Lawrence Berkeley National Laboratory
Recent Work

Title
STUDY OF INCOMPLETE FUSION FOR LIGHT HEAVY-ION SYSTEMS USING VELOCITY DISTRIBUTIONS

Permalink
https://escholarship.org/uc/item/5qw992dz

Author
Chan, Y.

Publication Date
1986-03-01
Submitted at the Symposium on the Many Facets of Heavy-Ion Fusion Reactions, Argonne, IL, March 24-26, 1986

STUDY OF INCOMPLETE FUSION FOR LIGHT HEAVY-ION SYSTEMS USING VELOCITY DISTRIBUTIONS

Y. Chan, C. Albiston, M. Bantel, A. Budzanowski, D. DiGregorio, R.G. Stokstad, S. Wald, S. Zhou, and Z. Zhou

March 1986

TWO-WEEK LOAN COPY
This is a Library Circulating Copy which may be borrowed for two weeks.

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098
DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.
Study of incomplete fusion for light heavy-ion systems using velocity distributions†

Y. Chan, C. Albiston, M. Bantel, A. Budzanowski, D. DiGregorio, R.G. Stokstad, S. Walda, S. Zhou, Z. Zhou

Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, Ca.94720.

† Work supported under DOE contracts DE-AC03-76SF00098 and DE-AM03-76SF000325. Presented at the "Symposium on the many facets of heavy-ion fusion", Argonne National Laboratory, Illinois, 1986.

a Present address: The Max-Planck Institute, Heidelberg, West Germany.
b Present address: Institute for Nuclear Physics, Cracow, Poland.
c Present address: Tandar, Buenos Aires, Argentina.
d Present address: The Weizmann Institute, Rehovot, Israel.
e Present address: The Institute of Atomic Energy, Beijing, China.
f Present address: Physics Department, Nanking University, Nanjing, China.
Study of incomplete fusion for light heavy-ion systems using velocity distributions‡

Y. Chan, C. Albiton, M. Bantel, A. Budzansowski, D. DiGregorio, R.G. Stokstad, S. Wald, S. Zhou, Z. Zhou

Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, Ca.94720.

1. Introduction

The fusion between two light heavy-ions to form a medium mass compound nucleus ($A_{CN}\leq 80$) has been an active area of research in the past two decades. Our present understanding of this subject is shown schematically in Fig.1. Of general interest is the high energy region [3] where the fission barrier of the compound nucleus diminishes and the question of whether a compound nucleus can still be populated and how it behaves at such high excitation energies remain relatively unexplored.

A notorious experimental problem in this energy domain is the identification of complete fusion processes. In fact, answers to various questions of current interest, such as limiting mechanisms for fusion, maximum possible compound nucleus temperature, incomplete fusion dynamics, as well as pre-compound and complex fragment emission etc., to a large extent depends very much on one's ability to identify complete fusion processes when they occur.

The present talk will discuss experimental results on incomplete fusion for light systems by studying the velocity distribution of fusion-like residues in the energy range of 6-20 MeV.

‡ Work supported under DOE contracts DE-AC03-76SF00098 and DE-AM03-76SF000326. Presented at the "Symposium on the many facets of heavy-ion fusion", Argonne National Laboratory, Illinois, 1986.

‡ Work supported under DOE contracts DE-AC03-76SF00098 and DE-AM03-76SF000326. Presented at the "Symposium on the many facets of heavy-ion fusion", Argonne National Laboratory, Illinois, 1986.
MeV/nucleon. Besides our own measurement, results from other groups, including the pioneering works done at the Hahn-Meitner Institute and the Argonne National Laboratory, are also cited.

It should be pointed out that the identification of fusion residues by their velocity distribution is an old and well known method. The significance of these more recent measurements lies in that (i) the experiments were performed with higher precision (typically with an absolute velocity determination ~ 0.1 cm/ns) and (ii) they cover a large number of systems and bombarding energies. The large data base enables one to address questions such as the global behavior of complete versus incomplete fusion, which is the main topic of this talk.

