Complete Fusion of heavy nuclei or fusion mechanism
Contents

1. Models with adiabatic and diabatic potentials
2. Dynamics of fusion in the dinuclear system model
3. Quasifission as a signature for the dinuclear system
4. Summary and conclusions
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1. **Fusion models with adiabatic and diabatic potentials**

Main collective coordinates are used for the description of the fusion process:

1. Relative internuclear distance $R$

2. Mass (charge) asymmetry coordinate $\eta$

3. Neck parameter

4. Nuclear deformations
Models using adiabatic potentials

Minimization of potential energy, essentially adiabatic dynamics in the internuclear distance, nuclei melt together.

Large probabilities of fusion for producing nuclei with similar projectile and target nuclei.
fusion

touching configuration

entrance
quasifission

η

R
b) Dinuclear system (DNS) concept

Fusion by transfer of nucleons between the nuclei (idea of V. Volkov, also von Oertzen), mainly dynamics in mass asymmetry degree of freedom, use of diabatic potentials, e.g. calculated with the diabatic two-center shell model.

\[ \eta \to 1 \]
fusion

entrance quasifission

touching configuration

R

η 1
Idea of Volkov (Dubna) to describe fusion reactions with the dinuclear system concept:

Fusion is assumed as a transfer of nucleons (or clusters) from the lighter nucleus to the heavier one in a dinuclear configuration.

This process is describable with the mass asymmetry coordinate \( \eta = \frac{(A_1 - A_2)}{(A_1 + A_2)} \).

If \( A_1 \) or \( A_2 \) get small, then \( |\eta| \to 1 \) and the system fuses.
The dinuclear system model uses two main degrees of freedom to describe the fusion and quasifission processes:

1. **Relative motion** of nuclei, capture of target and projectile into dinuclear system, decay of the dinuclear system: quasifission

2. **Transfer of nucleons** between nuclei, change of mass and charge asymmetries leading to fusion and quasifission
3. **Dynamics of fusion in the dinuclear system model**

Evaporation residue cross section for the production of superheavy nuclei:

\[
\sigma_{ER}(E_{cm}, J) = \sum_{J=0}^{J_{max}} \sigma_{cap}(E_{cm}, J) P_{CN}(E_{cm}, J) W_{sur}(E_{cm}, J)
\]
a) Partial capture cross section $\sigma_{\text{cap}}$

Dinuclear system is formed at the initial stage of the reaction, kinetic energy is transferred into potential and excitation energy.

$V(R)$

$B_{\text{qf}}$ = barrier for quasifission

touching point

$R$
b) Probability for complete fusion $P_{CN}$

DNS evolves in mass asymmetry coordinate by diffusion processes toward fusion and in the relative coordinate toward the decay of the dinuclear system which is quasifission.

$B^*_{\text{fus}} = \text{inner fusion barrier}$
Competition between fusion and quasifission, both processes are treated simultaneously.

Calculation of $P_{CN}$ and mass and charge distributions in $\eta$ and $R$:

Fokker-Planck equation, master equations, Kramers approximation
Kramers formula for $P_{CN}$:

Rate for fusion: $\Lambda_{\eta \ fus}$

Rate for quasifission: $\Lambda_{qf} = \Lambda_R + \Lambda_{\eta \ sym}$, i.e. decay in R and diffusion in $\eta$ to more symmetric DNS.

$$
P_{CN} = \frac{\Lambda_{\eta \ fus}}{\Lambda_{\eta fus} + \Lambda_{qf}}
$$

$$
P_{CN} \sim \exp\left(-(B^*_{fus} - B_{qf})/kT\right)
$$

Cold fusion (Pb-based reactions): $\Lambda_R \ll \Lambda_{\eta sym}$

Hot fusion ($^{48}\text{Ca}$ projectiles): $\Lambda_R \gg \Lambda_{\eta sym}$
Importance of minima in the driving potential

Shell and deformation effects lead to local minima in \( V(\eta) \). In liquid drop model the mean value of \( \eta \) runs to symmetric fragmentation: \( \eta \rightarrow 0 \), then quasifission.

Minima in \( V(\eta) \) hinder motion to \( \eta \rightarrow 0 \), then larger probability for fusion.

