Microscopic phase-space exploration of nuclear fission

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"Neutron star mergers: From gravitational waves to nucleosynthesis
International Workshop XLV on Gross Properties of Nuclei and Nuclear Excitations"
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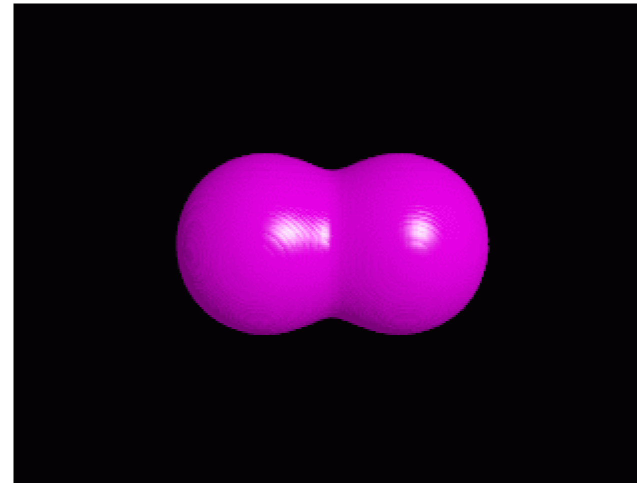
Outline

- Introduction
- Overview of theories for fission
- Stochastic mean-field (SMF) theory
- Spontaneous fission of ^{258}Fm
- Summary

Nuclear fission

- **Importance**
  - Astrophysical process
  - Energy production
  - Synthesis of super heavy elements
  - Production of radioactive isotopes



fission with TDHF

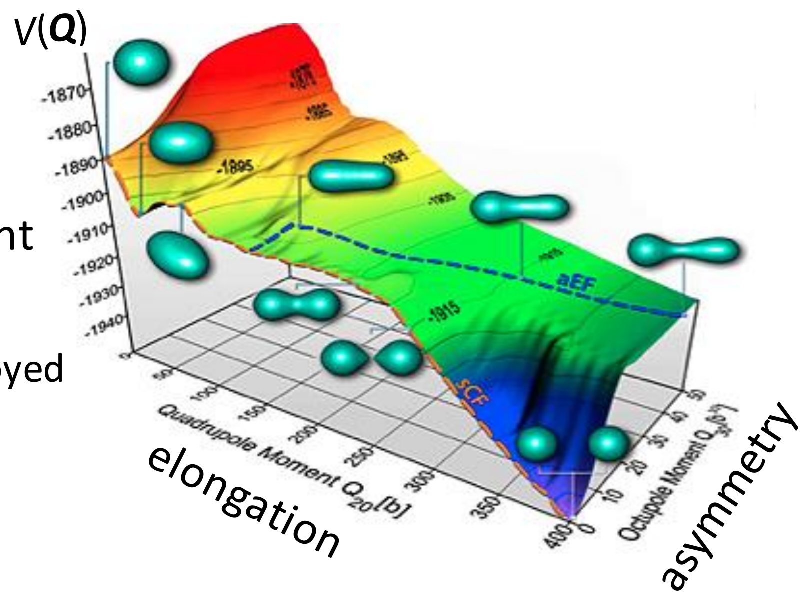
- **Theoretical challenges**
  - Large-amplitude process of quantum many-body system
  - Quantum tunneling of many-degrees of freedom
  - Coupling between collective and internal (single-particle) degrees of freedom

Theories for fission

- **Conventional strategy**

1. select a set of relevant collective degrees of freedom (DOF) ***Q***
   ex. elongation, mass asymmetry, etc.
2. construct potential energy *V*(***Q***) and collective inertia parameters
3. solve the equations of motion of ***Q*** to get fission observables
   lifetime, fragment mass/charge distribution, etc.

- Approaches based on the **macroscopic** model + shell correction have been successful
- **Microscopic** models are still under development
- With microscopic approaches
  - energy density functional (EDF) theory is employed
  - less phenomenological assumptions



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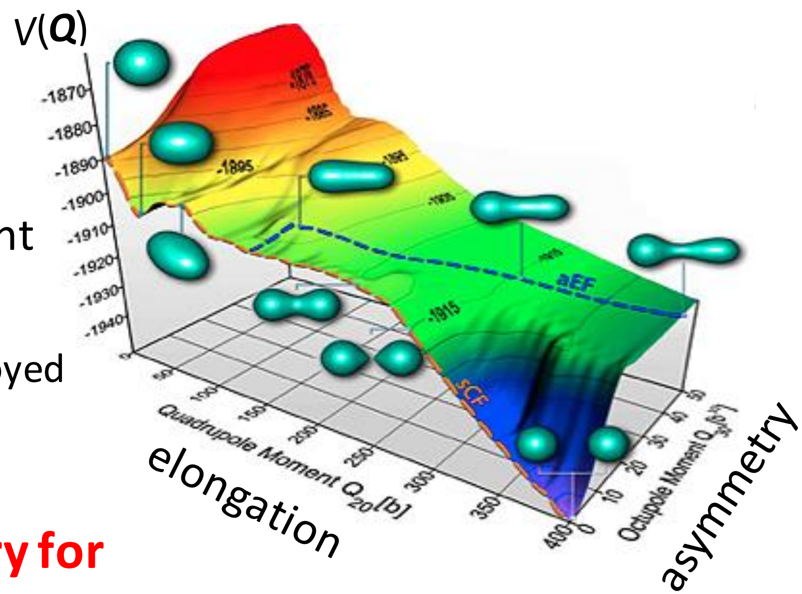
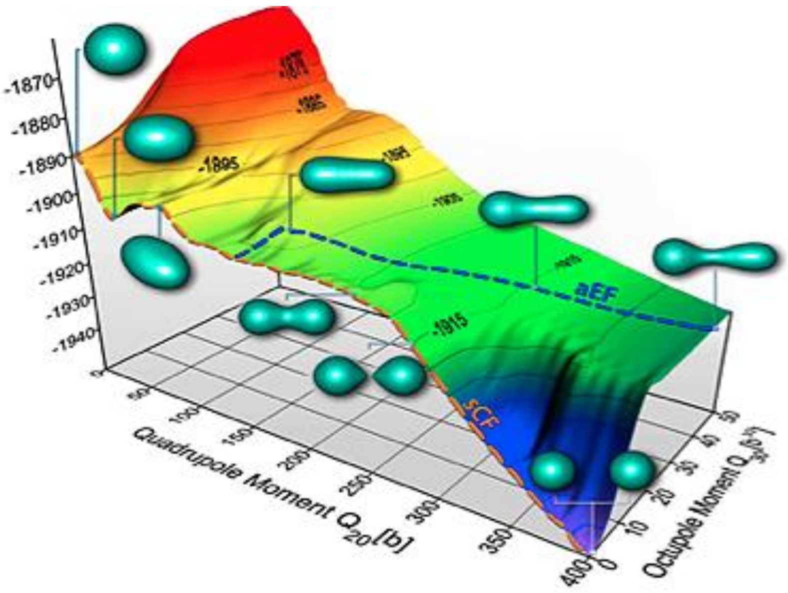


