Effect of entrance channel on the reaction mechanism in heavy ion collision

Avazbek Nasirov *

* Institute of Nuclear Physics Academy of Science of Uzbekistan

Institute of Theoretical Physics of Chinese Academy of Science

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In collaboration with colleagues:

Prof. G. G. Giardina, Dr. G. Mandaglio, Dr. M. Manganaro,
*INFN, Sezione di Catania, and*
*Dipartimento di Fisica dell'Università di Messina, Messina, Italy*

Prof. A.I. Muminov
*Institute of Nuclear Physics Tashkent, Uzbekistan*
1. Introduction:
2. Main characteristics of the entrance channel:
   - the initial angular momentum;
   - mass (charge) asymmetry of colliding nuclei;
   - shell structure of the colliding nuclei;
   - orientation angle of the axial symmetry axis for the deformed target or/and projectile.
3. Main equations and kinetic coefficients of the model.
4. Including of the shell effects in the dinuclear system model and description of the experimental data on the multinucleon transfer reactions:
   - mass and charge distribution;
   - nonequilibrium sharing of the excitation energy between fragments;
5. Conclusions.
Main characteristics of the entrance channel

The reaction mechanism in heavy ion collisions at low energies is determined by the behaviour of dinuclear system which depends on the characteristic of the entrance channel. In the experiment we can control initial charge (mass) asymmetry $(Z_1, A_1; Z_2, A_2)$ and beam energy $E_{c.m.}$. Orientation angle of axial symmetry axis of deformed nuclei $(\alpha_1, \alpha_2)$ relatively to the beam direction and impact parameter ($b$ or $L$-angular momentum) are not controlled by us. But increasing beam energy we increase the number of partial waves $L$ and orientation angles leading to formation of dinuclear system.

Importance of the shell structure of colliding and being formed nuclei in the reaction mechanism is seen from a hindrance in the cold fusion reactions, mass distribution of fusion-fission products and super deformed states of nuclei. Dinuclear system model allows to take into account all of them.
Manifestation of shell structure in fission

FIG. 1. Final-mass distribution for $^{254}\text{Fm}(sf)$ determined from radiochemical and $\gamma$-ray spectrometry measurements. Circles represent present data. Triangles represent data from Ref. 6. The solid curve represents a total yield of 200%.


Mass-energetic distribution of the binary products in heavy ion collisions. The N=126 and Z=82 magic numbers responsible for the maximum of quasifission fragments.

$^{48}$Ca (238MeV) + $^{248}$Cm $\rightarrow$ $^{296}$116
Role of the entrance channel

The reaction mechanism depends on
1) the initial angular momentum (included partial waves)
Evaporation residues

Super heavy elements

**Reaction Flow**

**Model Shapes**

1. **Distant Collisions**
   \[ r > R_{int} \]

2. **Peripheral Collisions**
   \[ r \approx R_{int} \]

3. **Solid-Contact Collisions**
   \[ r < R_{int} \]

4. **Deeply Penetrating Collisions**
   \[ r \ll R_{int} \]

**Reaction Characteristics**

1. **Elastic Scattering and Coulomb Excitation**

2. **Inelastic Scattering and Onset of Nucleon Exchange and Weak Kinetic-Energy Damping**

3. **Damped or Deep-Inelastic Reactions**
   - Characterized by: Substantial kinetic-energy damping and mass exchange, while retaining partial memory of entrance-channel masses and charges.

4. **Fusion-Fission-Like Reactions**
   - Characterized by: Loss of projectile and target identities and complete damping of kinetic energy.

**Total Reaction Cross Section**

**Compound-Nucleus Reactions Leading to Evaporation Residues and Fission**
Partial cross sections of compound nucleus (CN), fusion-like (FL), damped (D), quasielelastic (QE), Coulomb excitation (CE) and elastic (EL) processes. This assumption is true for the light system $Z_1 x Z_2 < 300$ only.

Figure 39. Schematic illustration of the $l$ dependence of the partial cross section for compound-nucleus (CN), fusion-like (FL), damped (D), quasielelastic (QE), Coulomb-excitation (CE), and elastic (EL) processes. The long-dashed line represents the geometrical partial cross section $d\sigma/dl = 2\pi \lambda^2 l$. Vertical dashed lines indicate the extensions of the various $l$ windows in a sharp cutoff model with the characteristic $l$ values noted at the abscissa. Hatched areas represent the diffuse $l$ windows assumed in a smooth cutoff model.
Fusion of light nuclei

Light nuclei are fused similar drops of liquid. Because Coulomb forces are not so strong relative to the nuclear forces and the surface tension energy is much larger than shell correction in nuclei, capture process is nearly equal to complete fusion: dinuclear system stability is very short.
In case of light system, system $Z_1 \times Z_2 < 300$, compound nucleus (CN), and damped (D), channels are dominann but fusion-like (FL), events are small due to small contribution of quasifission.

