Reaction cross sections for $^{16}O + ^{16}O$

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The total fusion cross section σ_f for $^{16}O + ^{16}O$ has been measured in 500 keV steps between 12.5 and 30.5 MeV c.m. energy via γ-ray techniques. The excitation function for σ_f shows clear evidence of periodic structure between 14 and 28 MeV (c.m.), as predicted by the optical model. These oscillations are out of phase with those observed in 90° elastic scattering. Individual yields of 12 nuclides formed in the reaction were also obtained. The narrow ($\Gamma \leq 1$ MeV) resonance at $E_{c.m.} = 26.5$ MeV, which is correlated in the ^{20}Ne and ^{16}O (3^-) channels, is suggested to be an "α-exchange" resonance.

[NUCLEAR REACTIONS $^{16}O + ^{16}O$ 12.5–30.5 MeV (c.m.); measured excitation functions for production of $A = 16$–31 reaction products; deduced evidence for broad shape resonances, and a narrow resonance at $E_{c.m.} = 26.5$ MeV.]

The identical-particle system $^{12}C + ^{12}C$ exhibits much structure in its reaction cross section excitation function, with a sequence of narrow resonances[1] below 8 MeV (c.m.) and several broad shape resonances[2] in the energy region between 8 and 30 MeV (c.m.). In contrast, there is no evidence[3] for narrow resonances in the reaction channels for $^{16}O + ^{16}O$ at energies below 12 MeV, and the predicted shape resonances at higher energies have only been systematically investigated via elastic scattering.[4] In the present experiment, we extend the reaction cross section measurements to 30.5 MeV (c.m.) via γ-ray techniques.

The experimental method has been presented in some detail previously,[5] so we will only discuss differences from the $^{16}O + ^{12}C$ work of Ref. 5. The primary difference was the target, which consisted of a film of Ta_2O_5 containing 45 $\mu g/cm^2$ of natural O, formed by anodizing clean Ta metal. The total target thickness was therefore 250 $\mu g/cm^2$ (determined by weighing), and the beam-energy steps were accordingly increased to 1 MeV because of the additional energy loss of the beam in the target. As before, the target was surrounded with a liquid nitrogen cooled shield to reduce carbon buildup, but because the presence of small amounts of C would tend to distort the measured nuclide distributions, many more points were repeated and two identical targets were used. No evidence for carbon buildup was observed during the course of the experiment. The relative normalizations of the data points were determined from Coulomb excitation of the Ta backing, and as before they agreed to within ±2% with those computed from charge collection. The absolute normalization was determined from the yield of ^{20}Ne in the $^{16}O + ^{12}C$ reaction at 40 MeV (lab), measured with the same target used in the previous experiment,[5] and has an estimated uncertainty of ±7%.

The excitation function for "total fusion" measured in the present experiment is shown in Fig. 1.

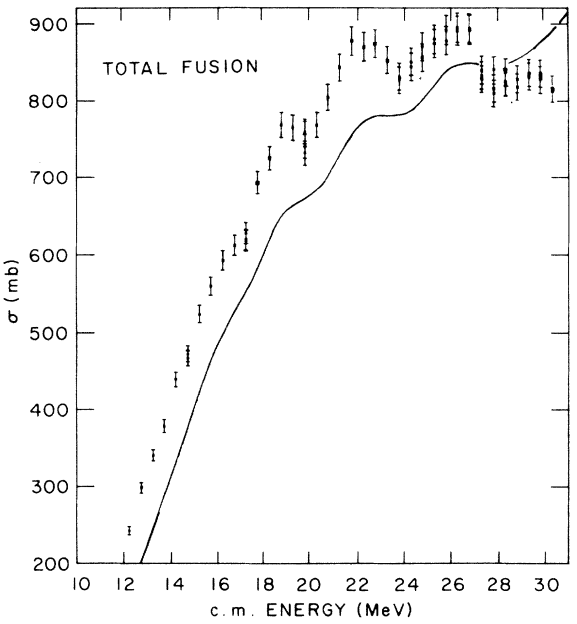

FIG. 1. Total fusion cross section for $^{16}O + ^{16}O$. The solid curve is the optical-model prediction for the total reaction cross section using the parameters (Ref. 6) of Table I. A constant 300 mb has been subtracted from the predictions to facilitate comparison with experimental data.

