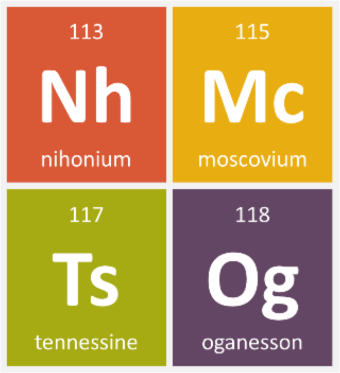
Open issues in physics of SHE
: nuclear reaction perspectives

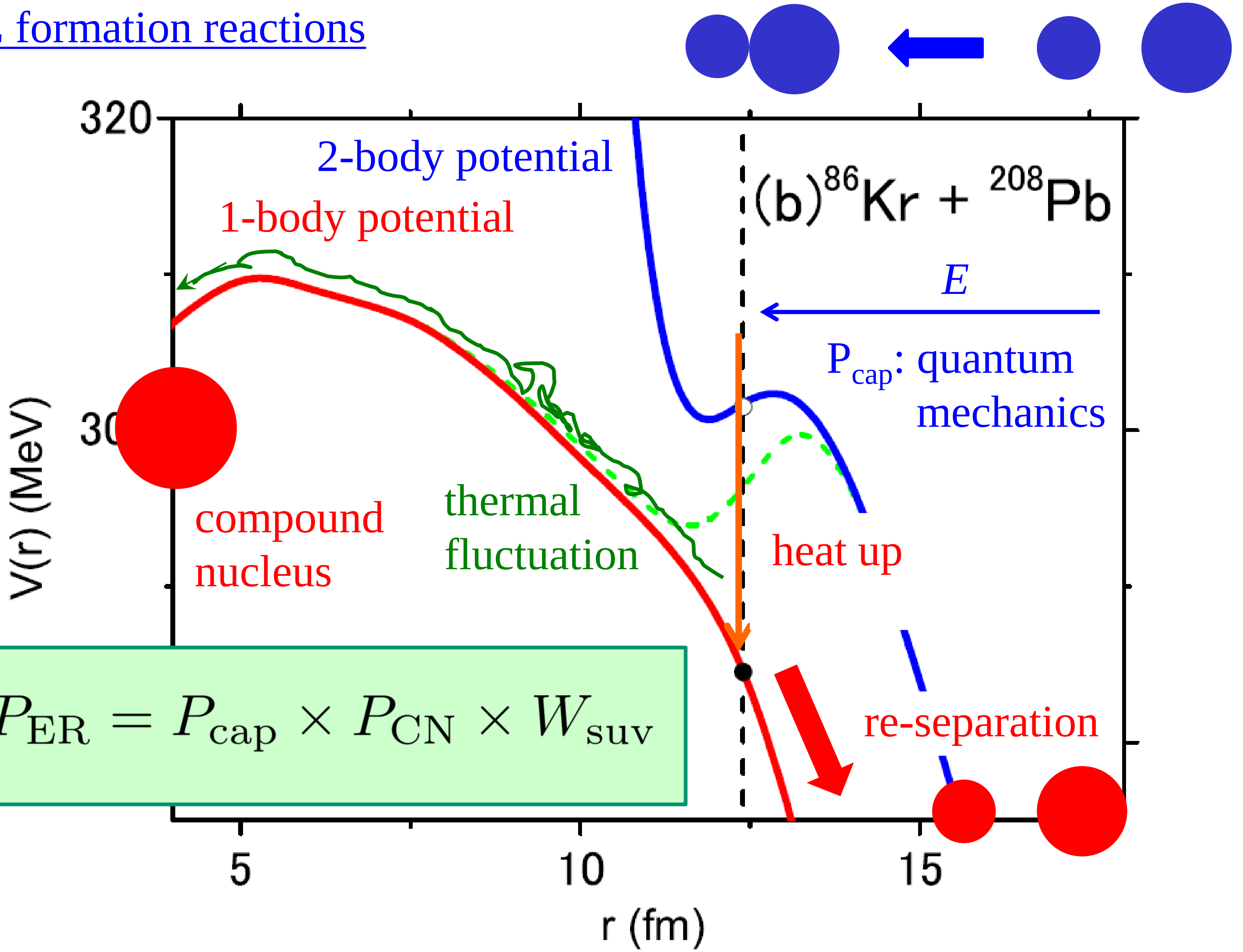


Kouichi Hagino
Kyoto University

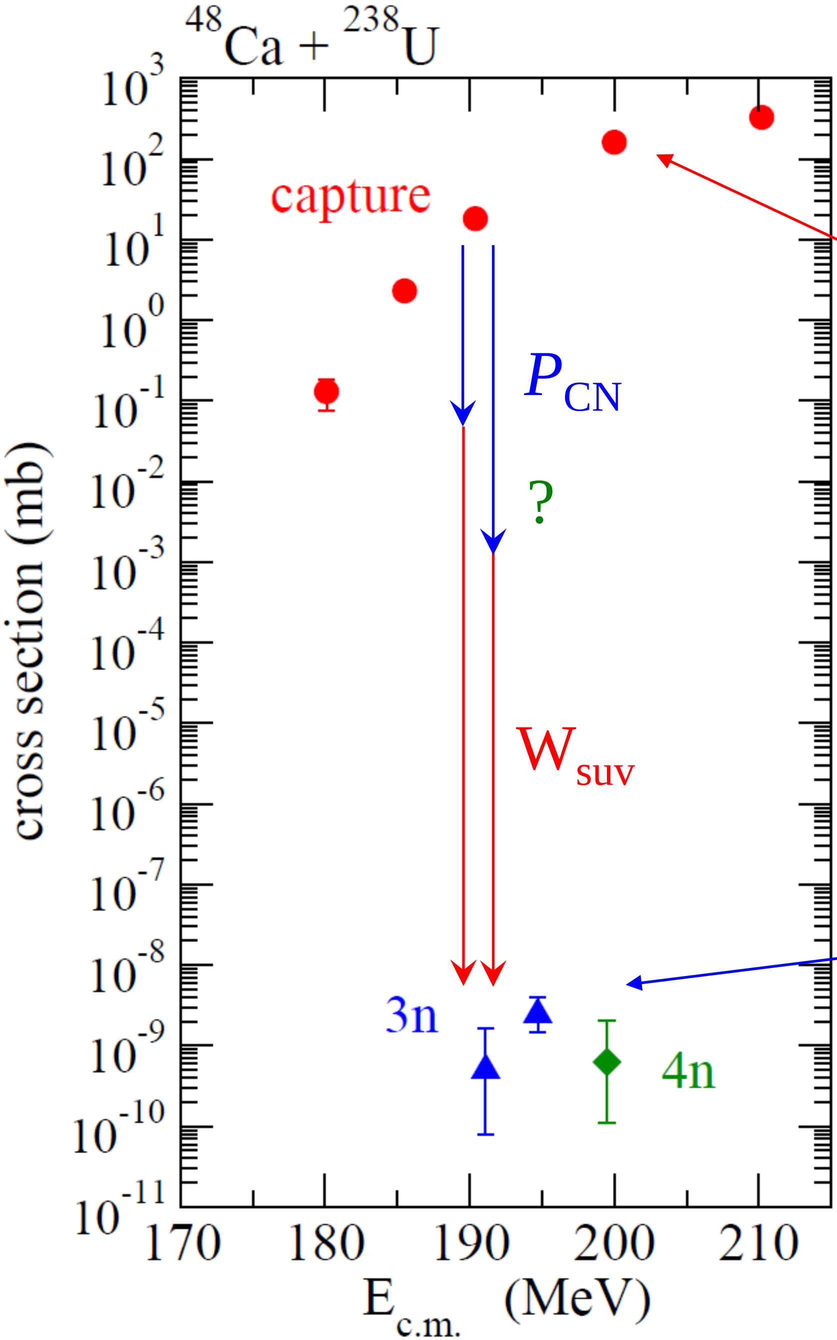
1. Introduction: fusion for superheavy elements
2. Theoretical issues in the Langevin approach
3. Towards a microscopic description for fusion/fission
4. Complexity of reaction dynamics
5. Summary