We aim to establish a microscopic theory for description of the fission process

Microscopic models

1. Static approach → talk by S.A. Giuliani



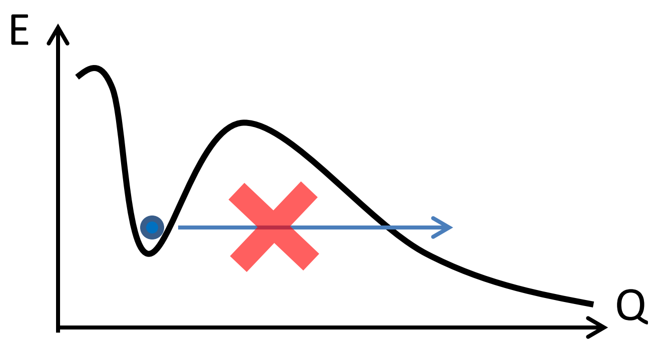
- With energy density functional theory (Skyrme, Gogny, RMF)
- Fission paths on the **potential energy surface** given by constrained mean-field calculations
- **Relevant DOF? Mass parameter?**
- **Dynamics is not fully treated**

2. Dynamical approaches

TDHF (Time-dependent Hartree-Fock)

- No need to select collective DOFs and compute mass parameters
- Fully non-adiabatic
- Collective motions are nearly classical
- No spontaneous symmetry breaking

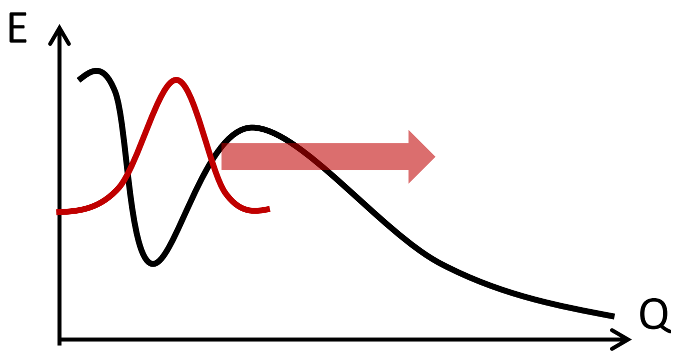
Negele et al, PRC**17**, 1098 (1978),
Umar and Simenel, PRC**89**, 031601 (2014).
YT, Lacroix, and Scamps, PRC**92**, 034601 (2015).



TDGCM (Time-dependent generator coordinate method)

- Quantum treatment of collective degrees of freedom
- Relevant DOF? Mass?
- Numerical cost rises rapidly with number of collective DOFs

Goutte et al PRC**71**, 024316 (2005),
Regnier et al, PRC**93**, 054611 (2016).



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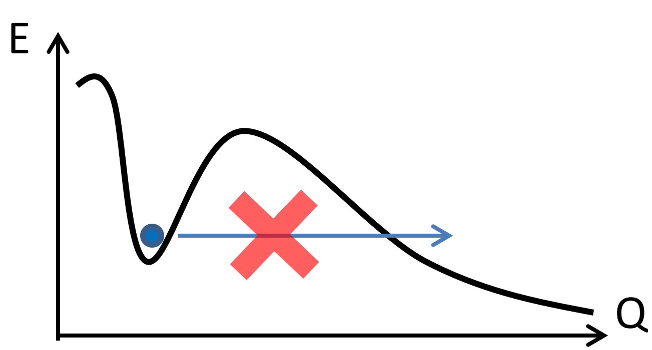

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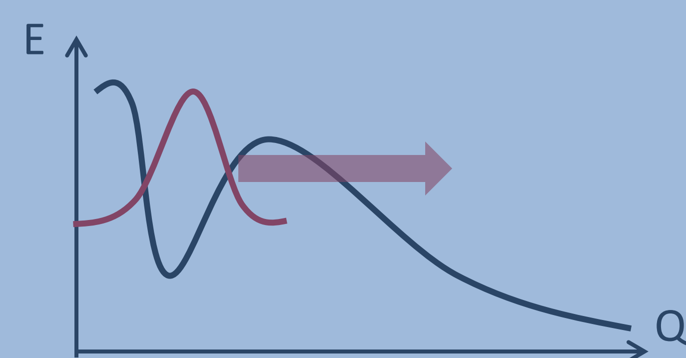

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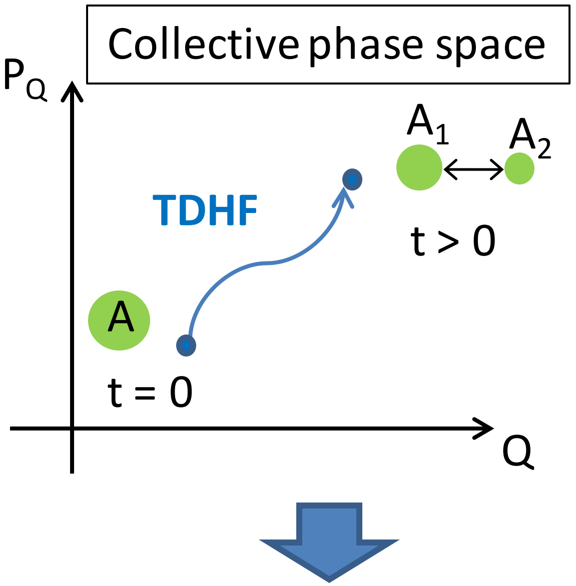
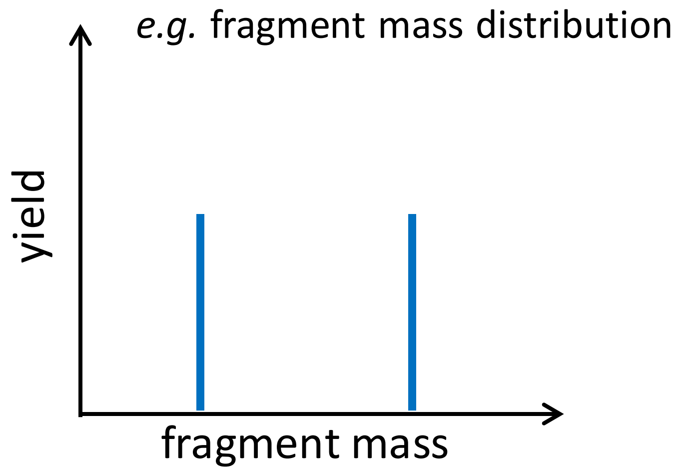
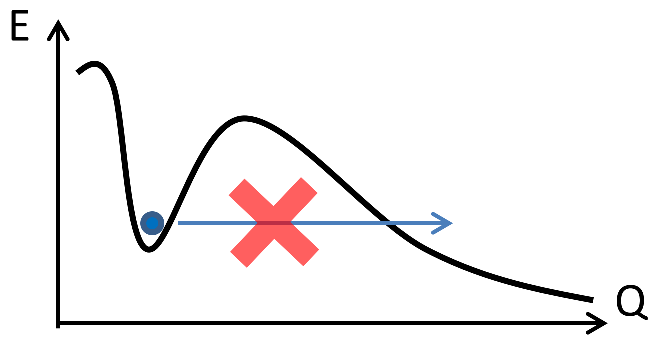






