Fusion cross sections of the $^{12}C+^{16}O$ reaction at $E(^{16}O)$ up to 150 MeV

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The evaporation residue yields have been measured for the $^{12}C+^{16}O$ reaction at five bombarding energies between 62 and 150 MeV. The important contributions of the fusion channels corresponding to 3α and 4α emission result in a total fusion cross section which saturates at higher energies and higher absolute value than previously reported. All observations are in favor of a complete fusion mechanism up to $E(^{16}O)=150$ MeV.

It is surprising to observe that for a well studied system like $^{12}C+^{16}O$, fusion cross sections have only been measured so far at ^{16}O bombarding energies up to 80 MeV. One of the reasons for this apparent lack of interest is perhaps due to the fact that the reported fusion cross sections (σ_F) already saturate[1] at $E(^{16}O)\simeq 40$ MeV and then stay constant[2] up to 80 MeV with $\sigma_F(\text{max.})=900\pm 50$ mb. In the present paper we will report on σ_F measurements for the $^{12}C+^{16}O$ reaction at energies up to $E(^{16}O)=150$ MeV but firstly we would like to stress briefly the importance of these measurements at higher energies.

In all previous studies of the $^{12}C+^{16}O$ fusion cross sections, the yields of evaporation residues (ER) with Z and A equal or lower than those of the projectile were not included in the evaluation of σ_F. This assumption is justified at low energies but it has been shown by Tabor *et al.*[3] that the 3α fusion channel corresponding to the evaporation of ^{16}O residues opens up already at $E(^{16}O)=49$ MeV and grows rapidly with increasing bombarding energies. It is thus evident that important flux contributions are missing in all previous cross sections reported at $E(^{16}O)\gtrsim 50$ MeV. For this reason, one of the main aims of the present work is to measure as accurately as possible the contributions of channels like 3α, $3\alpha p$, and 4α to evaluate correctly σ_F in the ^{16}O incident energy range from 60 to 150 MeV.

A second motivation results from the fact that two rather different interpretations[4,5] have been proposed recently to explain the features of the inclusive α particle spectrum observed in the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction at $E(^{16}O)=145$ MeV. This spectrum presents a continuum component on which is superimposed a finer structure corresponding to discrete states in ^{24}Mg. Takahashi *et al.*[4] explained the continuum component by a compound nucleus evaporation process but claimed that the experimental cross sections of the discrete states were higher by one order of magnitude than predicted by statistical model calculations. This conclusion was contradicted by Cormier *et al.*[5] who showed that both components of the spectrum could be reproduced by a compound nucleus process. It was thus concluded that, contrary to the suggestion given in Ref. 4, there was no evidence for direct processes in the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction at energies up to 150 MeV. The total fusion cross section is an essential input of the statistical model calculations reported in Refs. 4 and 5. Prior to the present experiment, no experimental cross sections had been measured at an energy of 145 MeV and the two groups adopted substantially different values of σ_F based on model predictions: $\sigma_F=500$ mb in Ref. 4 and $\sigma_F=820$ mb in Ref. 5. The used bombarding energy falls in the energy range covered by the present experiment and thus should enable us to favor one of the two proposed interpretations.

The third motivation is found in a recent article[6] where the energy spectra of $Z=6$–9 nuclei produced in the $^{12}C+^{16}O$ reaction at $E(^{16}O)=315$ MeV have been measured. All the spectra present a low energy component which corresponds to velocities of recoiling nuclei much higher than expected for a complete fusion mechanism. This observation is interpreted[6] as a signature of an incomplete momentum transfer component in the $^{12}C+^{16}O$ reaction. The onset of nonequilibrium phenomena in fusionlike processes[7] is at present a topic of active research and in this context it is interesting to compare our data taken at ^{16}O bombarding energies up to 9.4 MeV/nucleon for the $^{12}C+^{16}O$ reaction with the data of Ref. 6 which were obtained at 19.7 MeV/nucleon.

The experiments have been performed in two steps at the upgraded Strasbourg MP Tandem accelerator running at terminal voltages up to 16.6 MeV. In the first step, a natural C target of 70 $\mu g/cm^2$ thickness was bombarded with an ^{16}O beam at five bombarding energies: $E(^{16}O)=62$, 80, 100, 125, and 150 MeV. In the second step, the inverse reaction ^{12}C on ^{16}O (SiO_2 target of 125 $\mu g/cm^2$ thickness) was studied at the five ^{12}C bombarding energies corresponding to the same excitation energies of the compound nucleus ^{28}Si reached in step 1. The detection system consisted of a time of flight spectrometer combined with an ionization chamber and provided simultaneous A and Z identification. In the ^{16}O on ^{12}C reaction, the ^{16}O ER could not be extracted accurately due to slit scattering; this yield was deduced from the ^{12}C on ^{16}O reaction. It is well known that the main difficulty in the determination of the fusion cross section of "light" heavy ion reactions performed at a high bombarding energy comes from the yield evaluation of ER with A and Z close or lower than those of the projectile. The energy spectra of these products present generally two components: a low energy one associated with ER and a high energy one due to more direct processes. The standard method to unfold the two components is explained in Ref. 8 and is guided by a statistical model analysis. Energy spectra of the strongest observed isotopes measured at $E(^{16}O)=150$ MeV and $\theta_{lab}=6°$ are represented on Fig. 1. This figure also shows calculated energy spectra obtained with the statistical model code LILITA[9] and gives an illustration of the unfolding procedure. The narrow peaks in the energy spectra of the F

