rプロセスと核分裂:問題提起

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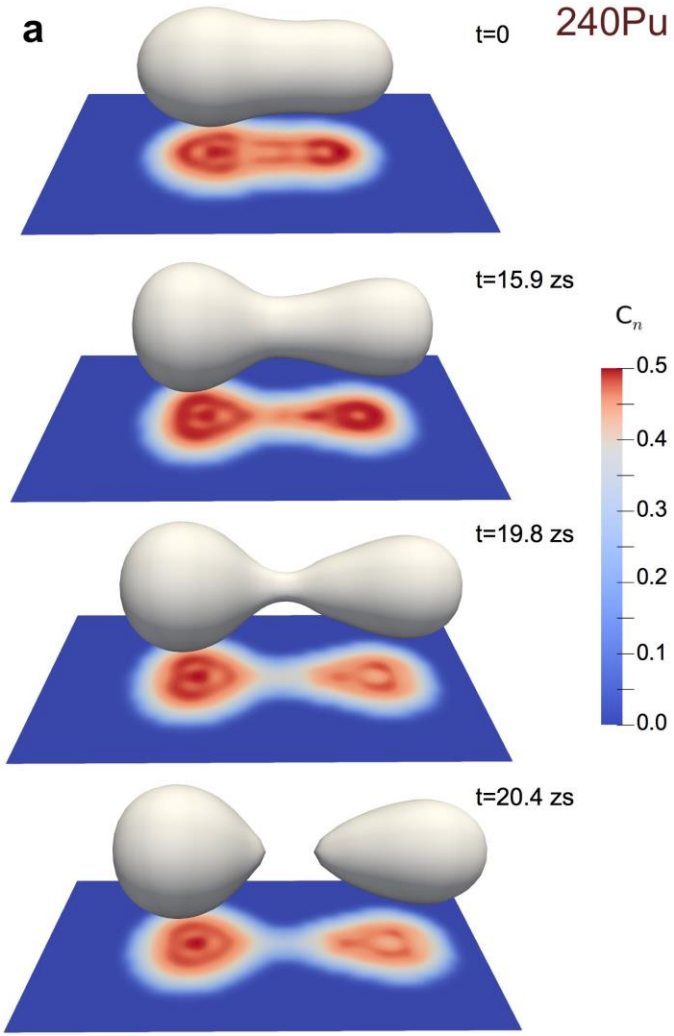
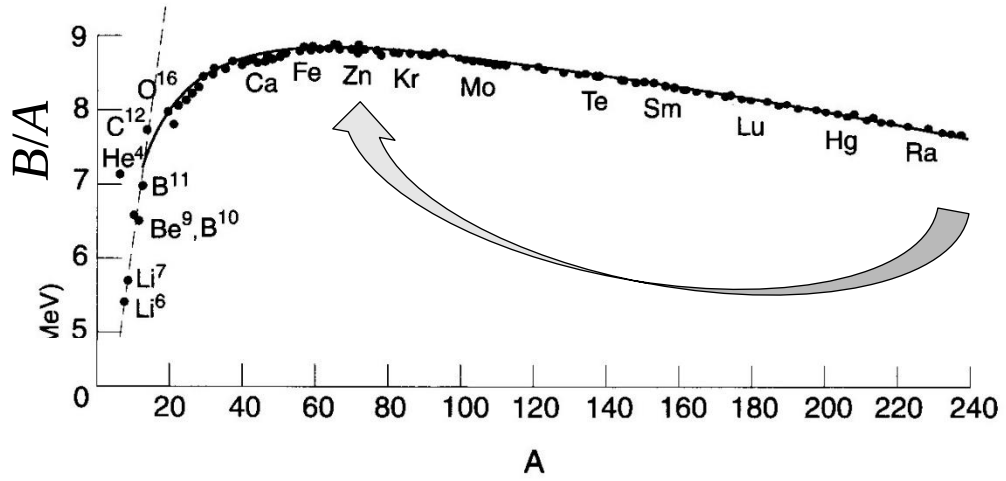
1. introduction: 核分裂のオーバービュー
2. r-process と核分裂:何が問題になるのか？
3. 微視的アプローチの必要性
4. CI アプローチの可能性(最近考えていること)
5. まとめ



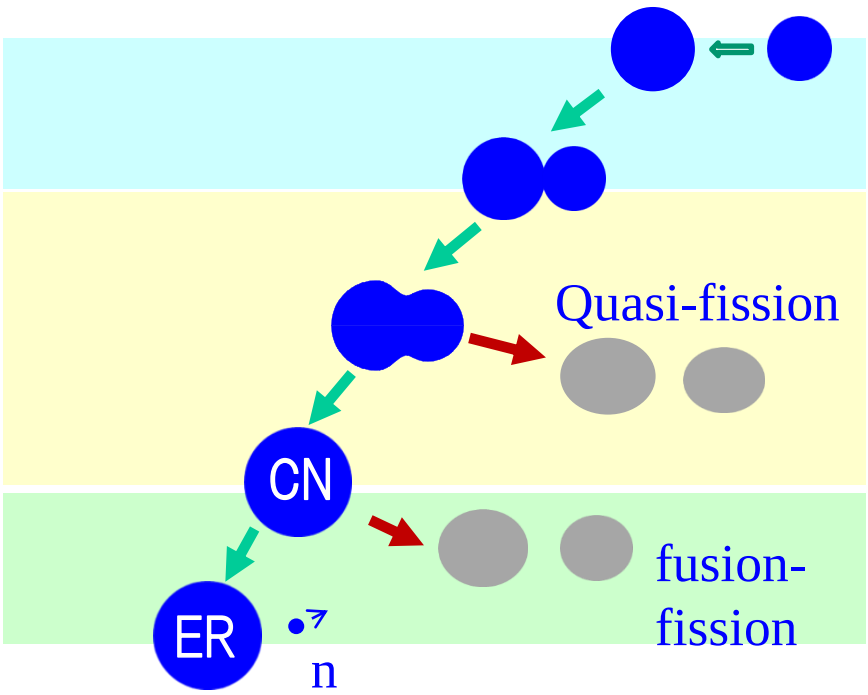
G. Scamps and C. Simenel, Nature 564 (2018) 382

