Teoretyczny opis de-ekscytacji jąder gorących

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Outline

- **Tworzenie jądra złożonego i przedrównowagowa emisja cząstek (HIPSE)**
- **Metoda termicznych fluktuacji kształtu i Gigantyczne Rezonanse Dipolowe**
- **Statystyczna deekscytacja jądra złożonego (GEMINI++)**
- **Równania Langevina i dynamika rozszczepienia**

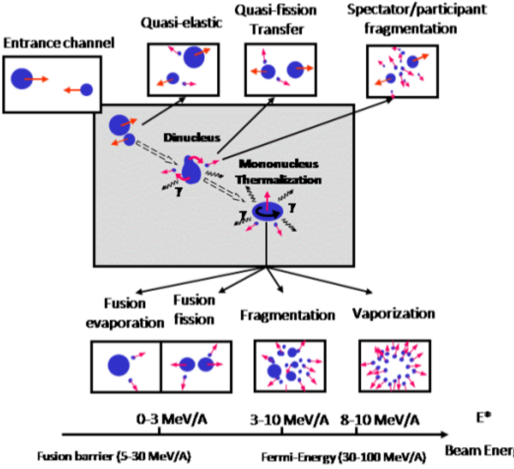


FIG. 33: *Illustration of the diversity of reaction mechanisms. Top: competing phenomena fossil quasi-target and quasi-projectile survive. Middle: competing phenomena where compound nucleus is eventually formed at the intermediate reaction stage. The excitation and/or beam energy for which these mechanisms appear are given in the bottom part (Ad from (Lacroix, 2002b)).*

Experimental Results - $^{48}Ti+^{40}Ca \rightarrow ^{88}Mo$

M. Ciemała et al. Phys. Rev. C 91, 054313 (2015)

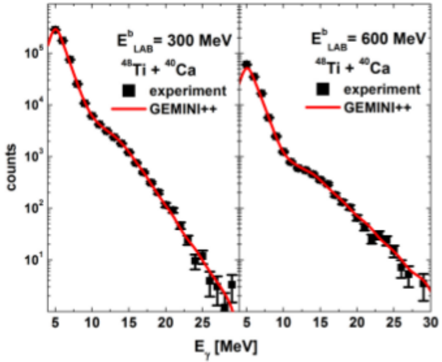
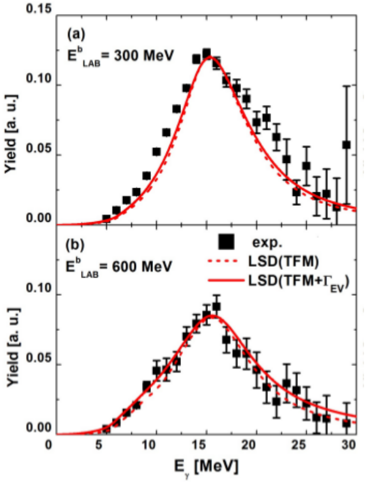
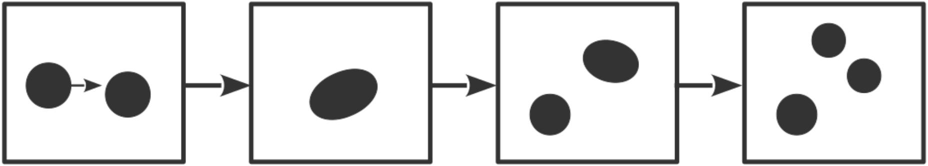


FIG. 9. (Color online) A comparison of the γ-ray spectra from the ^{48}Ti + ^{40}Ca reaction, at the beam energies of 300 MeV and 600 MeV, with the results of the *GEMINI++* fit (see text).



Sequential Fission Procedure

Dynamical evolution of compound nucleus and later each primary fission fragment.