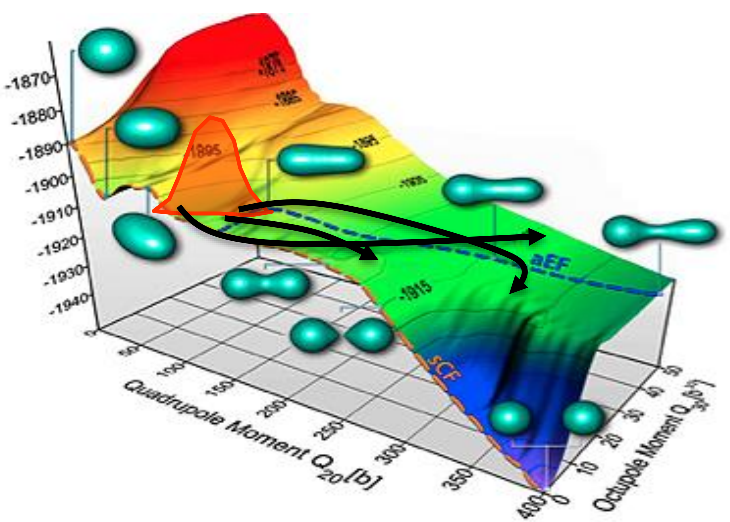
Our method

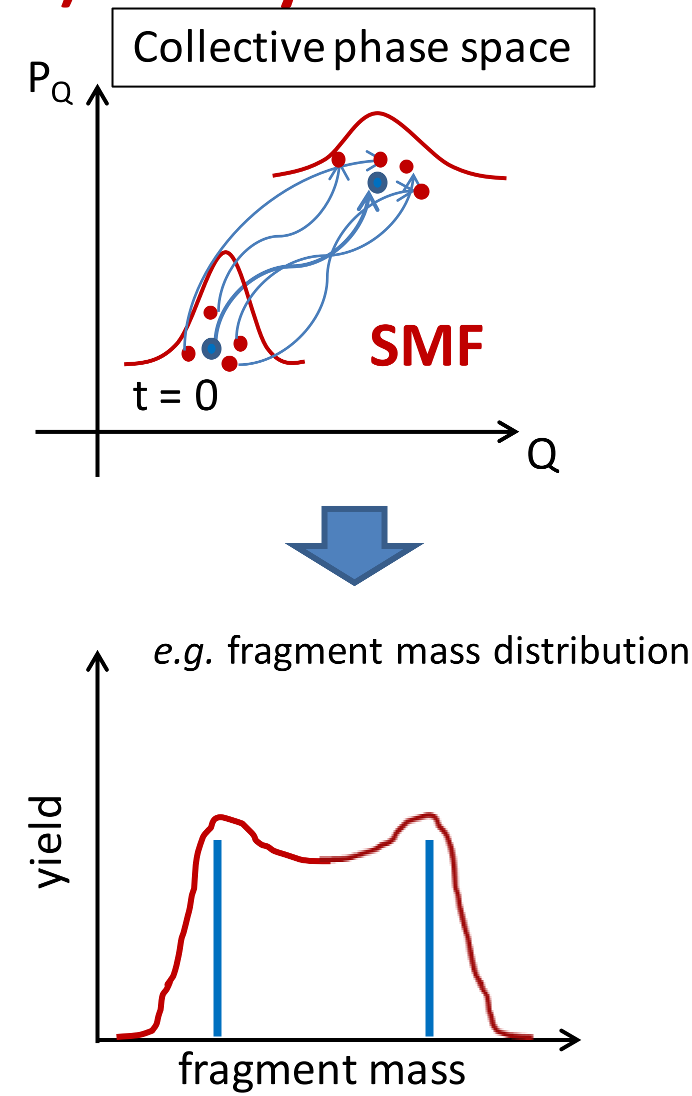
S. Ayik, PLB**658**, 174 (2008)

TDHF → Stochastic mean field (SMF) theory

- No need to select collective DOFs
- Fully non-adiabatic
- **Quantum fluctuations by initial-state sampling**
- **Symmetry breaking**

→ **microscopic and dynamical description of fission**





Stochastic mean-field theory

S. Ayik, PLB**658**, 174 (2008)

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

$$\rho^{(n)}(t=0) = \overline{\rho^{(n)}(t=0)} + \delta\rho^{(n)} = \frac{1}{N}\sum_{n=1}^{N}\rho^{(n)}(t=0) + \delta\rho^{(n)}$$

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

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

- Expectation values and dispersions of one-body observables

$$\langle Q\rangle \rightarrow \overline{Q^{(n)}} = \overline{\mathrm{Tr}[\rho^{(n)}Q]}$$

$$\langle Q^2\rangle - \langle Q\rangle^2 \rightarrow \overline{Q^{(n)2}} - \overline{Q^{(n)}}^2$$

