Brief Reports

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Selective population of states in ^{36}Ar by the ^{12}C(^{28}Si, α)^{36}Ar reaction

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Energy spectra of α-particles were measured at 0° for the systems ^{28}Si+^{12,13}C in the range $E_{\rm lab}(^{28}{\rm Si})=75-102$ MeV in 0.750 MeV steps. Transitions to discrete states in ^{36}Ar up to $\sim$20 MeV excitation energy via the ^{12}C(^{28}Si,α)^{36}Ar reaction are observed. The excitation functions measured for some of these transitions show structures $\sim$1 MeV wide. No strong (^{28}Si,α) transitions to discrete states are observed for the ^{28}Si+^{13}C system.

[NUCLEAR REACTIONS ^{12,13}C(^{28}Si, α), $E=75-102$ MeV, measured $\sigma(E)$, ^{36}Ar deduced levels.]

Nuclear reactions such as ^{12}C(^{12}C, α)^{20}Ne and ^{12}C(^{16}O, α)^{24}Mg have been extensively studied[1] to investigate highly-excited states in the residual nuclei. These reactions are well suited to the study of high-spin states[1] because the large amount of angular momentum brought into the system by the projectile is not readily dissipated by the emission of a single α particle. Recently, groups seen in the α-particle spectrum of the ^{12}C(^{16}O, α)^{24}Mg reaction have been interpreted as resulting from a ^{12}C transfer.[2,3] A relation has been suggested between these states and high-spin ^{12}C+^{12}C resonances, although there is some evidence questioning this interpretation.[4,5]

For heavier systems, at energies close and above the Coulomb barrier, the spectrum of α particles emitted through the fusion-evaporation mechanism is expected to consist mainly of a continuum, owing to the multiple-stage character of the process and the high density of states in the nuclei involved. We show in the present work that, for a system as heavy as ^{12}C+^{28}Si, highly-excited discrete states are populated in the residual nucleus via the emission of a single α particle. We observe, in the inclusive α-particle spectrum, groups corresponding to ^{12}C(^{28}Si,α) transitions to states in ^{36}Ar up to an excitation energy of $\sim$20 MeV. The existence of such transitions, despite the enormous increase in the number of available channels compared to the systems mentioned above, indicates that a powerful selective mechanism, maybe similar to the feeding of high-spin states in lighter systems, persists in nuclei heavier than expected.

The experiment was performed by detecting α particles in the forward direction using ^{12}C as the target nucleus and ^{28}Si as the projectile. This choice of a projectile-target combination was dictated by two considerations: (a) to reduce the interference of α particles from reactions on target contaminants, and (b) to avoid the detection of α particles resulting from breakup of the ^{12}C nucleus. ^{28}Si beams were obtained from the 14UD Pelletron of the Heinemann Accelerator Laboratory and measurements were made in the range $75 \le E_{\rm lab} \le 103$ MeV in 750 keV steps. Self-supporting natural carbon and isotopically enriched (90%) ^{13}C targets of 50 μg/cm^2 areal density were used. A ΔE-E telescope of Si surface barrier detectors (180 and 2000 μm), placed at 0°, was used to identify the α particles. The ^{28}Si beam was stopped by a 25 μm thick Ta foil placed in front of the telescope at a distance of 5 cm. In order to prevent C buildup on the target or the Ta shield, a large trap above the target was kept at liquid nitrogen temperature. The relative normalization was determined by measuring the yield of ^{28}Si ions, elastically scattered from a thin layer of Au evaporated onto the target in a monitor detector at 40° with respect to the incident beam. In order to enhance the appearance of discrete groups, the α-particle spectra (corrected for the energy loss in the Ta shield using an energy-dependent expression for the differential stopping power[6]) were transformed into Q-value spectra according to the kinematics of the two-body ^{12}C(^{28}Si, α)^{36}Ar reaction and the Q-

value spectra were summed for a range of incident energies. This procedure, similar to that used by Lazzarini *et al.*,[2] is expected to coherently build up the groups resulting from (^{28}Si, α) transitions to final states in ^{36}Ar and to smear out the spectrum of the α particles emitted in multistage processes. Figure 1(a) shows the result obtained by summing 13 spectra measured at $84 \le E_{\rm lab} \le 92.25$ MeV. The transitions to the ground and first-excited (2^+, 1.97 MeV) states in ^{36}Ar can be identified by their energies. Strong groups remain visible over the continuum spectrum up to high excitation energies. Figure 1(b) shows in comparison the spectrum obtained with a ^{13}C target, following the same procedure, except for using the kinematics of the ^{13}C(^{28}Si, α)^{37}Ar reaction. The absence of strong groups over the whole measured excitation range, as compared to the ^{12}C case, is noticeable. In order to isolate the groups seen in Fig. 1(a) from the continuum, an arbitrary smooth background, drawn as shown, was subtracted from the sum spectrum. The spectra obtained in three incident energy intervals are presented in Fig. 2. Discrete peaks extending to an excitation energy of ~20 MeV in ^{36}Ar can be followed throughout the range of measured incident energies. Although it is not possible to identify all these peaks as corresponding to known energy levels in ^{36}Ar, the severe kinematic constraints imposed by the procedure described above ensure that they correspond to a selective population of states in the ^{36}Ar nucleus. Within the experimental resolution, the widths of all these states seem to be of the same magnitude.

