# $^{28}Si + ^{28}Si$ reactions

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Evaporation residues from $^{28}Si$-induced reactions on $^{28}Si$ from 65–90 MeV have been studied by means of $\gamma$-ray spectroscopy. High spin states of the residual nuclei have been observed, and the yields of residual nuclei resulting from three particle removal from the initial compound nucleus $^{56}Ni$ are dominant. Experimental relative production cross sections of the residual nuclei are compared to evaporation-model calculations.

[NUCLEAR REACTION $^{28}Si(^{28}Si, X\gamma)$ at $E_{1ab}$= 65–90 MeV. $\sigma(E_\gamma, E)$, $\sigma(E_\gamma, \theta)$, and $\gamma\gamma$ coin. Deduced reaction cross sections. Ge(Li) detectors.]

## I. INTRODUCTION

Much interest has recently centered on cross sections of $fp$-shell products from light and heavy ion reactions. The present work is part of a series of investigations using $^{28}Si$ beams for studying reaction mechanisms and high-spin states via in-beam $\gamma$-ray spectroscopy.[1]

Since the deexcitation of nuclei produced in heavy ion reactions proceeds predominantly by $\gamma$-ray cascades through yrast states, we are able to use these reactions to study high-spin states of product nuclei. Furthermore the $\gamma$-ray yields due to transitions to the ground states of the reaction products can be used as a measure of the reaction cross sections. In the present work we have identified eight different reaction products of the initial compound nucleus $^{56}Ni$ by means of $\gamma$-ray singles and $\gamma$-$\gamma$ coincidence measurements.

Detailed and systematic studies are important for our understanding of nuclear reactions and for identification of new nuclear level schemes. Experimental cross sections for reaction products can be compared with the results of calculations using the various codes which have recently become available. Knowledge of reaction mechanisms and systematics of nuclear levels in a given mass region facilitate the identification of previously unobserved nuclei, even though the yields may not be strong.

## II. EXPERIMENTAL PROCEDURE

Beams of $^{28}Si$ were accelerated by the Florida State University Super-FN Tandem Van de Graaff after extraction from an inverted sputter source. The targets were made by evaporating ~400 $\mu g/cm^2$ $^{28}Si$ onto thick Ta backings. A gold flash and storage under vacuum minimized the oxidation. $\gamma$ rays were detected by means of a Ge(Li) detector with resolution ~2.3 keV [full width at half maximum (FWHM)] at 1332 keV. Energy and efficiency calibrations were obtained using a National Bureau of Standards (NBS) mixed radioactive source in separate runs. A Si(Li) detector was also used to look for low-energy photons.

Singles $\gamma$-ray spectra were measured at 90° to the beam direction for bombarding energies of 60, 65, 72, 77, 81, 85, and 90 MeV. Angular distributions were obtained for angles of 45, 55, 65, 75, 80, and 90° at a bombarding energy of 77 MeV. The Si(Li) detector also served as a monitor for these measurements. In all of the runs, beam-off spectra were taken immediately following bombardment to help identify nuclei being produced when the beam was on. They were also useful in assessing the contributions of long-lived activities interfering with the angular distribution and excitation curve measurements. The $\gamma$-$\gamma$ coincidence experiments were done at 77 MeV and used two Ge(Li) detectors at 90° to and on opposite sides of the beam line.

## III. RESULTS

Energy level schemes of reaction products were constructed using the measured values of the energies and intensities of the $\gamma$ rays (see Table I). After correction for the detector efficiency, the $\gamma$-ray intensities were checked for a smooth increase as lower energy levels were reached. Also corrections were made for feeding from radioactive reaction products. Relative reaction cross sections $\sigma_R$ were obtained by summing, for each product, the $\gamma$-ray yields corresponding to transitions to the ground state. The deduced reaction cross sections are shown in Fig. 1. The angular distributions and $\gamma$-$\gamma$ coincidence data were used to check the assignments to level schemes. The resulting level schemes for previously known nuclei are in excellent agreement with those based upon various reactions reported

 

