Damped Collisions of Heavy Ions.

Second Wind

• Dynamical model (DIC, fusion, fission, quasi-fission)

• Good agreement, at last!

• Neutron-rich superheavy nuclei

• Unexplored area of the nuclear map down the neutron shell N=126

• Summary
Low-energy collisions of HI and “nucleon rearrangement”

DI scattering, quasi-fission, fusion and regular fission are strongly overlapped processes (and very often indistinguishable).
Therefore one needs **simultaneous description** of all these processes.
At near barrier collisions “transfer” of 20, 30 nucleons is in fact “nucleon rearrangement”.

Unified degrees of freedom: \( R, \beta_1, \beta_2, \eta_Z, \eta_N \).
Unified set of dynamical equations: **Langevin type.**
What is behavior of valence nucleon at near-barrier collisions of HI?

Time-dependent Schrödinger equation shows that at low-energy collisions nucleons do not “jump” from one nucleus to another $<\psi_i(r_i)|\psi_k(r_k)>$. Wave functions of valence nucleons follow the two-center molecular states spreading over both nuclei.

Two-Center Shell Model and Adiabatic Potential Energy Surface are appropriate for description of such processes.
Time-dependent Driving Potential

\[ V_{\text{adiab}}(R, \beta_1, \beta_2, \eta, ...) = M_{\text{TCSM}}(R, \beta_1, \beta_2, \eta, ...) - M(\text{Proj}) - M(\text{Targ}) \]

\[ V_{\text{diab}}(R, \beta_1, \beta_2, \alpha, ...) = V_{12}^{\text{folding}}(Z_1, N_1, Z_2, N_2; R, \beta_1, \beta_2, ...) + M(A_1) + M(A_2) - M(\text{Proj}) - M(\text{Targ}) \]

\[ V_{\text{adiab}} \neq V_{\text{diab}} \quad \text{g.s.} \]

\[ V_{\text{adiab}} = V_{\text{diab}} \]

Potential energy (MeV)

Diabatic way

Adiabatic way

CN

248\text{Cm} + 48\text{Ca}

A_1

A_2

R (fm)

\[ V_{\text{adiab}}(R, \beta_1, \beta_2, \eta, ...) = M_{\text{TCSM}}(R, \beta_1, \beta_2, \eta, ...) - M(\text{Proj}) - M(\text{Targ}) \]

Time-dependent driving potential has to be used

\[ V(t) = V_{\text{diab}}(\xi) \cdot \exp(-\frac{t_{\text{int}}}{\tau_{\text{relax}}}) + V_{\text{adiab}}(\xi) \cdot [1 - \exp(-\frac{t_{\text{int}}}{\tau_{\text{relax}}})] \]

\[ \tau_{\text{relax}} \sim 10^{-21} \text{ s} \]

the same degrees of freedom (\( \xi = R, 0, \varphi_1, \varphi_2, \beta_1, \beta_2, \eta_Z, \eta_N \))!

All forces, \( F_i(t) = -\frac{\partial V}{\partial \xi_i} \), are quite smooth
System of coupled Langevin type Equations of Motion
Simulation of experiment and cross sections

\[
\frac{d^2\sigma_{Z\Lambda N}(E,\theta)}{d\Omega dE} = \int_0^\infty b db \frac{\Delta N_{Z\Lambda N}(b,E,\theta)}{N_{tot}(b)} \frac{1}{\sin(\theta)\Delta\theta\Delta E}
\]

Dynamics: \(10^6\) tested events (trajectories),
Statistical model: \(10^{-6}\) (3n), \(10^{-7}\) (4n) survival probability cross sections up to 0.1 pb can be calculated
$^{86}$Kr + $^{166}$Er collision at $E_{\text{c.m.}} = 464$ MeV (Coulomb barrier = 260 MeV)
Time analysis

**Time distribution**

- Events distribution for $E_{\text{loss}} > 30 \text{ MeV}$.
- Data for $^{86}\text{Kr} + ^{166}\text{Er}$, $E_{\text{cm}} = 464 \text{ MeV}$.
- Events categorized into fast, slow, and intermediate time intervals.