The observation of transitions to highly-excited discrete states in ^{36}Ar raises a number of questions

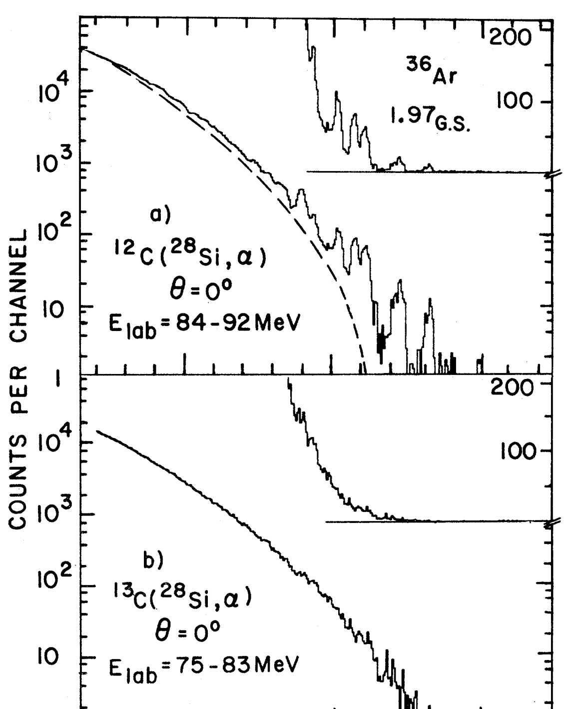

FIG. 1. Sum of Q-value spectra obtained as described in the text for (a) the ^{12}C+^{28}Si and (b) the ^{13}C+^{28}Si systems. The dashed line indicates the continuum background assumed.

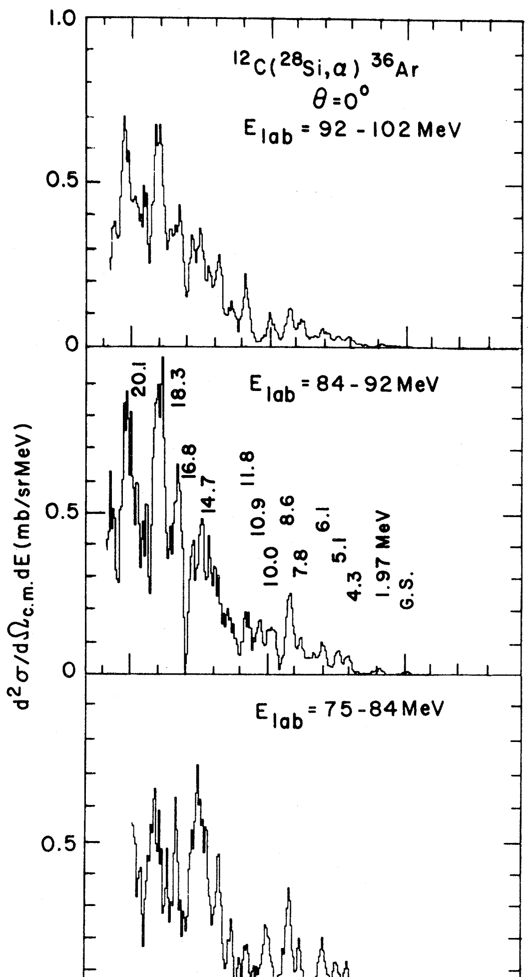

FIG. 2. Spectra of α particles from the ^{12}C(^{28}Si, α)^{36}Ar reaction obtained by subtraction of the smooth continuum background from the Q-value spectra, as shown in Fig. 1. The measured excitation energies of the populated states in ^{36}Ar are listed.

