BRIEF REPORTS

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Energy dependence of fusion evaporation-residue cross sections in the ^{28}Si + ^{12}C reaction

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(Received 10 September 1992)

Fusion evaporation-residue cross sections for the ^{28}Si + ^{12}C reaction have been measured in the energy range $18 \le E_{\rm c.m.} \le 136$ MeV using time-of-flight techniques. Velocity distributions of mass-identified reaction products were used to identify evaporation residues and to determine the complete-fusion cross sections at high energies. The data are in agreement with previously established systematics which indicate an entrance-channel mass-asymmetry dependence of the incomplete-fusion evaporation-residue process. The complete-fusion evaporation-residue cross sections and the deduced critical angular momenta are compared with earlier measurements and the predictions of existing models.

PACS number(s): 25.70.Jj

For more than a decade fusion evaporation-residue cross sections for the ^{28}Si + ^{12}C system have been measured [1–5] at center-of-mass energies ranging from 14 to 80 MeV. With one exception [1], the grouping and trend of the low-energy ($E_{\rm c.m.} \le 31$ MeV) data are in reasonable agreement. Higher-energy cross sections measured by Harmon *et al.* [5] show a rapid decrease with increasing energy. The critical angular momenta extracted from their complete-fusion evaporation-residue cross sections show a saturation at 22$\hbar$ which indicates an entrance-channel limitation of the fusion cross section at high energy when compared to other systems forming the same compound nucleus. The authors reported that this value for the critical angular momentum saturation is consistent with the results of an orbiting analysis of deep-inelastic scattering of ^{28}Si + ^{12}C [6] and supports the idea that the binary cross sections found in this reaction can be attributed to a dinuclear orbiting mechanism [7].

In this work we present evaporation-residue cross-section measurements for ^{28}Si + ^{12}C in the center-of-mass energy range from 18 to 136 MeV. Initially, data were taken at ^{28}Si bombarding energies of 309, 397, and 452 MeV as part of a systematic study [8,9] of the energy and target dependence of the incomplete-fusion evaporation-residue process. Additional measurements were then performed at lower energies resulting in data extending over one of the largest energy ranges ever measured for a light system.

The fusion evaporation-residue cross sections reported here at ^{28}Si bombarding energies between 60 and 178 MeV were measured at the Florida State University Superconducting Accelerator Laboratory. The ^{28}Si beams ranged in intensity from 5 to 30 particle nA and were incident on self-supporting (200 μg/cm^2) ^{12}C foils mounted in a 36-cm scattering chamber. The targets were monitored using a 500-μm Si surface-barrier detector positioned at 14.5° above the reaction plane. Mass identification of the reaction products was obtained with the use of a time-of-flight system consisting of a carbon-foil (10 μg/cm^2) channel plate to provide the start signal and a 500-μm Si surface-barrier detector to obtain the stop signal and energy of each particle. With a flight path of 2.7 m the detection system subtended a solid angle of 44 μsr. Angular distributions were measured over a range 3°–30°. The energy and time of flight of the reac-

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tion products were recorded on magnetic tape event by event. The data were then displayed in two-dimensional, mass-versus-energy spectra, gated for evaporation residues above mass 28, and sorted into energy histograms from which the yields were extracted. The product of the target thickness and solid angle was measured using the Rutherford scattering of 15-MeV ^{16}O ions from the ^{12}C targets.

Measurements were also performed at the Argonne National Laboratory ATLAS facility using pulsed ^{28}Si beams at bombarding energies of 309, 397, and 452 MeV. These beams were incident on a self-supporting (65 $\mu g/cm^2$) ^{12}C target mounted at the ATLAS 91-cm scattering chamber. Velocity distributions of the mass-identified reaction products were obtained over an angular range 3°–20° with two time-of-flight telescopes. Absolute cross sections were determined by measuring the elastic scattering of tandem energy (76.5 MeV) Si ions from the ^{12}C target at $\theta_{lab}=5°-15°$ and comparing with the Rutherford scattering predictions. The experimental procedure has been described in more detail elsewhere [8,9].