FRIB-TA Topical Program: the path to superheavy isotopes, June 3-8, 2024, MSU

SHE formation reactions



$$P_{\rm ER} = P_{\rm cap} \times P_{\rm CN} \times W_{\rm suv}$$



a very big theoretical challange:

no experimental data for P_{CN}

$$\sigma_{\text{cap}}(E) = \frac{\pi}{k^2}\sum_l (2l+1)T_l(E)$$

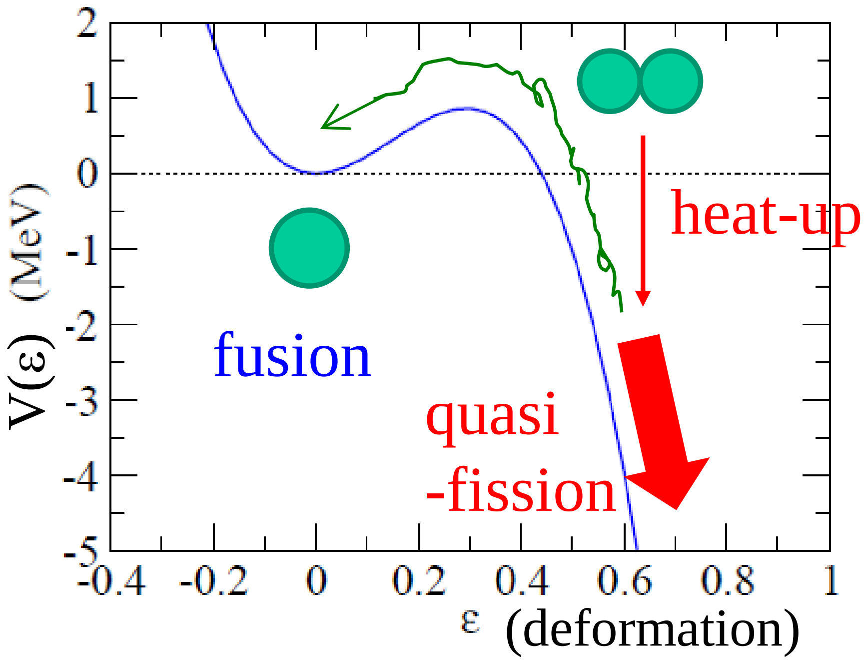
~~$$\sigma_{\text{CN}}(E) = \frac{\pi}{k^2}\sum_l (2l+1)T_l(E) \times P_{\text{CN}}$$~~

