Toward a microscopic description of the nuclear fission process

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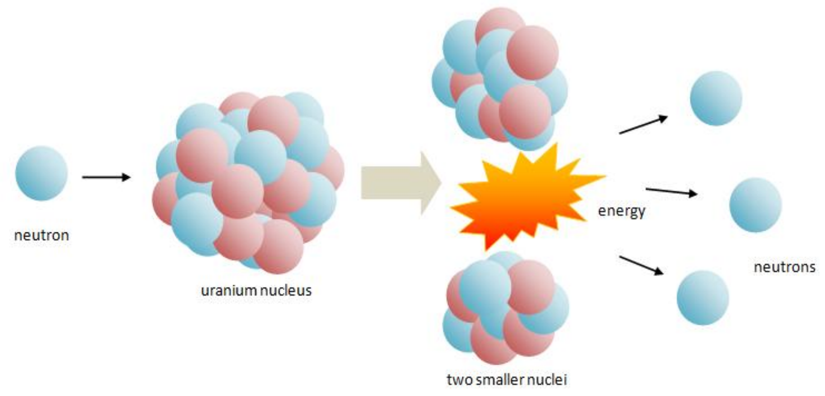
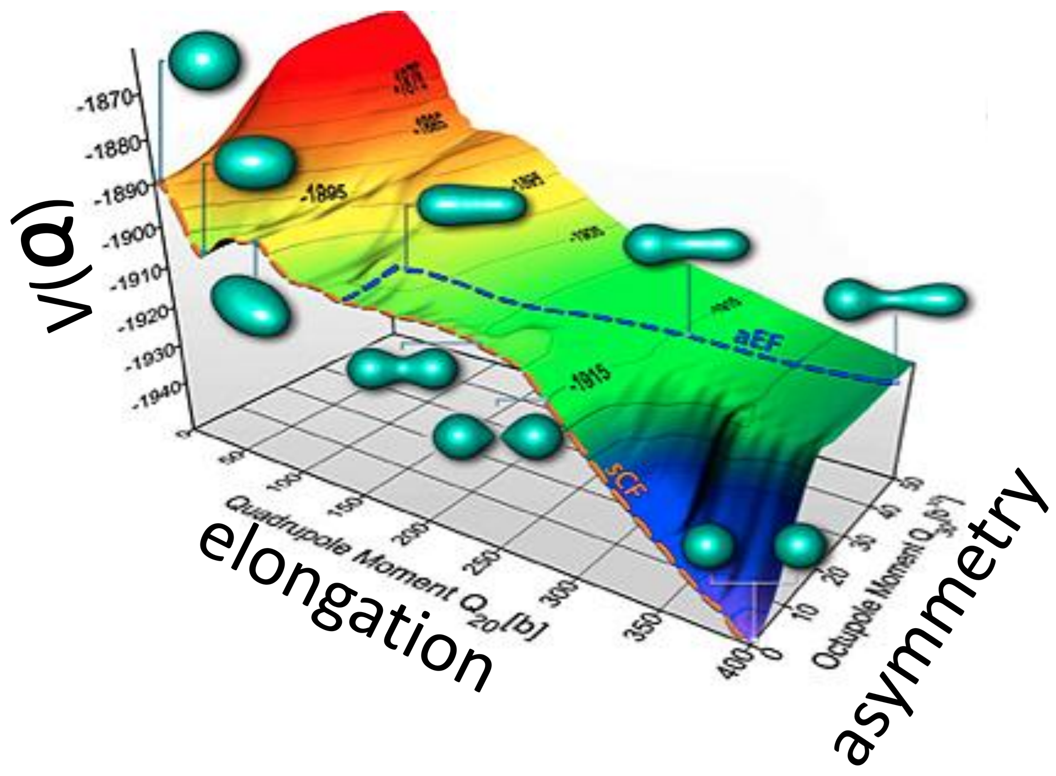
Introduction: Nuclear fission