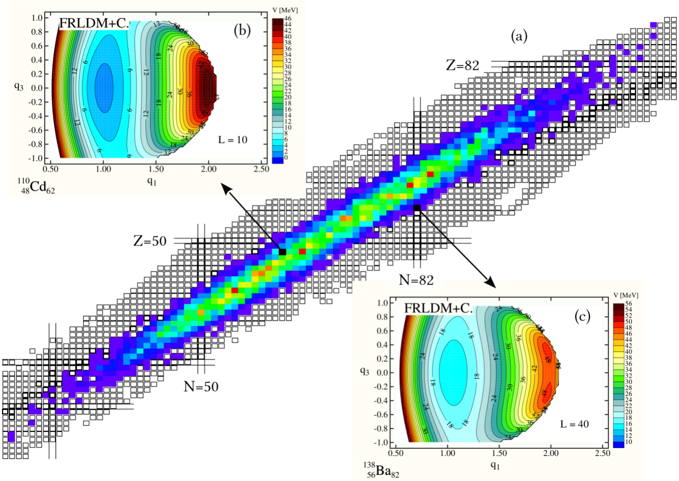


Fusion → CN → I fission → II fission

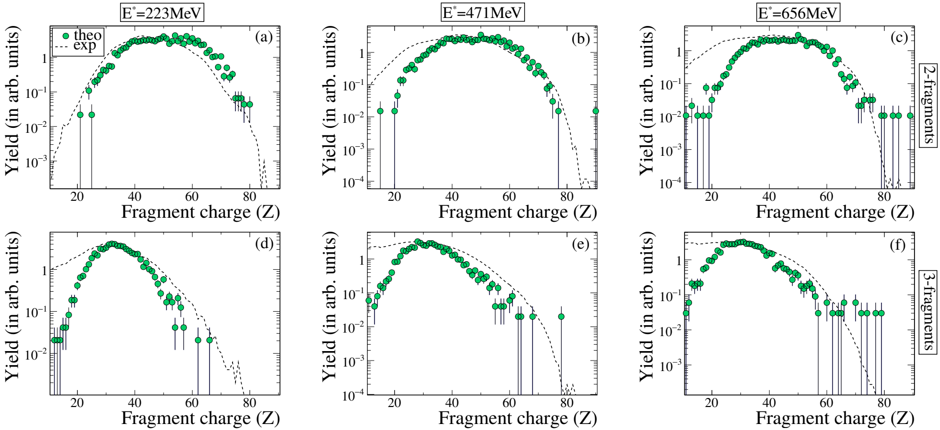
Xe+Sn central collision from 8 to 25 MeV/A measured with INDRA

Sequential Fission Procedure: II step

II. Dynamical evolution of each primary fission fragment.

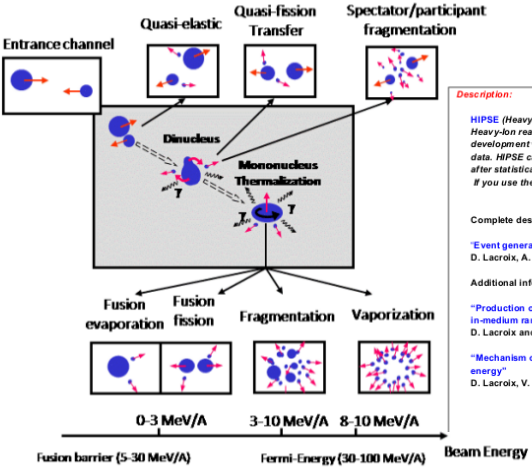


Final fragment charge distribution – Xe + Sn →Rf



E$_{lab}$=8 AMeV E$_{lab}$=12 AMeV E$_{lab}$=15 AMeV

Reaction scenarios - HIPSE



Description:

HIPSE (Heavy-Ion Phase-Space Exploration) is a phenomenological model dedicated to Heavy-Ion reactions around Fermi energy. The main goal of our group during its development was to identify minimal physical hypothesis to reproduce experimental data. HIPSE can be used as an event generator and gives access to partitions before and after statistical decay.

If you use the model or/and encounter problem, please contact us (Denis Lacroix).

Complete description of the model can be found in:

"Event generator for nuclear collisions at intermediate energies"
D. Lacroix, A. Van Lauwe, and D. Durand, *Physical Review C 69, 054604 (2004)*

Additional information and some applications can be found in:

"Production of light particles in low energy spallation and in fragmentation reaction by in-medium random clusterization"
D. Lacroix and D. Durand, *arXiv:nucl-th/0505053.*

"Mechanism of light cluster production in nucleon induced reactions at intermediate energy"
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HIPSE dynamical model

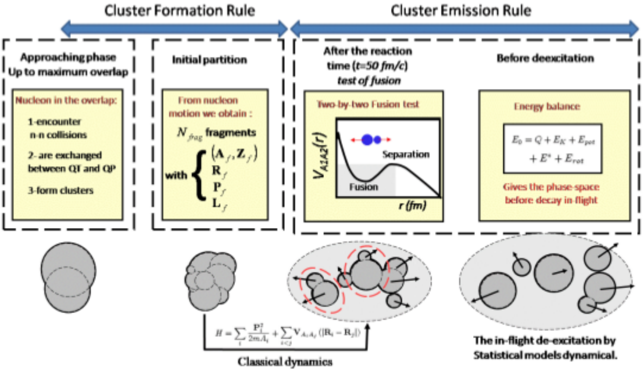

FIG. 38: *Illustration of the different steps to describe nuclear collisions. From left to right are shown: (i) the definition of the participant region after the approaching phase. (ii) the cluster formation. Properties of clusters are directly deduced from properties of nucleons issued from the Thomas-Fermi sampling and eventually distorted by the nucleon-nucleon direct collisions. (iii) Once clusters are formed and after some expansion, a test is made to check if they escape from the attraction of surrounding clusters. If not, the two attracting clusters fuse. (iv) Once the chemical freeze-out is reached, a global energy balance is made to check that the partition is energetically accessible. Then the excitation energy deduced from the energy balance is shared between clusters (v) The in-flight decay is performed. Calculation is stopped once all fragments are cold.*

HIPSE dynamical model

Download HIPSE (Heavy-Ion Phase-Space Exploration)

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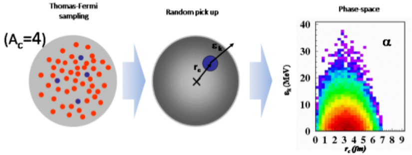


FIG. 35: *Left: Schematic illustration of the Thomas-Fermi sampling. To form an alpha particle, 4 nucleons (2 neutrons-2 protons) are picked up randomly. The phase-space is obtained by choosing 4 nucleons repeatedly and by computing the alpha properties from the nucleons properties. Right: The correlation between the position and kinetic energy per nucleon is obtained for the α particles using a random sampling assumption for the nucleons forming the α. This two-dimensional distribution corresponds to the total "accessible" phase-space to the α.*