Stochastic mean-field theory

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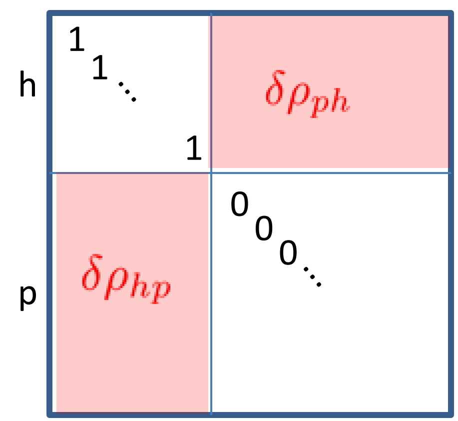
$$\rho^{(n)}(t=0) = \overline{\rho^{(n)}(t=0)} + \delta\rho^{(n)}$$

If the initial many-body state is a Slater determinant:

$$\overline{\delta\rho_{ij}^{(n)}} = 0$$

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

$$\rho_{ij}^{(n)}(t=0) = \delta_{ij}n_i + \delta\rho_{ij}^{(n)} =$$



- **Configuration-mixing effect**
- **Symmetries breaking**

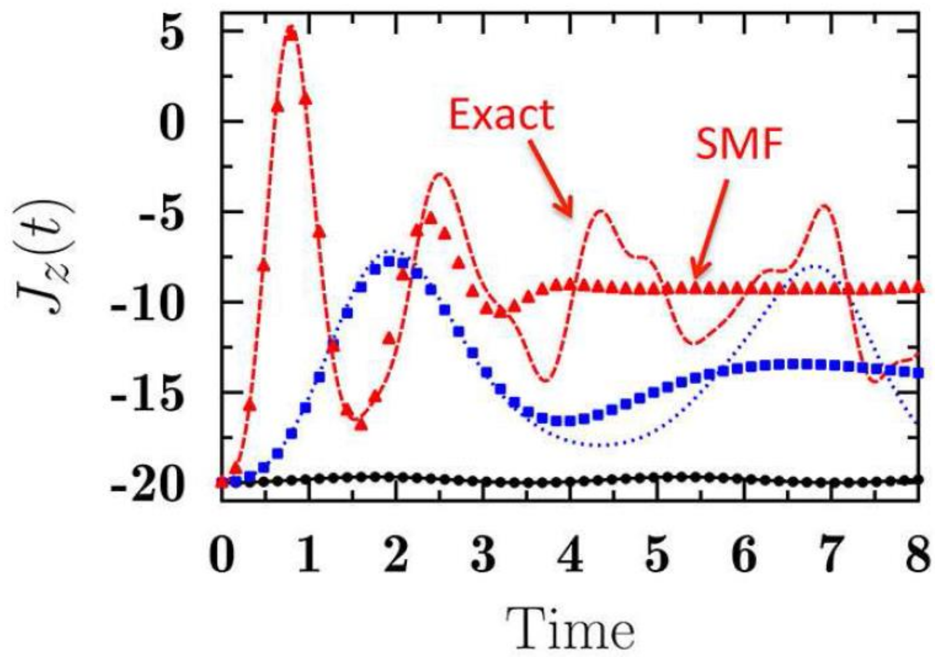
Stochastic mean-field theory

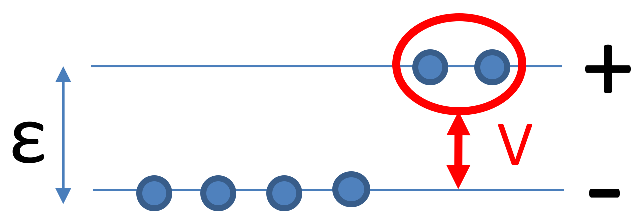
An application to an exactly solvable model

$$H = \varepsilon J_z - \frac{V}{2}\left(J_+^2 + J_-^2\right)$$

$$J_z = \frac{1}{2}\sum_{p=1}^{N}\left(c_{+p}^{\dagger}c_{+p} - c_{-p}^{\dagger}c_{-p}\right)$$

$$J_\pm = \sum_{p=1}^{N} c_{\pm p}^{\dagger}c_{\mp p},$$





Lacroix, Ayik, and Yilmaz, PRC**85**, 041602(R) (2012)

