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Brief Reports

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Structure in the fusion yield for $^{32}S+{}^{12}C$

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The total fusion cross section for $^{32}S+{}^{12}C$ has been measured over the center-of-mass energy range from 16 to 28 MeV. The data show structures having peak-to-valley variations of 5–10% of the total fusion yield.

In this work, we present the results of measurements of the total fusion yield for the $^{32}S+{}^{12}C$ reaction at center-of-mass (c.m.) energies ranging from 16–28 MeV, in steps of 110 keV. The ^{32}S nucleus is the next in a sequence of *sd*-shell "α-particle" nuclei (^{20}Ne, ^{24}Mg, ^{28}Si) whose fusion with ^{12}C has been measured and found to show prominent structure.[1–5] The excitation function for $^{28}Si+{}^{12}C$ fusion is particularly striking in that it displays a number of narrow ($\Gamma=400$–600 keV) resonancelike anomalies having peak amplitudes of 15% or more of the total fusion yield.[5] On the basis of sharp cutoff model calculations of the critical angular momentum for fusion, it has further been demonstrated that these structures occur at intervals corresponding to a separation of one unit of angular momentum. In contrast, the $^{12}C+{}^{24}Mg$ and $^{12}C+{}^{20}Ne$ fusion excitation functions have been observed[1,3,4] to display structures with a peak-to-valley variation of 5–10% of the fusion yield, having widths of ~ 2 MeV and occurring rather more sporadically in that the periodicity appears to be roughly every second partial wave at low energies but every partial wave at higher energies. An investigation of $^{32}S+{}^{12}C$ fusion would extend systematics and perhaps establish whether the $^{28}Si+{}^{12}C$ reaction is unique or represents a transition to a different behavior pattern for fusion oscillations. A further motivation for the present experiment is the fact that structure in the fusion yield appears to be in some way connected with the observation of anomalous back-angle elastic and inelastic scattering in these systems. For example, the three strongest anomalies in the $^{28}Si+{}^{12}C$ fusion yield are correlated with pronounced *minima* in the elastic scattering, and in the inelastic scattering to the first 2^+ state in ^{28}Si, at back angles.[6–8] Furthermore, the excitation functions for back-angle inelastic scattering to the first 2^+ state in ^{12}C and the first 4^+ state in ^{28}Si also show a minimum at the highest-energy "resonance" location.[6] Since the $^{12}C+{}^{32}S$ quasielastic data show similar, though weaker, structure, it would be of some interest to explore the fusion excitation function, especially since the ground-state nuclear shapes are rather rapidly fluctuating for the target nuclei under consideration, from strongly prolate deformed for ^{20}Ne and ^{24}Mg, to strongly oblate for ^{28}Si, to nearly spherical for ^{32}S.

In the present experiment, we have used γ-ray techniques to measure the fusion excitation function. The target consisted of a nominal 10 $\mu g/cm^2$ foil of natural C on a Au backing which was sufficiently thick to stop the recoiling fusion residues at all beam energies. The strong Coulomb excitation lines from the backing provided a cross check against the relative normalizations computed from charge collection. Deviations from smoothness in their yield of the order of 1% were observed, but the final relative normalizations were obtained by assuming that Coulex is locally smooth. The absolute normalization was determined from the yields of ^{20}Ne and ^{23}Na in the $^{16}O+{}^{12}C$ reaction[9] at ^{16}O laboratory energies of 33.25 and 38.50 MeV, and has an estimated uncertainty of 10%. For most of the fusion residues, it was possible to identify several characteristic lines in the spectra. The total fusion-evaporation yield was obtained by adding the intensities of all ground-state γ-ray transitions. Direct feeding to the ground state of a residue, and γ-ray transitions for which $E_\gamma > 4$ MeV, are not observed in this method. A few of the characteristic transitions included in the fusion cross section could also result from β decay of radioactive nuclides produced in the target. Thus, beam-off spectra were regularly taken, but no evidence for delayed-activity contamination of any important transition was observed.