not available

$$\sigma_{\text{ER}}(E) = \frac{\pi}{k^2}\sum_l (2l+1)T_l(E) \times P_{\text{CN}} \cdot W_{\text{suv}}$$

large uncertainties

Langevin approach for P_{CN}

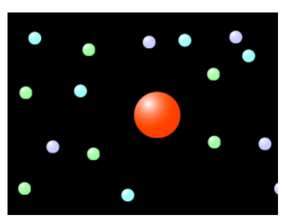


thermal fluctuation

⟶ Langevin method

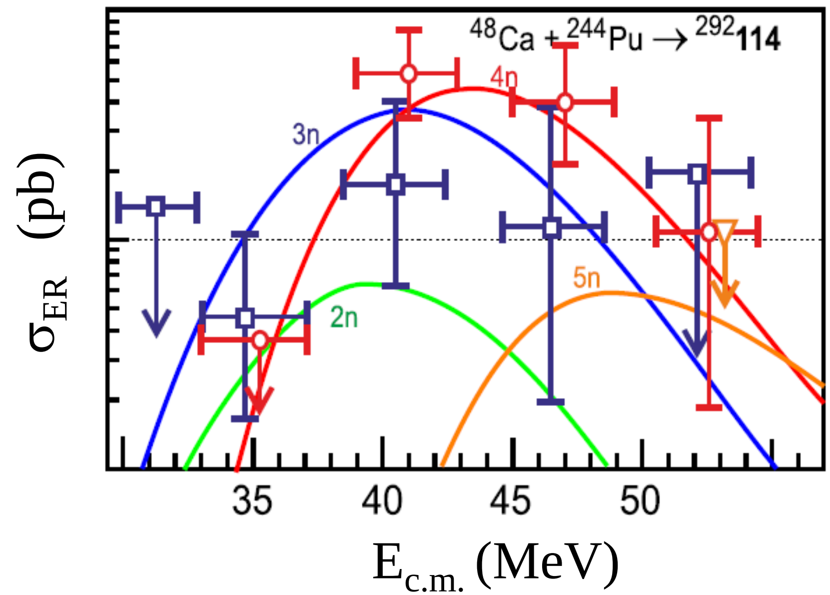
$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$

Browninan motion



multi-dimensional extension:

q:
- internuclear separation,
- deformation,
- asymmetry of the two fragments

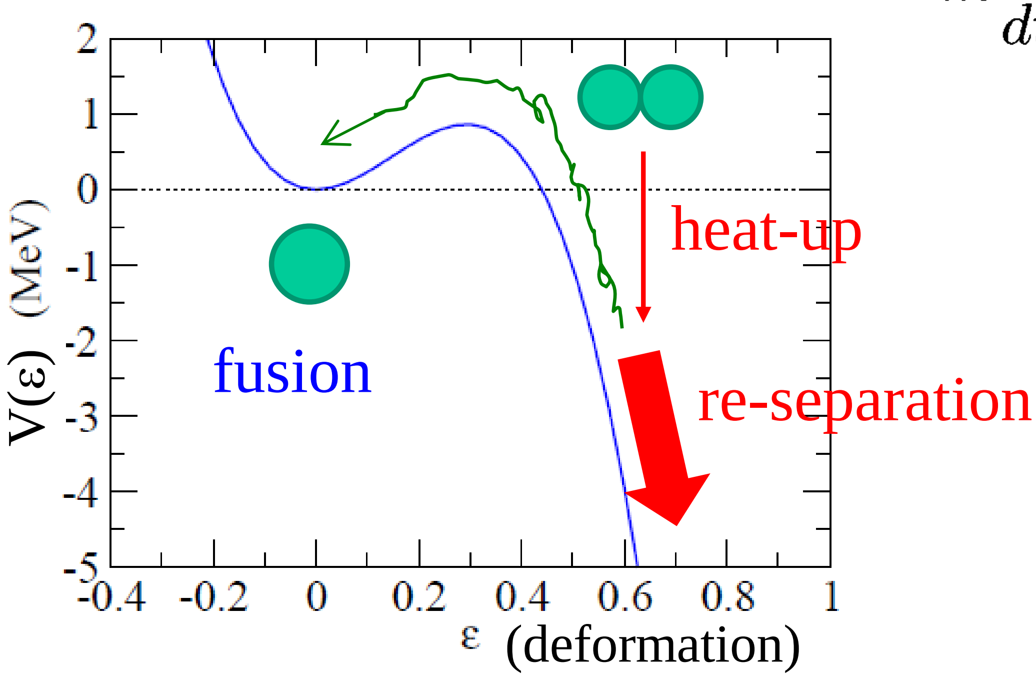


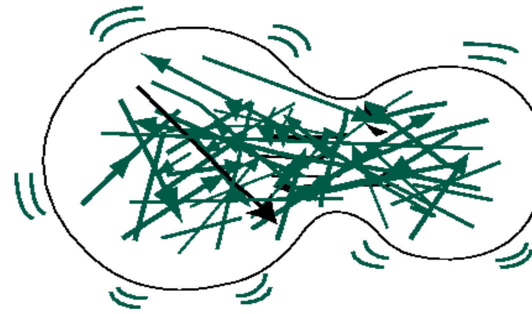
V.I. Zagrebaev and W. Greiner (2015)