- **Importance**
  - ✓Energy production
  - ✓Synthesis of super heavy elements
  - ✓Production of radioactive isotopes
  - ✓Astrophysical processes
- **Theoretical challenges**
- **Difficulties**
  - ✓large-amplitude motion of quantum many-body system
  - ✓coexistence of quantum and thermal effects
  - ✓couplings between "collective" and "internal" degrees of freedom





- **Conventional strategy:** Y. Tanimura, D. Lacroix, and G. Scamps, Phys. Rev. C92, 034601 (2015)
  1. select a set of relevant collective variables ***Q***, *ex. elongation, mass asymmetry, ...*
  2. construct a potential energy surface *V*(***Q***)
  3. solve the equations of motion of ***Q*** to get fission observables
- Approaches based on liquid-drop model of nuclei have been successful, but fully **microscopic** models based on nucleonic d.o.f. are still under development
- With **microscopic** approaches ...
  - ✓**Hartree-Fock theory** is to be employed
  - ✓Only an effective nucleon-nucleon force (+ less phenomenological assumptions) are needed as input

We aim to develop a microscopic method for description of the fission

Stochastic mean-field approach

We employ **time-dependent Hartree-Fock** (TDHF) together with **stochastic mean-field** (SMF) theory

In TDHF, time-dependent many-body state is approximated by a Slater determinant

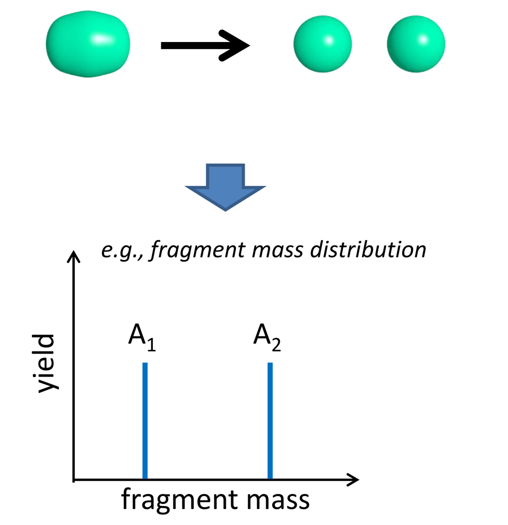
Advantages of TDHF:
- No need to select collective variables
- Fully non-adiabatic

Disadvantage of TDHF:
- Collective motion is nearly classical
- → **quantum fluctuation** of observables are severely underestimated

Quantum fluctuation missing in TDHF is essential for realistic fission calculations

TDHF equation

$$i\hbar\frac{\partial}{\partial t}\rho(t) = [h[\rho(t)], \rho(t)]$$



In SMF, evolution of quantum wave packet is mimicked by an ensemble of "classical" trajectories

S. Ayik, Phys. Lett. B**658**, 174 (2008),
D. Lacroix, S. Ayik, Eur. Phys. J. A (2014) 50: 95
D. Lacroix, Y. Tanimura, B. Yilmaz, and S. Ayik, Eur. Phys. J. A (2016) 52: 94

- Quantum fluctuation at $t = 0$ is taken into account by random sampling of one-body density matrix $\{\rho^{(n)}\}$