TABLE I. Parameters used in the optical-model calculations.

V (MeV)	r_0 (fm)	a (fm)	W (MeV)	r_I (fm)	a_I (fm)
17.0	1.35	0.49	$0.8 + 0.2\,E_{c.m.}$	1.27	0.15

There is, of course, some ambiguity in these measurements because of the fact that it is not possible to separate out the yield to certain reaction products (in this case principally ^{20}Ne) via direct-transfer processes as opposed to fusion-evaporation reactions. In addition, the reaction yield due to direct population of the ground state of the evaporation residues, or population via high-energy (>6 MeV) γ-ray transitions, could not be observed in this work. Neither of these processes is expected to lead to large errors in the determination of the total fusion cross section.

The most striking feature of the data presented in Fig. 1 is the sequence of broad resonances at regular intervals of about 3.5 MeV. Also shown in Fig. 1 is the optical-model prediction for the total reaction cross section using the parameters[6] listed in Table I. (To facilitate comparison with experiment, a constant 300 mb has been subtracted from

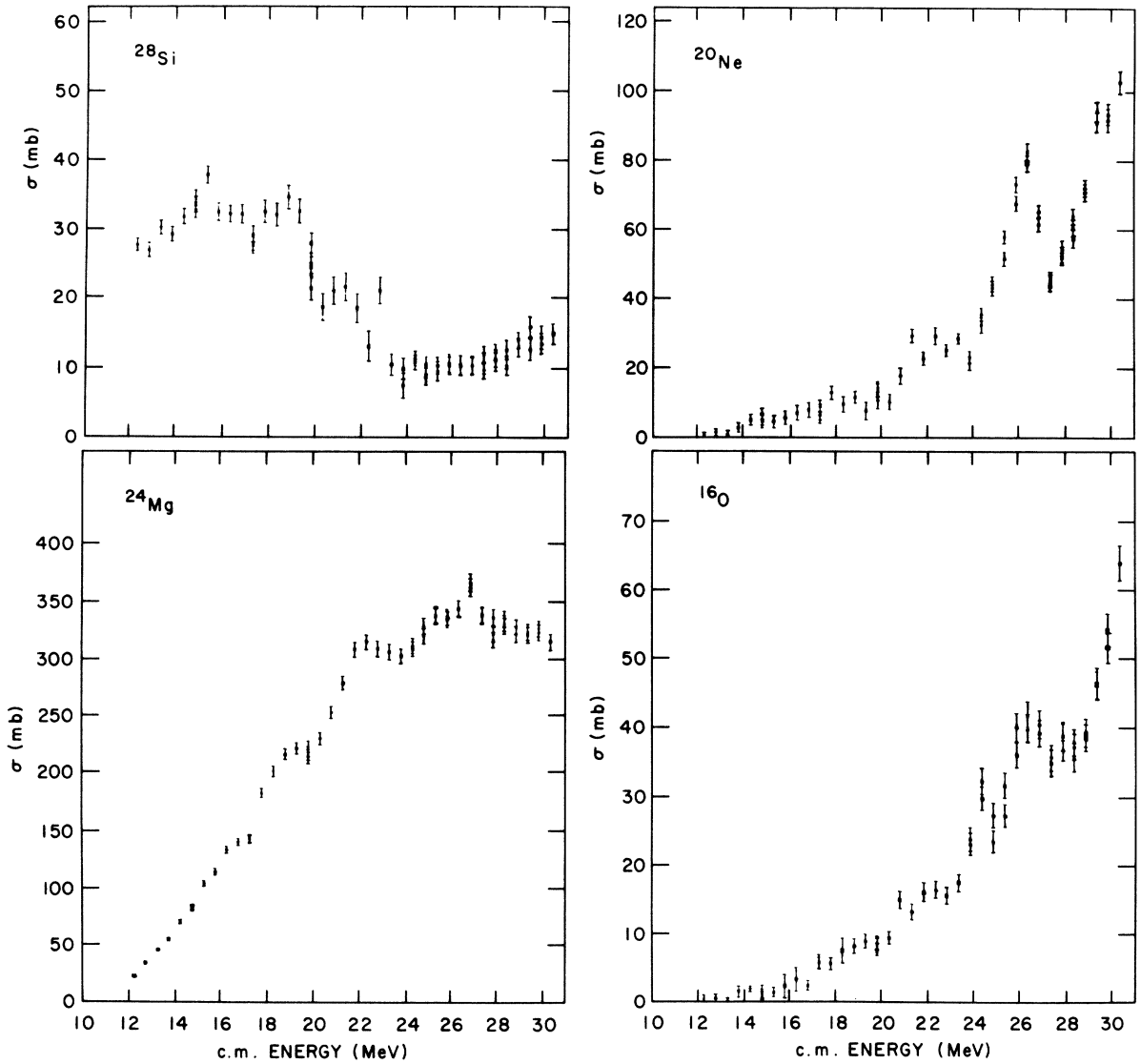

FIG. 2. Individual excitation functions for the production of ^{28}Si, ^{24}Mg, and ^{20}Ne. The cross section for exciting the 3^- state of ^{16}O is also shown. Note the strong resonance at 26.5 MeV in the ^{20}Ne channel, which also appears in the ^{16}O data.

