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**MASTER**THE  $^{18}\text{O}$  +  $^{12}\text{C}$  FUSION-EVAPORATION REACTION \*

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A study of the  $^{18}\text{O} + ^{12}\text{C}$  fusion evaporation reaction has been undertaken for 3 main reasons :

- 1) - to make a systematic study of the formation cross section for each individual evaporation residue over a broad excitation energy region in the compound nucleus  $^{30}\text{Si}$  : 30 to 62 MeV. Previously only total fusion cross-sections have been reported by Sperr et al <sup>1</sup> and, at lower energies by Eyal et al <sup>2</sup>. An entrance channel effect has also been looked for, at one bombarding energy, using the  $^{16}\text{O} + ^{14}\text{C}$  reaction.
- 2) - we want to compare all results to fusion-evaporation calculations done in the framework of the Hauser-Feshbach statistical model. Especially what can be learnt from such a comprehensive comparison ?
- 3) - we know that the  $^{16}\text{O} + ^{12}\text{C}$  reaction is one of the light heavy ion systems where oscillations have been found in the energy dependence of the total fusion cross section. A similar oscillation appears in the inelastic excitation of  $^{18}\text{O} + ^{12}\text{C}$  reaction as has been shown in our laboratory by Freeman and Haas using  $\gamma$ -techniques <sup>3</sup>. However, the total fusion cross section measured by Sperr et al <sup>1</sup> shows a smooth variation with bombarding energy. This has been confirmed by the  $\gamma$ -ray work <sup>3</sup> showing that even in the  $\alpha$  channels no marked oscillations were observed.

The reaction  $^{18}\text{O}$  on  $^{12}\text{C}$  has been studied for incident laboratory bombarding energies ranging from 32 MeV to 100 MeV, corresponding to center of mass energies ranging from 12 to 40 MeV. This includes our preceding measurement done at 100 MeV <sup>4</sup>. A conventional time of flight technique has been used with  $Z$ -identification. On fig. 1 are shown 3 typical mass spectra obtained at the 3 indicated laboratory bombarding energies at  $\theta_{\text{lab}} = 10^\circ$ . The time resolu-

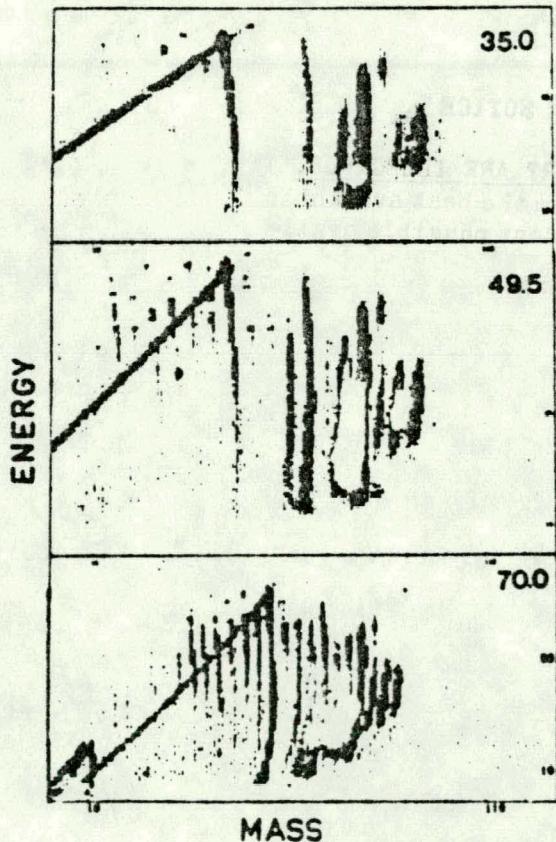


Fig. 1 : Energy versus mass spectra for the  $^{18}\text{O} + ^{12}\text{C}$  reaction measured at  $\theta_{\text{lab}} = 10^\circ$  at the three indicated laboratory bombarding energies.

tion of 200 ps was sufficient to separate completely all masses up to 30. The fusion-evaporation residues are located at masses  $\geq 20$ . Another characteristic is the growing importance of direct channels with bombarding energy. On fig. 2 are shown typical Z spectra measured at  $E_{\text{lab}} = 53.5$  MeV, using an ionization chamber of 10 cm long operating with a 90% Ar - 10%  $\text{CH}_4$  gas-mixture at a pressure of 15 Torr.

