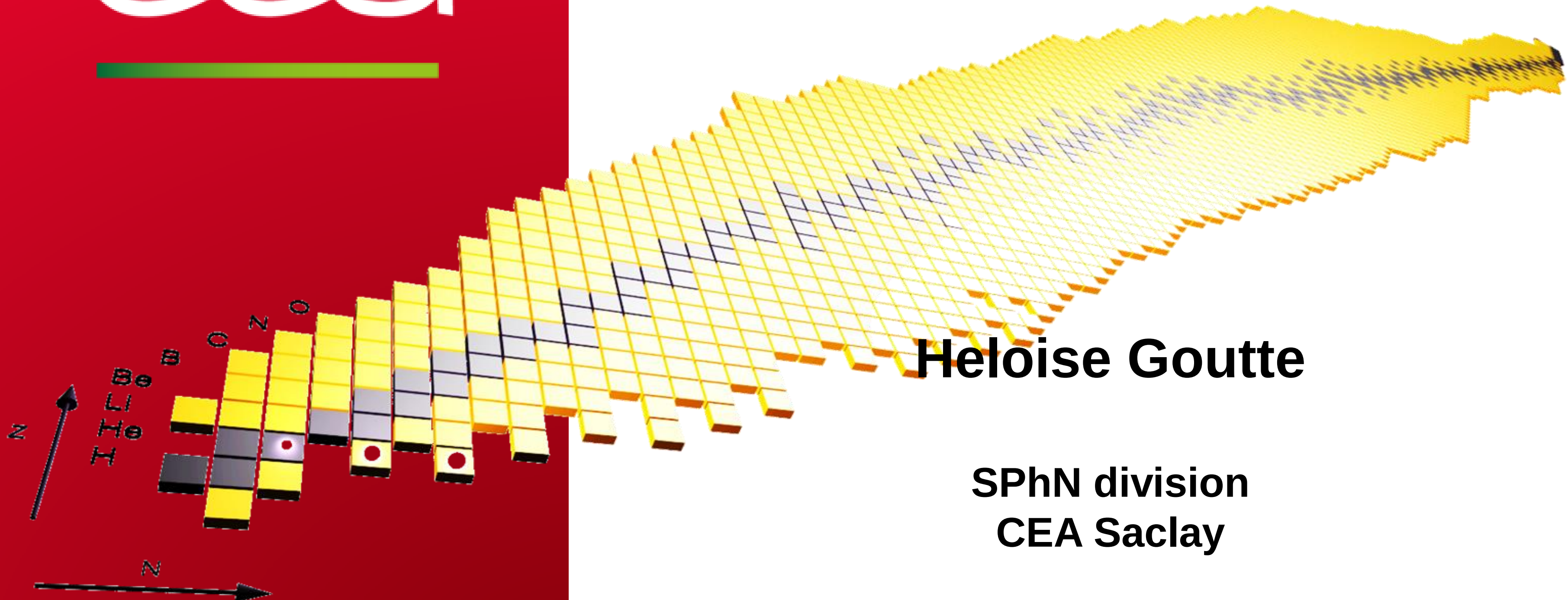
DE LA RECHERCHE À L'INDUSTRIE

Single particle degrees of freedom in fission



Heloise Goutte

SPhN division
CEA Saclay

www.cea.fr

Non exhaustive

Focused on:

- Fission fragment yields and properties

- Mean-field based approaches

What makes fission so particular ?

Fission is at the same time:

- an exceedingly complex mechanism linked to basic questions of many-body dynamics

- a tool for societal applications (various and numerous)
- a tool for the production of elements of interest (exotic nuclei, neutrinos)

The fission process raises many fundamental questions:

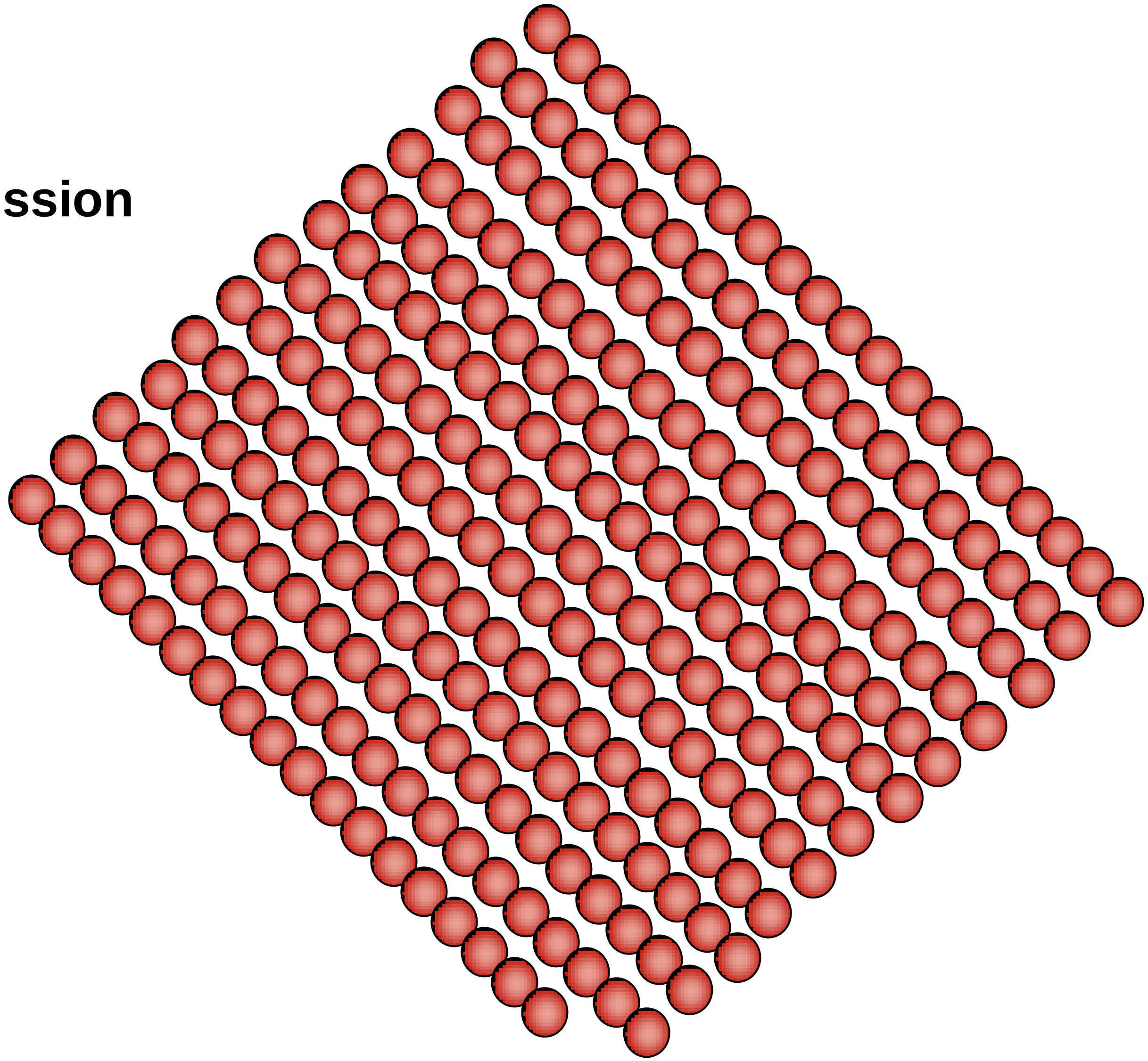
- What is driving the fission process ?
- How do shell effects manifest in fission ?
- What is the interplay between collective motion and individual excitations ?