the calculated reaction cross sections.) It is clear that the magnitude, location, and width of the observed gross structure (under the assumption of a smoothly varying direct-reaction background) are reasonably well reproduced by the optical model. What is perhaps even more interesting is the fact that the oscillations in the reaction cross section are *out of phase* with those in the 90° elastic-scattering data.[4,6] This behavior can be understood, however, by considering the analytic structure of the S matrix corresponding to scattering from the Gobbi potential. It can be shown[7,8] that the poles in this S matrix, and therefore the locations of the shape resonances for this system, correspond to the maxima in the *reaction* cross section. The structure in the 90° elastic scattering is primarily due to near-side, far-side interference and need not be in phase with the reaction data. In this regard, it is also interesting to note that the quasimolecular states calculated by Baye and Heenan[9] occur at systematically lower energies than the corresponding maxima in the 90° elastic scattering. The correlation with the peaks in the reaction cross section, however, is quite good, so that it seems unnecessary to propose changes in the optical-model potential to force agreement with the elastic data.

The individual yields of ^{28}Si, ^{24}Mg, and ^{20}Ne measured in this experiment are shown in Fig. 2. The broad structure observed in the total fusion cross section is clearly apparent in each of these exit channels, as well as in other channels such as ^{27}Al and ^{27}Si which have an α particle in their evaporation chain. In contrast, the light-particle evaporation channels such as ^{29}Si and ^{31}P display no structure, vividly demonstrating that the high angular momentum, peripheral partial waves involved in these resonances prefer to decay via α-particle emission.

