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Fusion cross section for $^{28}Si + ^{12}C$

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Fusion cross sections have been measured for the system $^{28}Si + ^{12}C$ from 50 to 105 MeV. No markedly smaller fusion cross sections were observed in comparison with the previously reported results for the other isotope systems $^{12}C + ^{29,30}Si$. Furthermore, the average energy dependence of the fusion cross sections for the three systems are well reproduced by the fusion barrier model with the same parameters. The maximum fusion cross sections for these systems are also well interpreted in terms of the statistical yrast line model.

[NUCLEAR REACTIONS $^{28}Si + ^{12}C$, $E_{lab} = 50-105$ MeV, measured fusion cross section, compared with fusion barrier, and statistical yrast line models.]

The recent observation of oscillatory behavior in the elastic and inelastic scattering excitation functions for the $4N$ nuclei systems[1-5] has generated many discussions concerning the mechanism involved. Such oscillations were also observed even in the fusion excitation functions for the $4N$ systems such as $^{16}O + ^{12}C$ and $^{24}Mg + ^{12}C$.[6,7] As the fusion cross section should correspond to the absorption part of the elastic and inelastic scattering, it is quite natural to think that these two oscillatory behaviors must be connected to each other. Our current knowledge, however, is not sufficient yet to understand these phenomena in a consistent way.

Recently Jordan *et al.*[8] have measured the fusion excitation functions for the system of $^{12}C + ^{28,29,30}Si$. They have reported that weak structure is observed in the fusion excitation function for $^{12}C + ^{28}Si$ while the remaining $^{12}C + ^{29,30}Si$ systems exhibit a smooth energy dependence. What is quite surprising from their results is that the fusion cross sections σ_{fus} for the $^{12}C + ^{28}Si$ system are much smaller than those for the other systems: at the same incident energy $E_{c.m.} = 25$ MeV the differences are as large as 300 mb [Fig. 1(a)]. In order to fit the experimental σ_{fus}

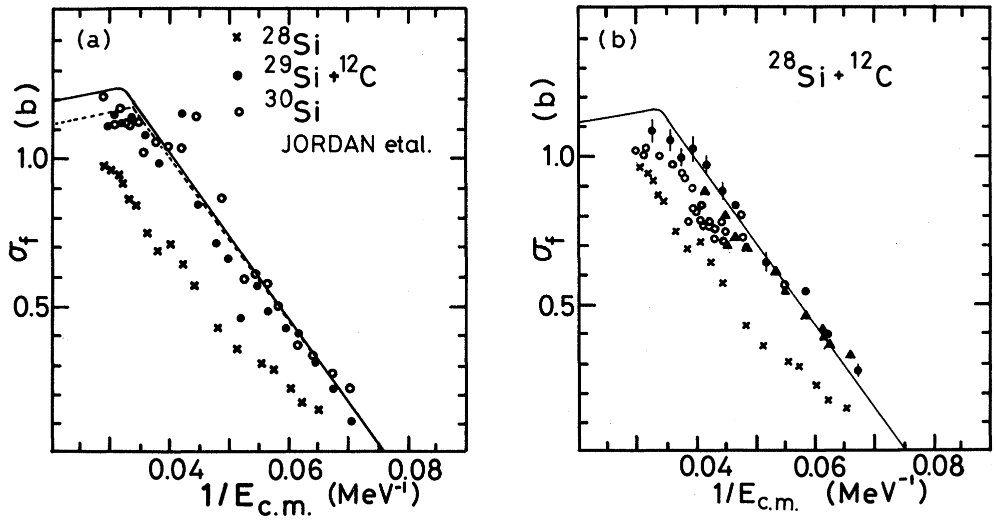

FIG. 1. (a) Fusion cross sections of the $^{12}C + ^{28}Si$ (crosses), $^{12}C + ^{29}Si$ (closed circles), and $^{12}C + ^{30}Si$ (open circles) systems taken from Ref. 8. The dotted and solid curves are the theoretical predictions for $^{12}C + ^{29}Si$ and for $^{12}C + ^{30}Si$, respectively (see text). (b) The fusion cross section of the $^{12}C + ^{28}Si$ system. The solid circles are from the present results, the crosses from Ref. 8, the closed triangles from Ref. 10, and the open circles from Ref. 11. The solid line is the calculated curve by the statistical yrast line and fusion barrier models (see text).