For $Z_1 \times Z_2 > 500$ this kind of classification is not true!
Angular momentum distribution for capture, quasifission and fusion in the $^{48}$Ca + $^{144}$Sm reaction

Angular momentum distributions for capture, quasifission, fusion for $^{48}$Ca(185 MeV)+ $^{144}$Sm

210 MeV

205 MeV

200 MeV

195 MeV

ELab=190 MeV

185 MeV

180 MeV
Role of the entrance channel

The reaction mechanism depends on
1) the initial angular momentum (included partial waves)
2) Initial mass asymmetry=$(A_1-A_2)/(A_1+A_2)$
Fusion angular momentum distribution for the reaction $^{16}\text{O} + ^{204}\text{Pb}$ и $^{96}\text{Zr} + ^{124}\text{Sn}$

G. Fazio, et al.

Compound nucleus $^{220}\text{Th}$
Is formed in the both reaction

Fig. 7. Comparison of evaporation residues for the $^{16}\text{O} + ^{204}\text{Pb}$ and $^{96}\text{Zr} + ^{124}\text{Sn}$ reactions leading to the $^{220}\text{Th}^*$ CN. The experimental data of the evaporation residues are taken from refs. [1,3].
Partial fusion cross section as a function of the entrance channel
The reaction mechanism depends on
1) the initial angular momentum (included partial waves)
2) Initial mass asymmetry = \((A_1 - A_2)/(A_1 + A_2)\)
3) shell structure of the colliding nuclei
Driving potential $U_{\text{driving}}(c)$ for reactions $^{40}\text{Ar}+^{172}\text{Hf}$, $^{86}\text{Kr}+^{130}\text{Xe}$, $^{124}\text{Sn}+^{92}\text{Zr}$ leading to formation of compound nucleus $^{216}\text{Th}$:

Due to peculiarities of shell structure $B_{\text{fus}}(\text{Kr}) > B_{\text{fus}}(\text{Kr})$ and, consequently, $\sigma_{\text{fus}}(\text{Kr+Xe}) < \sigma_{\text{fus}}(\text{Zr+Sn})$.

\[ U_{\text{driving}} = B_1 + B_2 - B_{(1+2)} + V(R) \]
The reaction mechanism depends on
1) the initial angular momentum (included partial waves)
2) Initial mass asymmetry=$\frac{A_1-A_2}{A_1+A_2}$
3) Shell structure of the colliding nuclei
4) Orientation angle of the axial symmetry axis for the deformed target or/and projectile
Partial fusion cross section as a function of the orientation of axial symmetry axis reactants

\[ \sigma_{\text{fus}}^{(L)} \text{ (mb)} \]

\( \alpha_1 = 90, \alpha_2 = 0 \)

\[ \sigma_{\text{fus}}^{(L)} \text{ (mb)} \]

\( \alpha_1 = 90, \alpha_2 = 90 \)

\[ \sigma_{\text{fus}}^{(L)} \text{ (mb)} \]

\( \alpha_1 = 0, \alpha_2 = 0 \)

Nasirov A.K. et al.

The role of orientation of nuclei symmetry axis in fusion dynamics,

Dependence of the driving potential (a) and quasifission barrier (b) on the mutual orientations of the axial symmetry axes of nuclei.
Application of the dinuclear system model to the study of synthesis of superheavy elements.

Potential energy surface for fusion of compound nucleus $^{284}_{114}$

- Entrance channel;  
- Fusion channel;  
- c and d are quasifission channels

$$U_{dr}(A, Z, \beta_1, \alpha_1; \beta_2, \alpha_2) = B_1 + B_2 + V(A, Z, \beta_1, \alpha_1; \beta_2, \alpha_2; R) - (B_{CN} + V_{CN}(L))$$
Comparisons of cross sections for complete fusion and formation evaporation residues

- $^{54}\text{Cr}^+ + {}^{248}\text{Cm}$
- $^{58}\text{Fe}^+ + {}^{244}\text{Pu}$
- $^{64}\text{Ni}^+ + {}^{238}\text{U}$
Potential energy surface of dinuclear system

\[ U_{dr} (A, Z, \beta_1, \beta_2) = B_1 + B_2 + V (A, Z, \beta_1, \beta_2; R) - B_{CN} - V_{CN} (L) \]
Competition between complete fusion and quasifission

Projectile

Dinuclear system
\( (E^*_{\text{DNS}}, L_{\text{DNS}}) \)

Target

Compound nucleus
\( (E^*_{\text{CN}}, L_{\text{CN}}) \)

Evaporation residue

Neutron

1\textsuperscript{st} stage

2\textsuperscript{nd} stage

3\textsuperscript{rd} stage

Fission \( B_f(L_{\text{CN}}) \)

\( \Gamma_f/(\Gamma_f+\Gamma_n) \)

Quasifission
\( (E_{\text{DNS}}-B_{\text{fus}})(E_{\text{DNS}}-B_{\text{fus}}) \)
Formation of binary fragments

Fusion – Fission  Quasi-Fission
Difference between classical paths of the capture and deep inelastic collisions