Single particle effects

Fission lifetimes

^{258}Fm : spontaneous fission

$T_{1/2sf} = 3.8\ 10^{-4}$ s



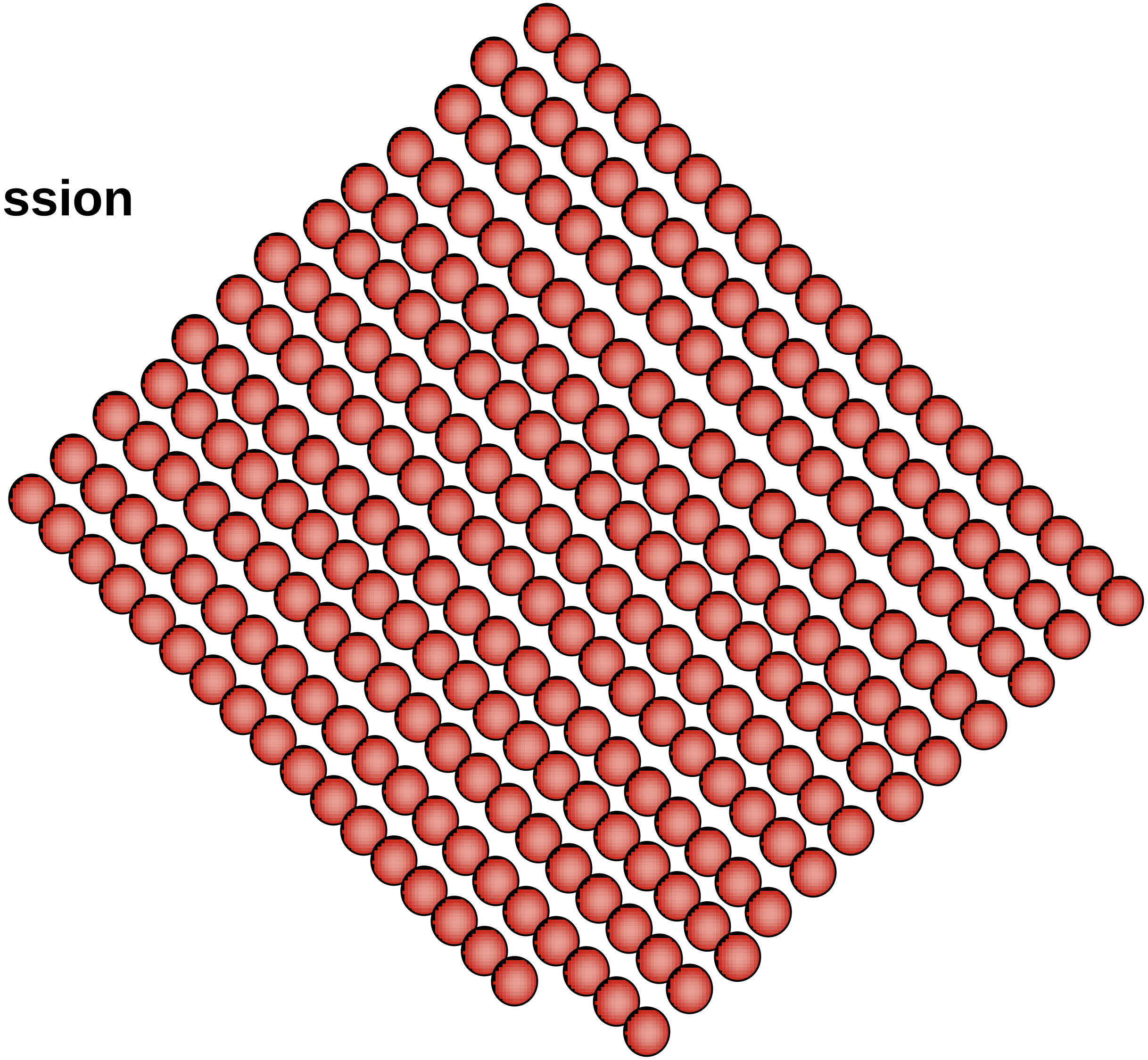
Fission lifetimes

^{258}Fm : spontaneous fission

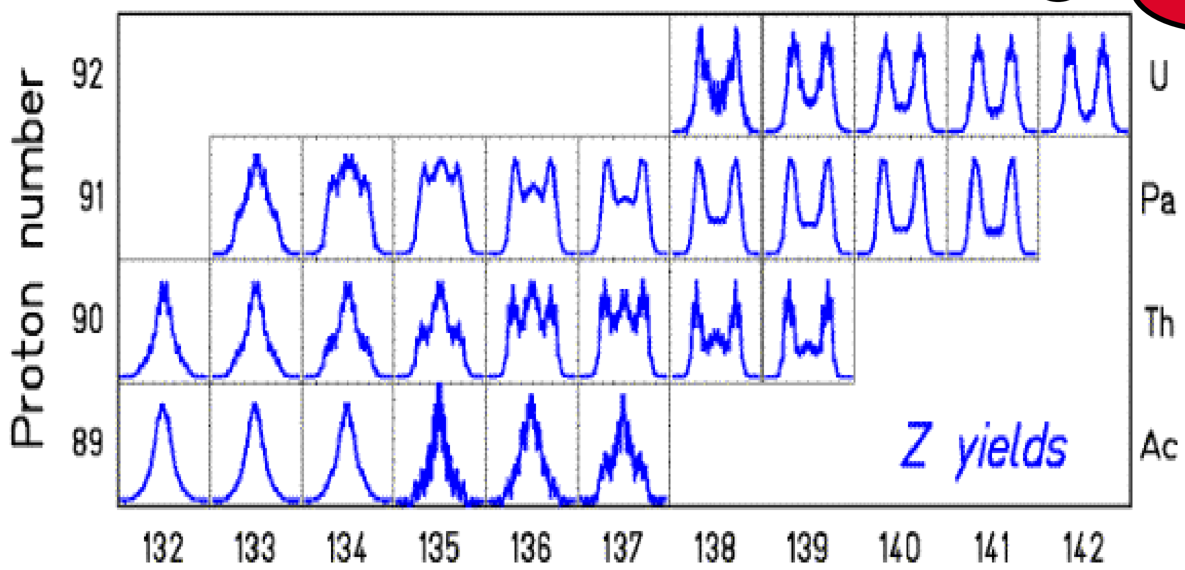
$T_{1/2sf}$ = 3.8 10^{-4} s

^{257}Fm : α -decay

$T_{1/2\alpha}$ = 8.7 10^{6} s



Fission yields



K-H Schmidt et al., NPA 665 (2000) 221

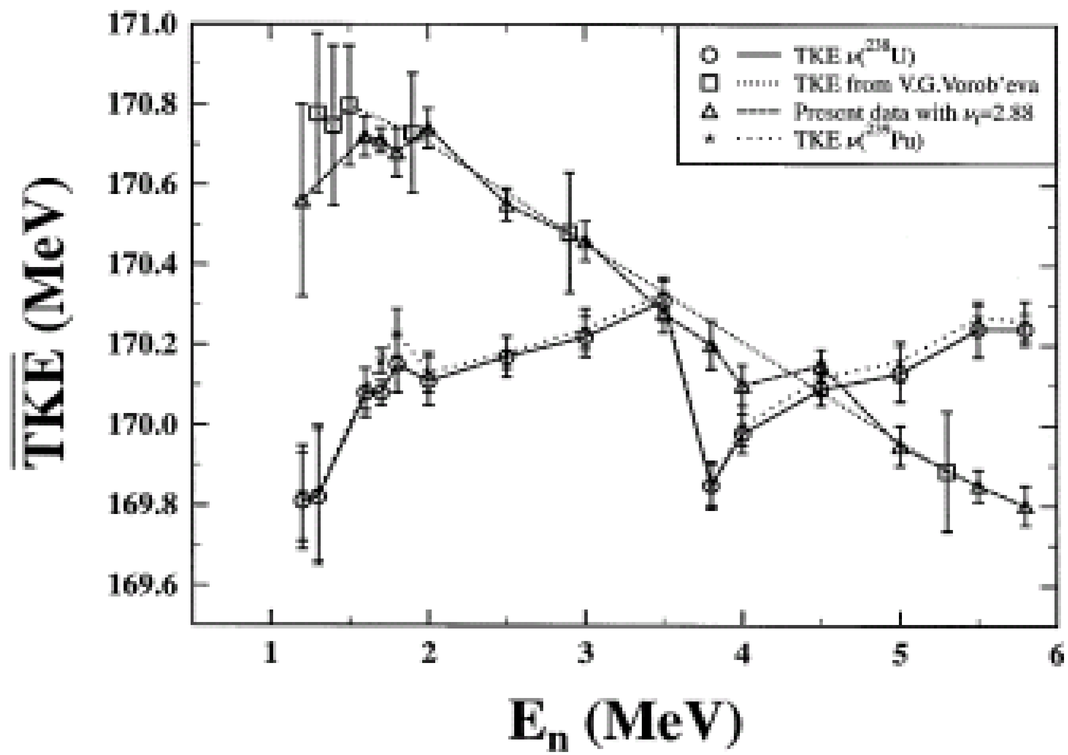
New results to come

STUDIES ON FISSION WITH ALADIN