Quasi-spin of Lipkin model with SMF

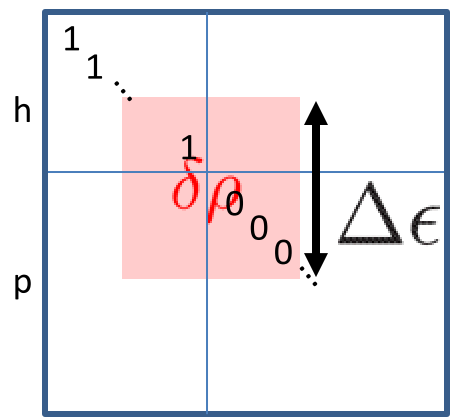
TDHF: nothing happens

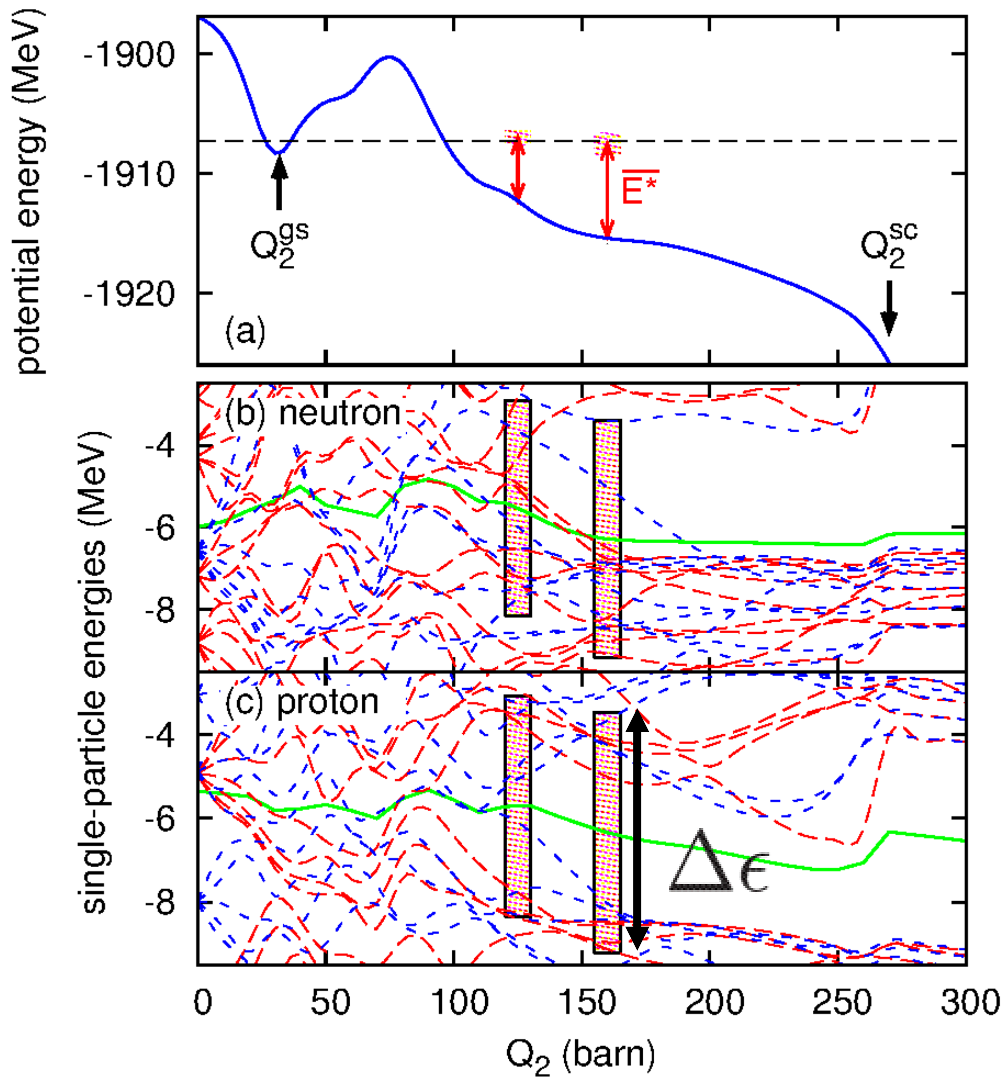
Application to spontaneous fission of ^{258}Fm

- Interaction: SLy4d + pairing
- $\delta\rho_{ij}$ is truncated within a window $\Delta\varepsilon$ around ε_F

$$\rho_{ij}^{(n)}(t=0) = \delta_{ij} n_i + \delta\rho_{ij}^{(n)}$$

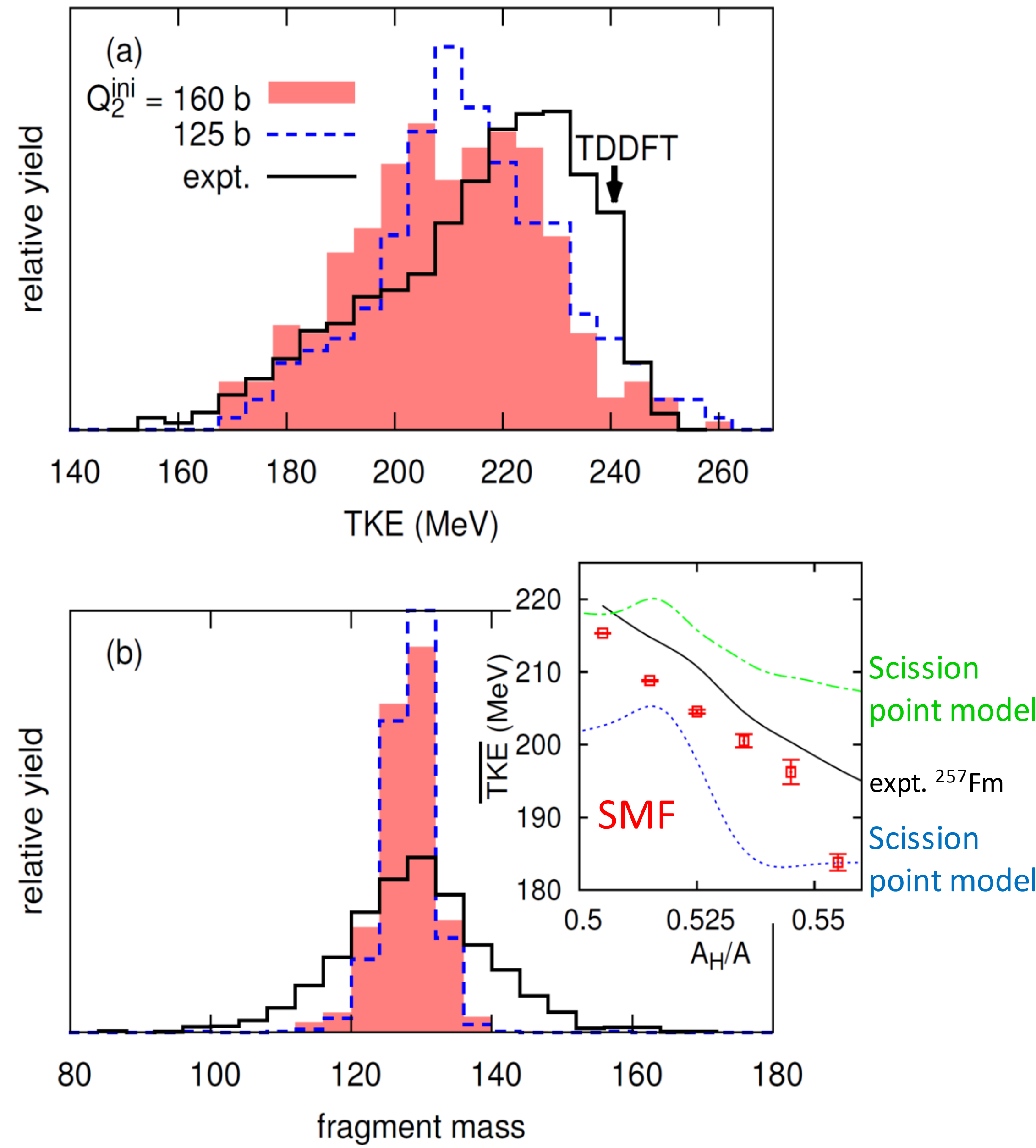
=





Total kinetic energy and fragment mass

- Width of distribution is reasonably reproduced
- Peak position is shifted from TDHF value
- Does not reproduce the asymmetric shape of TKE distribution