TKE-total kinetic energy

V(R) – nucleus-nucleus potential

E_{DNS}^* – excitation energy of double nuclear system

Full momentum transfer reactions

Capture = Fusion + Quasifission + Fast fission

Fusion = Fission + Evaporation residues

Fission >> Evaporation residues
Comparison of the friction coefficients, calculated by different methods


PRC56 (1997) 373

By Yamaji et al(microscopic):
Long dashed -- Temperatura= 2 MeV
Short dashed- - Temperatura= 1 MeV
Dotted - Temperatura= 0.5 MeV

S. Yamaji and A. Iwamoto, 
Friction coefficients

\[ \gamma_\lambda = \frac{2}{i\hbar^2 D_\lambda} \sum_{i,i',j,k} \left( n_j^{(i)} - n_k^{(i')} \right) \left| \frac{\partial V_{jk}(R, \beta_\lambda)}{\partial \beta_\lambda} \right|^2 \int_{t_0}^t dt' (t-t') \exp \left( \frac{t-t'}{\tau_{jk}} \right) \sin \left[ (\varepsilon_j - \varepsilon_k)(t-t') / \hbar \right] \]

\[ \frac{1}{\tau^{(aa)}_i} = \frac{\sqrt{2\pi}}{32\hbar \varepsilon^{(\alpha)}_{F_K}} \left[ (f_K - g)^2 + \frac{1}{2} (f_K + g)^2 \right] \left[ (\pi T_K)^2 + (\varepsilon_i - \lambda^{(\alpha)}_K)^2 \right] \left[ 1 + \exp \left( \frac{\lambda^{(\alpha)}_K - \varepsilon_i}{T_K} \right) \right]^{-1} \]

\[ \Gamma_j = \hbar / \tau_j \]

\( \varepsilon_j \) and \( \varepsilon_k \) are single particle energies of nucleons in dinuclear syste.;

Decay width of the single-particle excitations of nucleons caused by residual forces.

Expressions for the friction coefficients

\[ \gamma_R(R(t)) = \sum_{i,i'} \left| \frac{\partial V_{ii'}(R(t))}{\partial R} \right|^2 B_{ii'}^{(1)}(t), \quad (B.1) \]

\[ \gamma_\theta(R(t)) = \frac{1}{R^2} \sum_{i,i'} \left| \frac{\partial V_{ii'}(R(t))}{\partial \theta} \right|^2 B_{ii'}^{(1)}(t), \quad (B.2) \]

and the dynamic contribution to the nucleus-nucleus potential

\[ \delta V(R(t)) = \sum_{i,i'} \left| \frac{\partial V_{ii'}(R(t))}{\partial R} \right|^2 B_{ii'}^{(0)}(t), \quad (B.3) \]

\[ B_{ik}^{(n)}(t) = \frac{2}{\hbar} \int_0^t dt' (t - t')^n \exp \left( \frac{t' - t}{\tau_{ik}} \right) \]

\[ \times \sin \left[ \omega_{ik}(R(t')) (t - t') \right] [\tilde{\eta}_k(t') - \tilde{\eta}_i(t')], \quad (B.4) \]

\[ \hbar \omega_{ik} = \epsilon_i + \Lambda_{ii} - \epsilon_k - \Lambda_{kk}. \quad (B.5) \]
Relaxation time of the occupation numbers of single-particle states

\[
\frac{1}{\tau^{(\alpha)}_i} = \frac{\sqrt{2\pi}}{32\hbar \epsilon^{(\alpha)}_{F_K}} \left[ (f_K - g)^2 + \frac{1}{2} (f_K + g)^2 \right]
\times \left[ (\pi T_K)^2 + (\bar{\epsilon}_i - \lambda^{(\alpha)}_K)^2 \right] \left[ 1 + \exp \left( \frac{\lambda^{(\alpha)}_K - \bar{\epsilon}_i}{T_K} \right) \right]^{-1}, \quad (A.1)
\]

where

\[
T_K(t) = 3.46 \sqrt{\frac{E^*_K(t)}{\langle A_K(t) \rangle}} \quad (A.2)
\]
Constants of the effective nucleon-nucleon interaction (Migdal forces)

\[
\begin{align*}
\varepsilon_{F_K}^{(Z)} &= \varepsilon_F \left[ 1 - \frac{2}{3} (1 + 2 f'_K) \frac{\langle N_K \rangle - \langle Z_K \rangle}{\langle A_K \rangle} \right], \\
\varepsilon_{F_K}^{(N)} &= \varepsilon_F \left[ 1 + \frac{2}{3} (1 + 2 f'_K) \frac{\langle N_K \rangle - \langle Z_K \rangle}{\langle A_K \rangle} \right],
\end{align*}
\]

(A.14)

where \( \varepsilon_F = 37 \text{ MeV} \),

\[
\begin{align*}
f_K &= f_{in} - \frac{2}{\langle A_K \rangle^{1/3}} (f_{in} - f_{ex}), \\
f'_K &= f'_{in} - \frac{2}{\langle A_K \rangle^{1/3}} (f'_{in} - f'_{ex})
\end{align*}
\]

(A.15)

and \( f_{in} = 0.09, \ f'_{in} = 0.42, \ f_{ex} = -2.59, \ f'_{ex} = 0.54, \ g = 0.7 \) are the constants of the effective nucleon–nucleon interaction.

