FUSION CROSS SECTIONS FOR THE $^{16}\text{O}+^{16}\text{O}$ REACTION

B. FERNANDEZ*, C. GAARDE, J. S. LARSEN, S. PONTOPPIDAN and F. VIDEBAEK
The Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen Ø, Denmark

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Abstract: The fusion cross section for the $^{16}\text{O}+^{16}\text{O}$ reaction has been measured with a time-of-flight technique at energies $E_{\text{lab}} = 35, 45, 52, 60, 70$ and $80$ MeV. Excitation functions for the total fusion and for the individual evaporation residues have been deduced from one-angle measurements of mass yields as a function of energy by normalizing to the energies given above. The $^{16}\text{O}+^{12}\text{C}$ reaction has been studied by the same method at energies of $45, 52, 70$ and $80$ MeV, and fusion cross sections and mass distributions are given. Small amplitude oscillations are observed in the fusion cross section for the $^{16}\text{O}+^{16}\text{O}$ reaction and are explained as effects of the individual grazing angular momenta. The measured fusion cross section is compared with a TDHF calculation of this quantity. A possible low angular momentum cut for fusion as predicted by the TDHF calculation is examined.

NUCLEAR REACTIONS $^{16}\text{O}, ^{12}\text{C}(^{16}\text{O}, X), E = 35-80$ MeV: measured $\sigma(E, \theta), E = 35, 45, 52, 60, 70, 80$ MeV, $\sigma(E, 7.5^\circ) 35 \leq E \leq 70$ MeV, $\sigma(E, 6^\circ) 70 \leq E \leq 80$ MeV; deduced fusion $\sigma(E)$.

1. Introduction

Light heavy ion fusion has for some years received considerable attention. These lighter systems are on the one hand complex enough to show trends of the heavier systems, but on the other hand they exhibit some specific features which are not yet completely understood: (a) the maximum fusion cross section can vary appreciably between systems which differ by only a few nucleons, and (b) oscillations have been observed in the fusion cross sections for some reactions: $^{12}\text{C}+^{12}\text{C}$ and $^{16}\text{O}+^{12}\text{C}$.

However, while the reactions $^{12}\text{C}+^{12}\text{C}$ and $^{16}\text{O}+^{12}\text{C}$ are experimentally well studied and reported in the literature, this is not the case for the $^{16}\text{O}+^{16}\text{O}$ reaction. Only recently have measurements of the fusion cross section above the barrier been reported $^1,^2$). In the latter paper a $\gamma$-yield technique is used with the usual problems of different accuracy and sensitivity for the different final nuclei. The technique is, however, very useful for measurements of excitation functions, and results of such measurements are reported in the energy interval $E_{\text{lab}} = 25$ to $60$ MeV. Small

* Permanent address: CEN, Saclay, France.
amplitude oscillations with a period of 3.5 MeV (c.m.) are observed in the 2π channel, and this being the strongest channel also in the total fusion cross section.

It is an interesting question whether the oscillations are of the same nature as the oscillations observed in the reactions involving 12C [refs. 3, 4]. We should in this connection point to the difference observed for these reactions below the Coulomb barrier with narrow resonances for e.g. the 12C + 12C reaction 5), but not for the 16O + 16O reaction 6).

Another interesting aspect of this reaction is the recent development of realistic three-dimensional time-dependent Hartree-Fock calculations 7). The simple models one has to work with could be especially valid for this system. The fusion cross section as function of energy is an aspect of the calculation which is relatively well defined. The data for this reaction are therefore important for testing these calculations.

The TDHF calculations predict a low cut in the angular momenta that leads to fusion. This “bouncing off” for the smallest impact parameters starts already at an energy of 0.83 MeV/A corresponding to \( E_{\text{lab}} = 54 \) MeV, and at 80 MeV only \( l > 10 \) leads to fusion – an interesting prediction.

We should in this connection point to the relatively high energy for this system one can reach with tandem accelerators. At e.g. \( E_{\text{lab}} = 80 \) MeV we see that \( E_{\text{c.m.}}/B \approx 4 \), and the energy per nucleon available (above the Coulomb barrier) is around 1 MeV/A.

In the present experiment we have measured the fusion cross section with a time-of-flight technique for the 16O + 16O reaction from \( E_{\text{lab}} = 35 \) to 80 MeV. We have extracted excitation functions for individual masses of the evaporation residues in this energy interval. We believe that our cross sections are accurate to about 5 %. In obtaining this accuracy we have corrected for the carbon present in the target.

We have therefore also measured the fusion cross section and mass distribution for the 16O + 12C reaction. We have extended the data on the fusion cross section for this reaction up to 80 MeV 16O energy, corresponding to \( E_{\text{c.m.}} = 34.3 \) MeV.

2. Experimental procedure

The beams of 16O in the energy region from 35 to 80 MeV were supplied by the super FN tandem accelerator at the Niels Bohr Institute. The outgoing products were measured in a time-of-flight setup.

The targets consisted of self-supporting TiO2 films obtained by the sputtering of TiO2 onto BaCl2 coated glass plates 8). The TiO2 was pressed into 1 cm³ blocks and the sputter beam (Ar) was defocused and moved continuously over the TiO2 surface to avoid local heating. The sputtering of a set of targets lasted as long as 12 h and a significant part of the carbon contamination came during sputtering. The target thickness ranged from 120–180 \( \mu g/cm² \). The carbon targets used in the experiments were around 50 \( \mu g/cm² \).

The TiO2 targets were very stable, i.e. the ratio between Ti and O was found to
be constant for a given target to a level of 1%. This was tested directly by measuring the elastic yield at a given angle and energy at the beginning and at the end of fusion cross section measurements. It was tested indirectly by the amount of Ti and O obtained from optical model fits to the elastic data with the same target at different energies. Including all targets and all energies the ratio Ti:O was found to be 1:(1.93 ± 0.02).

The beam is led into the scattering chamber through a 1 cm diameter tube which is part of a liquid nitrogen trap. Another cold trap is placed just above the target to reduce carbon build-up during the experiments.

The slit system consisted of 3 sets of slits yielding a final beam spot of 1 × 1 mm². The smallness of the slits causes, however, problems in an experiment where the energy spectra studied are continuous. This problem is discussed below.