Evidences for single particle excitations during fission

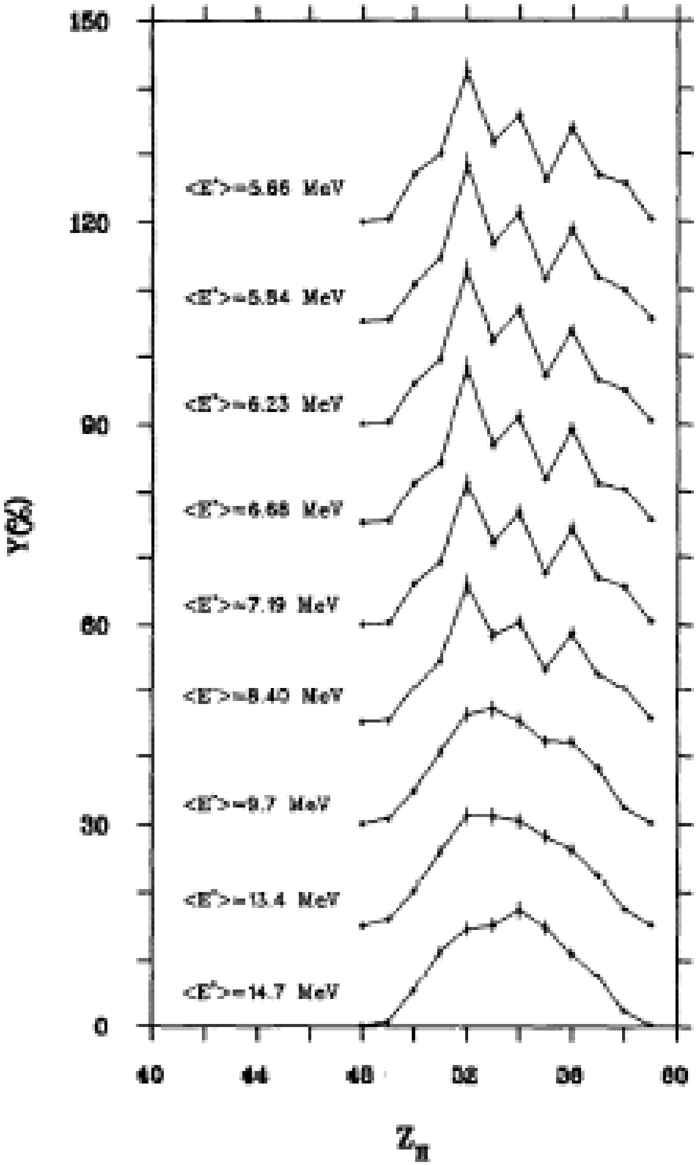
A possible experimental evidence: 1/2

mean total kinetic energy of the fission fragments



F. Vives et al. NPA662 (2000) 63

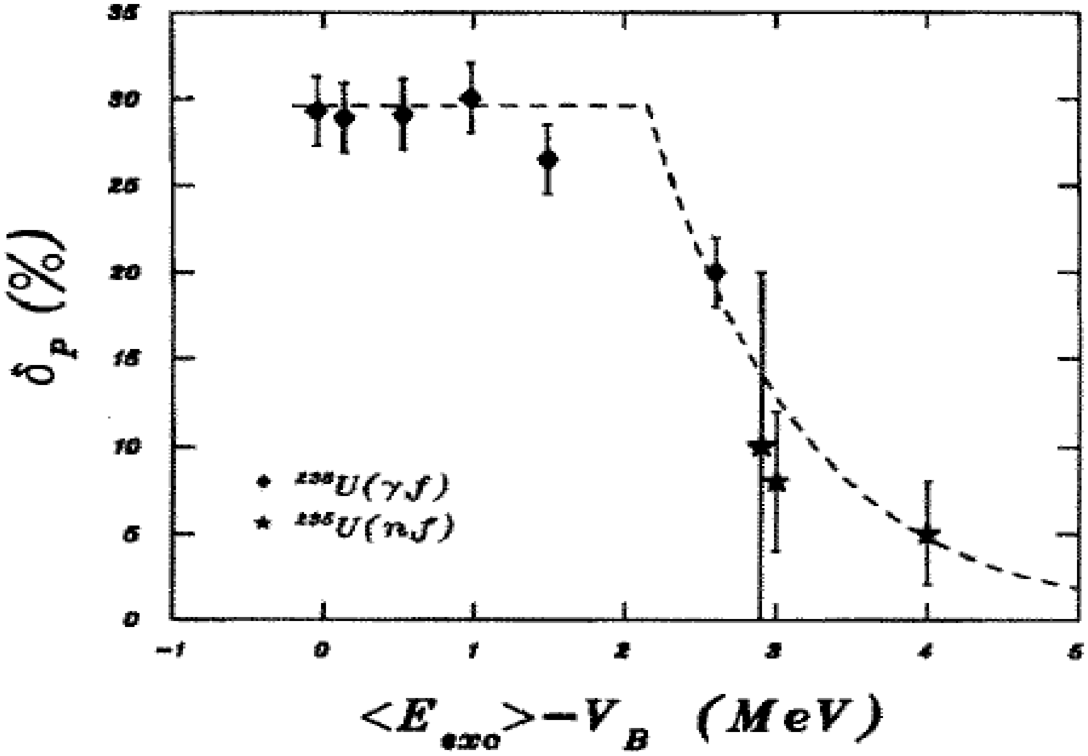
A possible experimental evidence: 2/2



Odd-even effects
in fission fragment distributions

S. Pomme et al., NPA 560 (1993) 689

Odd –even effects



S. Pomme et al., NPA 560 (1993) 689

Origin of odd-even effects …. under discussion