Change of single-particle energies and transition matrix elements of nucleons

\[ \tilde{\epsilon}_P(R(t)) = \epsilon_P + \langle P | U_T(r) | P \rangle, \]
\[ \tilde{\epsilon}_T(R(t)) = \epsilon_T + \langle T | U_P(r - R(t)) | T \rangle, \]
\[ \chi_{PP}^{(T)}(R(t)) = \langle P | U_T(r) | P' \rangle, \]
\[ \chi_{TT}^{(P)}(R(t)) = \langle T | U_P(r - R(t)) | T' \rangle, \]
\[ g_{PT}(R(t)) = \frac{1}{2} \langle P | U_P(r - R(t)) + U_T(r) | T \rangle. \]

\[ P \equiv (n_P, j_P, l_P, m_P) \text{ and } \tilde{T} \equiv (n_T, j_T, l_T, m_T) \]
About matrix elements for nucleon exchange between nuclei of dinuclear system

\[ g_{PT}(\mathbf{R}) = \int d\mathbf{r} \Psi_T^*(\mathbf{r}) \]
\[ \times \left[ \frac{1}{2} \{U_T(\mathbf{r}) + U_P(\mathbf{r} - \mathbf{R})\} \right] \Psi_P(\mathbf{r} - \mathbf{R}), \]

\[ g_{PT}(R) = \frac{(-1)^{m_r-1/2}}{16\pi^3} [(2j_P + 1) \times (2j_T + 1)]^{1/2} \sum_L i^L \left( j_T - \frac{1}{2}, j_P \frac{1}{2} \right| L0) \]
\[ \times (j_T - m_T, j_P m_P|L0) \int dp p^2 j_L(pR) \]
\[ \times \left[ \left\{ \varepsilon_P - \frac{\hbar^2}{2m} p^2 \right\} + \left\{ \varepsilon_T - \frac{\hbar^2}{2m} p^2 \right\} \right] \varphi_T^*(p) \varphi_P(p). \]
Comparison results of using wave functions of spherical and deformed shapes of heavy nucleus (Phys.of Atom Nucl. 70 (2006)p.1485-1490)

Fig. 2. The same as in Fig. 1, but for $^{48}$Ca + $^{208}$Pb reaction.
Shortly about calculation of non-equilibrium sharing of excitation energy between fragments of DNS

\[ i\hbar \frac{\partial \tilde{n}_i}{\partial t} = \sum_k \left[ V_{ik}(\mathbf{R}) \tilde{n}_{ki} - V_{ki}(\mathbf{R}) \tilde{n}_{ik} \right] - \frac{i\hbar}{\tau_i} \left[ \tilde{n}_i - \tilde{n}_i^{\text{eq}} \right], \]

\[ n_i(t + \Delta t) = \tilde{n}_i(t) \]

\[ + \sum_k \int_{t}^{t+\Delta t} \mathrm{d}t' \Omega_{ik}(t', t') \frac{\sin[\tilde{\omega}_{ki}(\mathbf{R}(t'))(t' - t)]}{\tilde{\omega}_{ki}(\mathbf{R}(t'))} \times \left[ \tilde{n}_k(t') - \tilde{n}_i(t') \right]. \]  

(24)

\[ \Omega_{ik}(t, t') = \frac{2}{\hbar^2} \mathrm{Re} \left\{ \frac{V_{ik}(\mathbf{R}(t)) V_{ki}(\mathbf{R}(t'))}{\tilde{\omega}_{ki}(\mathbf{R}(t'))} \right\} \]  

\[ \times \exp \left[ i \int_{t'}^{t} \mathrm{d}t'' \tilde{\omega}_{ki}(\mathbf{R}(t'')) \right]. \]
The change of nuclear shape

The change of the nuclear shape was taken into account by solving of equations of motion for the quadrupole ($2^+$) and octupole ($3^-$) collective excitations in nucleus $i$ ($i=1,2$):

$$\frac{d^2 \beta_\lambda^{(i)}}{dt^2} + \gamma_\lambda^{(i)} \frac{d \beta_\lambda^{(i)}}{dt} + \omega_\lambda^{(i)} = \sqrt{\frac{2\lambda + 1}{4\pi}} \frac{R_0^{(i)}}{D_\lambda^{(i)}} \left. \frac{dU(R, \beta_\lambda^{(i)})}{dR} \right|_{\beta_0^{(i)}}$$

where $\omega_\lambda$, $\gamma_\lambda$ and $D_\lambda$ are the frequency, damping and mass coefficients for the surface vibration multipolarity $\lambda$, respectively;

$$\gamma_\lambda = \frac{2}{i\hbar^2 D_\lambda_{i,i',j,k}} \sum (n_j^{(i)} - n_k^{(i)}) \left| \frac{\partial V_{jk}(R, \beta_\lambda)}{\partial \beta_\lambda} \right|^2 \int_{t_0}^t dt' (t-t') \exp \left( \frac{t-t'}{\tau_{jk}} \right) \sin [(\varepsilon_j - \varepsilon_k)(t-t')/\hbar]$$

$$D_\lambda = \hbar (2\lambda + 1) \left( \frac{3}{4\pi} ZeR^\lambda \right)^2 \left/ 2B(E\lambda;0^+_1 \rightarrow \lambda_1) \right.$$