2. Complete fusion, incomplete fusion, and fusion-residue-like products

At bombarding energies not too far above the interaction barrier, the complete fusion of heavy-ions comprises a dominant part of the total reaction cross section. A complete fusion event is characterized by full linear momentum transfer to the target and the formation of an equilibrated compound nucleus. Residues are final remnants of this highly excited parent nucleus which decays statistically via the emission of light particles (γ, n, p, d, t, 3He, α etc.) and possibly complex fragments. Further increase of the bombarding energy induces a variety of other reaction mechanisms such as pre-compound emission, massive-transfer, break-up fusion etc., which could also lead to residue-like products. We shall refer to these as incomplete fusion processes.

Unlike situation at much higher bombarding energies, the residue-like products in our measurement are quite well separated from the beam and are easily identifiable. Fig.2(a) shows an energy versus mass spectrum for particles detected at Θ_{LAB} = 12° for the "^{40}Ca + ^{16}O" reaction at 19.6 MeV/nucleon, corresponding to a compound nucleus temperature of 5.8 MeV. It can be seen that in addition to a continuous population of masses, there is a concentrated residue-like group with masses lying between A ~ 30 - 45 amu. However, this group as a whole does not behave like normal residues resulting from a complete fusion process. The observed mass distribution is wider in comparison with evaporation model predictions (with skewness towards the lower mass region), and has a substantially wider angular distribution than expected (Fig.2(b) and (c)). It is obvious that more detailed decomposition of this group is necessary before any meaningful comparison with theoretical models could be made.

3. Identification of complete fusion by the method of velocity centroids

One advantage of the lighter mass heavy-ion systems is that the large recoil velocity of the parent emitter makes precise kinematical measurements of the heavy residues possible. The experimental method is based on the assertion that the velocity of a compound nucleus
Fig. 2 (a) Experimental mass distribution for residue-like products. Observed mass yield (b) and (c) angular distribution for the residue-like group compared with evaporation model calculations.
prior to its decay can be determined by studying the velocity distribution (for instance, the Galilean-invariant \( \frac{1}{v^2}d^2\sigma/dv_0 \)) of the final residues. This is mainly due to the fact that a compound nucleus decays statistically with equal probability for emitting particles in the forward and backward directions (symmetric about 90°) in its rest frame. Consequently the velocities of the residues are strongly correlated with that of the initial parent velocity. In fact, if the residues are detected at 0°, then the centroid of the invariant velocity spectrum is exactly equal to the compound nucleus velocity, \( V_{CN} \), regardless of the actual spectrum shape.

By comparing the differences between the empirically measured parent emitter velocity, \( V_{obs} \), to that of the expected velocity for complete fusion, \( V_{CM} \), one can learn about the relative importance of incomplete fusion contributions.

In the specific case of isotropic emission in the rest frame of the emitter, analytical expressions for the velocity spectra as well as the location of the centroids can be derived. Gomez del Campo et al. have shown that in this case the shape of the invariant velocity spectra is a simple gaussian centered at

\[
<v> = V_{CN}\cos\Theta
\]

where \( V_{CN} \) is the initial compound nucleus velocity and \( \Theta \) is the detection angle in the laboratory.

This can be readily understood geometrically as shown in Fig.3. The laboratory detection angle defines a plane in the velocity space about which the velocity spectrum in the laboratory has reflectional symmetry. The distance of this plane to the origin is given by \( V_{CN}\cos\Theta \). The centroids are independent of the residue masses in this case and the quantity of interest, \( R = V_{obs}/V_{CN} \), is equal to \( <v>/V_{CN}\cos\Theta \). Here \( <v> \) is the empirical centroid of the invariant velocity spectrum. This assumption is expected to be valid at high bombarding energies where a large number of particles are emitted and many different decay paths can lead to the same final nuclei.

