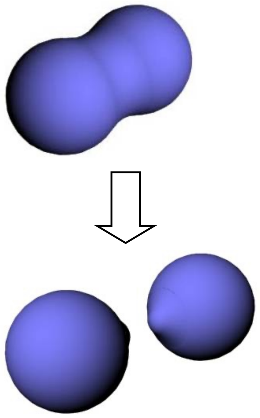
Transition-state dynamics in barrier-top nuclear fission



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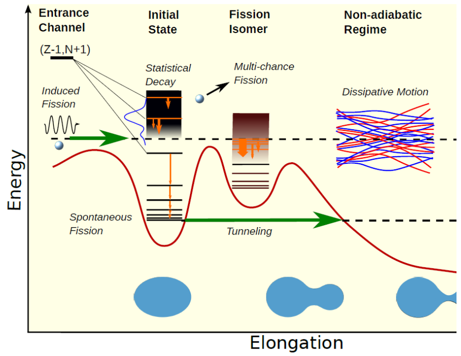
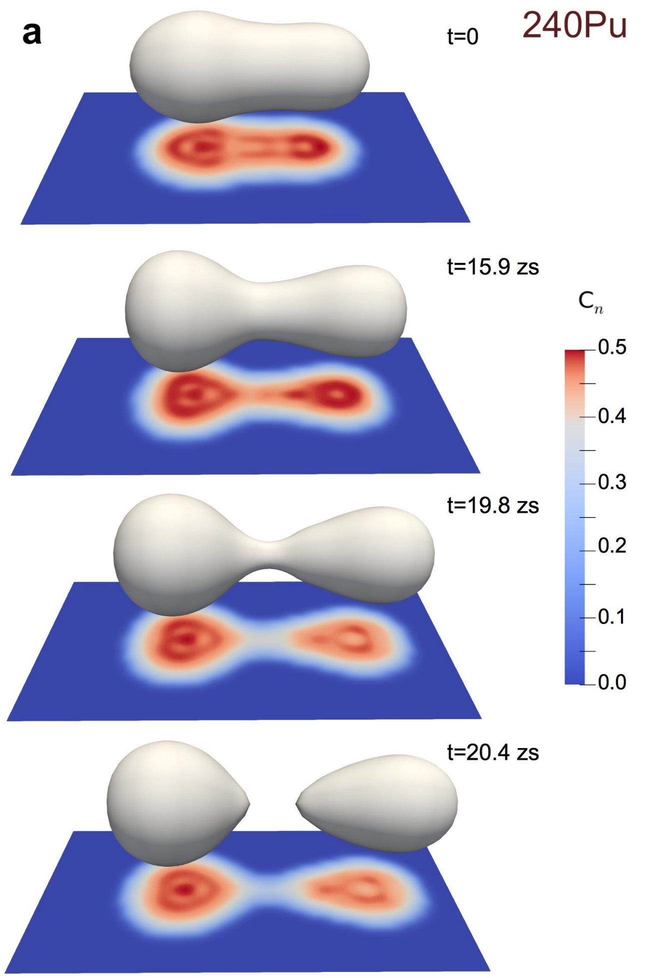


1. Introduction
2. Shell Model for induced fission
3. Summary

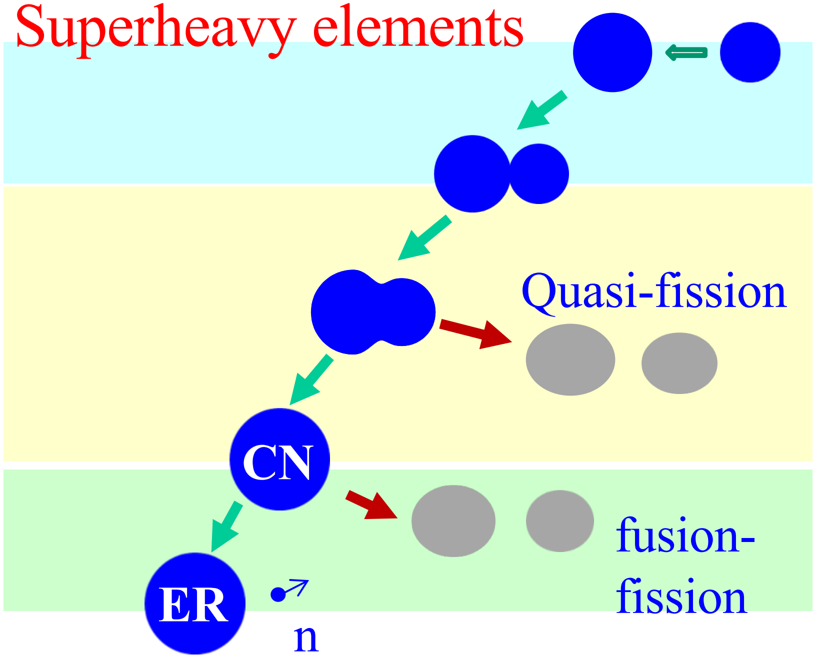
International Symposium on Physics of Unstable Nuclei (ISPUN23), Phu Quoc Island, Vietnam, 2023.5.4-8