by the semiclassical fusion barrier expression $\sigma_{\text{fus}} = \pi R_B^2(1 - V_B/E_{\text{c.m.}})$, they gave the values $R_B = 7.40$ fm and $V_B = 15.0$ MeV for ^{12}C + ^{28}Si, $R_B = 8.31$ fm and $V_B = 13.7$ MeV for ^{12}C + ^{29}Si, and $R_B = 8.80$ fm and $V_B = 13.7$ MeV for ^{12}C + ^{30}Si. The differences of values of R_B and V_B for ^{12}C + ^{28}Si, thus deduced from their experiments, are much larger than those due to the isotope mass dependence for R_B and V_B. Although the physical origin of these differences is not seriously discussed by Jordan *et al.*,[8] we believe that this fact may be a crucial key point to understand the oscillation behavior for the $4N$ systems if their results are really true. It is, however, sometimes dangerous to elaborate on theoretical considerations before the experimental results are well confirmed since the absolute experimental σ_{fus} may have a large error as has been discussed by Kovar *et al.*[9]

With the motivation discussed above, we have decided to remeasure the fusion excitation function for the ^{28}Si + ^{12}C system and in this report we shall show that there is no noticeably small fusion cross section in the ^{28}Si + ^{12}C system and so the oscillation behavior has no obvious connection with a small value of σ_{fus}.

To perform the measurement of the fusion excitation function for the ^{28}Si + ^{12}C system, we have used the ^{28}Si beam instead of the ^{12}C beam, as this method may be more reliable because the momentum of the evaporation residues increases and no low energy cutoff of the products is to be seen consequently in the two-dimensional E-ΔE spectrum. Furthermore, a ^{12}C target contains fewer contaminants than a ^{28}Si target made of a chemical compound. Beams of ^{28}Si were accelerated by the 12 UD Pelletron tandem accelerator at the University of Tsukuba in the energy range of $E_{\text{lab}} = 50$–115 MeV. Self-supporting ^{12}C targets of $\sim 50\ \mu\text{g/cm}^2$ were used. The beam which passed through the collimator system made a spot of 2 mm diameter on the targets and did not change the position under the various focusing conditions. The beam was stopped by a small Faraday cup of 10 mm diameter at a distance 200 mm from the target in order to prevent the beam from hitting the detector at forward angle. Evaporation residues from complete fusion reactions and the elastically scattered ^{28}Si were detected in two sets of counter telescopes consisting of a gas flow ionization chamber followed by a solid state detector. The full angular distributions were measured in the angular range of $\theta_L = 2.5°$–$16°$ at the 11 incident energy points.

Data were stored in a two-dimensional E vs ΔE matrix by using a PDP-11/50 on-line data acquisition computer system. The evaporation residues with $Z > 14$ were summed for determining the experimental σ_{fus} and were accumulated until the statistical error became less than 3%. Using the Rutherford cross sections at forward angles, it was possible to deduce the absolute fusion cross sections independently of the beam current and target thickness. In this method the main part of errors in absolute cross sections is due to the error of angles $\Delta\theta$ which was estimated to be $\pm 0.05°$. The experimental error in the absolute fusion cross sections were consequently determined within 10%.

In Fig. 1(b), the results are shown together with those of other experiments.[8,10] The data of Lesko *et al.*[11] are somewhat in between the data of Jordan *et al.*[8] and ours while the results of Ref. 10 are in good agreement with the present results at lower energies. It should, however, be noted that the same kind of weak structure containing two minima, as observed in Ref. 8, is also seen in the present measurement though the absolute cross sections are different from each other. We compare the experimental fusion cross sections over the full energy range by using the following expressions for σ_{fus}: in region I (at lower energies) $\sigma_{\text{fus}}^{(\text{I})} = \pi R_B^2[1 - V_B(R_B)/E_{\text{c.m.}}]$ as usual, in region II (at higher energies) $\sigma_{\text{fus}}^{(\text{II})} = (\pi I/\mu) \times [1 + (Q - \Delta Q)/E_{\text{c.m.}}]$ from the statistical yrast line model.[12] The same parameter set, given below, is used for the three different (^{12}C + Si)-isotope systems. For $\sigma_{\text{fus}}^{(\text{I})}$, $V_B(R_B)$ is evaluated by the equivalent Coulomb barrier height[13] at R_B as $V_B(R_B) = V_C(R_C) = Z_1 Z_2 e^2/R_C$ where $R_C = R_0 + \Delta R_C$, $R_B = R_0 + \Delta R_B$, $\Delta R_C = 3.75$ fm, and $\Delta R_B = 2.85$ fm. R_0 is the sum of the half density radii between two