A significant contribution to velocity peakshape analysis (including anisotropic emission) comes from the HMI group. By carefully studying the shapes of the velocity spectra at low energies where there is only complete fusion, and guided by particle emission sequences calculated by evaporation codes, Morgenstern et al. have established a semi-empirical basis for
spectrum decomposition. They suggest that for nucleon emission one should use peakshapes of
the form

\[
\frac{1}{v^2} \frac{d^2\sigma}{dvd\Omega} \propto \exp\left(\frac{\left(v - V_p \cos\Theta\right)^2 + V_p^2 \sin^2\Theta}{2s_A^2}\right) \times \left[\frac{\sqrt{\left(v - V_p \cos\Theta\right)^2 + V_p^2 \sin^2\Theta}}{vsin\Theta}\right]
\]

where \(v, V_p\) and \(\Theta\) are the residue velocity, parent emitter velocity, and detection angle in the
laboratory respectively. The width parameter \(s_A\) reflects the dynamics of the de-excitation
process. This shape corresponds to a Maxwellian emitter with a \(1/sin\Theta_{CM}\) angular distribution
in the center of mass frame. For \(\alpha\)-particle emission, an extra parameter \(V_\alpha\) is introduced and
the exponent is replaced by

\[
\exp\left(\frac{\left[\sqrt{(v - V_p \cos\Theta)^2 + V_p^2 \sin^2\Theta} - V_\alpha\right]^2}{2s_A^2}\right)
\]

Fig.4 shows some typical residue invariant velocity spectra at both low and high bombarding
energies. Generally speaking, the spectra at high energies are very broad and structureless. It
turns out that the centroid velocity shifts at these energies are also quite large that uncertain­
ties due to different peakshape analysis procedures are not significant. One must exercise
cau­tion in the low energy domain, however, where probably the most reliable peakshapes are
those directly generated from Monte-Carlo evaporation codes.

The effective parent velocities in this report were obtained by assuming a single com­
ponent peakshape of the form :

\[
\frac{1}{v^2} \frac{d^2\sigma}{dvd\Omega} \propto \exp\left(\frac{\left(v - V_p \cos\Theta\right)^2 + V_p^2 \sin^2\Theta}{2s_A^2}\right) \times \left[\frac{\sqrt{\left(v - V_p \cos\Theta\right)^2 + V_p^2 \sin^2\Theta}}{vsin\Theta}\right]^{n_A}
\]

This corresponds to a \([1/sin\Theta_{CM}]^{n_A}\) angular distribution in the center of mass. \(V_p, s_A\) and \(n_A\)
are fitting parameters with the latter being constrained to take on values between \(0 \leq n_A \leq 1\).
In most cases, the best fit results for \(n_A\) are quite small (i.e. closer to the isotropic limit \(n_A =
0\) at high energies.

4. Experiment

Reactions between \(^{14}\text{N}\), \(^{16}\text{O}\), \(^{19}\text{F}\), \(^{20}\text{Ne}\) projectiles and \(^{26}\text{Mg}\), \(^{27}\text{Al}\), \(^{28}\text{Si}\), \(^{40}\text{Ca}\), \(^{58,60}\text{Ni}\) tar­
ggets have been studied in the bombarding energy range of 7-20MeV/nucleon (Table 1). The
Fig. 4 Examples of experimental residue velocity spectra. (a) is taken from Ref. 10, (b) present work for $^{20}\text{Ne} + ^{26}\text{Mg}$ at 11 MeV/nucleon, and (c) is taken from Kovar et al., Ref. 18.
experiments were performed at the 88-inch Cyclotron of the Lawrence Berkeley Laboratory.

Time-of-flight techniques were used to measure the velocities of the residue-like products directly. The main advantages of the TOF measurements are:

(i) Low cutoff threshold.

By using very thin carbon conversion foils (≤ 10 μg/cm²) for the start channel plate detector in combination with a thin target, one can detect residues with very slow velocities.

(ii) Very precise and accurate measurements can be made by using, if necessary, long flight paths.

The major drawback is the very small solid angle one has to deal with, in particular in coincidence experiments.

In order to measure the absolute laboratory velocities of the residue-like products, an accurate calibration of the velocity scale is crucial. To obtain the initial velocities of the residues, corrections for energy loss in the target and channel plate carbon foils were made.