TABLE I. Present results for the $^{28}Si+^{28}Si$ reactions at 77 MeV.

| $E_\gamma$ (±0.5 keV) | $I_\gamma$ [a] | Assignment | $E_\gamma^{lit}$ (keV) |
|---|---|---|---|
| 237.5 | 2.8 | $^{51}Mn$ | 237.37 ±0.15 |
| 279.6 [b] | 5.4 | | |
| 348.8 | 1.5 | $^{51}Mn$ | 348.7 |
| 377.7 | 6.6 | $^{53}Mn$ | 377.85 ±0.09 |
| 411.7 | 1.2 | $^{54}Fe$ | 411.4 ±0.5 |
| 430.0 | 2.3 | $^{51}Mn$ | 429.7 |
| 459.3 | 6.0 | $^{51}Mn$ | 459.0 |
| 471.1 | 5.2 | | |
| 547.6 | 9.6 | | |
| 610.0 | 7.5 | $^{50}Cr$ | 609.9 ±0.5 |
| 661.8 | 7.7 | $^{50}Cr$ | 661.7 ±0.5 |
| 680.2 | 2.8 | | |
| 701.5 | 15.3 | $^{53}Fe$ | 701.1 ±0.1 |
| 704.7 | 2.6 | | |
| 723.2 | 4.1 | $^{51}Mn$ | 723.0 |
| 741.2 | 4.6 | $^{53}Fe$ | 741.1 ±0.1 |
| 746.3 | 9.1 | $^{53}Mn$ | 747.0 ±0.5 |
| 783.4 | 32.2 | $^{50}Cr$ | 783.4 ±0.5 |
| 831.9 | 3.3 | $^{54}Co$ | 831.8 ±0.5 |
| 870.1 | 3.7 | $^{52}Mn$ | 869.6 ±0.2 |
| 876.4 | 3.6 | | |
| 902.5 | 4.2 | $^{51}Mn$ | 902.1 |
| 930.4 [c] | 3.3 | ($^{52}Mn$) | 929.7 ±0.3 |
| 935.3 | 2.0 | $^{52}Cr$ | 935.5 ±0.2 |
| 944.1 | 9.5 | | |
| 956.2 | 3.1 | | |
| 963.4 | 3.4 | | |
| 969.4 | 0.97 | | |
| 1011.1 | 19.3 | $^{53}Fe$ | 1011.2 ±0.2 |
| 1015.3 | 2.5 | | |
| 1098.1 | 32.3 | $^{50}Cr$ | 1098.2 ±0.5 |
| 1122.4 | 13.7 | $^{53}Mn$ | 1122.3 ±0.3 |
| 1130.2 | 5.8 | $^{54}Fe$ | 1129.9 ±0.3 |
| 1251.4 | 31.9 | $^{51}Mn$, $^{53}Mn$ | 1250.8, 1252.1 ±0.2 |
| 1282.7 | 24.4 | $^{50}Cr$ | 1283.1 ±0.5 |
| 1317.2 | 1.5 | | |
| 1328.9 | 27.0 | $^{53}Fe$ | 1328.2 ±0.3 |
| 1408.4 | 11.9 | $^{54}Fe$ | 1408.1 ±0.2 |
| 1434.8 | 7.8 | $^{52}Cr$ | 1434.3 ±0.2 |
| 1441.0 | 49.8 | $^{53}Mn$ | 1440.8 ±0.7 |
| 1468.6 | 5.2 | $^{51}Mn$ | 1468.5 |
| 1499.8 | 4.0 | | |
| 1581.6 | 15.1 | $^{50}Cr$ | 1581.1 ±0.5 |
| 1596.4 | 8.0 | $^{50}Cr$ | 1595.7 ±0.5 |
| 1690.2 | 3.2 | $^{54}Co$ | 1689.9 ±0.5 |
| 1762.6 | 13.3 | $^{51}Mn$ | 1761.8 |
| 1773.9 | 15.0 | | |
| 1970.1 | 3.8 | | |
| 2140.0 | 3.2 | $^{51}Mn$ | 2140.4 ±0.2 |
| 2148.6 | 3.8 | | |
| 2208.1 | 3.4 | | |
| 2242.1 | 6.3 | | |
| 2338.3 | 6.5 | $^{53}Fe$ | 2339.4 ±0.5 |

[a] Uncertainties are 10–30%.
[b] Probably contaminant.
[c] Possible doublet.

in the Nuclear Data Sheets,[2-5] updated where possible by more recent results.[6-14] The placements of the observed $\gamma$ rays are indicated in Table I.