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

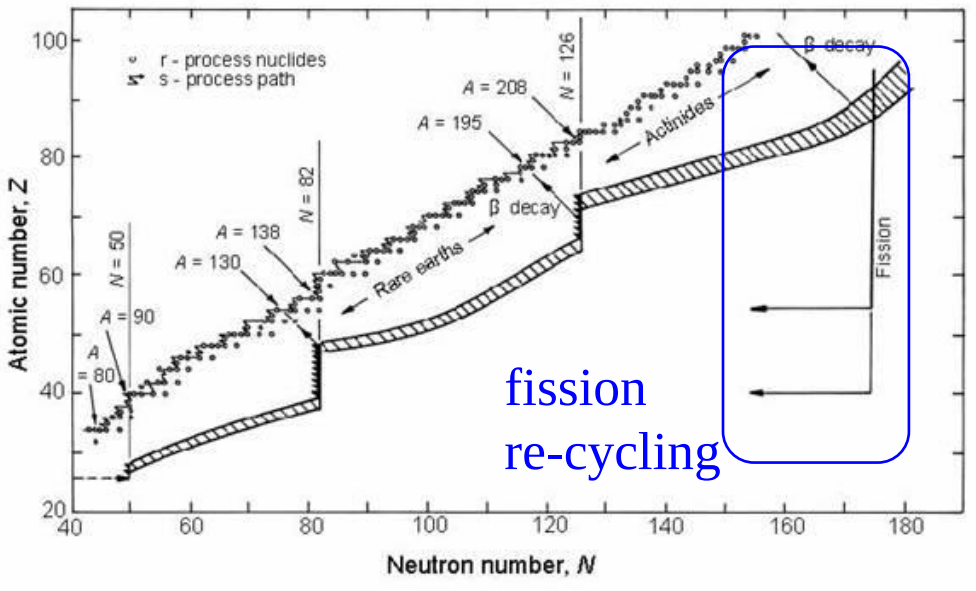


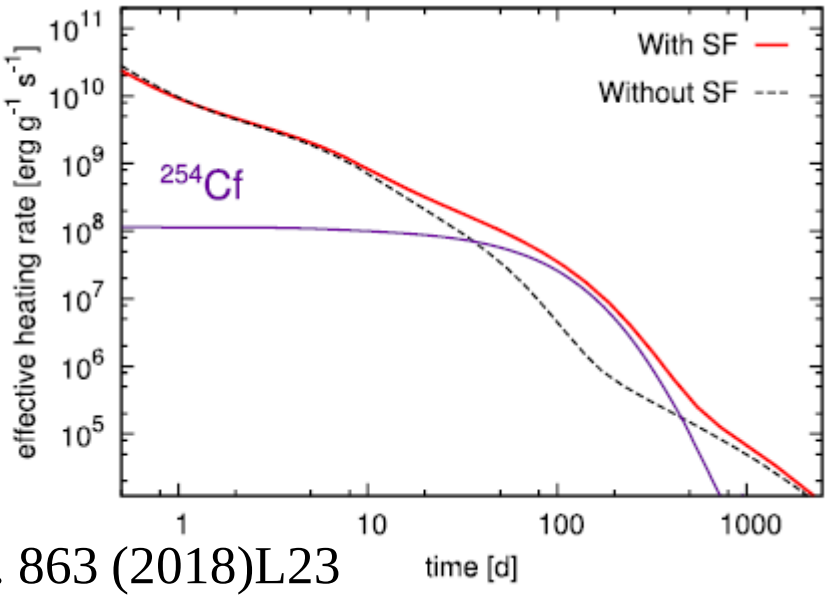
- important role in:
  - energy production
  - superheavy elements
  - r-process nucleosynthesis
  - production of neutron-rich nuclei

