{27}Al	1014.46±0.03)
1021.5	97	^{49}V	1021.4 ±0.3
1063.0	13	(^{49}V	1064.3 ±0.3)
1077.2	9	^{53}Mn	1076.2 ±0.3
1097.7	57	^{50}Cr	1097.5 ±0.5
1121.3	21	^{53}Mn	1122.3 ±0.3
1165.2	19	^{51}Cr	1164.6 ±0.3
1177.0	20	a	
1228.4	13	a	
1241.1	66	^{49}V	1240.2 ±0.4
1250.3	42	(^{53}Mn	1252.1 ±0.2)
1257.9	17	^{53}Mn	1257.2 ±0.2
1282.3	44	^{50}Cr	1282.0 ±0.5
1290.8	18	^{49}Cr (+^{53}Mn	1289.6 ±0.5 1289.8 ±0.3)
1332.9	27	^{52}Cr	1333.8 ±0.2
1415.3	109	^{52}Mn	1416.5 ±1.0
1433.7	114	^{52}Cr	1434.3 ±0.2
1441.0	25	^{53}Mn	1441.4 ±0.3
1479.0	14	^{51}Cr	1480.3 ±0.3
1512.2	11	a	
1526.2	16	a	
1581.4	29	^{50}Cr	1581.1 ±0.5
1596.1	27	^{50}Cr	1595.7 ±0.5
1635.5	21	^{52}Cr	1636.7 ±0.3
1702.0	10	^{52}Cr	1700.9 ±1.0
2037.6	50	^{52}Mn	2038.0 ±1.0

[a]Not placed in a decay scheme.

level schemes of the residual nuclei were constructed. After correction for the detector efficiency, the γ-ray intensities were checked for smooth increases as lower energy levels are reached. The $\gamma\gamma$ coincidence data were used to confirm the proposed level schemes and to look for new levels. Partial angular distribution measurements were used to verify the anisotropy of γ rays reported in other experiments. The resulting level schemes are in excellent agreement with those based upon various reactions reported in the Nuclear Data Sheets,[3-7] updated where possible by more recent results.[8-16]

One of the strongest reactions in the present work is ^{27}Al(^{28}Si, $2pn$)^{52}Mn. The results of $\gamma\gamma$ coincidence measurements are shown in Fig. 2 along with level schemes of ^{52}Mn. Gating on the 869-keV γ ray produces a spectrum with strong peaks corresponding to the expected[9,10] transitions between levels up to $J^\pi = (11^+)$. The spectrum for the 1415-keV gate is consistent with that scheme, as are the spectra due to gates on the other γ rays assigned to this level scheme. These results verify the production of ^{52}Mn in ^{27}Al + ^{28}Si and are consistent with the high-spin sequence of levels based upon the 6^+ ground state (g.s.) found with other (HI, xn, $yp\gamma$) reactions. The coincidence spectra for gates on the 1433-, 1098-, and 271-keV γ rays show γ rays which are consistent with the ^{52}Cr level scheme. The measurements[12,13] of ^{50}Ti(α, $2n$)^{52}Cr and ^{51}V(^{7}Li, $\alpha 2n$) give evidence for the same sequence of levels from the 0^+ g.s. up to 7231 keV. The 1333-keV $4^+ \rightarrow 2^+$ transition is seen also in the present work. Evidence for levels up to $J^\pi = 10^+$ in ^{50}Cr is in agreement with other results[16] using several heavy ion (HI) induced re-