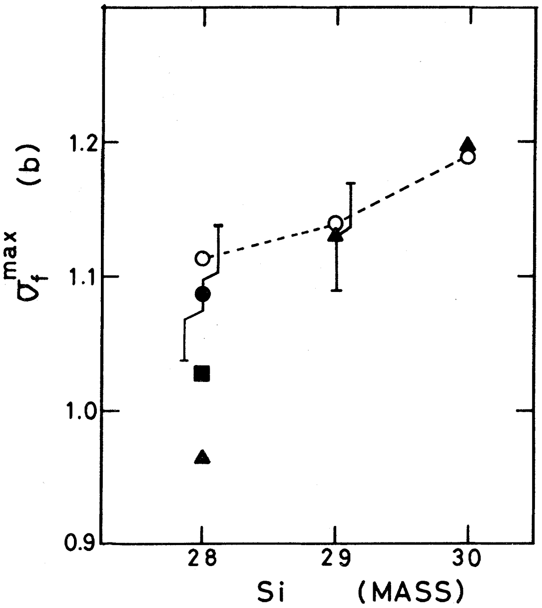

FIG. 2. $\sigma_{\text{fus}}^{\text{max}}$ in the ^{12}C + ^{28,29,30}Si systems. The closed triangles are the results from Ref. 8, the closed square from Ref. 11, and the closed circle from the present result. The open circles are the theoretical $\sigma_{\text{fus}}^{\text{max}}$ at the crossing point evaluated by the fusion barrier and the statistical yrast line models.

ions and can be expressed as $R_0 = R_1 + R_2$ where $R_1 = 1.12A_i^{1/3} - 0.86A_i^{-1/3}$ ($i = 1$ or 2). For $\sigma_{\text{fus}}^{(\text{II})}$, the moment of inertia of the statistical yrast line is calculated as $I = \frac{2}{3}AM\langle r^2\rangle_A\alpha$ where M is the nucleon mass. In addition α is the scaling factor and the mean square radius of the compound nucleus $\langle r^2\rangle_A$ can be evaluated as $\langle r^2\rangle_A = \frac{3}{5}(1.12A^{1/3})^2 \times (1 + 3.84A^{-2/3})$. For the numerical values of α and ΔQ, the following fixed values are used: $\alpha = 0.85$ and $\Delta Q = 10$ MeV.

The calculated results for $^{12}\text{C} + ^{29,30}\text{Si}$ are in good agreement with the experimental data of Jordan *et al.*[8] as shown in Fig. 1(a) while the theoretical curve for $^{28}\text{Si} + ^{12}\text{C}$ agrees rather well with our experimental data points [Fig. 1(b)]. In Fig. 2, the experimental and theoretical maximum fusion cross sections $\sigma_{\text{fus}}^{\text{max}}$ at the crossing point between regions I and II are shown. The theoretical predictions reproduce reasonably well the experimental $\sigma_{\text{fus}}^{\text{max}}$ for $^{28}\text{Si} + ^{12}\text{C}$ from our present study. This fact seems to indicate that the different behavior of $\sigma_{\text{fus}}^{\text{max}}$ from system to system is not due to a nuclear structure effect as discussed by Jordan *et al.* but rather due to the combined effect of the three different quantities of Q value, μ, and moment of inertia I in three systems.

As a conclusion we have also observed evidence of weak structure in the fusion excitation function for $^{28}\text{Si} + ^{12}\text{C}$ but the absolute magnitudes of the cross section are significantly different from those of Ref. 8. This suggests that the cross section enhancement of elastic and inelastic scattering at backward angles does not cause automatically a considerably reduced fusion cross section. The present experimental σ_{fus} for $^{28}\text{Si} + ^{12}\text{C}$ and those measured in Ref. 8 for $^{12}\text{C} + ^{29,30}\text{Si}$ are well reproduced by the semiclassical fusion barrier expression with the same parameter set. In addition, the behavior of $\sigma_{\text{fus}}^{\text{max}}$ for the different isotope systems is well interpreted in terms of the statistical yrast line model.[12]

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