Random walks on tabulated five-dimensional potential-energy surfaces

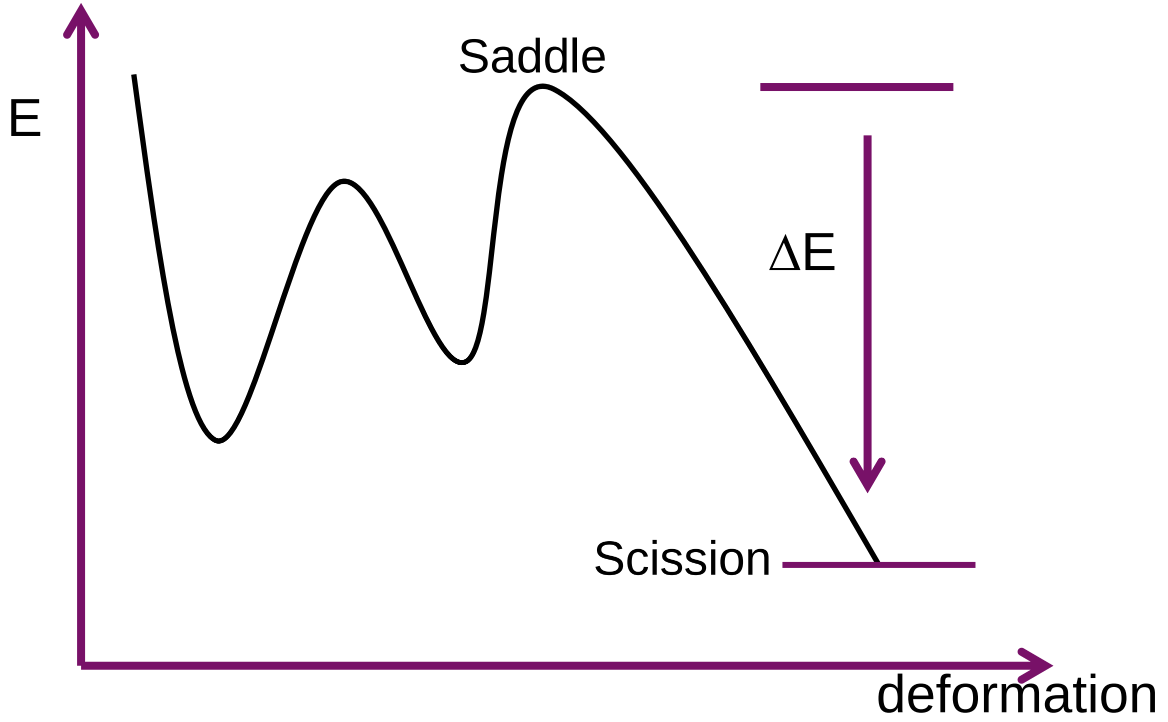
P. Moller et al., PRC 90 014601 (2014).

How the total intrinsic energy shared between the fission fragments ?

K.-H. Schmidt, and B. Jurado PRL104, 212501 (2010).

From saddle to scission

Energy gain from saddle to scission



ΔE may feed :

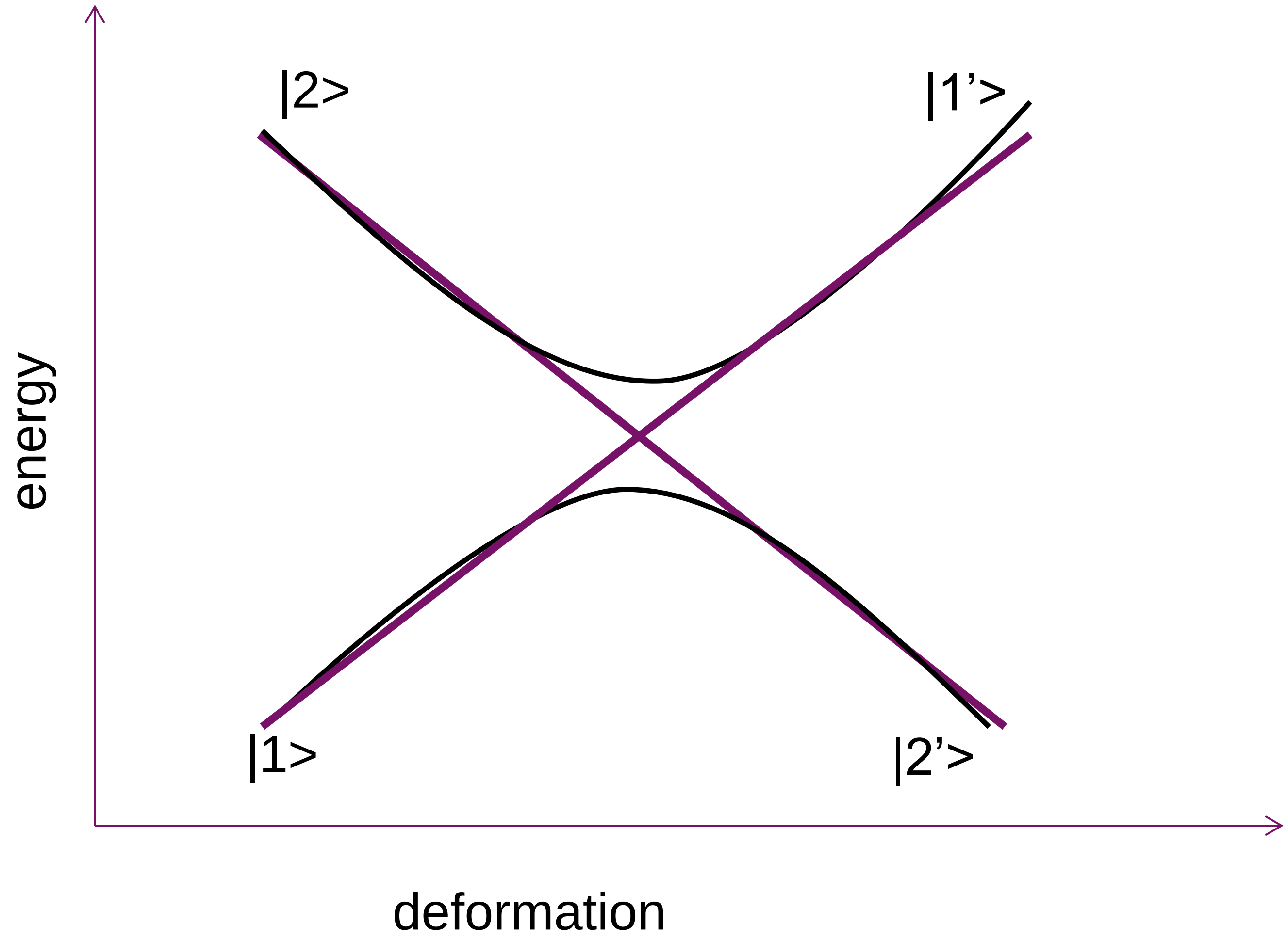
- Precission kinetic energy in fission direction
- Excitation of collective modes
- Intrinsic excitations