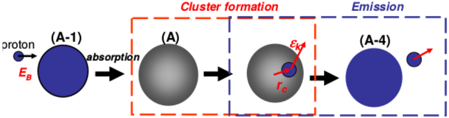


FIG. 34: *Schematic representation of a three steps nucleon-induced reaction. In this simplified experiment, a nucleon with beam energy close to the Fermi energy is absorbed by a nucleus. Then, we assume that the cluster emission occurs in two steps, first the cluster is formed in the medium and then it escape.*

HIPSE - Results

LACROIX, VAN LAUWE, AND DURAND PHYSICAL REVIEW C **69**, 054604 (2004)

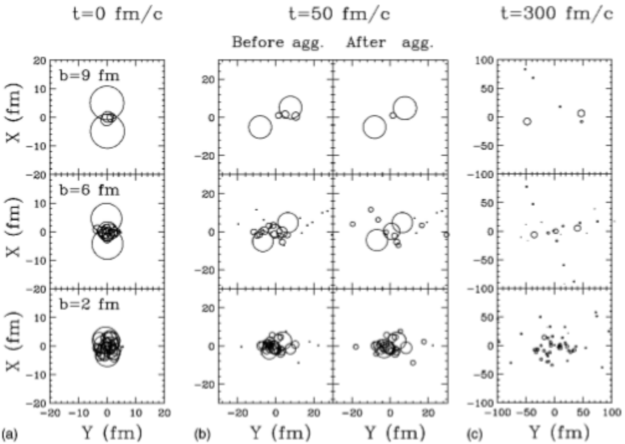


FIG. 2. Example of nuclear dynamics obtained for the reaction ^{129}Xe+^{120}Sn at E = 50 MeV/nucleon. From top to bottom, the initial impact parameters b=9 fm, b=6 fm, and b = 2 fm are presented. In each case, from left to right figures correspond to the initial cluster configuration (t=0 fm/c), the configuration before and after the reaggregation (t=50 fm/c), and during the deexcitation (t = 300 fm/c).

HIPSE

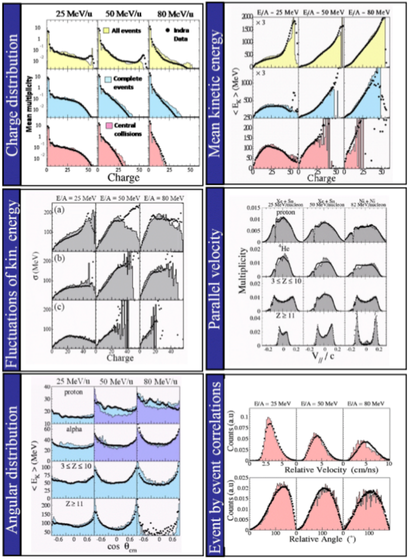
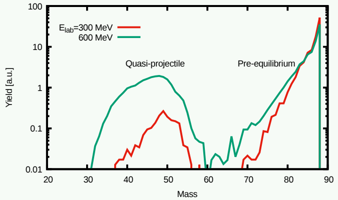
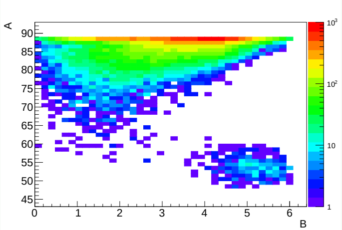


FIG. 40: *Several observables (filled circles) extracted from $^{129}Xe + ^{119}Sn$ experiments at beam energies E_B = 25, 50, 80 MeV/A are systematically compared with filtered events generated with the HIPSE model (solid lines). When the selection type of the data is not mentioned, namely "all events", "complete events" or "central collisions", data correspond to complete events, i.e. events where at least 80% of the charge has been detected. Comparison are taken from (Lacroix et al., 2004b; Van Lauwe, 2003).*

Entrance channel effect - ^{48}Ti+^{40}Ca$\rightarrow$ ^{88}Mo

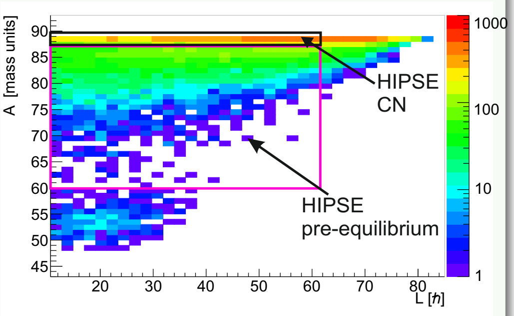
Mass distribution





The correlation of the prefragment mass with the impact parameter in ^{48}Ti(600 MeV)+^{40}Ca.

Outcome from the HIPSE code



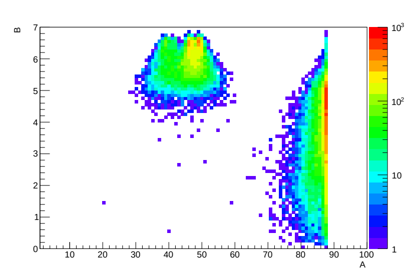
Compound nuclei created by HIPSE code. The L_{cut}=64 $\hbar$ marks the spin at which the fission barrier vanishes.