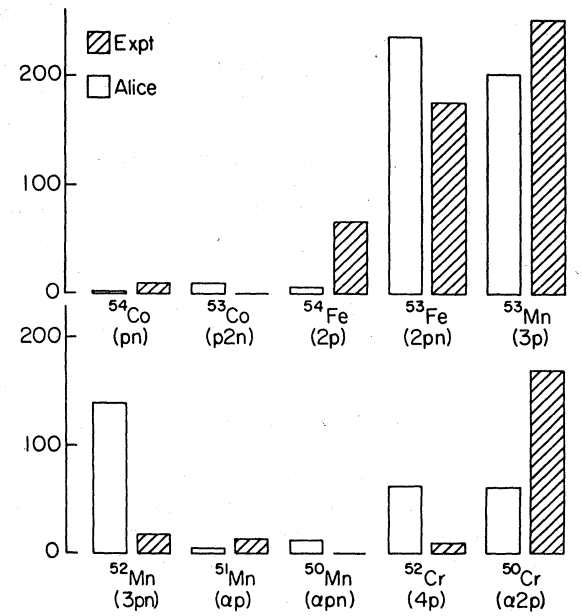


FIG. 1. Reaction cross sections for $^{28}Si+^{28}Si$ at 77 MeV compared with the results of ALICE calculations. Where possible, the experimental cross sections were corrected for anisotropy.

The strongest reaction in the present work is $^{28}Si(^{28}Si, 3p)^{53}Mn$ and the level scheme of $^{53}Mn$ is consistent with the results[13] for the $^{40}Ca(^{16}O, 3p)$-$^{53}Mn$ reaction. The 377.8 level was also seen, but this is produced mainly by $\beta^+$ decay of the $^{53}Fe$ ground state since none of the expected $\gamma$ rays feeding this level are found. The second most abundant product is $^{53}Fe$. The $\gamma$-ray singles results from the reaction $^{28}Si(^{28}Si, 2pn)^{53}Fe$ agree with the previously known level scheme for $^{53}Fe$.

Our measurements also reveal $\gamma$ rays which fit into the $^{54}Fe$ level scheme proposed[4] on the basis of the reaction $^{51}V(^{7}Li, 4n)^{54}Fe$. Agreement between these two results are excellent. The present results for $^{50}Cr$ are consistent with the levels up to and including the 7610.9 keV, $J^\pi = 12^+$ level reported[6] in the $^{40}Ca(^{16}O, 2p\alpha)$ reaction. Weak yields were observed for the nuclei $^{54}Co$, $^{52}Cr$, $^{52}Mn$, and $^{51}Mn$. For the latter, levels up to $\frac{19}{2}^-$, 4138.7 keV were observed, consistent with $^{40}Ca(^{14}N, 2pn)$ results.[8]

Additional measurements were made in order to study the $\sigma_R$ as a function of bombarding energy (see Fig. 2). The reactions in which two and three nucleons are removed from $^{56}Ni$ are strongest near 74 and 80 MeV, respectively. The excitation curves for reactions involving an $\alpha$ particle have maxima at energies ~10 MeV higher. The yield for four-particle removal ($3pn$) is still increasing at 90 MeV.