fission in SHE



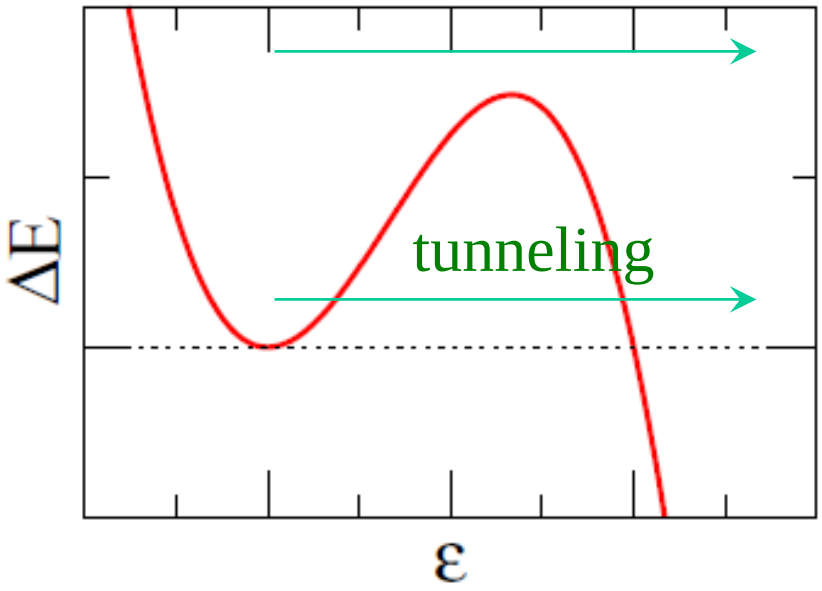
fission in r-process nucleosynthesis



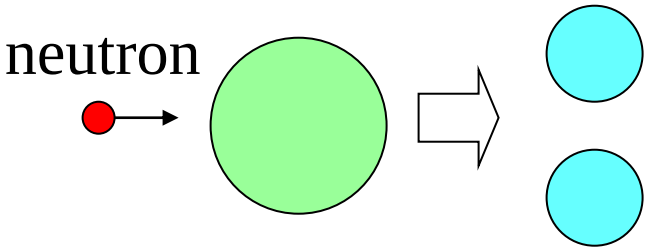


Y. Zhu et al.,
Astrophys. J. Lett. 863 (2018)L23

➢ various fission processes

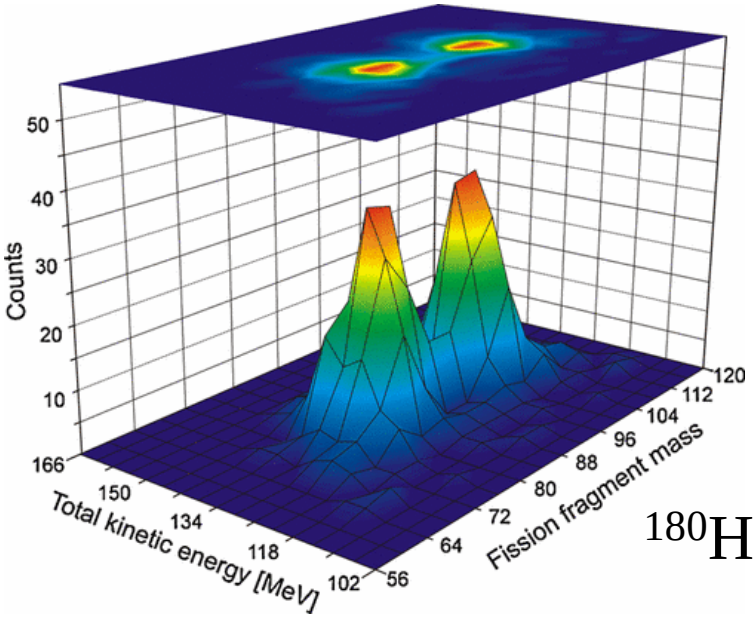


induced fission



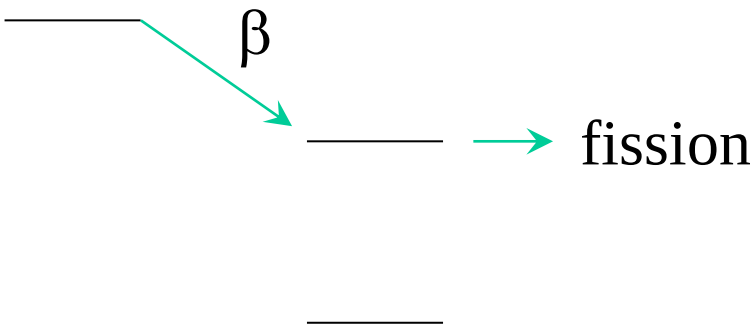
spontaneous fission

asymmetric fission

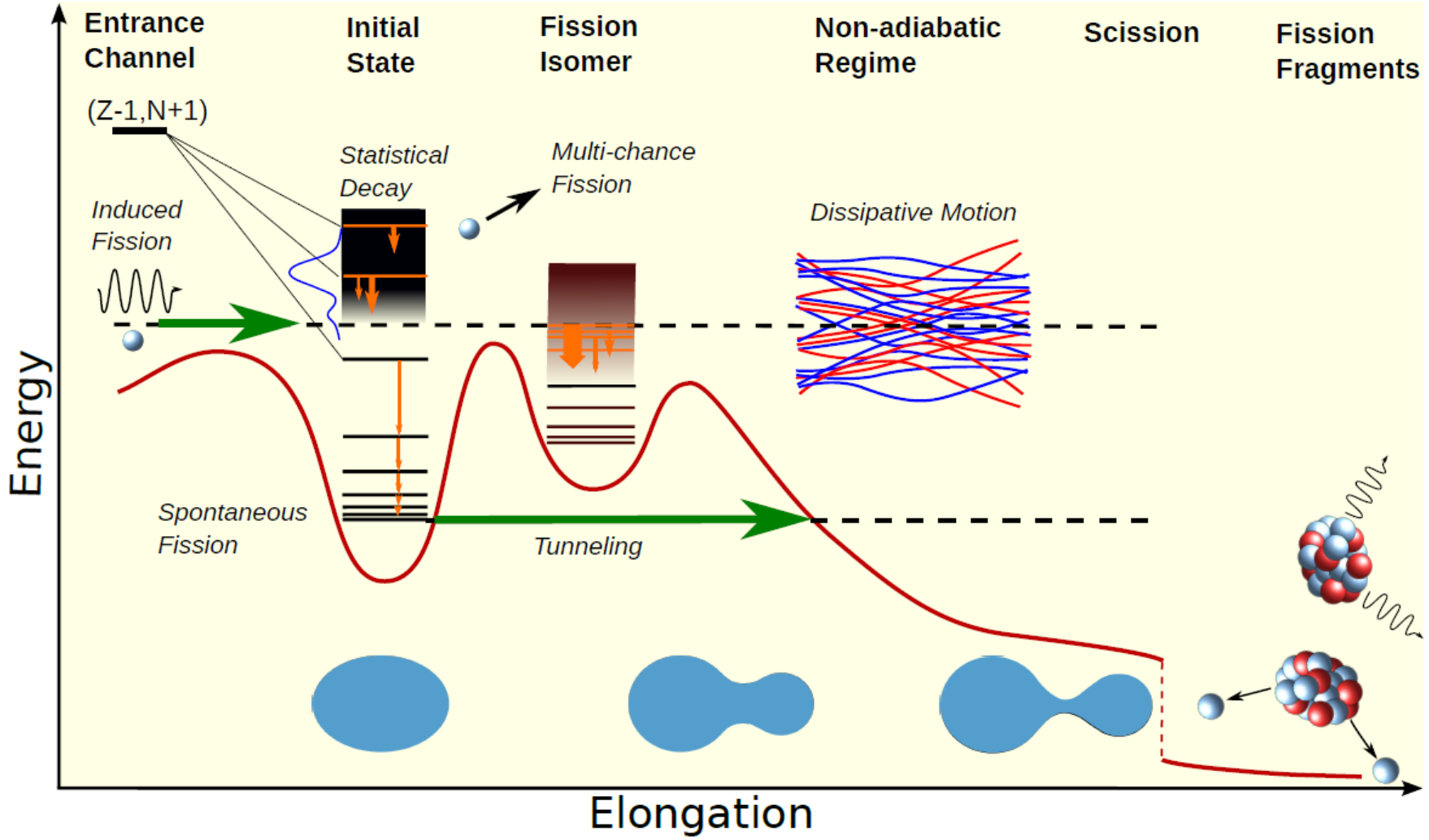


^{180}Hg

beta-delayed fission



A.N. Andreyev et al., PRL105(‘10)252502

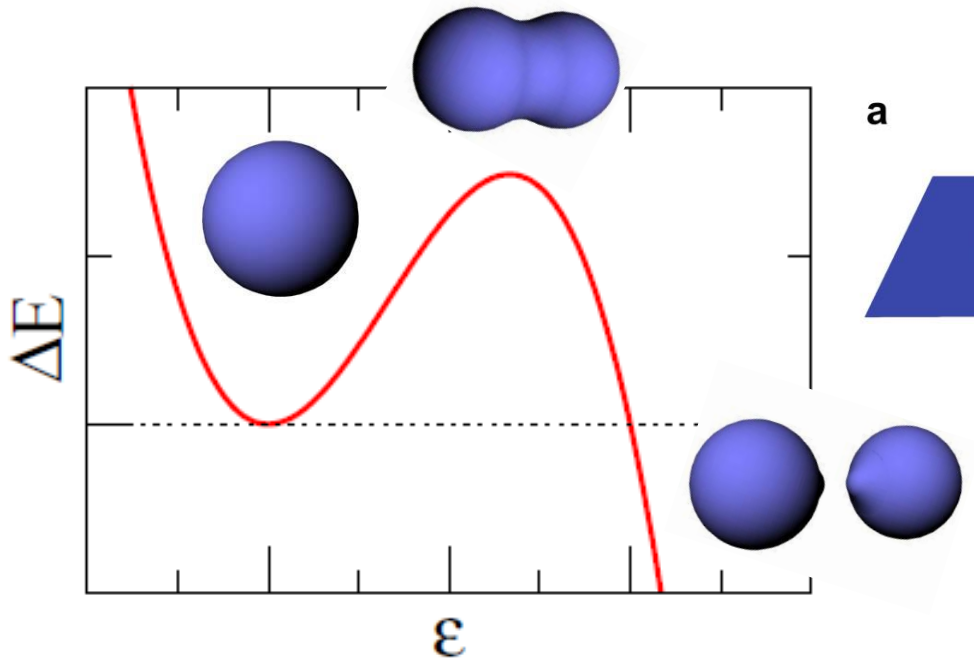


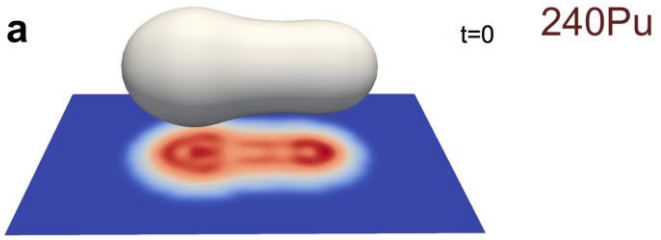
"Future of fission theory"
M. Bender et al., J. of Phys. G47, 113002 (2020)

➢ macroscopic understanding:

competition between the surface and the Coulomb energies

→ fission barrier





➢ a microscopic understanding:

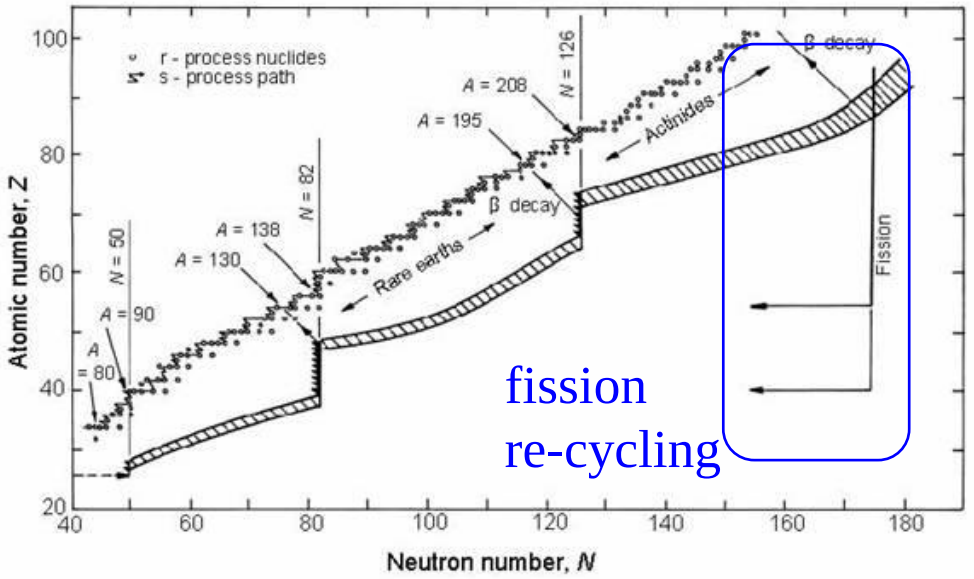
far from complete!