K.M. et al Acta Phys. Pol. B Proc. Supp. 11, 109 (2018)

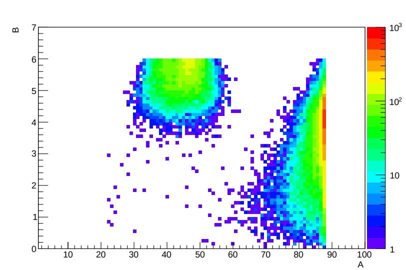
Entrance channel effect - ^{48}Ti+^{40}Ca$\rightarrow$ ^{88}Mo

Distance between colliding nuclei and compound mass

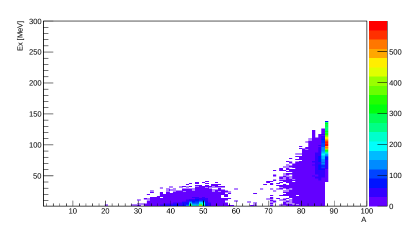
300 MeV

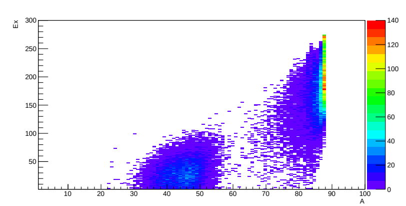


600MeV

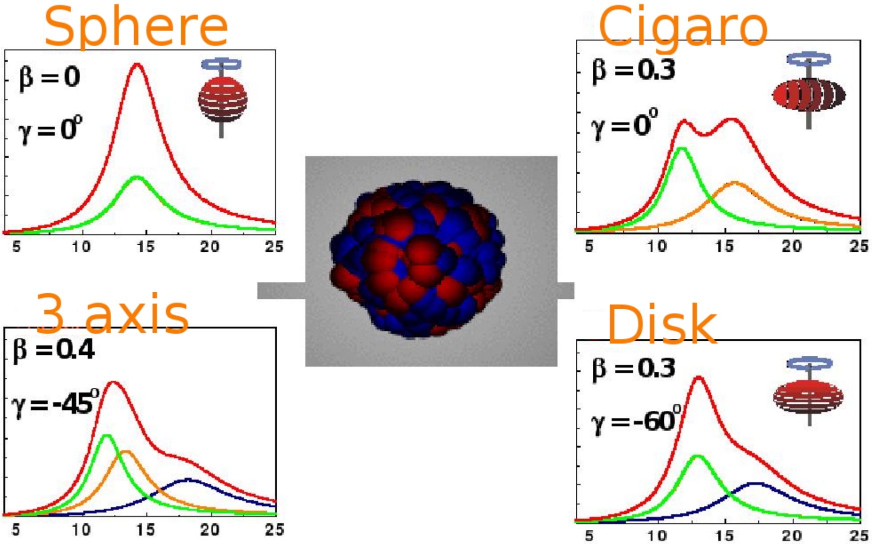


Excitation energy of composed nuclei

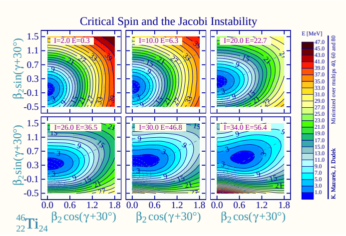


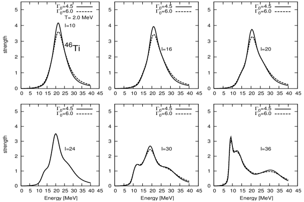


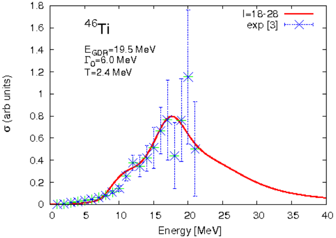
Giant Dipole Resonance - GDR

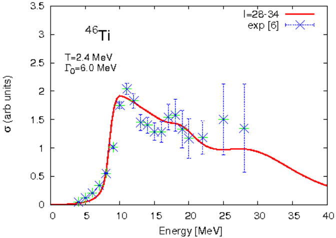


Thermal Shape Fluctuation Model - GDR





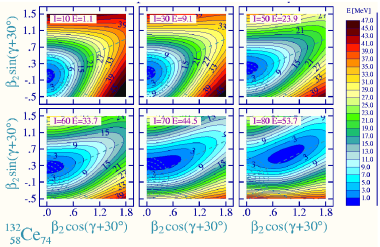


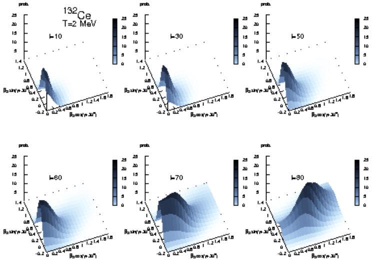


Experiment: A. Maj et al., Nucl. Phys. A 731, 319 (2004).