Nuclear Fission

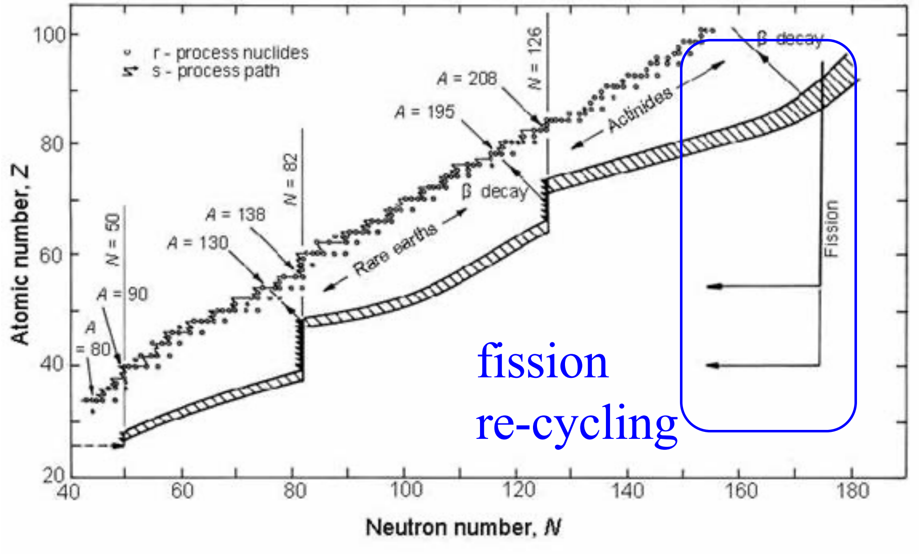


G. Scamps and C. Simenel,
Nature 564 (2018) 382

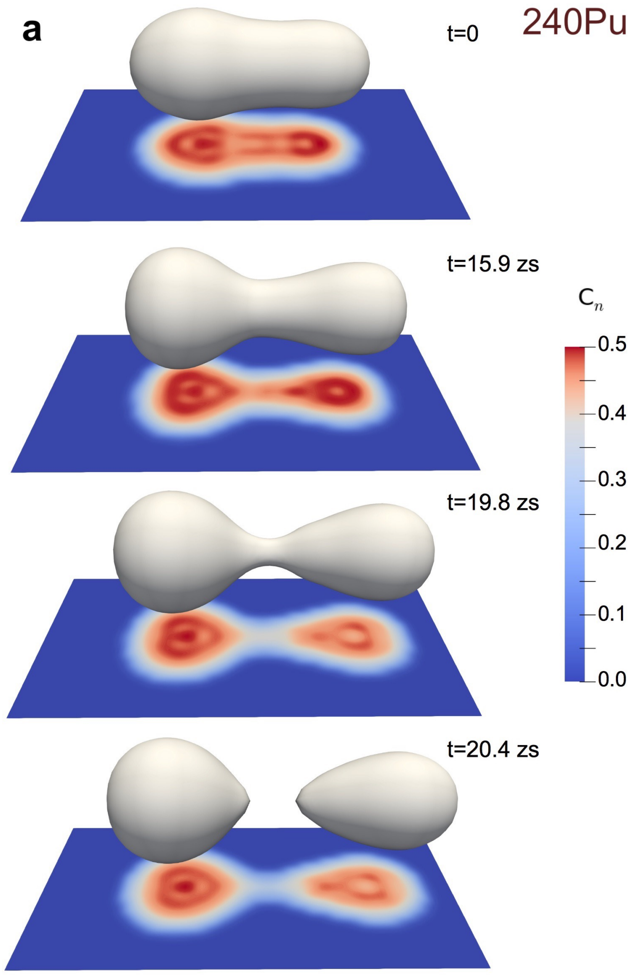
Superheavy elements



r-process nucleosynthesis



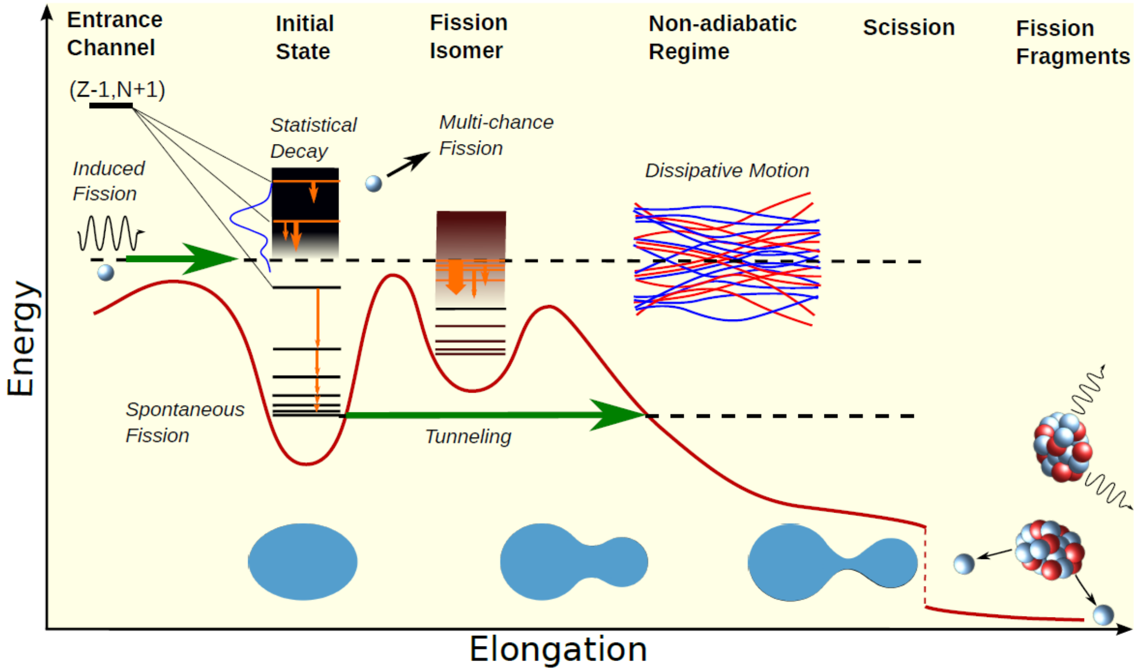
Nuclear Fission



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

large change of nuclear shape
→ microscopic description
: far from complete

an ultimate goal of nuclear physics

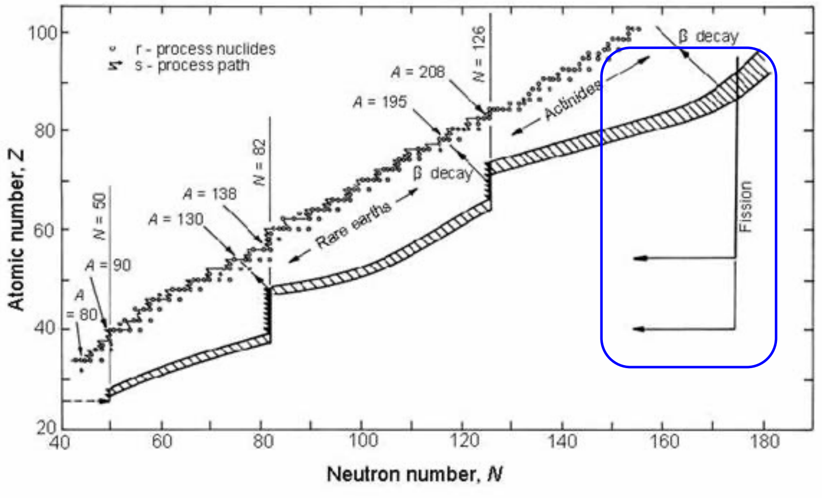


M. Bender et al.,
J. of Phys. G47, 113002 (2020)

“Future of fission theory” White paper