The details of the time-of-flight setup are described in ref. 9). The particles to be detected pass a thin carbon foil (≈ 5 μg/cm²). Electrons produced by this passage are amplified in a channel plate resulting in a charge pulse 0.7 nsec wide and typically 0.2 V. This signal is eventually amplified and then used in a front trigger discriminator to get the stop signal for a time-to-amplitude converter. The flight path is 63 cm and the stop detector is a 100 mm² Si surface-barrier detector over-biased by 200 % and thermoelectrically cooled to -10 °C to obtain optimum energy.

Fig. 1. Contour plot of two-dimensional $E$ versus $E_{\text{ch}}$ spectrum for a TiO₂ target. The lowest contour represents 0.25 count per channel. The vertical line through the elastic peak originates from accidental coincidences giving rise to incorrect time-of-flight signals. The line going diagonally from the origin to the elastic peak is caused by pile-up in the stop detector giving incorrect energy signals. Contributions to the tail in $A = 16$ are discussed in sect. 3 in the text.
and time resolution. The signal is split into a voltage-sensitive preamplifier (timing) and a charge-sensitive preamplifier (energy). Typical time resolution was 200 psec and the energy resolution was 200–300 keV.

The angle and solid angle defining aperture is a 9 mm diameter hole in front of the solid-state detector placed 72 cm from the target. This corresponds to a solid angle of 0.1 msr and the large distance also results in a well defined scattering angle, $\Delta \theta \approx 0.05^\circ$.

The resulting energy and time signals were digitized and processed using an RC 4000 computer. Two-dimensional mass ($A \propto E t^2$) versus energy spectra were formed on-line. Fig. 1 shows a contour plot of such a spectrum and in fig. 2 is given the projection onto the mass axis of this spectrum. The projection covers the mass range $A = 18–31$ and the energy range $E = 0–75$ MeV (to avoid the accidental coincidences). Examples of projections on the energy axis are shown in figs. 4 and 13. The resulting mass resolution is around 0.5 mass unit when no energy restriction is imposed and the mass distribution can be obtained from such projections. At the lowest bombarding energy the different mass yields are extracted from the two-
dimensional spectra. This is because the mass lines for the heavy evaporation residues at low energies (≈ 5 MeV) bend over because the full energy is not recorded, an effect we ascribe to a reduced electric field in the surface of the solid-state detector.

The total fusion cross sections are based on measurement from 4° to 30° in varying angular steps, whereas the excitation functions are obtained from spectra at an angle $\theta = 7.5°$ up to 70 MeV and at $\theta = 6.0°$ from 70–80 MeV.

The yields in the angular distributions were normalized to the elastic yield measured in a monitor detector at $\theta = 27°$. The absolute cross sections were obtained from optical model fits to the simultaneously measured elastic yields.

As a further check of the consistency of the data the fusion cross section for the $^{16}\text{O} + ^{16}\text{O}$ reaction was remeasured at bombarding energies of 60 and 80 MeV with Al$_2$O$_3$ targets. These were prepared by anodizing an Al foil and thereafter desolving the remaining Al in a solution of 1% HCl in alcohol. The thickness was around 50 $\mu$g/cm$^2$. With the Al$_2$O$_3$ target the elastic data at forward angles are more difficult to extract and the absolute normalization is therefore based on elastic scattering for O and Al calculated with the optical parameters determined with the TiO$_2$ target. The errors in the fusion cross section are therefore not independent of the results from the TiO$_2$ target but with this in mind the fusion cross section and mass distributions are reproduced within the uncertainty, as shown in table 2 and fig. 7.

3. Experimental results

Angular distributions for masses with $A \geq 12$ were measured from $\theta_{\text{lab}} = 4°$ to 30° for the $^{16}\text{O} + ^{16}\text{O}$ reaction at bombarding energies of 35, 45, 52, 60, 70 and 80 MeV. Further, the excitation function for the fusion yield at $\theta_{\text{lab}} = 7.5°$ was obtained from 35 to 70 MeV in steps of 1 MeV and at 6° from 70 to 80 MeV in steps of 2 MeV.

From the $^{16}\text{O} + ^{12}\text{C}$ reaction we have similar angular distributions at 45, 52, 70 and 80 MeV, whereas the data at 35 MeV are only for four angles. The excitation function covers in this case 60–70 MeV at $\theta = 7.5°$ and 70–80 MeV at $\theta = 6°$.

Fig. 3 depicts the angular distributions at the highest and lowest bombarding energies for the evaporation residues in units of b/rad which means that the area under the curves represents the total fusion cross section. The total yield of the masses 21–32 is included while for $A = 20$ only a non-direct part contributes. The way the division is done is discussed below.

Energy and angular distributions of individual masses are characteristic of the process by which the evaporation residue is formed. This is illustrated in figs. 4 and 5. Fig. 5 shows the angular distributions of individual masses at a medium bombarding energy. The distributions are quite different whether three nucleons ($A = 29$), a mixture of one $\alpha$-particle and four nucleons ($A = 28$), one $\alpha$-particle and one nucleon ($A = 27$) or two $\alpha$-particles ($A = 24$) are emitted.
Fig. 3. Angular distributions for the sum of evaporation residues. The lines are drawn to guide the eye and used for calculation of the area, the total fusion cross section.

Fig. 4. Energy spectra for $A = 27$ at different angles indicating the preference of emission of the $\alpha$-particle at forward or backward angles.

Fig. 5. Angular distributions of individual evaporation residues.
Fig. 6. Elastic scattering angular distributions. At $E_{cm} = 26$ and 35 MeV two and three independent measurements, respectively, are shown with different symbols. The full drawn curves correspond to set 1 in table 1 for the optical model parameters. The hashed curve is calculated with parameters set 2. In the dotted curve at $E_{cm} = 35$ and 40 MeV the imaginary term is increased for the set 1 from 3.9 to 5.0 MeV at 35 MeV and from 4.4 to 5.6 MeV at $E_{cm} = 40$ MeV. At $E_{cm} = 30$ MeV, $\theta_{cm} = 15^o$ was measured as the first and repeated as the last angle at this energy. The figure shows the agreement.