Thermal Shape Fluctuation Model - GDR

[K. Pomorski, J. Dudek, Phys. Rev. C 67,044316(2003)]. (A=Z+N; t=(N-Z)/A)





The macroscopic energy: Lublin - Strasbourg Drop

$$E_{LSD}(Z,N;def) = b_{vol}(1-\kappa_{vol}t^2)A$$
$$+b_{surf}(1-\kappa_{surf}t^2)A^{2/3}B_{surf}(def)$$
$$+b_{curv}(1+\kappa_{curv}t^2)A^{1/3}B_{curv}(def)$$
$$+\frac{3}{5}e^2\frac{Z^2}{r_0^{ch}A^{1/3}}B_{Coul}(def) - C_4\frac{Z^2}{A}$$
$$-10\cdot\exp(-4.2|t|)$$

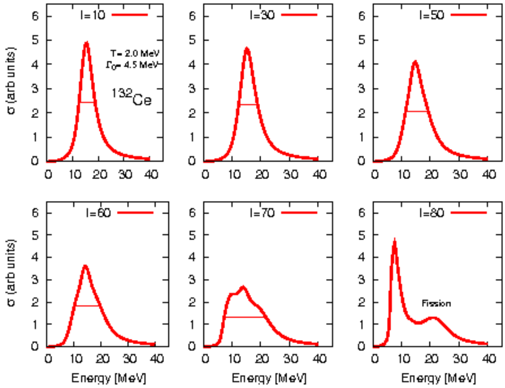
Free energy

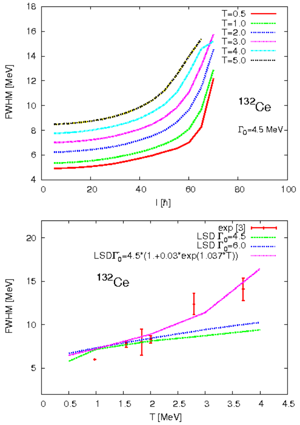
$$F(T) = E_{LSD} + \frac{I(I+1)}{2\mathcal{J}(def)} - TS(def,I,T)$$

The GDR probability

$$p(def;I;T) = exp\left\{-\frac{F(T)}{kT}\right\}$$

Thermal Shape Fluctuation Model - GDR





$$\sigma(E_\gamma, T, I) = \sum_{(x,y)} p((def); I; T) \sum_{k=1}^{5} f_k(E_\gamma, (def))$$

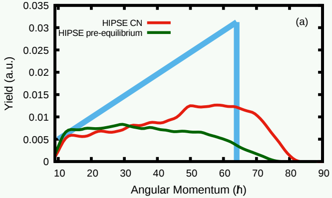
$$f_k(E_\gamma, (def)) = \frac{\sigma_k \Gamma_k E_\gamma^2}{(E_\gamma^2 - E_{GDR,k}^2)^2 + E_\gamma^2 \Gamma_k^2}$$

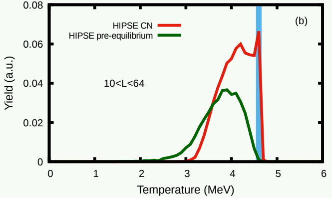
K. M., M. Kmiecik, A. Maj, J. Dudek,

N. Schunck, Acta Phys. Pol. B 38, 1455 (2007)

Entrance channel effect - $^{48}Ti + ^{40}Ca \rightarrow {}^{88}Mo$

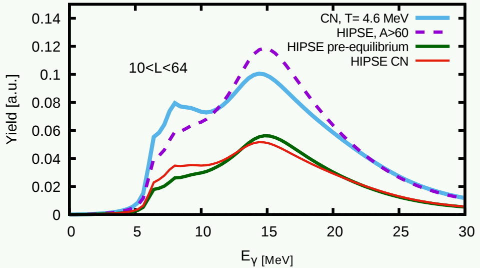
Angular momentum and temperature distribution





Blue line shows the values of the spin/ temperature taken usually for hot compound nucleus ^{88}Mo.

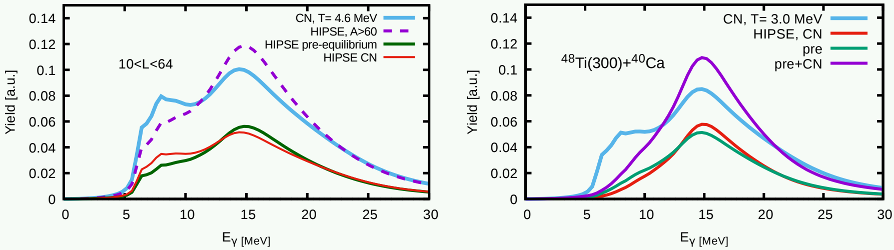
HIPSE + TSFM



- The strength functions of the GDR built in compound nucleus ^{88}Mo (CN)
- For ensemble of nuclei generated in the HIPSE code:
  - compound nucleus (HIPSE CN), the nuclei produced with pre-equilibrium
  - emission (HIPSE pre-equilibrium) and integrated over the prefragment mass
  - distribution (HIPSE A>60).
- All calculations were done for 10-64 $\hbar$ range of angular momentum.

