Towards a microscopic understanding of **low-energy induced fission** and its implication to fission in **r-process nucleosynthesis**

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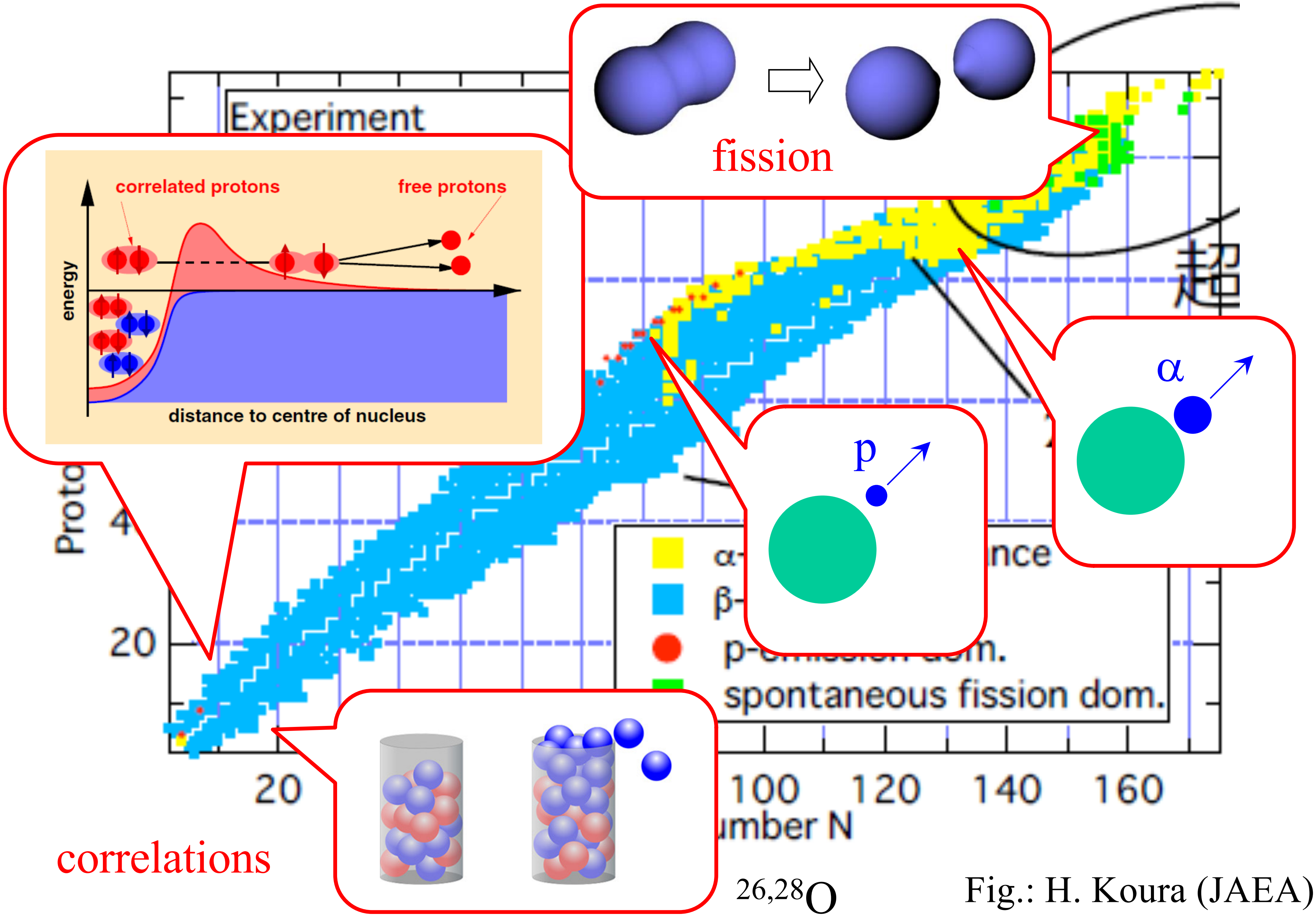
1. Introduction: nuclear fission
2. Shell Model for induced fission
3. Summary

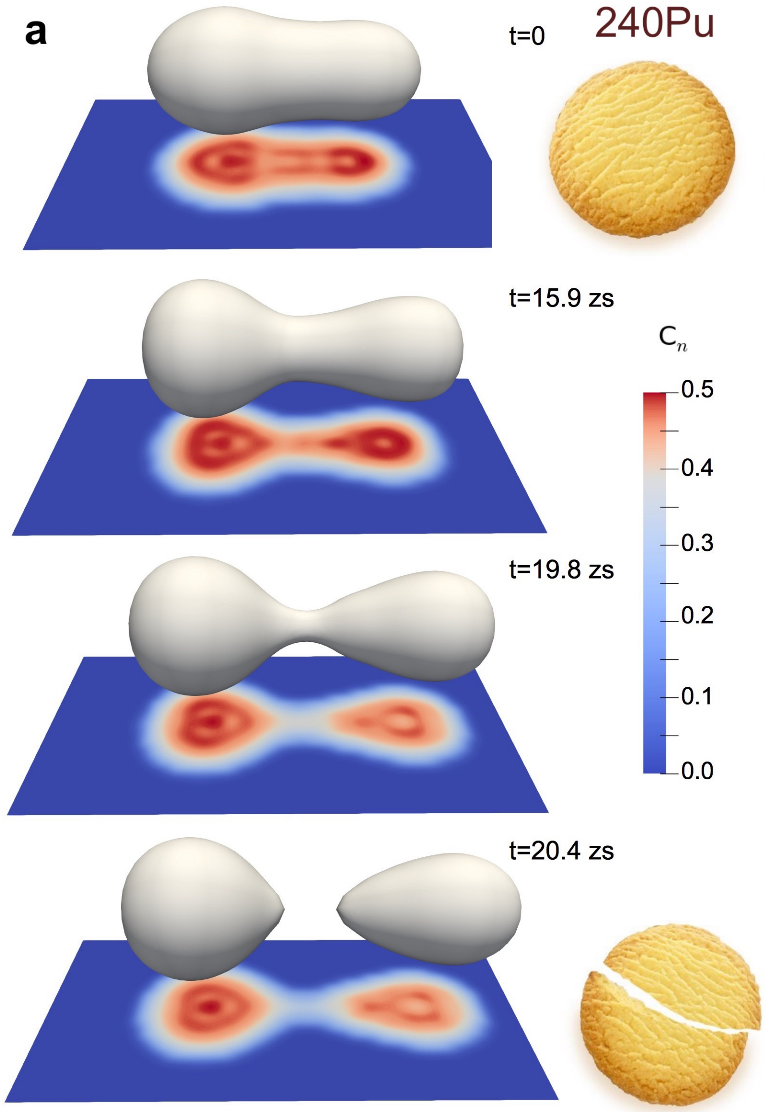
G.F. Bertsch and K.H., Phys. Rev. C107, 044615 (2023).