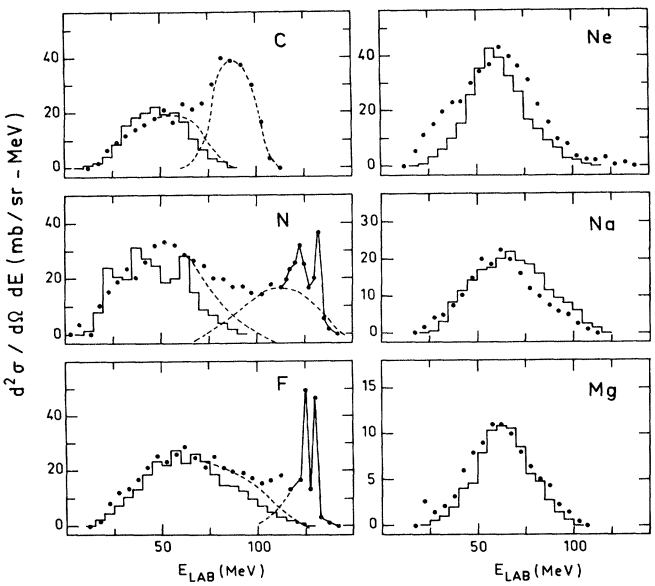

FIG. 1. Energy spectra of isotopes produced in the $^{12}C+^{16}O$ reaction at $E(^{16}O)=150$ MeV and $\theta_{lab}=6°$. The histograms are the results of statistical model calculations with the code LILITA. The unfolding procedure (see text) of the high and low energy components in the spectra are illustrated by the dashed lines.

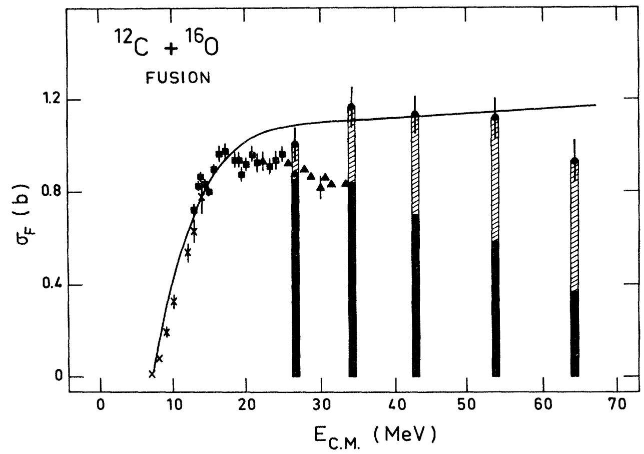

FIG. 2. Fusion cross sections (σ_F) as a function of the bombarding energy ($E_{c.m.}$) for the $^{12}C+^{16}O$ reaction. The values measured in the present work are given by points. Those indicated by crosses, squares, and triangles are taken from Refs. 10, 1, and 2, respectively. The black and hatched histograms represent cross sections measured in our experiment for ER with $Z>8$ and $Z=6$, 7, and 8, respectively. The solid line is a fit to the variation of σ_F vs $E_{c.m.}$ in the framework of the Glas and Mosel description (Ref. 11) with the following parameters: $V_B=7.7$ MeV, $r_B=1.56$ fm, $V_C=2.2$ MeV, $r_C=1.28$ fm, and $\hbar\omega=5$ MeV.

and N isotopes correspond to a particle transfer mechanism where the velocities of the fragments are close to the initial velocity of the projectile. In the spectra of the C and N isotropes, the broad high energy components (dashed lines in Fig. 1) are probably due to mechanisms like deep inelastic transfer to the continuum or projectile excitation followed by light particle emission. From the energy spectra of the different isotopes shown in Fig. 1, it can be seen that the positions and line shapes of the measured and calculated low energy components ($E_{lab}\simeq 50$–60 MeV) are in reasonable agreement at $E(^{16}O)=150$ MeV. This agreement was confirmed at all the bombarding energies used in the present experiment and is good indication of complete fusion followed by statistical decay of a ^{28}Si compound nucleus for energies up to $E(^{16}O)=150$ MeV in the $^{12}C+^{16}O$ reaction. Absolute values of the fusion cross sections have been obtained after integration of the ER angular distributions (measured at each energy from $\theta_{lab}=3°$–$40°$) and optical model analysis of the elastic scattering data. From the results summarized in Table I, it can be seen that the contribution of the $x\alpha$ ($x=2$, 3, and 4) channels is very important and represents $\sim 50\%$ of the total fusion cross section in the studied range of energy. The strong cross sections of the 3α and 4α channels which increase with energy compete with the decreasing yield of $Z>8$ ER and result in a roughly constant value of σ_F (see Fig. 2) tending to decrease at the highest measured energy. The total fusion cross section reaches a maximum of $\sigma_F\simeq 1150$ mb between $E_{c.m.}=34$–54 MeV which is by far larger ($\simeq 250$ mb) than the values obtained in previous experiments.[1,2]