### Table 1

<table>
<thead>
<tr>
<th>Set</th>
<th>$V$ (MeV)</th>
<th>$r_x$ (fm)</th>
<th>$a_x$ (fm)</th>
<th>$W$ (MeV)</th>
<th>$r_1$ (fm)</th>
<th>$a_1$ (fm)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$12 + 0.25 E_{cm}$</td>
<td>1.35</td>
<td>0.49</td>
<td>$0.4 + 0.1 E_{cm}$</td>
<td>1.35</td>
<td>0.49</td>
<td>$^{10}$)</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>1.35</td>
<td>0.49</td>
<td>$0.8 + 0.2 E_{cm}$</td>
<td>1.27</td>
<td>0.15</td>
<td>$^{11})$</td>
</tr>
<tr>
<td>3</td>
<td>$7.5 + 0.4 E_{cm}$</td>
<td>1.35</td>
<td>0.45</td>
<td>$0.4 + 0.125 E_{cm}$</td>
<td>1.35</td>
<td>0.45</td>
<td>$^{27})$</td>
</tr>
</tbody>
</table>

The elastic scattering and reaction cross section for sets 1 and 2 are shown in figs. 6 and 7. Set 3 is used for the absolute normalization at $\theta_{lab} = 4^o$ and $5^o$ for the $^{16}$O+$^{12}$C reaction.
The absolute cross section scale is determined from optical model fits to the elastic scattering data. For the $^{16}$O + $^{16}$O reaction this scale is dependent on the optical parameters chosen, because at the very forward angles the $^{16}$O peak cannot be separated from the Ti peak. The elastic angular distributions are shown in fig. 6. Also shown are calculated cross sections using different optical model parameters. The full drawn curves are based on parameters from ref. 10) (set 1 in table 1). At 26 and 30 MeV cross sections calculated with parameters from ref. 11) (set 2 in table 1) are shown as the dashed curves. The effect of increasing the imaginary potential in the former potential from 3.9 to 5.0 MeV at 35 MeV and from 4.4 to 5.6 MeV at $E_{\text{c.m.}} = 40$ MeV is illustrated by the dotted curves for $E_{\text{c.m.}} = 35$ and 40 MeV.

It is seen that the potential from ref. 10) modified with an increased imaginary depth accounts well for the data, whereas the potential from ref. 11) does not. Attempts were made for fixed $r_R$ and $a_R$ to vary $V$ around the value given in set 1 with the conclusion that the energy dependence needed to fit the present data is one very close to $V = 12 + 0.25 E_{\text{c.m.}}$ MeV, as of ref. 10).

In establishing the absolute cross section scale the angle definition is important. This is especially the case in the present experiment where the forward angle data are used to avoid as much as possible the dependence on optical model calculations. A systematic change in scattering angle of 0.05° is observed to change the qualities of fits for energy spectra as well as for the elastic scattering on Ti.

We conclude that the absolute cross section scale is determined from elastic scattering with an accuracy of 2 %. E.g., the normalization constant obtained from fitting all the 12 data points at 52 MeV is determined with a standard deviation of 1.3 %.

For the $^{16}$O + $^{12}$C reaction these problems do not arise since the elastic yields can be extracted at $\theta_{\text{lab}} = 4^\circ$ and 5° where the dependence on optical parameters is small.

The tail in the beam mentioned above has to be taken into account to get the absolute cross section. The energy spectra of the evaporation residues are continuous and it is therefore impossible to distinguish between evaporation residues produced by particles in the energy tail of the beam and those of full energy. The tail in the $A = 16$ energy spectrum as shown in fig. 1 has been analyzed and it is found to contain, apart from real inelastic events, three major contributions: (i) A bump (around channel 450 in fig. 1) due to particles from the elastic peak losing energy in the grid of the start detector. The intensity of the bump is 3 % of the elastic peak, consistent with the 97 % transmission of the grid. (ii) A continuous tail from particles arriving at the target with energy less than the beam energy (mainly caused by the smallness of the slits). This part of the tail contained in some cases as much as 7 % of the intensity in the elastic peak. (iii) A continuous tail from particles not giving full energy signals in the stop detector (1–2 % of the elastic intensity). The correction in the fusion cross section has to be treated individually in the three cases and the
total correction ranged from \((2 \pm 1)\%\) to \((8 \pm 3)\%\) for 35 and 80 MeV bombarding energy respectively.

For the \(^{16}\text{O} + ^{16}\text{O}\) reaction the yields must be corrected for the \(^{12}\text{C}\) contaminant in the target. As mentioned above most of the carbon is built up during the making of the target and very little during the experiment. The correction for carbon is made in two ways. Angular distributions are extracted for masses that have large cross sections in the \(^{16}\text{O} + ^{12}\text{C}\) reaction and small in the \(^{16}\text{O} + ^{16}\text{O}\). This procedure is only possible with complete measurements for the \(^{16}\text{O} + ^{12}\text{C}\) reaction at the same bombarding energies. The carbon correction is also determined from the elastic carbon yield, but this procedure is often less accurate. The correction from carbon is generally smaller than 5\%\), except for 80 MeV. This energy is chosen to illustrate the way the correction is done (fig. 2). Mass 22 is seen to have a large cross section for the \(^{16}\text{O} + ^{12}\text{C}\) reaction and at this energy it is assumed that all mass 22 in the \(^{16}\text{O} + ^{16}\text{O}\) measurement is from the carbon contaminant. The energy spectra and angular distributions for mass 22 are consistent with this interpretation. The disadvantage in this procedure is that small amounts of \(M = 22\) from the \(^{16}\text{O} + ^{16}\text{O}\) reaction itself cannot be determined. The correction for carbon was in this case \((8.5 \pm 3)\%\).

The total fusion cross sections are given in table 2. For the \(^{16}\text{O} + ^{16}\text{O}\) reaction we included masses with \(A > 20\), and for \(A = 20\) the part of the energy spectrum corresponding to \(Q > -12\) MeV \((E_{\text{ex}} = 9.40\) MeV\). This division is guided by the shape of the spectrum for \(A = 20\). The mutual excitation of the \(2^+\) \((4.43\) MeV\) state in \(^{12}\text{C}\) and the \(4.97\) MeV state in \(^{20}\text{Ne}\) is seen as a peak in the spectra. In fig. 13 is shown the spectrum at \(\theta_{\text{lab}} = 5^\circ\) and angular distributions at 80 MeV.