Importance of a microscopic approach

- ➢ r-process nucleosynthesis

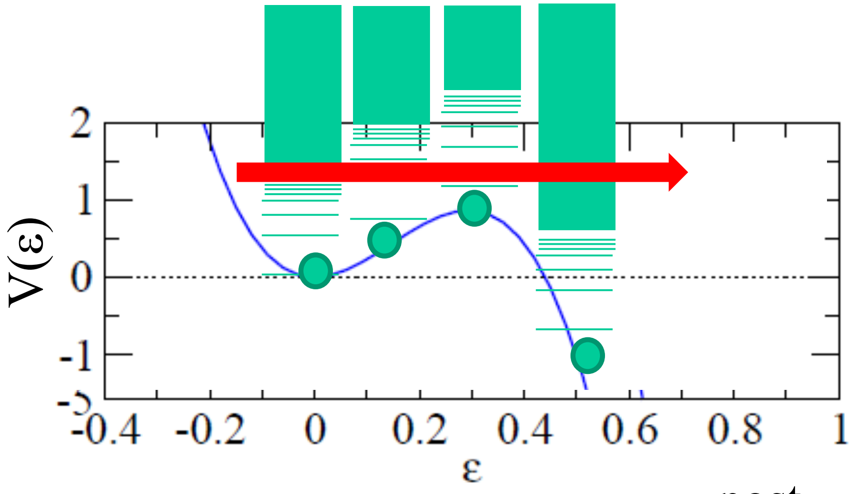


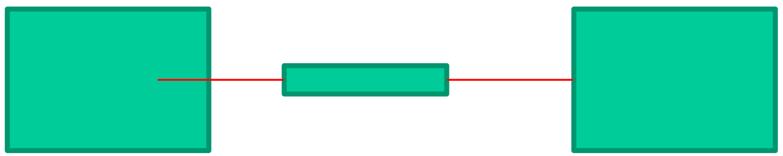
(neutron induced) fission of neutron-rich nuclei

→ low E^* and low $\rho(E^*)$

- ✓ Validity of statistical models?
- ✓ Validity of the Langevin approach?

- ➢ barrier-top fission





CN

barrier-top

post barrier

high ρ(E)

low ρ(E)

↓

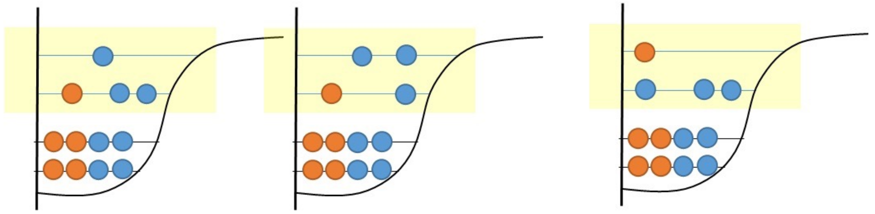
discrete levels

high ρ(E)

How to connect to a many-body Hamiltonian?

Shell model approach?