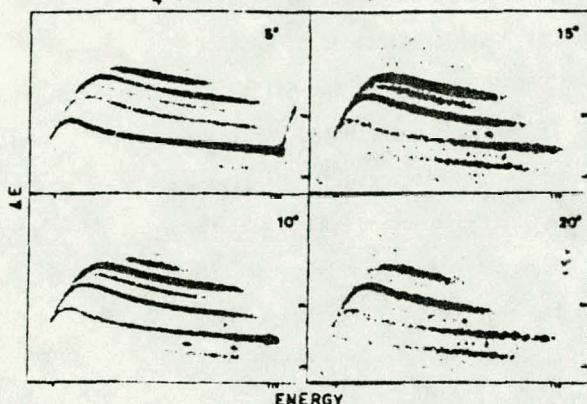


Fig. 2 : Energy-loss versus energy spectra measured for the  $^{180}$  ( $E_{\text{lab}} = 53.5$  MeV) +  $^{12}\text{C}$  reaction at the four indicated laboratory angles.

All cross sections have been obtained by integration of the angular distributions we measured for laboratory angles ranging from  $4^\circ$  to  $25^\circ$ . One measurement of  $^{16}\text{O}$  on  $^{14}\text{C}$  was made at  $E_{\text{lab}} = 50$  MeV and also an independent measurement of  $^{16}\text{O}$  on  $^{12}\text{C}$ . The  $^{12}\text{C}$  contamination of the  $^{14}\text{C}$  target could be therefore correctly estimated using the elastic scattering data.

On the left hand side of Fig. 3 are presented the relative cross-sections summed for each element over the corresponding isotopes. The advantage of this representation versus bombarding energy is that it shows directly the dominant deexcitation channels the compound nucleus will follow and how they behave with increasing angular momenta in the entrance channel. The following remarks can be made :

- 1) - the dominant fusion-evaporation process up to  $E_{\text{c.m.}} = 30$  MeV is the production of magnesium isotopes ( $\alpha n$  channels) and it follows closely

the energy dependence of the total fusion cross section. This is not the case for the  $^{16}\text{O} + ^{12}\text{C}$  reaction where the  $2\alpha$  channel to  $^{20}\text{Ne}$ , which is the most able one to carry away angular momenta, dominates for the same energy range.

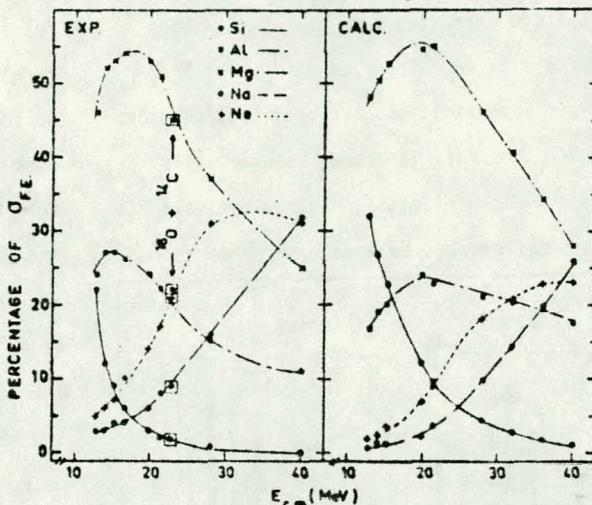


Fig. 3 : Experimental and calculated cross sections versus center of mass bombarding energies for the  $^{180} + ^{12}\text{C}$  fusion evaporation element residues.

- 2) - a striking aspect of these curves is that all reaction channels are varying strongly : the  $\alpha$  and  $2\alpha$  as well as the nucleon ones. This is not the case for the carbon + carbon systems we have also studied recently <sup>5</sup> or for  $^{16}\text{O} + ^{12}\text{C}$  <sup>6</sup>.
- 3) - the corresponding results for the  $^{16}\text{O} + ^{14}\text{C}$  reaction are presented on Fig. 3, by the squares. The energy has been corrected to the same excitation energy of the compound nucleus  $^{30}\text{Si}$ . The excellent agreement with the  $^{18}\text{O} + ^{12}\text{C}$  data demonstrates that the results are not measureably dependent on the way in which the compound nucleus is formed. The very low Q difference (934 keV) between these two systems certainly explains this agreement by the fact that nearly the same angular momenta contribute to the fusion process.