**Energy distribution**

- Distribution of energy loss ($E_{\text{loss}}$) for $^{86}\text{Kr} + ^{166}\text{Er}$, $E_{\text{cm}} = 464 \text{ MeV}$.
- Peaks for quasi-elastic, DIP, and Quasi-Fission.

**Mass distribution**

- Distribution of fragment mass number versus TKE (Total Kinetic Energy) for $E_{\text{cm}}$.
- Peaks for Quasi-Fission.
- Scission line denoted by $V_{\text{sciss}}$. 

**Time intervals**

- $t_{\text{int}} < 4 \times 10^{-21} \text{ s}$
- $4 \times 10^{-21} \text{ s} < t_{\text{int}} < 2 \times 10^{-20} \text{ s}$
- $2 \times 10^{-20} \text{ s} < t_{\text{int}}$
$^{48}\text{Ca} + ^{248}\text{Cm}$ collisions at $E_{cm} = 203$ MeV (Shell effects)
Transfer reactions in damped collision of very heavy nuclei?

- Diagram showing deep-inelastic scattering in the collision of U and Cm.
- Graphs illustrating the cross-section for PLF and TLF fission fragments in the reaction $^{238}\text{U} + ^{248}\text{Cm}$, E.c.m. = 800 MeV.
- Ordinary (symmetrizing) quasi-fission and anti-symmetrizing quasi-fission pathways.

Potential energy (MeV) vs. mass number for these processes.
Production of SHE along the stability line in low-energy collisions of actinide nuclei

238U + 248Cm

"cold" fusion

"hot" fusion
238U + 248Cm. Energy and angular distributions
238U + 248Cm. Excitation energies and survival probability
Production of neutron-rich SHE in low-energy collisions of heavy actinide nuclei
How to explore the north-east part of the nuclear map?
Production on new heavy nuclei in the region of N=126

Isotope production with radioactive beams, Dasso, Pollarolo, Winther, PRL 1994

Proton transfer along the neutron closed shells:
\[ {}^{136}\text{Xe}_{N=82} + {}^{208}\text{Pb}_{N=126} \rightarrow {}^{136+\Delta Z}\text{Xe}_{N=82} + {}^{208-\Delta Z}\text{Y}_{N=126} + Q \approx 0 \]

Reactions with \( Q \approx 0 \) are very favorable for proton transfer. The use of \(^{132}\text{Sn}\) is even better!
Production on new heavy nuclei in the region of $N=126$ in the Xe + Pb collisions

Several tens of new neutron-rich nuclides can be produced with cross section higher than one microbarn in the near-barrier collision of $^{136}$Xe with $^{208}$Pb.
Summary

- **Transport dynamical model** based on Langevin-type equations of motion and time-dependent driving potential (8 degrees of freedom) **seems to be appropriate** for description of low-energy heavy ion collisions (including those with large mass and charge rearrangement).

- **SH neutron-rich nuclei** close to the island of stability can be produced in low-energy collisions of actinides (U + Cm like).

- Near-barrier collisions of heavy ions (Xe+Pb like) allow us to fill and explore also the **north-east area of the nuclear map** (important for astrophysical investigations).

- New kind of separators (and/or new experimental methods) are needed to perform such experiments.
Excitation functions for production of SHE in collisions of actinides
Production on new heavy nuclei in the $^{136}\text{Xe} + ^{208}\text{Pb}$ collisions

Several tens of new neutron-rich nuclides can be produced with cross section higher than one microbarn in the near-barrier collision of $^{136}\text{Xe}$ with $^{208}\text{Pb}$.
Comparison with experiment on multi-nucleon transfer

Landscape of the potential energy

Experiment: L. Corradi et al., 2002

(-3p)

(-2p)

(-1p)