Fusion excitation functions for two of the strongest evaporation residues (which together make up 70% to 90% of the total fusion yield) are shown in Fig. 1, and the total fusion cross section is illustrated in Fig. 2. Structures can be observed in both the $^{42}Ca(2p)$ and $^{39}K(\alpha,p)$ yields. These are the same evaporation channels that showed significant anomalies in the $^{28}Si+{}^{12}C$ system.[5] Here, however, the amplitude of the oscillations is significantly smaller, being less than 10% of the total yield as opposed to the results for $^{28}Si+{}^{12}C$, where peak-to-valley ratios exceeding 15% were observed in some cases. In this respect, the situation is similar to that for $^{12}C+{}^{24}Mg$, for which fluctuation amplitudes of less than 10% were reported.[3] A further similarity between these two systems is the fact that the structure visible in Fig. 2 is not strongly periodic. Significant oscillations in the total fusion excitation function are observed at $E_{c.m.}=17.7$, 19.9, 21.0, (23.2), (24.2), 25.7, and 26.5 MeV. (an expanded view of the region near the latter two "resonances" is shown in Fig. 3). In a sharp cutoff model, the critical angular momenta for fusion corresponding to these

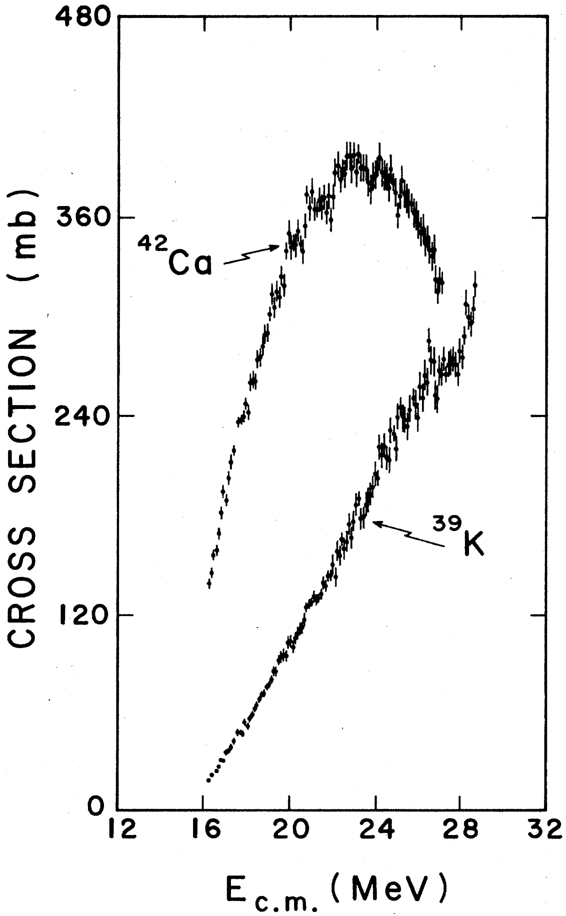

FIG. 1. Production cross sections for ^{42}Ca ($2p$ evaporation) and ^{39}K (αp evaporation) for the $^{32}S+^{12}C$ reaction.