Advancing physics at next RIBF (ADRIB24), 2024.1.23-24

Introduction: particle emission decays of unstable nuclei

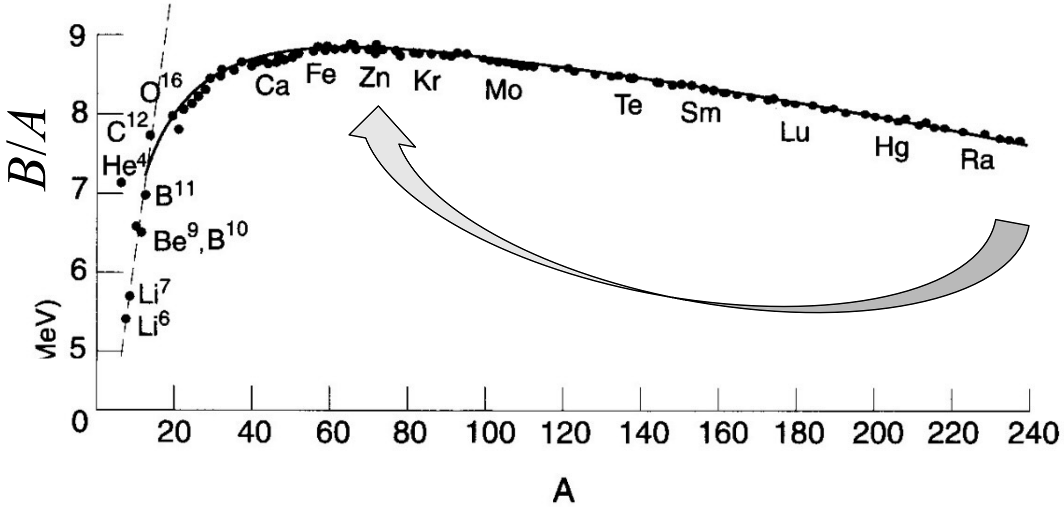


Nuclear Fission



G. Scamps and C. Simenel, Nature 564 (2018) 382

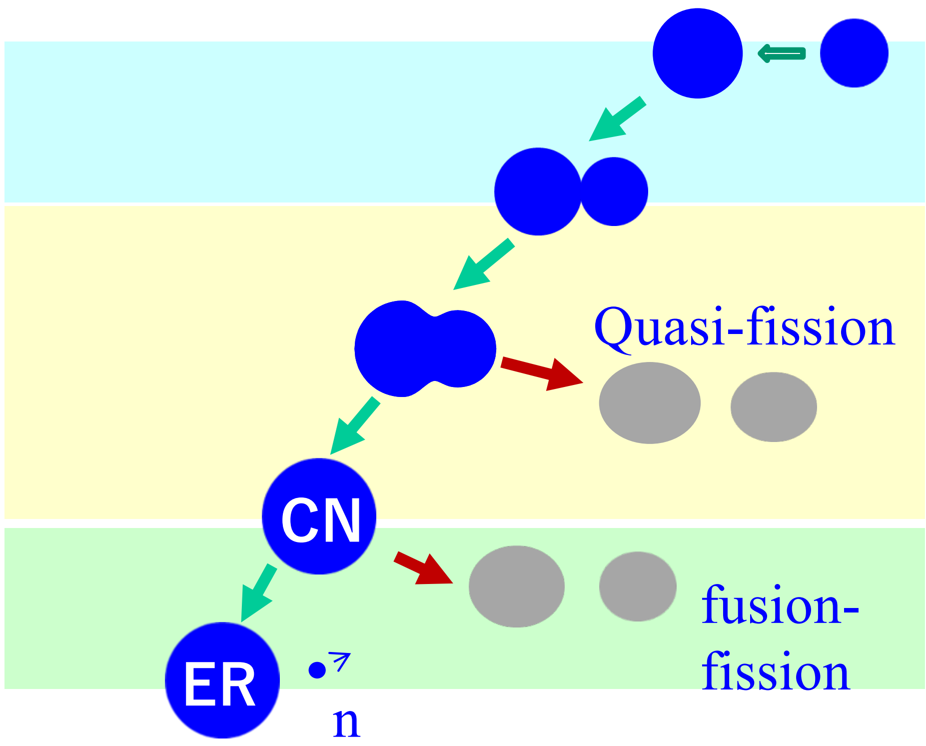
- discovered about 80 years ago (in 1938) by Hahn and Strassmann
- a primary decay mode of heavy nuclei



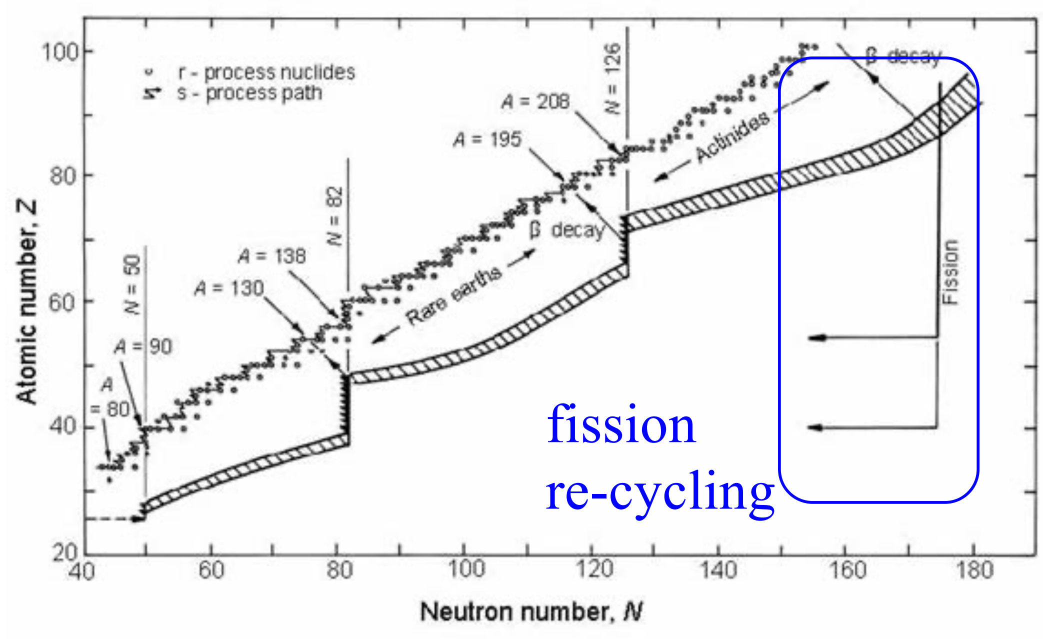
- important role in:
  - energy production
  - superheavy elements
  - r-process nucleosynthesis
  - production of neutron-rich nuclei