Shell model



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

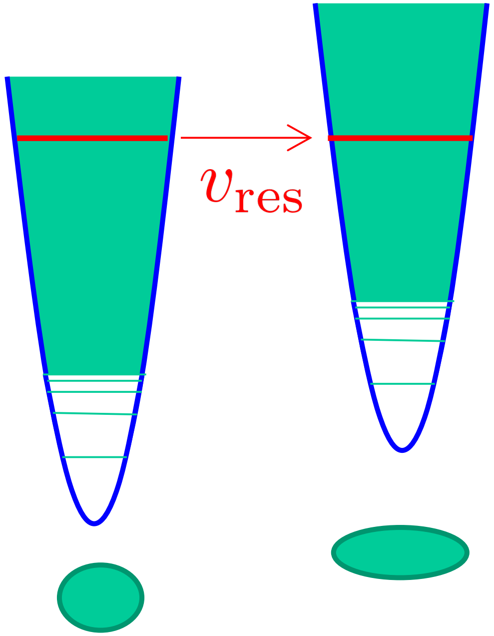
Figure: Noritaka Shimizu (Tsukuba)

many-particle many-hole configurations
in a mean-field potential
→mixing by <u>residual interactions</u>

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

GCM with excited states

A similar approach for nuclear fission?

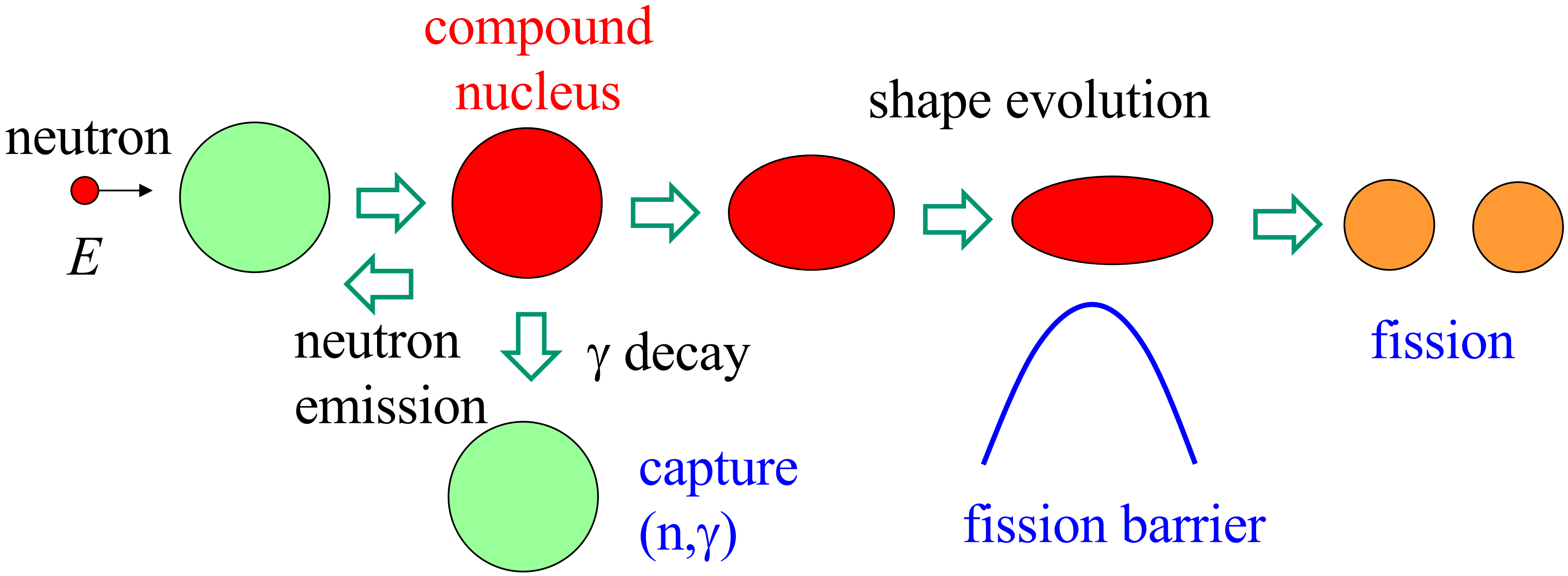


- Many-body configurations in a MF pot. for each shape
- hopping due to res. int.

→ shape evolution

a good connection to
nuclear reaction theory

a process which we would like to dicscuss



compound nucleus

neutron

E

shape evolution

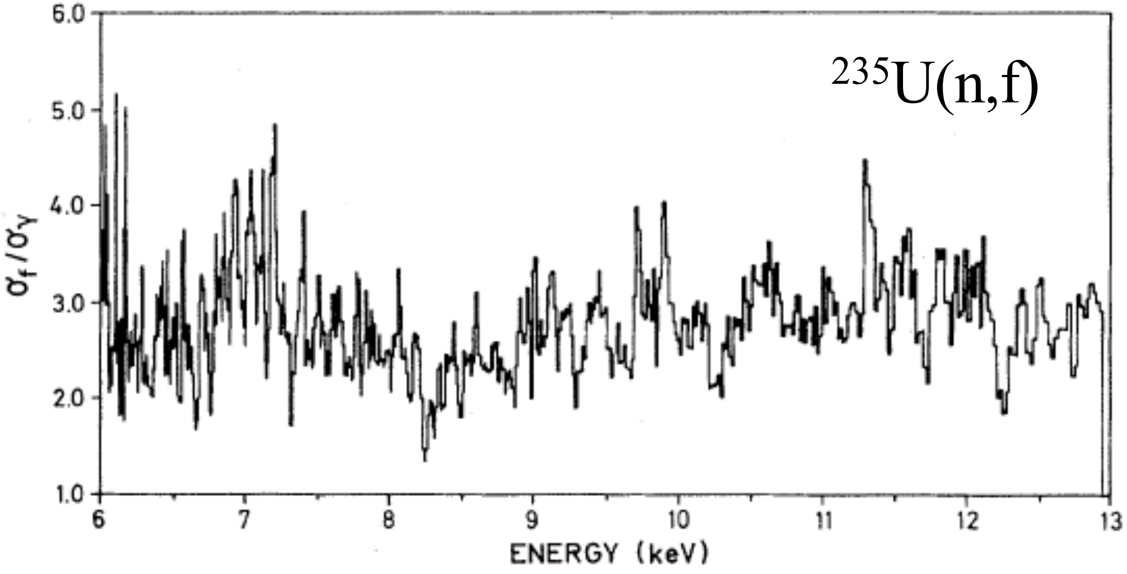
neutron emission

γ decay

capture (n,γ)