Adiabatic versus diabatic

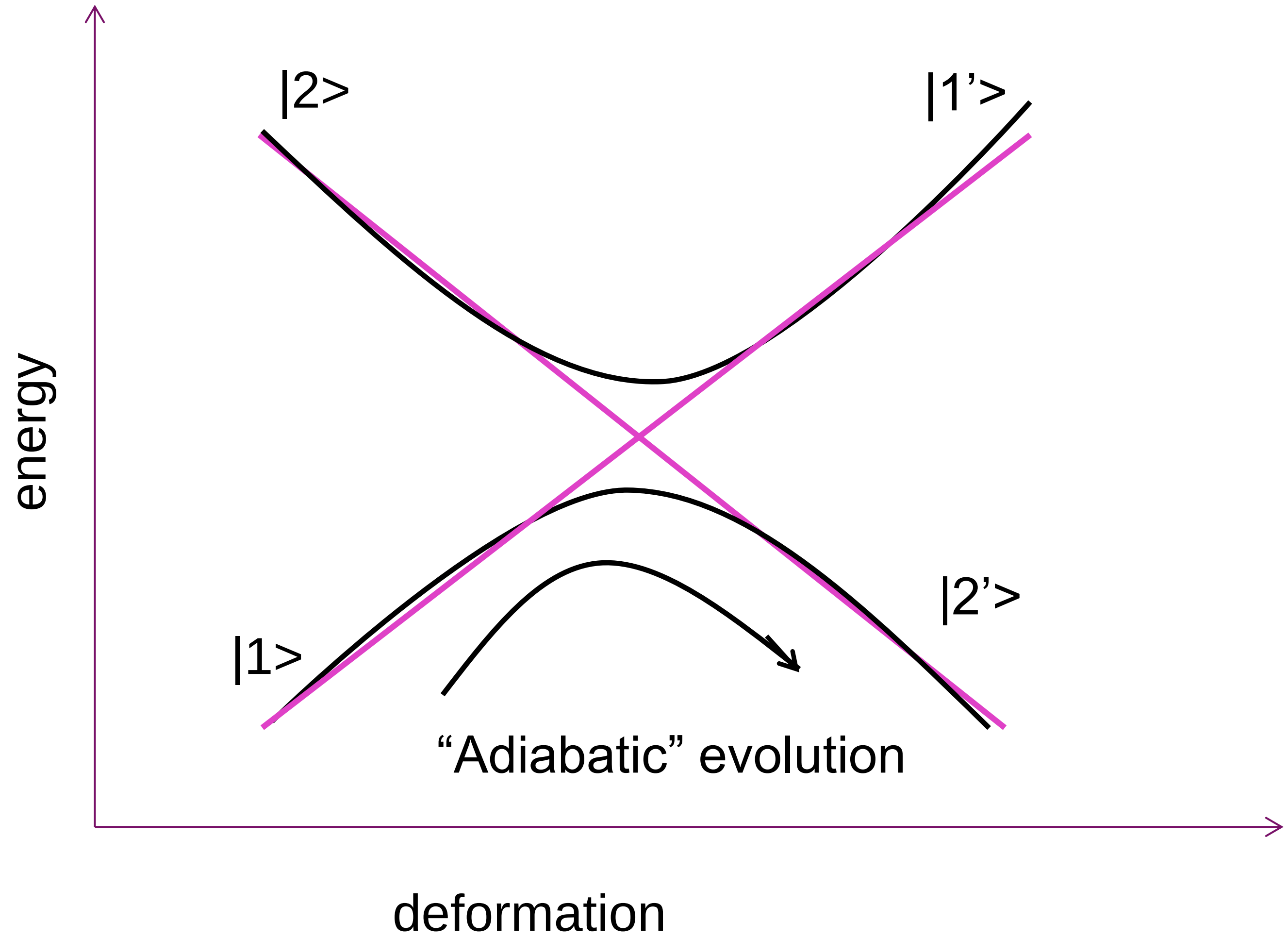
In thermodynamics, an adiabatic process is a process that occurs without the transfer of heat or matter between a system and its surroundings.

Approximately, a transfer may be regarded as adiabatic if it happens in an extremely short time, so that there is no opportunity for significant heat exchange.

Landau Zener level crossing



Landau Zener level crossing

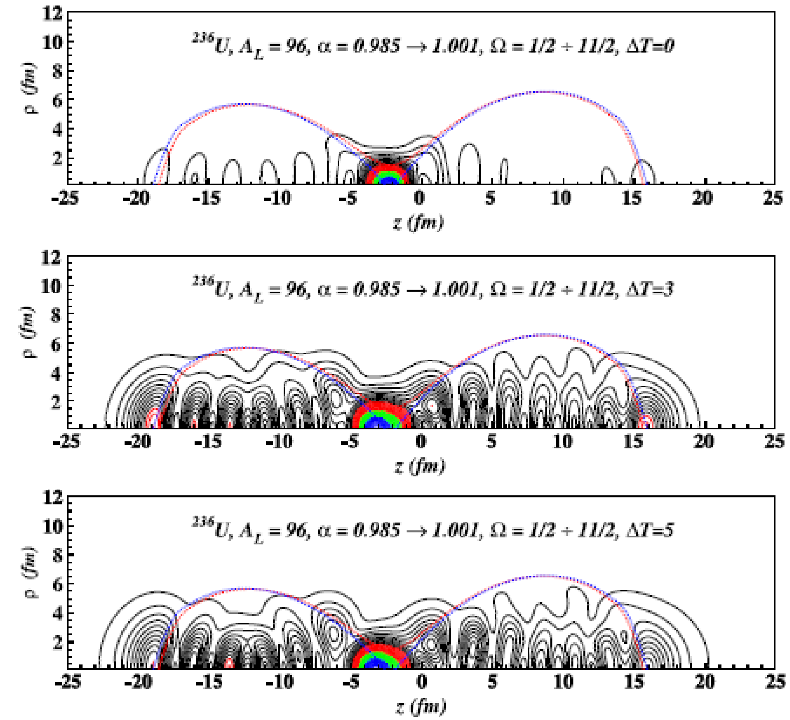


Dynamical scission model by M. Rizea et N. Carjan

M. Rizea, N. Carjan, NPA 909 (2013) 50.

Transition from 2 fragments connected by a thin neck and 2 separated fragments,
which takes place in a time interval ΔT

-> to study the evolution of all occupied (neutron) states by solving the TD Schrodinger equation with time-dependent potential.



lor online.) Spatial distribution $S_{em}(\rho, z)$ of the unbound neutrons, immediately-after scission,

The duration of the neck rupture is taken as a parameter

For $\Delta T > 6.10^{-22}$s the adiabatic limit is reached (no scission neutrons)

What could be done now beyond the adiabatic TD GCM+GOA ?

Preliminary remarks

What are the pertinent correlations during the fission process ?

- Short range correlations
- Large amplitude vibrations along the fission path
- Large amplitude vibrations transverse to the fission path
- Pairing correlations, pairing vibrations
- Particle-hole excitations

Preliminary remarks

What are the pertinent correlations during the fission process ?

- Short range correlations
- Large amplitude vibrations along the fission path
- Large amplitude vibrations transverse to the fission path
- Pairing correlations, pairing vibrations
- Particle-hole excitations

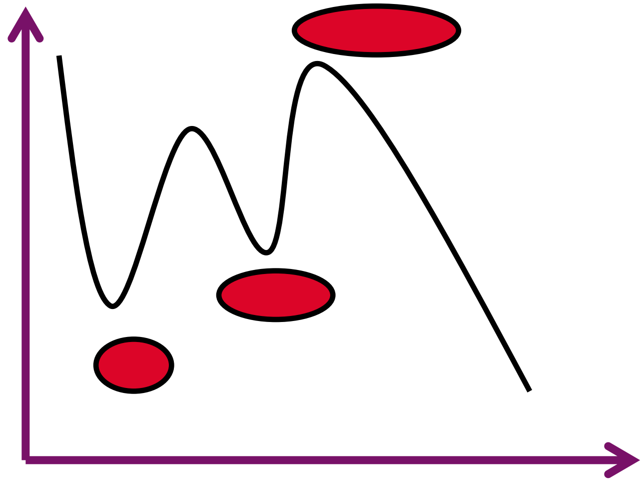
Remark 1 :

The effective force should be able to treat both collective and intrinsic excitations and to provide at the same time both global as well as spectroscopic properties.

→ Gogny force is well suited

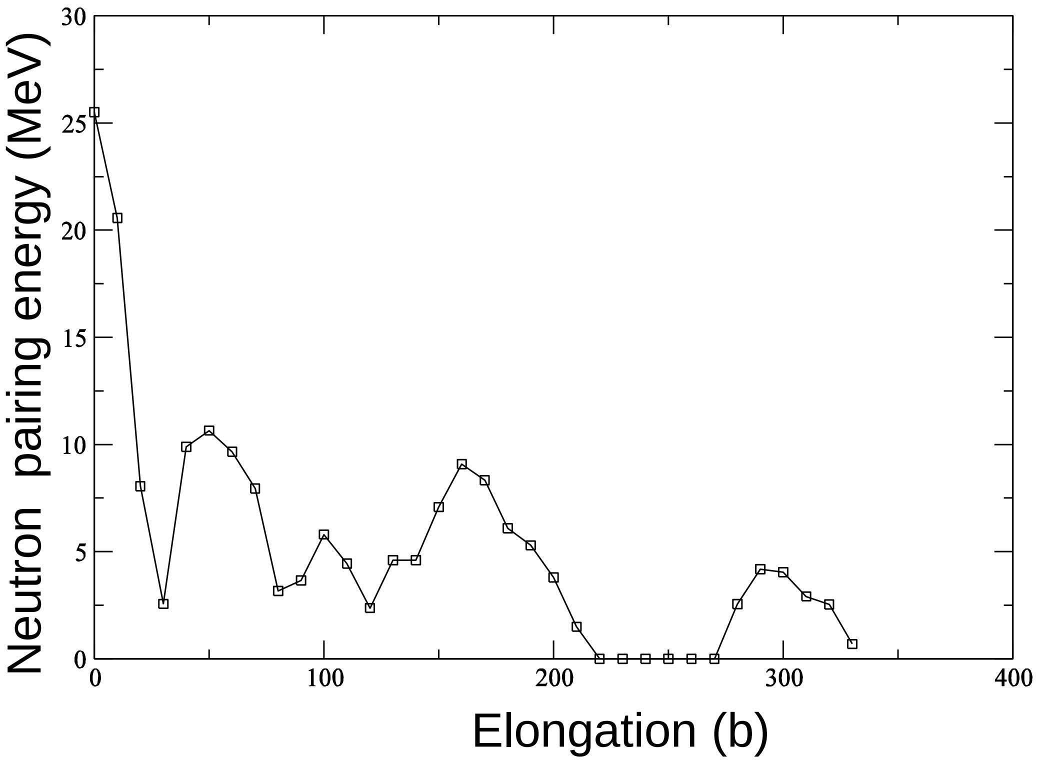
Remark 2 :