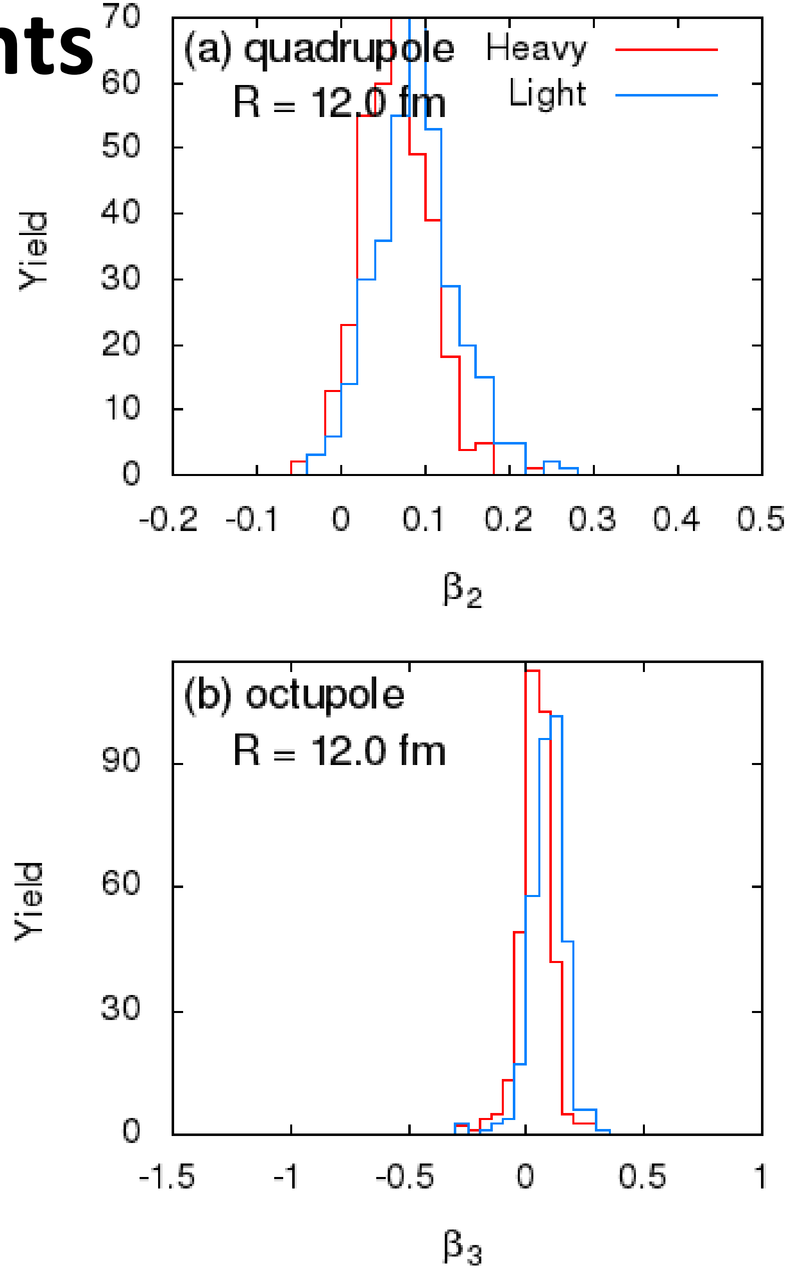
Wilkins et al., PRC**14**, 1832 (1976)