fission barrier

fission



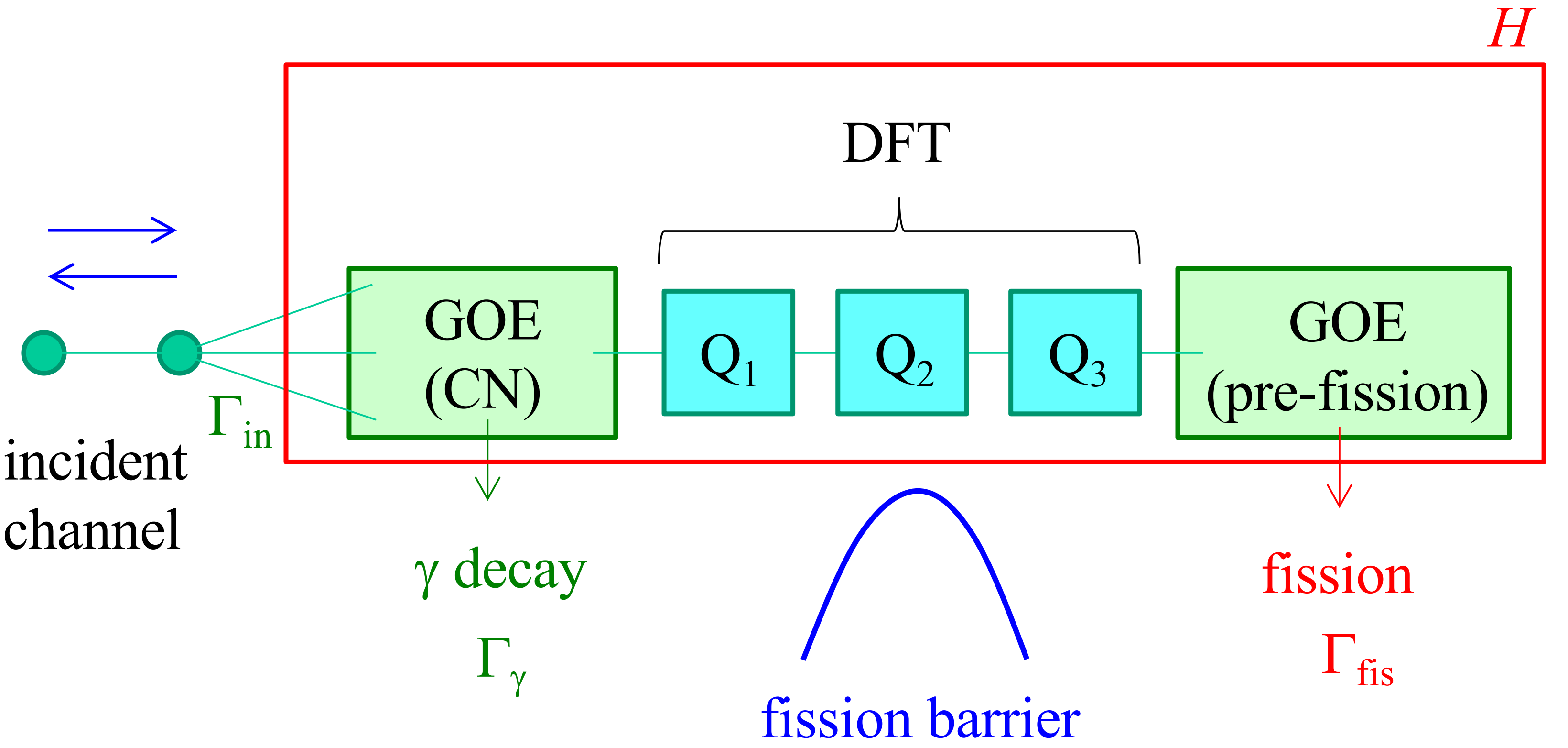
branching ratio

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

sensitive to intermediate structure

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

a process which we would like to dicscuss



Reaction theory (absorption probability):

$$\boxed{\begin{aligned} T_{\text{fis}} &= Tr[\Gamma_{\text{in}} G(E) \Gamma_{\text{fis}} G^\dagger(E)] \\ T_{\text{cap}} &= Tr[\Gamma_{\text{in}} G(E) \Gamma_{\gamma} G^\dagger(E)] \end{aligned}}$$

“Datta formula”