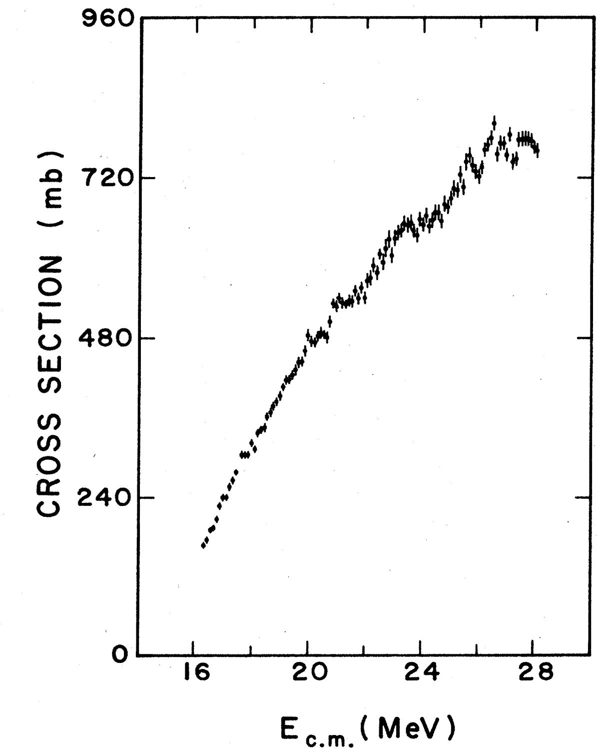

FIG. 2. Total fusion cross section for $^{32}S+^{12}C$, including the data shown in Fig. 1 plus the yields of $^{43,42}Sc$, ^{41}Ca, ^{40}K, and $^{38,37,36}Ar$ measured in the present experiment. The latter account for 10%–30% of the total yield over the entire energy range illustrated.

energies, as calculated from the total fusion cross section given in Fig. 2, are $l_c=6.7$, 9.4, 10.2, (12.0), (12.8), 13.8, and 14.4, respectively. In contrast, the critical angular momenta associated with the anomalies seen in the $^{28}Si+^{12}C$ fusion excitation function are separated one from the other by approximately one unit of angular momentum. Furthermore, the correlation of maxima in the fusion cross section with pronounced minima in the back-angle elastic and inelastic scattering cross sections is weaker here than it is for $^{28}Si+^{12}C$. There is only one minimum[8] in the back-angle $^{12}C+^{32}S$ elastic and inelastic cross sections over the energy range covered by the present work. It occurs at $E_{c.m.}=26.5$ MeV, which does, in fact, correspond to one of the maxima in the fusion yield. However, no other correlation between the two data sets can be discerned.

In summary, the total fusion cross section for $^{32}S+^{12}C$ in the c.m. energy range from 16–28 MeV has been measured and found to display structure with peak-to-valley variation of 5–10%, occurring at rather irregular intervals. One of these anomalies, at $E_{c.m.}=26.5$ MeV, is correlated with a pronounced minimum in the back-angle elastic and inelastic scattering excitation function, but no other correlations are present. In all respects, the $^{32}S+^{12}C$ fusion excitation function resembles that obtained for $^{12}C+^{24}Mg$, suggesting that

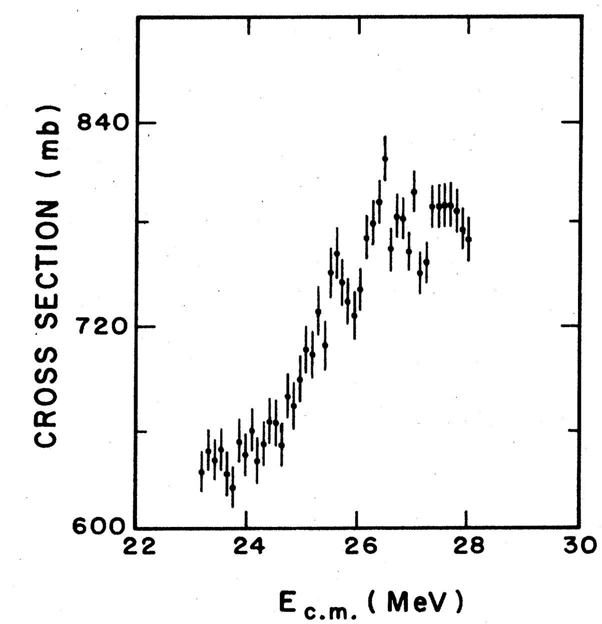

FIG. 3. Expansion of the data of Fig. 2 about the region from $E_{c.m.}=22$–28 MeV showing the "resonances" at $E_{c.m.}=25.6$ and 26.5 MeV.

the ground-state deformation of the target does not play an important role in determining the existence and behavior of fusion oscillations for *sd*-shell α-particle nuclei. Finally, it appears that the strong, regular oscillations observed for $^{28}Si + ^{12}C$ are, in fact, somewhat unique, and do not represent a transition to a different behavior for upper *sd*-shell nuclei.

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