### Table 2

Mass distributions and total fusion cross section for the \(^{16}\text{O} + ^{16}\text{O}\) reaction

<table>
<thead>
<tr>
<th>(E_{\text{lab}}) (MeV)</th>
<th>35</th>
<th>45</th>
<th>52</th>
<th>60</th>
<th>70</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A = 20)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>14± 7</td>
<td>40±10</td>
<td>96±10</td>
<td>140±14</td>
<td>158±15</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>164±10</td>
<td>352±18</td>
<td>366±18</td>
<td>340±20</td>
<td>252±14</td>
<td>168±12</td>
</tr>
<tr>
<td>25</td>
<td>5± 5</td>
<td>12± 6</td>
<td>86±10</td>
<td>197±15</td>
<td>278±15</td>
<td>288±15</td>
</tr>
<tr>
<td>26</td>
<td>51±15</td>
<td>379±20</td>
<td>382±20</td>
<td>243±15</td>
<td>128±10</td>
<td>70±10</td>
</tr>
<tr>
<td>27</td>
<td>30±10</td>
<td>26± 5</td>
<td>22± 7</td>
<td>23± 5</td>
<td>50± 5</td>
<td>79±10</td>
</tr>
<tr>
<td>28</td>
<td>36± 5</td>
<td>106±10</td>
<td>145±15</td>
<td>138±10</td>
<td>104±10</td>
<td>64±10</td>
</tr>
<tr>
<td>29</td>
<td>195±10</td>
<td>117±10</td>
<td>65± 7</td>
<td>25± 5</td>
<td>7± 2</td>
<td>2± 1</td>
</tr>
<tr>
<td>30</td>
<td>5± 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>765±35</td>
<td>1010±40</td>
<td>1120±40</td>
<td>1120±50</td>
<td>1125±55</td>
<td>1150±60</td>
</tr>
</tbody>
</table>

\(\sigma_{\text{fus}}\) (mb)  

\(1115 \pm 50^a\)  

\(1125 \pm 60^b\)

\(^a\) Numbers obtained with \(\text{Al}_2\text{O}_3\) targets.
TABLE 3
Comparison of mass distributions at $E_{c.m.} = 30$ MeV

<table>
<thead>
<tr>
<th>$E_{lab} = 60$ MeV</th>
<th>Kolata a) (mb)</th>
<th>Weidinger b) (mb)</th>
<th>Present (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A = 20$</td>
<td>93.7 ± 6.6</td>
<td>93 ± 16</td>
<td>96 ± 10</td>
</tr>
<tr>
<td>22</td>
<td>3.3 ± 1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>36.3 ± 2.5</td>
<td>7 ± 10</td>
<td>63 ± 8</td>
</tr>
<tr>
<td>24</td>
<td>323 ± 23</td>
<td>252 ± 24</td>
<td>340 ± 20</td>
</tr>
<tr>
<td>25</td>
<td>14.4 ± 1.6</td>
<td>197 ± 9</td>
<td>243 ± 15</td>
</tr>
<tr>
<td>26</td>
<td>75 ± 5</td>
<td>219 ± 25</td>
<td>197 ± 15</td>
</tr>
<tr>
<td>27</td>
<td>168 ± 13</td>
<td>197 ± 9</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>14.4 ± 1.6</td>
<td>25 ± 9</td>
<td>23 ± 5</td>
</tr>
<tr>
<td>29</td>
<td>112 ± 8</td>
<td>161 ± 19</td>
<td>138 ± 10</td>
</tr>
<tr>
<td>30</td>
<td>12 ± 2</td>
<td></td>
<td>25 ± 5</td>
</tr>
<tr>
<td>31</td>
<td>16 ± 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{fus}$ (mb)</td>
<td>851 ± 60</td>
<td>1017 ± 153</td>
<td>1120 ± 50</td>
</tr>
</tbody>
</table>

a) Ref. 2).  b) Ref. 1).  

Fig. 7. Excitation function for the total fusion cross section. The triangles represent full angular distributions with the error bars indicating the absolute magnitude of the uncertainty. The filled circles represent one-angle measurements with error bars only showing the relative uncertainty. The curves are optical model reaction cross sections corresponding to the curves in fig. 6.

For the $^{16}$O+$^{12}$C reaction the fusion cross section includes $A \geq 19$. The direct reaction contribution in e.g. $A = 20$, is negligible in this case. The $3\alpha$ channel is not included for this reaction as it is for the $^{16}$O+$^{16}$O reaction.

In fig. 7 the fusion yield is given at $\theta_{lab} = 7.5^\circ$ in steps of 1 MeV up to 70 MeV, and at $\theta_{lab} = 6^\circ$ from 70 to 80 MeV in steps of 2 MeV. The fusion yields are measured relative to the elastic Ti yield, and from a calculated elastic Ti cross section (parameters from ref. 12)) the relative cross section as function of energy is deduced.
Fig. 8. Excitation function for the fusion cross section for the $^{16}$O+$^{12}$C reaction. The filled points and the curve are taken from refs. 5, 13. In the present experiment complete angular distributions were obtained at $E_{\text{lab}} = 45, 52, 70$ and 80 MeV (large open triangles). The small open triangles represent one-angle measurements of fusion yields ($\theta_{\text{lab}} = 7.5^\circ$ from 60 to 70 MeV and $\theta_{\text{lab}} = 6^\circ$ from 70 to 80 MeV). The cross sections given correspond to masses $A = 19$–$22$, and the $3\sigma$ channel is therefore not included.

Fig. 9. Mass distributions of evaporation residues from the $^{16}$O+$^{16}$O reaction. See also table 2 where errors are given. The thin bars at 45 and 70 MeV are calculated mass distributions.
The excitation function is then normalized to the cross sections determined from complete angular distributions. Therefore the assumption is that the yield at a particular angle relative to the total fusion yield changes slowly as a function of energy. The uncertainties in the data points are statistical only.

The results for $^{16}\text{O}+^{12}\text{C}$ of refs. 4,13) are shown in fig. 8 together with results from the present experiments.

Mass distributions have also been extracted from the spectra and angular distribution, as illustrated in figs. 2 and 5. The results are given in table 3 and figs. 9, 10 and 11. For the $^{16}\text{O}+^{12}\text{C}$ reaction the mass distribution at 35 MeV has large uncertainties because it is based on few angles, and was used to get an estimate on the carbon contamination for the $^{16}\text{O}+^{16}\text{O}$ reaction. The mass distribution at 60 MeV for $^{16}\text{O}+^{12}\text{C}$ is taken from ref. 1).