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

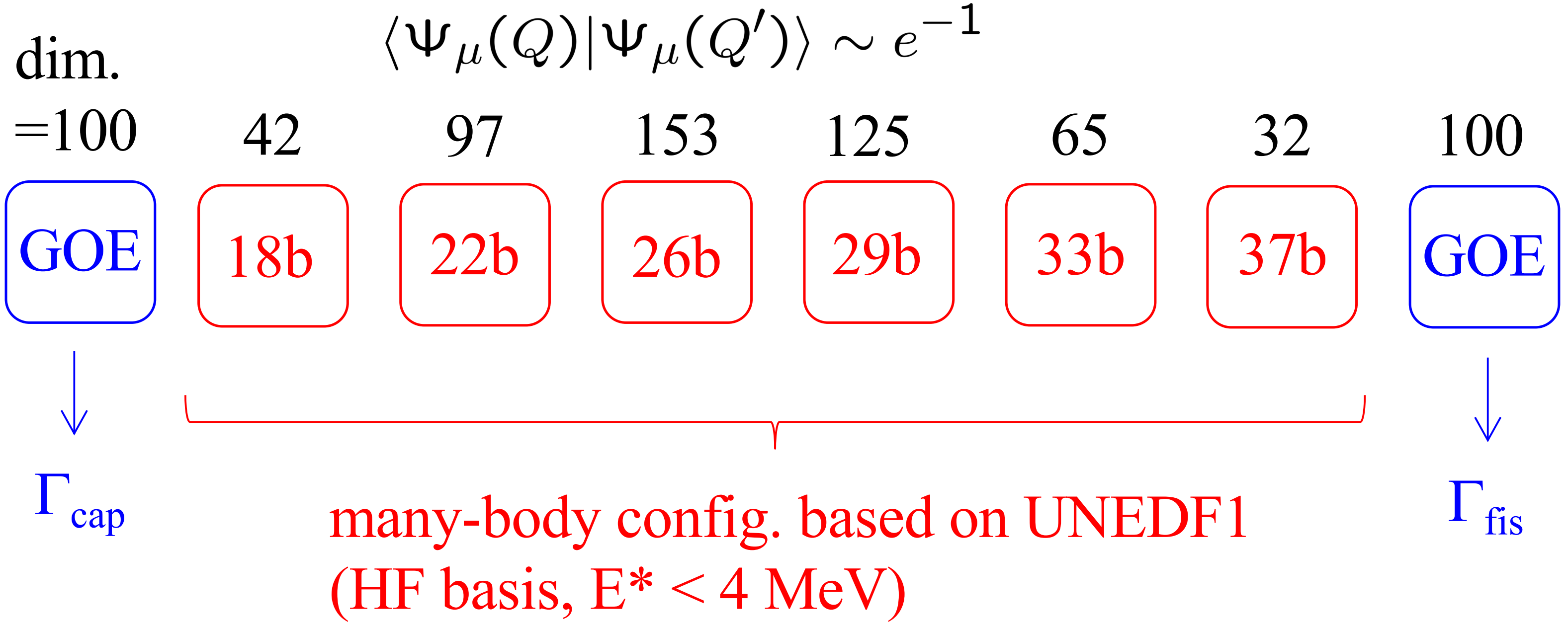
Calculations based on Skyrme Hartree-Fock method

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

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



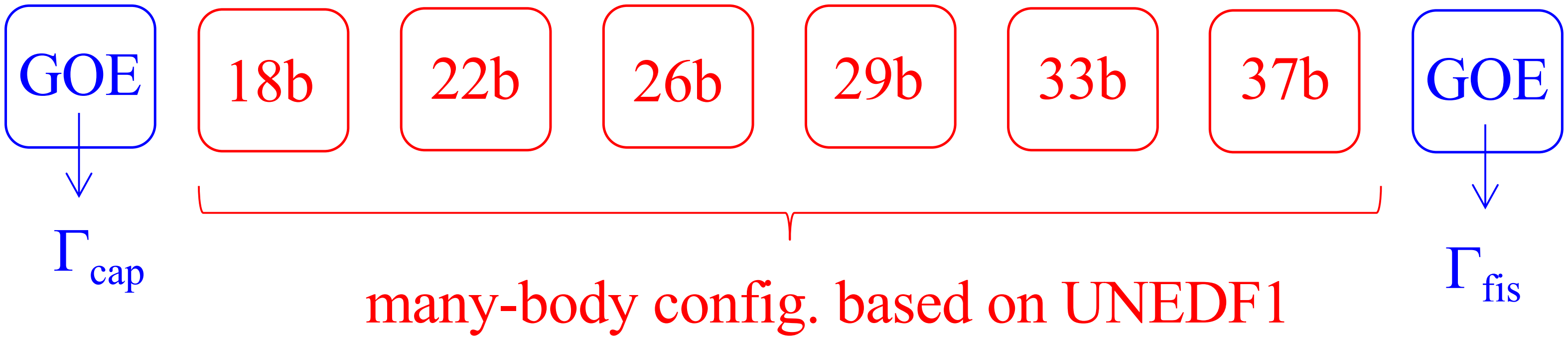
dim.							
=100	42	97	153	125	65	32	100
GOE	18b	22b	26b	29b	33b	37b	GOE
Γ_{cap}							Γ_{fis}

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

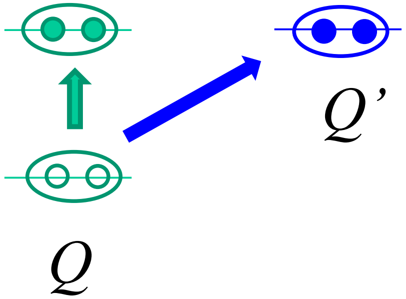
714x714 Hamiltonian matrix

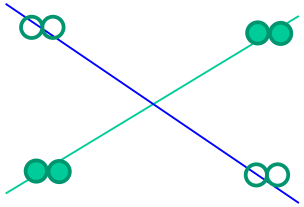
Calculations based on Skyrme Hartree-Fock method