Deformation of fragments

"Projection" of motion of wavepacket onto certain collective subspace

- Quadrupole deformation is relaxed after scission

- Octupole deformation oscillates after scission

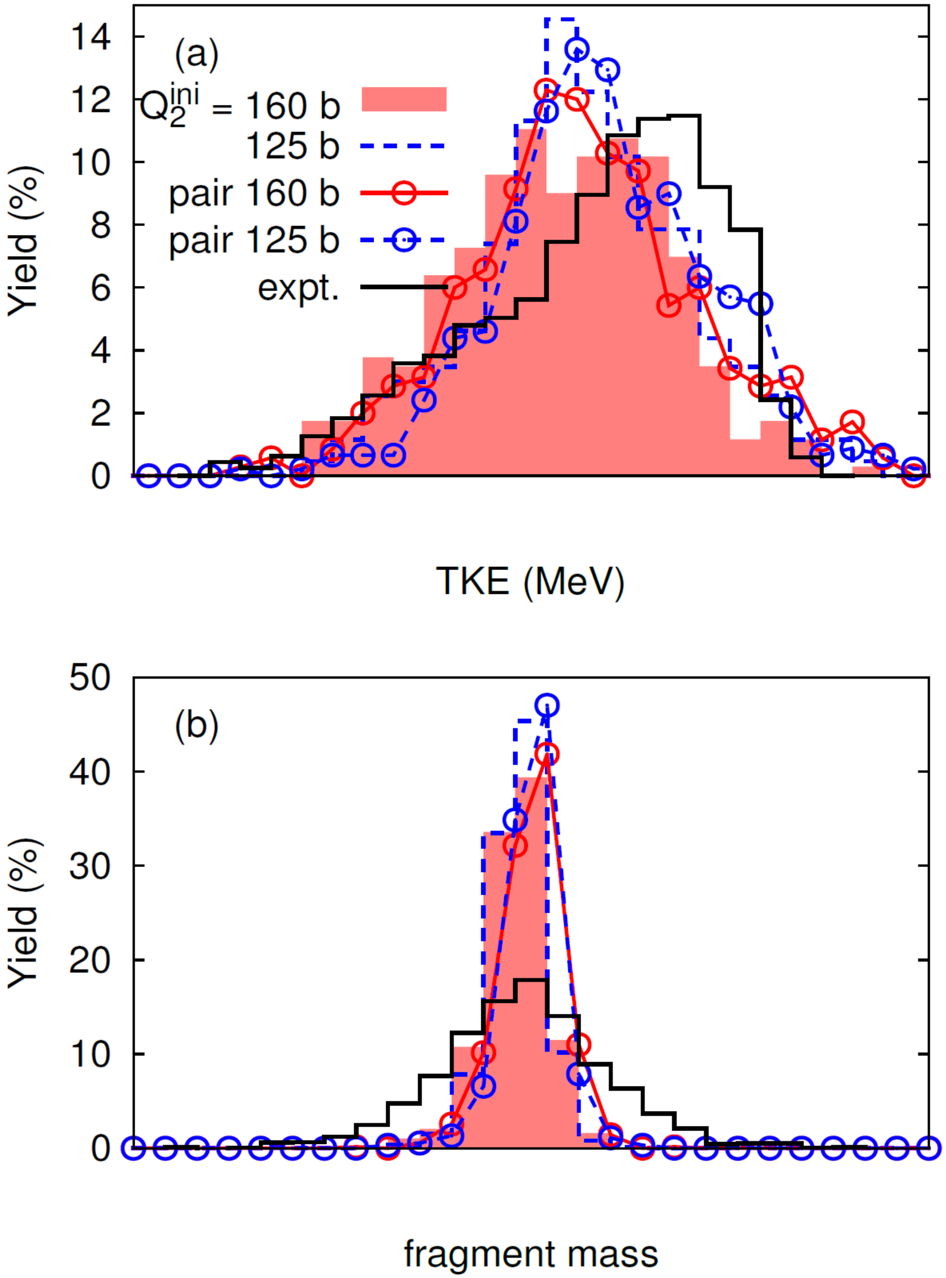


Summary and perspectives

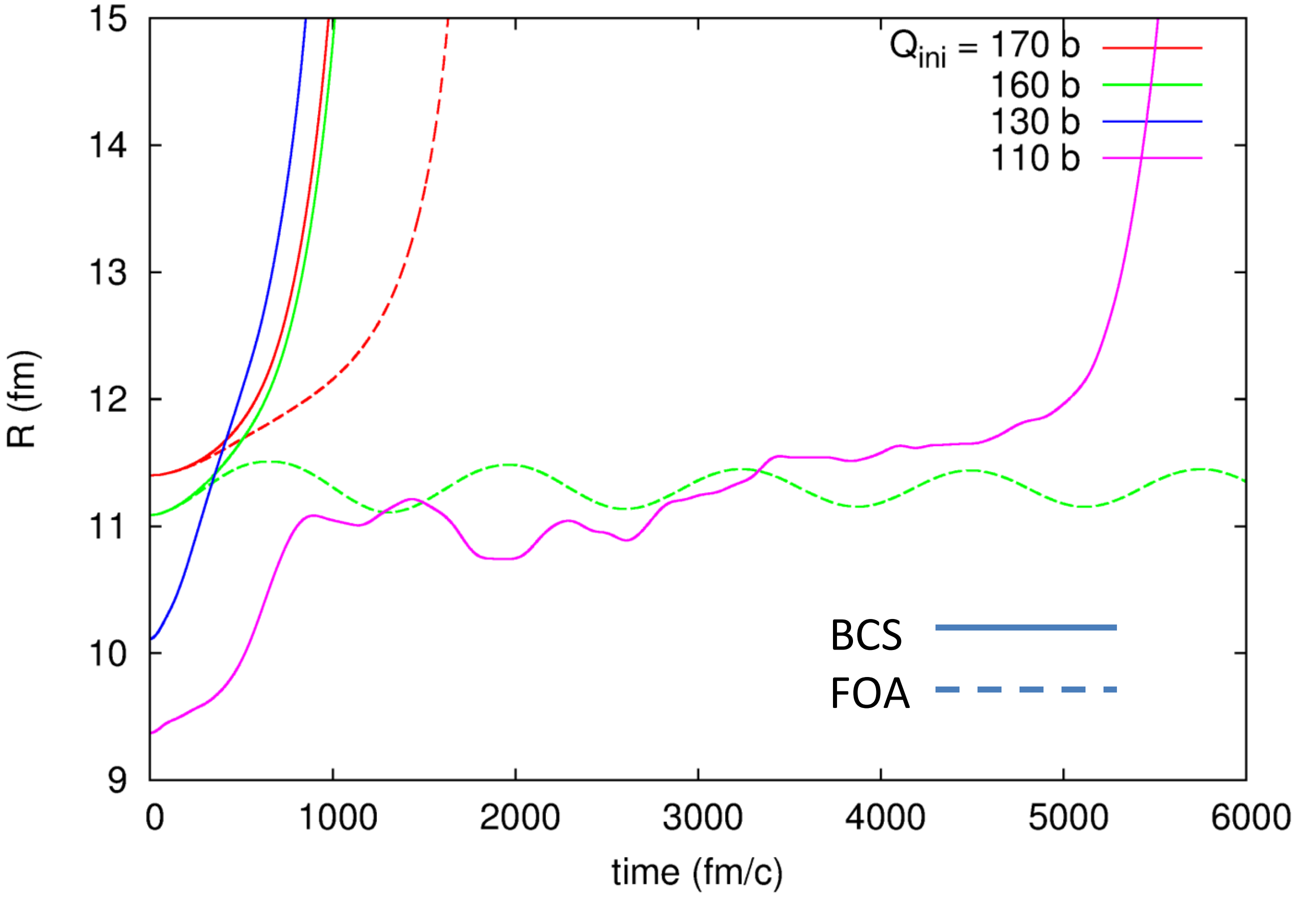
- **Aim: Fully microscopic and dynamical description for fission**
- **We applied the SMF theory to take into account the quantum fluctuations missing in TDHF**
  - fluctuation of ρ_{ij} is introduced at $t = 0$ by random sampling
  - spontaneous fission of ^{258}Fm: **possible to obtain realistic TKE and fragment-mass distributions**

- Induced fission
- Initial fluctuation determined from GCM calculation
- Systematic calculations