Entrance channel effect - ^{48}Ti+^{40}Ca$\rightarrow$ ^{88}Mo

HIPSE + TSFM



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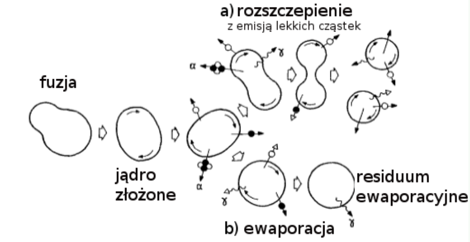
Fission of the Nucleus as a Stochastic Process

Stochastic process – or often random process, is a collection of random variables representing the evolution of some system of random values over time. This is the probabilistic counterpart to a deterministic process (or deterministic system). Instead of describing a process which can only evolve in one way (as in the case, for example, of solutions of an ordinary differential equation), in a stochastic, or random process, there is some indeterminacy: even if the initial condition (or starting point) is known, there are several (often infinitely many) directions in which the process may evolve.(http://pl.wikipedia.org)

Binary fission



Statistical model of compound nucleus decay

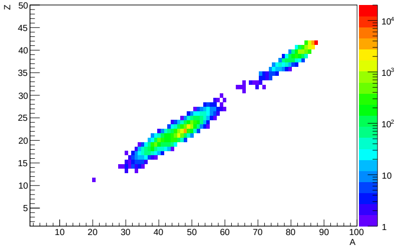
GEMIN++ statistical model (R.j. Charity, Phys. Rev. C82,014610 (2010))

- is widely used statistical model code
- adopts a default set of parameters obtained by fitting data from several previous experiemnts
  - parameters are tuned for heavy nuclei (A>150)
  - there aren't many experimental data to fix parametrs for medium-light nuclei
- tunning parameters of GEMINI++ are:
  - level density
  - Coulomb barrier distribution
  - yrast energy parametrization
  - etc. . .

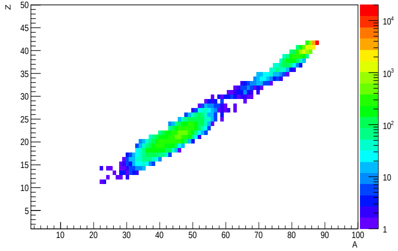
M. Ciemała: In the present studies, the statistical code GEMINI++ with an option allowing to treat explicitly the GDR emission [Ciemala et al. Acta Phys. Pol B44, 611 (2013)] was employed for the first time for such an analysis.

Mass/charge distribution of initial set of nuclei done with HIPSE

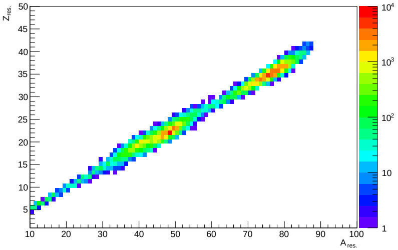
300 MeV

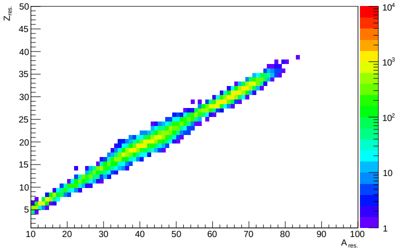


600MeV



Mass/charge distribution after de-excitation with GEMINI++

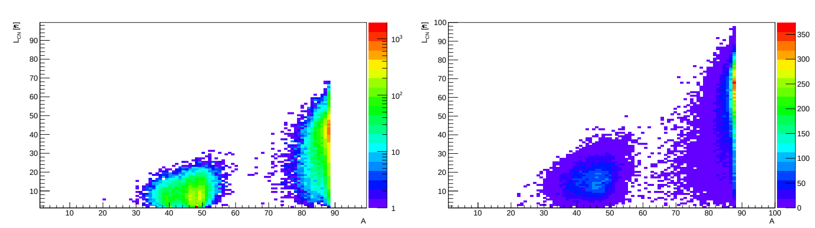




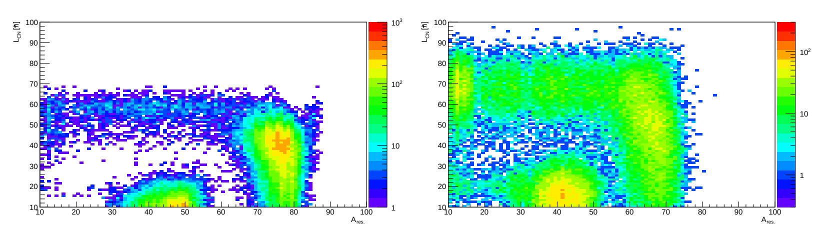
Entrance channel effect - ^{48}Ti+^{40}Ca$\rightarrow$ ^{88}Mo