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



- ✓ overlap: $\langle \Psi_\mu(Q)|\Psi_\mu(Q')\rangle \sim e^{-1}$
- ✓ pairing: $v_{\text{pair}} = -GP^\dagger P$
- ✓ diabatic:



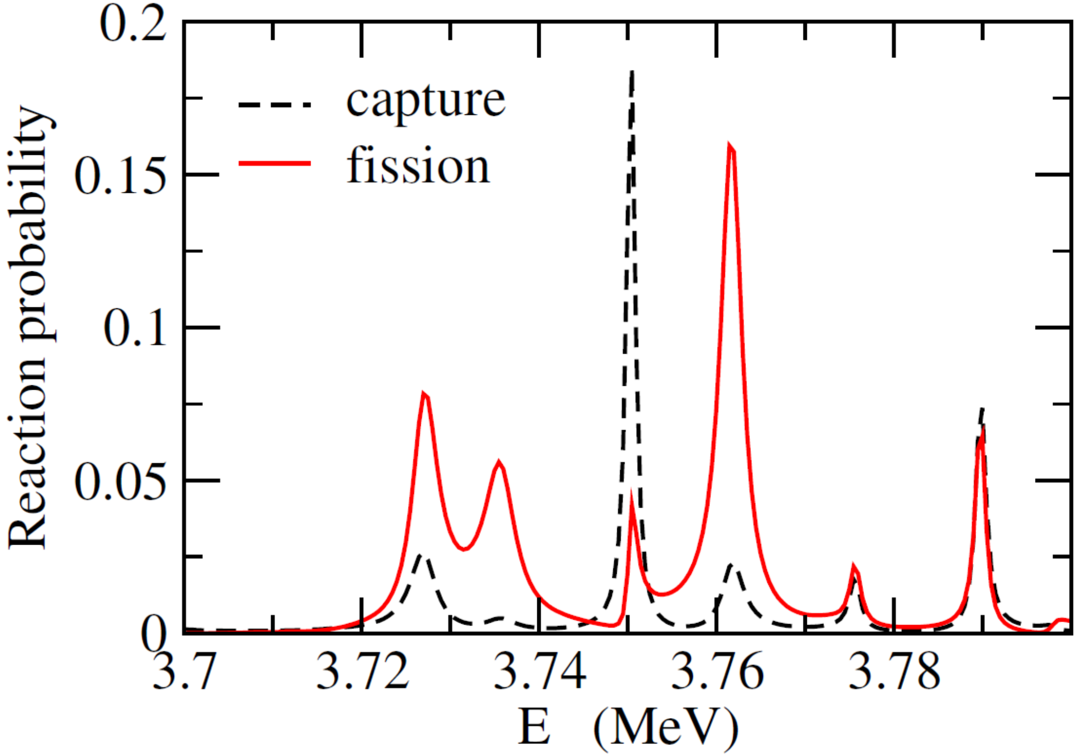


$$\frac{\langle \Psi_\mu(Q)|H|\Psi_\mu(Q')\rangle}{\langle \Psi_\mu(Q)|\Psi_\mu(Q')\rangle} \sim E_\mu(\bar{Q}) - h_2(\Delta Q)^2$$

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

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

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



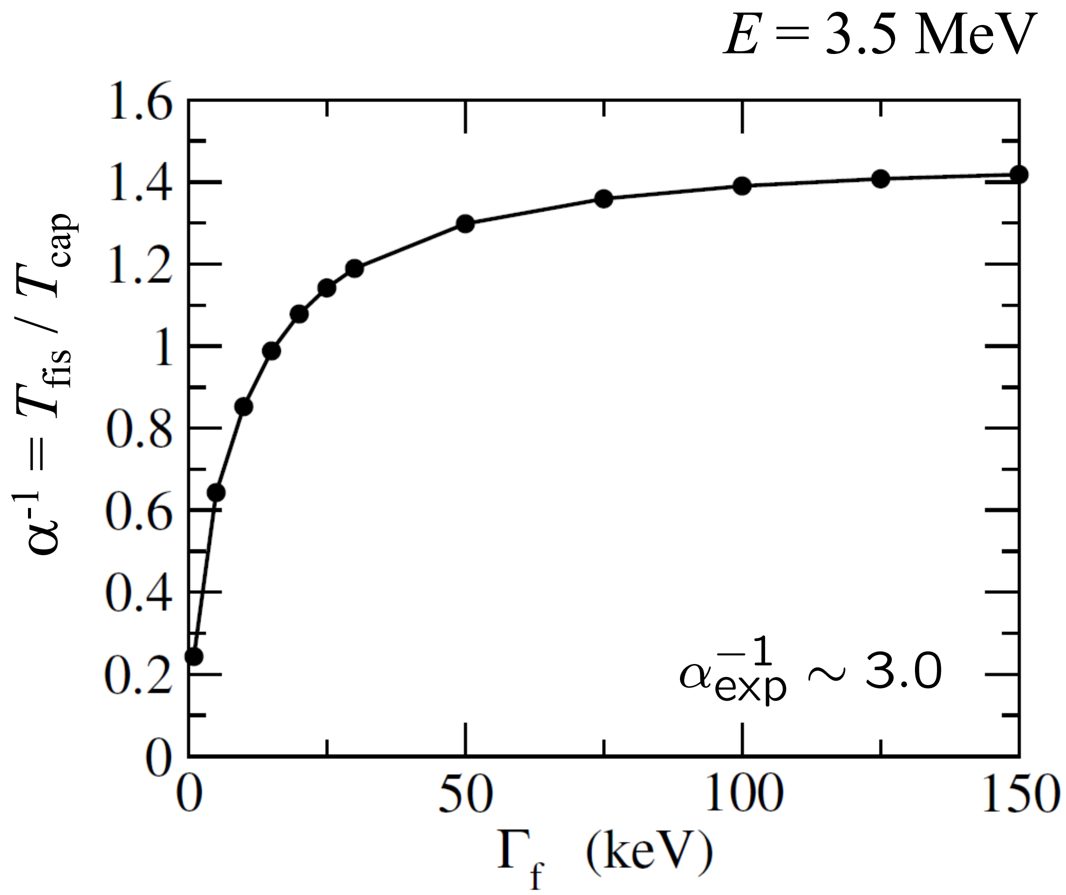
$\Gamma_{\text{in}} = 0.01$ MeV
$\Gamma_{\text{cap}} = 0.00125$ MeV
$\Gamma_{\text{fis}} = 0.015$ MeV