Fission is dealing with large deformations and shapes from equilibrium up to far from equilibrium



-> different regimes of correlations

Pairing correlations



Large variations of the pairing correlations along the fission path

→Different regimes coexist

What about pair breaking in the description of the fission process with the HFB approach ?

What HFB shows is : when we deform the nucleus, pairing correlations change, which can be interpreted as creation or destruction of pairs.

Pairs are not diatomic molecules that you have to break to create odd fragments

This is only an interpretation : the number of pairs is not integer and correlations they represent is certainly non spatial !!!

Do we have breaking during the fission process in the HFB approach ?
Yes !

Effects of the pairing correlations on …

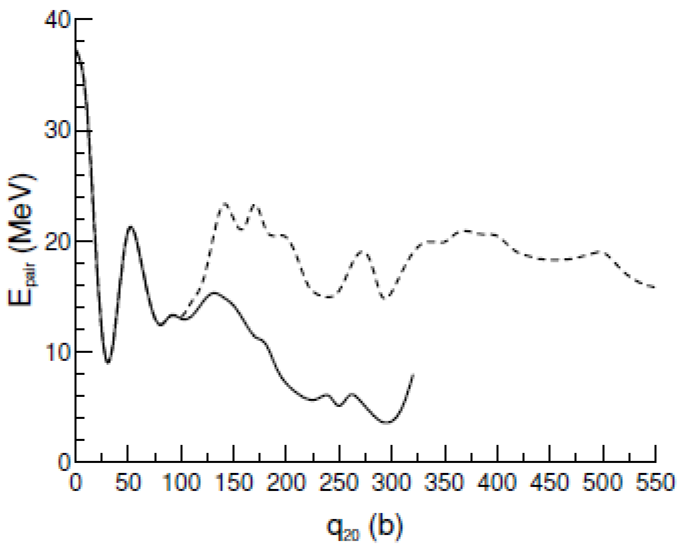
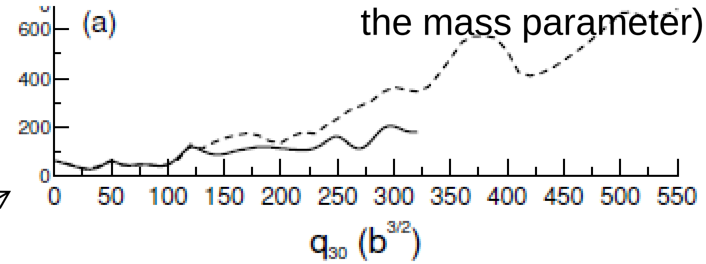


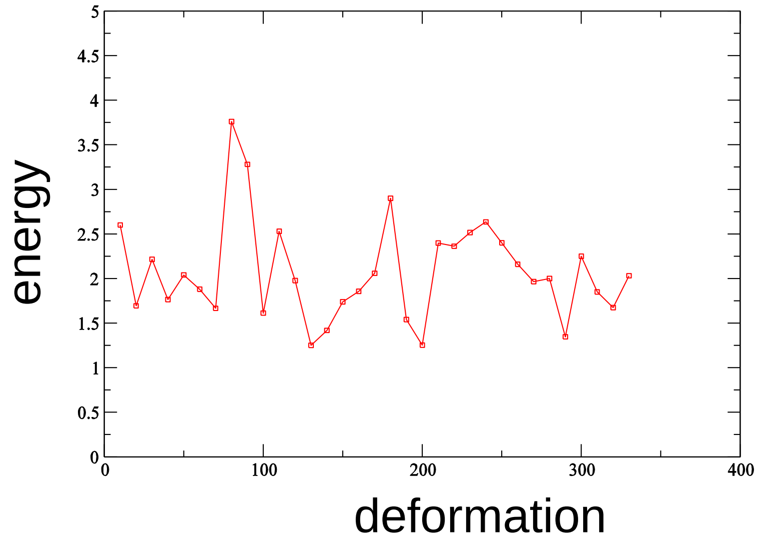
FIG. 4. Pairing energy as a function of q_{20} along the asymmetric (solid line) and the symmetric (dashed line) fission paths in ^{238}U.

Mass parameters

(here is plotted the inverse of the mass parameter)



Energy of the lowest q.p.



Pairing correlations play an important role during the fission process

TD-GCM+GOA
based on HFB
0 and 2qp states

PhD work of R. BERNARD

R. Bernard, H. G, D. Gogny, and W. Younes PRC 84, 044308 (2011).

Coupling between collective and intrinsic excitations

Nuclear state

$$\left|\Psi(t)\right\rangle = \sum_i \int d\{q\} f_i(\{q\},t) \left|\Phi_i(\{q\})\right\rangle,$$

i= intrinsic excitations
{q} =collective coordinates

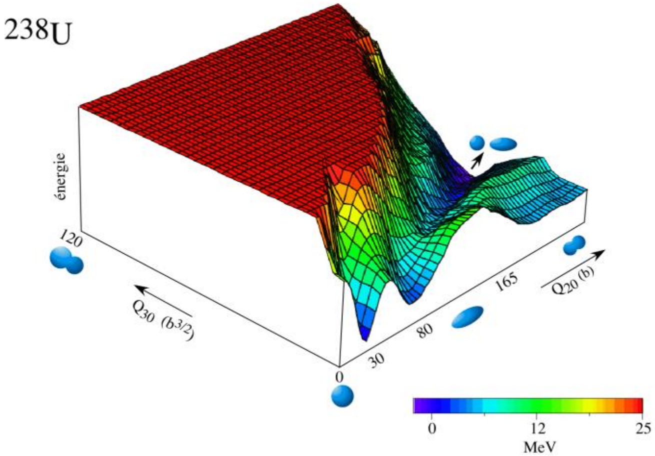
Vibrations related to the movement in the fission direction

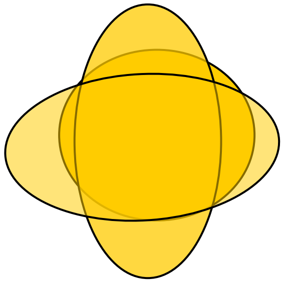
+

Vibrations related to the motion perpendicular to fission

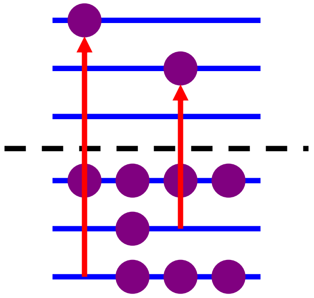
+

Quasi-particle excitations at each step of the collective motion (for each step of the deformation)





