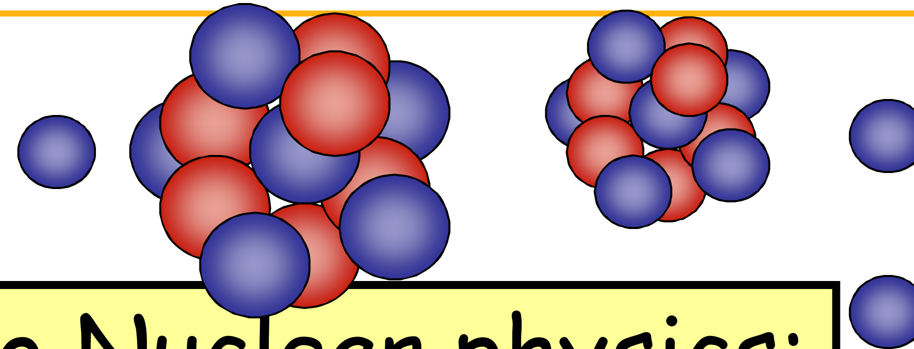
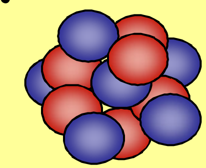


Introduction to Nuclear physics;



The nucleus a complex system

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The nucleus : a complex system

I) Some features about the nucleus

discovery
radius
binding energy
nucleon-nucleon interaction
life time

II) Modeling of the nucleus

liquid drop
shell model
mean field

III) Examples of recent studies

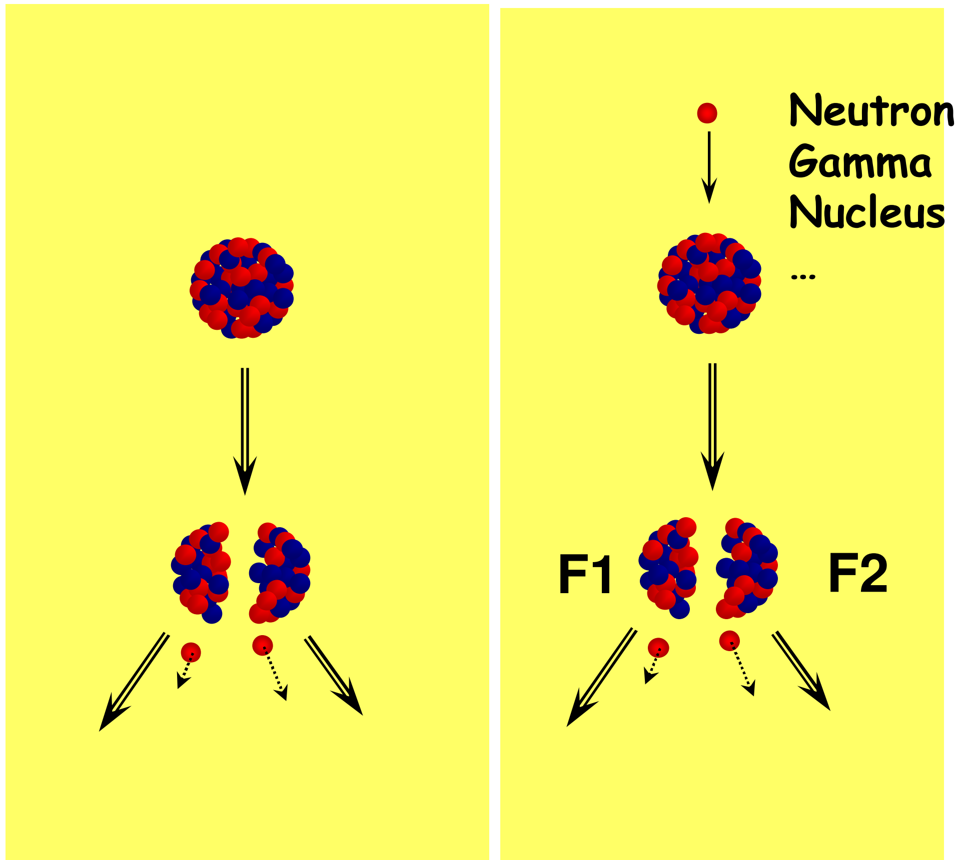
exotic nuclei
isomers
shape coexistence
super heavy

IV) Toward a microscopic description of the fission process

IV) Nuclear fission

The fission process

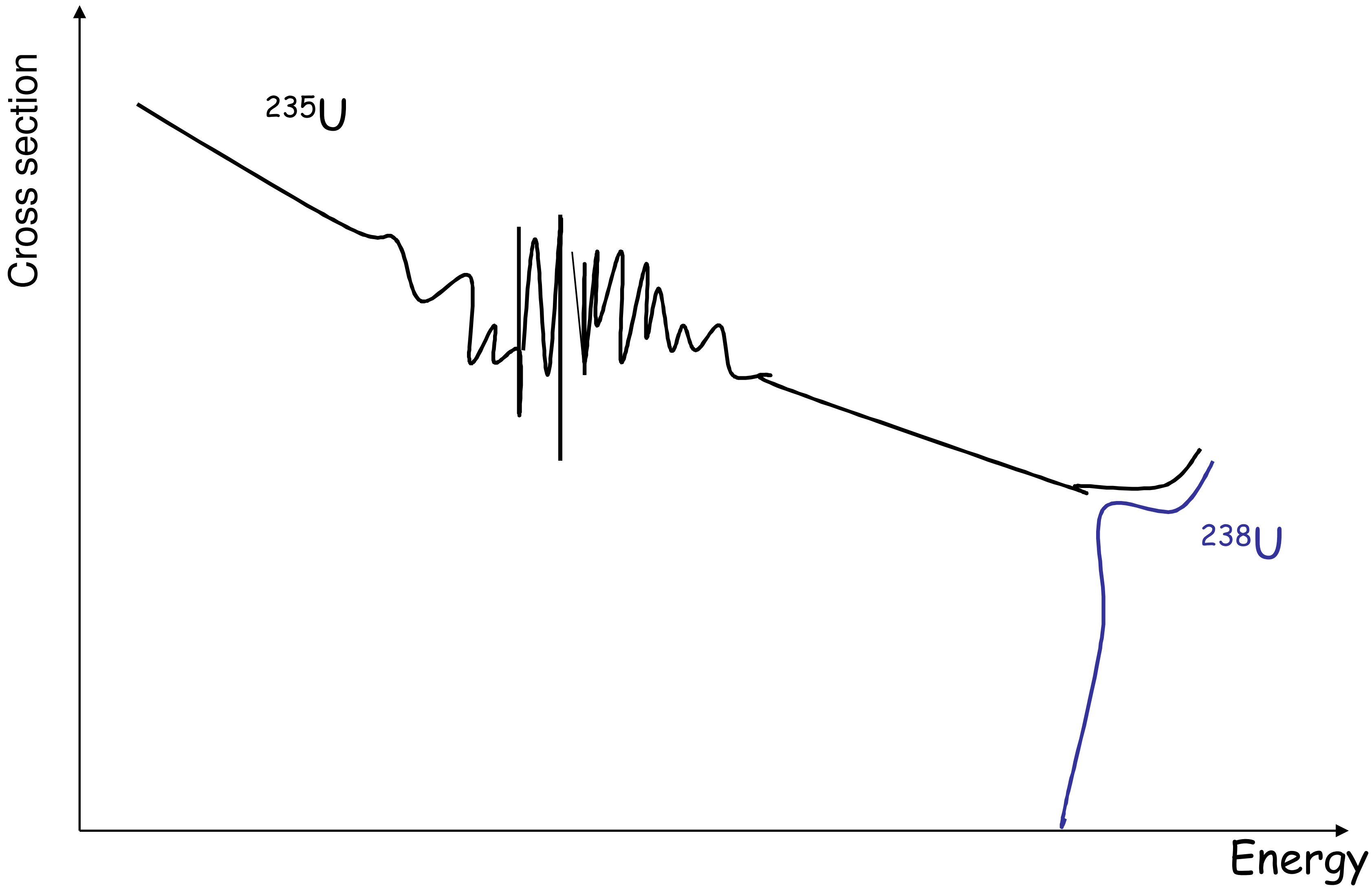
spontaneous | induced



From D. Goutte

Only 19 nuclei are known to fission spontaneously

Fission cross section



Energy balance

High energy released per fission ~ 200 MeV

to compare :

- combustion of 1 atom of carbon = 4 ev
- fission of 1 g of ^{235}U releases the same amount of energy than 2.55 tons of coal

The ~ 200 MeV of energy release are shared as:

Kinetic energy of the fission products	168 MeV
Kinetic energy of the neutrons	5 MeV
Prompt γ emission	7 MeV
Delayed γ emission	6 MeV
Delayed β emission	7 MeV
Neutrinos	10 MeV