In fig. 11, the excitation functions are shown for the individual masses. As described above for the total fusion cross section the yields for the different masses are normalized at the energies where complete angular distributions are measured.
Fig. 11. Excitation functions of individual evaporation residues from the $^{16}\text{O} + ^{16}\text{O}$ reaction. The full drawn line represents the excitation function for $^{24}\text{Mg}$ measured by Kolata et al. 2).

The uncertainties are mainly statistical but also reflect the separation of the mass regions in the two-dimensional spectra.

From the same data we have also extracted the cross section at $\theta_{\text{lab}} = 7.5$ for the $^{16}\text{O}(^{16}\text{O}, ^{12}\text{C})^{20}\text{Ne}$ reaction to definite states in $^{12}\text{C}$ and $^{20}\text{Ne}$. The results are shown in fig. 12 which also shows part of the fusion cross section.
4. Discussion

4.1. THE $^{16}$O+$^{16}$O REACTION

4.1.1. Fusion and reaction cross sections. The results for the fusion cross section are shown in fig. 7 together with the calculated total reaction cross section. The fusion cross section is seen to increase up to $E_{\text{c.m.}}$ around 26 MeV and then to stay almost constant in the energy region studied. The maximal value for the fusion cross section of around 1125 mb is somewhat larger than expected from the general systematics observed for reactions involving nuclei in the p-shell.

In the region up to around $E_{\text{c.m.}} = 26$ MeV the fusion cross section accounts for about 90% of the calculated reaction cross section. This is confirmed in an experiment by Rossner et al. who find $\sigma_{\text{quas}} = 110$ mb for the transfer plus inelastic cross section. This value is averaged over energy (49 to 65 MeV) and a $1/\sin \theta$ angular distribution is assumed to calculate the cross section. They find as we do in the present experiment that only the $\alpha$-transfer channels and the inelastic channels give significant contributions to the total cross section. This is understood as a conse-
Fig. 13. Energy spectrum at $\theta_{\text{lab}} = 5^\circ$ for $A = 20$ and angular distributions for different sections of the energy spectra. The shapes are indicative of the separation between direct and compound reactions.

Figures 13 shows the energy spectrum at $\theta_{\text{lab}} = 5^\circ$ for $A = 20$ and angular distributions for different sections of the energy spectra. The shapes are indicative of the separation between direct and compound reactions.

Figures 13. Energy spectrum at $\theta_{\text{lab}} = 5^\circ$ for $A = 20$ and angular distributions for different sections of the energy spectra. The shapes are indicative of the separation between direct and compound reactions.

The sequence of the large negative $Q$-values for the one- and two-nucleon transfer reactions.

At $E_{\text{c.m.}} = 26$ MeV attempts were made to account for the total reaction cross section. The mass-12 yield is used instead of the mass-20 yield to determine the $^{16}\text{O}(^{16}\text{O}, ^{12}\text{C})^{20}\text{Ne}$ cross section in order to avoid subtracting the $A = 20$ contribution from the $^{16}\text{O} + ^{12}\text{C}$ fusion reaction. We find $\sigma_{^{12}\text{C}} \approx 45 \pm 8$ mb where the "less than" sign comes from the not specifically measured (but small) contribution from the Ti in the target. For the inelastic reaction the published angular distribution
in ref. \(^\text{14}\)) at \(E_{\text{c.m.}} = 25.75\ \text{MeV}\), and \(\theta_{\text{c.m.}} > 20^\circ\) is used to continue our measured inelastic cross section at \(E_{\text{c.m.}} = 26\ \text{MeV}\). We find \(\sigma_{\text{inel}} = 80 \pm 25\ \text{mb}\) with the large uncertainties caused by the rather poor background conditions we have in the \(A = 16\) spectrum.

Therefore \(\sigma_{\text{total,react}} = \sigma_{\text{fus}} + \sigma_{\text{QC}} + \sigma_{\text{inel}} = (1120 \pm 45) + (45 \pm 8) + (80 \pm 25)\ \text{mb} = 1245 \pm 55\ \text{mb}\) \([\sigma_R = 1230 \pm 55\ \text{mb}\] using the value from Rossner et al. \(^\text{14}\)) for the quasielastic cross section.

The calculated reaction cross section is 1230 mb at \(E_{\text{c.m.}} = 26\ \text{MeV}\) with the optical model parameters from ref. \(^\text{10}\)). These parameters describe well the elastic scattering as shown in fig. 6. The reaction cross section corresponding to the extremely surface-transparent potential with \(r_1 = 1.27\ \text{fm}, a_1 = 0.15\ \text{fm}\) \([\text{ref. 11}]\) gives \(\sigma_R = 1140\ \text{mb}\). This potential, however, does not describe the elastic data well, as also shown in fig. 6. We conclude that the measured total reaction cross section in the energy region \(E_{\text{c.m.}} = 25-30\ \text{MeV}\) is accounted for by the calculated \(\sigma_R\) consistent with the elastic scattering data.

At 80 MeV bombarding energy the one- and two-nucleon transfer cross sections are also small. As demonstrated in fig. 13 there seems to be a natural division in the mass 20 spectrum at \(E_{\text{ex}} \approx 20\ \text{MeV}\). The yield for \(0 \leq E_{\text{ex}} \leq 20\ \text{MeV}\) corresponds to a cross section of 44 mb which is ascribed to the transfer reaction \(^{16}\text{O}(^{16}\text{O},^{20}\text{Ne})^{12}\text{C}\). This cross section added to \(\sigma_{\text{fus}} = 1150\ \text{mb}\) gives \(1195 \pm 60\ \text{mb}\), whereas \(\sigma_R = 1450\ \text{mb}\) \((W = 4.4\ \text{MeV})\) or \(1486\ \text{mb}\) \((W = 5.6\ \text{MeV})\). That means that the remaining 250–300 mb is going into channels with masses 12 and 16 as final products. The present experiment cannot decide on the distribution on these two channels since the \(\text{Ti}(^{16}\text{O},^{12}\text{C})\) reactions give a contribution to the mass-12 spectra. In conclusion at 80 MeV bombarding energy there is a significant cross section into the inelastic channel eventually followed by \(\alpha\)-emission and three-body reactions (or both).

4.1.2. Comparison with other data. Weidinger et al. \(^\text{1}\)) have measured the fusion cross section at \(E_{\text{c.m.}} = 30\ \text{MeV}\) in a time-of-flight experiment. They find \(\sigma_{\text{fus}} = 1000 \pm 150\ \text{mb}\) whereas the present experiment gives \(1120 \pm 50\ \text{mb}\). The mass distributions are compared in table 3.

