Theory of nuclear fission: present and perspectives

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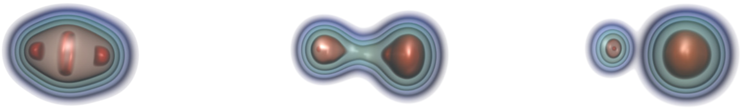
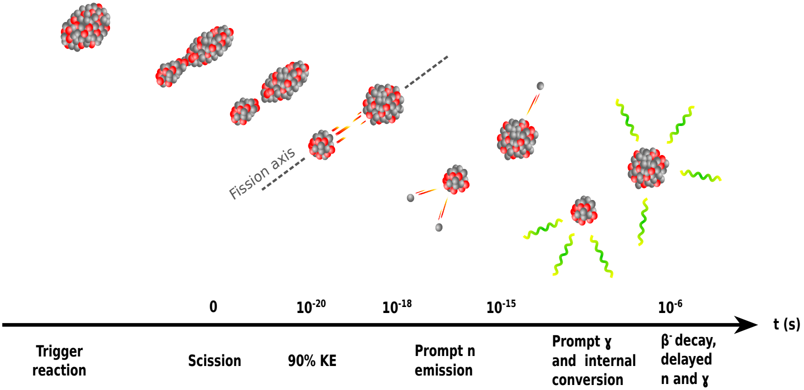


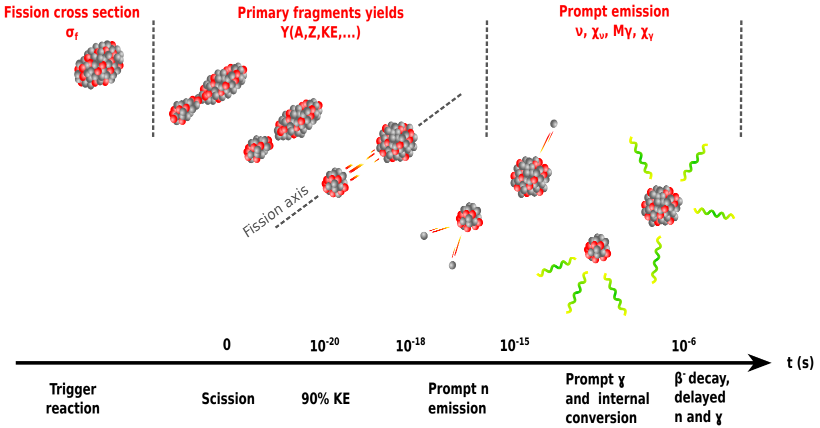
Nuclear fission and its observables



Difficult to tackle with a reaction theory

- Huge number of output channels
- Interest for observables at t$< \infty$

Nuclear fission and its observables



- σ_f: 'One channel' reaction theory
- Y(A, Z, KE...): Scission point models, many-body dynamics
- $\nu, \chi_\nu, M_\gamma, \chi_\nu$: Statistical deexcitation models

Different models for different needs

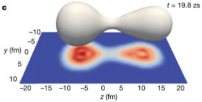
Fission cross section
σ_f

~1%
U,Pu

Primary fragments yields
Y(A,Z,KE,...)

~1% on Y(A,Z)
U,Pu

actinides
super-heavy
exotic nuclei

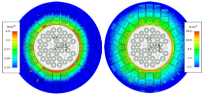


hundreds of
heavy neutron-rich
nuclei

Prompt emission
ν, χ_ν, M_γ, χ_γ

~0.1% on ν
U,Pu

~7.5% on E_γ
U, Pu



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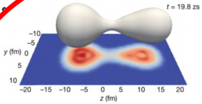

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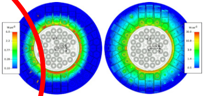