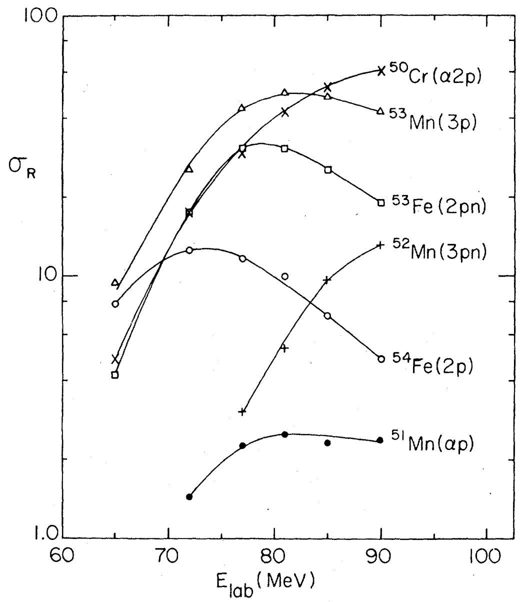


FIG. 2. Excitation functions for the production of the various nuclei in the $^{28}Si + ^{28}Si$ reactions. The lines are to guide the eye.

Four $\gamma$ rays, with energies 471.1, 547.6, 680.2, and 944.1 keV, had enough strength to be analyzed but could not be placed in level schemes. Nuclei to which assignments are likely are $^{53}$Co and $^{50}$Mn

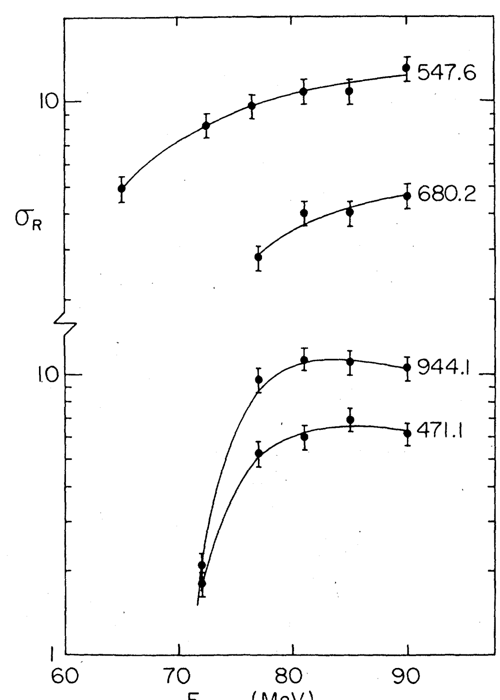


FIG. 3. Excitation functions for $\gamma$ rays which are produced in $^{28}Si + ^{28}Si$ but are not placed into known level schemes. The lines are to guide the eye.

which, as shown in Fig. 1, are predicted[15] to be produced in $^{28}Si + ^{28}Si$. Weak evidence is found in our data for the 944.1-keV $\gamma$ ray in coincidence with 471.1, so they may come from the same nucleus.

Further information on these $\gamma$ rays was obtained from measured angular distributions and excitation functions. The excitation functions are shown in Fig. 3. The yields of the 547.6- and 680.2-keV $\gamma$ rays are increasing at 90 MeV, similar to the $\alpha 2p$ product. An assignment of these $\gamma$ rays to $^{28}Si(^{28}Si, \alpha pn)^{50}Mn$ is plausible. The excitation functions for the 471.1- and 944.1-keV $\gamma$ rays have shapes similar to each other and to the $3p$ product. These two $\gamma$ rays, then, may be due to deexcitation of $^{53}$Co produced in the $(^{28}Si, p2n)$ reaction.

The results of the angular distribution measurements show that the angular distributions for the 471.1- and 944.1-keV $\gamma$ rays have shapes consistent with dipole transitions. For the other unassigned $\gamma$ rays no distinctive shape was found.

The 1690.2-keV $\gamma$ ray, assigned to $^{54}$Co, has the shape expected for dipole transitions. In the literature, only a range of spins ($J_i = 5-9$) is known for the 1889 keV level which is deexcited by the 1690.2 keV transition. The present results would then restrict the spin to $J = 6$, 7, or 8.