5. General behavior of the observed velocity shifts

Several important features of the observed velocity-centroid shifts are summarized in the following:

(A) Residue mass dependence

For a given reaction and bombarding energy, the centroid shift increases slightly with lower residue masses. Fig.5 shows the general behavior of the velocity centroids as a function of the observed residue masses for ¹⁶O+⁴⁰Ca, ¹⁹F+⁴⁰Ca, and ²⁰Ne+⁴⁰Ca at different energies. This is somewhat what expected if several thermal parent species are present. For E/A>8MeV/nucleon, even the highest masses show noticeable centroid shifts. This may be due to the fact that the parent nuclei populated by incomplete fusion, with mass A_InCF < A_CN, are lower in excitation energy and evaporate less particles. Consequently the final residue mass distributions are similar to and mix strongly with those from complete fusion.

Fig.5 Velocity centroid difference for different reactions as a function of the observed fragment mass.
Table 1. List of reactions studied in this work.

<table>
<thead>
<tr>
<th>$V_{\text{loc}}$ (cm/ns)</th>
<th>$&lt;R&gt;$ (%)</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.89</td>
<td>$^{24}\text{Mg} + ^{24}\text{Mg}$</td>
</tr>
<tr>
<td>2</td>
<td>3.02</td>
<td>$^{19}\text{F} + ^{58}\text{Ni}$</td>
</tr>
<tr>
<td>3</td>
<td>3.13</td>
<td>$^{19}\text{F} + ^{40}\text{Ca}$</td>
</tr>
<tr>
<td>4</td>
<td>3.22</td>
<td>$^{19}\text{F} + ^{28}\text{Si}$</td>
</tr>
<tr>
<td>5</td>
<td>3.24</td>
<td>$^{20}\text{Ne} + ^{40}\text{Ca}$</td>
</tr>
<tr>
<td>6</td>
<td>3.25</td>
<td>$^{19}\text{F} + ^{27}\text{Al}$</td>
</tr>
<tr>
<td>7</td>
<td>3.34</td>
<td>$^{20}\text{Ne} + ^{24}\text{Mg}$</td>
</tr>
<tr>
<td>8</td>
<td>3.56</td>
<td>$^{16}\text{O} + ^{27}\text{Al}$</td>
</tr>
<tr>
<td>9</td>
<td>3.68</td>
<td>$^{16}\text{O} + ^{40}\text{Ca}$</td>
</tr>
<tr>
<td>10</td>
<td>3.73</td>
<td>$^{19}\text{F} + ^{58}\text{Ni}$</td>
</tr>
<tr>
<td>11</td>
<td>3.81</td>
<td>$^{19}\text{F} + ^{40}\text{Ca}$</td>
</tr>
<tr>
<td>12</td>
<td>3.89</td>
<td>$^{19}\text{F} + ^{28}\text{Si}$</td>
</tr>
<tr>
<td>13</td>
<td>3.92</td>
<td>$^{19}\text{F} + ^{27}\text{Al}$</td>
</tr>
<tr>
<td>14</td>
<td>4.10</td>
<td>$^{20}\text{Ne} + ^{24}\text{Mg}$</td>
</tr>
<tr>
<td>15</td>
<td>4.11</td>
<td>$^{21}\text{Ne} + ^{26}\text{Mg}$</td>
</tr>
<tr>
<td>16</td>
<td>4.13</td>
<td>$^{14}\text{N} + ^{38}\text{Ni}$</td>
</tr>
<tr>
<td>17</td>
<td>4.21</td>
<td>$^{20}\text{Ne} + ^{24}\text{Mg}$</td>
</tr>
<tr>
<td>18</td>
<td>4.23</td>
<td>$^{20}\text{Ne} + ^{26}\text{Mg}$</td>
</tr>
<tr>
<td>19</td>
<td>4.23</td>
<td>$^{14}\text{N} + ^{40}\text{Ca}$</td>
</tr>
<tr>
<td>20</td>
<td>4.31</td>
<td>$^{14}\text{N} + ^{28}\text{Si}$</td>
</tr>
<tr>
<td>21</td>
<td>4.34</td>
<td>$^{14}\text{N} + ^{27}\text{Al}$</td>
</tr>
<tr>
<td>22</td>
<td>4.36</td>
<td>$^{20}\text{Ne} + ^{38}\text{Ni}$</td>
</tr>
<tr>
<td>23</td>
<td>4.45</td>
<td>$^{20}\text{Ne} + ^{40}\text{Ca}$</td>
</tr>
<tr>
<td>24</td>
<td>4.53</td>
<td>$^{20}\text{Ne} + ^{27}\text{Al}$</td>
</tr>
<tr>
<td>25</td>
<td>4.57</td>
<td>$^{20}\text{Ne} + ^{26}\text{Mg}$</td>
</tr>
<tr>
<td>26</td>
<td>4.60</td>
<td>$^{16}\text{O} + ^{60}\text{Ni}$</td>
</tr>
<tr>
<td>27</td>
<td>4.68</td>
<td>$^{16}\text{O} + ^{40}\text{Ca}$</td>
</tr>
<tr>
<td>28</td>
<td>4.78</td>
<td>$^{16}\text{O} + ^{27}\text{Al}$</td>
</tr>
<tr>
<td>29</td>
<td>4.84</td>
<td>$^{14}\text{N} + ^{40}\text{Ca}$</td>
</tr>
<tr>
<td>30</td>
<td>5.43</td>
<td>$^{14}\text{N} + ^{58}\text{Ni}$</td>
</tr>
<tr>
<td>31</td>
<td>5.50</td>
<td>$^{14}\text{N} + ^{40}\text{Ca}$</td>
</tr>
<tr>
<td>32</td>
<td>5.73</td>
<td>$^{16}\text{O} + ^{27}\text{Al}$</td>
</tr>
<tr>
<td>33</td>
<td>5.80</td>
<td>$^{16}\text{O} + ^{40}\text{Ca}$</td>
</tr>
<tr>
<td>34</td>
<td>5.87</td>
<td>$^{16}\text{O} + ^{60}\text{Ni}$</td>
</tr>
</tbody>
</table>