The importance of the fission process

- Energy production

  nuclear power plant

  study of new fuel cycles

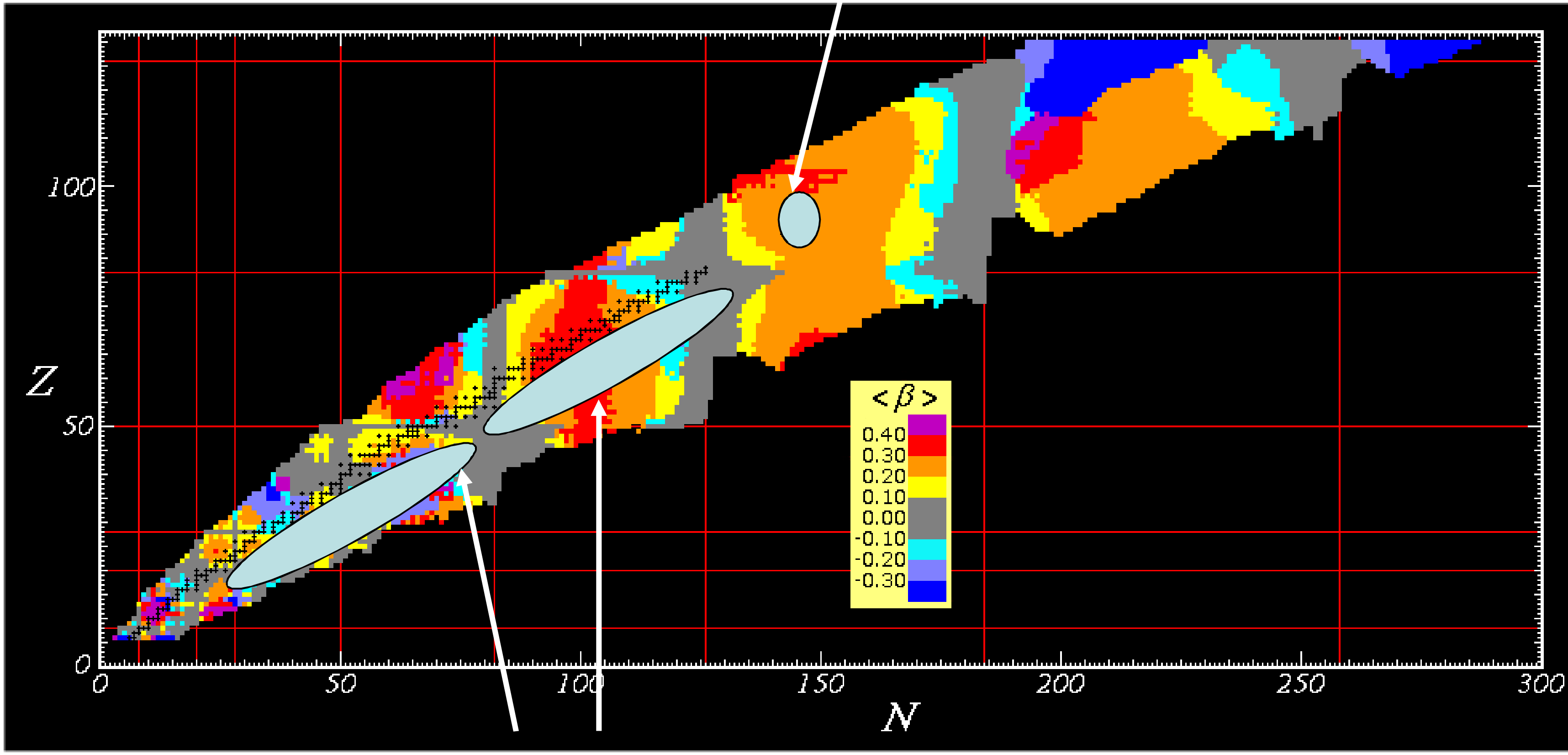
- Production of exotic nuclei
  - ALTO (IPN Orsay, France) , SPIRAL2 (GANIL, France)

- Astrophysics
  - r-process limitation

    limitation in the production of Super Heavy Elements
  - Fission cycling

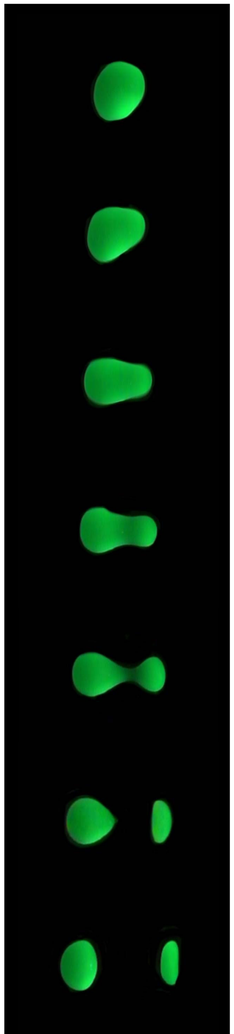
    * depopulation of heavy region
    * enhancement in fission-fragment region
    * structure in nuclide distribution from fission fragments
  - Fission competition in beta-decay towards stability

Actinides (U, Pu...)



Fission fragments

A schematic description of the fission process



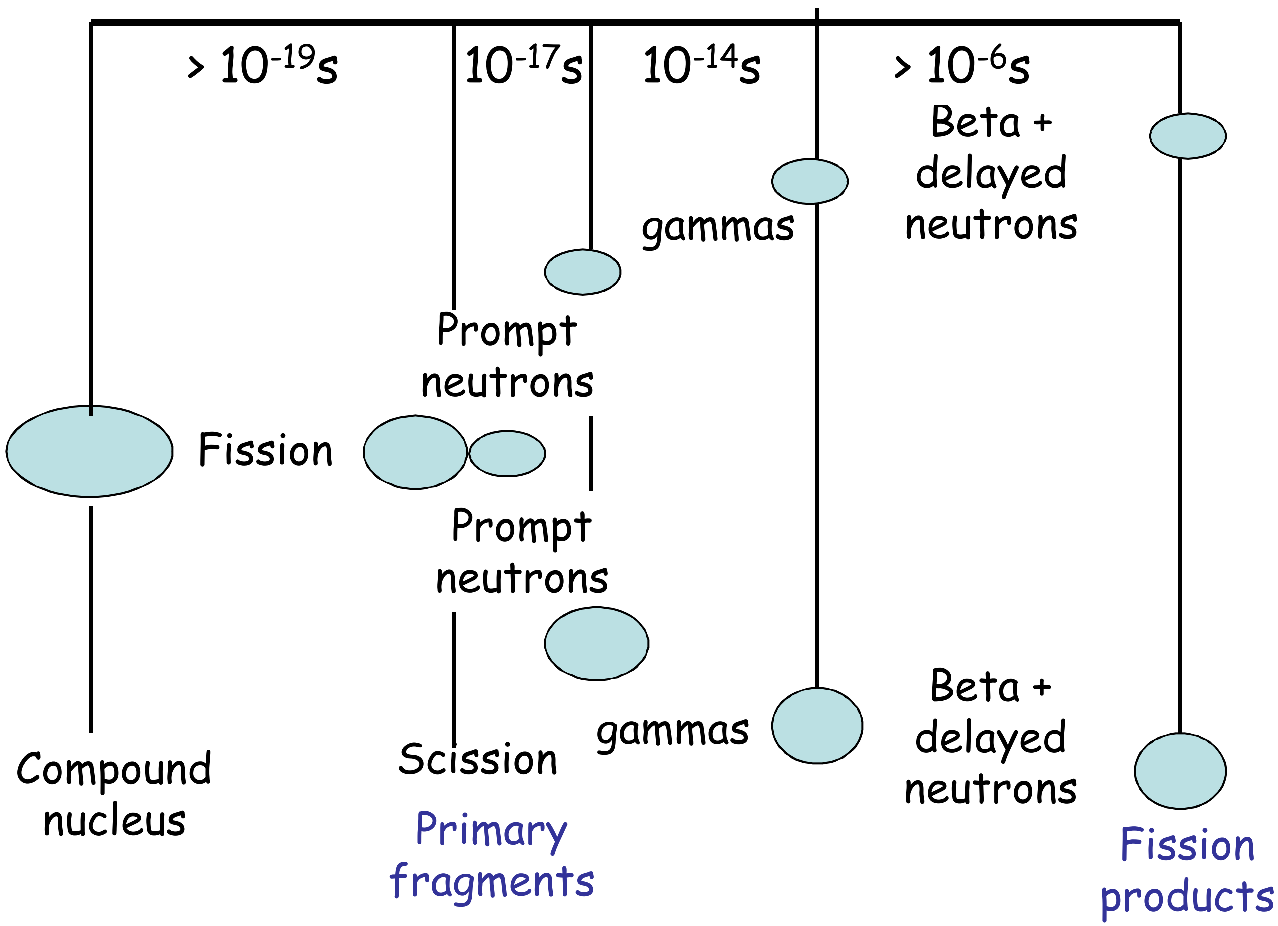
• Competition between coulomb repulsion and the attractive nuclear interaction :

-> oscillation of the nucleus due two this competition
-> the system goes through the saddle point (a critical point) after which the potential energy decreases.

Then
•rapid increase of the deformation up to the scission point (break into two fragments)

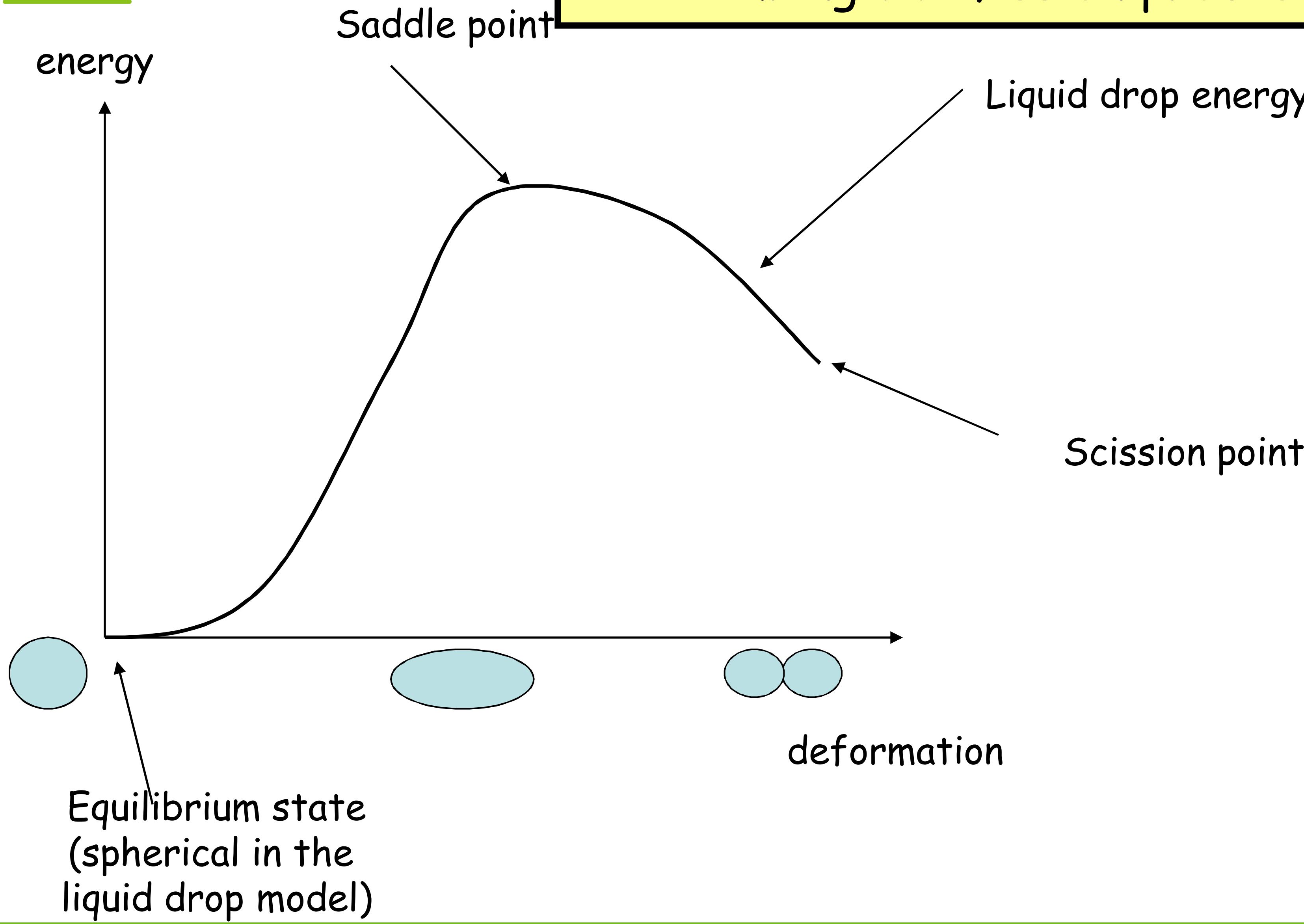
Then
•separation of the fragments
• desexcitation of the fragments