Landscape of the cross section

proton stripping

neutron pick-up

\[ E_{\text{lab}} = 328.4 \text{ MeV} \]
Deep inelastic scattering and quasi-fission phenomena

**Experiment: Wilcke et al., 1980**

(a) Angular distribution
(b) $^{136}$Xe + $^{209}$Bi
   - $E_{\text{c.m.}} = 569$ MeV
   - $E$ - distribution
(c) $Z$ - distribution

**Experiment: Itkis et al., 2002**

- Coulomb barrier
- Contact point
- 48Ca + 248Cm, $E_{\text{c.m.}} = 203$ MeV
- DI, QF, QF
- Kinetic energy (MeV)
- Fragment mass number
- 2-D energy-mass number plot
- $1_{\text{int}} < 2 \times 10^{21}$
- $2 \times 10^{21} < 1_{\text{int}} < 2 \times 10^{20}$
- $2 \times 10^{20} < 1_{\text{int}}$
A “gap” in the upper part of the Nuclear Map
Synthesis of superheavy elements (cold and hot fusion)

Cold synthesis:
$^{208}\text{Pb} + ^{54}\text{Ni}, ^{70}\text{Zn}, \ldots \rightarrow ^{276}110, ^{278}112, \ldots$

Hot synthesis:
$^{238}\text{U}, \ldots, ^{249}\text{Cf} + ^{48}\text{Ca} \rightarrow ^{286}112, \ldots, ^{297}118$
We are still far from the line of stability.
"Cold" synthesis of SHE

\[
\sigma_{\text{ER}}^{Xn}(E) = \frac{\pi}{k_2} \sum_{\ell=0}^{\infty} (2\ell+1) P_{\text{cont}}(E, \ell) P_{\text{CN}}(E^*, \ell) P_{\text{xn}}(E^*, \ell)
\]

Fusion probability, \( P_{\text{CN}}(E, \ell) \):

\[
P_{\text{CN}}(E^*, \ell) = \frac{\rho_0}{1 + \exp\left[\frac{E^* - E_{\text{in}}(\ell)}{\Delta}\right]}
\]

Fusion probability, \( P_{\text{CN}}^0 \):

\[
P_{\text{CN}}^0 = \frac{\rho_0}{1 + \exp\left[\frac{E^* - E_{\text{in}}(\ell)}{\Delta}\right]}
\]
“Cold” and “Hot” synthesis of SHE
Beyond $^{48}$Ca: How much $^{50}$Ti is worse?

\[ \frac{\sigma^{(48\text{Ca})}}{\sigma^{(50\text{Ti})}} \text{ two orders of magnitude} \]

<table>
<thead>
<tr>
<th>$^{256}102$</th>
<th>$^{258}104$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{ld}$</td>
<td>$B_{l}$</td>
</tr>
<tr>
<td>1.26</td>
<td>0.77</td>
</tr>
<tr>
<td>$3W$</td>
<td>$3W$</td>
</tr>
<tr>
<td>4.48</td>
<td>4.49</td>
</tr>
<tr>
<td>$B_{r}$</td>
<td>$B_{r}$</td>
</tr>
<tr>
<td>5.7</td>
<td>5.3</td>
</tr>
<tr>
<td>$E_{n}$</td>
<td>$E_{n}$</td>
</tr>
<tr>
<td>7.1</td>
<td>7.8</td>
</tr>
</tbody>
</table>

$P_{xn}(E^*, l=0)$

$E^*$ vs $P_{CG}(E^*)$
Beyond $^{48}\text{Ca}$: $^{50}\text{Ti}$-induced fusion reactions
Fusion of “fission fragments”: $^{136}\text{Xe} + ^{136}\text{Xe} \rightarrow ^{272}108$

if OK then $^{132}\text{Sn} + ^{176}\text{Yb} \rightarrow ^{308}120$

Accelerated fission fragments hardly may be used for production of SH nuclei
Radioactive Ion Beams for the production of neutron rich superheavy nuclei