Probing the fission dynamics with time-dependent approaches based on energy density functional

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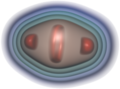
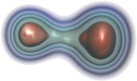
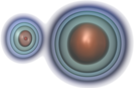
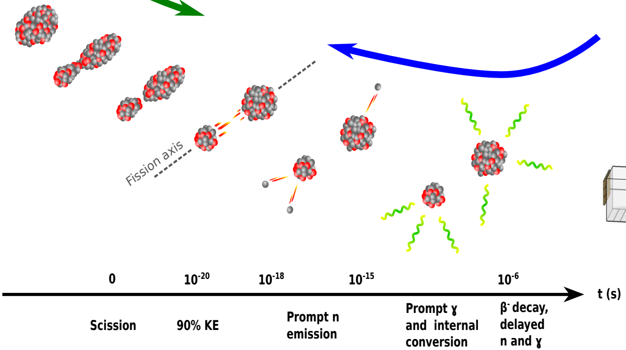




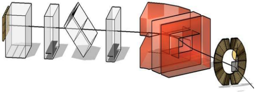
Probing the fission dynamics

Many-body calculations based on energy density functional

Fission time scale ?
Scission neutron ?
Fragments characteristics ?
Fragments deexcitation ?

VAMOS@Spiral1
SOFIA@GSI
Falstaff@NFS
Fission@Licorne
...

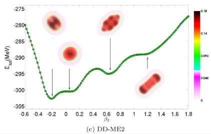




Dynamics from energy density functional

Basic application of energy density functional theory (EDF)

From a density functional (*e.g. Skyrme, Gogny, RDF, etc*) to the energy and nucleon density of a nuclear ground state



J.P. Ebran *et. al.* Phys. Rev. C 90, 054329 (2014)

Fission dynamics from energy density functional (EDF)

- Generalizing to a time dependent problem
- Dealing with both large collective motions and single particle excitations (close to scission)

TD-GCM

The system is described by a mixing of static densities (*e.g.* different shapes). The weights associated to each density evolve in time.

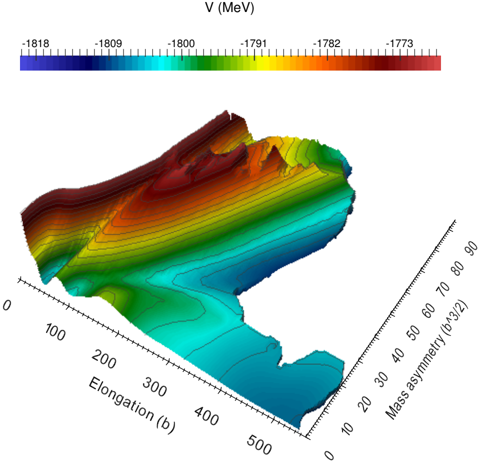
TD-EDF

The system is described by its nuclear density that can evolve in time

Time Dependent Generator Coordinate Method (TD-GCM)

Example of a n + ^{239}Pu fission

1. Choose the collective variables:
   - elongation (Q_{20} in b),
   - mass asymmetry (Q_{30} in $b^{3/2}$)
2. Calculate potential energy surface and inertia tensor
3. Define initial wave packet for the probability amplitude
4. Compute time evolution of probability amplitude
5. Extract fission fragment distribution by computing the flux of the probability amplitude across the scission line



Interpolated potential energy surface for (n+^{239}Pu) fission

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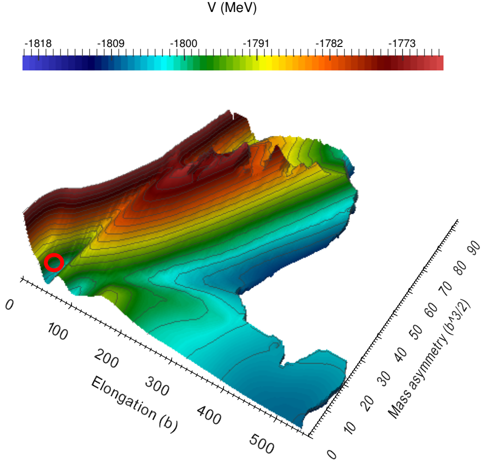

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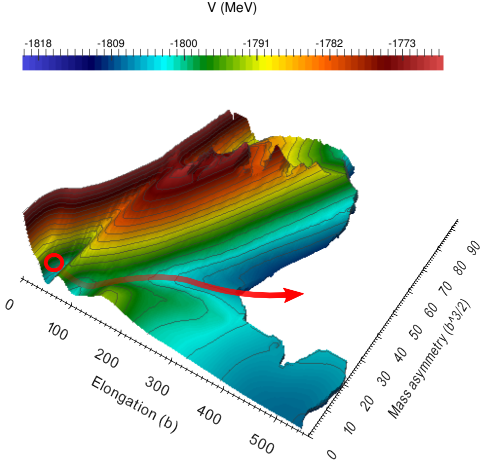