✓ large amplitude motion

fission in r-process nucleosynthesis

- fission of neutron-rich nuclei
  - ✓ neutron-induced fission
  - ✓ beta-delayed fission

- important quantities
  - ✓ mass distributions
  - ✓ charge distributions
  - ✓ branching ratios
    (n-cap., fis., beta-decay)



fission in r-process nucleosynthesis

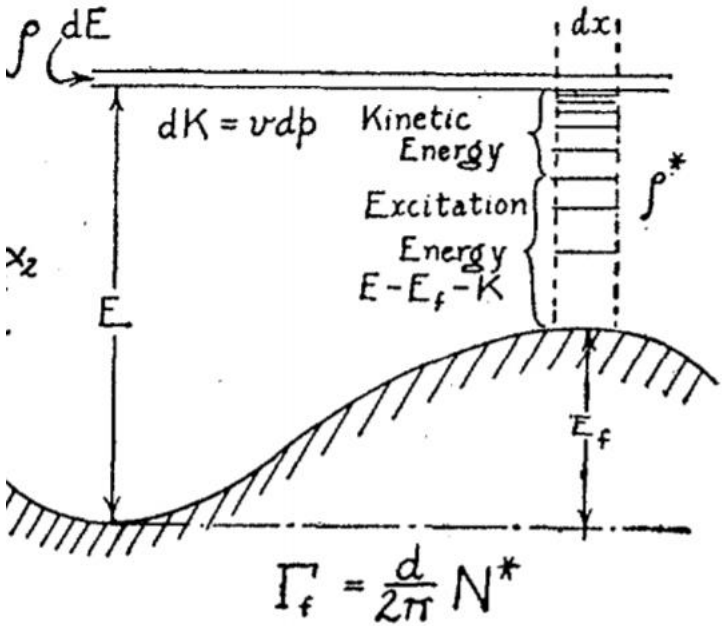
- ✓ low E^*
- ✓ low $\rho(E^*)$

➢ fission of neutron-rich nuclei

- ✓ neutron-induced fission
- ✓ beta-delayed fission

➢ important quantities

- ✓ mass distributions
- ✓ charge distributions
- ✓ branching ratios
  (n-cap., fis., beta-decay)



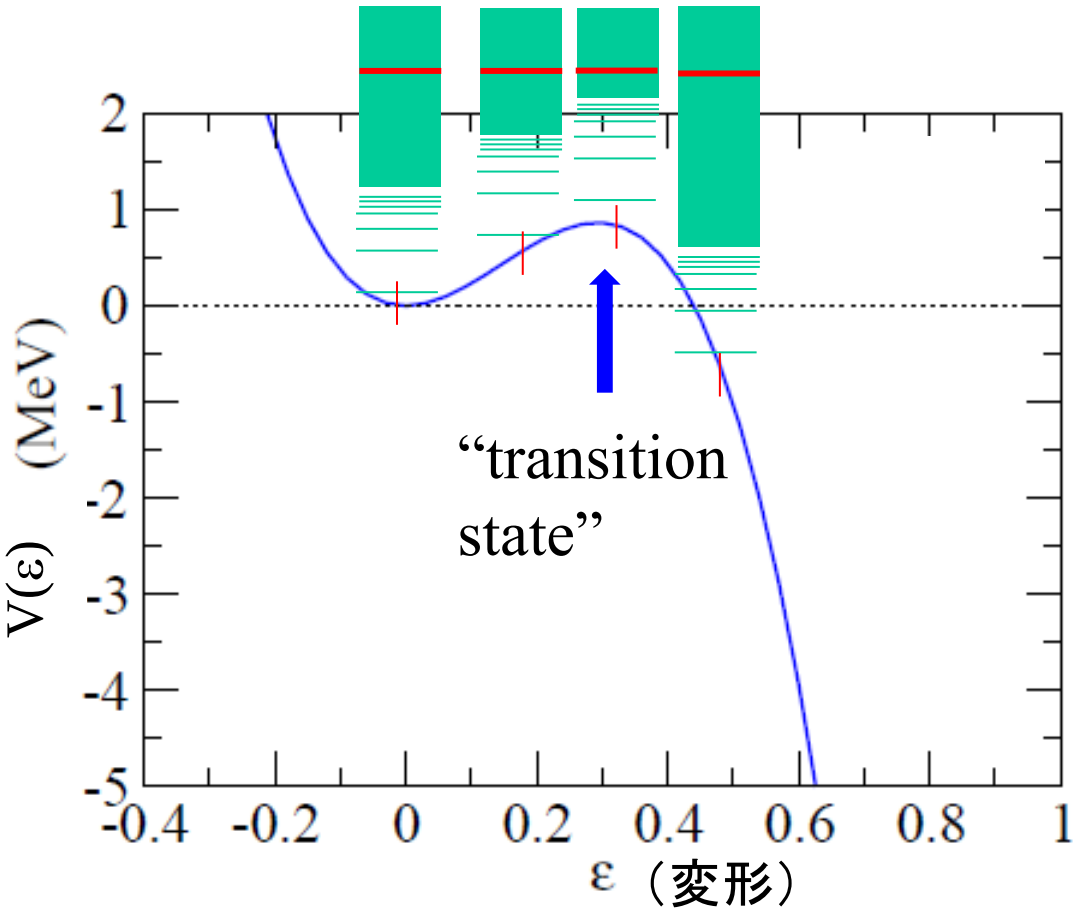
N. Bohr and J.A. Wheeler,
Phys. Rev. 56, 426 (1939)

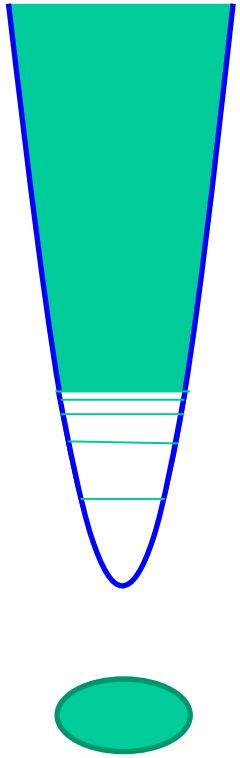
→ validity of the BW theory?
validity of the Langevin?

➢ microscopic framework: desired

- ✓ how to connect to a many-body Hamiltonian?

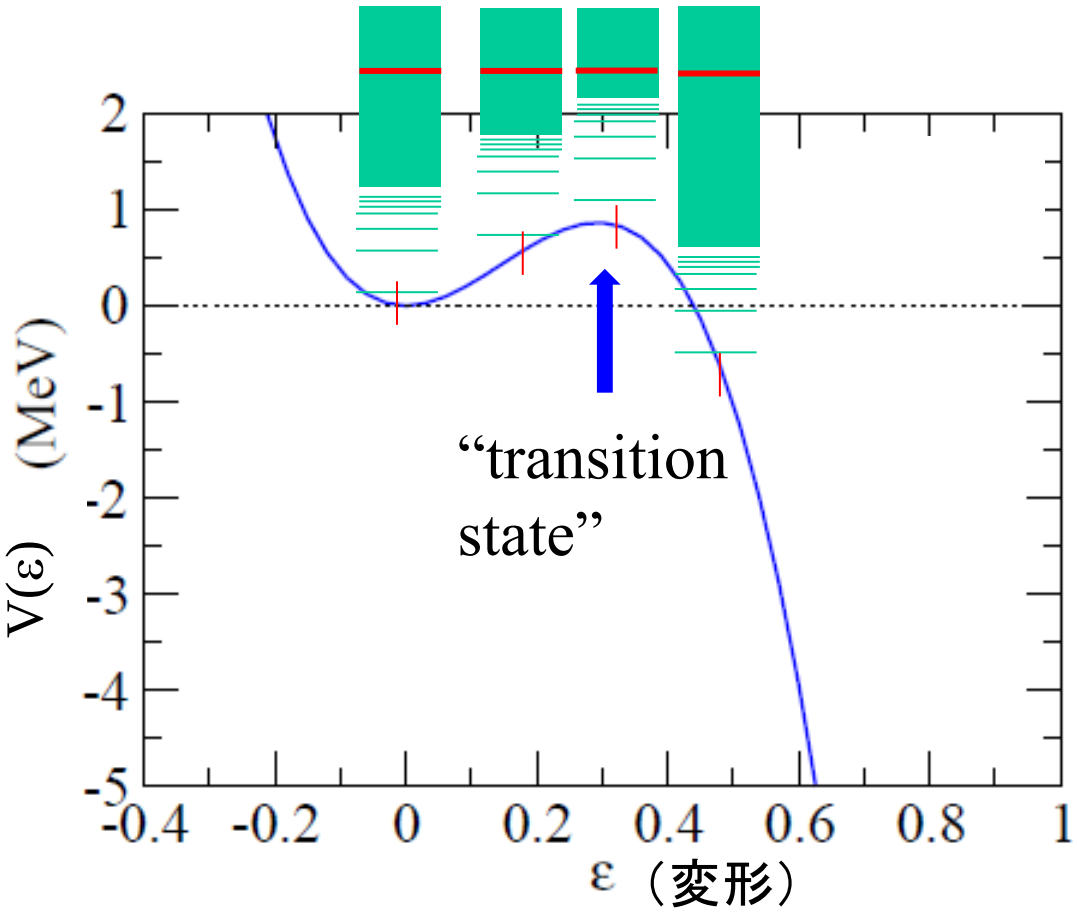
CI アプローチの可能性?