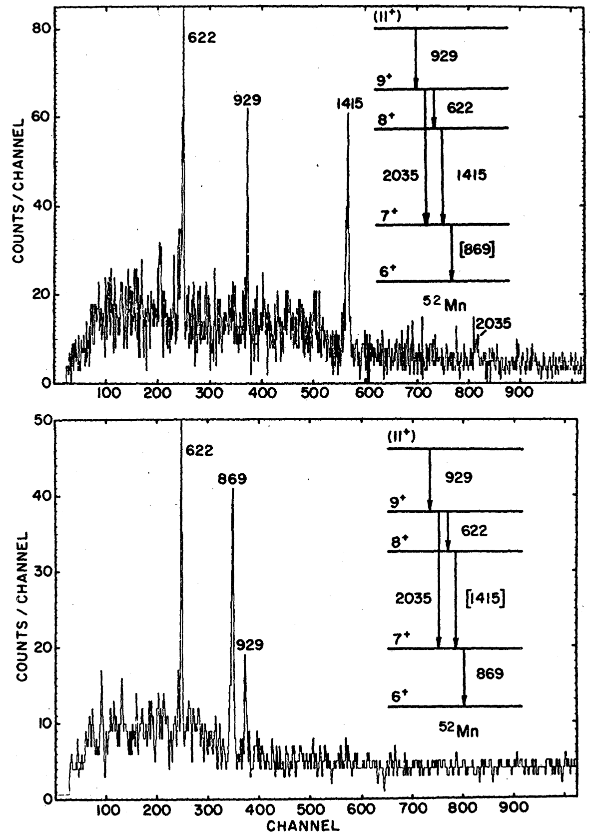

FIG. 2. Coincidence results for the ^{27}Al(^{28}Si, $2pn$)^{52}Mn reaction. The γ rays on which gates were set are indicated by brackets in the level diagrams.

actions. The γ-ray intensities show a smooth increase as lower levels are reached. Our level scheme for ^{49}Cr is consistent with the results[15] from ^{46}Ti($\alpha, n\gamma$), with γ-ray energies and intensities observed for levels up to $E_x = 3187$ keV and $J^\pi \sim \frac{13}{2}^-$. [The I_γ(936.8) is not obtained because of the strong 935.5-keV γ ray from ^{52}Cr.] The present results also show the production of ^{49}V in the ^{27}Al + ^{28}Si reaction. The present population of high spin states in ^{49}V is consistent with the results[15] from the ^{46}Ti(α, p) reaction.

The evidence for the weaker reactions comes only from the γ-ray singles measurements. The 1441.0- and 1121.3-keV γ rays could be due to the $\frac{13}{2}^- \rightarrow \frac{11}{2}^-$ and $\frac{11}{2}^- \rightarrow \frac{7}{2}^-$ transitions between levels adopted[7] from ^{40}Ca(^{16}O, $3p$)^{53}Mn data. Evidence for the production of ^{52}Fe consists of (a) the 169.1- and 447.4-keV γ rays which are close in energy to the ones expected from β^+ decay to ^{52}Mn and (b) the 848.2-keV γ ray which is probably due to the $2^+ \rightarrow 0^+$ transition, reported[16] to be 849.0 $\pm$ 1.5 keV. The weak intensity observed here may also be shared by an interfering ^{52}Cr γ ray.

Likewise, the production of ^{53}Fe is weak, but the yield is impossible to determine in the present study because of the interference of nearby ^{52}Cr peaks. The weak 236.6-keV γ ray observed in ^{27}Al + ^{28}Si may be due to the 237.40 $\pm$ 15-keV transition assigned[14] to ^{51}Mn. Finally, the 1165.2- and 1479.0-keV γ rays are close in energy to ones assigned[15] to ^{51}Cr in the ^{48}Ti(α, n) reaction.

Useful information for studying reaction mechanisms and fusion cross sections is obtained from excitation curves measured with thin targets. In the present work, we present data at four bombarding energies, with energy spreads of ~4 MeV due to energy loss in the target. Shown in Fig. 3 are the data for the individual products in the ^{27}Al + ^{28}Si reactions. Our results show the $2pn$ and $3p$ yields peaking at ~70–75 MeV. The yields for