The values of $\omega_\lambda$ and reduced electric-multipole transition rate $B_{E\lambda}$ are obtained from the Tables in G. Audi, A.H. Wapstra, Nucl. Phys. A 595, 509 (1995).
The measured evaporation cross section can be described by the formula:

$$\sigma_{ER}(E^*) = \sum_{\ell=0}^{\ell_f} \sigma_{\text{cap}}(E_{\text{c.m.}}, \ell) P_{\text{CN}}(E^*, \ell) W_{\text{surv}}(E^*, \ell)$$

where

$$\sigma_{\text{fus}}(E_{\text{c.m.}}, \ell) = \sigma_{\text{cap}}(E_{\text{c.m.}}, \ell) P_{\text{CN}}(E^*, \ell)$$

is considered as the cross section of compound nucleus formation; $W_{\text{surv}}$ is the survival probability of the heated and rotating nucleus.
Calculation of the competition between complete fusion and quasifission: $P_{\text{cn}}(E_{\text{DNS}}, L)$

\[
P_{\text{CN}}(E_{\text{DNS}}^*, \ell) = \sum_{Z_{\text{sym}}}^{Z_{\text{max}}} Y_Z(E_{\text{DNS}}^*, \ell) P_{\text{CN}}^{(Z)}(E_{\text{DNS}}^*, \ell),
\]

where

\[
P_{\text{CN}}^{(Z)} = \frac{\rho(E_{\text{DNS}}^*(Z) - B_{\text{fus}}^*(Z))}{\rho(E_{\text{DNS}}^*(Z) - B_{\text{fus}}^*(Z)) + \rho(E_{\text{DNS}}^*(Z) - B_{\text{qf}}^*(Z))},
\]

\[
\frac{\partial}{\partial t} Y_Z(E_{Z}^*, \ell, t) = \Delta_{Z+1}^{(-)} Y_{Z+1}(E_{Z}^*, \ell, t) + \Delta_{Z-1}^{(+)} Y_{Z-1}(E_{Z}^*, \ell, t)
\]

\[
- (\Delta_{Z}^{(-)} + \Delta_{Z}^{(+)} + \Lambda_{Z}^{\text{qf}}) Y_Z(E_{Z}^*, \ell, t), \quad \text{for } Z = 2, 3, \ldots, Z_{\text{tot}} - 2.
\]

Here, the transition coefficients of multinucleon transfer are calculated as in Ref. 18

\[
\Delta_{Z}^{(\pm)} = \frac{1}{\Delta t} \sum_{P,T} |g_{P,T}^{(Z)}|^2 n_{T,P}^{(Z)}(1 - n_{P,T}^{(Z)}(t)) \frac{\sin^2(\Delta t (\tilde{\epsilon}_{PZ} - \tilde{\epsilon}_{TZ})/2\hbar)}{((\tilde{\epsilon}_{PZ} - \tilde{\epsilon}_{TZ})^2/4),
\]

Evolution of the mass distribution of quasifission fragments

\[ {^{48}\text{Ca}} (244 \text{ MeV}) + ^{244}\text{Pu} \]
Explanation of the lack of quasifission fragment yields at the expected place of mass distribution in the $^{48}\text{Ca} + ^{144}\text{Sm}$ reaction.
Calculation of decay of dinuclear system

\[ \theta_{DNS} = \theta_{cap} + \Omega_{DNS} \cdot \tau(T_Z(\ell, E^*_Z(\ell))) \]
\[ \tau(T_Z) = \frac{\hbar}{\Gamma_{qf}(T_Z)} \]

\[ \Gamma_{qf}(\Theta) = K_{rot} \omega_m \left( \sqrt{\frac{\gamma^2}{(2\mu_{qf})^2} + \omega_{qf}^2} - \frac{\gamma}{2\mu_{qf}} \right) \]
\[ \times \exp \left( -\frac{B_{qf}}{T_Z} \right) \right) / (2\pi \omega_{qf}) \]  
(21)

\[ \omega_m^2 = \mu_{qf}^{-1} \left| \frac{\partial^2 V(R)}{\partial R^2} \right|_{R=R_m} \]
\[ \omega_{qf}^2 = \mu_{qf}^{-1} \left| \frac{\partial^2 V(R)}{\partial R^2} \right|_{R=R_{qf}} \]
Equations of motion used to find capture of projectile by target

\[ \mu(R) \frac{d\dot{R}}{dt} + \gamma_R(R) \dot{R}(t) = -\frac{\partial V(R)}{\partial R} - \dot{R}^2 \frac{\partial \mu(R)}{\partial R} \]