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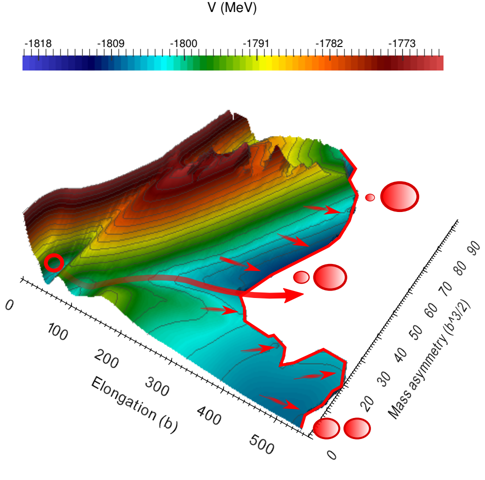


Interpolated potential energy surface for (n+^{239}Pu) fission

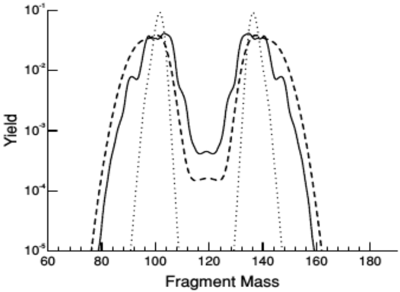
Development of this microscopic approach

2005: First calculation for ^{238}U
H. Goutte *et al.*, Phys. Rev. C **71**, 024316

2012: Fission yields of ^{236}U and ^{240}Pu
W. Younes *et al.*, LLNL-TR-586678

- Promising results
- High numerical costs

2D PES	40000 HFB states
Dynamics	10 zs ($10^{-21}s$)



Pre-neutron mass yields for ^{238}U at 2.4 MeV above the fission barrier (H. Goutte *et al.*).
solid line: dynamics calculation
dashed line: Whal evaluation (2002)

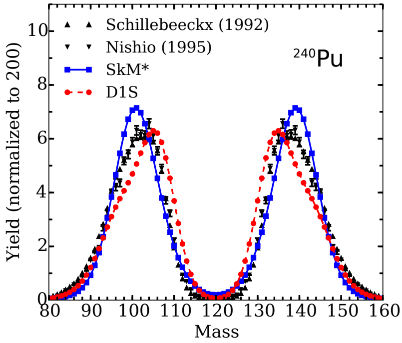
Upgrade numerical methods

FELIX-1.0 D. Regnier *et al.*, Comput. Phys. Commun. **122**, 350-363 (2016)
FELIX-2.0 accepted in Comput. Phys. Commun.

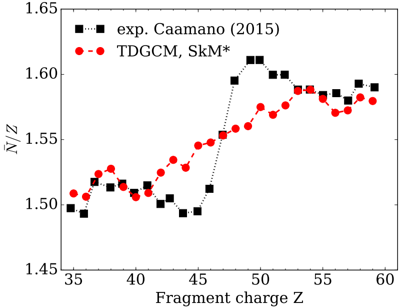
New applications

D. Regnier *et al.*, Phys. Rev. C **93**, 054611 (2016)
A. Zdeb *et al.*, Phys. Rev. C **95**, 054608 (2017)
H. Tao *et al.*, Phys. Rev. C **96**, 024319 (2017)

Mass and charge of the primary fragments for a ^{240}Pu fission



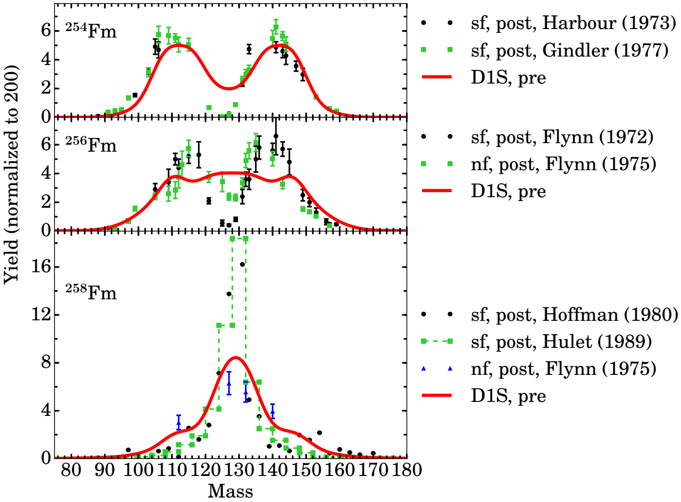
Mass yields of the primary fragments. The initial energy is taken 1 MeV above the fission barrier. D. Regnier *et al.*, Phys. Rev. C **93**, 054611 (2016).