On the right hand side of fig. 3 are presented the

corresponding predictions of the evaporation calculation code LILITA from Gomez del Campo and Stockstadt<sup>7</sup> : it calculates the statistical Hauser-Feshbach cross sections by a Monte-Carlo technique. The critical angular momenta introduced in these calculations are extracted from the total fusion cross section data from Sperr et al<sup>1</sup> using the sharp cut-off approximation. An overall satisfactory agreement with the data is found. However it is interesting to look in detail, isotope by isotope, for the main differences between experience and

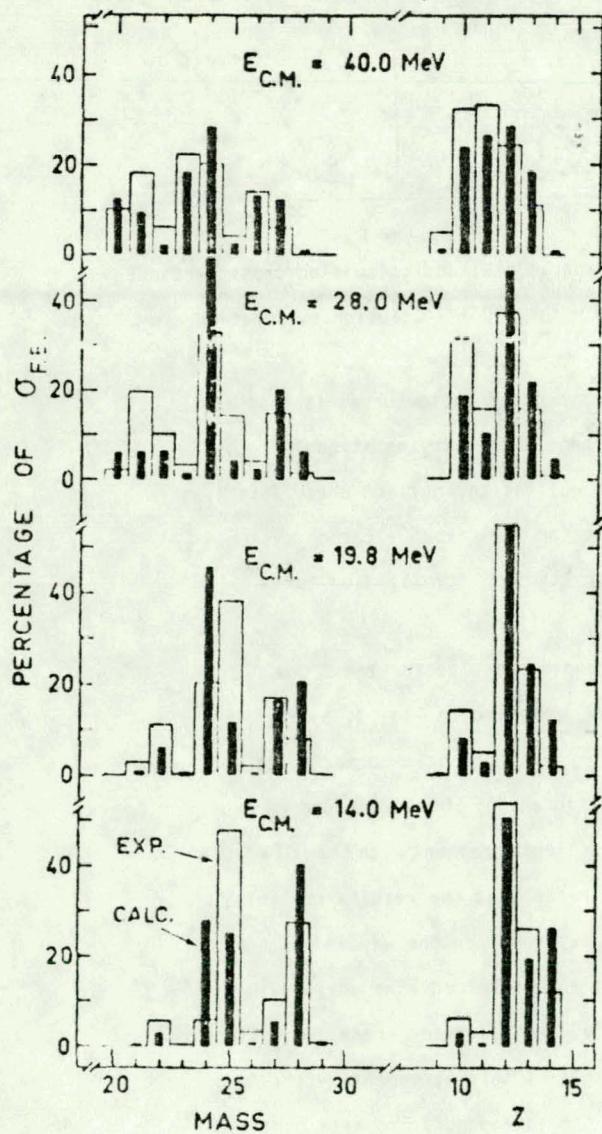


Fig. 4 : Comparison of the experimental mass and Z cross sections to those calculated with the code LILITA.

theory. On Fig. 4 are reported, at 4 energies which cover the considered energy range, the mass as well as the Z distributions. The comparison with the calculated distributions shows that, if the Z ones are quite well reproduced, the mass distributions are not so well predicted. On the other hand, the different calculation codes we used lead approximatively to the same results. We compared in our previous work at  $E_{c.m.} = 40$  MeV<sup>4</sup> the predictions of CASCADE<sup>8</sup> from Pühlhofer and GROGI 2 of Grover and Gilat<sup>9</sup>. The results of LILITA which are presented on Fig. 4 are in good agreement with those results. We also tried the code JULIAN from Hillmann and Eyal<sup>10</sup> with the same conclusion. Though the more accurate predictions are obtained with the code CASCADE the cheaper one to run is LILITA ... which explains our choice !