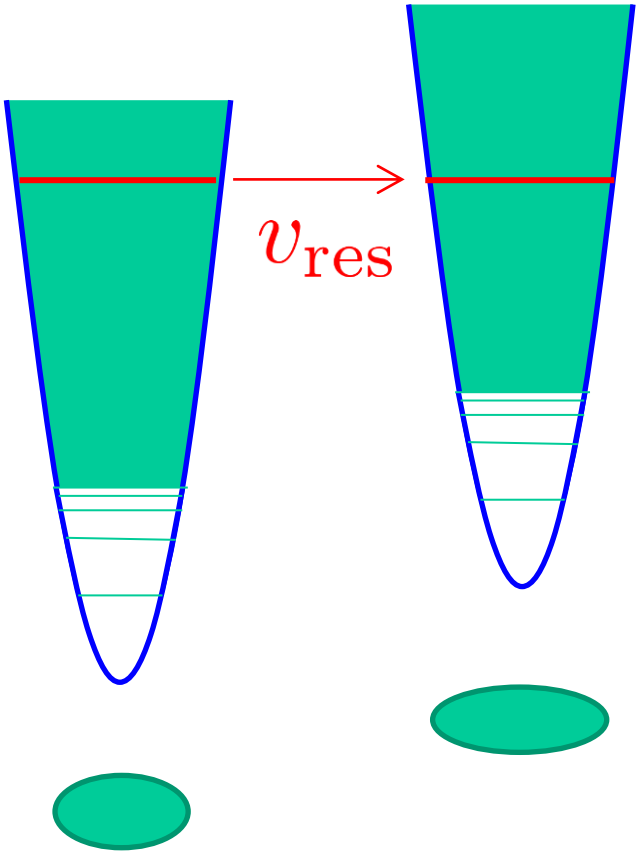




形を決めたときの平均場ポテンシャルでの準位

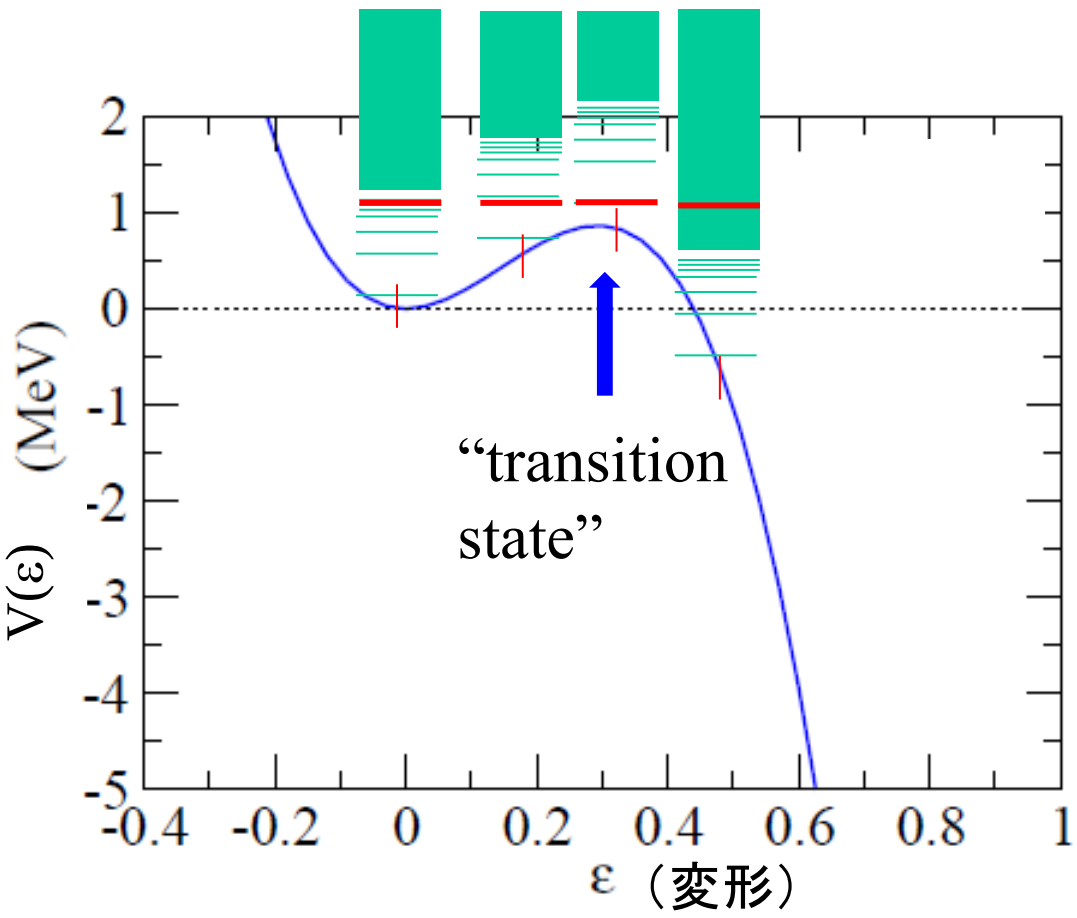
CI アプローチの可能性?





残留相互作用による
ホッピング

CI アプローチの可能性?



励起エネルギーが低い場合には準位密度がスカスカの領域を通る

→transition state theory の妥当性が議論できる

どのくらい E^* が大きければBW公式はよくなるのか?

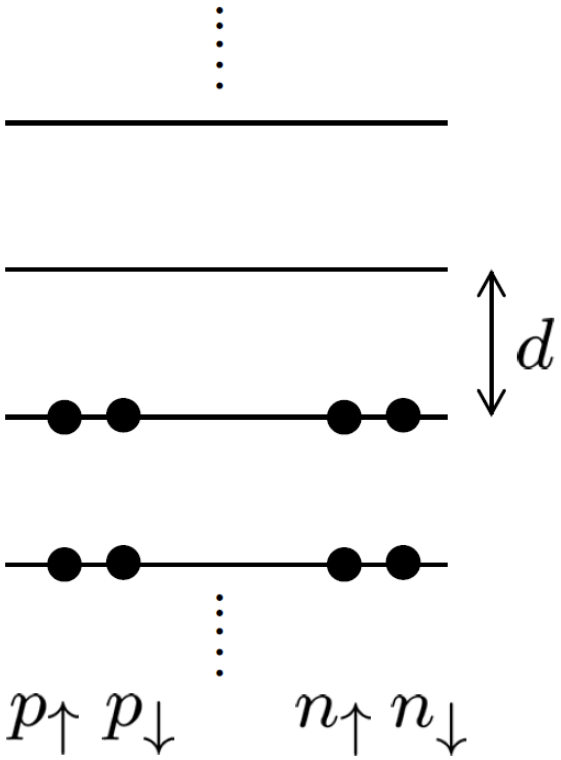
現実的な問題:

