High energy fission reaction via Langevin 4D calculations

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Stochastic approach

Dynamical effect

• path from equilibrium to scission slowed-down by the nuclear viscosity
• description of the time evolution of the collective variables like the evolution of Brownian particle that interacts stochastically with a heat bath.
• excess of prescission particles
• all the parameters of the two dimensional fission fragment distribution and their dependence on various parameters of compound nucleus

Observables

• Pre- and post-scission particle multiplicity
• Mass, charge, angular distributions of the fragments
• Total Kinetic Energy distribution
• Isotopic distribution, $\langle N/Z \rangle$....

Limitations

• Wide domain in compound nucleus mass (from 50 to 250)
• Excitation energy $E^{\star}$ (from 30 to 250MeV)
• Angular momentum L (from 0 to 100hbar)

Stochastic aproach

Langevin Equations

$$\frac{dq_i}{dt} = \sum_j [M^{-1}(\vec{q})]_{ij} p_j$$

$$\frac{dp_i}{dt} = -\frac{1}{2}\sum_{j,k} \frac{d[M^{-1}(\vec{q})]_{jk}}{dq_i} p_j p_k - \frac{V(\vec{q})}{dq_i} - \sum_{j,k} \gamma_{ij}(\vec{q})[M^{-1}(\vec{q})]_{jk} p_k + \sum_j g_{ij}(\vec{q})\Gamma_j(t)$$

Ingredients

Inertia ($[M^{-1}(\vec{q})]_{ij}$)
Friction ($\gamma_i(t)$) and fluctuation (g_{ik})
Macroscopic potential ($V(\vec{q})$)

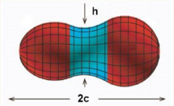
Coupling to the evaporation

Pre and post- scission emission of neutrons, protons, α and γ.

Model ingredients

Collective coordinates (4D)

- Description of the nuclear shape by elongation, neck and asymmetry - 3 parameters.
- **K** spin about the fission (symmetry) axis



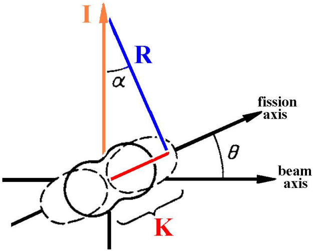
- c - the elongation of the nucleus
- h - constriction coordinate
- α - mass-asymmetry parameter related to the ratio of the masses of nascent fragments

Energies

- Potential energy in deformation space e.g: LSD

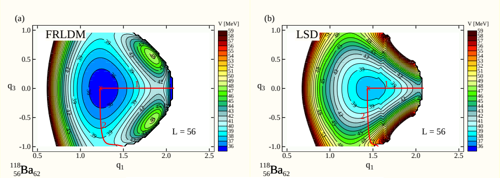
$$
\begin{aligned}
\mathbf{E_{lsd}(Z,N;q)} &= \mathbf{b_{vol}\{1-\kappa_{vol}T^2\}\,A + b_{surf}\{1-\kappa_{surf}T^2\}\,A^{2/3}B_{surf}(q)} \\
&+ \mathbf{b_{curv}\{1-\kappa_{curv}T^2\}\,A^{1/3}B_{curv}(q) + \frac{3}{5}e^2\frac{Z^2}{r_0^{ch}A^{1/3}}B_{Coul}(q)} \\
\mathbf{T} &= \mathbf{(N-Z)/A}
\end{aligned}
$$

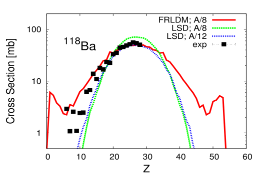
- Rotational energy: $E_{rot}(q,I,K) = \frac{\hbar^2 I(I+1)}{2J_{\parallel}(q)} + \frac{\hbar^2 K^2}{2J_{\perp}(q)}$



Fission Dynamics - 3D Langevin Equations

Potential Energy Surface tests: LSD or FRLDM

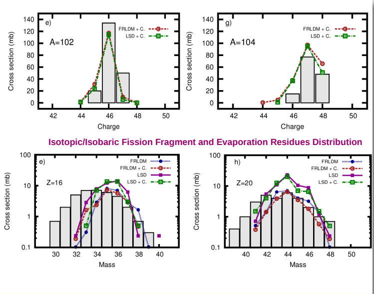




The change of the fission fragment mass distribution due to different PES taken to solve Langevin equations

Sierk et al., PRC 33 (1986) 2039, Möller et al. PRL 92, 072501 (2004) G. Ademard et al., PRC ***83****, 054619 (2011), K. M. et al., PRC* ***84****, 014610 (2011)*

