Effects of the entrance channel in the formation of quasifission, fast fission, and fusion-fission cross sections

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Content

- Introduction

- Ambiguities at separation of the fusion-fission and quasifission contributions due to overlap their mass-angle distributions in measured data.

- Difference between fast fission and quasifission.

- Complication of the reaction mechanism by the orbital angular momentum and orientation angles of the axial symmetry axis of deformed reactants

- Conclusions
The experimental knowledge about fusion-fission reactions at sub- and near-barrier energies has grown considerably in the last twenty years due to synthesis of new superheavy elements and new isotopes of heavy elements.

The theoretical models are able to reproduce and predict the main features of such processes, even the cross sections for synthesis of superheavy elements estimated more or less to the experimental data. But properly understanding the fusion dynamics for heavy systems requires many more ingredients. The need for the advanced methods for analysis of the experimental data to disentangle various concurrent effects is clearly felt.
For heavy systems, capture inside of the Coulomb barrier, i.e. formation of a dinuclear system is not the sufficient condition for fusion:

Capture = Quasifission + Fast-fission + Fusion-Fission + Evaporation residues
Capture is a trapping kinetic energy path of system into potential well due to dissipation of relative kinetic energy in the entrance channel.
Fast fission is a decay of mononucleus formed by evolution of dinuclear system having very large angular momentum which decreases the fission barrier.

Fast-fission

\[ L > L_{Bf=0} \]

Evolution of Dinuclear system

Target

1st stage

Projectile

2nd stage

\[ \frac{f}{f+n} \]

Evolution of Fast-fission

Quasifission

\[ L > L_{Bf=0} \]

FIG. 10. Same as Fig. 9 for \( Z = 70 \) to 100. There are no solid points for \( Z = 90 \) and \( Z = 100 \) since no triaxial ground states exist for these nuclei.
Quasifission is a decay of dinuclear system formed at capture of projectile-nucleus by target-nucleus during its evolution by the mass and charge transfer between its constituents. The quasifission products can be mixed with ones of deep-inelastic collisions, fusion-fission and fast fission processes.

About mixing of quasifission and deep-inelastic collision products.

A – Deep inelastic collision products

B-quasifission products
What is questionable in fusion-fission reactions?

Dynamics of complete fusion and role of the entrance channel in formation of heavy ion collision reactions are questionable or they have different interpretation still now. For example,

-- what mechanism is fusion makes the main contribution to formation of compound nucleus: increasing the neck between interacting nucleus or multinucleon transfer at relatively restricted neck size?

-- details of angular momentum distribution of dinuclear system and compound nucleus which determines the angular distribution of reaction products, cross sections of evaporation residue, fusion-fission and quasifission products;

-- separation of fusion-fission fragments from the quasifission and fast-fission products;
The observed decrease of the quasifission contribution by increase of the collision energy in $^{48}$Ca+$^{154}$Sm reaction. (from paper Knyazheva G.N. et al. Phys. Rev. C 75, 064602(2007).)
Evolution of the mass distribution of quasifission fragments

$\text{Spheres}$

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

Comparison of the capture, fusion-fission, quasifission and fast fission cross sections obtained in this work with data from experiments


and evaporation residues

Stefanini A.M. et al.
The disappearance of the quasifission contribution in the experimental mass distribution at increasing the excitation energy from $E_{\text{CN}} = 49$ MeV to 57 MeV is explained by its drift to mass symmetric area and concentration of their angular distribution into smaller forward angles where there is detectors due to technical reasons (A.K. Nasirov et al. Phys.Rev.C79 (2009) 024606).
The absence of the quasifission contributions in the experimental mass distribution in $^{48}\text{Ca}+^{144}\text{Sm}$ reaction is explained by their placing in the mass symmetric area and mixing with the mass distribution of fusion-fission products. (A.K. Nasirov et al. Phys.Rev.C79 (2009) 024606).
Explanation of the lack of quasifission fragment yields at the expected place of mass distribution in the $^{48}\text{Ca}+^{144}\text{Sm}$ reaction.
We can conclude that the identification of the quasifission fragments among the measured fissionlike products may be difficult due to overlap of their mass and/or angular distributions with ones of the fusion-fission fragments.
Separation of fusion-fission fragments from the quasifission and fast-fission products
Quasifission (a) fast fission (b), complete fusion (c,d) partial cross sections for $^{36}\text{S}+^{238}\text{U}$ reaction.
1. Comparison of the capture, quasifission, complete fusion and fast fission cross sections calculated for $^{36}\text{S}+^{238}\text{U}$ reaction in the framework of dinuclear system model.
The dependence of the separation of fusion-fission fragments from the quasifission and fast-fission products on the limiting value of angular momentum $\ell_{\text{CN}}$