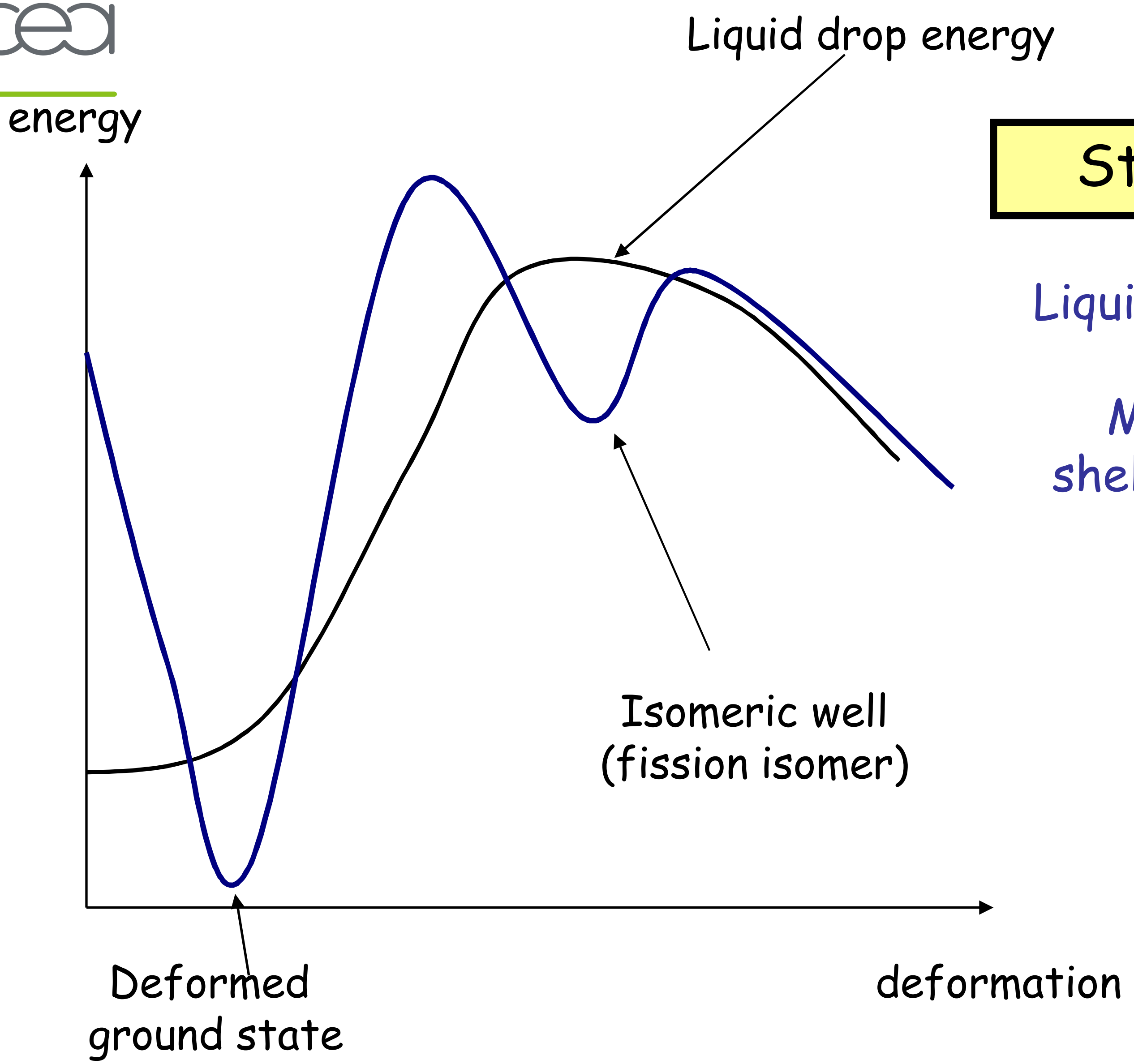
Time scale



J.F. Berger cours Ecole Joliot Curie 2006

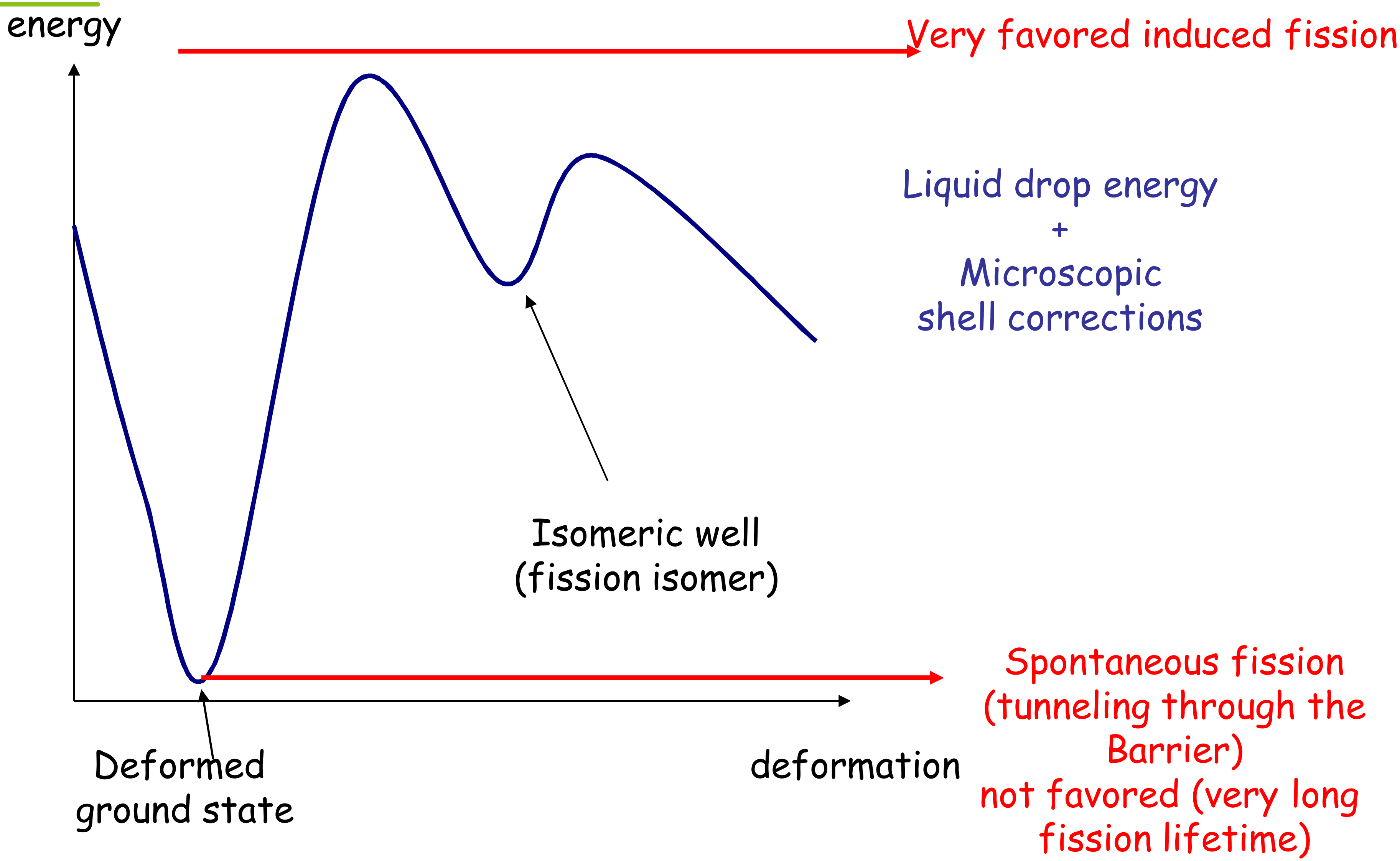
Evolution of the liquid drop energy during the fission process





Structure effects

Liquid drop energy
+
Microscopic
shell corrections


energy
Very favored induced fission
Liquid drop energy
+
Microscopic
shell corrections
Isomeric well
(fission isomer)
Spontaneous fission
(tunneling through the
Barrier)
not favored (very long
fission lifetime)
Deformed
ground state
deformation

Recent experimental studies: some examples

- Cross section measurements
    - absolute measurement for reference nuclei ($^{235-238}U$ and ^{239}Pu)
    - measurement of n-induced fission cross section for minor actinides from 1 eV to 1 GeV. (ex : n_Tof collaboration)
    - surrogate reactions ex: (t,pf) instead of (n,f)

- Fission fragment distributions
    - mass, charge, kinetic energy distributions

- Ternary fission

- Fission/quasi-fission, superheavy production

- Neutron emission (prompt and delayed)