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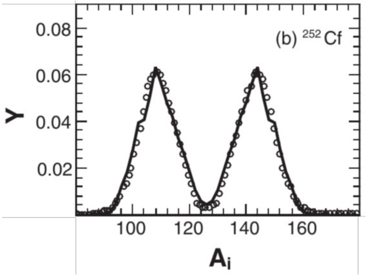
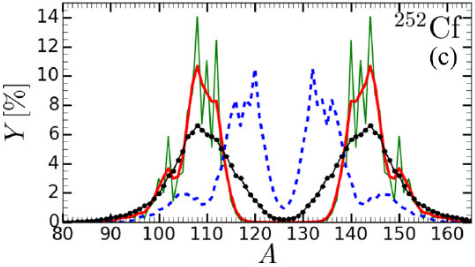
Scission point models

1. Open system treatment:
   $\psi(\boldsymbol{r}_1\sigma_1, \cdots, \boldsymbol{r}_A\sigma_A) = \psi_{\text{shape}} \times \psi_{\text{intrinsic}}$
2. Statistical distribution of states close to scission shapes



Pasca *et al.*, PRC 99 (2019)



Lemaitre *et al.*, PRC 99 (2019)

✓ Fast calculations

✗ High dependency to the phase-space considered

Scission point models

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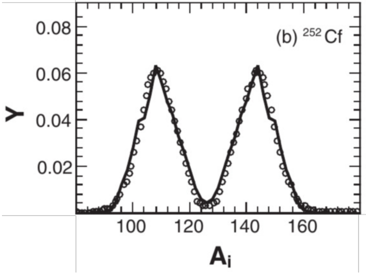
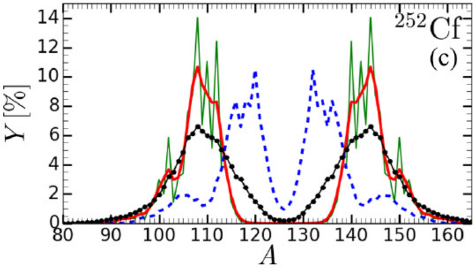


Pasca *et al.*, PRC 99 (2019)



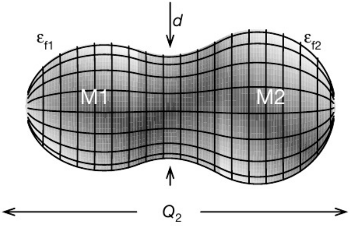
Lemaitre *et al.*, PRC 99 (2019)

✓ Fast calculations

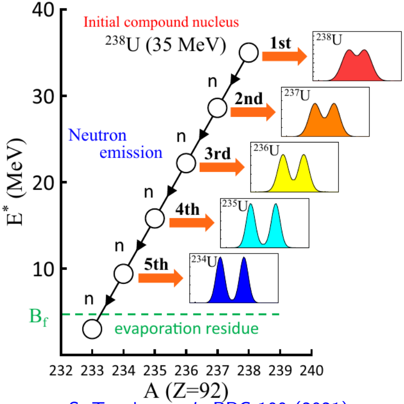
✗ High dependency to the phase-space considered

Langevin dynamics

1. Open system treatment:
   $\psi = \psi_{\text{shape}} \times$ thermal bath of intrinsic degrees of freedom
2. Dynamics of the shape coordinates



P. Möller *et al.*, Nature 409 (2001)

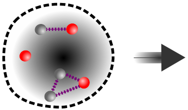


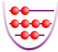
S. Tanaka *et al.*, PRC 100 (2021)

✓ Particle evaporation (neutrons, gamma rays)

✗ No information on internal fragments characteristics (e.g. spins)

Fission at the time dependent mean-field level



$|\psi(t)\rangle =$  $(t)\rangle$

Recent successes:

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

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

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

G. Scamps *et al.*, PRC **92**, 011602(R) (2015)

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

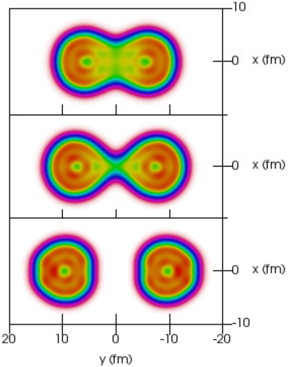
A. Bulgac *et al.*, PRL **116**, 122504 (2016)