Two main differences between experimental and calculated distributions can be outlined :

- 1) - the calculated nucleon cross sections (leading to Si and Al isotopes) are generally overestimated whereas the  $2\alpha n$  channels (Neon isotopes) are underestimated. This is a quite general behavior of such evaporation calculations also observed, for example in the C + C systems<sup>5</sup> or by Pühlhofer et al for  $^{19}F + ^{12}C$ <sup>8</sup>.
- 2) - whereas the total prediction for the Magnesium isotopes is correct an inversion in the cross sections predicted for  $^{24}Mg$  and  $^{25}Mg$  is observed as shown in fig. 5.

It is often suggested that pre-compound, or better incomplete fusion occurs in such reactions and here also such a mechanism could explain both observed discrepancies if one assumes that an  $\alpha$  particle is emitted before fusion : instead of  $^{18}O + ^{12}C$  a  $^{14}C + ^{12}C$  fusion reaction could lead, by neutron evaporation to  $^{25}Mg$ , and by  $\alpha n$  to Neon isotopes (the  $\alpha$  particle is only bound by 6.2 MeV in  $^{18}O$ ). However, the  $^{16}O + ^{14}C$  measurement rules out such a

hypothesis because we obtained, within the experimental errors, exactly the same cross sections as in the  $^{18}\text{O} + ^{12}\text{C}$  reaction for each Mg isotope and also for each Neon isotope.

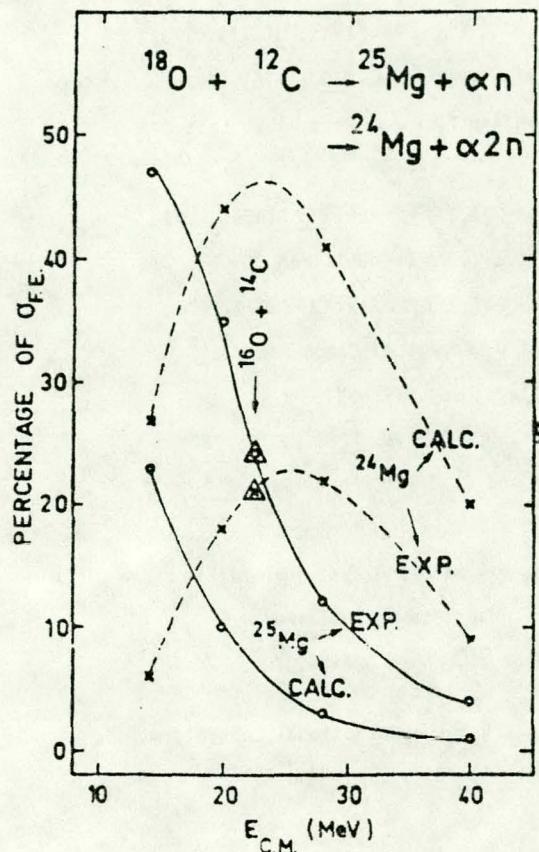


Fig. 5 : Comparison between experimental and predicted cross-sections for  $^{24}\text{Mg}$  and  $^{25}\text{Mg}$  versus center of mass bombarding energy.

One can also look at all these results by analysing how the increasing angular momenta are evacuated when the energy is increased. On Fig. 6 are presented very recent results of calculations by Abe and Haas <sup>11</sup> who count the number of all open channels available per unit of flux versus the grazing angular momenta. Also plotted are the level densities for the grazing angular momentum  $J_g$ ,  $J_g - 1$  and  $J_g - 2$ , corresponding to the minimum of the first curve. In fact these 3 contributions dominate, at each energy, the total reaction cross-section. One observes also that, for  $^{18}\text{O} + ^{12}\text{C}$ , in