Surrogate reactions

To Study the fission of ${}^{A}Z_{N}$

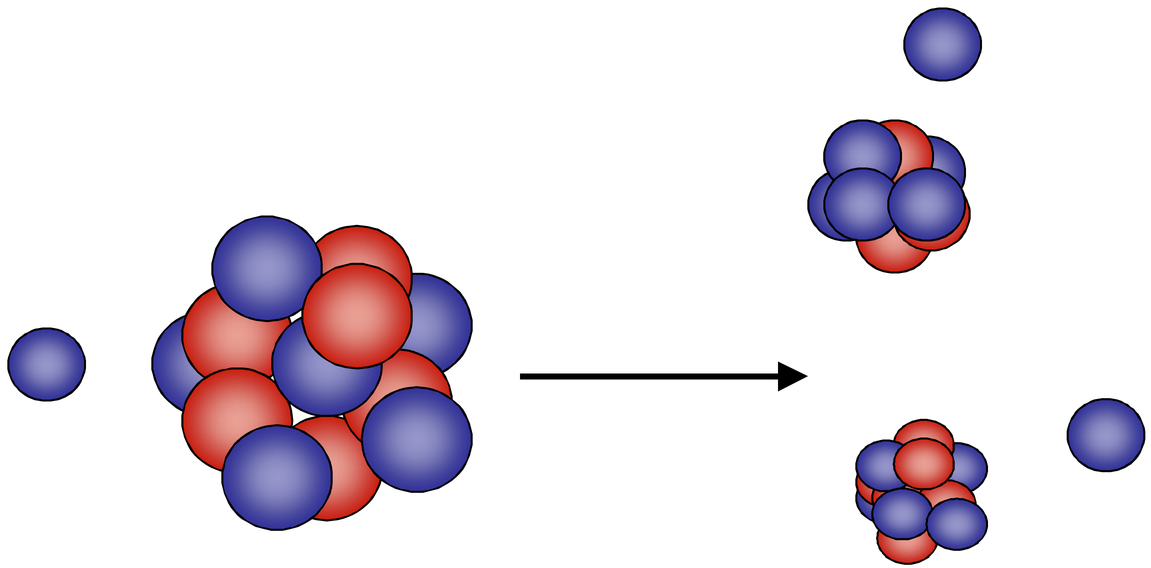
Usual study : n+ ${}^{A-1}Z_{N-1}$ -> ${}^{A}Z_{N}$ -> fission

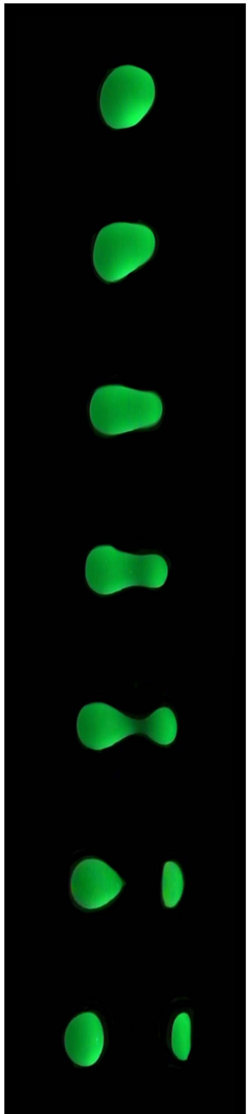
Not possible to make a target

But a target which is possible is ${}^{A-2}Z_{N-2}$

Surrogate reaction : t + ${}^{A-2}Z_{N-2}$ -> ${}^{A+1}(Z+1)_{N}$ -> p+ ${}^{A}Z_{N}$ -> fission

What kind of problem can appear with this surrogate technique ?





The fission process : a challenge for the theory

* From a theoretical point of view, fission appears as a large amplitude motion, in which intervene:

* A large rearrangement of the internal structure of the nucleus with an important role played by the shell effects

* Many types of deformations simultaneously

* Dynamical effects: couplings between collective modes, couplings between collective modes and intrinsic excitations.

$\Rightarrow$ A laboratory for theoretical predictions

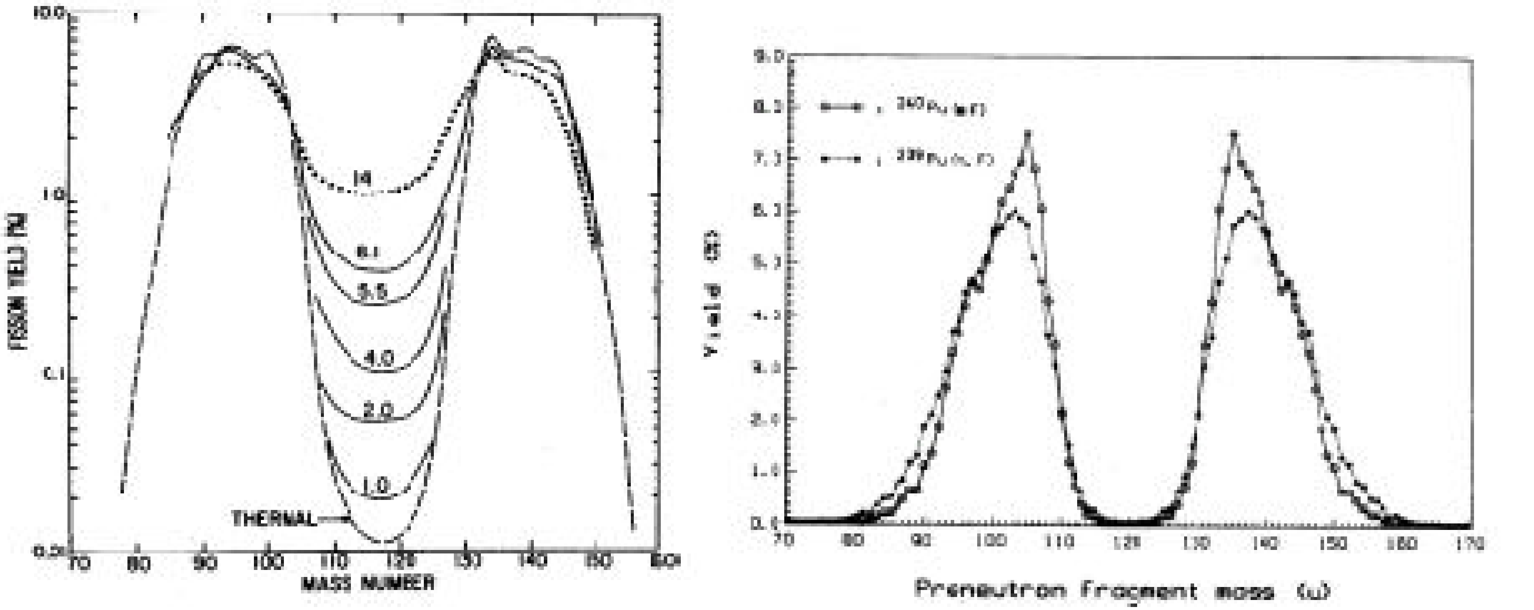
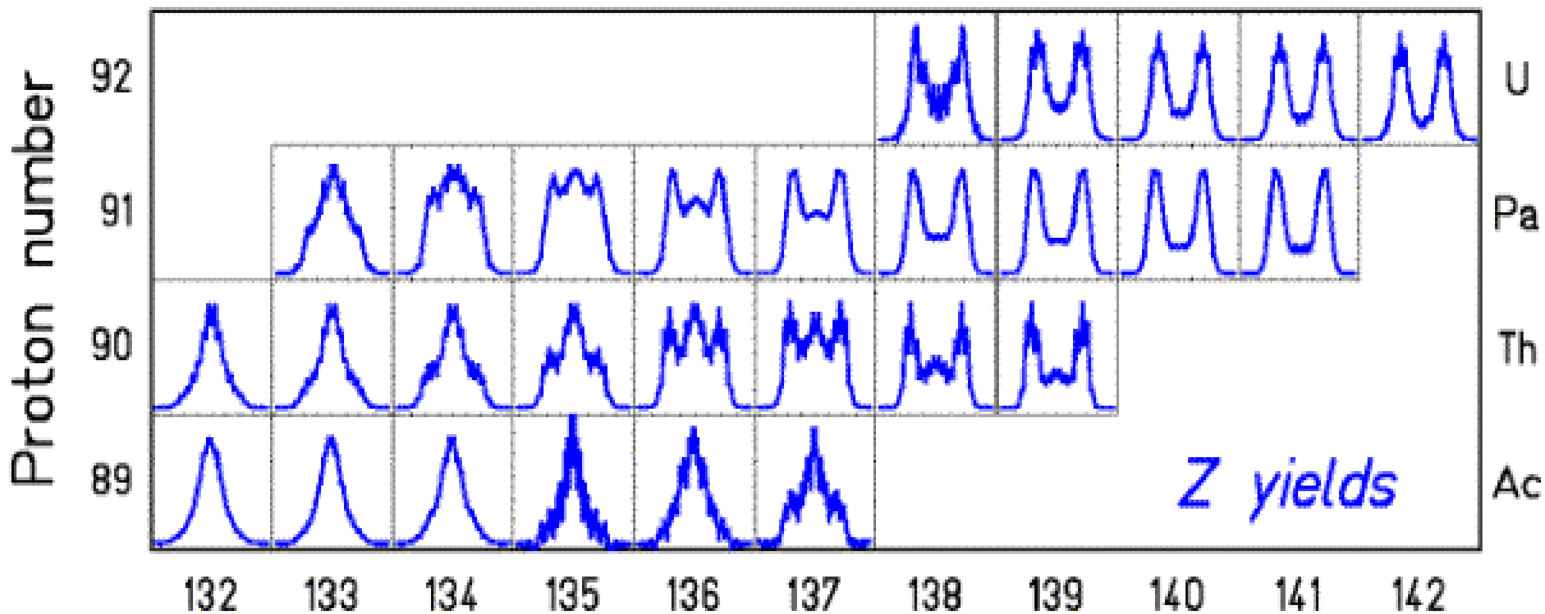


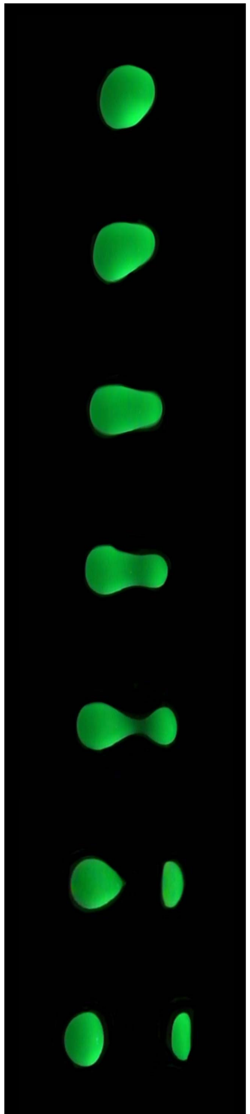
FIG. 6 A gauche, distributions en masse des fragments de la fission du noyau ^{236}U induite par des neutrons ayant des énergies comprises entre la valeur thermique (0.025 eV) et 14 MeV sur le noyau ^{235}U. A droite, comparaisons entre les distributions en masse des fragments du ^{240}Pu mesurées dans la fission spontanée du noyau et dans la fission induite par des neutrons thermiques sur le ^{239}Pu. Ces diagrammes sont tirés des Réfs. [32] et [33].