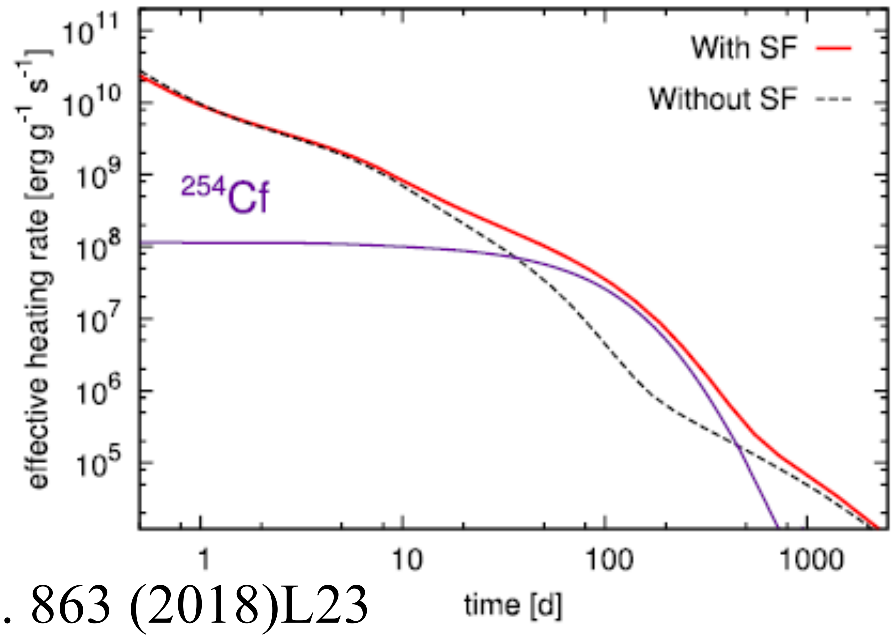
cf. the previous talk by Suzuki-san

Superheavy elements



fission in r-process nucleosynthesis



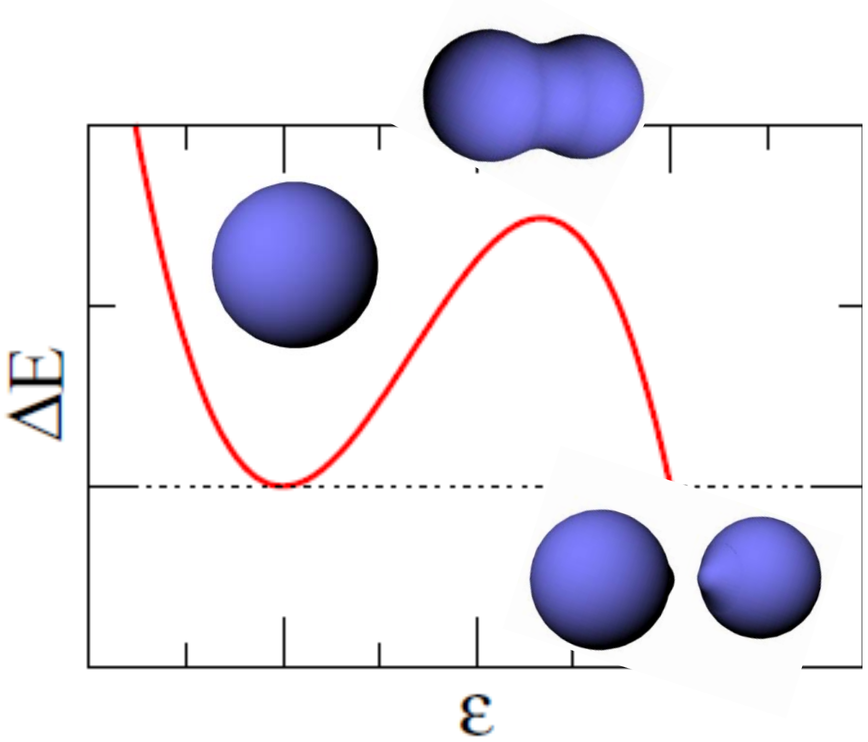


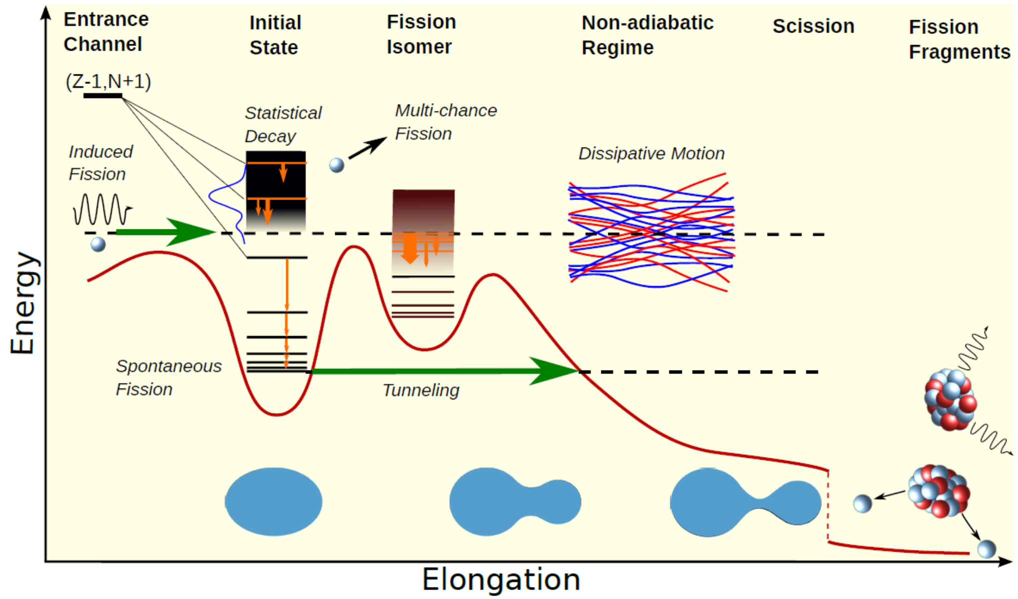
Y. Zhu et al.,
Astrophys. J. Lett. 863 (2018)L23

➢ macroscopic understanding:

competition between the surface and the Coulomb energies

→ fission barrier





"Future of fission theory"
M. Bender et al., J. of Phys. G47, 113002 (2020)

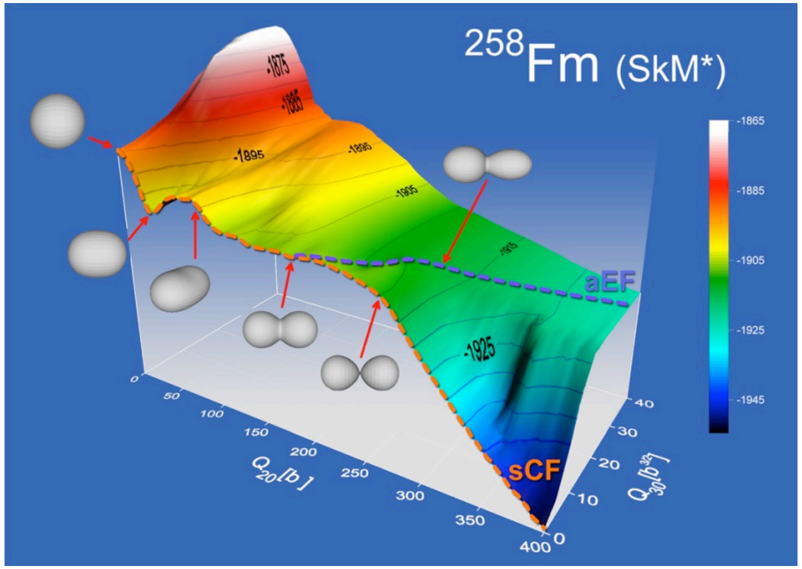
➢ a microscopic understanding:

large change of nuclear shape

→ microscopic description : far from complete

an ultimate goal of nuclear physics

- spontaneous fission



A. Staszczak, A. Baran, J. Dobaczewski, and W. Nazarewicz, PRC80 (‘09) 014309

constrained Hartree-Fock (+B) method:

$$\delta\langle\Phi|H-\lambda Q_{20}|\Phi\rangle = 0$$

$$\rightarrow \Phi(Q_{20}),\ \ E(Q_{20})$$

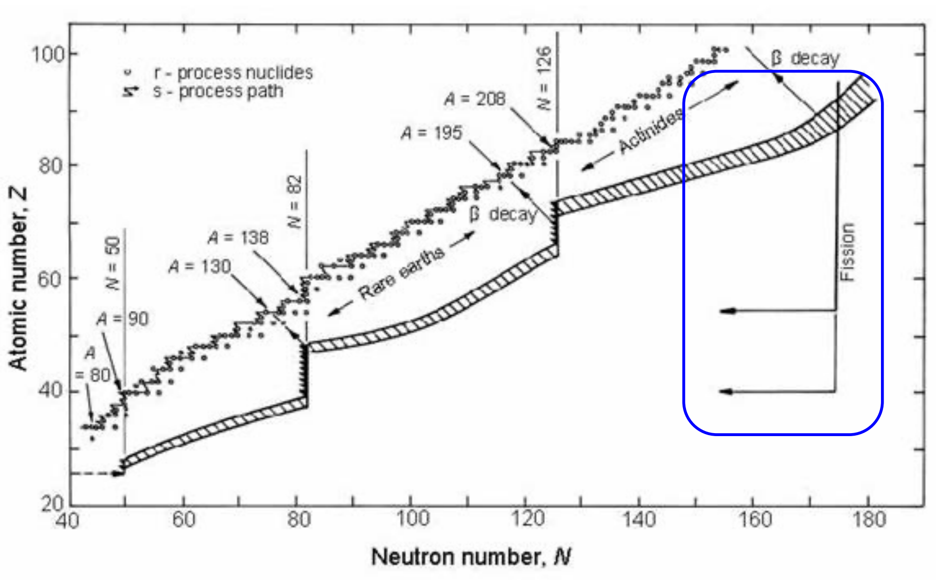
$$\rightarrow P = \exp\left[-2\int dq\sqrt{\frac{2B(q)}{\hbar^2}(V(q)-E)}\right]$$

- induced fission

almost nothing has been developed for a microscopic theory

Importance of a microscopic approach

- r-process nucleosynthesis



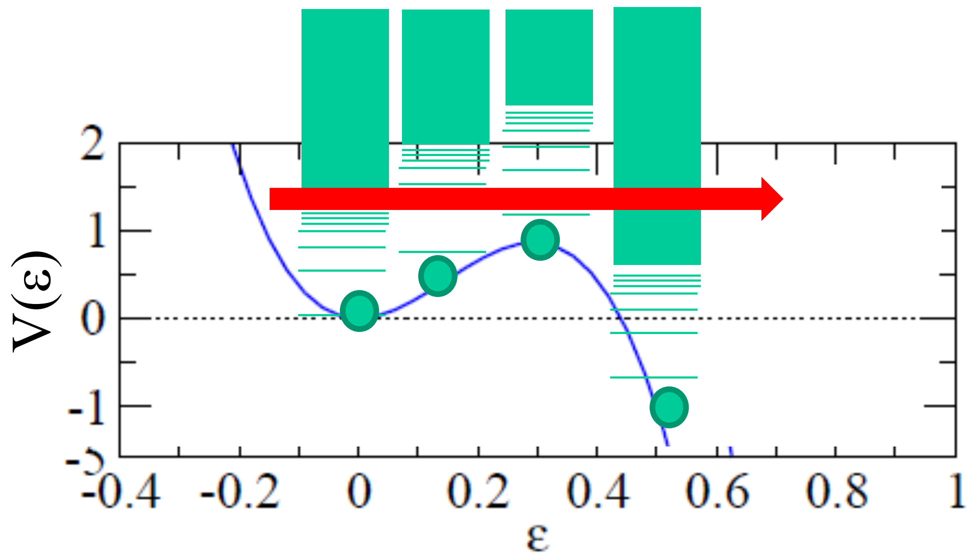
(neutron induced) fission of neutron-rich nuclei