\[ L_0 = J_R \dot{\theta} + J_1 \dot{\theta}_1 + J_2 \dot{\theta}_2, \]

\[ \frac{dL}{dt} = \gamma_\theta(R)R(t) \left[ \dot{\theta}R(t) - \dot{\theta}_1 R_{1_{\text{eff}}} - \dot{\theta}_2 R_{2_{\text{eff}}} \right] \]

\[ E_{rot} = \frac{J_R \theta^2}{2} + \frac{J_1 \theta_1^2}{2} + \frac{J_2 \theta_2^2}{2} \]
Dynamics of capture of projectile by target-nucleus and complete fusion

\[ \sigma_{\text{cap}} (E_{\text{lab}}, L; \alpha_1, \alpha_2) = (2L + 1) \ T(E_{\text{lab}}, L; \alpha_1, \alpha_2) \]

\[ T(E_{\text{lab}}, L; \alpha_1, \alpha_2) = \begin{cases} 
1, & \text{if } L_{\text{min}} \leq L \leq L_{\text{dyn}} \\
0, & \text{if } L < L_{\text{min}} \text{ or } L > L_{\text{dyn}} 
\end{cases} \]

\( L_{\text{dyn}} \) and \( L_{\text{min}} \) are determined by dynamics of collision and calculated by solution of equations of motion for the collision trajectory:

\[ \sigma_{\text{fus}} (E_{\text{lab}}, L) = \langle \sigma_{\text{cap}} (E_{\text{lab}}, L; \alpha_1, \alpha_2) \ P_{\text{CN}} (E_{\text{lab}}, L; \alpha_1, \alpha_2) \rangle_{\{\alpha\}} \]
Nucleus-nucleus interaction potential

\[ V_C(R, \alpha_1, \alpha_2) = \frac{Z_1 Z_2}{R} e^2 + \frac{Z_1 Z_2}{R^3} e^2 \left\{ \left( \frac{9}{20\pi} \right)^{1/2} \sum_{i=1}^{2} R_{0i}^2 \beta_2^{(i)} P_2(\cos \alpha_i) + \frac{3}{7\pi} \sum_{i=1}^{2} R_{0i}^2 \left[ \beta_2^{(i)} P_2(\cos \alpha_i) \right]^2 \right\} \]

\[ V_{nucl}(R, \alpha_1, \alpha_2) = \int \rho_1^{(0)}(\vec{r} - \vec{R}) f_{eff} \left[ \rho_1^{(0)} + \rho_2^{(0)} \right] \rho_2^{(0)}(\vec{r}) d^3\vec{r} \]

\[ \rho_i^{(0)}(\vec{r}, \vec{R}_i, \alpha_i, \theta_i, \beta_2^{(i)}) = \left\{ 1 + \exp \left[ \frac{|\vec{r} - \vec{R}_i(t)| - R_{0i}(1 + \beta_2^{(i)}Y_{20}(\theta_i, \alpha_i))}{a} \right] \right\}^{-1} \]

\[ V_{rot} = \hbar^2 \frac{l(l+1)}{2\mu[R(\alpha_1, \alpha_2)]^2 + J_1 + J_2} \]
Hamiltonian for calculation of the transport coefficients

The macroscopic motion of nucleus and microscopic motion of nucleons must be calculated simultaneously.

\[ H = H_{\text{coll}} + H_{\text{micr}} + \delta V \]  

where

\[ H_{\text{coll}} = \frac{P^2}{2 \mu} + U(R) - \text{for the relative motion of nuclei;} \] \hspace{1cm} (2)

\[ H_{\text{micr}} = \sum_{i_p} \varepsilon_{i_p} \hat{a}_{i_p}^+ \hat{a}_{i_p} + \sum_{i_T} \varepsilon_{i_T} \hat{a}_{i_T}^+ \hat{a}_{i_T} - \text{for nucleons of nuclei;} \] \hspace{1cm} (3)

\[ \delta V = \sum_{i_p, j_T} g_{i_p j_T} (R)(\hat{a}_{i_p}^+ \hat{a}_{j_T} + \hat{a}_{j_T}^+ \hat{a}_{i_p}) + \sum_{i_p, j_p} \Lambda^{(T)}_{i_p j_p} (R)\hat{a}_{i_p}^+ \hat{a}_{j_p} + \sum_{i_p, j_T} \Lambda^{(P)}_{i_T j_T} (R)\hat{a}_{i_T}^+ \hat{a}_{j_T} - \] \hspace{1cm} (4)

nucleon exchange between nuclei and particle - hole excitation s in nuclei;

\[ g_{i_p j_T} \text{ and } \Lambda^{(P)}_{i_T j_T} - \text{matrix elements of nucleon exchange between nuclei and particle - hole excitation s in them caused by meanfield of partner nucleus.} \]
Master equations for the nucleon occupation numbers and Equation of motion for the relative distance

\[ i\hbar \frac{\partial \hat{n}(t)}{\partial t} = \left[H(R(t), \hat{n}(t))\right], \quad (5) \quad n_i(t) = a_i^+ a_i \quad i=P,T \]