L.E. Glendenin, et al. Phys. Rev. C 24 (1981) 2600.
C. Wagemans, et al. Phys. Rev. C 90 (1984) 218.

Fission fragment charge distributions



K-H Schmidt et al., Nucl. Phys. A665 (2000) 221



Theoretical studies of the fission process
Why new studies now ?

- Fundamental questions : a process, not fully understood

- A large amount of new experimental results :
fission in new conditions
(exotic nuclei, super heavies, new energy range …)

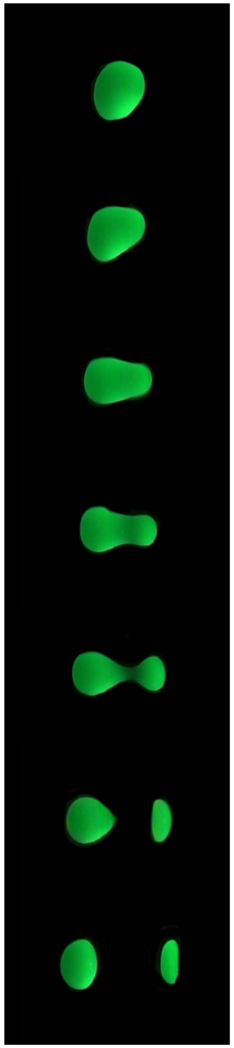
- Need for predictions for nuclear data
  Energy production
  Production of exotic nuclei : ALTO, SPIRAL2

- Progress made these last decades in the
microscopic description of the atomic nuclei

- New super-calculators

Recent microscopic fission studies

Towards a description :



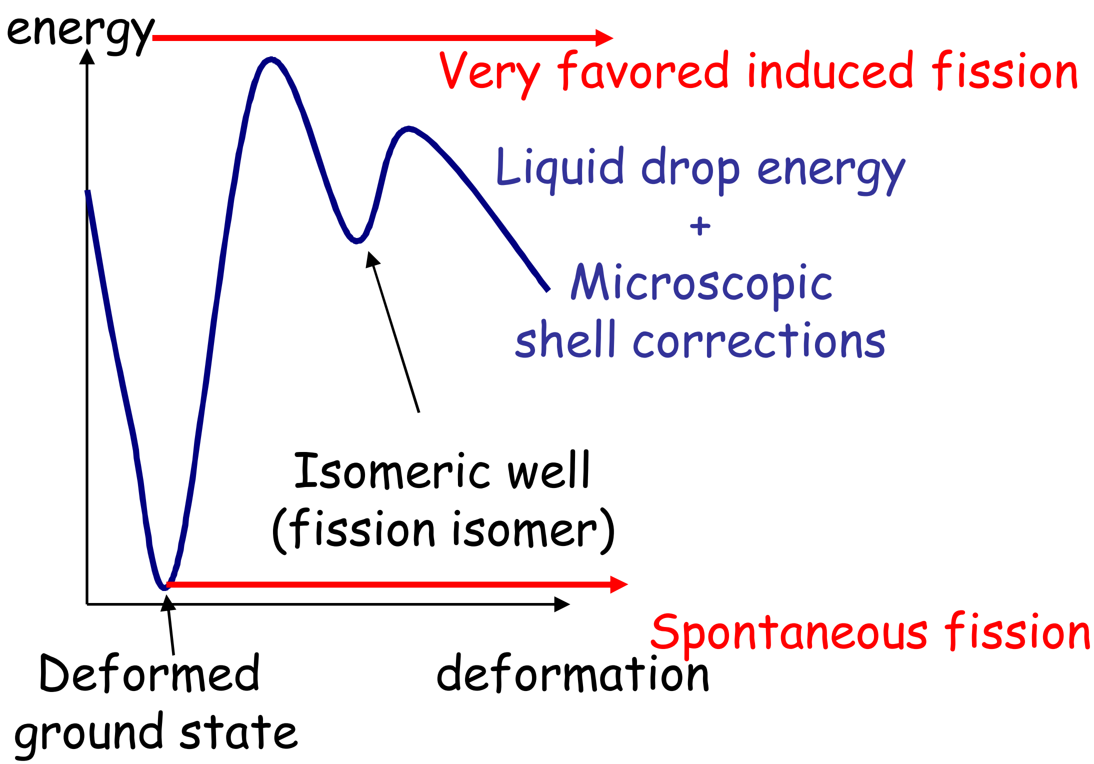
• as « *ab-initio* » as possible : microscopic description in terms of nucleons in interaction (mean field based approach)

• applicable to the different aspects of the process :
  * properties of the fissioning system (deformation of the ground state, fission isomer energy)
  * dynamical evolution
  * properties of the fragments (mass, charge, energy …)

• able to give quantitative results, which directly compared to experimental data.

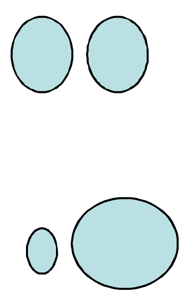
→The ultimate goal is to have a coherent, quantum, microscopic, and time dependent description of the structure of the nucleus and of the dynamics of the process.

What is missing in this description ?



- Description of the dynamics (time evolution)

-Description of the different fragmentations



Assumptions of the present approach

* fission dynamics is governed by the evolution of a few collective parameters q_i (elongation and asymmetry)

Why these two degrees of freedom are important ?



* Internal structure is at equilibrium at each step of the collective movement

→Assumption valid only for low-energy fission

$$\left|\Psi(t)\right\rangle = \int dq_i \; f(q_i, t) \left|\Phi_{q_i}\right\rangle$$

Fission dynamics results from a time evolution in a collective space

A two-steps formalism

1) **STATIC calculations** : determination of $\left|\Phi_{q_i}\right\rangle$

Analysis of the nuclear properties as functions of the deformations

Constrained- Hartree-Fock-Bogoliubov method using the D1S Gogny effective interaction

2) **DYNAMICAL calculations** : determination of $f(q_i,t)$

Time evolution in the fission channel

Formalism based on the Time dependent Generator Coordinate Method (TDGCM+GOA)

Formalism (1)

Constrained Hartree-Fock-Bogoliubov approach

$$\delta \left\langle \Phi_{q_i} \middle| \hat{H} - \sum_i \lambda_i \hat{Q}_i - \lambda_N \hat{N} - \lambda_Z \hat{Z} \middle| \Phi_{q_i} \right\rangle = 0$$

with

$$\begin{cases} \left\langle \Phi_{q_i} \middle| \hat{N}(\hat{Z}) \middle| \Phi_{q_i} \right\rangle = N\,(Z) \\ \left\langle \Phi_{q_i} \middle| \hat{Q}_i \middle| \Phi_{q_i} \right\rangle = q_i \end{cases}$$

Most commonly used constraints : q_{20}, q_{30} q_{22}, q_{40} and q_{10}

Formalism (2)

Time Dependent Generator Coordinate Method

$$\frac{\partial}{\partial f^*(q_i,t)} \int_{t_1}^{t_2} \langle \psi(t) | \hat{H} - i\hbar \frac{\partial}{\partial t} | \psi(t) \rangle dt = 0$$ with the same $\hat{H}$ than in HFB

Using the Gaussian Overlap Approximation, it leads to a Schrödinger-type Equation :

$$\boxed{H_{coll}\, g(q_i,t) = i\hbar \frac{\partial g(q_i t)}{\partial t}}$$

with

$$H_{coll} = -\frac{\hbar^2}{2} \sum_{i,j} \frac{\partial}{\partial q_i} B_{ij}(q_i) \frac{\partial}{\partial q_j} + \langle \Phi_{q_i} | \hat{H} | \Phi_{q_i} \rangle - \Delta V(q_i)$$

→ With this method the collective Hamiltonian is entirely derived by microscopic ingredients and the Gogny D1S force

Results

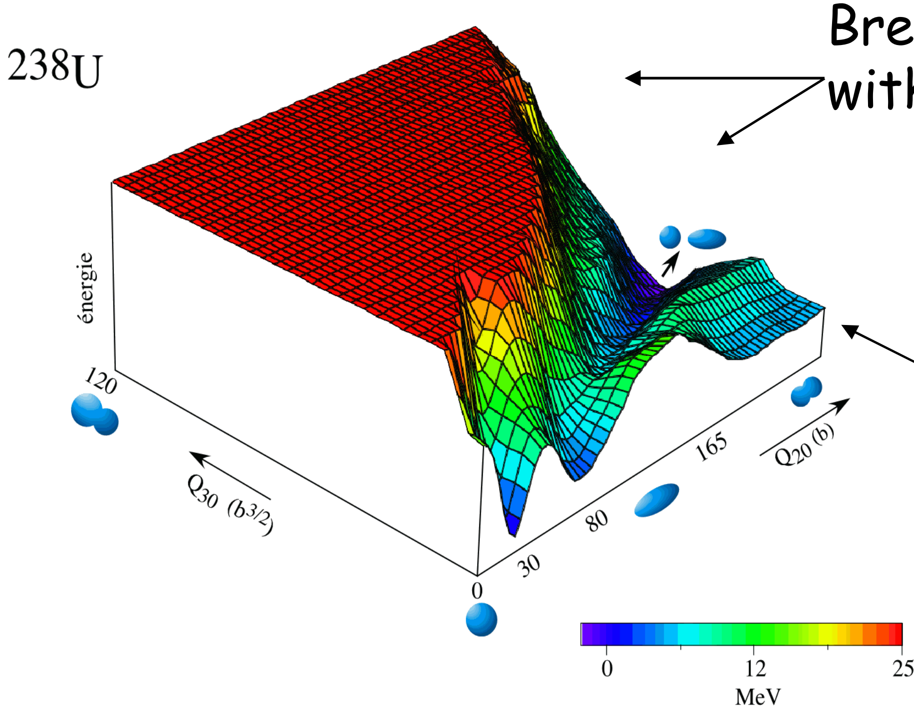
1) Static results:

* Properties of the fissioning system
  potential energy landscape of the fissioning system

* Properties of the fragments
  definition of the scission configurations
  total kinetic energy
  deformation
  number of evaporated neutrons