The excitation function for production of ^{20}Ne is particularly interesting because of the very strong, relatively narrow resonance at 26.5 MeV, which is correlated with a similar structure in the ^{16}O (3^-) yield (Fig. 2). This resonance was previously observed in the $^{16}O(^{16}O, ^{12}C)^{20}Ne$ reaction[8] to the first few excited states of ^{20}Ne, but neither the magnitude of the cross section for exciting this resonance nor the extent to which it dominates the yield of ^{20}Ne near 26.5 MeV (c.m.) could be guessed from previous data. It was suggested in Ref. 8 that this structure provided evidence for quasimolecular resonances in the $^{16}O+^{16}O$ system. From the broader perspective provided by systematic measurements of various reaction products, it seems that the shape resonance is here coupled to a doorway state which is an "α-exchange" resonance of the type discussed by Krause, Schied, and Greiner.[10] These authors did not, however, consider coupling of the resonance to the 3^- state in ^{16}O, which appears to be required from the experimental data (Fig. 2). It seems likely that the 20.5 MeV resonance in the $^{16}O+^{12}C$ reaction, which has similar properties,[5] is also an α-exchange resonance.

The individual yields of 12 reaction products at

TABLE II. Comparison of measured cross sections at 30 MeV (c.m.).

Nuclide	E_γ [a] (keV)	σ (mb) This work	Ref. 11	Ref. 12
^{16}O [b]	6129.4	51.6 ± 3.6	•••	•••
^{20}Ne	1633.6	93.7 ± 6.6	93 ± 16	63 ± 15
^{22}Na	(890.9), (1527.9)	•••	3.3 ± 1.1	•••
^{23}Na	439.9	36.3 ± 2.5	67 ± 10	47 ± 10
^{24}Mg	1368.6	323 ± 23	252 ± 24	345 ± 70
^{26}Mg	1808.7	23.5 ± 1.7	82 ± 14	•••
^{26}Al	416.9, (829.6) [c], (2069), (3403.5), (3507.5)	51.9 ± 3.6	137 ± 16	25 ± 5
^{27}Al	843.8, 1014.5, 2210.5, 3004.2	167 ± 12	180 ± 22	(22 ± 4) [d]
^{27}Si	(780.3), 956.8, (2163.3)	1 ± 1	17 ± 9	•••
^{28}Si	1778.9	14.4 ± 1.6	25^{+50}_{-25}	13 ± 3
^{29}Si	1273.3, 2028.2, (2425.6)	112 ± 8	161 ± 19	140 ± 28
^{30}P	(677.2), 709.0, 1454.0, 1973.0	12 ± 2	•••	16 ± 3
^{31}P	1266.1, 2233.7	16 ± 2	•••	3.8 ± 0.8
Total fusion		851 ± 60	1017 ± 153	(675 ± 135) [d]

[a] γ rays whose yields were summed to determine the yield of a given nuclide; γ-ray energies in parentheses represent known ground state transitions which were not observed in the present experiment.

[b] Not included in the total fusion cross section.

[c] $1^+ \rightarrow 0^+$ transition into isomeric state of 228 keV.

[d] Does not include all ^{27}Al transitions.

30 MeV (c.m.) measured in this experiment are compared with the results of Weidinger *et al.*,[11] and to the γ-ray measurements of the Stanford group[12] in Table II. The agreement is reasonably good for major reaction products, with relatively large discrepancies occurring only for very weak channels such as ^{27}Si or for those in which the cross section is rapidly increasing such as ^{26}Al, ^{26}Mg, or ^{23}Na. This is in contrast to the marked disagreement in the ^{20}Ne production cross section from $^{16}O + ^{12}C$ at 26 MeV (c.m.), which is not yet understood.

In conclusion, the results discussed above provide clear evidence for the predicted shape resonances in the total reaction cross section for $^{16}O + ^{16}O$. It is seen that the oscillations in the reaction channels are out of phase with those in the 90° elastic scattering data, and that the quasimolecular resonances of Baye and Heenan[9] correspond more closely to the peaks in the fusion cross section. Furthermore, the comparison of individual yields of various reaction products demonstrates that the 26.5 MeV structure in the ^{20}Ne channel, as well as the similar structure at 20.5 MeV in the fusion cross section for $^{16}O + ^{12}C$, are likely to be α-transfer resonances coupled to the shape resonance, thereby acting as doorway states. Both resonances are also coupled to the 3^- state in ^{16}O.

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