Fig. 6 Observed mass-averaged velocity ratio for different reactions. The data points are numbered according to Table 1.
(B) Angular dependence

In certain cases, the velocity shift also increases slightly with larger laboratory detection angles.

(C) An apparent threshold behavior

Fig. 6 shows a plot of the mass-averaged velocity ratio \( <R> \) against the local relative velocity of the reactants at the barrier,

\[
V_{\text{loc}} = \sqrt{\frac{2(E_{\text{cm}} - V_C) + V_C}{\mu}}
\]

where \( V_C \) is the Coulomb energy in the c.m. system with \( r_{\text{coul}} = 1.45 \text{ fm} \). It is quite clear from this plot that the deviation of \( <R> \) from the nominal value of 1.0 (complete fusion) increases with increasing bombarding energy for all systems. This is expected as the incomplete fusion contributions are becoming more prominent at higher bombarding energy. The deviation from complete fusion appears to have an approximate threshold at about 5 MeV/nucleon above the Coulomb barrier and varies almost linearly with \( V_{\text{loc}} \). By fitting a straight line through the data points, the following threshold and slope parameters are obtained:

\[
R = 1 - \beta (V_{\text{loc}} - V_{\text{th}}) \quad \text{for} \quad V_{\text{loc}} \geq V_{\text{th}}
\]

\[
\beta = 0.08 \text{ (ns/cm)}
\]

\[
V_{\text{th}} = 3.54 \text{ (cm/ns)}
\]

One should expect a smooth rather than a sharp transition in the threshold region. It would be very interesting to understand the meaning of the threshold and slope of this graph in terms of macroscopic dynamical models or from nucleon-nucleon interaction considerations.

The positive value of \( \beta \) implies that for these reactions the escaped particles are predominantly originated from the lighter projectile rather than the target.