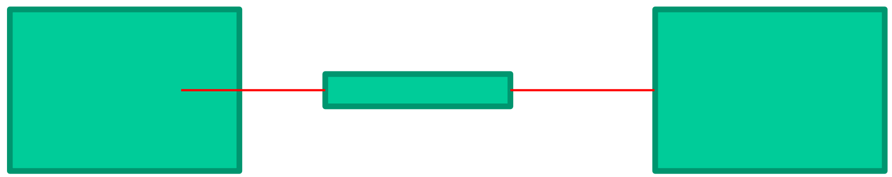
→ low E^* and low $\rho(E^*)$

✓ Validity of statistical models?

✓ Validity of the Langevin approach?

- barrier-top fission



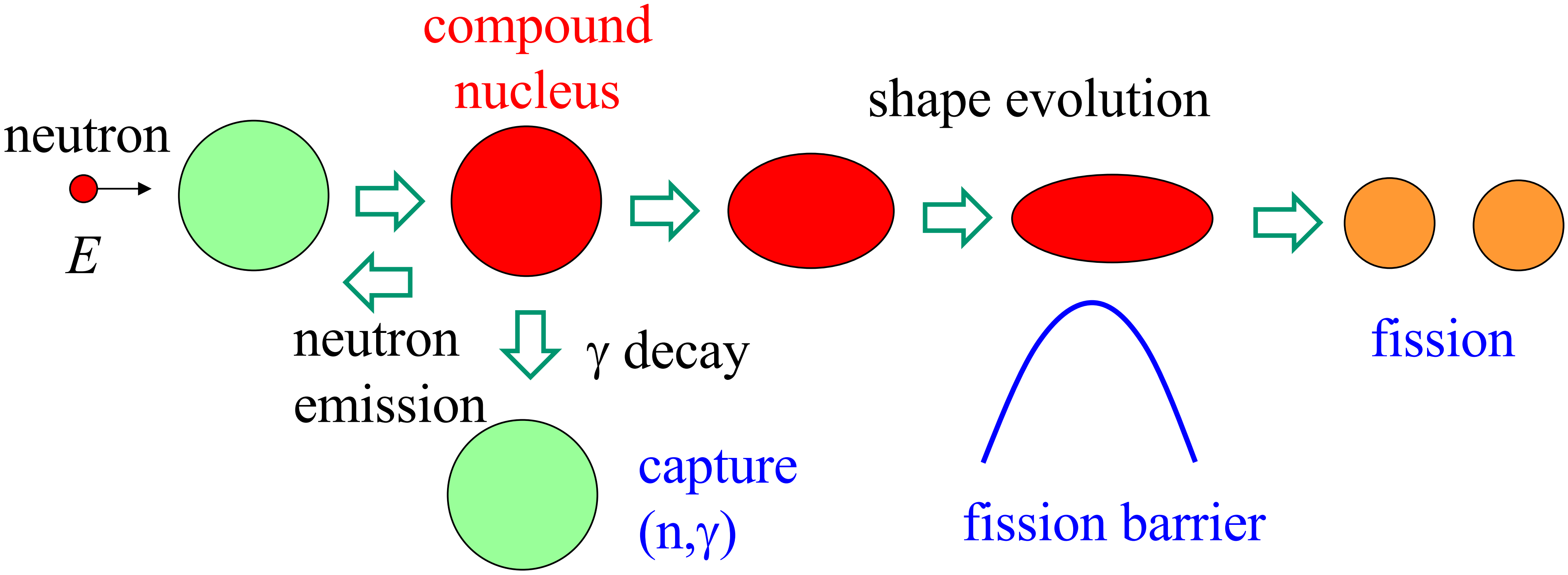


↓

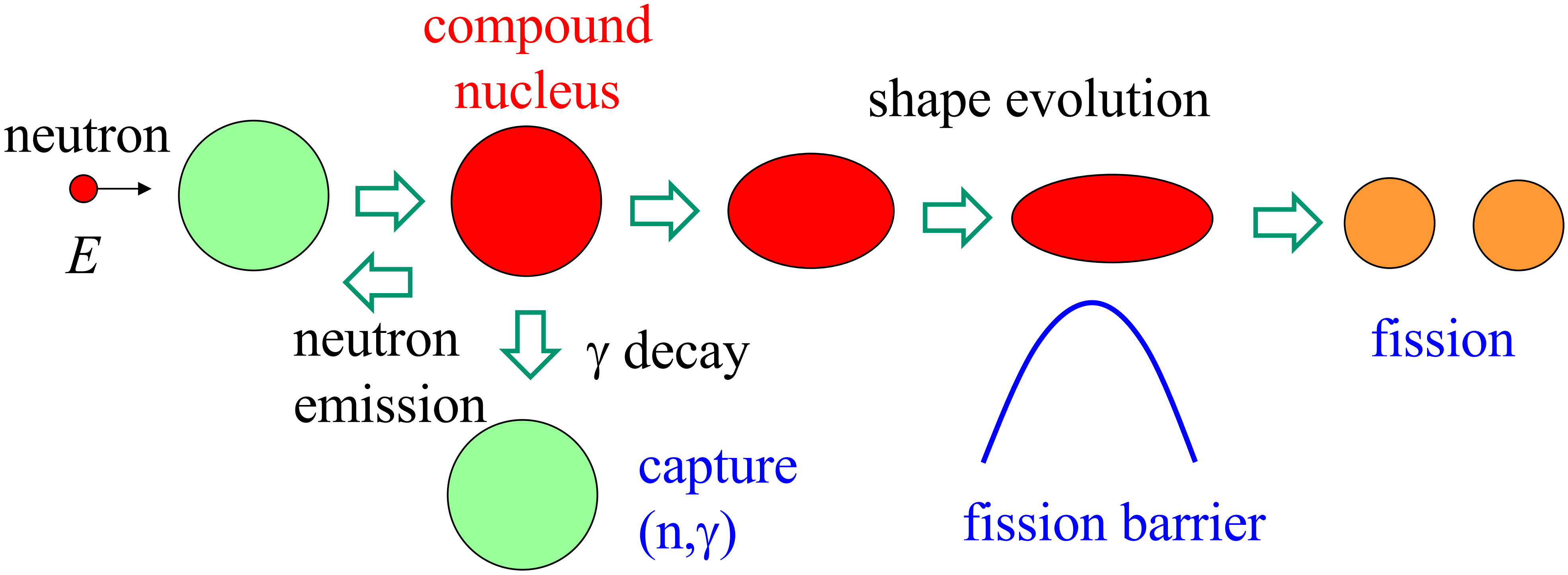
discrete levels

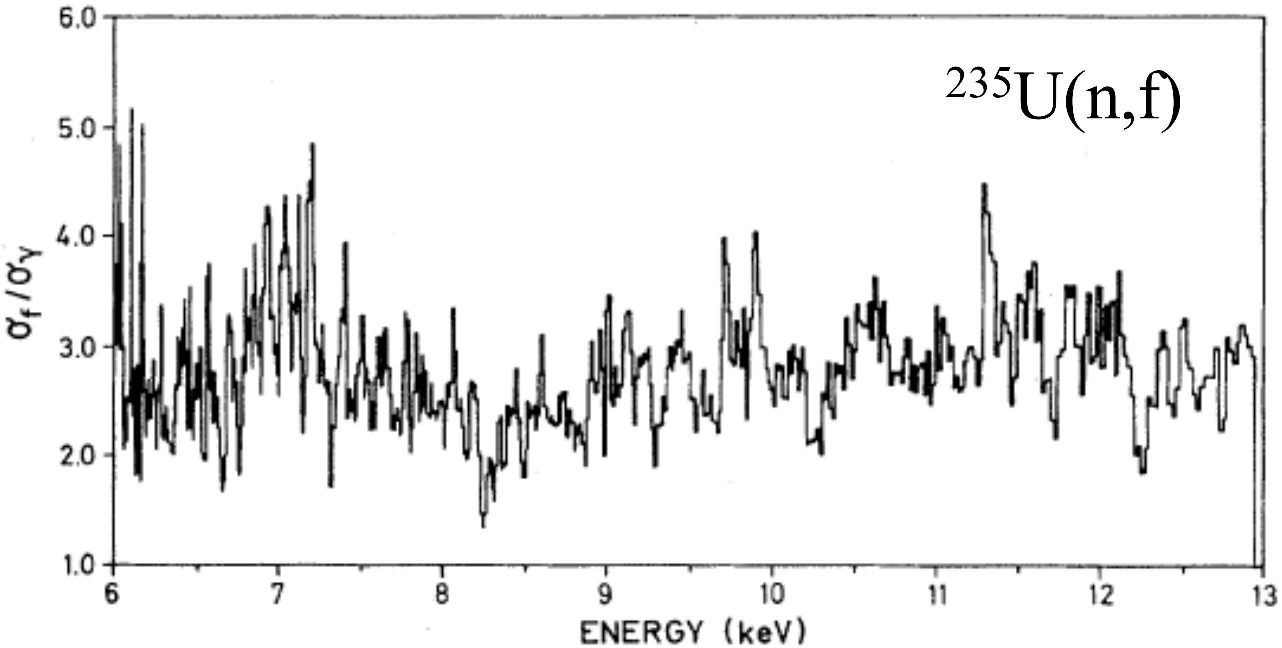
How to connect to a many-body Hamiltonian?

a process which we would like to dicscuss



a process which we would like to dicscuss



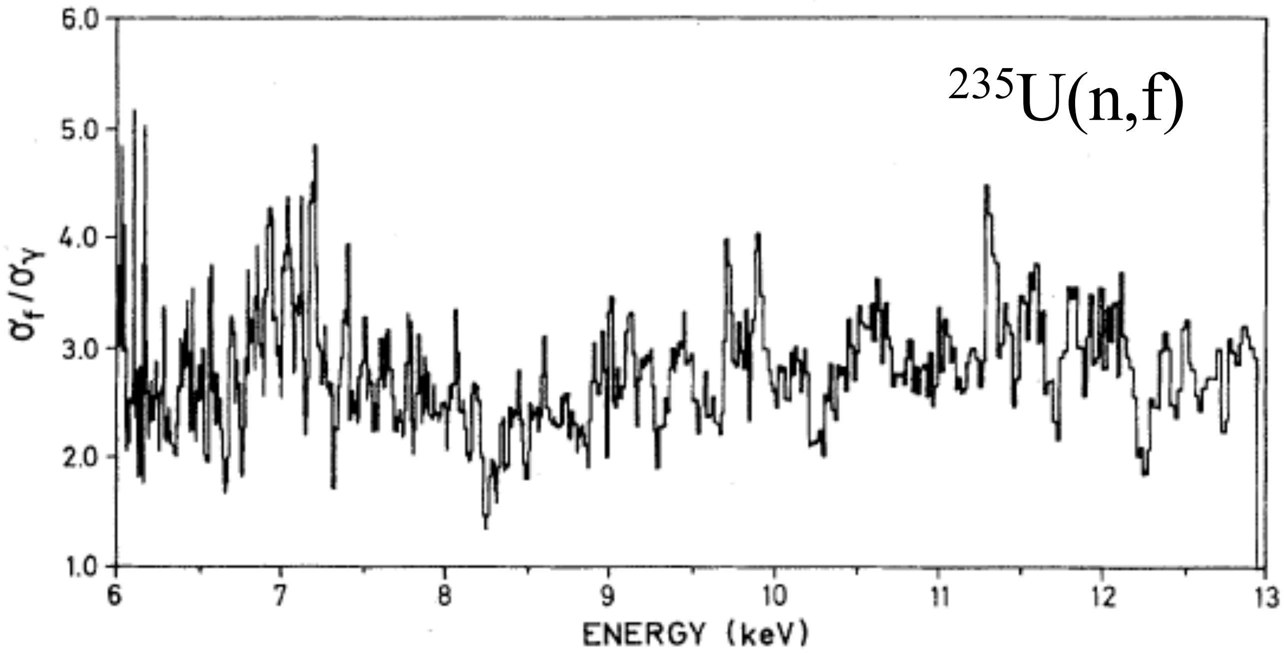


branching ratio

$$\alpha^{-1} = \frac{\sigma_f}{\sigma_\gamma}$$

sensitive to intermediate structure

M.S. Moore et al., PRC30 ('84) 214