2020: Deformation of the fragments

G. Scamps *et al.*, Nature 564 (2018)

2021: Spin of the fragments

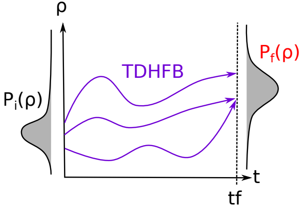
A. Bulgac *et al.*, PRL **126**, (2021)



✓ Dynamics through scission (diabatic aspect)

✗ Fragments mass yields (lack of 1-body fluctuations)

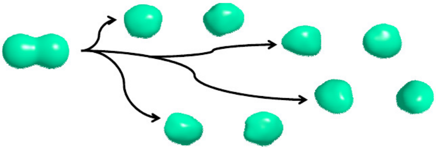
Including fluctuations with a statistical ensemble of trajectories

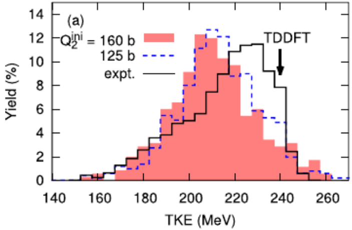


- Statistical distribution of initial states (i.e. Wigner transform)
- Classical averaging of observables

Example: Stochastic Mean Field dynamics of fission

D. Lacroix *et al.*, EPJA 50 (2014)



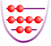
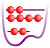


Y. Tanimura *et al.*, PRL **118** (2017)

✓ Fragment kinetic energy distribution (large fluctuations)

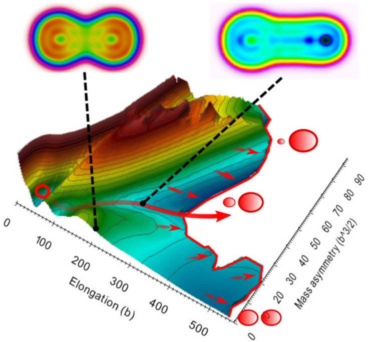
✗ No tunnelling through fission barrier (lack of quantum interferences)

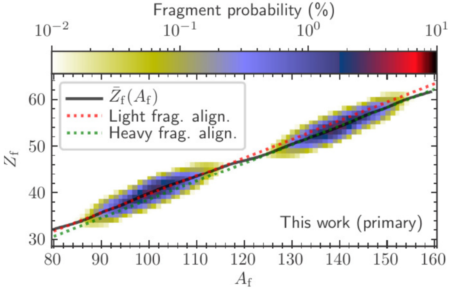
Quantum interferences: Time Dependent Generator Coordinate Method

$|\psi(t)\rangle = f_1(t)|$  $\rangle + f_2(t)|$  $\rangle + \cdots$

Constrained HFB solutions with ≠ shapes, time independent

1. Set of parameterized states
2. Dynamics in a collective space





M. Verriere *et al.*, PRC 103 (2021)

✓ Quantum tunnelling through fission barrier

✗ Dynamics through scission (diabatic aspect)

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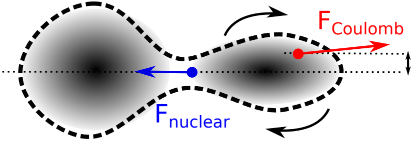
Primary fragments intrinsic spins



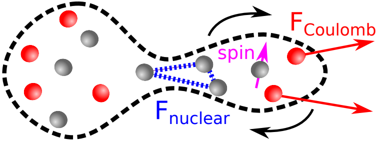
Fragments spins impact strongly

- the predictions of gamma observables,
- the population of isomeric states in the fission products.