Pre and Post-scission emission



The secondary emission as a doorway to better reproduction of the isotopic/isobaric mass and charge FF and evaporation residues distribuions, pre and post scission particle multiplicities

K. M. et al., PRC 88, 054614 (2013),

K. M. et al.,Acta Phys. Pol. **B44**, 293 (2013),

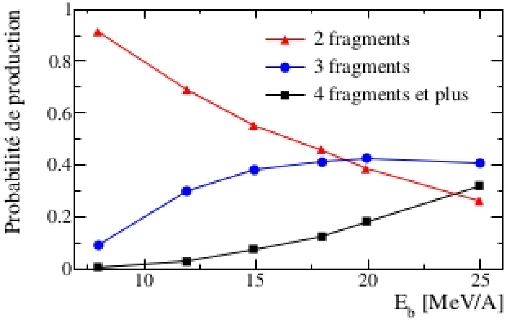
Fission or multifragmentation?

Experimental data

- Xe+Sn central collision from 8 to 25 MeV/A measured with INDRA

Reaction mechanism

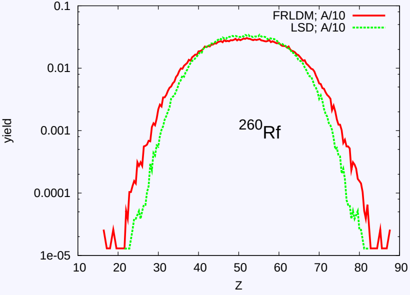
- The number of fragments (Z≥10) increases with beam energy
- Formation of the compound nucleus?
- From fission to multifragmentation



A. Chbihi et al, JoP: Conf. Ser. 420, 012999(2013)

Results: Fission Fragment charge distribution

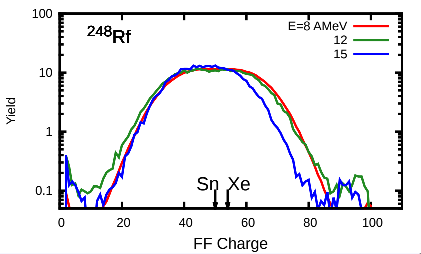
Potential Energy model vs FF charge



The charge distribution for ^{260}Rf for fission channel calculated with the FRLDM (red) and LSD (green).

K. M. et al PRC 84, 014610 (2011)

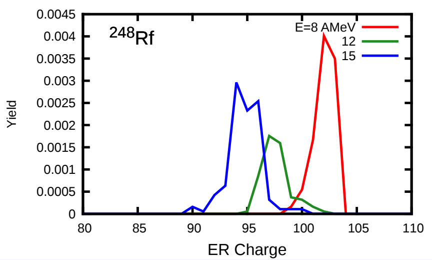
Excitation energy vs FF charge

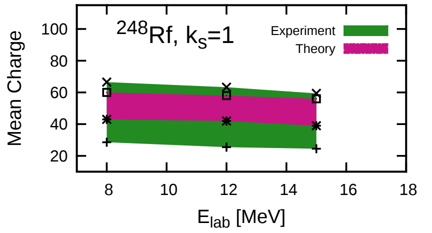


The fission fragments before the postscission particle emission.

Charge Distribution – Xe + Sn → Rf

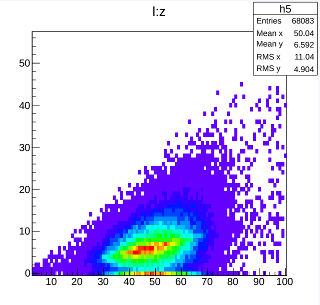
Primary fission

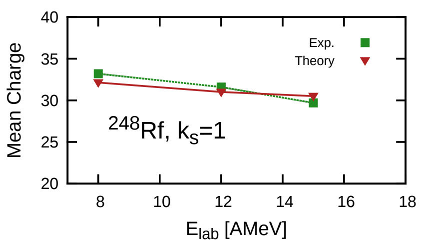




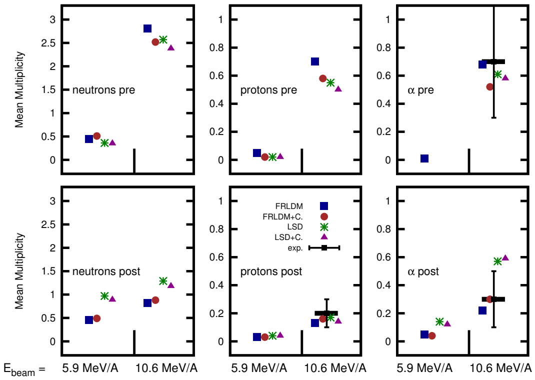
Exp: D. Gruyer et al, EPJ Web of Conferences 62, 07006 (2013)