successful,
at least phenomenologically

Langevin approach for P_{CN}

$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$





nuclear intrinsic d.o.f.
: internal environment

→ open quantum systems

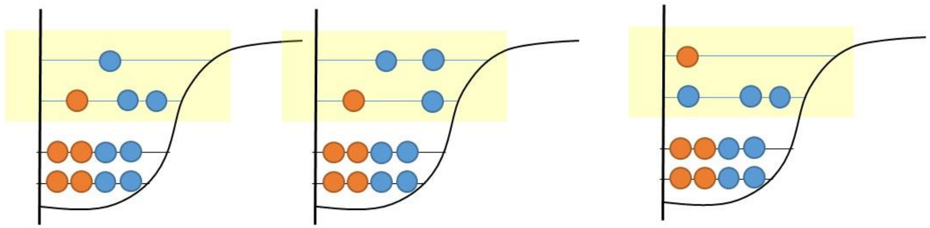
Theoretical issues

✓how to thermaize? mechanisms?
✓is thermal equilibrium OK?
✓Is Markovian approximation OK?
✓quantum effects?

▪a quantal theory for friction
▪a **microscopic** approach

Shell model approach (for fission)?

Shell model

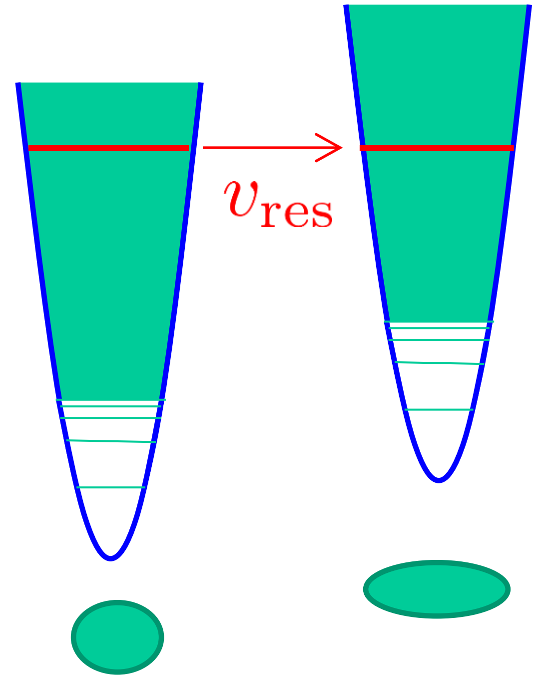


$$|\Psi\rangle = v_1|m_1\rangle + v_2|m_2\rangle + v_3|m_3\rangle + \cdots$$

Figure: Noritaka Shimizu (Tsukuba)

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

A similar approach for nuclear fission?