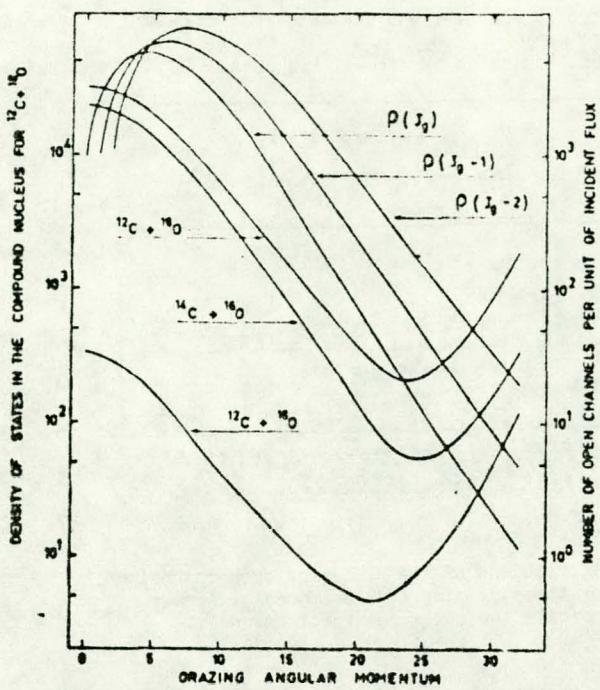


Fig. 6 : Calculated density of states in the compound nucleus  $^{30}\text{Si}$  for the three indicated grazing angular momenta. The number of open channels versus  $J_g$  is also reported for the three indicated reactions.

the energy range considered here, the number of open channels able to evacuate the grazing angular momenta is nearly a factor 100 higher compared to  $^{18}\text{O} + ^{12}\text{C}$ . This explains the absence of resonant structure in the  $^{18}\text{O} + ^{12}\text{C}$  fusion channels. Moreover, the cross section for the Mg isotopes follows closely the decrease of the available channels. At the highest energies ( $E_{\text{c.m.}} = 40$  MeV corresponds to  $\varepsilon_g = 24$  h) the calculations show that the compound nucleus cannot absorb the highest angular momenta and in fact one observes experimentally the large increase of the direct components. On Fig. 7 are presented for 3 angular momenta the corresponding distributions of the number of open channels. This figure is a very nice illustration of the competition between the different possible outgoing channels and illustrates the main advantage of these non limitative calculations in the framework of the statistical model. At low energies ( $\varepsilon_g = 4$ ) neutron channels dominate

whereas at high energy the 5 strong direct channels we observed (indicated by arrows) are open.

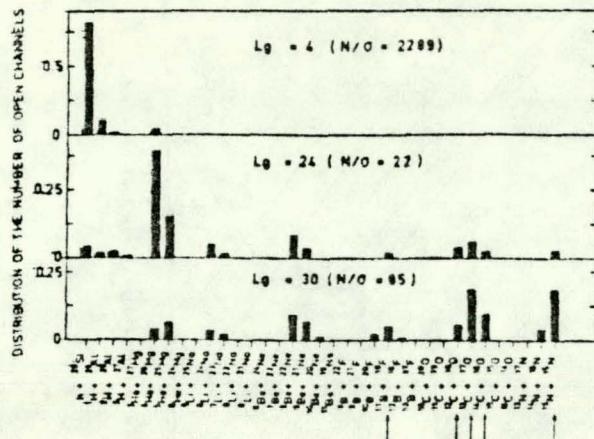


Fig. 7 : Distribution of the number of open channels for three grazing angular momenta. Arrows indicate the observed direct channels.

As it is shown in the table, 5 different reactions leading to  $^{30}\text{Si}$  as compound nucleus can be used to check entrance channel effects, due either to 0

Reaction leading to $^{30}\text{Si}$ as C.N.	Mass Excess (MeV)	Channel-spin	Lowest binding energy (MeV)
$^{18}\text{O} + ^{12}\text{C}$	- 0.8	0	$\alpha : 6.2$
$^{17}\text{O} + ^{13}\text{C}$	+ 2.3	3	$n : 4.9$
$^{16}\text{O} + ^{14}\text{C}$	- 1.7	0	$\alpha : 7.2$
$^{15}\text{N} + ^{15}\text{N}$	+ 0.2	1	$p : 10.2$
$^{19}\text{F} + ^{11}\text{B}$	+ 7.2	2	$\alpha : 4.0$

effects and/or channel spin effects. Conjeaud et al.<sup>12</sup> in Saclay have compared the total fusion cross-sections for  $^{18}\text{O} + ^{12}\text{C}$  and  $^{17}\text{O} + ^{13}\text{C}$  : the differences for the extracted critical angular momenta reflect exactly the mass excess differences. Therefore it will be also interesting to look for an eventual channel spin effect for this system. Such a complete study is also a good check for incomplete fusion processes. At least at one energy we have shown that such reaction mechanism cannot account

for the measured spectra but it is also clear that exclusive measurements will be necessary.

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