branching ratio

$$\alpha^{-1} = \frac{\sigma_f}{\sigma_\gamma}$$

Important questions for r-process nucleosynthesis

- How will a fission barrier be modified for neutron-rich nuclei?

  cf. Sasano-san' experiment

- What is an influence of pairing for (n,f) reactions?
- How does the branching ratio evolve towards n-rich nuclei?

  (n,f) versus (n,γ)

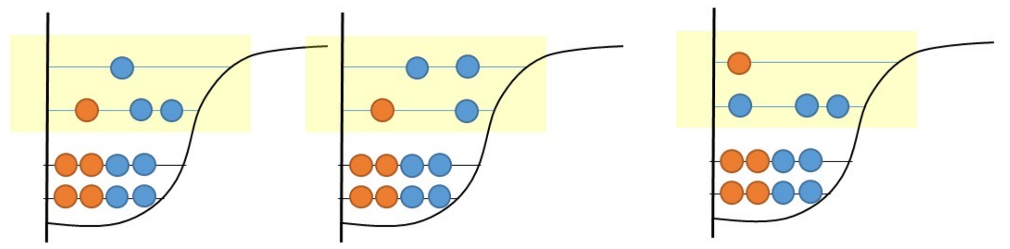
- How does fission compete with alpha/cluster decays in neutron-rich heavy nuclei?

a microscopic approach may be crucial to address these questions

Shell model approach?

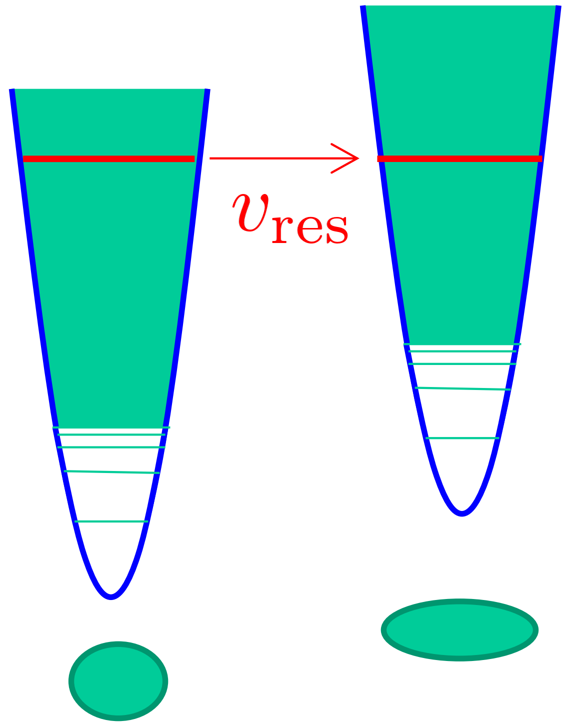
A similar approach for nuclear fission?