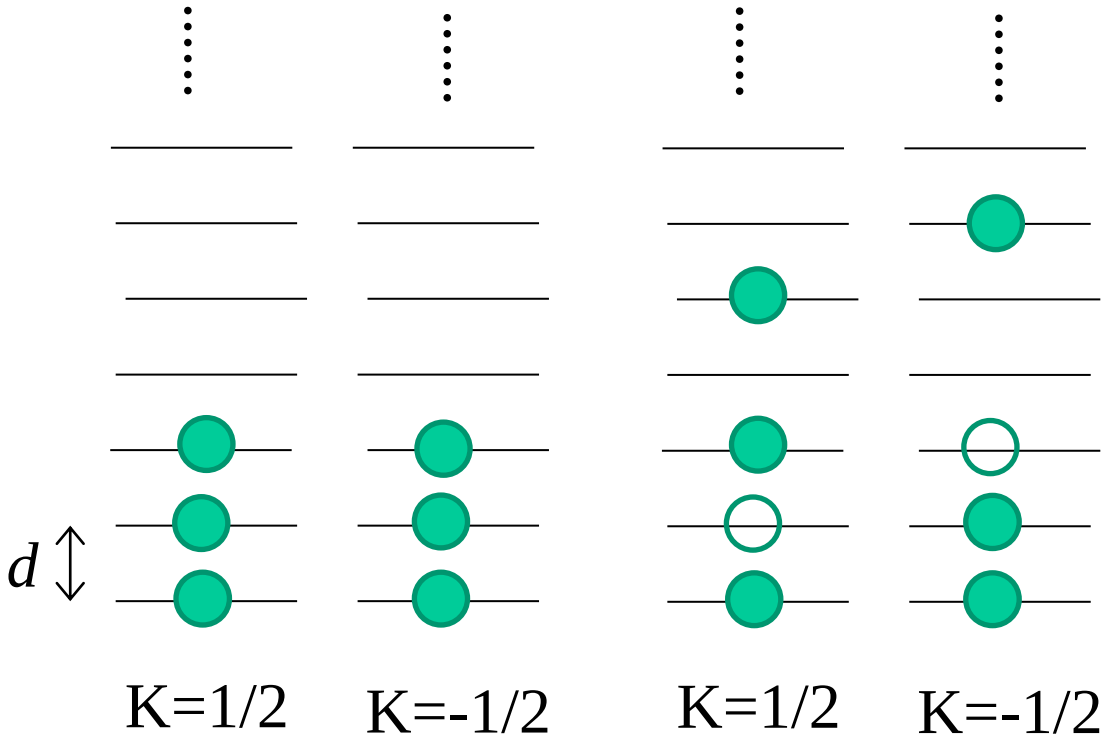
- ✓ 模型空間をどのように truncate するのか?
- ✓ 非直交性の問題をどう取り扱うか?

CI アプローチの実現

G.F. Bertsch and K.H.,
arXiv: 2102.07084 [nucl-th]

一様な一粒子軌道





0p0h 状態

2p2h 状態 (E*=6ε)

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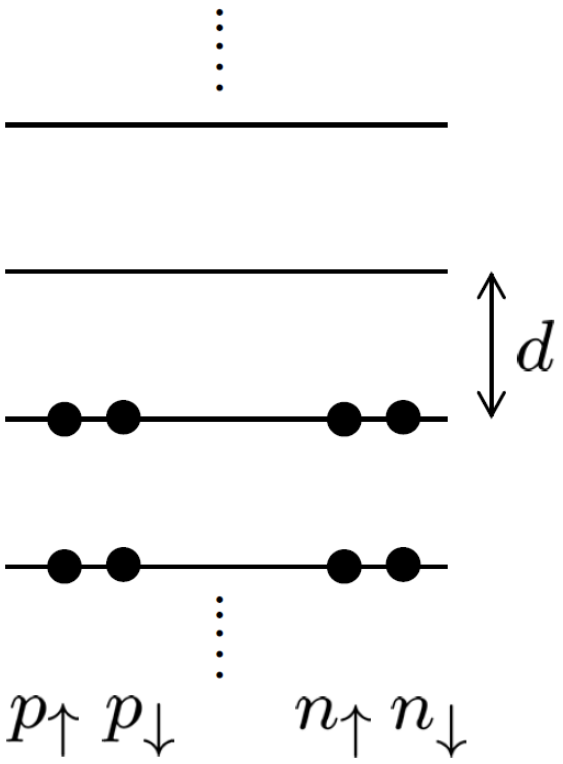
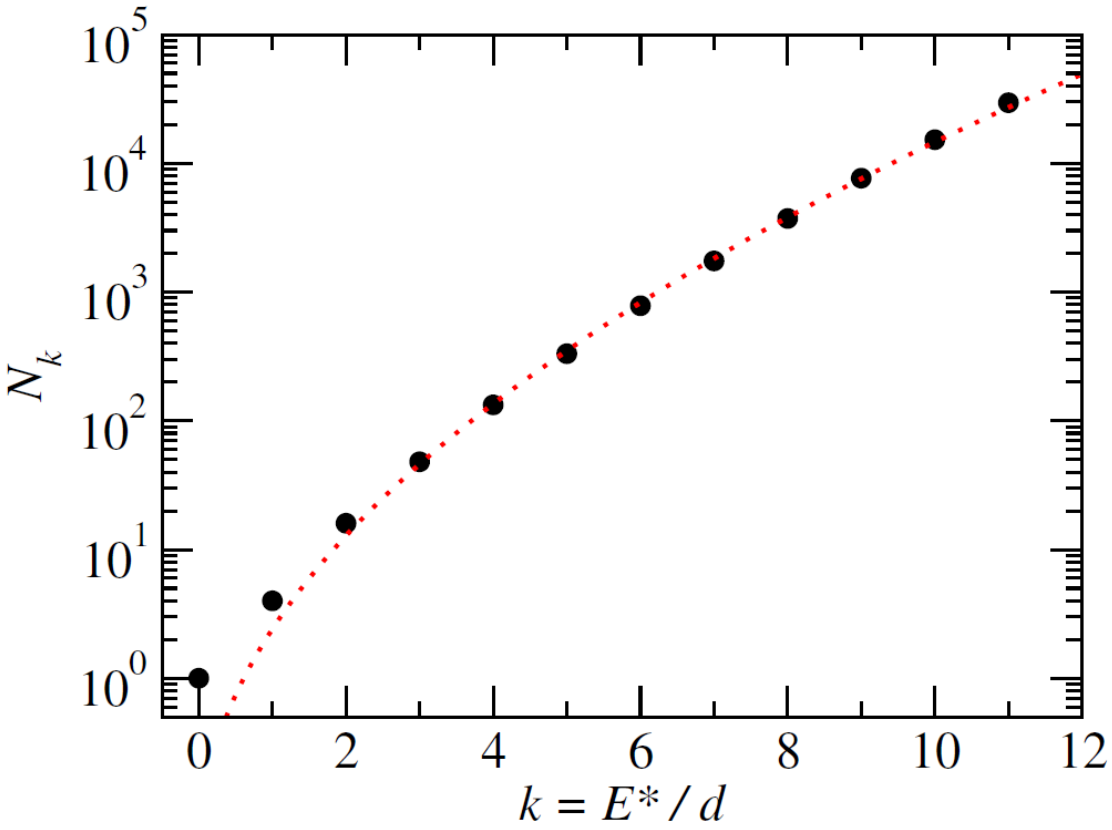
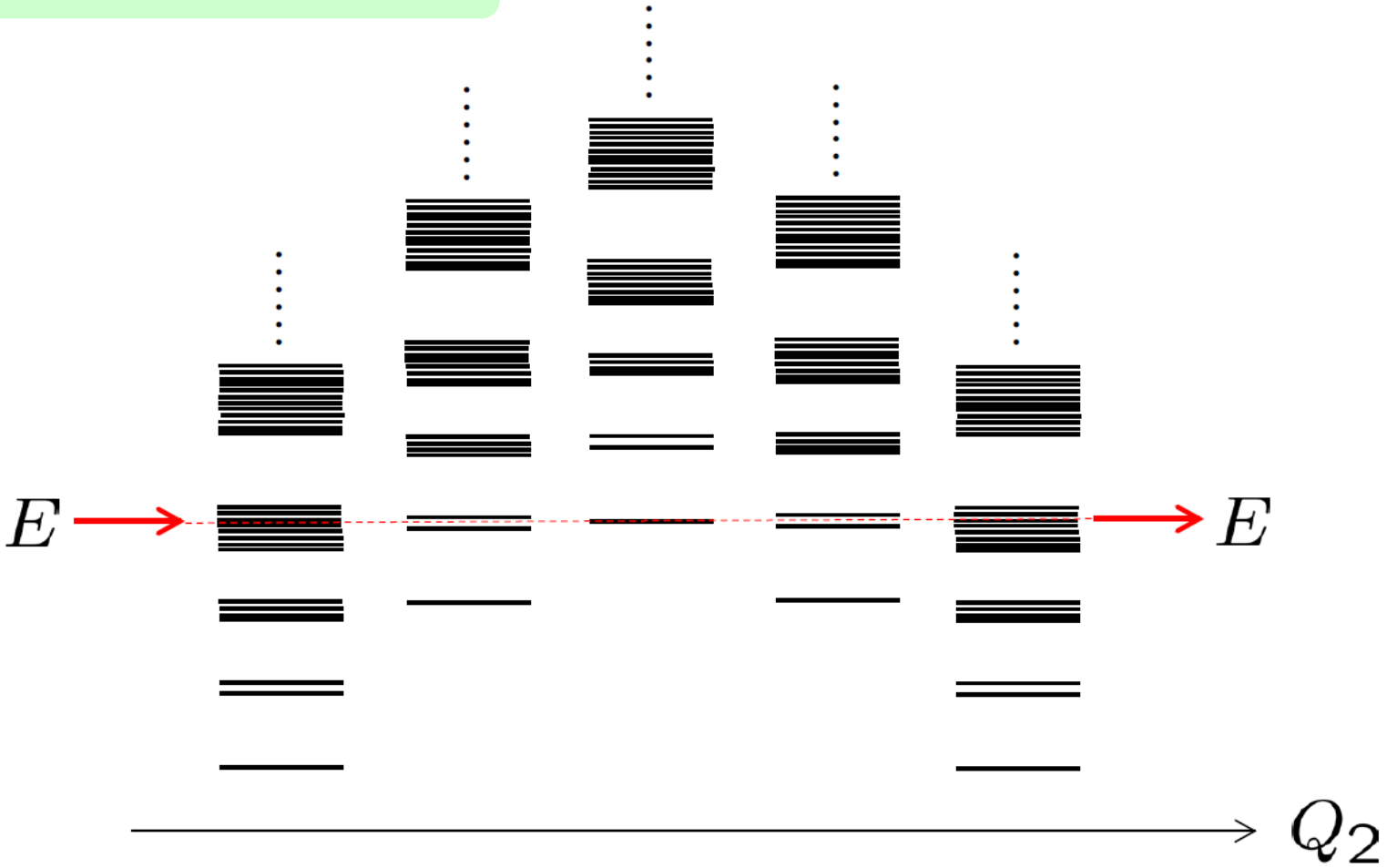
一様な一粒子軌道