At the three highest energies the velocity spectrum for each residue mass ($12 \le A \le 39$) was decomposed with a Gaussian fitting procedure [8,9] to determine the evaporation-residue and complete-fusion contributions. The position and width of the complete-fusion component were taken from statistical-model calculations performed with the code LILITA [10]. The shape of the velocity spectra was found to be consistent with the assumption that contributions to incomplete fusion corresponding to preequilibrium emission from the ^{28}Si projectile were negligible. For the lower-energy data no attempt was made to separate the evaporation-residue cross sections into complete-fusion and incomplete-fusion components. However, the energy spectra were used to exclude any yield that was clearly not due to evaporation.

The total evaporation-residue (ER) and complete-fusion evaporation-residue (CFER) cross sections, found by integrating the angular distributions, are listed in Table I. Due to the decomposition procedure, the cross sections at the three highest energies should be considered as upper limits. The ratios of the CFER to total ER cross sections extracted from the present data are compared to those reported earlier for the $^{28}Si+^{28}Si$ [8] and $^{28}Si+^{40}Ca$ [9] systems in Fig. 1. The solid curves shown in the figure are systematic trends established by

TABLE I. Experimental cross sections and critical angular momenta.

E_{lab} (MeV)	$E_{c.m.}$ (MeV)	σ_{ER} (mb)	σ_{CFER} (mb)	$l_{cr}(\hbar)$
60	18	620±30	620±30	11.0±0.3
82.6	24.8	930±90	930±90	16.3±0.8
100	30	940±86	940±86	18.0±0.8
125	37.5	1040±96	1040±96	21.3±1.0
150	45	1185±86	1185±86	25.1±0.9
178	53.4	1150±81	1150±81	27.0±1.0
309	92.7	1222±183	772±131	29.3±2.5
397	119	1100±165	597±101	29.2±2.5
452	136	1171±176	537±91	29.5±2.5

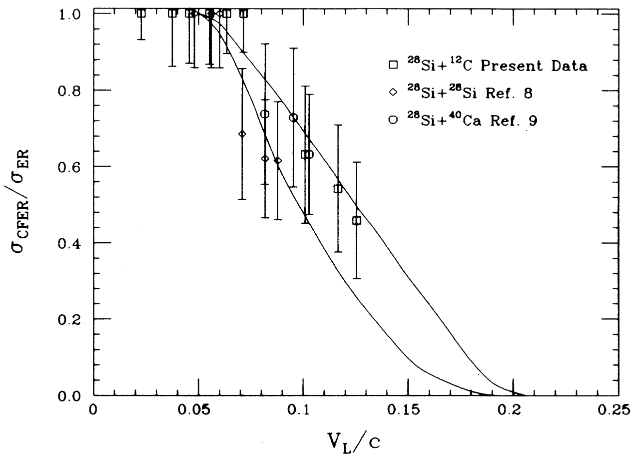

FIG. 1. The ratio of complete-fusion evaporation-residue cross section to total evaporation-residue cross section as a function of the velocity of the lighter nucleus V_L/c. The data for $^{28}Si+^{12}C$ (squares), $^{28}Si+^{28}Si$ (diamonds), and $^{28}Si+^{40}Ca$ (circles) are from the present study, Ref. [8], and Ref. [9], respectively. The curves represent the trends from Ref. [11]. In that study, it was found that the mass-asymmetric systems fell primarily along the upper curve, while the symmetric systems clustered around the lower curve.