The measurements for the unassigned $\gamma$ rays, then, suggest placement in $^{53}$Co and $^{50}$Mn, both of which are expected to be populated in the $^{28}Si + ^{28}Si$ reaction. The production of $^{50}$Mn is confirmed by the beam-off spectrum in which $^{50}$Cr $\gamma$ rays are present from radioactivity of the high-spin isomer in $^{50}$Mn. Further measurements to study the levels of $^{53}$Co and $^{50}$Mn are planned.

## IV. DISCUSSION

In the present work eight nuclei were produced with sufficient strength for the study of high-spin states. The data are consistent with results using other heavy ion reactions. Identification of all but a few $\gamma$ rays was possible, allowing a study of reaction cross sections $\sigma_R$ for the $^{28}Si + ^{28}Si$ reaction. The total $\gamma$-ray yields corresponding to transitions to the ground states were summed and used to calculate $\sigma_R$ for each evaporation residue.

It is interesting to compare the present results with theoretical predictions. For this we have performed evaporation model calculations[15] using the code ALICE, allowing for the emission of neutrons, protons, deuterons, and $\alpha$ particles from the compound nucleus $^{56}$Ni. The results are normalized such that the experimental and calculated values of the sums of the $2pn$ and $3p$ cross sections are equivalent. As can be seen

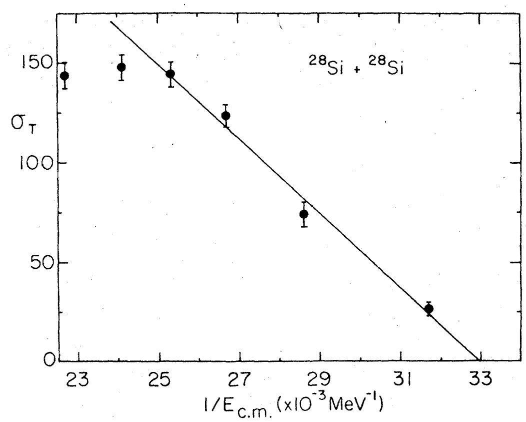


FIG. 4. Total fusion cross section as a function of bombarding energy. The solid line is a linear fit through the data points for energies less than 85 MeV.

from Figs. 1 and 2, these two reactions are dominant. Also, from Fig. 1 one sees that the reaction product due to $\alpha 2p$ removal is greatly underpredicted, as is the case for the $2p$ evaporation. If $\alpha$ emission is included, the experimental results show that three-particle evaporations are dominant at 77 MeV.

The sums of the reaction cross sections as a function of bombarding energy should represent the energy dependence of the fusion cross section, even though absolute cross sections have not been obtained. A linear dependence of $\sigma_T$ vs $1/E_{c.m.}$ would be expected[16,17] at these relatively low bombarding energies. Such a plot is useful as an indication of the success of $\gamma$-ray spectroscopy for determining reaction cross sections. As shown in Fig. 4, the present data can be fit with a straight line up to about 80 MeV. From the intercept on the $1/E_{c.m.}$ axis, a value is obtained for the potential energy at the fusion threshold, $V_B = 30.3 \pm 0.3$ MeV. This is in excellent agreement with values found in other heavy ion fusion studies.[17] The eventual deviation from linearity above $E_{c.m.} \approx 40$ MeV is similar to the behavior found for other heavy ion fusion reactions.[17,18]

The present work, with the production of five nuclei two or three particles away from the $^{56}Ni$ compound nucleus, shows the usefulness of $\gamma$-ray yields for measuring reaction cross sections and for studying high-spin states in $fp$-shell nuclei. Clearly, more experimental and theoretical work is necessary for a complete understanding of the reaction mechanism. The present work indicates promising prospects for studying high-spin states in $fp$-shell nuclei using $^{28}Si$ beams.

*Note added in proof.* In recent results by Lister *et al.* [Phys. Rev. C 18, 2169 (1978)], $\gamma$ rays with energies 470.8 and 944.7 keV were assigned to dipole transitions at high excitation in $^{53}Mn$. Our measured angular distributions and excitation functions for $\gamma$ rays of similar energies are consistent with that proposed level scheme.

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