energy average

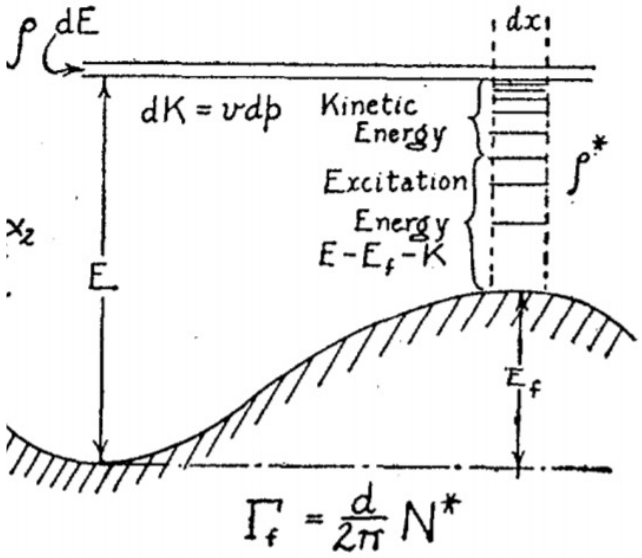
$$\boxed{\alpha^{-1} = \frac{\int_{\Delta E} T_{\mathsf{fis}}(E')dE'}{\int_{\Delta E} T_{\mathsf{cap}}(E')dE'}}$$

$\Delta E = 0.5$ MeV

insensitivity property



transition state theory (TST)



- insensitive to Γ_f (post-barrier dynamics)
  →compatible to the assumption in TST
- decays via many configurations → somewhat different from the idea of TST

sensitivity test

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

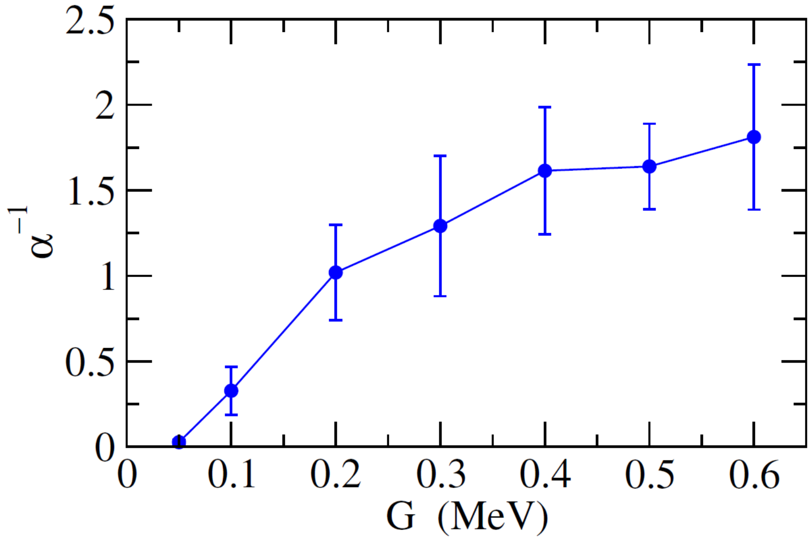
$h_2 \rightarrow 2h_2$
$G_{pair} = 0.2$ MeV
$h_2 = 0.3$ MeV
$\rightarrow \alpha^{-1} = 1.10$

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
$\rightarrow \alpha^{-1} = 0.37$

$h_2 \rightarrow 0$
$G_{pair} = 0.2$ MeV
$h_2 = 0.0$ MeV
$\rightarrow \alpha^{-1} = 0.13$

cf. $\alpha^{-1}_{exp} \sim 3.0$



- sensitive to the pairing, though less than in spontaneous fission

- h_2 effect is not negligible, but insensitive to h_2 when it is large

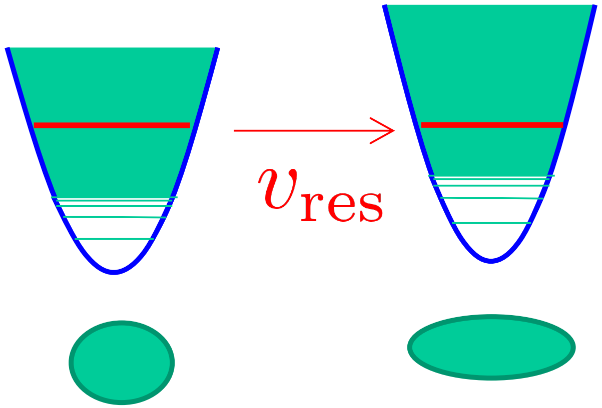
Summary

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

Uzawa, Hagino, Bertsch, arXiv:2303.16488

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