2) Dynamical results
  fission fragment mass distributions

Static results: 2D potential energy surface

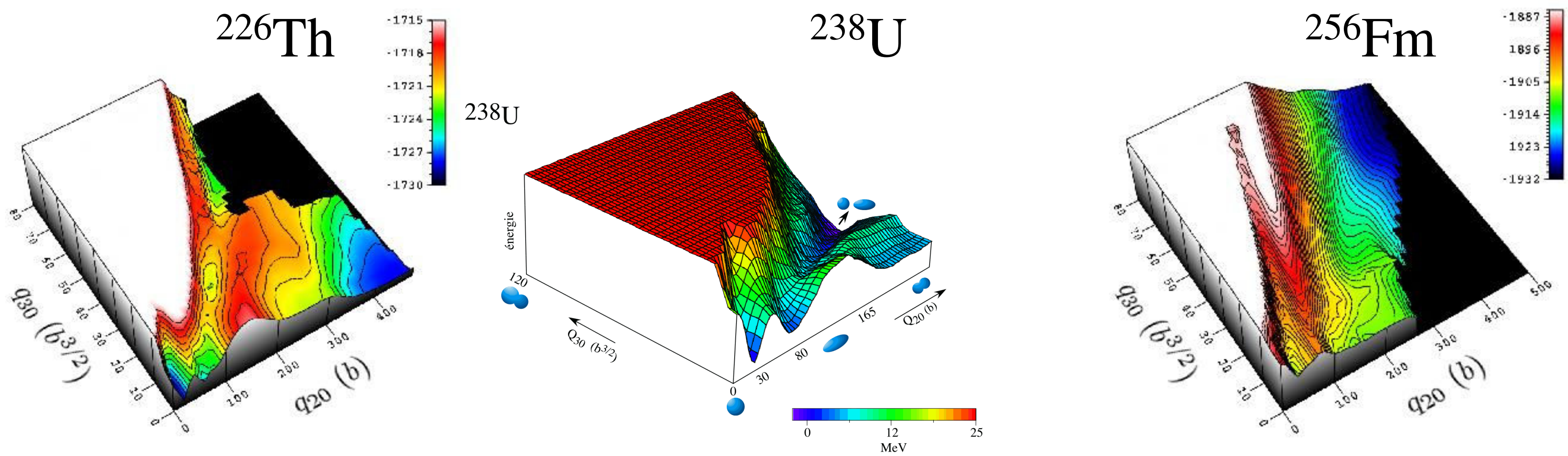


Breaking in two fragments with different masses

2 fragments with the same mass

H. Goutte, P. Casoli, J.-F. Berger, Nucl. Phys. A 734, 217 (2004)

Topology of the surfaces

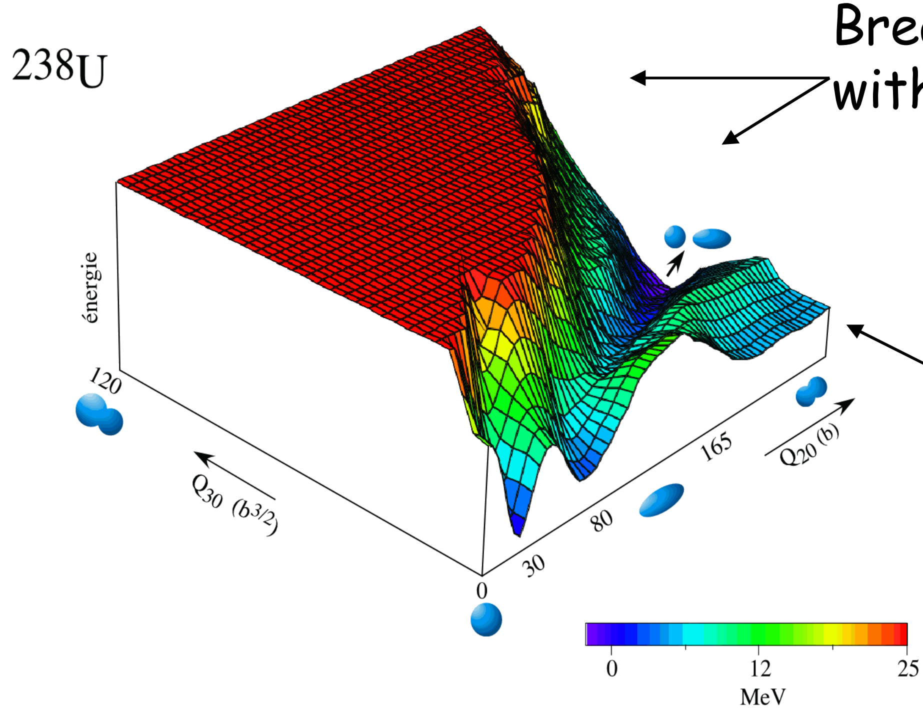


* Superdeformed minima in ^{226}Th and ^{238}U
No SD minima for the systems with N ≥ 156 (ex ^{256}Fm)
J.P. Delaroche, M. Girod, H. Goutte, J. Libert, NPA 771, 103 (2006)

* Third minimum in ^{226}Th

* Different topologies of the surfaces;
competitions between symmetric and asymmetric valleys

How can we determine the scission configurations ?



Breaking in two fragments with different masses

2 fragments with the same mass

H. Goutte, P. Casoli, J.-F. Berger, Nucl. Phys. A 734, 217 (2004)

Scission configurations

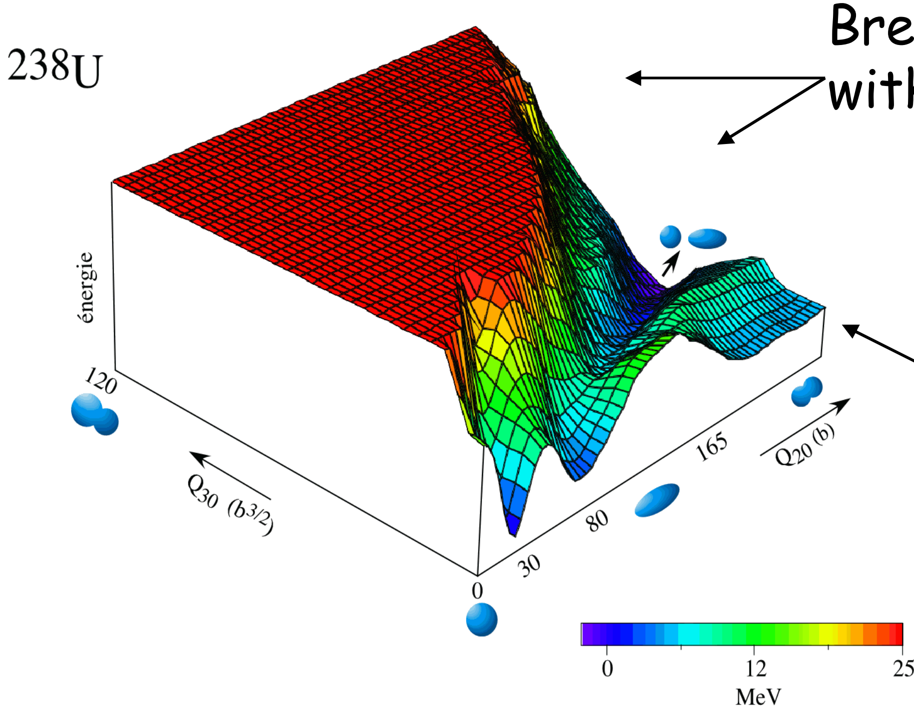
No topological definition of the exit points

<u>Different prescriptions :</u>

* E_{nucl} less than 1% of E_{coul}
  L.Bonneau et al., PRC75 064313 (2007)

* "low density" in the neck

  + energy drop (≈ 15 MeV)
  + decrease of the hexadecapole (≈ 1/3)
  J.-F. Berger et al., NPA428 23c (1984)



Breaking in two fragments with different masses

2 fragments with the same mass

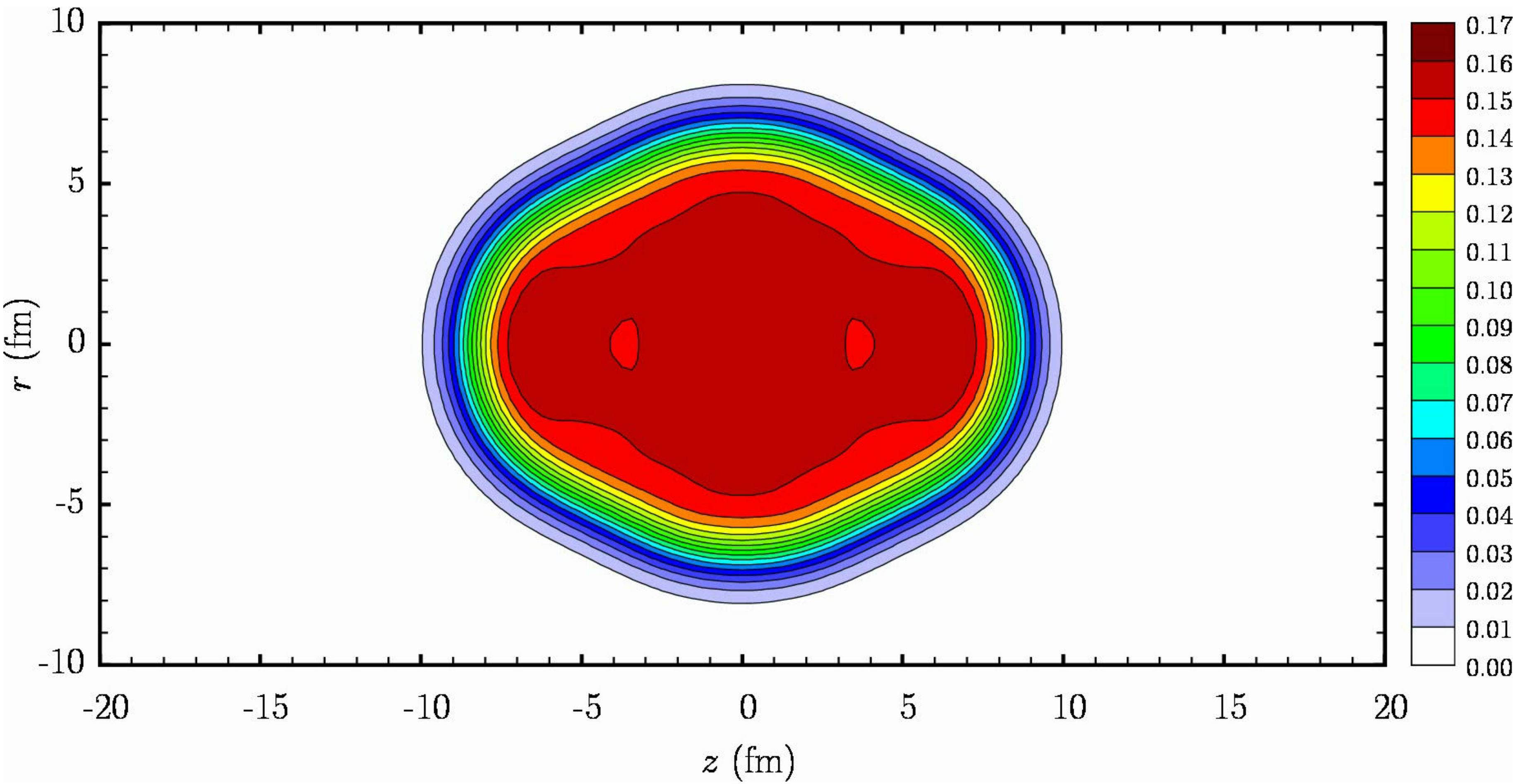
H. Goutte, P. Casoli, J.-F. Berger, Nucl. Phys. A 734, 217 (2004)