Shell model



$$|\Psi\rangle = v_1|m_1\rangle + v_2|m_2\rangle + v_3|m_3\rangle + \cdots$$

Figure: Noritaka Shimizu (Tsukuba)



many-particle many-hole configurations in a mean-field potential

→mixing by residual interactions

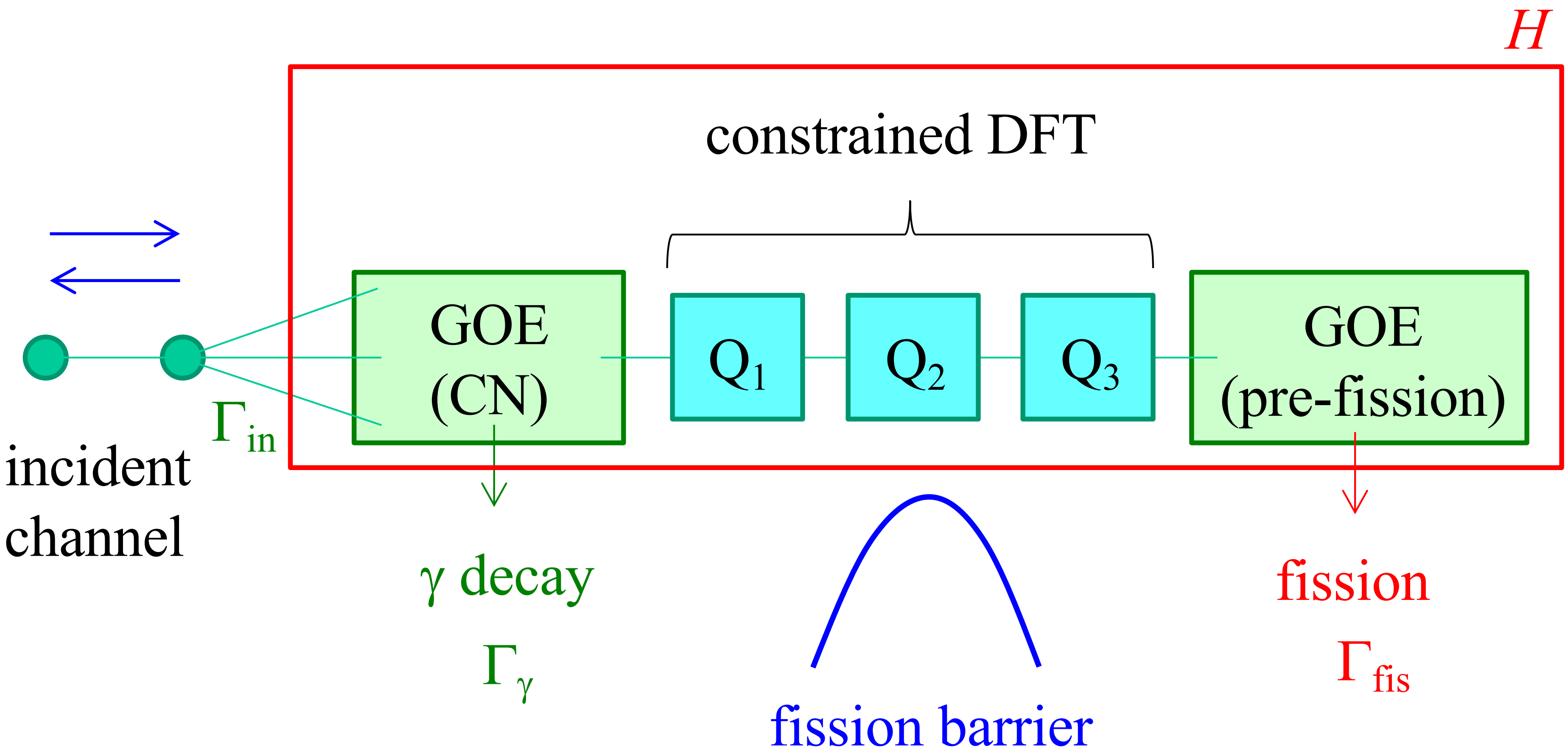
$$|\Psi\rangle = \int dQ \sum_i f_i(Q)|\Phi_Q(i)\rangle$$

GCM with excited states

- Many-body configurations in a MF pot. for each shape
- hopping due to res. int.

→ shape evolution

a good connection to nuclear reaction theory a process which we would like to dicscuss



Reaction theory (absorption probability):

$$T_{\text{fis}} = Tr[\Gamma_{\text{in}} G(E) \Gamma_{\text{fis}} G^{\dagger}(E)]$$

$$T_{\text{cap}} = Tr[\Gamma_{\text{in}} G(E) \Gamma_{\gamma} G^{\dagger}(E)]$$

"Datta formula"

$$G(E) = [H - i\Gamma/2 - EO]^{-1}$$

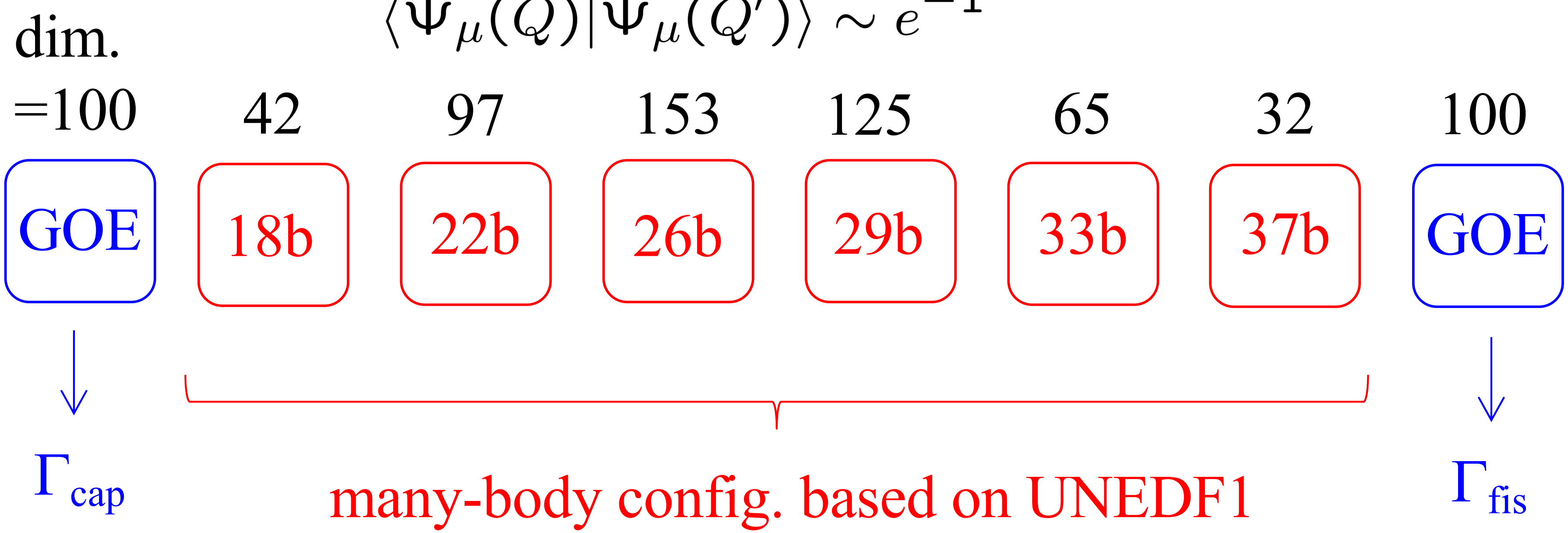
Calculations for ^{235}U(n,f) based on Skyrme HF method

G.F. Bertsch and K.H., Phys. Rev. C107, 044615 (2023).

Simplifications:

- ✓ ^{236}U : only neutron configurations, up to 4 MeV
- ✓ Dynamics of the first barrier: axial symmetry
- ✓ seniority-zero config. only: occupation of (K, -K)
- ✓ a scaled fission barrier with $B_f = 4$ MeV

$$\langle \Psi_\mu(Q) | \Psi_\mu(Q') \rangle \sim e^{-1}$$



many-body config. based on UNEDF1
(HF basis, E* < 4 MeV)

714x714 Hamiltonian matrix

Calculations based on Skyrme Hartree-Fock method

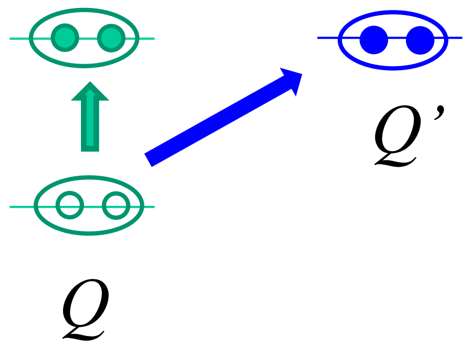
G.F. Bertsch and K.H., Phys. Rev. C107, 044615 (2023).