Idea of A. Sandulescu and W. Greiner (1976) for optimum selection of target and projectile: choice of fragmentations in minima of \( V(\eta) \).
Example: $^{54}\text{Cr} + ^{208}\text{Pb} \rightarrow ^{262}\text{Sg}$

$B_{\text{sym}}^\eta = 3.6 \text{ MeV}$, $B_{\text{sym}}^{\text{sym}} = 5.7 \text{ MeV}$, $B_{\text{qf}} = 2.7 \text{ MeV}$

Dependence of fusion probability $P_{\text{CN}}$ on barrier height $B_{\text{sym}}^\eta$. 
$^{54}\text{Cr} + ^{208}\text{Pb} \rightarrow ^{262}\text{Sg}$
Optimum excitation energy for Pb-based fusion reactions

\[ E_{\text{CN}}^* = E_{\text{cm}} + Q \]
\[ \approx V(\eta) + B_{\text{fus}}^* \]
c) **Survival probability** $W_{\text{sur}}$

De-excitation of excited compound nucleus by neutron emission in competition with fission. Other decays ($\gamma$-, $\alpha$-decays) can be neglected.

For Pb-based reactions with emission of one neutron:

$$W_{\text{sur}}(E_{CN}^*, J) = P_{1n}(E_{CN}^*, J) \frac{\Gamma_n(E_{CN}^*, J)}{\Gamma_{tot}(E_{CN}^*, J)}$$

$$\Gamma_{tot} \approx \Gamma_n + \Gamma_f$$

$\Gamma_n$ = width for neutron emission

$\Gamma_f$ = fission width, $\Gamma_f \gg \Gamma_n$

$P_{1n}$ = probability of realisation of 1n channel
d) Results for cold and hot fusion reactions

**Cold reactions:** $^A_{Z} + ^{208}_{Pb} \rightarrow$ superheavy + n

<table>
<thead>
<tr>
<th>React.</th>
<th>Super-heavy</th>
<th>$E^*_{CN}$ (MeV)</th>
<th>$P_{CN}$</th>
<th>$\sigma_{cap}$ (mb)</th>
<th>$W_{sur}$</th>
<th>$\sigma_{ER}^{th}$</th>
<th>$\sigma_{ER}^{ex}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{50}<em>{Ti} + ^{208}</em>{Pb}$ + n</td>
<td>$^{257}_{104}$</td>
<td>16.1</td>
<td>3x10^{-2}</td>
<td>5.3</td>
<td>9x10^{-5}</td>
<td>14.3 nb</td>
<td>10 nb</td>
</tr>
<tr>
<td>$^{70}<em>{Zn} + ^{208}</em>{Pb}$ + n</td>
<td>$^{272}_{112}$</td>
<td>9.8</td>
<td>1x10^{-6}</td>
<td>3.0</td>
<td>6x10^{-4}</td>
<td>1.8 pb</td>
<td>0.5 pb</td>
</tr>
<tr>
<td>$^{86}<em>{Kr} + ^{208}</em>{Pb}$ + n</td>
<td>$^{293}_{118}$</td>
<td>13.3</td>
<td>1.5x10^{-10}</td>
<td>1.7</td>
<td>2x10^{-2}</td>
<td>5.1 fb</td>
<td>&lt; 0.5pb</td>
</tr>
</tbody>
</table>
\[ \text{ANi} + {}^{208}\text{Pb} \rightarrow 110 \]
$Z=114$
3. Quasifission as a signature for dinuclear systems
$E^*_{\text{CN}} = 42 \text{ MeV}$
$^{48}\text{Ca} + ^{244}\text{Cm}$ ▲
$E_{\text{cm}} = 207$ MeV

$^{48}\text{Ca} + ^{246}\text{Cm}$ ●
$E_{\text{cm}} = 205.5$ MeV

$^{48}\text{Ca} + ^{248}\text{Cm}$ ■
$E_{\text{cm}} = 204$ MeV
4. Summary and conclusions

- The concept of the nuclear molecule or dinuclear system describes nuclear structure phenomena connected with cluster structures, the fusion of heavy nuclei to superheavy nuclei, the competing quasifission and fission.

- The dynamics of the dinuclear system has two main degrees of freedom: the relative motion of the nuclei and the mass asymmetry degree of freedom.
- Superheavy nuclei are produced in heavy ion collisions in a process of three stages:
- (1) Capture of nuclei in a dinuclear system,
- (2) Fusion to compound nucleus by nucleon transfer between touching nuclei in competition with quasifission, which is the decay of the dinuclear system,
- (3) De-excitation of compound nucleus by neutron emission into the ground state of superheavy nucleus.
The dinuclear system has a repulsive, diabatic potential energy surface towards smaller internuclear distances. This potential hinders the nuclei to amalgamate directly.

The transfer of nucleons and the quasifission are statistical diffusion processes in the excited dinuclear system. They are described by Fokker-Planck or master equations or simply by the Kramers approximation. Fusion and quasifission are simultaneously treated.
A precise prediction of **optimum** production cross sections for superheavy nuclei can be obtained from the calculation of **isotopic series** of reactions. The cross sections depend sensitively on the interplay between fusion and survival probabilities.

For elements \( Z > 118 \) the production cross sections seem to be lower than 0.1 pb.