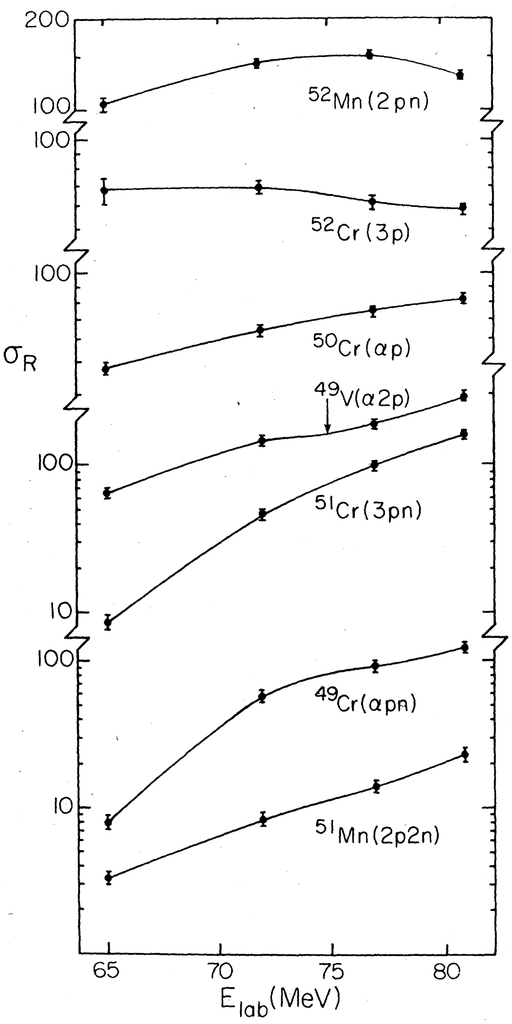

FIG. 3. Reaction cross section excitation functions for the products in ^{27}Al + ^{28}Si. The solid lines are to guide the eye.

TABLE II. Thin-target results for ^{27}Al + ^{28}Si at 72 MeV. Relative production cross sections are derived from the strengths of transitions to the ground states of the residual nuclei.

residual nucleus	adopted [a] E_γ (keV)	E_γ [b] (keV)	I_γ [c]	Present Work relative cross section [d] σ_R^{expt}	$\left[\frac{\sigma_R^{expt}}{\sigma_R^{ALICE}}\right]$ [e]
^{53}Fe	741.1 ± 0.1	(743.7)	f	⋯	⋯
	1328.2 ± 0.3	(1332.9)			
^{53}Mn	1441.4 ± 0.3	1441.0	18	(< 12)	(<3.9)
^{52}Fe	849.0 ± 1.5	848.2	9	6	0.49
^{52}Mn	869.3 ± 0.5	869.2	143	[100]	0.80
^{52}Cr	1434.3 ± 0.2	1433.7	70	49 [g]	1.3
^{51}Mn	237.4 ± 0.15	236.6	8	6	2.1
^{51}Cr	749.0 ± 0.2	(749)	3		
	1164.6 ± 0.3	1165.2	15	33	1.6
	1480.3 ± 0.3	1479.0	29		
^{50}Cr	782.9 ± 0.5	783.3	63	44	8.3
^{49}Cr	271.4 ± 0.3	271.9	59	41	4.8
^{49}V	1021.4 ± 0.3	1021.5	106		
	1064.3 ± 0.3	1063.0	30	100	7.1
	1154.9 ± 0.3	(1155)	7		

[a] Energies of transitions to the ground states of the residual nuclei. The values are taken from references in text.
[b] Uncertainties in the energies are ±0.6 keV.
[c] γ-ray yield at $\theta_{lab} = 90°$. Uncertainties are < 10%.
[d] Normalized so that $\sigma_R(^{52}\mathrm{Mn}) = 100$. Corrections are included for the anistropy of γ-ray yields.
[e] In the ALICE calculations, and energy range of 68–72 MeV was used to allow for energy loss in the target.
[f] Unavailable due to interference from strong γ rays assigned to other nuclei.
[g] Corrected for feeding from the ^{52}Mn(2$^+$) isomer.

reactions involving α particles and/or four particle emission are still increasing at 81 MeV.

IV. DISCUSSION

In the present work, five nuclides were produced with sufficient strength for the study of high-spin states, and the data are consistent with previous experiments using other HI reactions. In the even-A nuclei, states at 4–7 MeV excitation were observed up to spins of ~11$\hbar$. In the odd-A cases, the highest energy states observed here have $E_x \sim 3$ MeV and $J = \frac{15}{2}$.