+



Towards a microscopic derivation of an Hamiltonian for the fission process

Nuclear state

$$|\Psi(t)\rangle = \sum_i \int dq\, f_i(\{q\},t) |\Phi_i(\{q\})\rangle,$$

at each step of the collective movement the system is developed on a basis which includes excited states

Variational principle

$$\frac{\partial}{\partial f_i^*(\{q\},t)} \int_{t_1}^{t_2} \langle \Psi(t) | \hat{H} - i\hbar \frac{\partial}{\partial t} | \Psi(t) \rangle = 0.$$

Generalized Hill-Wheeler equation

$$\sum_i \int dq (\langle \Phi_j(q') | \hat{H} | \Phi_i(q) \rangle - i\hbar \frac{\partial}{\partial t} \langle \Phi_j(q') | \Phi_i(q) \rangle) f_i(q,t) = 0.$$

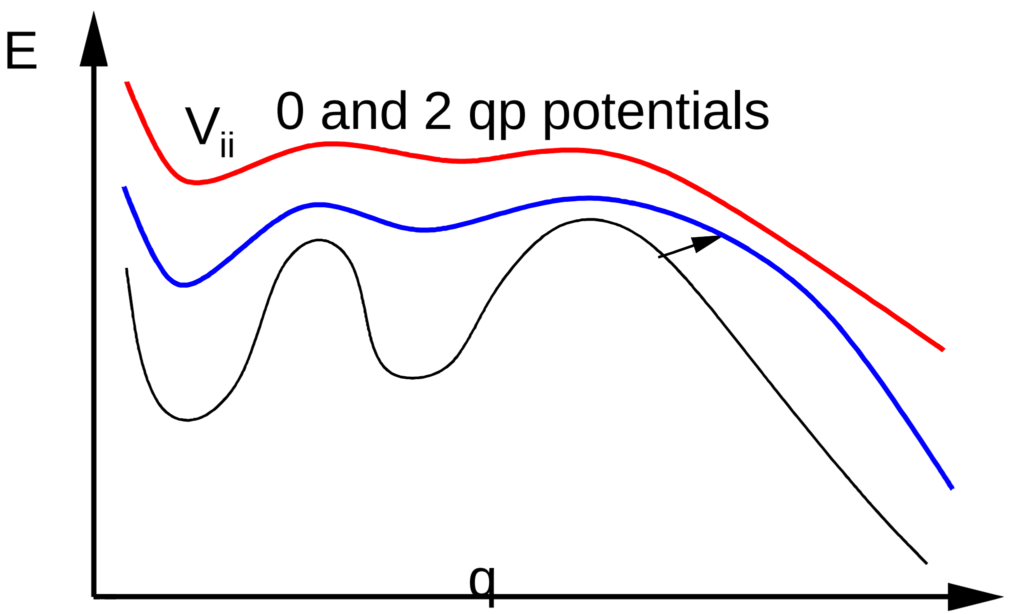
-> simplification of this non-local integro-differential equation into a Schrodinger equation

Collective intrinsic Hamiltonian

$$\left(H^{CI}(\overline{q}) - i\hbar \frac{\partial}{\partial t} \right) g(\overline{q}) = 0$$

$$H^{CI}(\overline{q}) = V(\overline{q}) + \left[T(\overline{q}) P \right]^{(1)} + \left[\frac{1}{2M(\overline{q})} P \right]^{(2)}$$

$$P = i\hbar \frac{\partial}{\partial q}$$



Is this coupling to intrinsic excitations a dissipation ?

No !

Dissipation is for a loss of energy over time typically due to the action of friction or turbulence.

Here there is no loss of amplitude of the wave function.
The Hamiltonian is hermitian.

This coupling between intrinsic excitations and collective modes does not correspond to dissipation.

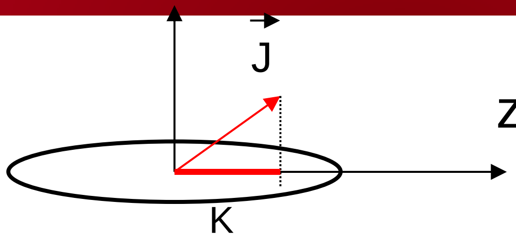
$$\sum_i \int dq \left(\left\langle \Phi_j(q') \middle| \hat{H} \middle| \Phi_i(q) \right\rangle - i\hbar \frac{\partial}{\partial t} \left\langle \Phi_j(q') \middle| \Phi_i(q) \right\rangle \right) f_i(q,t) = 0.$$

During fission from collective excited states, the probabilities for non-adiabatic transitions of nucleons may be very large

if

there is a deformation region in which the frequencies of collective and single-particle motions become comparable.

What are the pertinent single particle excitations ?



- Quantum number K :

Axial symmetry in an even-even nucleus -> K=0

Only K=0 excited states are coupled to HFB vacuum

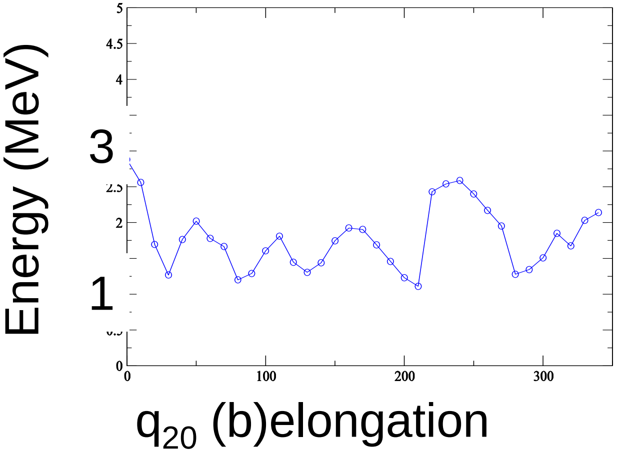
- Lowest excitation energies:

  * E(2qp) < 5MeV

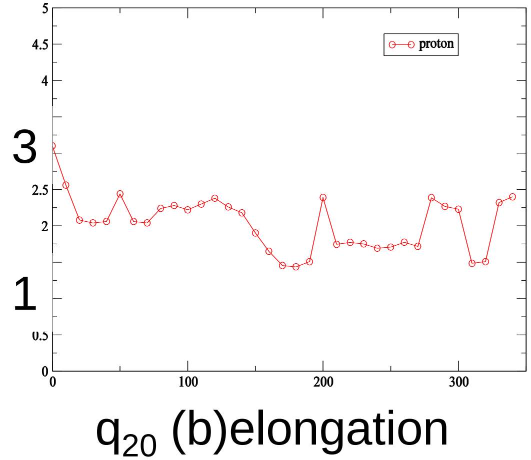
  * N q.p. excitations neglected with N>2

- Particle number: <N>=N+ε

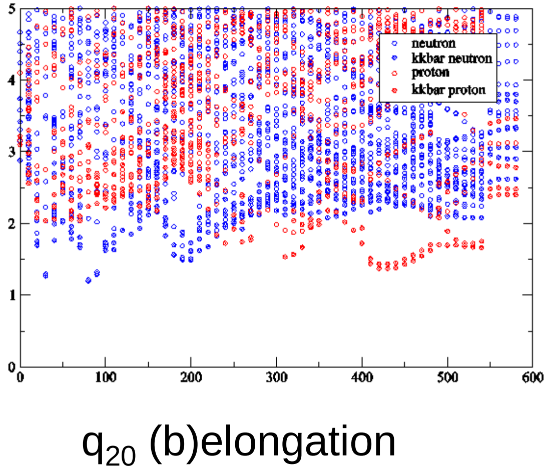
Single particle states



Energy of the lowest neutron 2qp excitation along the asymmetric path



Energy of the lowest proton 2qp excitation along the asymmetric path



Intrinsic excitations along the symmetric path

-> Excitation energies are higher than 1.5 MeV but are low enough to be taken into account in the fission process

-> Around 30 excitations below 5 MeV if no constraint on the particle number

-> only a few if the particle number is constrained

What's next ?