GOE → Γ_{cap} | 18b | 22b | 26b | 29b | 33b | 37b | GOE → Γ_{fis}

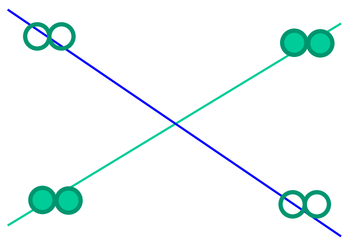
many-body config. based on UNEDF1

✓ overlap: $\langle \Psi_\mu(Q) | \Psi_\mu(Q') \rangle \sim e^{-1}$

✓ pairing: $v_{\text{pair}} = -GP^\dagger P$



✓ diabatic:

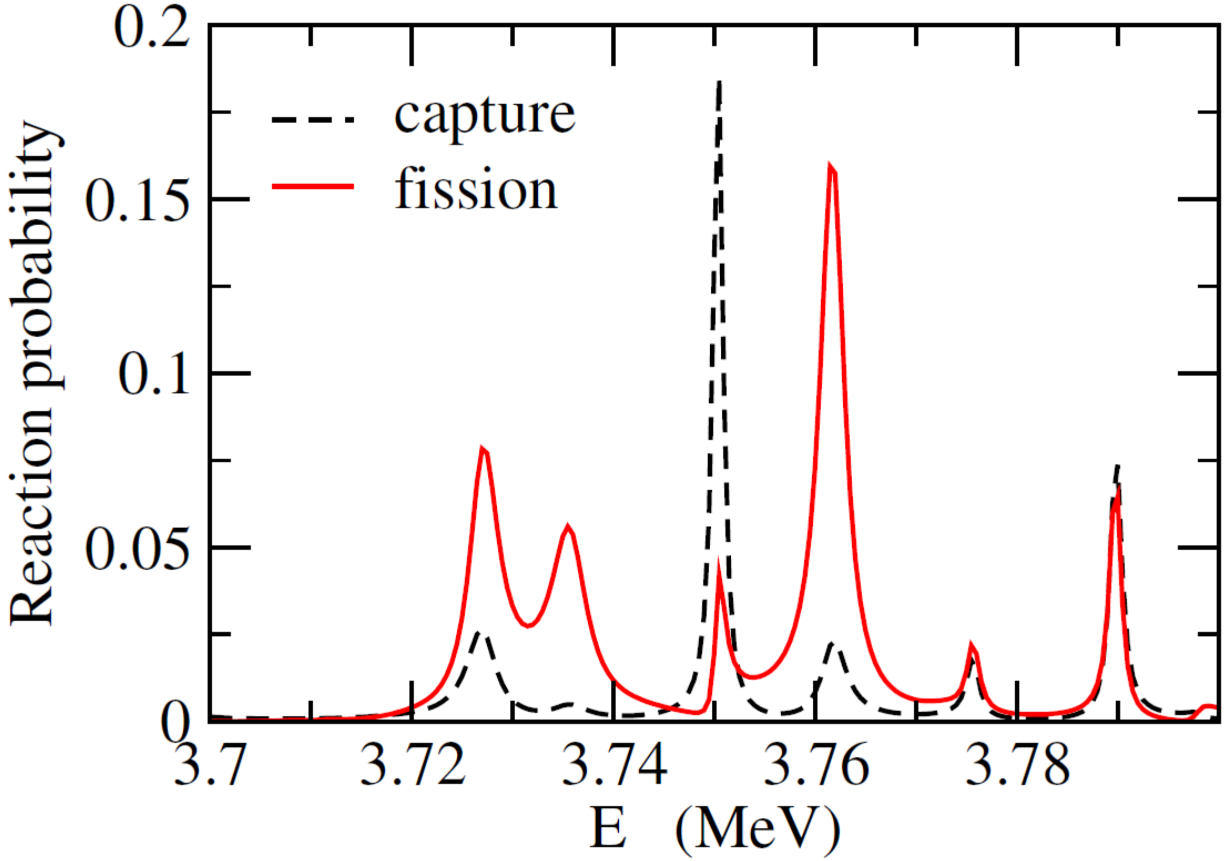


$$\frac{\langle \Psi_\mu(Q) | H | \Psi_\mu(Q') \rangle}{\langle \Psi_\mu(Q) | \Psi_\mu(Q') \rangle} \sim E_\mu(\bar{Q}) - h_2(\Delta Q)^2$$

✓ Γ_{cap}: exp. data (scaled according to N_{GOE}), Γ_{fis}: insensitivity

$$T_{\text{fis}}(E) = Tr[\Gamma_{\text{in}} G(E) \Gamma_{\text{fis}} G^{\dagger}(E)]$$

$$T_{\text{cap}}(E) = Tr[\Gamma_{\text{in}} G(E) \Gamma_{\gamma} G^{\dagger}(E)]$$



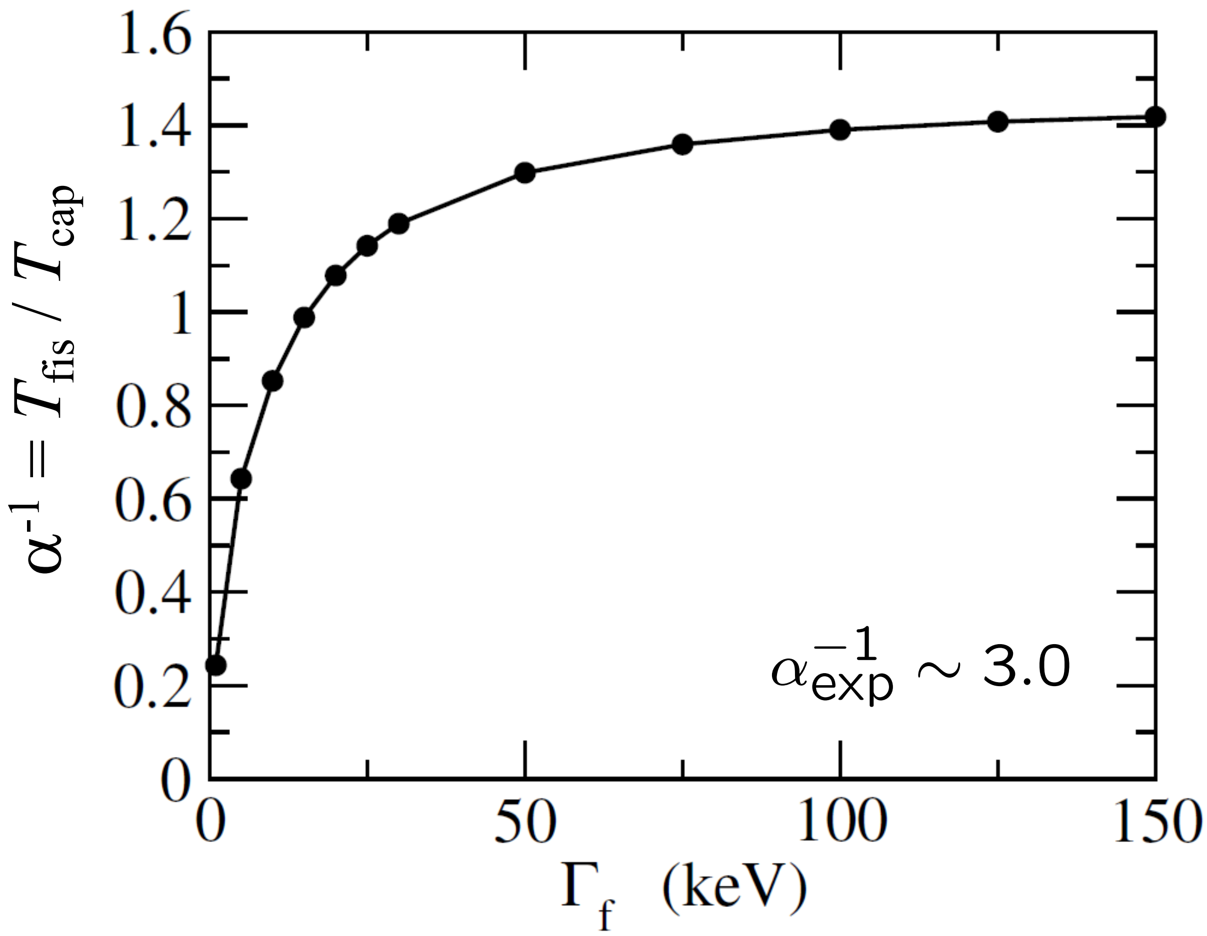
$\Gamma_{\text{in}} = 0.01$ MeV
$\Gamma_{\text{cap}} = 0.00125$ MeV
$\Gamma_{\text{fis}} = 0.015$ MeV

energy average

$$\alpha^{-1} = \frac{\int_{\Delta E} T_{\text{fis}}(E')dE'}{\int_{\Delta E} T_{\text{cap}}(E')dE'}$$