Angular momentum of initial set of nuclei

300 MeV 600MeV

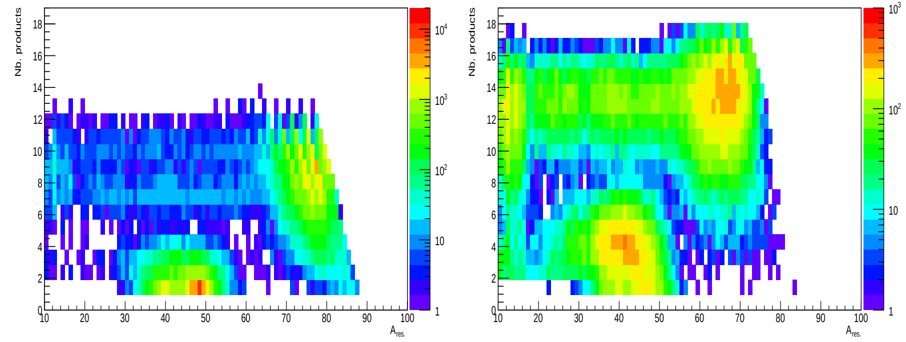


Angular momentum after de-excitation with GEMINI++



Entrance channel effect - $^{48}Ti+^{40}Ca \rightarrow$ ^{88}Mo

Number of products of de-excitation

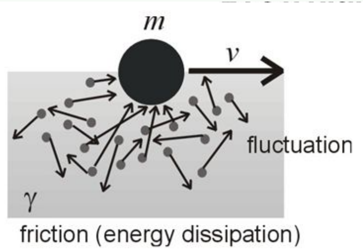


Stochastic approach

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

Brownian motion

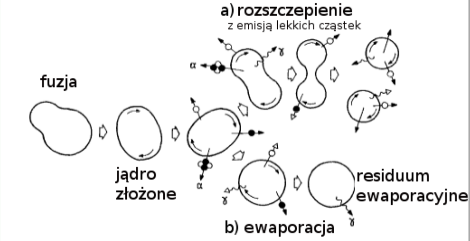


Stochastic Approach

Observables

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

Binary fission



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 100 $\hbar$)

"Fission-fragment distributions within dynamical approach" K. M., P. N. Nadtochy, E. G. Ryabov, G. D. Adeev, Eur. Phys. J. A, 53 (2017) 79E

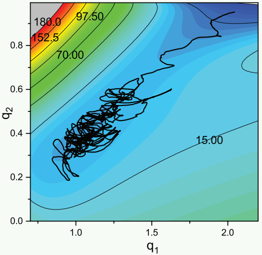
Stochastic Approach

Langevin Equations

are stochastic differential equations describing the time evolution of a subset of the degrees of freedom. These degrees of freedom typically are collective (macroscopic) variables changing only slowly in comparison to the other (microscopic) variables of the system. The fast (microscopic) variables are responsible for the stochastic nature of the Langevin equation.

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

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



V_{po}

Ingredients

Inertia $([M^{-1}(\vec{q})]_{ij})$
Friction $(\gamma_i(t))$ and fluctuation (g_{ik})
Macroscopic potential $(V(\vec{q},K) \to F(\vec{q},K) = V(\vec{q},K) - a(\vec{q})T^2)$

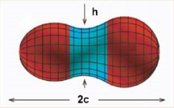
Coupling to the evaporation

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

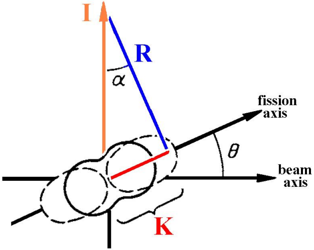


- c - the elongation of the nucleus
- h - constriction coordinate
- α - mass-asymmetry parameter related to the ratio of the masses of nascent fragments

Tilting coordinates - K

$$\delta \mathbf{K} = -\frac{\gamma_{\mathbf{K}}^2 \mathbf{I}^2}{2} \frac{\partial \mathbf{V}}{\partial \mathbf{K}} \delta \mathbf{t} + \gamma_{\mathbf{K}} \mathbf{I} \psi \sqrt{\mathbf{T} \delta \mathbf{t}}$$

where ψ - random number, γ_K - friction parameter (coupling K with heat bath)– J.P.Leastone,S.G.McCalla,PRC79,044611



"Fission-fragment distributions within dynamical approach" K. M., P. N. Nadtochy, E. G. Ryabov, G. D. Adeev, Eur. Phys. J. A, 53 (2017) 79E

Model Ingredients

Energies

- Potential energy in deformation space e.g: FRLDM + Wigner or LSD + Congruence

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

- Rotational energy:

$$E_{rot}(q,I,K) = \frac{\hbar^2 I(I+1)}{2J_\perp(q)} + \frac{\hbar^2K^2}{2J_{eff}(q)}\quad \text{where}$$

$J_{eff}^{-1} = J_{||}^{-1} - J_{\perp}^{-1}$ - the rigid-body moments of inertia.

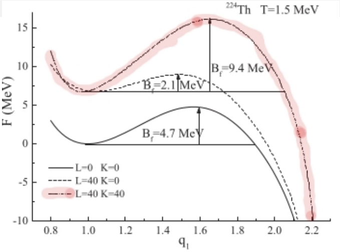
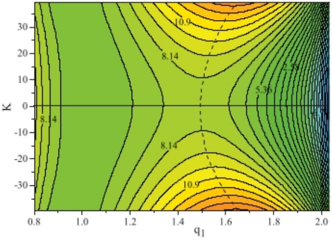


FIG. 1. The Helmholtz free energy along the mean fission trajectory for the ^{224}Th compound nucleus as the function of the elongation parameter q_1, and corresponding fission barriers (B_f) for different combinations of L and K values.

PHYSICAL REVIEW C **85**, 064619 (2012)



Model Ingredients

P.N.Nadtochy, et al., PRC 89,014616

Dissipation of the driving forces

- The wall and window formula reduced by chaos-weighted viscosity parameter $k_s(\vec{q})$.

J. Błocki, J.-J. Shi, W.J.Świątecki, Nucl. Phys. A554, 387;
G. Chaudhuri, Santanu Pal, Phys.Rev C63, 064603

$\eta_{cwwf} = \mu \eta_{wf}$; μ - measure of the chaos in the single particle motion and depends on the instantaneus shape of the nucleus

- The friction parameter controlling coupling between K coordinate and the heat bath.