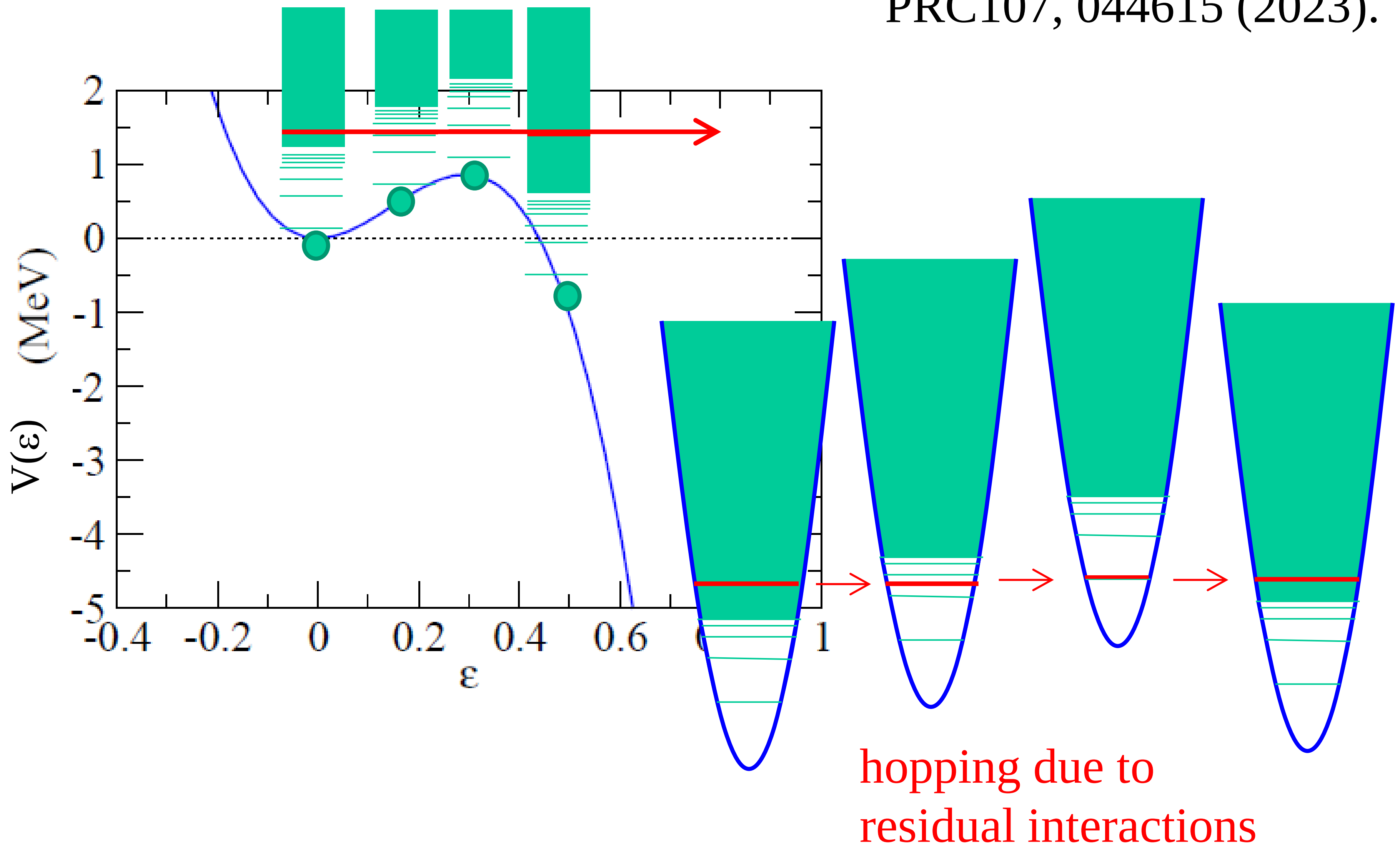


- Many-body configurations in a MF pot. for each shape
- hopping due to res. int.

→ shape evolution

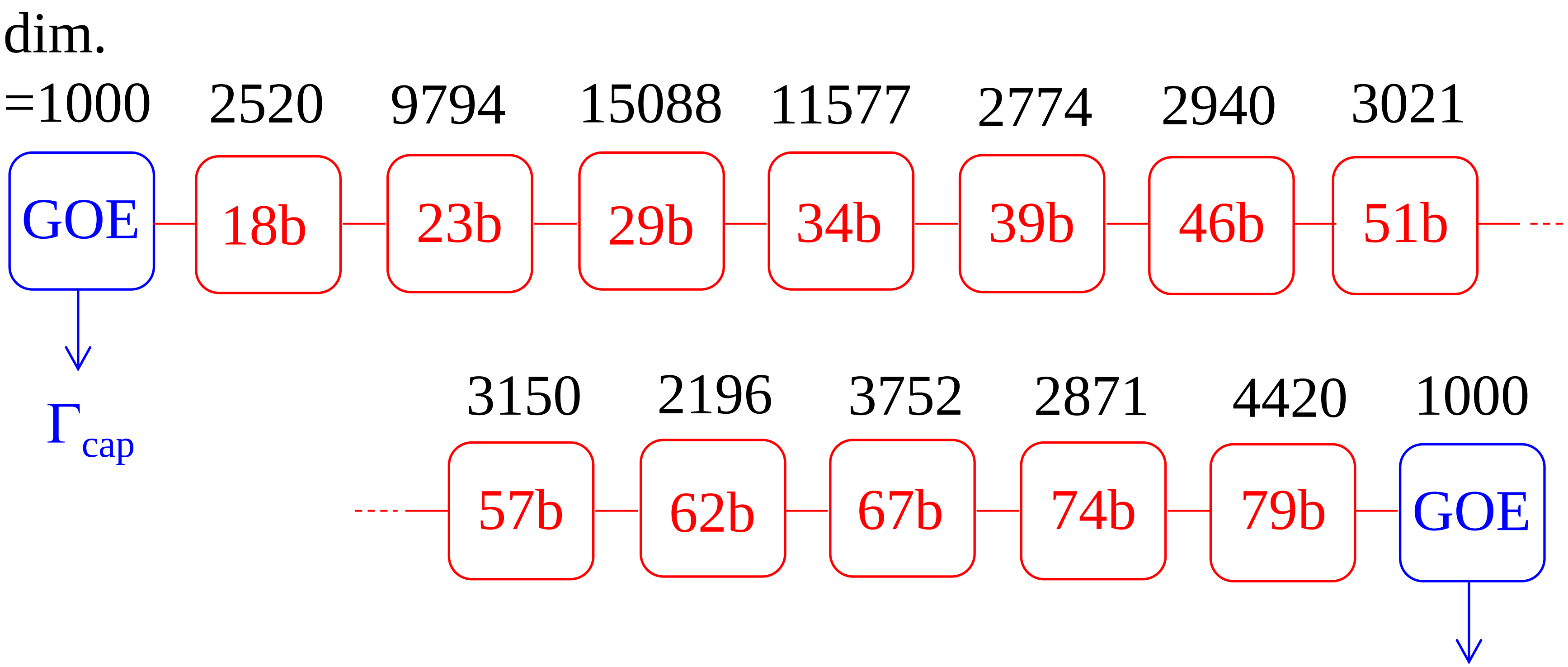
Towards a microscopic description for induced fission

G.F. Bertsch and K.Hagino,
PRC107, 044615 (2023).



Application to low-energy fission of ^{236}U

G.F. Bertsch and K.H., Phys. Rev. C107, 044615 (2023).
K. Uzawa, K.H., and G.F. Bertsch, arXiv:2403.04255.