(D) Projectile dependence

It is possible that structural particle thresholds of the projectile play an important role in the incomplete fusion mechanism. To see how this is reflected in our data, Fig. 7 shows the excitation functions for different projectiles (\( ^{14}N, \quad ^{16}O, \quad \text{and} \quad ^{20}Ne \)) on the same \( ^{40}Ca \) target. Within errors there are no drastic differences between these reactions. In fact, for \( ^{14}N + ^{40}Ca \), where the projectile is not an \( \alpha \)-cluster nucleus and has a low threshold for proton emission, the excitation function displays similar strong fall-off as for the \( ^{16}O \) and \( ^{20}Ne \) projectiles. This indicates that the particle-emission threshold of the individual projectiles is not the most dominating factor in determining the likelihood of the occurrence of incomplete fusion, but other dynamical factors such as the successful capture of the projectile remnant, kinematical matching conditions etc., can be of equal importance. Still another possibility is that individual
Fig. 7 Comparison of velocity ratios induced by different projectiles on the same target.

Fig. 8 Velocity ratio for different mass asymmetry entrance channels.

Fig. 9 Comparison of fusion cross section for different entrance channels populating the same compound nucleus for: (a) CN = $^{56}$Ni, Ref. 5 and (b) CN = $^{59}$Cu, Ref. 6.
nucleon-nucleon interaction plays a very important role in these processes.

(E) Entrance channel dependence

There is evidence that the observed velocity shift depends on the mass asymmetry of the entrance channel. Fig. 8 shows a comparison between the $^{20}\text{Ne} + ^{26}\text{Mg}$ and the $^{14}\text{N} + ^{40}\text{Ca}$ reactions corresponding to $\eta = 0.13$ and 0.48, where $\eta \equiv (A_T - A_P)/(A_T + A_P)$ is the mass asymmetry parameter. It is quite clear from this figure that the former reaction, which is more symmetric with respect to the projectile and target masses, exhibits a smaller velocity shift at comparable $v_{loc}$ than the other one. A more direct evidence of this comes from the comparison of different entrance channels populating the same compound nucleus. Fig. 9(a) and 9(b) show such comparisons for the $^{56}\text{Ni}$ ($^{16}\text{O} + ^{40}\text{Ca}, ^{28}\text{Si} + ^{28}\text{Si}$) and $^{59}\text{Cu}$ ($^{19}\text{F} + ^{40}\text{Ca}, ^{32}\text{S} + ^{27}\text{Al}$) systems taken from the works of Kovar et al.\textsuperscript{5} and Rosner et al.\textsuperscript{6} These authors conclude that incomplete fusion is more important for asymmetric entrance channels.

Another important observation\textsuperscript{7} is that for systems with $A_P > A_T$, for instance, $^{40}\text{Ar} + ^{12}\text{C}$, the observed centroid shifts are always positive, i.e., $V_{obs} > V_{CM}$. Together with (C) this implies that there is a larger probability for the missing mass coming from the lighter reactant.

(F) The width parameter $s_A$

Fig. 10 shows the extracted width parameter, $s_A$, for the residue velocity spectra plotted against the observed residue masses. It varies from 0.15 cm/ns for the heavier residues to 0.6 cm/ns for the lighter ones. On the average, the increment in $s_A$ is about 0.13 cm/ns per evaporated nucleon mass. It is more difficult to compare these numbers to evaporation model predictions since the differences tend to be small and sensitive to the input parameters of the code.

8. The $v_L$ systematics of incomplete fusion

Linear momentum transfer study for heavy, fissile systems has indicated that the local contact velocity of the projectile and target at the barrier, $v_{loc}$, is a useful parameter for systematic comparison\textsuperscript{8}. Some earlier works\textsuperscript{9} for light systems also adopted this approach.

One significant result from the velocity measurements is that the escaped particles are preferentially originated from the lighter reactant. This fact, not contained in the context of $v_{loc}$, should be included.

A very interesting systematic parameter has been suggested by Morgenstern et al.\textsuperscript{10} Instead of $v_{loc}$, they consider the velocity of the lighter reactant in the center of mass, namely,

$$v_L = \frac{A_H}{A_H + A_L} v_{rel} \quad v_H = \frac{A_L}{A_H + A_L} v_{rel}$$
Widths of the observed Invariant Velocity Spectra.