T. Dosing, J. Randrup, Nucl. Phys. A 433,215; J. Randrup, Nucl.Phys. A 383, 468

$$\gamma_K = \frac{1}{R_N R_{cm} \sqrt{2\pi^3 n_0}} \frac{J_{\parallel} | J_{eff} | J_R}{J_{\perp}^3}$$

where R_N - neck radius, R_{cm}- distance between the center of the nascent fragments, n_0=0.0263 MeV zs fm^{-4} - the bulk flux in standard nuclear mass and $J_R = M_0 R_{cm}^2/4$ for reflection symmetric shape.

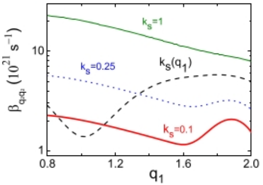


FIG. 2. (Color online) The reduced friction coefficient $\beta_{q_2q_2}$ as a function of elongation collective coordinate for the one-body dissipation mechanism with values of the reduction coefficient from the wall formula $k_s = 1$ (thin solid curve), 0.25 (dotted curve), and 0.1 (thick solid curve) and found on the basis of the "chaos-weighted wall formula" $k_s(q_1)$ (dashed curve) [51].

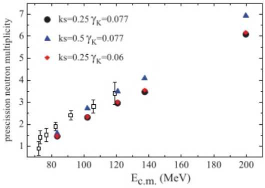
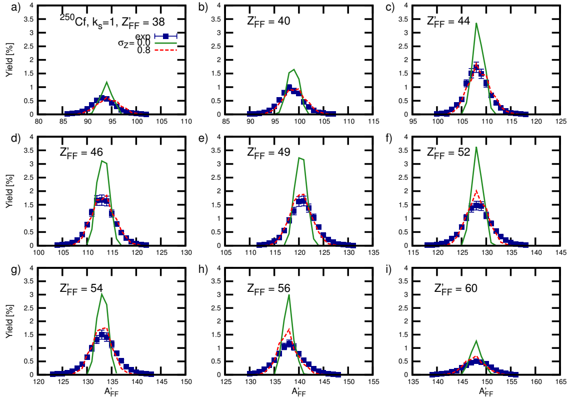
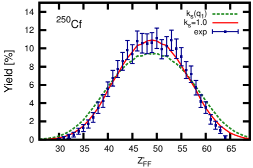


FIG. 7. (Color online) The prescission neutron multiplicity for the compound nucleus ^{224}Th as a function of center-of-mass energy. The open symbols are experimental data from Ref. [71]. The filled symbols are the calculated results with different values of k_s and γ_K, which are marked with the same symbols as in Fig. 6.

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

The charge variance is necessary to reproduce the isotopic distribution.





A finite charge dispersion is necessary to reproduce the isotopic distribution.

$$Z_{FFi}^{UCD} = \frac{A_{FFi} Z_{fiss}}{A_{fiss}}$$

$$Z_{FFi}^{NUCD} = Z_{FFi}^{UCD} \pm 1; \pm 2 \ldots$$

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

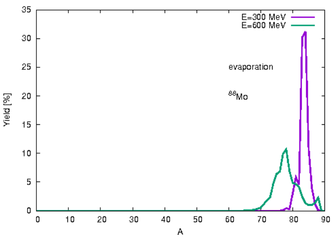
M. Caamano et al. PRC **88**, 024605 (2014)

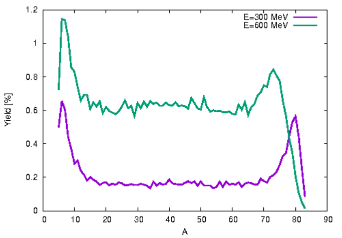
A.V. Karpov, G.D. Adeev Phys.At.Nucl. 65,1596 (2002);

Eur.Phys.J. A 14,169 (2002)

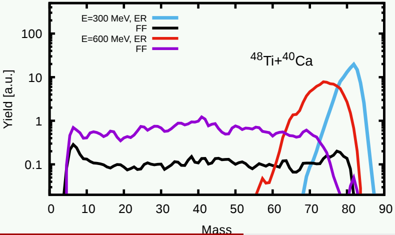
Entrance channel effect - ^{48}Ti+^{40}Ca→ ^{88}Mo

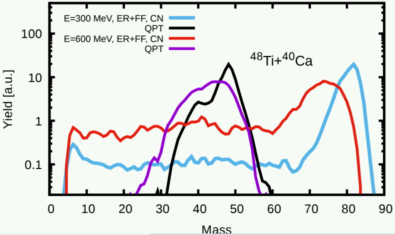
CN + 4DLangevin





HIPSE + 4DLangevin





Summary

- The study of the pre-equilibrium particle emission is crucial for discussion of de-excitation of hot nuclei.
- The preliminary estimation of the influence of the pre-equilibrium emission on the shape of the GDR strength function has been done with the Thermal Shape Fluctuation Model.
- The difference between GDR emitted from HIPSE CN and standard CN is due to higher spin influence in the later.
- The pre-equilibrium emission causes the lowering of the spin and temperature of prefragments thus the low-energy component in GDR spectrum is suppressed.
- Fission, evaporation observables by coupling HIPSE prefragments with statistical (GENIMI++) and dynamical (4DLangevin) de-excitation codes.
- Plans: applying the experiemntal filters and compare with the data.