The two sets of data agree fairly well with the exception of the cross section for \(A = 23\). Weidinger et al. correct for carbon contamination of the target by assuming that all \(A = 25\) is from carbon, whereas we claim (from the angular distribution of \(A = 25\)) that part of \(A = 25\) is from \(^{16}\text{O}\). A carbon correction that is too large would decrease the cross section for \(A = 23\) (figs. 9 and 10).

Kolata et al. \(^\text{2}\)) have measured the \(\gamma\)-ray yield from the \(^{16}\text{O} + ^{16}\text{O}\) reaction, between 12.5 and 30.5 MeV c.m. energy. The fusion cross section is determined from the sum of yields for the different final nuclei. At \(E_{\text{c.m.}} = 30\ \text{MeV}\) they find \(850 \pm 60\ \text{mb}\), a significant discrepancy from our value. By comparison of the excitation function for \(A = 24\) with that of \(^{24}\text{Mg}\) (shown as a solid curve in fig. 11), a striking similarity in the variations with energy is seen. At \(E_{\text{c.m.}} = 30\ \text{MeV}\) the difference in absolute value is less than 2%. The mass distributions are summarized in table 3 from which is
seen that the $\gamma$-ray fusion cross section differs especially for $A = 26$. The mass distributions from a time-of-flight measurement are based on spectra as shown in fig. 2, and it is difficult to make mistakes in the relative cross sections whereas a $\gamma$-ray technique is dependent on a detailed knowledge on decay modes for the different final nuclei. The angular distribution for a final product with $A = 26$ is very different for the $^{16}\text{O} + ^{12}\text{C}$ and the $^{16}\text{O} + ^{16}\text{O}$ reactions, making the assignment of the present cross section unambiguous.

### Table 4

Mass distributions and fusion cross sections for the $^{16}\text{O} + ^{12}\text{C}$ reaction

<table>
<thead>
<tr>
<th>$E_{\text{lab}}$ (MeV)</th>
<th>35</th>
<th>45</th>
<th>52</th>
<th>70</th>
<th>80</th>
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<tr>
<td>$E_{\text{c.m.}}$ (MeV)</td>
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$\sigma_{\text{fus}}$ (mb)

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The numbers for $E_{\text{lab}} = 35$ MeV are based on only four measured angles resulting in large uncertainties.

Recently, measurements of the fusion cross section for the $^{16}\text{O} + ^{16}\text{O}$ reaction have been performed at Argonne National Laboratory in the energy range $E_{\text{lab}} = 30–60$ MeV [ref. 29]). A $\Delta E$-$E$ telescope with a thin $\Delta E$ detector is used in these experiments. The fusion cross sections do agree with the present data around $E_{\text{lab}} = 45$ MeV, but both at lower and higher energies the Argonne data give smaller cross sections. The discrepancy is at present not understood.

4.1.3. The nucleus-nucleus potential. The fusion cross section as function of energy can with certain assumptions be related to the nucleus-nucleus potential. Analyses of fusion data to establish such a relation have recently been made by Glas and Mosel 15), Bass 16) and Schröder and Huizenga 17).

Fig. 14 shows the results of analysis of the present data following the prescription given by Glas and Mosel 15). The figure illustrates the information that can be extracted from fusion data within such a model and the role of the uncertainties. It is assumed that friction can be neglected, an assumption that is questionable for distances where the nuclear potential is large. It is further assumed that fusion occurs for angular momenta from zero to $l_{\text{max}}$. In the model we discuss in the next section this is not the case.
A general problem in the analysis of fusion data as referred to above is the experimental definition of the cross section. In most experiments where only the evaporation residues or their $\gamma$-decay are observed, preequilibrium emission of particles followed by fusion of the rest of the system cannot be distinguished from normal fusion.

4.1.4. *Time-dependent Hartree-Fock calculation of the fusion cross section.* A three-dimensional TDHF calculation has been performed for the $^{16}\text{O} + ^{16}\text{O}$ reaction (7). The calculation is made with a single determinant and with symmetry restrictions corresponding to a picture of the scattering of two wave functions each describing four $\alpha$-particle like objects. A further symmetry through the c.m. restricts the system to stay symmetric also after the collision. The total binding energy and the surface energy are fairly well reproduced.

![Fig. 14. The $^{16}\text{O} + ^{16}\text{O}$ nuclear+Coulomb potentials are shown together with two sets of values $V(R)$ extracted from the data in fig. 7 using the expression $\sigma_{\text{int}} = \pi R^2 (1 - V(R)/E_{\text{c.m.}})$. The nuclear potentials are: the real part of the optical potential, set 2 of table 1 (dotted), the proximity potential (dashed) and a potential calculated by Zint and Mosel (dot-dash). Also shown (filled circle) is a point calculated from systematics of elastic data (Christensen and Winther) (20).]
For a given bombarding energy and impact parameter the reaction is defined as leading to fusion if the system sticks together for more than $2 \times 10^{-2}$ sec.

The results are shown in fig. 15, and it is seen that the calculations with no adjustable parameters reproduce the overall shape and magnitude of the measured fusion cross section. An interesting aspect of this calculation is that at sufficiently high energy ($E_{\text{c.m.}} > 27$ MeV) the two ions "bounce off" for the small impact parameters against an inner barrier of dynamical origin. E.g., at $E_{\text{c.m.}} = 40$ MeV the impact parameters corresponding to $0 < l < 10$ should lead to inelastic scattering (in this model). In fact, the results of the TDHF calculations are consistent with a picture with a critical distance for both the high and low $l$-cuts (up to $E_{\text{c.m.}} = 40$ MeV).

The agreement with the experimental results is therefore dependent on the existence of the low $l$-cut. We shall comment on this question below.

![Fig. 15](image-url)

Fig. 15. As a function of $1/E_{\text{c.m.}}$ we show the fusion cross section measured and calculated by a TDHF method $^1$). The curve is the calculated reaction cross section.