The measured fusion cross sections are reported as a function of bombarding energy on Fig. 2 together with data from Refs. 1, 2, and 10. One should notice that at $E_{c.m.}=26.6$ and 34.3 MeV there is excellent agreement between our results for nuclei with $Z>8$, $A>16$, and the values of σ_F reported in Refs. 1 and 2, respectively. The variation of σ_F vs $E_{c.m.}$ has been analyzed with the model of Glas and Mosel[11] using the parameter set given in the caption of Fig. 2.

All experimental observations in the present experiment including energy spectra of the produced nuclei, angular distributions, and A and Z distributions are well reproduced by statistical model calculations. A detailed Hauser-Feshbach statistical analysis of the A and Z distributions at the five

TABLE I. Partial and total fusion cross sections, critical (l_c) and grazing (l_g) angular momenta for the $^{12}C+^{16}O$ reaction.

$E_{c.m.}$ (MeV)	σ_{Ne} (mb)	σ_O (mb)	σ_C (mb)	$\sigma_{Z>8}$ (mb)	σ_F (mb)	l_c ($\hbar$)[a]	l_g ($\hbar$)[b]
26.6	268 ± 30	157 ± 22	· · ·	852 ± 50	1010 ± 70	15.8 ± 0.6	17.5
34.3	197 ± 25	303 ± 30	20 ± 10	833 ± 50	1170 ± 80	19.5 ± 0.7	21.5
42.9	198 ± 20	292 ± 30	85 ± 15	700 ± 45	1131 ± 85	21.5 ± 0.8	24.5
53.6	217 ± 25	232 ± 28	151 ± 21	583 ± 40	1124 ± 90	24.1 ± 0.9	27.0
64.3	145 ± 20	231 ± 27	170 ± 25	368 ± 30	943 ± 75	24.2 ± 0.9	31.0

[a]Deduced values from σ_F using the sharp cut-off approximation.

[b]From optical model analysis ($T_l=0.5$).

bombarding energies will be presented in a forthcoming paper.[12] Similar experimental A and Z distributions were observed in the ^{16}O on ^{12}C reaction and in the ^{12}C on ^{16}O reaction at the same compound nucleus (CN) excitation energies. There is no significant departure from a complete fusion mechanism in the $^{12}C+^{16}O$ reaction up to $E(^{16}O)=150$ MeV.

The critical angular momenta (l_c) for complete fusion extracted from the measured σ_F are reported in Table I. The highest energy point suggests the existence of a maximum angular momentum limit $\sim 24\hbar$, which is about four units lower than predicted for $A=28$ according to the rotating liquid drop model. As mentioned before the two different interpretations[4,5] of the inclusive α spectrum in the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction rely both on calculated values of σ_F (or l_c). At $E_{c.m.}=62.1$ MeV the critical angular momentum deduced in the present work $l_c \simeq 24\pm 1\hbar$ is close to the value used by Cormier et al.[5] ($l_c=22\hbar$) but is in disagreement with the l_c used by Takahashi et al.[4] ($l_c=17\hbar$). We thus confirm the conclusion reached in Ref. 5 that the compound nucleus process exhausts the observed strengths to the ^{24}Mg discrete states and that there is no evidence for a direct process in this reaction.

In a recent paper, Gomez del Campo et al.[13] applied to the $^{12}C+^{16}O$ reaction at $E(^{16}O)=120$ MeV the crystal blocking method to measure nuclear deexcitation times. In agreement with our conclusion, their results are consistent with statistical model calculations. The reported relative ER yields are very similar to those extracted in the present work at $E(^{16}O)=125$ MeV.

The energy spectra of the $^{12}C+^{16}O\,Z=6$–9 reaction products at $E(^{16}O)=315$ MeV (Ref. 6) are equivalent in shape (see Fig. 1 of Ref. 6) to the spectra shown in Fig. 1. The only difference can be found in the position of the low energy groups which have an energy appreciably higher than expected for complete fusion ER. In Ref. 6, it was concluded that there was an important incomplete momentum transfer component in the $^{12}C+^{16}O$ reaction at $E(^{16}O)=315$ MeV. This conclusion combined with the results of the present work calls for a transition from complete to incomplete fusion in the $^{12}C+^{16}O$ reaction at energies between 10 and 20 MeV nucleon.

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