The identification of all but a few γ rays makes possible a study of the reaction cross sections σ_R for ^{27}Al + ^{28}Si. The σ_R were deduced by summing, for each evaporation residue, the total γ-ray yield corresponding to transitions to the g.s. The thin target results at $E = 72$ MeV are shown in Table II. The anisotropy of the γ-ray yields was taken into account in the σ_R column by using angular distribution coefficients found in the literature for HI-induced reactions and was checked by limited angular distribution measurements for ^{27}Al + ^{28}Si. The overall uncertainty in σ_R is < 10%.

The contributions to the γ-ray yields due to radioactive decay of other reaction products are expected to be less than the uncertainties due to other factors. The amount of the ^{52}Mn(2$^+$) 21.3-

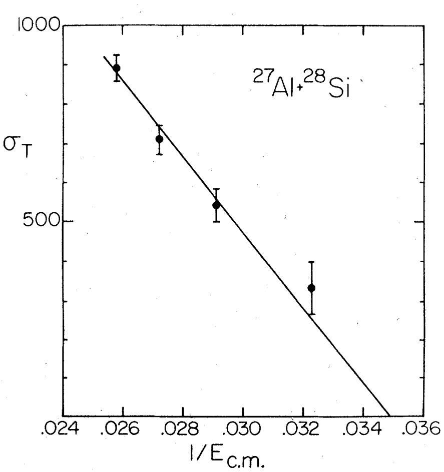

FIG. 4. Fusion excitation functions for the ^{27}Al + ^{28}Si reaction. Effective beam energies, calculated from the expected energy loss in the target, were used.

Mn decay contributing to the 1433.8-keV γ-ray yield would be ~50% of the $^{52}Mn(2^+)$ yield which is given by $I_\gamma(169.1)+I_\gamma(447.4)$. This means that ~10% of $I_\gamma(1433.8)$ comes from β^+ decay. The other activities of reaction products either have long lifetimes or lead to deexcitation of low-spin states so that their contributions to the σ_R deduced from the $^{27}Al+^{28}Si$ reactions are negligible. Beam-off spectra confirm this conclusion, showing only peaks due to $^{52}Mn(\beta^+)^{52}Cr$. Likewise, the $^{52}Fe(12^+)$ 56-s isomeric decay, found[11] in $^{40}Ca(^{14}N,pn)^{52}Fe$, is not observed in $^{27}Al+^{28}Si$ at this bombarding energy.

As shown in Table II, ^{52}Mn has the largest yield. This corresponds to the evaporation of two protons and one neutron from the initial ^{55}Co compound system. The other strongly produced nuclides are the stable ^{50}Cr and ^{52}Cr and nuclides one proton or neutron lighter. If α emission is included, the results imply that two- and three-particle evaporations are dominant at this bombarding energy.

The expected reaction cross sections were calculated using the evaporation model code ALICE.[17] The emission of neutrons, protons, deuterons, and α particles from the ^{55}Co compound nucleus was assumed. The results, shown in Table II as the ratios $\sigma_{\exp}/\sigma_{\text{ALICE}}$, are normalized so that the experimental and calculated values of the total σ_R for channels which cannot involve α particles are equal. The experimental and calculated σ_R of the individual products corresponding to those channels are quite consistent. On the other hand, the experimental σ_R values for channels which can be associated with α emission show enhancements over the calculated values which are well outside the experimental uncertainties. A different normalization which brings the α-channel results into agreement leads to large discrepancies for the more numerous *xnyp* channels.

A further analysis of the present work can be made by assuming that the energy dependence of the total reaction cross sections represents the fusion excitation function. A plot of σ_{fusion} vs $1/E_{\text{c.m.}}$ is expected to show a linear relationship for low-energy HI reactions,[18,19] and extrapolation to the abscissa yields the potential energy at the fusion threshold, V_B. The results of the $^{27}Al+^{28}Si$ measurements are shown in Fig. 4, and $V_B=28.7\pm0.8$ MeV has been deduced. This is consistent with the values found in other HI reaction studies[18,19] of fusion excitation functions.

The present work, with the production of five nuclei two or three particles away from ^{55}Co, shows the usefulness of γ-ray measurements for deducing reaction cross sections and for studying high-spin states in fp-shell nuclei. Further experimental and theoretical work is in progress at this laboratory to study fp-shell nuclei with ^{28}Si beams.

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