4.1.5. Oscillations in the fusion cross section. In subsect. 4.1.2, we have pointed to the striking similarities in the excitation function for $^{24}\text{Mg}$ from a $\gamma$-experiment $^2$) and for $A = 24$ from the present TOF experiment, fig. 11. We therefore conclude that the variations of the fusion cross section with energy are real. Fig. 7 shows that also the calculated reaction cross section exhibits oscillations that are seen to be in phase with the measured fusion cross section.
The calculations show that the oscillations observed in the (calculated) cross section are due to the contribution from the different partial waves. In this light system of identical particles the spacing between the energies at which the different (even) partial waves become grazing is large. Furthermore, the absorption suggested by the elastic data is small and one therefore sees the effect of each partial wave separately. The oscillations at e.g. 38, 45 and 52 MeV are in this way related to the angular momenta \( l = 14, 16 \) and \( 18\hbar \) becoming the grazing angular momenta at these energies.

Also the excitation function for the individual masses exhibits oscillations. The \( A = 24 \) has already been mentioned. In fig. 12 is shown the excitation function for some specific transitions in the direct \((^{16}\text{O}, \text{ }^{12}\text{C})\) reaction. The very pronounced resonance around 52 MeV has been observed previously \(^{21}\) and is seen to coincide with the onset of the \( l = 18\hbar \) partial wave. We have attempted to calculate the direct cross section for the transitions in question as a function of bombarding energy. We have used the code DWUCK \(^{22}\) and treated the \( \alpha \)-transfer in a zero-range and no-recoil approximation. We only observed a small effect in the calculated excitation function, but cannot exclude the failure to explain the resonance as due to the simplicity of the reaction model.

It is further seen from fig. 11 that there might be an effect in \( A = 27 \) around 52 MeV. The yield for \( A = 28 \) is too small relative to \( A = 27 \) and 29 to extract an excitation function for \( A = 28 \).

We conclude that the pronounced oscillations seen in the total fusion cross section, in the \( 2\alpha \) channel \((A = 24)\) and in the direct \( \alpha \)-transfer channel seem to be related to particular angular momenta in the entrance channel. In the energy region where oscillations are observed the highest spins in the compound nucleus are expected to decay by \( 2\alpha \) emission and the highest spins correspond to grazing partial waves.

4.1.6. Decay of the compound nucleus. The mass distributions are shown in fig. 9 together with calculated mass distributions at 45 and 70 MeV. These calculations have been made with the evaporation code GROGI \(^2\), ref. \(^{23}\), with parameters \( a = A/7.5 \text{ MeV}^{-1}, J = J_{\text{rigid}} \) with \( r_0 = 1.20 \text{ fm} \) and \( \delta = 1.2 \) and 2.4 MeV for odd-\( A \) and doubly even nuclei, respectively. The initial compound population was calculated from transmission coefficients from the optical model and including angular momenta up to some maximal value as to correspond to the measured fusion cross section.

No attempt to fit the measured mass distributions was made, but a fair agreement is obtained as demonstrated in fig. 9. In this mass region some data do exist on the level density parameter, but the data refer to low spin states. We have also used such parameters \(^{24}\), but obtained a poorer agreement with the data.

In particular the yields in the \( 3\alpha \) channel are much smaller than the measured values. For this channel the inclusion of the low-lying levels in the final nucleus would increase the calculated yields. We have not attempted such a procedure.
The calculations show that at 80 MeV bombarding energy the first \( \alpha \)-particle is emitted so as to leave \( ^{28}\text{Si} \) at an average \( E_{\text{ex}} \) of 31 MeV and with average angular momentum of \( 9\hbar \). This corresponds rather well to the compound system \( ^{28}\text{Si} \) obtained from \( ^{16}\text{O} + ^{12}\text{C} \) at 35 MeV \( ^{16}\text{O} \) bombarding energy. The difference merely being that the energy is sharp.

We see in comparing figs. 9 and 10 that except for \( A = 25 \) the two mass distributions \( ^{16}\text{O} + ^{16}\text{O} \) (80 MeV) and \( ^{16}\text{O} + ^{12}\text{C} \) (35 MeV) do look quite similar, indicating that a compound picture with statistical decay seems relevant for the decay of \( ^{28}\text{Si} \) formed by \( ^{16}\text{O} + ^{12}\text{C} \) (at fairly low bombarding energy) or by \( \alpha \)-decay of \( ^{32}\text{S} \) at high excitation energy.

4.1.7. Low \( l \)-cut. Test of TDHF prediction. The TDHF calculation predicts a low \( l \)-cut of \( 10\hbar \) at 80 MeV corresponding to 200 mb. We have tried to test this aspect of the calculation.

In fig. 16 is shown schematically the population and decay of the compound nucleus \( ^{32}\text{S} \) as formed at 80 MeV bombarding energy. The statistical calculation shows that

![Figure 16](image-url)

Fig. 16. The figure schematically shows the initial population and the proton (dotted) and \( \alpha \) (dashed) decay of the compound nucleus \( ^{32}\text{S} \). The effect of a low \( l \)-cut at \( l = 10\hbar \) is given by the dashed-dotted curve. Also shown are contour lines in the daughter nuclei \( ^{31}\text{P} \) and \( ^{28}\text{Si} \) where the population cross section is half the maximum value.
the high angular momenta decay by α-emission from an average spin $I_s^{(32S)}$ of 18ℏ ending up in $^{28}\text{Si}$ at $E_{\text{ex}} \approx 31$ MeV and $I_{\text{ssSi}} \approx 9$ℏ. Protons are emitted from the low spin states with an average $I_p^{(32S)} \approx 10$ℏ ending up in $^{31}\text{P}$ at $E_{\text{ex}} \approx 38$ MeV and $I_{\text{sp}} \approx 9$ℏ. The ratio between α, p and neutron decay is calculated to be 808:255:87, corresponding to the sum $\sigma_{\text{fus}} = 1150$ mb.

The figure shows that a low cut of 10ℏ in the spin distribution would have a major effect on the ratio between α and nucleon emission.

In the experiment the masses 29, 30 and 31 must be the result of nucleon emission in the first step of the particle emission. Also $A = 28$ is above 60 MeV bombarding energy the result of four-nucleon emission. This is quite obvious from the angular distribution of $A = 28$. In fig. 17 we show the cross section for masses 28–31 as function of energy. For $A = 28$ the 1α emission is excluded at $E_{\text{lab}} = 45$ and 52 MeV. This division of $A = 28$ will only make a small contribution to the error on the cross section for the sum of the masses.