Nucleon density

$^{240}Pu \rightarrow {}^{120}Ag + {}^{120}Ag$

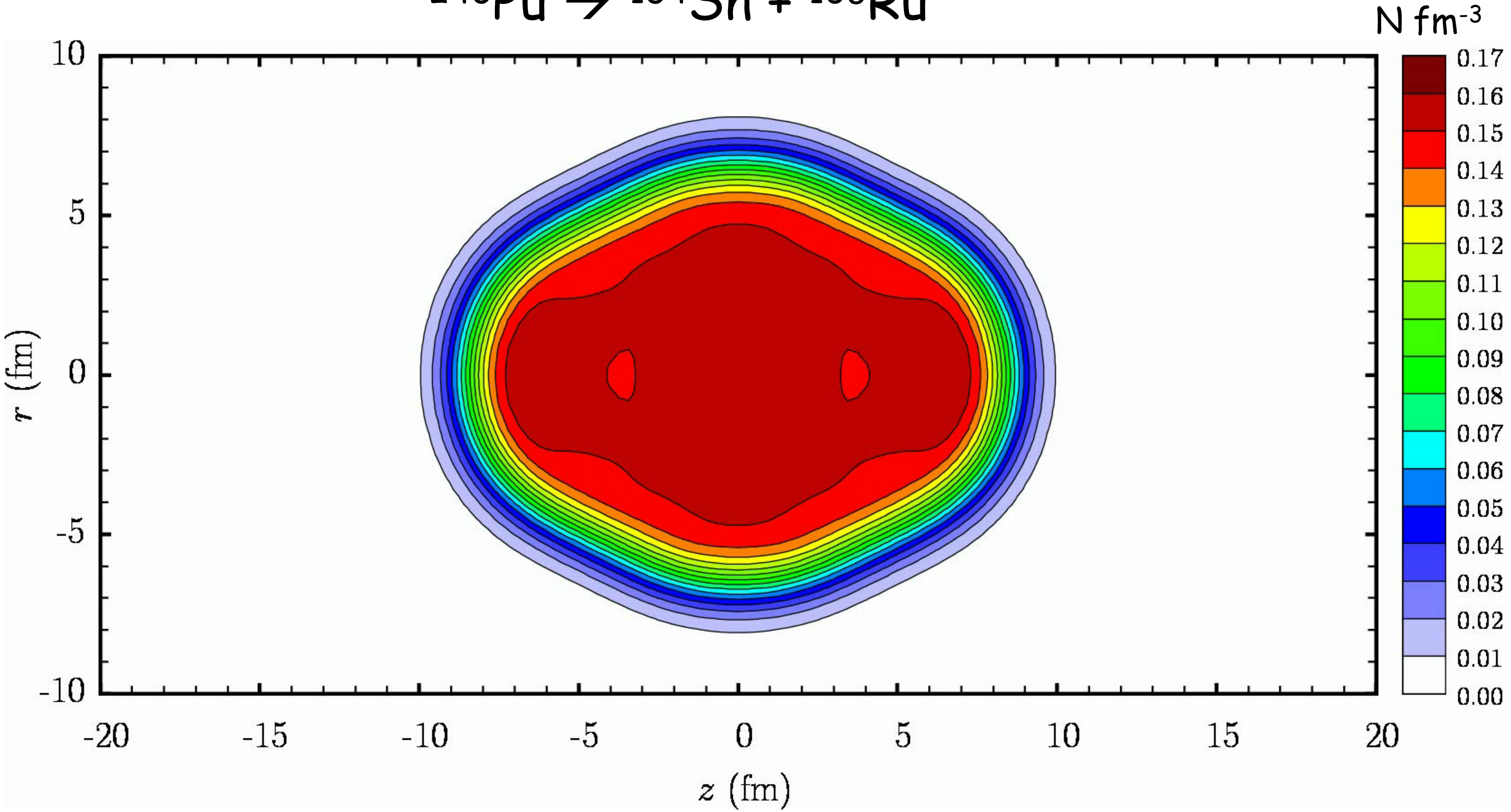
N fm^{-3}

N fm^{-3}



Nucleon density

$^{240}Pu \rightarrow {}^{134}Sn + {}^{106}Ru$



For the different scission configurations we determine :

- masses and charges of the fragments,
- distance between the fragments
- deformations of the fragments,
- . . .

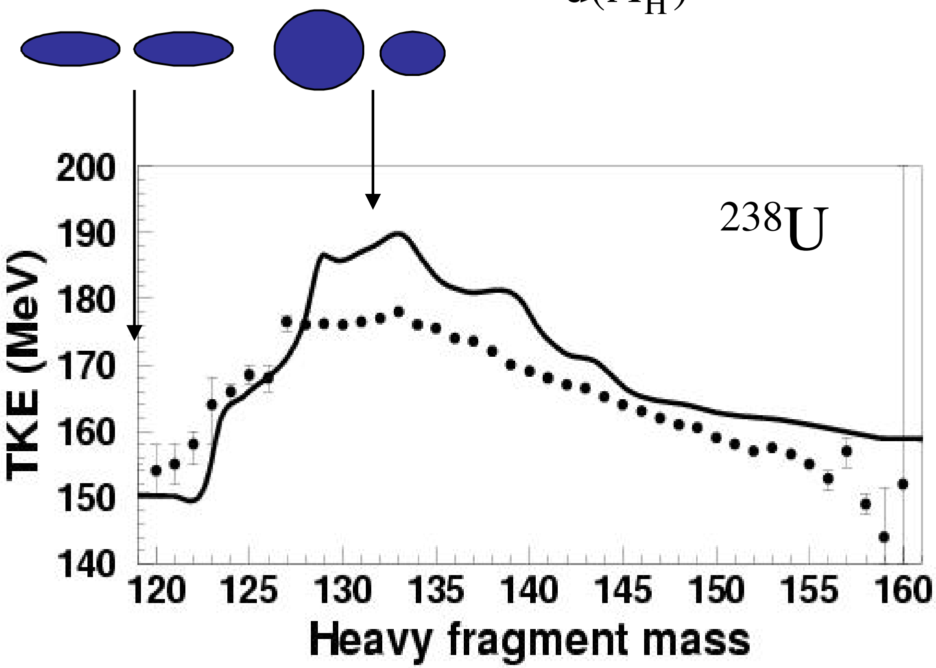
We can derive :

- kinetic energy distributions
- « 1D static» mass and charge distributions,
- fragment deformation energy,
- polarisation of the fragments,
- . . .

Total kinetic energy distribution

Exp: S. Pommé et al. Nucl. Phys. A572 (1994)

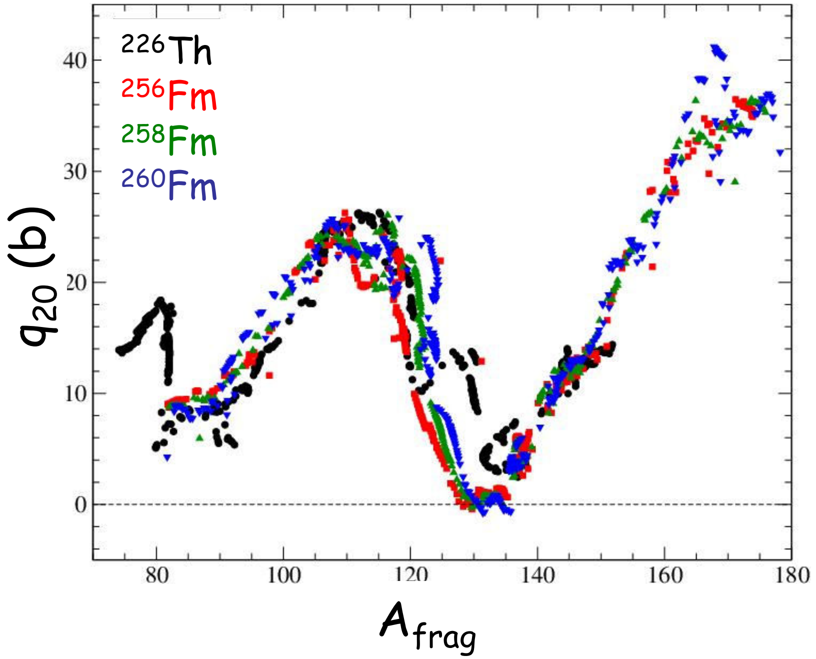
$$\mathrm{TKE}\,(A_H) \approx \frac{Z_H Z_L e^2}{d(A_H)}$$



- Good overall agreement
- Over-estimation (up to 6%)