Morgenstern *et al.* [11]. The results of that study indicate that the CFER process is more likely for an asymmetric system than for a symmetric system at the same relative velocity. A common onset of incomplete fusion for systems with different mass asymmetry in the entrance channel was found only when the data were plotted as a function of the center-of-mass velocity of the lighter reaction partner at contact; i.e.,

$$v_L=[A_H/(A_H+A_L)]v_{rel} ,$$

where A_H and A_L are the masses of the heavier and lighter reaction partners, respectively. The relative velocity, v_{rel}, is defined as

$$v_{rel}=[2(E_{c.m.}-V_C)/\mu]^{1/2} ,$$

where $E_{c.m.}$ and V_C are the center-of-mass kinetic and Coulomb energies, respectively, and μ is the reduced mass. Asymmetric systems were found to fall primarily along the upper curve, while the symmetric systems clustered around the lower curve. Within the errors, the present data agree with the Morgenstern systematics and support the entrance-channel mass-asymmetry dependence of the incomplete-fusion evaporation-residue process. This agreement also supports our decomposition of the velocity spectra at the three highest energies and our assumption that the CFER cross section is equal to the ER cross section at the lower energies.

The total CFER cross sections measured in the present study are compared with the results of a number of previous experiments [2,4,5] in Fig. 2. The solid and dashed curves shown in the figure are the predictions of the critical distance [12] and the proximity [13] fusion models, respectively. As can be seen in the figure, our results are in reasonable agreement with the earlier measurements and

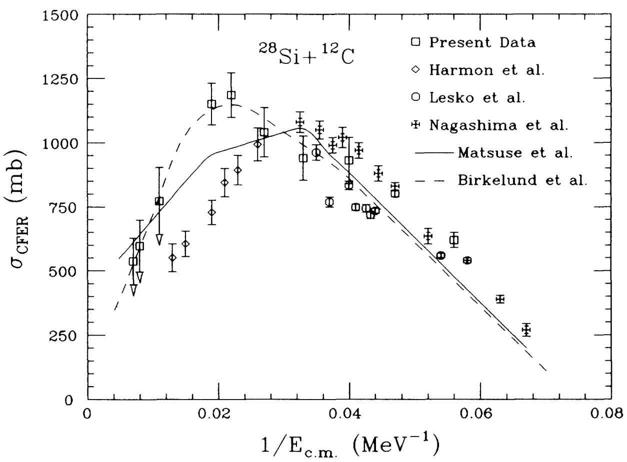

FIG. 2. Complete-fusion evaporation-residue cross sections for the $^{28}Si+^{12}C$ reaction. The data are from Ref. [2] (circles), Ref. [4] (crosses), Ref. [5] (diamonds), and the present work (squares). The solid and dashed curves are the results of fusion-model calculations of Refs. [12,13], respectively.

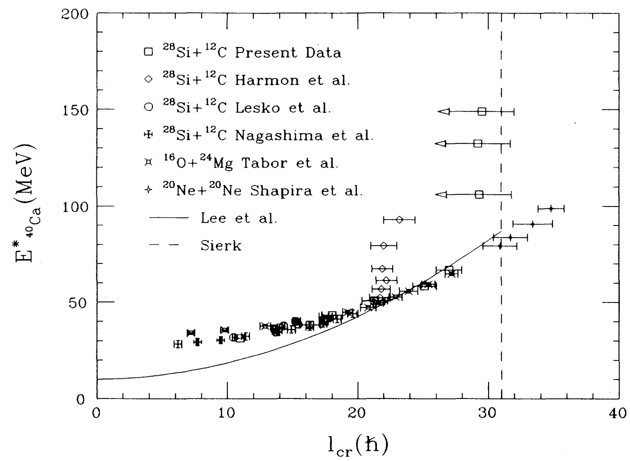

FIG. 3. Compound-nucleus excitation energy vs critical angular momenta extracted from the cross sections shown in Fig. 2 and those reported for $^{16}O+^{24}Mg$ [17] and $^{20}Ne+^{20}Ne$ [18]. The solid curve corresponds to the statistical yrast line [19] with $r_0=1.2$ fm and $\Delta Q=10$ MeV. The dashed line indicates the angular momentum at which the fission barrier vanishes as predicted by the Sierk model [20].

