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# Fusion Cross Sections of Light Heavy-Ion Systems: Resonances and Shell Effects*

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The total fusion cross sections for the systems $^{12}C+^{12}C$, $^{18}O+^{12}C$, and $^{19}F+^{12}C$ have been measured as a function of bombarding energy and compared with results for other light heavy-ion systems. The presence or absence of oscillations in the fusion excitation function and the overall magnitude of the cross section at high energies appear to depend on the structure of the colliding nuclei.

The energy dependence of the cross section for the complete fusion of two complex nuclei has received considerable recent attention.[1] In most cases the measured excitation functions are smooth, as is consistent with macroscopic models of such processes. In a recent study of the $^{16}O+^{12}C$ system, unexpected oscillatory structure was seen in the energy dependence of the fusion cross section.[2] In the present study we have bombarded $^{12}C$ targets with several other ions, near in mass to $^{16}O$, in order to establish the range of nuclei over which structure is seen in the fusion excitation function, and also to delineate the macroscopic features of the fusion process.

The fusion cross sections for the systems $^{12}C+^{12}C$, $^{18}O+^{12}C$, and $^{19}F+^{12}C$ were measured as a function of bombarding energy using beams obtained from the Argonne National Laboratory FN tandem accelerator. The experimental procedure and uncertainties have been described previously.[2] All reaction products with higher $Z$ than the incident ions were assumed to be evaporation residues and were included in defining the fusion cross section.

The fusion cross sections $[\sigma_{fus}(E)]$ for the three systems studied are shown in Fig. 1 as a function of c.m. energy. The solid lines in Fig. 1 are calculated using the model of Glas and Mosel[3] which is based on the assumption that fusion occurs whenever the nuclei reach a critical separation distance, $R_c$. The parameters used to fit the data are listed in Table I. The experimental results confirm the qualitative prediction of the model that $\sigma_{fus}$ for such a light system should saturate at some critical bombarding energy and then decrease or remain roughly constant at higher energies.

There are two qualitative features in our exper-

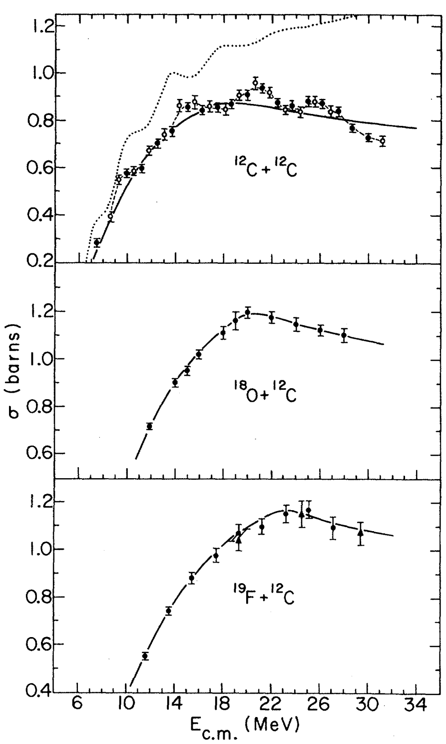


FIG. 1. Total fusion cross section for $^{12}C+^{12}C$, $^{18}O+^{12}C$, and $^{19}F+^{12}C$, as a function of the c.m. energy. The open circles in the case of $^{12}C+^{12}C$ represent measurements at $\theta_{lab}=6°$ only, where the total fusion cross section was estimated from the ratio $\sigma_{fus}/[d\sigma_{fus}/d\Omega(6°)]$ at neighboring energy points. The triangles in the case of $^{19}F+^{12}C$ are values taken from Ref. 12. The solid lines are model calculations (see text). For $^{12}C+^{12}C$ the dotted curve is the reaction cross section calculated from the optical model.

TABLE I. Parameters for the fusion cross section using the expression and the notation for $\sigma_{fus}$ of Ref. 3. The values of $\hbar\omega$, characterizing the low-energy behavior, are not given. $V_c$ was kept fixed at −10 MeV for all four systems.

| System | $V_B$ (MeV) | $R_B$ (fm) | $R_c$ (fm) |
|---|---|---|---|
| $^{12}C + ^{12}C$ | 6.17 ± 0.10 | 6.65 ± 0.18 | 4.35 ± 0.23 |
| $^{16}O + ^{12}C$ | 7.69 ± 0.10 | 7.55 ± 0.14 | 4.47 ± 0.14 |
| $^{18}O + ^{12}C$ | 7.51 ± 0.05 | 7.86 ± 0.10 | 5.11 ± 0.10 |
| $^{19}F + ^{12}C$ | 8.08 ± 0.07 | 7.64 ± 0.15 | 5.11 ± 0.15 |

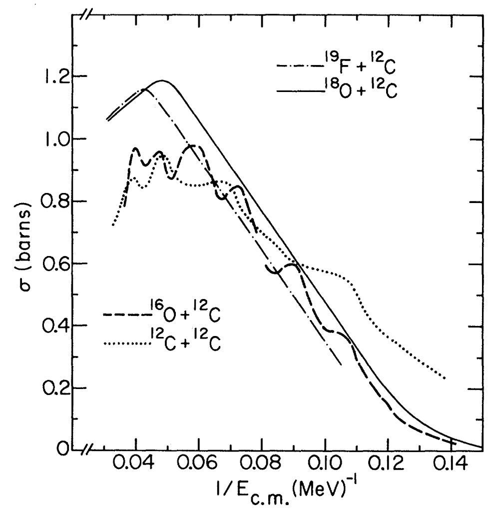


FIG. 2. Total fusion cross sections as a function of $1/E_{c.m.}$. For the sake of clarity only lines connecting the data points are shown. The low-energy part for $^{16}O + ^{12}C$ was taken from Ref. 7.