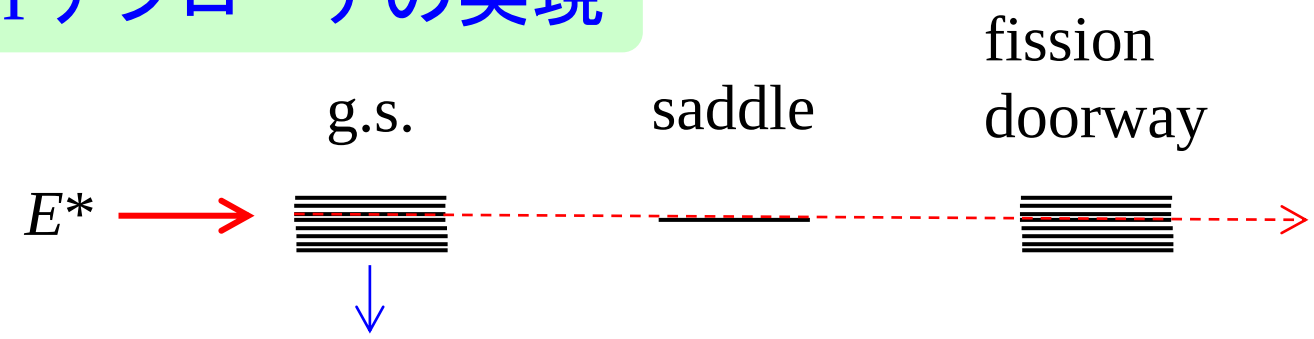
CI アプローチの実現



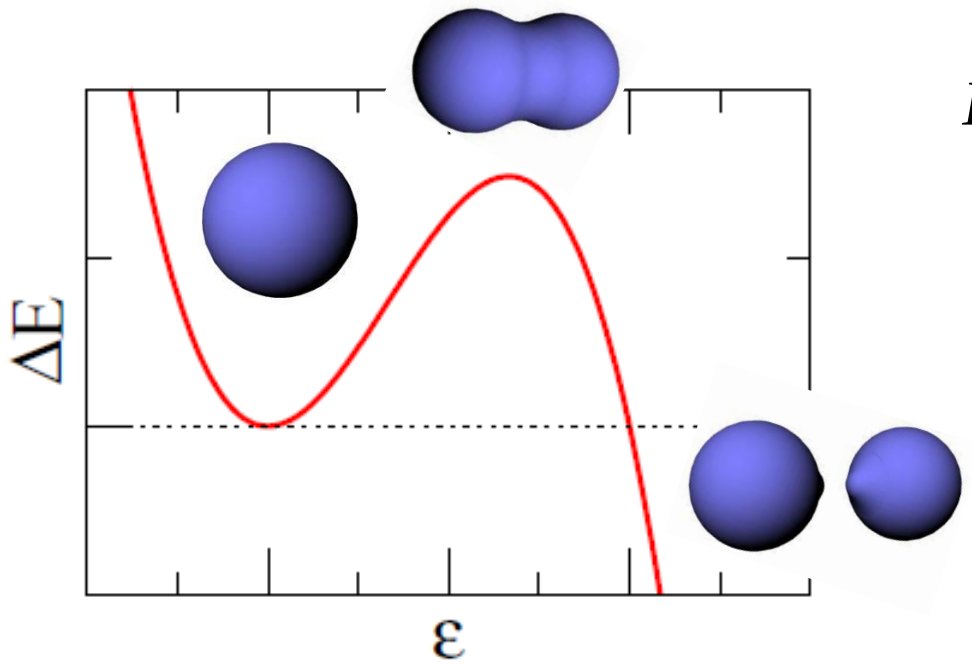
$$H = \sum_{\mu} \epsilon_{\mu} a^{\dagger}_{\mu} a_{\mu} + \sum v_{\mu\nu\mu'\nu'} a^{\dagger}_{\mu} a^{\dagger}_{\nu} a_{\nu'} a_{\mu'}$$

ガウス分布に従ってランダムに発生 (pn 相互作用のみ)

CI アプローチの実現

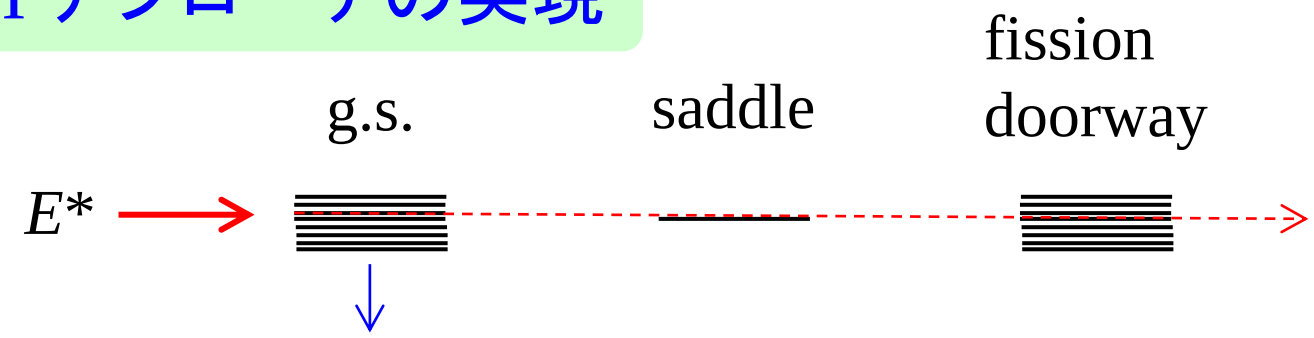


$$H = \begin{pmatrix} H_k - i\Gamma_{\rm cap}/2 & V & 0 \\ V & H_0 & V \\ 0 & V & H_k - i\Gamma_{\rm fis}/2 \end{pmatrix}$$