→ To study the transition just before scission - just after scission with this state of the art approach

first test may probably be done in simpler cases such as shape coexistence mechanisms

TD GCM based on TDHF(B)

$$\left|\Psi(t)\right\rangle = \int dq\, f(\{q\},t)\left|\Phi(\{q\},t)\right\rangle,$$

Variations with respect to f and |Φ>
+ Gaussian Overlap Approximation

K. Goeke
Supplement of the Progress of Theoretical Physics, Nos. 74 & 75, 1983

→ In practice; to propagate two neighbored TDHF trajectories IΦ(q,t)) and IΦ(δq,t)) and to work out additionally the time evolution of the width α (t) of the GCM wave function

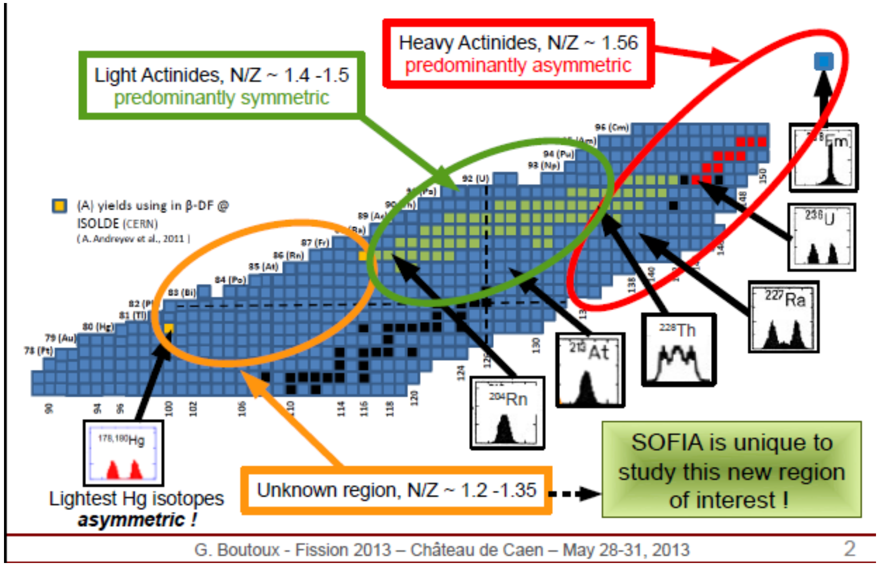
What is needed now?   (Personal view 1/2)

- **Systematics:** To look at global evolutions (as function of E*, N, Z of the fissioning system…), to challenge a theory, search for systematic effects,

G. Pellereau et al. EPJ Web of conf 62 06005(2013)
J. Randrup and P. Moller, PRC88, 064606 (2013)
S. Goriely et al. PRL111, 242502 (2013).

- **Investigation** of new mass regions

SOFIA
STUDIES ON FISSION WITH ALADIN



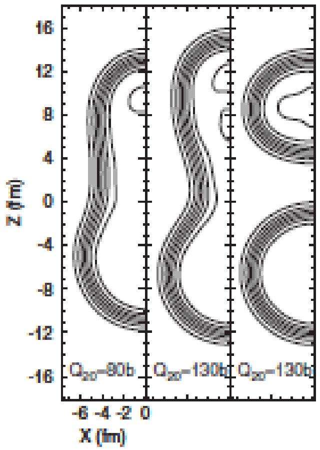
- **Correlations :** to explore correlations between several observables
Ex: FALSATFF@NFS, …

What is needed then ? (Personal view 2/2)

Theoretical improvements related to mean-field based approaches :

→ Better know/control/introduce the relevant deformations during the fission process (see N. Dubray)

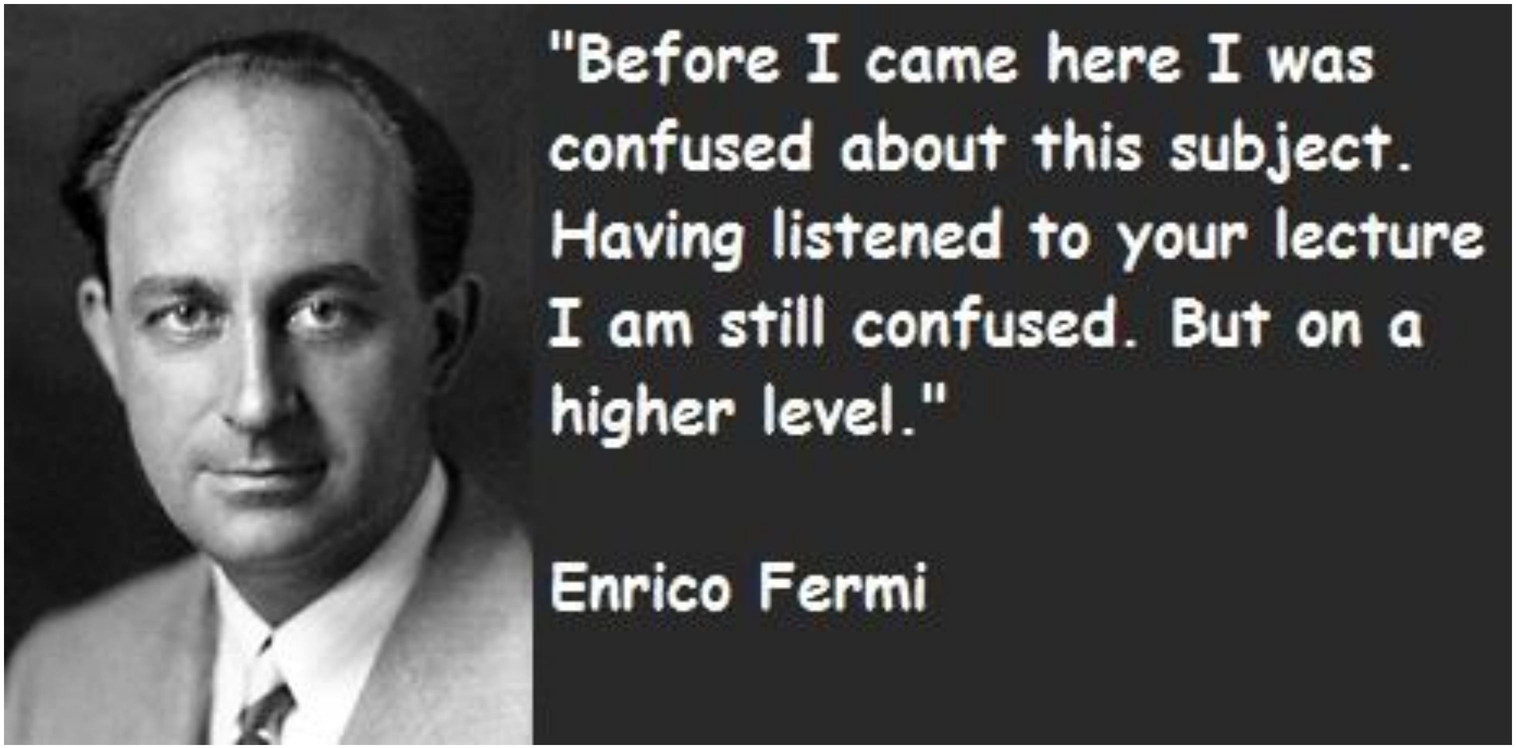
→ Introduce excitation energy/temperature in HFB calculations



→ Better define the fission fragments at scission
(projection on good particle numbers in the fragments,
quantum localization …) W. Younes, D. Gogny, PRL 107, 132501 (2011).

→ Enrich the dynamical approaches
(N dimensional propagation, coupling between collective modes and intrinsic excitations …

C. Simenel, A.S. Umar, PRC89, 03160(R) (2014).


"Before I came here I was confused about this subject. Having listened to your lecture I am still confused. But on a higher level."
Enrico Fermi