Questions

- What is the distribution of primary fragments spins ?
- How does it vary with the mass/charge of the fragments ?
- What mechanisms produce this spin ?

Primary fragments intrinsic spins



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- What is the distribution of primary fragments spins ?
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A recent measurement at ALTO

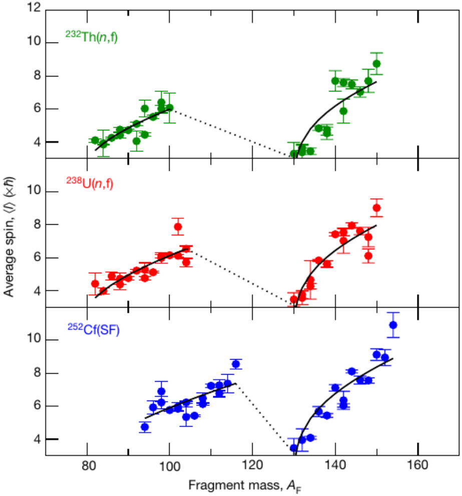
Post-neutron fragments average spins from Yrast transitions measurements

After emission of n and statistical γ:

- Sawtooth shape of the post-neutron spins
- No event by event correlation between the spins

Before emission of n and statistical γ:

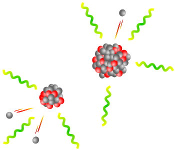
- No event by event correlation between the spins
- Generation of angular momentum after scission

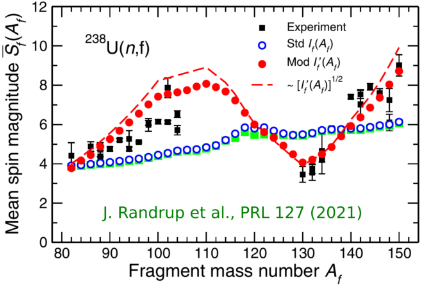


J. Wilson *et al.*, Nature 590 (2021)

Theory insight: from statistical deexcitation simulations

From $E^*, \boldsymbol{J}, \pi$ of the fragments





I. Stetcu *et al.*, arXiv:2108.04347 (2021) (CGMF):

- No sawtooth on primary fragments spins...
  and yet a sawtooth after statistical n/γ emission

J. Randrup *et al.*, PRL 127 (2021) (FREYA):

- Deformation of the fragments at scission $\Longrightarrow$ sawtooth in the spins
- Mostely uncorrelated primary fragments spins.

M. Travar *et al.*, PLB 817 (2021) (VESPA & FIFRELIN):

- Experimental sawtooth shape for M_γ
- Best reproduced with a sawtooth for primary fragments spins

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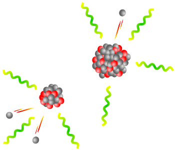

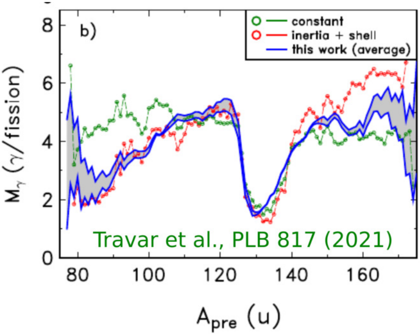

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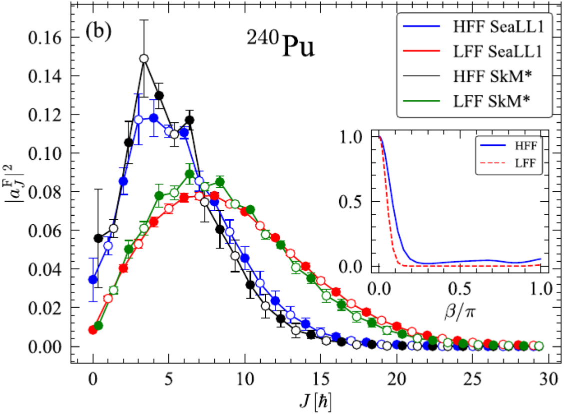
New microscopic theory insight: from TDHFB