H_k: the Hamiltonian with the configuraitons at E_k*

CI アプローチの実現



$$H = \begin{pmatrix} H_k - i\Gamma_{\rm cap}/2 & V & 0 \\ V & H_0 & V \\ 0 & V & H_k - i\Gamma_{\rm fis}/2 \end{pmatrix}$$

Reaction theory:

$$T_{\rm cap}(E) = \mathcal{N} \sum_{k\in 1{\rm st}} |(H-E)^{-1}_{ki}|^2 \, \Gamma_{\rm cap}$$

$$T_{\rm fis}(E) = \mathcal{N} \sum_{k\in 3{\rm rd}} |(H-E)^{-1}_{ki}|^2 \, \Gamma_{\rm fis}$$

i: 入射チャンネル（1st ブロックのいずれかの config.）

分岐比: $$Br = \frac{\int dE\, T_{\rm fis}(E)}{\int dE\, T_{\rm cap}(E)}$$ cf. $$Br_{\rm BW} = \frac{1}{2\pi\rho_1}\frac{1}{\Gamma_{\rm cap}}$$

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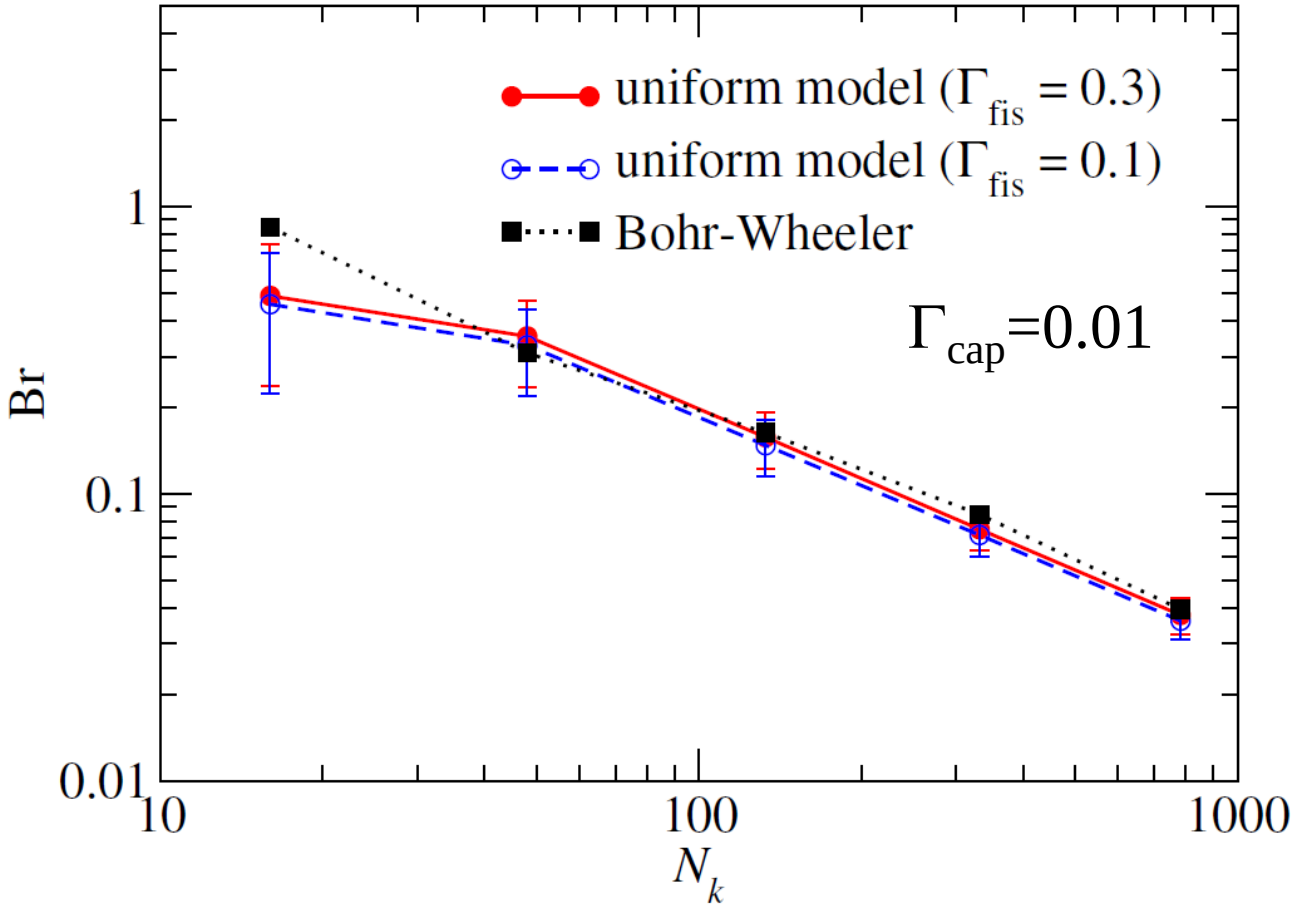


- ✓ Γ_{fis}（scission のダイナミックス）にあまり依存しない
- ✓ BW 公式とよく一致（k=2 を除く）

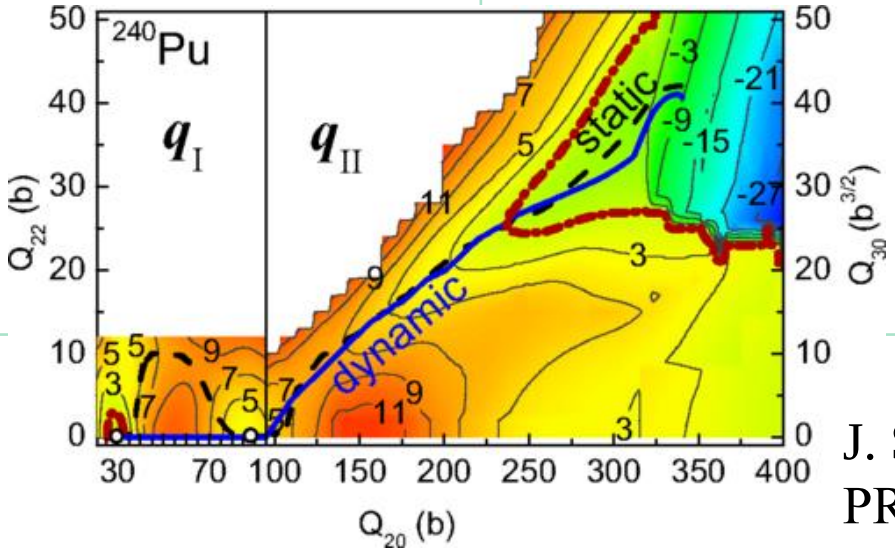
→多体ハミルトニアンを用いて初めて BW 理論を実現

まとめ

r-プロセス：中性子過剰核の核分裂

low E^*, low $\rho(E^*)$に対応できる（微視的）アプローチが必要

	Time-indep. approach	Time-dep. approach
Induced fission	✓Bohr-Wheeler (statistical model) **✓CI approach**	✓Langevin-type Wada, Abe, Aritomo, Chiba….. Moller, Randrup
Spontaneous fission	✓PES+Mass+WKB	✓Im.-time TDHF (Negele) ✓Time-dep. Hill-Wheeler (Goutte et al.) ✓TDHF(B) (Bulgac…..)



J. Sadhukhan, W. Nazarewicz, N. Schunck, PRC93(‘16)011304(R)