\[ i\hbar \frac{\partial \hat{P}(t)}{\partial t} = \left[H(R(t), \hat{P}(t))\right], \quad (6) \quad P \equiv (n_p, j_p, l_p, m_p) \]

\[ i\hbar \frac{\partial \tilde{n}_i(t)}{\partial t} = \left[H, n_i(t)\right] - \frac{i\hbar}{\tau_i} \left[n_i(t) - n_{i eq}(R(t))\right] \]

\[ \tilde{n}_i = \tilde{n}_{i eq}(R(t)) \left[1 - \exp \left(-\frac{\Delta t}{\tau_i}\right)\right] + n_i(t) \exp \left(-\frac{\Delta t}{\tau_i}\right) \quad (7) \]

\[ n_i(t) = \tilde{n}_i(t - \Delta t) + \sum_k \overline{W}_{ik}(R(t), \Delta t) [\tilde{n}_k(t - \Delta t) - \tilde{n}_i(t - \Delta t)] \quad (8) \]

\[ \overline{W}_{ik}(R(t), \Delta t) = |V_{ik}(R(t))|^2, \quad V_{ik}(R) = \langle i | V(R) | k \rangle \quad (9) \]

Partition of excitation energy between reaction products in heavy ion collisions

G.G. Adamian¹, R.V. Jolos¹, A.K. Nasirov²

Non-equilibrium sharing of excitation energy in the deep-inelastic collisions is explained by nuclear shell structure.

Effect of shell structure on energy dissipation in heavy-ion collisions

R.V. Jolos\textsuperscript{1}, A.K. Nasirov\textsuperscript{1,2,\textsuperscript{a}}, G.G. Adamian\textsuperscript{2,3}, and A.I. Muminov\textsuperscript{2}

\textsuperscript{1} Joint Institute for Nuclear Research, 141980, Dubna, Russia
\textsuperscript{2} Heavy Ion Physics Department, Institute of Nuclear Physics, 702132 Ulugbek, Tashkent, Uzbekistan
\textsuperscript{3} Institut für Theoretische Physik der Justus-Liebig-Universität, D-35392 Giessen, Germany

\[ E_{P(T)}^*(t + \Delta t) = E_{P(T)}^*(t) + \sum_{i_P(j_T)} \left[ \tilde{\varepsilon}_{i_P(j_T)}(R(t)) - \lambda_{P(T)}(R(t)) \right] \times \left[ \tilde{n}_{i_P(j_T)}(t + \Delta t) - \tilde{n}_{i_P(j_T)}(t) \right]. \] (28)
Conclusions

• Initial mass and charge asymmetry of colliding nuclei and their shell structure play decisive role in the reaction mechanism.

• To analyze the experimental data in detail theoretical model has to include the shell structure characteristics.

• The transport coefficients, friction coefficient and nucleus-nucleus potential used in the dinuclear system model allow us to reproduce or to interpret experimental data revealing the role of the entrance channel of reaction.
Thank you for your attention
What we know about quasifission fragments?

- The mass distribution of its fragments has a maximum usually near magic numbers $Z=20, 28, 50, 82$ and $N=20, 28, 50, 82$;
- Total kinetic energy distribution is very close to Viola systematics as for fusion-fission: $TKE = Z_1 Z_2 e^2 / D(A_1, A_2)$;
- Angular distribution of fragments has more large anisotropy in comparison with that of fusion-fission.

We would like to stress that angular distribution of quasifission fragments is mainly anisotropic but it may be isotropic and angular distribution of fusion-fission fragments may be isotropic in dependence on the reaction dynamics.
Comparison of the capture, fusion-fission and quasifission cross sections obtained in this work with data from experiments


and evaporation residues

Stefanini A.M. et al.
Overlap of yields of binary fragments coming from fusion fission and quasifission channels of reaction

Evolution of the mass distribution of quasifission fragments

$^{48}\text{Ca} + ^{154}\text{Sm}$

Spheres

$t(10^{-21}\text{s})$

$A$
The rotational angle of the dinuclear system as a function of the orbital angular momentum (a) and (b), and angular distribution of the yield of quasifission fragments (c) and (d).
\[ TKE = K_1 + K_2 \]

\[ P(M_1, M_2, TKE) = \sum P(M_1, M_2, TKE) \]

\[ <TKE> = \sum TKE P(M_1, M_2, TKE) \]
Explanation of the lack of quasifission fragment yields at the expected place of mass distribution in the $^{48}\text{Ca}+^{144}\text{Sm}$ reaction.
Formation probability of compound nucleus from dinuclear system

\[ \sigma^\ell_{\text{fus}}(E) = \sigma^\ell_{\text{capture}}(E) P_{\text{CN}}(E, \ell), \]

\[ P_{\text{CN}}(E, \ell) = \sum_{Z=2}^{Z_{\text{tot}}/2} Y_Z(E) P_{\text{CN}}^{(Z)}(E, \ell, Z), \]

\[ < \sigma^{(i)}_{\{\alpha_P, \alpha_T\}} (E) > = \int_0^{\pi/2} \sin \alpha_P \int_0^{\pi/2} \sigma^{(i)}_{\{\alpha_P, \alpha_T\}} (E; \alpha_P, \alpha_T) \sin \alpha_T d\alpha_T d\alpha_P, \]

where \(i = \text{fus or fission}\) and \(\alpha_P\) and \(\alpha_T\) are the orientation angles of the axial symmetry axes of the projectile and target nuclei, respectively.