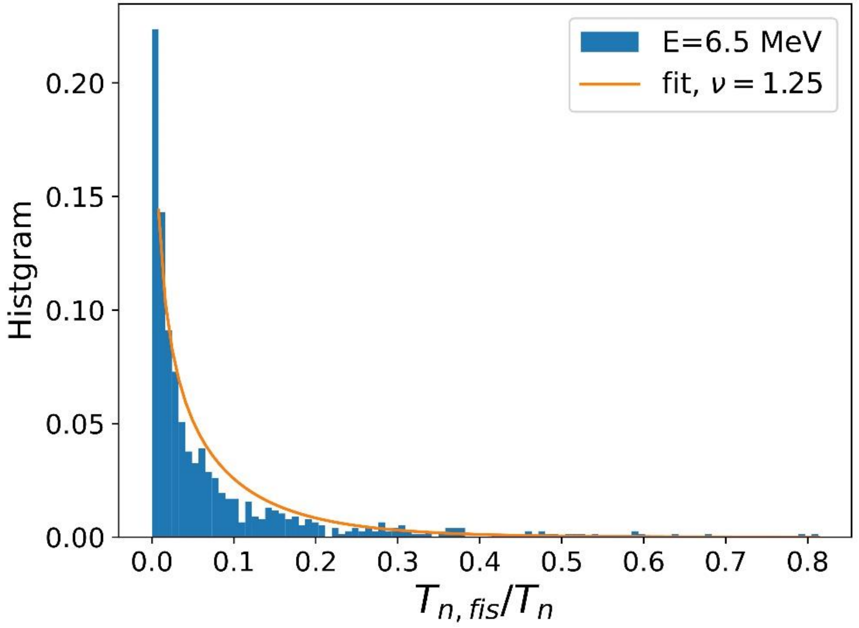
Skyrme UNEDF1, seniority zero config. up to 5 MeV
$\longrightarrow$ 66,103 x 66,103 dim. Hamiltonian

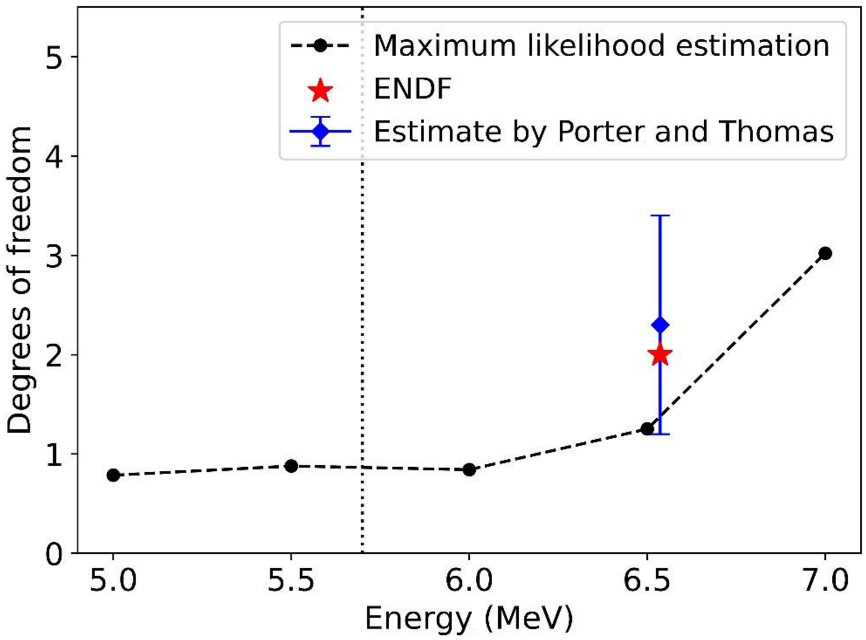
$$T_{CN\to \text{fis}} = \text{Tr}[\Gamma_n G \Gamma_{\text{fis}} G^\dagger]; \quad G = (H - NE)^{-1}$$

Application to low-energy fission of ^{236}U

G.F. Bertsch and K.H., Phys. Rev. C107, 044615 (2023).
K. Uzawa, K.H., and G.F. Bertsch, arXiv:2403.04255.

$$P_\nu(x) = \frac{\nu}{2\Gamma(\nu/2)} \left(\frac{\nu x}{2}\right)^{\nu/2-1} e^{-\nu x/2}$$