H. Goutte, J.-F. Berger, P. Casoli and D. Gogny, Phys. Rev. C 71, 024316 (2005)

Quadrupole deformation of the fission fragments at scission



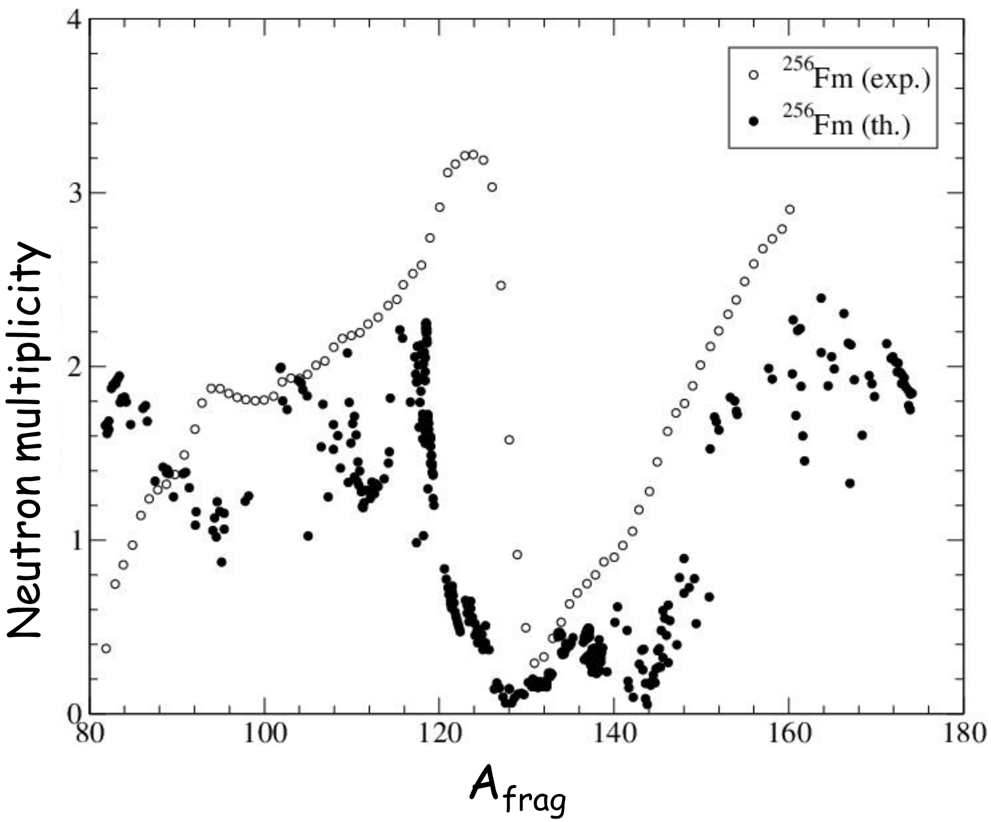
The fragment deformation do not strongly depend upon the fissioning system

We find the well-known saw-tooth structure: minima for A~ 82 and 130
maxima for A~ 112 and 170

Due to shell effects :
N = 82 and Z = 50
N = 50 and Z = 28

N. Dubray, H. Goutte, J.-P. Delaroche, Phys. Rev. C 77, 014310 (2008)

Prompt neutron emission



$$\nu(A) = \frac{E_{def}(A)}{E_k + B_n^*(A)}$$

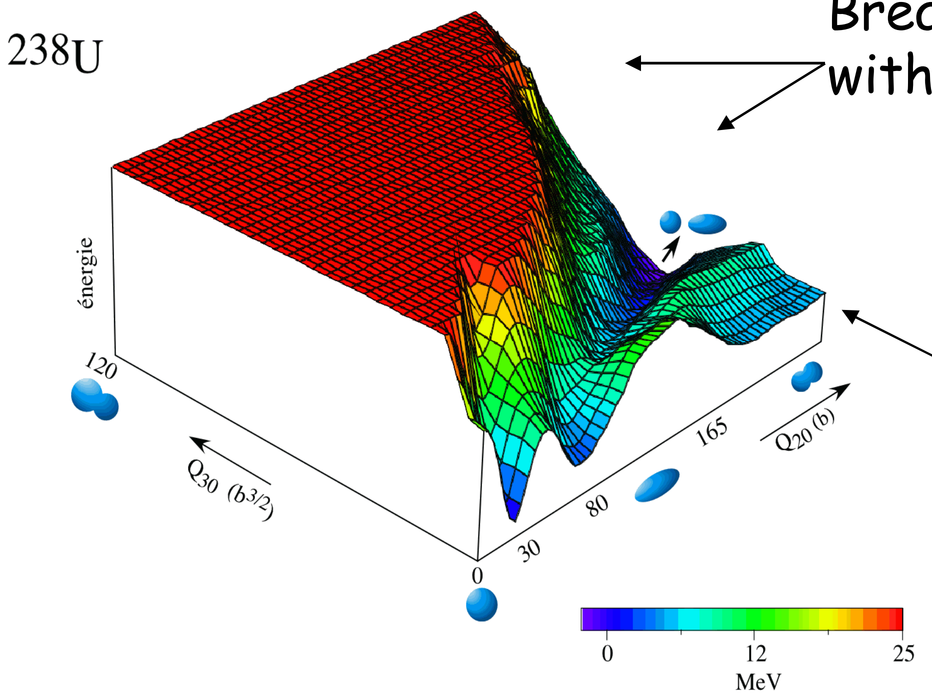
Good qualitative agreement

but

under estimation
probably due to the neglect of intrinsic excitations of the fission fragments

J.E. Gindler PRC 19, 1806 (1979)
N. Dubray, H. Goutte, J.-P. Delaroche, Phys. Rev. C 77, 014310 (2008)

Time dependent propagation



Breaking in two fragments with different masses

2 fragments with the same mass

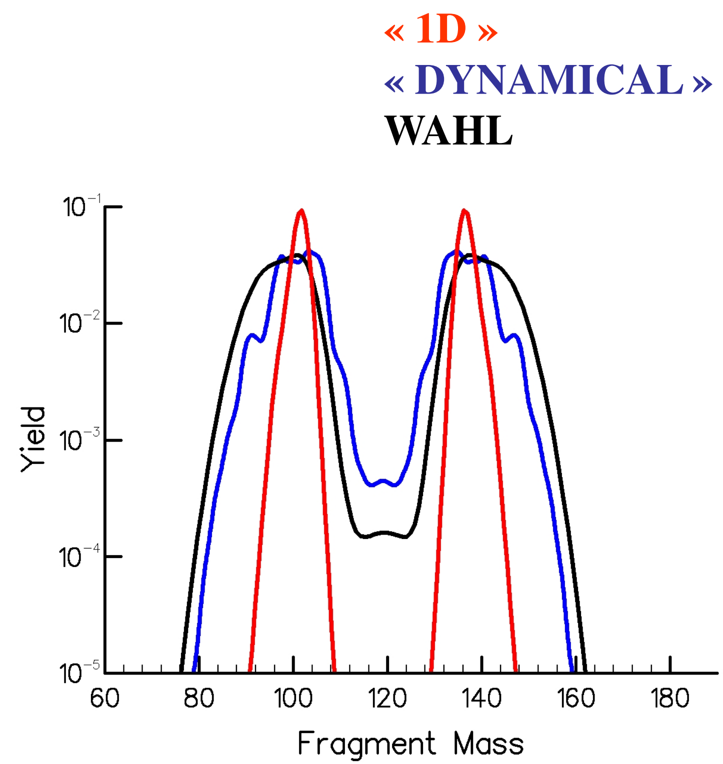
Dynamical effects on mass distributions

Comparisons between 1D and « dynamical » distributions

• Same location of the maxima
→ Due to properties of the potential energy surface (well-known shell effects)

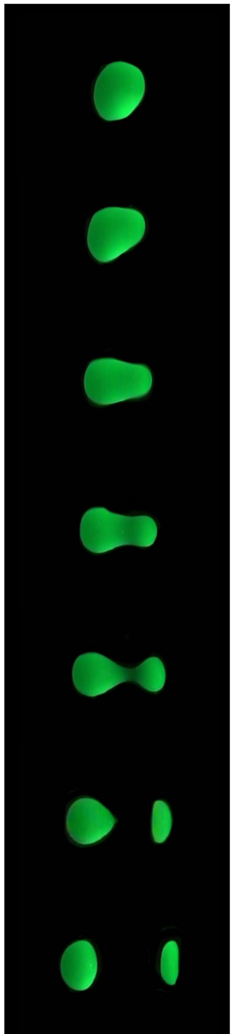
• Spreading of the peaks
→ Due to dynamical effects :
(interaction between the 2 collective modes via potential energy surface and tensor of inertia)

• Good agreement with experiment

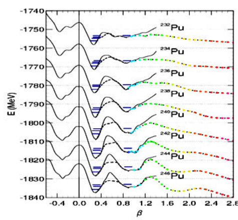


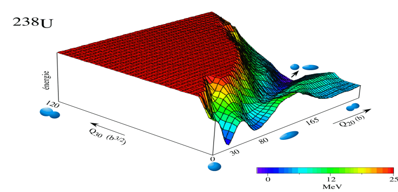
H. Goutte, J.-F. Berger, P. Casoli and D. Gogny, Phys. Rev. C71 (2005) 024316

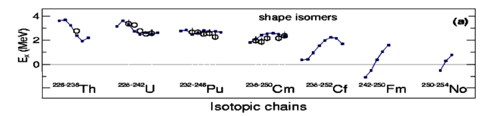
Conclusion

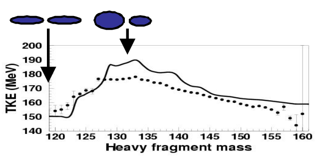


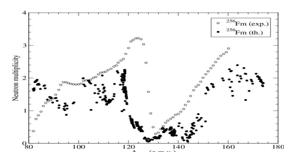
« Coherent » determination of the properties of the fissioning system, the fission dynamics, and observables of the fragments.

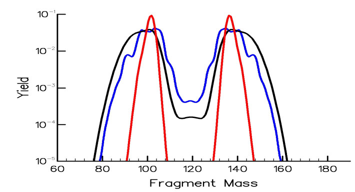












-> good qualitative agreement with the exp. data, even if there are no free parameters

-> this strengthen our idea that microscopic approaches based on the mean field and the Gogny force are pertinent for the study of nuclear structure and fission.

Experiments important for our studies

Static properties of the fissioning systems

* spectroscopy of heavy nuclei

R.D. Herzberg et al. Nature (London) 442 (2006), 896.

Collective dynamics

* fission fragment distributions

(influence of the incident energy, of the mass of the fissioning system, fission modes, odd-even effects …)

Properties of the fragments

* measurements correlated in kinetic energy, mass, charge, neutron emission in which each fragment is identified in Z and A.
* spectroscopy of the fission fragments

-> Need for existing facilities (CERN-nTOF, ISOLDE, SPIRAL, GSI, ILL, …)
and future (FAIR, SPIRAL2, EURISOL, …)

SOME GENERAL CONCLUSIONS ABOUT THE NUCLEAR PHYSICS

Current subjects under study in the community (non exhaustive list)

* Structure of exotic nuclei

* to improve the theoretical approaches for the many-body problem

* to develop the same approach for both nuclear structure and nuclear reaction (ex: fission process)

* …

To my opinion, nuclear physics both experimental and theoretical is a very fantastic subject

Don't hesitate to contact me for PhD or post doc or any question
Heloise.goutte@cea.fr