Quasifission processes in $^{40,48}$Ca+$^{144,154}$Sm reactions


Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, RU-141980 Dubna, Moscow region, Russia

A. M. Stefanini, B. R. Behera, L. Corradi, E. Fioretto, A. Gadea, A. Latina, and S. Szilner

Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Padova, Italy

M. Trotta

Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, I-80126 Napoli, Italy

S. Beghini, G. Montagnoli, and F. Scarlassara

Dipartimento di Fisica and INFN-Sezione di Padova, Università di Padova, I-35131 Padova, Italy

F. Haas and N. Rowley

IREs, UMR7500, IN2P3-CNRS/Université Louis Pasteur, BP28, F-67037, Strasbourg Cedex 2, France

P. R. S. Gomes

Instituto de Fisica, Universidade Federal Fluminense, Av. Litoranea s/n, 24210-340 Niteroi, Brazil

A. Szanto de Toledo

Instituto de Fisica, Universidade de São Paulo, CP 66318, 05315-970 São Paulo, Brazil

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The rotational angle of the dinuclear system as a function of the orbital angular momentum (a) and (b), and angular distribution of the yield of quasifission fragments (c) and (d).
Collective enhancement of level density of DNS

\[ K_{\text{rot}}(E_{\text{DNS}}) = \begin{cases} 
(\sigma_\perp^2 - 1)f(E_{\text{DNS}}) + 1, & \text{if } \sigma_\perp > 1, \\
1, & \text{if } \sigma_\perp \leq 1,
\end{cases} \]

where \( \sigma_\perp = J_{(\text{DNS})}T/\hbar^2 \); \( f(E) = (1+\exp[(E-E_{cr})/d_{cr}]) \);
\( E_{cr} = 120\tilde{\beta}_2^2A^{1/3} \text{ MeV} \); \( d_{cr} = 1400\tilde{\beta}_2^2A^{2/3} \). \( \tilde{\beta} \) is the effective quadrupole deformation for the dinuclear system. We find it from the calculated \( J_{\perp}^{(\text{DNS})} \).
About anisotropy of reaction fragments

\[
A = \frac{W(180^\circ)}{W(90^\circ)} \approx 1 + \frac{\langle J^2 \rangle}{4K_0} = 1 + \frac{\langle J^2 \rangle \hbar^2}{4TJ_{\text{eff}}}.
\]

\[
J_{\text{eff}} = \frac{J_{\perp}J_{\parallel}}{(J_{\perp} + J_{\parallel})}
\]

\(J_{\perp}\) is moment of inertia of system relative to axis perpendicular to its symmetry axis; \(J_{\parallel}\) is moment of inertia of system relative to axis parallel to symmetry axis; \(T\) is the effective temperature of system; \(J\) is total spin of system \(\mathbf{J} = \mathbf{I} + \mathbf{L}\)

About anisotropy of reaction fragments

\[
\langle \ell^2 (E) \rangle_{(i)} = \frac{\sum_{\ell=0}^{\ell_d} \ell^2 \langle \sigma^{(\ell)}_{(i)} \rangle_{\alpha_P, \alpha_T} (E)}{\sum_{\ell=0}^{\ell_d} \langle \sigma^{(\ell)}_{(i)} \rangle_{\alpha_P, \alpha_T} (E)}
\]

with

\[
\langle \sigma^{(\ell)}_{(i)} \rangle_{\{\alpha_P, \alpha_T\}} (E) = \int_0^{\pi/2} \sin \alpha_P \int_0^{\pi/2} \sin \alpha_T \times \sigma^{(\ell)}_{(i)} (E; \alpha_P, \alpha_T) d\alpha_T d\alpha_P,
\]

\[
< A > = \frac{\sigma_{qfiss} A_{qfiss} + \sigma_{fus} A_{fus} + \sigma_{fiss} A_{fiss}}{\sigma_{qfiss} + \sigma_{fus} + \sigma_{fiss}}
\]
Method of calculations are presented in our papers

1. Fazio G.  et al. Formation of heavy and superheavy elements by reactions with massive nuclei//

2. Fazio G.  et al. Strong influence of the entrance channel on the formation of compound nuclei $^{216,222}$Th and their evaporation residues//

3. Nasirov A.K. et al. The role of orientation of nuclei symmetry axis in fusion dynamics//

4. Nasirov A.K. et al. Angular anisotropy of the fusion-fission and quasifission fragments //
Dependence of the driving potential (a) and quasifission barrier (b) on the mutual orientations of the axial symmetry axes of nuclei.