Average neutron excess $\bar{N}/Z$ of primary fragments.

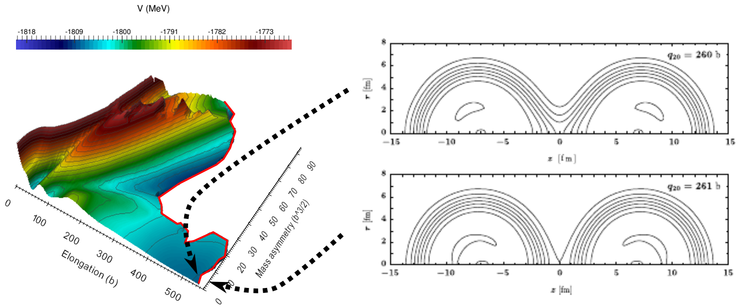
- Qualitative reproduction of the mass yields for actinides
- Missing the non-adiabatic rupture of the neck

Symmetric/asymmetric yields transitions in Fm isotopic chains



Work in progress on Th isotopes for comparison with the last SOFIA campaign

Major issue: discontinuity at scission

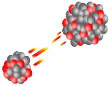


The dynamics must only be computed on a continuous part of the deformation space. In the final configurations:

- masses of the fragments are defined up to the number of particles in the neck,
- the nuclear force is still acting between the two fragments.

Discontinuity at scission prevents us to compute post-scission fragment observables

TD-EDF for the superfluid dynamics in the vicinity of scission



1. Goal: characterize the primary fragments
2. Method: Time dependent energy density functional with pairing

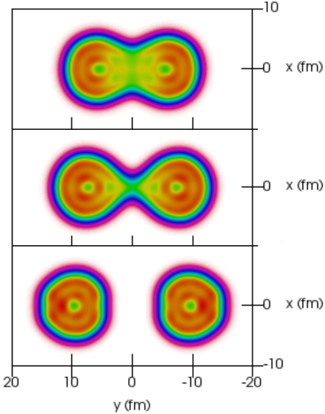
- trajectory of an average fragmentation
- diabatic dynamics

Its recent application to fission enables the prediction of new observables *e.g.* the average energy repartition between the fragments.

It also opens new opportunities concerning:

- scission neutrons
- spin of the fragments ?

Limit: only averaged observables over all possible fragmentations (no yields)



Density of protons for a symmetric fission of ^{258}Fm

Development of this microscopic approach

2014: ^{258}Fm ^{264}Fm (no pairing)

C. Simenel *et al.*, Phys. Rev. C **89**, 031601(R) (2014)

2015: ^{258}Fm with pairing (TDBCS)

G. Scamps *et al.*, Phys. Rev. C **92**, 011602(R) (2015)

≃ 1 week on a few CPU

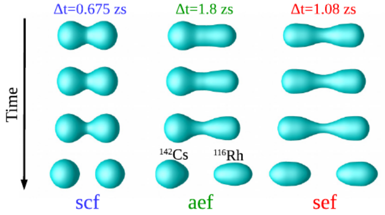
- 60 to 80% of the total excitation energy is generated during the rapid descent to scission

2016: ^{240}Pu with pairing (full TDHFB)

A. Bulgac *et al.*, PRL **116**, 122504 (2016)

≃ 10h on 1700 GPU

- TKE reproduction within 3%



Iso-density surfaces for three fission modes of a ^{258}Fm. G. Scamps *et al.*, Phys. Rev. C **92**, 011602(R) (2015).

- Only a few applications up to now
- Rich approach bringing new insight into scission

Outlook & Perspectives

Improved numerical methods and increased computational power provides new opportunities to bridge theory with the state of the art experiments.

Perspectives

- TD-GCM: great description of collective motion but mostly adiabatic method
  - Test the validity outside of the actinide region
  - Inclusion of additional collective degrees of freedom
  - Systematic calculations for the R-process of nucleosynthesis
- TD-EDF: acces to new fragment observables but only one collective trajectory
  - More applications comparable with experiments
  - Investigation on the role of pairing in fission

Big challenge: merging the benefits of the two methods

- Correlated fission observables such as TKE(A,Z)
- Impact far beyond the fission process (heavy ion reactions, super-heavy production, *etc*)

  Work in progress: SMF to predict pair transfer in heavy ion collisions...

Thank you for your attention !

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