Most probable fragmentation only, full separation of the fragments ($\simeq$ 25 fm)

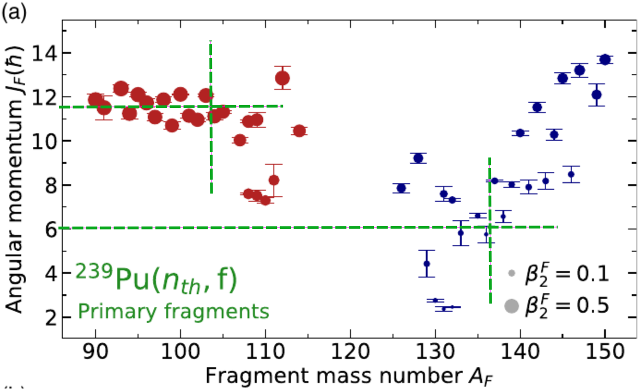


A. Bulgac *et al.*, PRL 126 (2021)

- Close to a statistical distribution $\propto (2J+1)exp\left(-J(J+1)/2\sigma^2\right)$
- Most probable fragmentations: $\bar{J}_{\text{light}} \simeq 9.9\hbar > \bar{J}_{\text{heavy}} \simeq 6.3\hbar$

New microscopic theory insight: from constrained HFB

Spin distributions for $\simeq$ 1500 static configurations close to scission

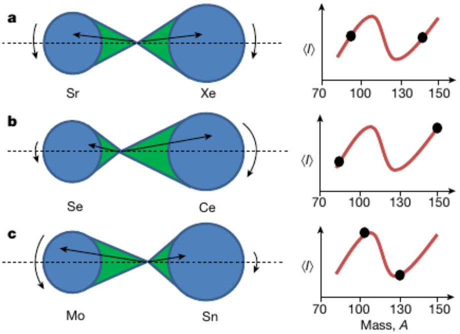


P. Marevic *et al.*, PRC 104 (2021)

- Large structure effects
- Most probable fragmentations: $\bar{J}_{\text{light}} \simeq 11.5\hbar > \bar{J}_{\text{heavy}} \simeq 6\hbar$

To put it in a nutshell...

1. First predictions on primary fragments spins from microscopic theories
2. $\bar{J}_{\text{light}} > \bar{J}_{\text{heavy}}$ for the most probable fragmentation
3. Spins seems correlated to the deformation close to scission
4. A clean comparison microscopy+deexcitation theory versus observation is still missing



J. Wilson *et al.*, Nature 590 (2021)

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Modernizing, standardizing and sharing our simulation tools

Released (open source):

EDF based approaches:

- HFODD: static HFB
  N. Schunck *et al.*, CPC 216 (2017)
- Sky3D: TDHF, TDBCS
  B. Schuetrumpf *et al.*, CPC 229 (2018)
- LISE: TDSLDA (TDHFB)
  S. Jin *et al.*, arXiv:2009.00745 (2020)
- FELIX: TDGCM
  D. Regnier *et al.*, CPC 225 (2018)

Fission fragment deexcitation:

- GEF: Weisskopf-Ewing
  K.-H Schmidt *et al.*, NDS 131 (2016)
- FREYA: Weisskopf-Ewing
  J. Verbeke *et al.*, CPC 222 (2018)
- CGMF: Hauser-Feshbach
  P. Talou *et al.*, arXiv:2011.10444 (2021)

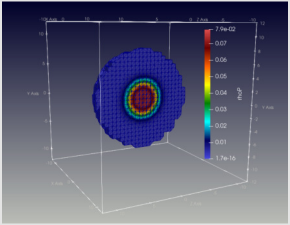
Forthcoming:

HFB3 (N. Dubray *et al.*)