Reactions:

- $^1$H + $^{36}$Ca 184 MeV [5°]
- $^1$H + $^{36}$Ca 184 MeV [12°]
- $^1$H + $^{84}$Ca 200 MeV [5°]
- $^1$H + $^{84}$Ca 160 MeV [5°]
- $^6$Ne + $^{100}$Mo 250 MeV [5°]
- $^7$Li + $^{32}$S 160 MeV [5°]
- $^7$Li + $^{32}$S 220 MeV [5°]
- $^7$Li + $^{32}$S 229 MeV [5°]
- $^7$Li + $^{32}$S 229 MeV [10°]
- $^7$Li + $^{32}$S 229 MeV [5°]


Fig. 10 Extracted width parameter $s_A$ for various reactions as a function of observed residue mass.
where $L$ and $H$ denotes the lighter and heavier reactant respectively. Notice that one always have $v_L > v_H$. Fig.11(a) shows a plot of $\sigma_{CF}/\sigma_{CF+ICF}$ as a function of $v_L$ taken from Ref.10. The experimental data populates a narrow domain instead of a single universal curve, and the more symmetric the entrance channel, the closer it lies to the upper boundary of the domain (i.e., less incomplete fusion) at comparable $v_L$.

Two important quantities can be deduced from this plot: (i) the onset energy (or relative velocity) for incomplete fusion to become significant and (ii) the upper limit where complete fusion vanishes. These values turn out to be\(^{10}\):

$$v_{onset}/c = 0.06 \pm 0.02$$
$$v_{limit}/c = 0.19 \pm 0.02.$$

where $c$ is the velocity of light. The latter number is found to be consistent with results obtained from linear momentum transfer study ($\text{LMT}_{\text{limit/nucleon}} \approx 180\text{MeV}/c$) for heavy systems at high bombarding energies\(^{11}\). The velocity ratios, $R$, of the present work and data taken from Stephans et al.\(^{12}\) are plotted against $v_L$ in Fig.11(b). In general, the same trend in mass asymmetry dependence is observed.

The well known systematics for heavy systems\(^{8}\) can be transformed easily to the $v_L$ scheme since for heavy targets, $v_L \rightarrow v_{rel}$.

7. Interpretation of the systematic behavior

How can one understand the general behavior of the incomplete fusion data? A valid model should be able to explain all features mentioned in Section 5, including the fact that the escaped particles come out preferentially from the lighter partner of the colliding nuclei. There are two approaches to this problem.

(i) Models\(^{10,12,13}\) based on promptly emitted nucleons.

The probability for nucleons escaping from the interaction region as a function of bombarding energy is assumed to be proportional to the non-overlapping portion(s) of the Fermi-spheres for the projectile and target nuclei in the momentum space. Vandenbosch\(^{13}\) has pointed out that the portion of the Fermi sphere of the projectile that lies outside the particle binding threshold of the target nucleus can escape without being captured. This non-overlapping volume is crudely proportional to the separation velocity of the center of the two spheres, for small $v_{loc}$. It is interesting to notice that in this picture, the slope of the $R$ vs. $v_{loc}$ curve (Fig.6) is related to the inverse of the Fermi-momentum and the threshold is given by the particle binding energy.
Fig. 11 (a) $V_L$-systematics plot taken from the work of Morgenstern et al. (Ref. 10) and (b) velocity ratios plotted against $v_L$ for the present work and data from Ref. 12.
Stephans et al.\textsuperscript{12} approached this problem by comparing the momentum overlap between the reactants and the compound nucleus instead. The basic idea is illustrated in Fig.12. For small $v_{\text{rel}}$, the momenta of the nucleons from both the light and heavy nuclei are well within the limits of the compound nucleus. With increasing $v_{\text{rel}}$ however, some nucleons will have momenta exceeding the compound nucleus Fermi-sphere. These nucleons can escape leading to incomplete fusion. A more precise construction of the Fermi spheres with realistic density parameters is shown in Fig.13(a) taken from Ref.12. By considering only nucleons escaping from the projectile the authors found good agreement with experimental data (Fig.13(b)). Of course there are no a priori reasons why nucleons originated from the target could be neglected.