This sum can be calculated as the cross section for emitting a nucleon in the first decay minus the cross section for emitting α-particles in the further decay. The calculations show, however, that this latter cross section is very small and uncertainties in this correction do not influence strongly the calculated yield of masses 28–31.

![Fig. 17. The measured cross section for the masses 28–31 (for $A = 28$ only the four-nucleon part) together with calculated cross sections with different parameters for the first step of the decay of $^{32}\text{S}$. The dotted curve is calculated with the adjusted $\sigma(^{28}\text{Si})$ value and with a low l-cut as given by the TDHF calculation of ref. 7).](image)
The results of such calculations are shown in fig. 17. The standard values as given above for $a$, $\delta$ and moment of inertia lead to a calculated cross section more than 50% too high.

The ratio between nucleon and $\alpha$ emission was also calculated with parameters corresponding to a liquid drop model. It is assumed that at sufficient excitation energy (above the yrast line) a liquid drop description is adequate. The effective excitation energy relevant for calculation of the level density is then obtained by subtracting pair and shell corrections. These corrections are taken as the difference between the experimental mass and the spherical liquid drop mass $^{25}$. Such a procedure has recently been discussed by Pühlhofer $^{26}$.

The nucleon-$\alpha$ ratio calculated in this picture gives much poorer agreement with the data than the standard parameters shown in fig. 17. We do not conclude from this that the picture is not relevant as other effects could be important, e.g. a difference in deformation for the two daughter nuclei. This could have a significant effect on the level density.

We have next tried to change the $a$-value for $^{28}$Si as to fit the experimental value for $\sigma_{28-31}$ at 45 MeV bombarding energy and calculate $\sigma_{28-31}$ at the higher energies. The change in $a$ for $^{28}$Si (from the standard value $a = A/7.5$) is as small as 10% (increase) to get a 50% change in $\sigma_{28-31}$. As the last step of the calculation a cut in spin is introduced as predicted by the TDHF calculations.

It should be pointed out that in this procedure we are not dependent (or at least only indirectly through the nucleon-$\alpha$ correction) on details for levels in the final nuclei but only on the constancy of ratios between $a_{31_p} : a_{28_{Si}}$ for the density of states 10 to 25 MeV above the yrast line.

It is seen from fig. 16 that a low $l$-cut at $E_{c.m.} = 40$ MeV of 10$h$ decreases the nucleon emission by more than a factor of 2. This is also illustrated in fig. 17 in the decrease of the calculated cross section for masses 28–31. Very little is, however, known about the level density far from the yrast line which makes it difficult alone from the yield of masses 28–31 to make firm conclusions on the existence of a low $l$-cut.

Another question is the importance of non-statistical processes. A pre-equilibrium emission of a nucleon (from the low non-fusing partial waves) followed by the fusion of the rest of the system would lead to a mass distribution similar to that from a normal fusion reaction. Such a nucleon emission channel is not included in the TDHF calculations of ref. $^{7}$.

4.2. THE $^{16}$O+$^{12}$C REACTION

In fig. 8 is shown the total fusion cross section for the $^{16}$O+$^{12}$C reaction together with data from refs. $^{4,13}$. We observe a good agreement with the measurements at 45 and 52 MeV bombarding but do not observe the decrease in cross section at 63 MeV ($E_{c.m.} \approx 27$ MeV). It can be concluded that the fairly large oscillations observed at lower energy do not seem to be present at higher energies.
TABLE 5
Cross sections for different channels for the $^{16}$O + $^{16}$O reaction together with calculated total reaction cross sections

<table>
<thead>
<tr>
<th>$E_{lab}$ (MeV)</th>
<th>$\sigma_{inl}$ (mb)</th>
<th>$\sigma^{^{16}$O, $^{12}$C} (mb)</th>
<th>$\sigma_{inel}$ (mb)</th>
<th>$\sigma_{g}$ (calc) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>1120 ± 45</td>
<td>45 ± 8</td>
<td>80 ± 25</td>
<td>1230</td>
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<tr>
<td>80</td>
<td>1150 ± 60</td>
<td>44 ± 5</td>
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<td>1450 ($W = 4.4$ MeV)</td>
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<td>1486 ($W = 5.6$ MeV)</td>
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The measured mass distributions are shown in fig. 10. The figure demonstrates especially when compared with the corresponding mass distribution for $^{16}$O + $^{16}$O that the emission of 3$\alpha$ particles could be a strong channel. It is, however, difficult experimentally to distinguish between the $^{16}$O evaporation residues and $^{16}$O ions from other reactions. So from 60 to 80 MeV bombarding energy we do not expect to have the full fusion cross section as given in fig. 8. It has not been attempted to calculate the 3$\alpha$ contribution with the rather limited success for the similar problem in the $^{16}$O + $^{16}$O reaction.

5. Summary

In the present study accurate measurements of the fusion cross section and mass distributions for the $^{16}$O + $^{16}$O reaction have been made at energies 35, 45, 52, 60, 70 and 80 MeV with a time-of-flight technique. Excitation functions for the total fusion and for the individual masses have been deduced from one-angle measurements of mass yields as function of energy by normalizing at the energies mentioned above.

The $^{16}$O + $^{12}$C reaction has been studied by the same method at energies 45, 52, 70 and 80 MeV, and fusion cross sections and mass distributions were determined.

For the $^{16}$O + $^{16}$O reaction we find small amplitude oscillations in the fusion cross section. These variations seem closely related to similar oscillations in the total reaction cross section. This latter quantity is calculated with optical model parameter that gives excellent fits to the measured elastic yields. In the calculated $\sigma_{g}$ we understand the oscillations as effects of the individual (even) angular momenta.

We only with certainty observe oscillations in the 2$\alpha$ channel and the ($^{16}$O, $^{12}$C) reaction and in both cases this can be explained as an effect of the grazing angular momenta.

At $E_{lab} = 52$ MeV, the total reaction cross section is accounted for within the accuracy (5 %) of the measurement.

We have at two energies calculated the mass distribution in a statistical model. We have not tried to fit the measured distributions but standard parameters reproduce the general trends of the data.
We have further tried to test the prediction of TDHF as to a possible low cut in the angular momenta leading to fusion. We are, however, too dependent on parameters in the statistical model to make firm statements on such a cut in I. The analysis points to a significant lower cut than predicted but we have pointed to the possibility of this low cut not showing up in the mass distributions for the heavy evaporation residues because of preequilibrium nucleons.

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