concerning both the character of the populated states and the mechanism of the transitions: (a) Do these transitions proceed via the total fusion of the ^{28}Si and ^{12}C nuclei or via a more peripheral collision, which might, for example, be interpreted as a ^{8}Be transfer? (b) Which property in the observed ^{36}Ar states makes them selectively populated in the transitions? Are transitions to final states with high spins possibly favored by angular momentum matching conditions similar to those invoked earlier for (^{16}O, α) transitions? (c) Is the absence of strong discrete transitions in the $^{28}Si+^{13}C$ system a consequence of the higher density of states involved in the odd system than in the $^{12}C+^{28}Si$ system or has it a different nuclear structure origin? To investigate the importance of the fusion-evaporation mechanism, calculations were performed in the framework of the statistical Hauser-Feschbach model. The results, to be detailed elsewhere, show reasonable agreement both in shape and intensity between the calculated α-particle spectrum and the continuum part of the experimental spectrum, confirming that evaporation α particles indeed form the bulk of the observed spectrum. Cross sections of transitions to low-lying states in ^{36}Ar were found to be consistent with values obtained here for the lowest ^{36}Ar states. It has been shown very recently that in the case of the $^{12}C(^{16}O, \alpha)^{24}Mg$ reaction, discrete groups seen in the α-particle spectrum may be interpreted as corresponding to transitions to states in a narrow window close to the yrast line in ^{24}Mg and may be reproduced by a statistical model calculation, owing to stringent angular momentum matching conditions.[7] It may be that the same mechanism is responsible for the transitions observed here, leading to the possible interpretation of these states as high-spin states close to the ^{36}Ar yrast line.

An interesting aspect of these transitions is provided by their energy dependence. Figure 3 shows the excitation functions of three prominent α-particle groups chosen in a region where the continuum spectrum tails off and is a small fraction of the yield. Although the error bars in these curves are large, significant structures 0.7–1 MeV wide are seen, superimposed on monotonously decreasing cross sections. The overall correlations of the structures observed for the three transitions is rather poor, except perhaps for maxima around $E_{c.m.}=26$ MeV, but their widths seem inconsistent with fluctuations of statistical origin. A similar behavior has been observed in the $^{24}Mg(^{12}C, \alpha)^{32}S$ reaction to the ground and first-excited states of ^{32}S,[8] where grazing partial waves were found to be contributing to the transitions. The structures observed here may be related to the resonance behavior exhibited in the $^{12}C+^{28}Si$ system by the backward-angle elastic scattering[9] and reaction[10] data. The excitation function of the 180° elastic scattering,[9] shown in Fig. 3 for comparison, has indeed some qualitative

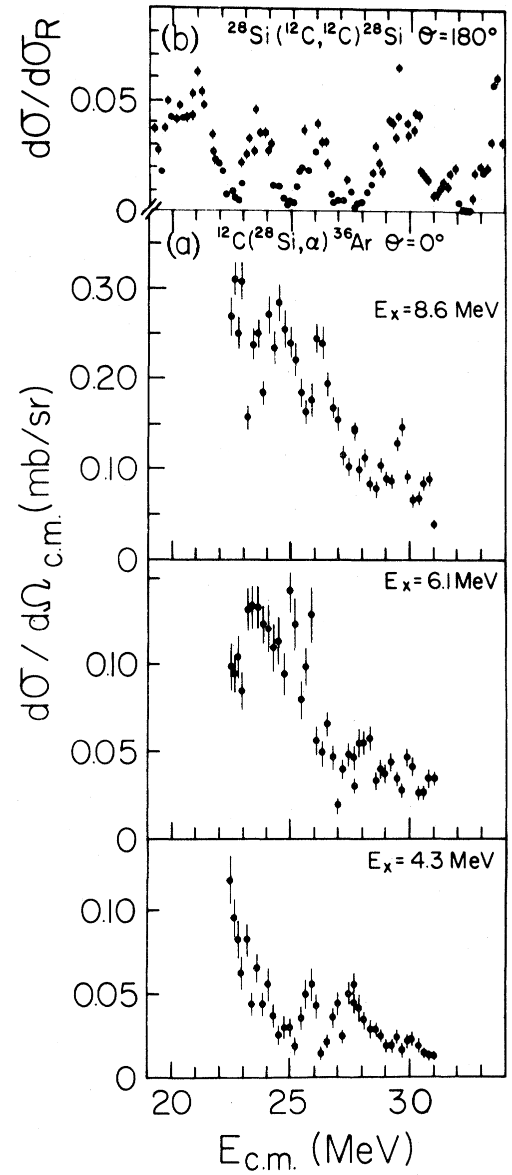

FIG. 3. Excitation functions of (a) three α-particle groups corresponding to $^{12}C(^{28}Si, \alpha)^{36}Ar$ transitions to states in ^{36}Ar at the indicated excitation energies; the bars include statistical errors and the errors estimated in background subtraction. (b) $^{12}C+^{28}Si$ elastic cross section at $\theta_{c.m.}=180°$ (Ref. 9).

similarity with the behavior of the (^{28}Si, α) transitions, especially with the strong transition to the 8.6 MeV level. More complete and precise data would be needed to confirm such a correlation; together with a better understanding of the mechanism of the transitions, they might add interesting information on the nature of the resonance behavior of these systems.

In summary, the inclusive α-particle spectrum emitted by the $^{12}C+^{28}Si$ system shows discrete peaks corresponding to states selectively populated in ^{36}Ar, superimposed on a continuum spectrum of evaporation. Structures are observed in the excitation functions of some of these transitions.

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