More realistic Fermi-jet model calculation has been performed by Möhring et al.\textsuperscript{14} (Fig.14). Generally speaking, the calculation underpredicts the magnitude of the observed effect.

(ii) Binary reaction models

Another approach to understand the systematics is by considering conventional binary-transfer reactions. For a given entrance channel and bombarding energy, one can evaluate the primary cross section for all binary outgoing channels according to a certain reaction model. Massive-transfer processes leading to heavy primary fragments close to the compound nucleus mass are included as sources of the residue-like products. By assuming a known velocity and angular distribution of the primary nuclei, the weighted average velocity of the fragments can be calculated. This effective parent velocity is to be compared with the experimentally observed average emitter velocity. Both striping-like and pickup-like processes should be included.

Fig.15 shows such a comparison for the $^{14}\text{N}+^{40}\text{Ca}$ system. The primary binary cross sections are generated by the Wilczynski sum-rule model\textsuperscript{15} and the initial velocity of the heavy fragments are obtained by assuming the other partner travels with beam velocity along $0^\circ$. By using a relatively large $T$ parameter (5MeV) in the phase space factor,
Fig. 13 (a) Construction of the Fermi-spheres and (b) the fit to experimental data reproduced from Ref. 12.

Fig. 14 Comparison of simple Fermi-jet calculations with experimental data (Ref. 14).

Sum-rule Model Comparison

Fig. 15 Comparison of sum-rule model calculation and experimental data for $^{14}\text{N}+^{40}\text{Ca}$. Primary fragment masses included in the calculation are from A=32 to 54. The dashed curve is for T=2.5 MeV and the dotted curve is for T=5.0 MeV.
exp[−(Q_{gs}−Q_{c})/T], the behavior of the \(<v>/\nu_{CF}\) ratio at low to medium energies could be qualitatively reproduced. Above a certain bombarding energy, the calculated ratio remains constant in contrast to the behavior of the data. Since this model does not give any kinematics or angular distribution information, the comparison should be at best regarded as schematic. It would be desirable to have a macroscopic binary reaction model that can provide both cross section and energetics. The overlap-model of Harvey and Homeyer\(^{16}\) gives comparable results.

8. Coincidence measurements

There are relatively few exclusive measurements emphasizing on velocity distributions reported thus far. Most coincidence measurements attempt to identify the uncaptured particles associated with the incomplete fusion process. The work of Budzanowski et al.\(^{17}\) concludes that at 20 MeV/nucleon, on the average only half of the \(^{16}\)O projectile is captured by the \(^{40}\)Ca target. Kovar et al.\(^{18}\) have observed for the same reaction but at lower energies (8.5 MeV/nucleon) a strong correlation between both fast and thermal α-particles with the slower residue-like products. Both measurements however suffer from counting statistics. A more recent coincidence experiment for \(^{40}\)Ar+\(^{12}\)C at 8 MeV/nucleon (with much better statistics) reported by Morgenstern et al.\(^{19}\) concludes that the experimental data supports a binary massive-transfer type reaction mechanism rather than prompt nucleon emissions.

9. Summary

The residue velocity distribution approach has contributed a lot to our understanding\(^{18}\) of the high energy behavior of complete fusion for light heavy-ion systems. An interesting systematics for complete fusion versus incomplete fusion has been established\(^{10}\) based on the center of mass velocity of the lighter reactant. The mechanism responsible for this behavior, however, is still not clear. While the schematic nucleon Fermi-velocity models provide interesting insight into this problem, quantitative agreement with experimental data is still lacking. It is likely that only at the very high bombarding energies that fast nucleon emission can play an important role.

1. References :

16) B.G. Harvey et al., LBL preprint LBL-16882.
19) H. Morgenstern et al., "Study of the Reaction Mechanisms of Incomplete Fusion with the Reactions $^{40}$Ar+$^{11}$B, $^{12,13}$C at 7 MeV/amu " preprint HMI-P 86/1 R.

1. Tables

Table 1. List of reactions studied in the present work.
This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.