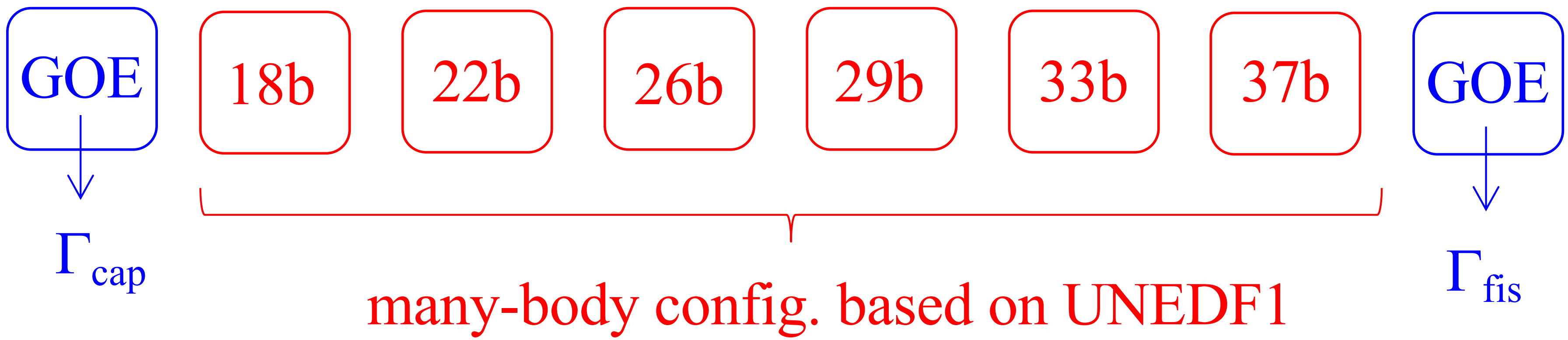
$\Delta E = 0.5$ MeV

insensitivity property

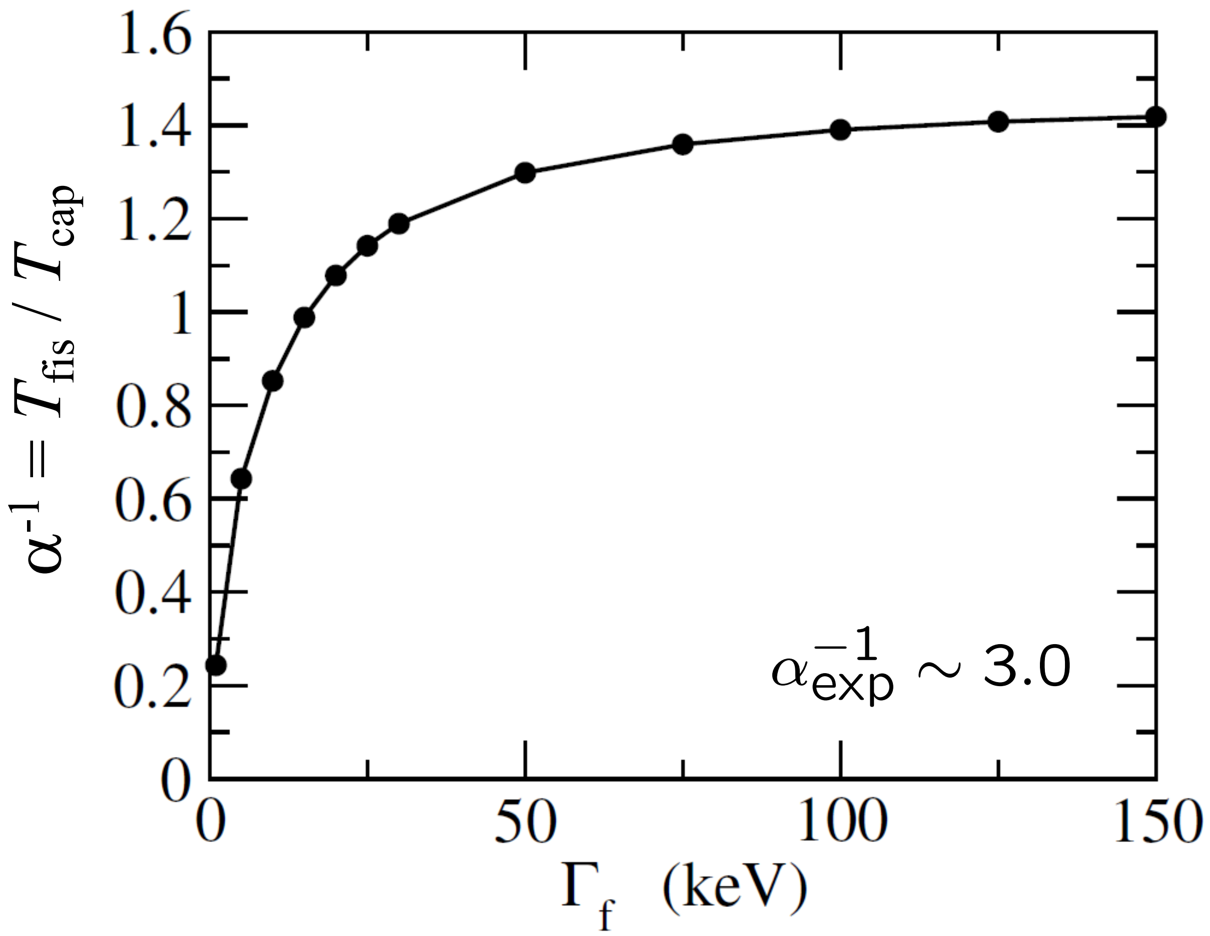


insensitive to Γ_f
(post-barrier dynamics)
→the main assumption of TST

cf. Analytic discussion with a 2GOE+1Q model
K.H. and G.F. Bertsch, arXiv: 2310.09537 (2023)



insensitivity property



base set
$G_{pair} = 0.2$ MeV
$h_2 = 0.15$ MeV
$\rightarrow \alpha^{-1} = 0.95$

$G_{pair} \rightarrow G_{pair}/2$
$G_{pair} = 0.1$ MeV
$h_2 = 0.15$ MeV
$\rightarrow \alpha^{-1} = 0.37$

sensitive to the pairing, though less than in spontaneous fission

Further developments:

- seniority non-zero configurations with a schematic model
  K. Uzawa and K. Hagino, PRC108 ('23) 024319

- an analytical derivation of transition-state-theory
  K. Hagino and G.F. Bertsch, arXiv: 2310.09537

- validity of the discrete-basis formalism for barrier penetration
  K. Hagino, arXiv: 2311.00925
  G.F. Bertsch and K. Hagino, arXiv: 2401.10533

- fluctuation of fission width
  K. Uzawa and K. Hagino, in preparation

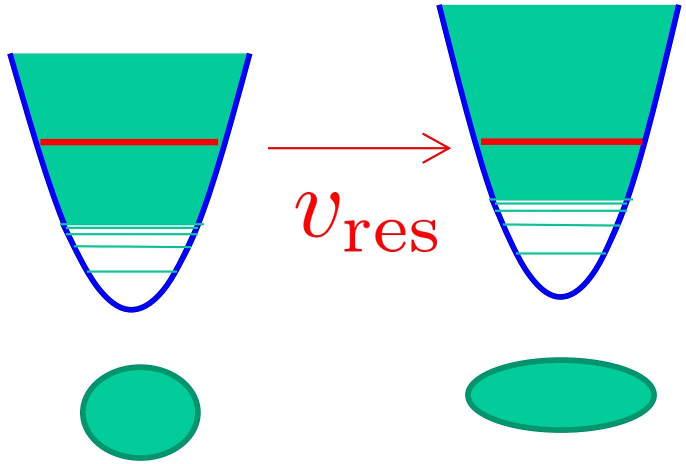
Summary

r-process nucleosynthesis: fission of neutron-rich nuclei

requires a microscopic approach applicable to low E^* and $\rho(E^*)$

\# also for barrier-top fission

➡ a new approach: shell model + GCM



an application to induced fission of ^{236}U based on Skyrme EDF

- ✓ neutron configurations only
- ✓ pairing and diabatic interactions
- ✓ truncation at 4 MeV

→an importance of the pairing interaction

Future perspectives: seniority non-zero config. →pn res. interaction

K. Uzawa and K. Hagino, PRC108 ('23) 024319

a large scale calculation (~ 10^6 dim.)