imental results which are striking. First, the excitation function for $^{12}C + ^{12}C$ exhibits oscillations similar to those observed previously[2] for $^{16}O + ^{12}C$, while no such behavior is apparent in the measurements for $^{18}O + ^{12}C$ or $^{19}F + ^{12}C$. The maxima in $^{12}C + ^{12}C$ appear at about 5.5 MeV intervals at $E_{c.m.} = 9.5$, 15, 20.5, and 26 MeV.[4] This spacing is larger than that seen in the $^{16}O + ^{12}C$ system, where it was ~3.5 MeV. Many narrow resonances in the $^{12}C + ^{12}C$ system have been observed in particular reaction channels.[5] However, the oscillations in $\sigma_{fus}$ are not obviously correlated with the known structure in specific channels, with the possible exception[4] of the gross structure in the 90° elastic scattering of $^{12}C$ on $^{12}C$.[6]

The second striking feature is that the structureless excitation functions observed for $^{18}O + ^{12}C$ and $^{19}F + ^{12}C$ are characterized by a significantly higher maximum value of $\sigma_{fus}$ than the other systems (see Fig. 2). Glas and Mosel[8] have predicted an anomalous decrease in the high-energy fusion cross section, through its dependence on $R_c$, whenever the interacting nuclei have closed-shell structure and are not easily excited. While the average behavior of the data in Fig. 2 and the corresponding $R_c$ values in Table I are in qualitative agreement with this prediction, a possible alternative interpretation is suggested by comparison with results for other systems[9-11] in which the measured fusion excitation functions show a well-defined maximum (see Table II). The result for $^{14}N + ^{12}C$ is particularly interesting: Even though $^{14}N$ has two unpaired nucleons which are presumably easily excited, $\sigma_{fus}^{max}$ is less than 1.0 b, similar to the $^{16}O + ^{12}C$ and $^{12}C + ^{12}C$ values. All three of these systems involve the interaction of two $1p$-shell nuclei. The systems in which a $1p$-shell nucleus collides with another which has some nucleons in the $s$-$d$ shell exhibit maximum fusion cross sections of ~1.2 b. If this apparently simple feature is more than accidental, it is difficult to see how it would emerge from the model of Glas and Mosel.[3,8] It is tempting to associate the abrupt change in $\sigma_{fus}^{max}$ with the introduction of nucleons into a new major oscillator shell; the mean-square radius of nucleons within one shell tends to remain constant with changing nuclear mass, but changes abruptly for a new shell.

The source of the oscillations in $\sigma_{fus}(E)$ is not clear at this point. There is no mechanism for generating resonances in the classical model of

TABLE II. Maximum values of the high-energy fusion cross section $\sigma_{fus}^{max}$ for various systems.

| System | $\sigma_{fus}^{max}$ (mb) | Ref. |
|---|---|---|
| $^{12}C + ^{12}C$ | 940 ± 30 | This work |
| $^{12}C + ^{14}N$ | 980 ± 70 | 4,9 |
| $^{12}C + ^{16}O$ | 970 ± 30 | 2 |
| $^{12}C + ^{18}O$ | 1200 ± 30 | This work |
| $^{12}C + ^{19}F$ | 1150 ± 40 | This work |
| $^{12}C + ^{27}Al$ | 1190 ± 120 | 10 |
| $^{16}O + ^{40}Ca$ | 1180 ± 70 | 11 |

Ref. 3. However, it was noted in the case of $^{16}$O + $^{12}$C that structure does arise in the reaction cross section predicted with an optical-model potential, when the radius of the imaginary term is reduced from the value needed to fit elastic scattering data. For the $^{12}$C + $^{12}$C case structure is seen in the reaction cross section calculated with the elastic parameters,[6] even without a reduction in the imaginary radius, as is shown by the dotted curve in Fig. 1. Better fits to the magnitude of the high-energy cross section and to the observed oscillatory pattern may be obtained by reducing the imaginary radius and adjusting other parameters slightly. It is not clear whether such adjustments are very meaningful; since $\sigma_{fus}$ is not the *total* reaction cross section, the imaginary potential that fits $\sigma_{fus}(E)$ does not represent the total absorption and such potentials bear no simple relationship to those required to fit elastic scattering.

To summarize, we see two qualitative effects: the oscillatory structure and the change in the maximum value of the fusion cross section. The two effects seem to be correlated in the limited data we have; perhaps they both depend on the strength of surface absorption. But it is not clear at present whether the resonances occur only for tightly bound, closed-shell nuclei, whether they are perhaps a feature of $\alpha$-particle nuclei or of $1p$-shell nuclei, whether they are indeed shape resonances or more special structures. Nor is it clear whether the maximum value of the fusion cross sections depends on the presence of loosely bound valence nucleons and low-lying excited states, or rather depends on the shell in which the outer nucleons reside. More data are clearly needed, but in any case the present measurements establish that large qualitative differences in the behavior of the fusion cross section exist between light systems which differ only slightly in mass.

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