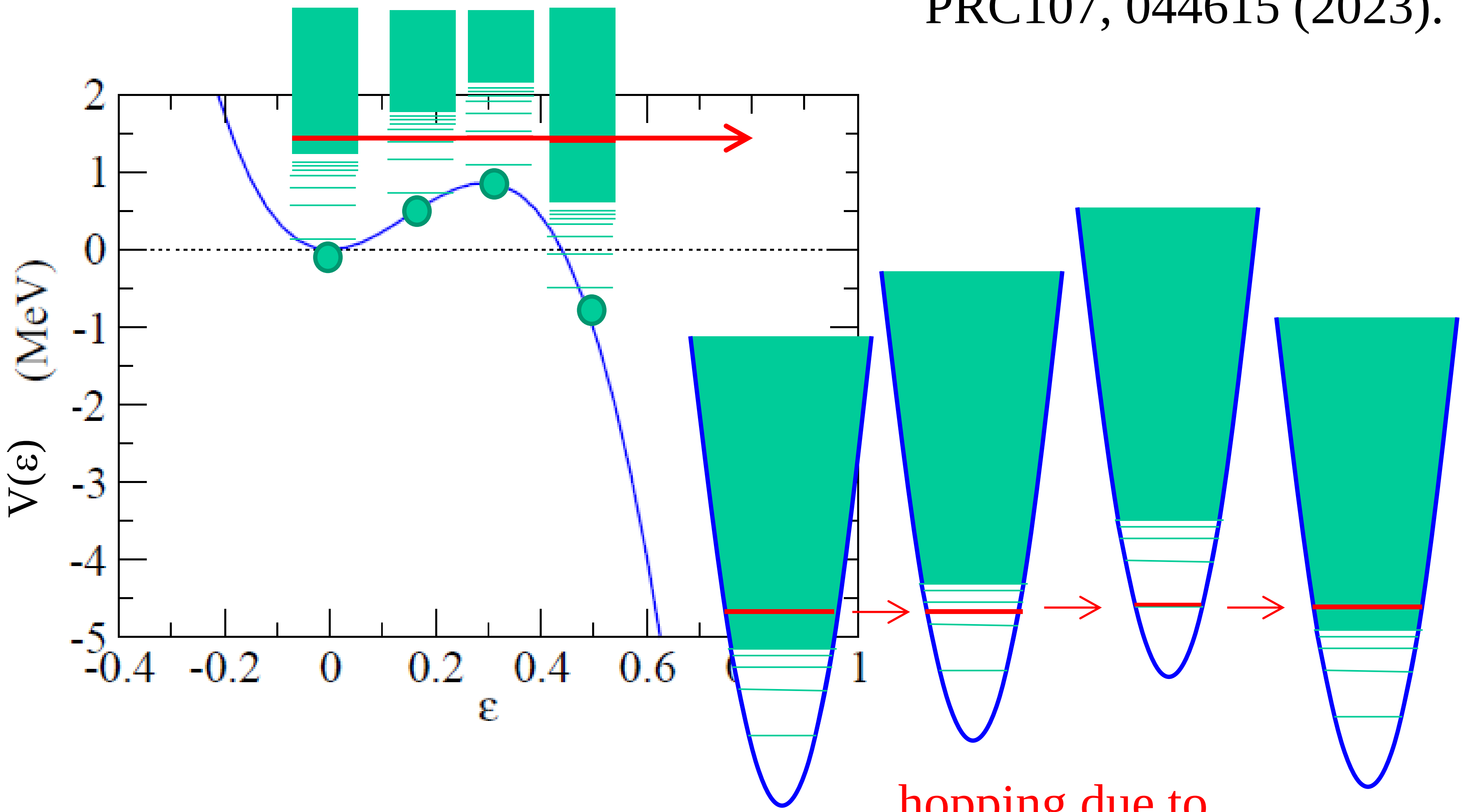


Only a small number of freedom participate in induced fission

← the transition state theory

Towards a microscopic description for induced fission

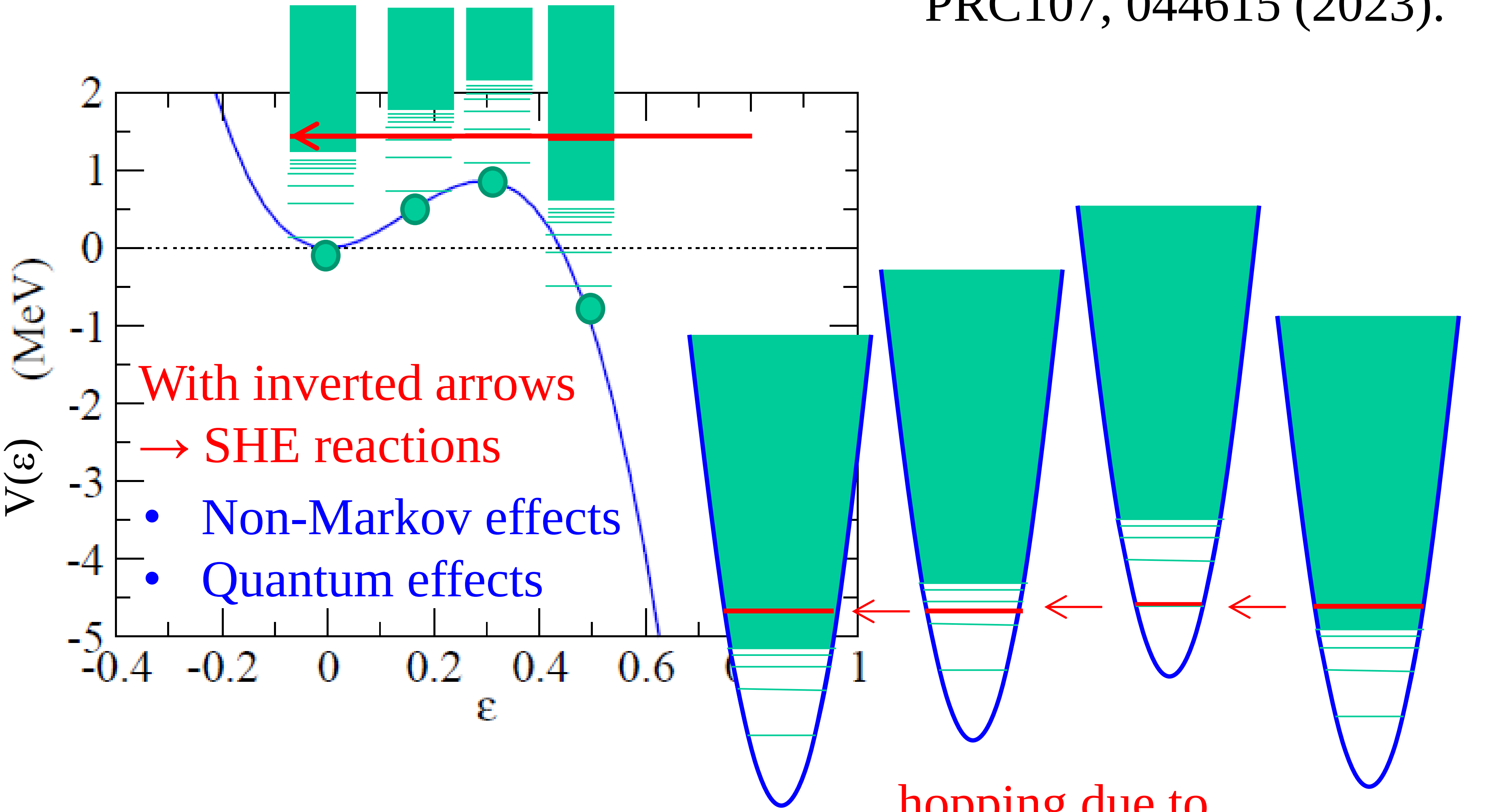
G.F. Bertsch and K.Hagino, PRC107, 044615 (2023).