the theoretical predictions. Our high-energy data do not show as rapid a decrease with increasing energy as the Harmon results [5], however, it should be stressed that our data at the three highest energies are upper limits for the CFER cross sections. Also, it is possible that the cross sections reported here at inverse center-of-mass energies around 0.02 MeV^{-1} may include as much as 10% incomplete fusion as suggested by the Morgenstern systematics shown in Fig. 1. However, it should be pointed out that our results are in good agreement with another very recent study [14] of the $^{28}Si+^{12}C$ system at $31.2 \le E_{c.m.} \le 46.2$ MeV, and earlier measurements for the $^{32}S+^{12}C$ system at $E_{c.m.}=39.5$ MeV [15] and the $^{35}Cl+^{12}C$ system at $E_{c.m.}=46$ and 51 MeV [16].

The critical angular momenta extracted from the CFER cross sections using the sharp cutoff approximation are listed in Table I. These data are compared with previous results for $^{28}Si+^{12}C$ [2,4,5], $^{16}O+^{24}Mg$ [17], and $^{20}Ne+^{20}Ne$ [18] in Fig. 3 where the excitation energy of the compound nucleus is displayed as a function of the critical angular momentum. The solid curve shown in the figure corresponds to the statistical yrast line [19] calculated with $r_0=1.2$ fm and $\Delta Q=10$ MeV. With the exception of the data of Harmon *et al.* [5], the experimental results in the intermediate excitation-energy range ($40<E^*<70$ MeV) are reproduced rather well by this parametrization. The data of Harmon *et al.* [5] show a saturation in the critical angular momentum of about $22\hbar$ which, they argued, indicates the existence of a limitation on the high-energy cross section imposed by the entrance channel. The authors also pointed out that this is consistent with the results of an orbiting analysis of deep-inelastic scattering of $^{28}Si+^{12}C$ [6]. The present data show a saturation in the critical angular momenta of about $29\hbar$ consistent with the value at which the fission barrier of the ^{40}Ca compound nucleus vanishes as calculated with the Sierk [20] model and shown as the dashed line in the figure. However, since our high-energy data are only upper limits, we cannot rule out the possibility of an entrance-channel limitation on the CFER cross sections as indicated by the Harmon *et al.* [5] data. On the other hand, we should point out that the critical angular momentum saturation of $29\hbar$ is in good agreement with systematics which have been established through the compilation of results for a wide variety of nuclear systems in a recent study [21]. It is also interesting to note that a Bass model calculation [22] using the standard parametrization (parameter set 1 of Table III of Ref. [5]) predicts this behavior quite well.

In conclusion, we have presented the results of fusion evaporation-residue cross-section measurements for $^{28}Si+^{12}C$ over one of the largest energy ranges ever explored for a light system. Velocity spectra of individual evaporation-residue masses were decomposed with the aid of statistical-model calculations to determine the complete-fusion cross sections at energies where the incomplete-momentum transfer is significant. The present data support previously established systematics which indicate that the incomplete-fusion evaporation-residue process depends on the mass asymmetry in the entrance channel. The critical angular momenta extracted from the complete-fusion evaporation-residue cross sections show a saturation at high energies which is consistent with the calculated fission-barrier limit of the compound nucleus. However, since our high-energy data should be considered as upper limits, we cannot rule out the possible existence of an entrance-channel limitation on the high-energy fusion cross section as suggested in an earlier study. Additional measurements for the $^{28}Si+^{12}C$, $^{16}O+^{24}Mg$, and $^{20}Ne+^{20}Ne$ systems at high excitation energies ($E^*>100$ MeV) are required to determine whether the fusion cross section is limited by the properties of the entrance channel or the ^{40}Ca compound nucleus.

We would like to thank T. Matsuse for theoretical calculations and F. Porto for providing us unpublished results. This work was supported in part by the U.S. Department of Energy under Contract Nos. DE-FG05-88ER40459, W-31-109-ENG-38, and DE-AC02-79ER10420, and the National Science Foundation under Contract No. PHY-8900689.

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