Secondary fission





Particle Multiplicities



Reaction:

$^{84}\mathrm{Kr}+^{27}\mathrm{Al}\rightarrow\ ^{111}\mathrm{In}$

K.M. et al EPJ Web of Conf. 62, 02002 (2013);

Y. Futami, *et al.*, Nucl. Phys.

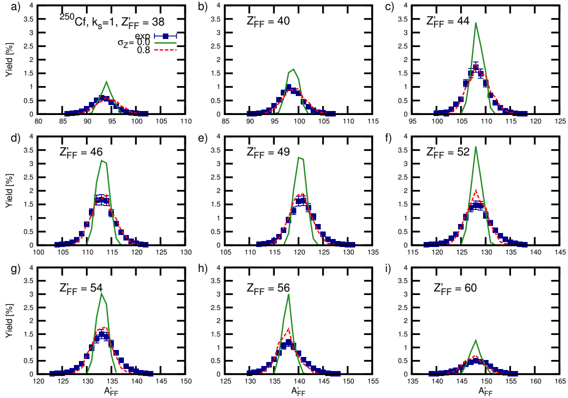
A 607, 85 (1996).

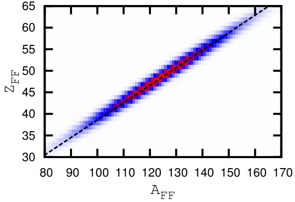
The particle multiplicity emitted during fission (pre) and from the evaporation residue (ER) coming from the primary and secondary FF of the ^{248}**Rf** compound nucleus. The particle multiplicity from Abdu Chbihi (priv. comm.)

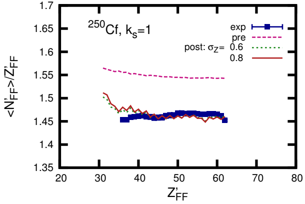
E_{lab} [AMeV]	primary				secondary			
	$\langle p_{pre}\rangle$	$\langle p_{exp}\rangle$	$\langle \alpha_{pre}\rangle$	$\langle \alpha_{exp}\rangle$	$\langle p_{pre}\rangle$	$\langle p_{exp}\rangle$	$\langle \alpha_{pre}\rangle$	$\langle \alpha_{exp}\rangle$
8	0.8236	0.696	0.005	0.417	0.038	0.197	0.055	0.794
12	3.7837	1.838	0.079	1.321	0.153	0.475	0.146	2.418
15	6.648	2.367	0.183	1.876	0.188	0.567	0.181	3.367

Isotopic distributions: U + C→Cf (E_{lab}=6.2 AMeV)

The charge variance is nescessary to reproduce the isotopic distribution.







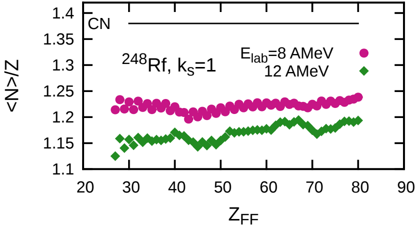
K.M., C. Schmitt, P. Nadtochy PRC 91, 041603(R) (2015),

M. Caamano et al. PRC **88**, 024605 (2014)

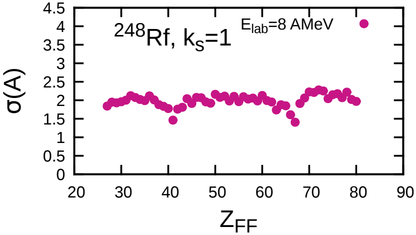
$N/Z(^{250}Cf)$=1.55

Link with the symmetry energy?

Isotopic distribution – Xe + Sn



The predicted neutron excess for fission of ^{248}Rf for two excitation energies.



The widths of the isotopic distribution of the primary fission fragments.

W. A. Friedman, PRC 69, 031601(R) (2004)

$$\sigma^{-2} = 8(C_{sym}/T)(Z/A)^3[Z/(z_1 z_2)]$$

Can we learn something new about the symmetry energy with help of Langevin equations?

Summary

- Total number of nucleons emitted is well reproduced but the problem with the evaporation code.
- Isotopic distribution is very sensitive but we need more experimental data.
- For symmetric projectile-target systems - 4D Langevin could be the way to descriminate between fission, and other possible channels such as quassifission or multifragmentation.
- Fission times can be studied too:
  For Xe+Sn @ 12AMeV: $\langle t^{Langevin} \rangle \approx 8{\cdot}10^{-21}$s
  $\langle t^{exp} \rangle \approx 2.2{\cdot}10^{-21}$s