$$\rho^{(n)}(t=0) = \overline{\rho^{(n)}(t=0)} + \delta\rho^{(n)}$$

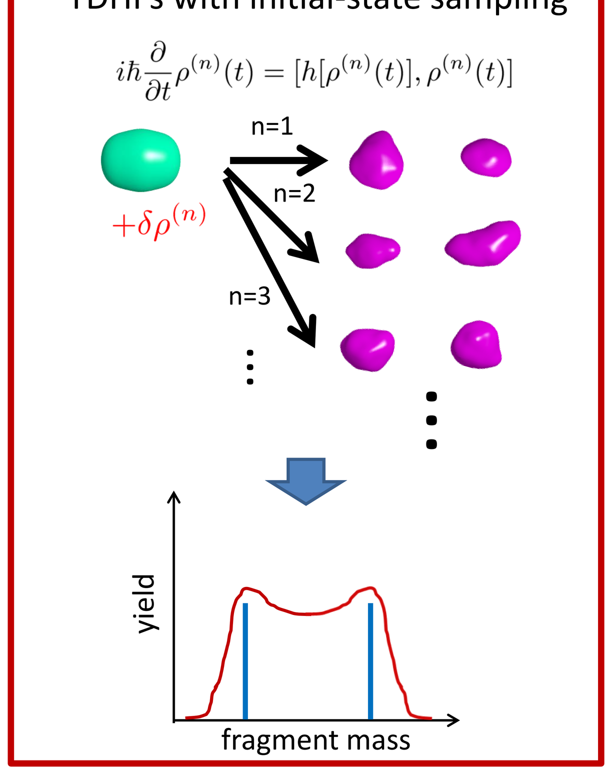
- Gaussian distribution is assumed for $\delta\rho^{(n)}$:

$$\overline{\delta\rho_{ij}^{(n)}} = 0$$
$$\overline{\delta\rho_{ij}^{(n)}\delta\rho_{i'j'}^{(n)*}} = \frac{1}{2}\delta_{ii'}\delta_{jj'}[n_i(1-n_j)+n_j(1-n_i)]$$

n_i: occupation numbers

- Evolution of a quantum wave packet is simulated by an ensemble of classical (TDHF) trajectories

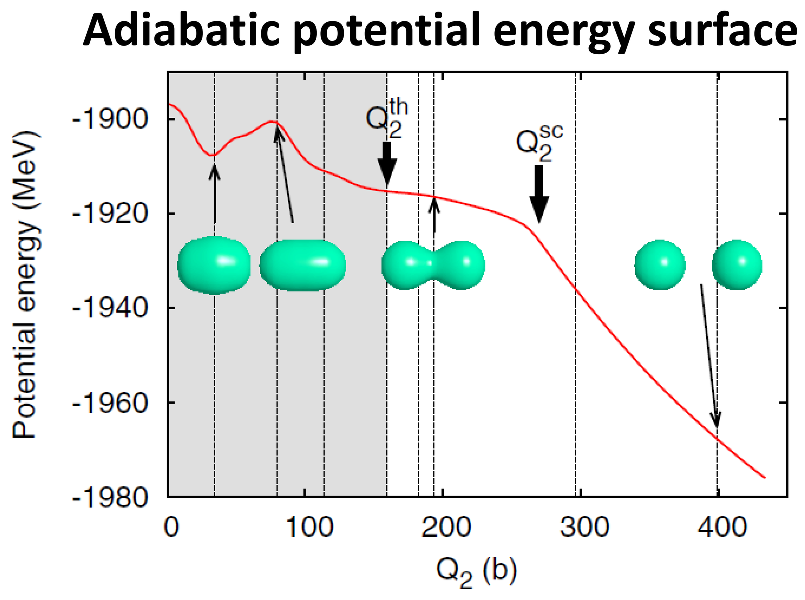
$$i\hbar\frac{\partial}{\partial t}\rho^{(n)} = [h[\rho^{(n)}], \rho^{(n)}]$$



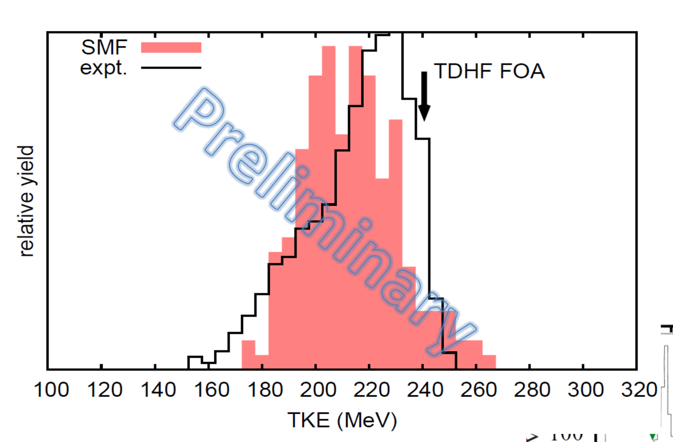
Application to spontaneous fission of ^{258}Fm