$\mathcal{J}_0$ is the moment of inertia of spherical nucleus and

$\mathcal{J}_{\text{eff}} = J_{\perp} J_{\parallel} / (J_{\perp} - J_{\parallel})$,

where $J_{\perp}$ and $J_{\parallel}$ the moment of inertia of fissile system relative to its perpendicular and parallel symmetry axes. This quantity is used to fit experimental angular distribution of fission fragments at determination fission cross section

\[
K_0^2 = \frac{\langle J_{\text{eff}}^2 \rangle}{\hbar^2} T
\]

\[
\rho(K) \sim \exp \left[ -\frac{K^2}{2K_0^2} \right]
\]

The analysis of experimental data deals with the limiting value of angular momentum \( \ell_{\text{CN}} \) for complete fusion, as in paper by R.S. Naik et al.

\[
W(\theta) = \sum_{J=0}^{J_{\text{CN}}} (2J + 1)^2 \exp\left[-\frac{(J + 1/2)^2 \sin^2 \theta}{4K_0^2(FF)}\right] J_0[i(J + 1/2)^2 \sin^2 \theta / 4K_0^2(FF)]
\]

\[
+ \sum_{J=J_{\text{CN}}}^{J_{\text{max}}} (2J + 1)^2 \exp\left[-\frac{(J + 1/2)^2 \sin^2 \theta}{4K_0^2(QF)}\right] J_0[i(J + 1/2)^2 \sin^2 \theta / 4K_0^2(QF)]
\]

\[
erf\left[(J + 1/2)/(2K_0^2(QF))^{1/2}\right]
\]

assuming \( M = 0 \), i.e., assuming the spins of the target and projectile were zero, where \( J_0 \) is the zero order Bessel function with imaginary argument and the error function \( erf[(J + 1/2)/(2K_0^2)^{1/2}] \) is defined as

\[
\frac{J_{\text{CN}}^2}{J_{\text{max}}^2} = \frac{\sigma_{\text{CN}}}{\sigma_{\text{capture}}} = P_{\text{CN}}.
\]
So, the method of the analysis of the experimental data of the angular distribution of the fissionlike fragment needs to be modified when there is significant contribution of the quasifission fragments in the measured data. Because quasifission process can take place at all values of orbital angular momentum leading to capture. But to do this we should know surely how estimate presented yield of quasifission fragments.
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. The smallness of \( P_{\text{CN}} \) means hindrance to fusion caused by huge contribution of quasifission process:

\[
\sigma_{\text{qfis}}(E_{\text{c.m.}}, \ell) = \sigma_{\text{cap}}(E_{\text{c.m.}}, \ell) (1 - P_{\text{CN}}(E^*, \ell))
\]
Potential energy surface of dinuclear system

- entrance channel;
- fusion channel;
- and d are quasifission channels

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

Conclusions

The complete fusion mechanism in the heavy ion collisions strongly depends on the entrance channel peculiarities: mass (charge) asymmetry, shell structure of interacting nuclei, beam energy and angular momentum (impact parameter of collision).

The hindrance to formation of the compound nucleus is mainly caused by quasifission and fast-fission processes which are in competition with complete fusion.

Mass and angular distributions of the fusion-fission, quasifission and fast-fission processes may overlap making difficulties at analysis experimental data.

Quasifission takes place at all values orbital angular momentum.

The experiments by registration of binary fragments of reactions in coincidence with neutrons, charged particles and gamma-quanta allow to reconstruct true reaction mechanism.