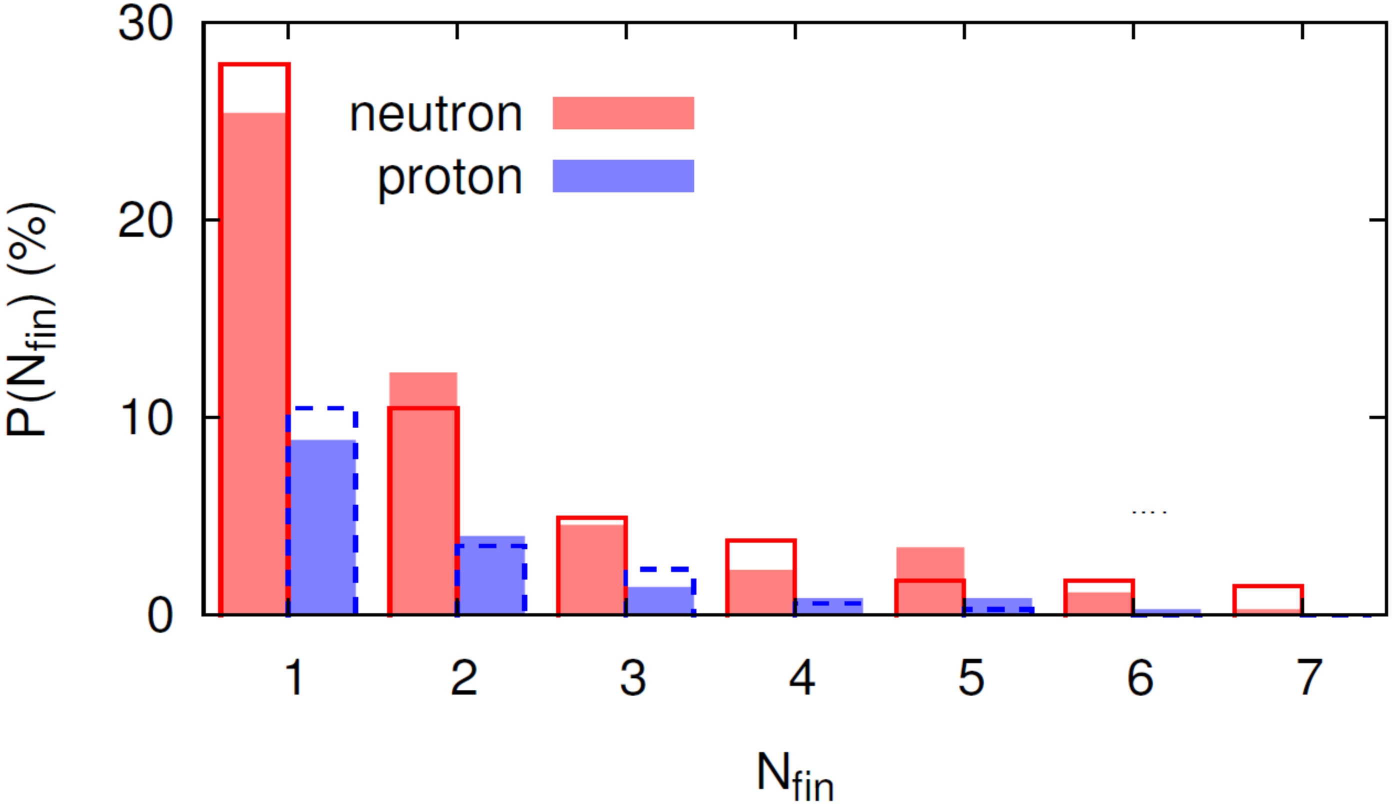
With and without dynamical pairing



TDHF + BCS and TDHF FOA



Evaporation of particles



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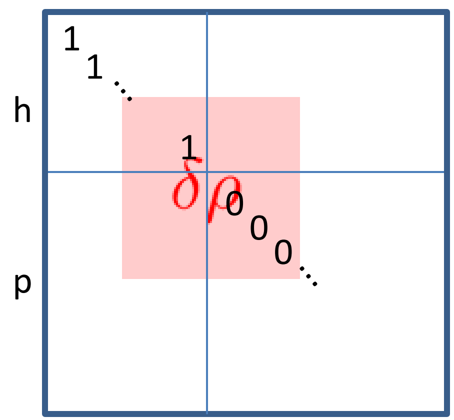

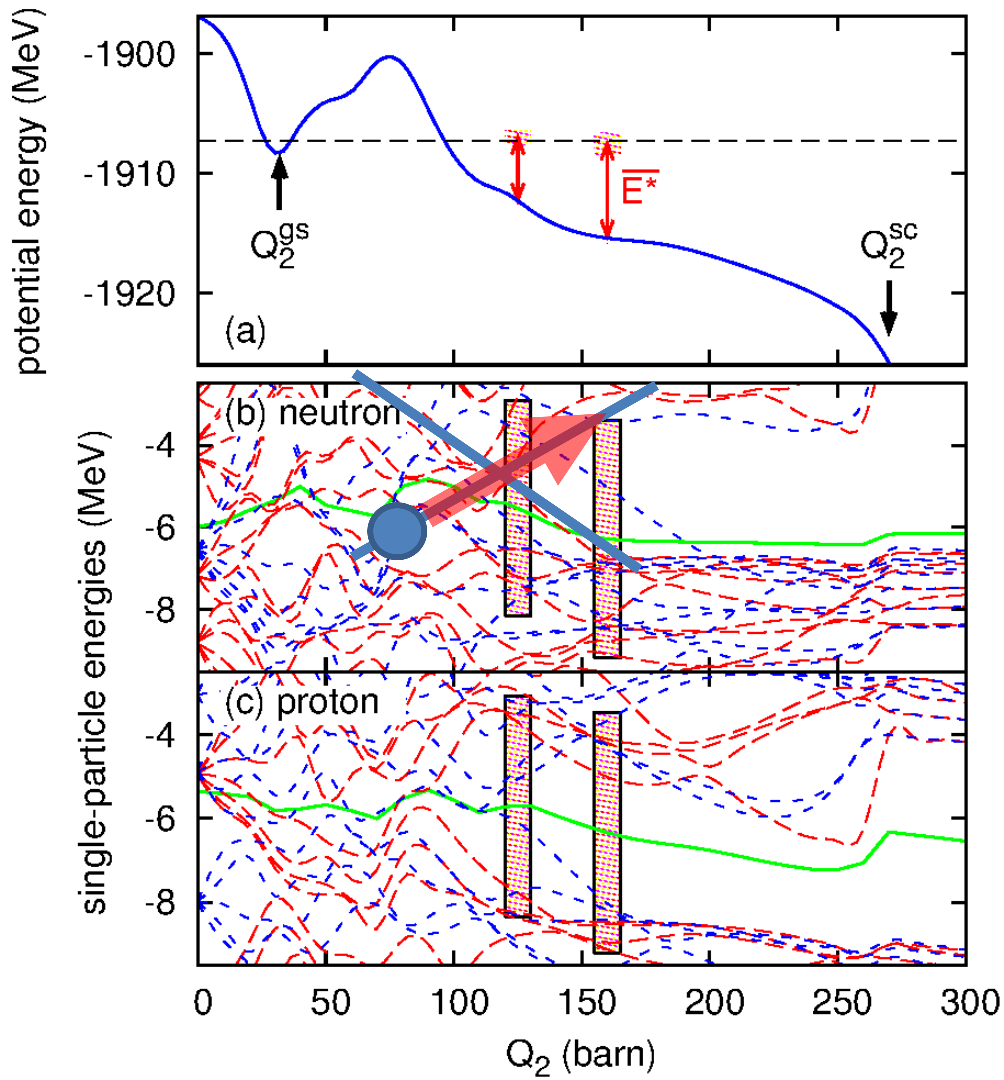

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