A new HFB solver with Gogny EDF

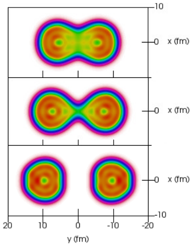
? (D. Regnier *et al.*)

An exploratory TDHF solver based on finite elements

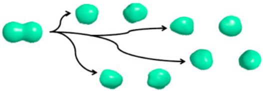


Goals for microscopic dynamical approaches

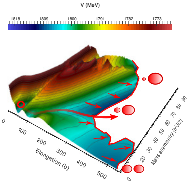
Diabaticity



1-body fluctuations



Quantum coherence

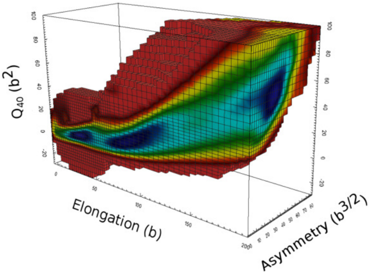


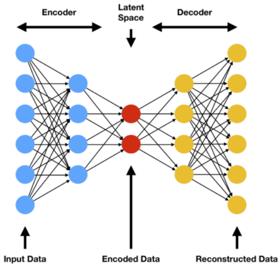
Challenges

- Account at the same time for diabatic motion, large fluctuations and quantum coherence.
- Predict correlated yields $Y(A, Z, KE...)$,
- including new observables E^*, spins, etc,
- and for all fissionning systems !

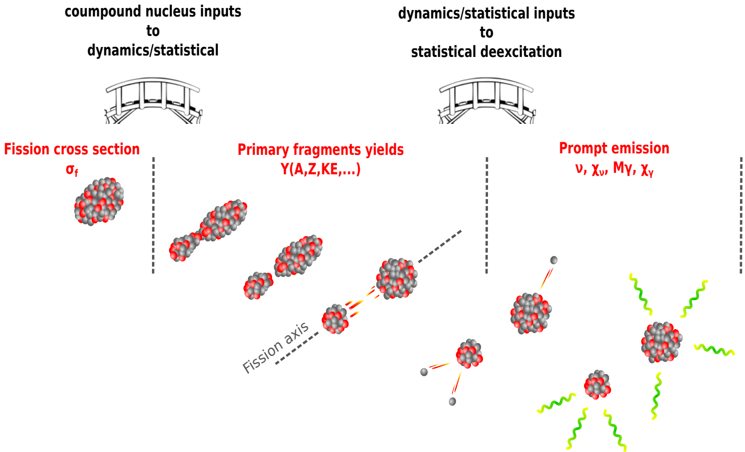
Non exhaustive list of ongoing projects on microscopic dynamics

- TDGCM in 3-dimensions
  N. Dubray *et al.*, D. Vretenar *et al.*
- QP extension of the TDGCM
  N. Pillet *et al.*
- AI to build collective space
  R.-L. Lasseri *et al.*, M. Verriere *et al.*
- Phase space fermion dynamics
  D. Lacroix *et al.*
- Time dependent density matrix
  P. Stevenson *et al.*
- Multiconfiguration TDHF
  D. Regnier *et al.*



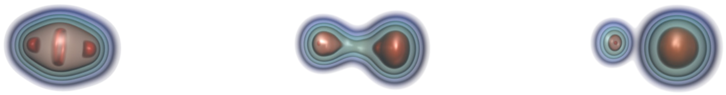


Ultimately...bridging the three steps of the fission process



Observables of interest

- Prompt emission of exotic fissioning systems
- Scission neutrons ?
- Impact of the input channel (spin, energy) on the fission yields



Thank you for your attention !

Some more reviews forseeing the 'future'...

- Future of nuclear fission theory,
  M. Bender *et al.*, J. Phys. G: Nucl. Part. Phys. **47** (2020)
- Nuclear Fission Dynamics: Past, Present, Needs, and Future,
  A. Bulgac *et al.*, Front. in Phys. **8** (2020)