- Interaction: SLy4d + pure pairing force
- Starting from Q_2 = 180 barn
- 200 SMF events are generated

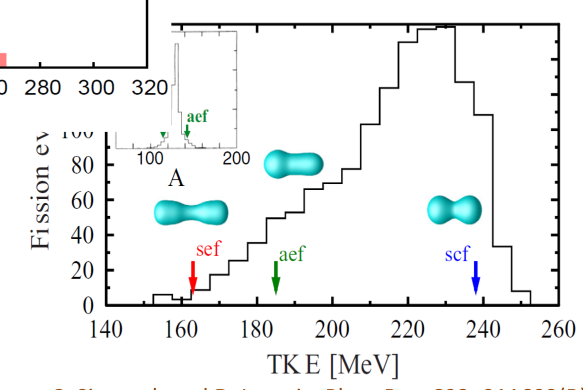
Adiabatic potential energy surface



Total kinetic energy of fragments

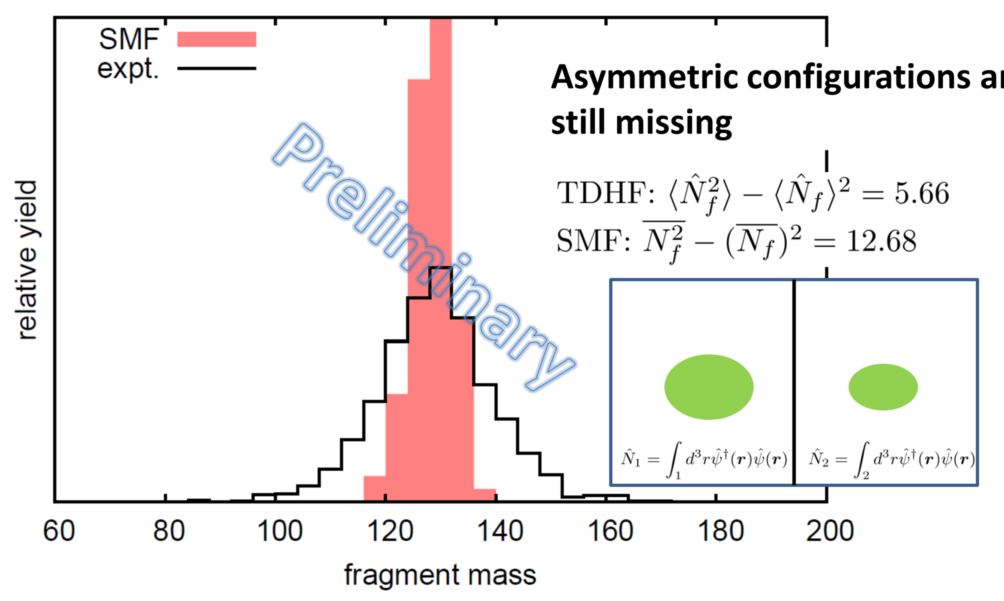


- **Width of distribution is reasonably reproduced**
- **Peak position is shifted from TDHF value**
- **Does not reproduce the asymmetric TKE distribution**
- **Asymmetric and elongated configurations are missing?**



G. Scamps, C. Simenel, and D. Lacroix, Phys. Rev. C92, 011602(R) (2015)
E. K. Hulet et al., Phys. Rev. Lett. 56, 313 (1986)

Fragment-mass distribution



Summary

- **Aim: Fully microscopic description of nuclear fission**
- **We tested the TDHF+SMF theory to take into account the quantum fluctuation missing in TDHF**
  - ✓quantum fluctuation at t = 0 is simulated by random sampling of initial state
  - ✓only input is the effective NN interaction and the initial condition
  - ✓**possible to obtain fission observables**
- Fission of ^{258}Fm → asymmetric and elongated fission modes are still missing
- Condition for initial sampling can be improved