hopping due to residual interactions

Towards a microscopic description for induced fission

G.F. Bertsch and K.Hagino,
PRC107, 044615 (2023).

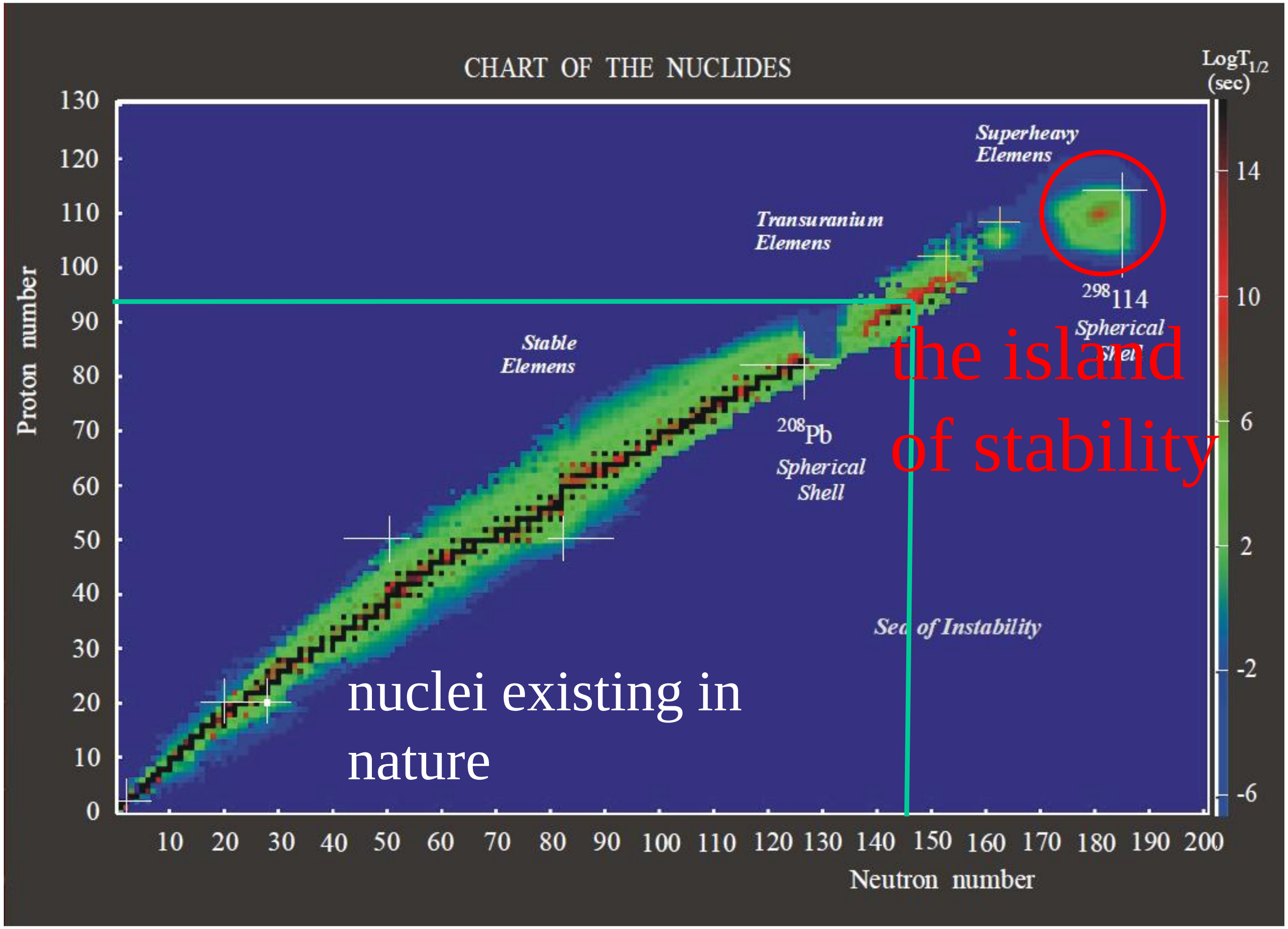


With inverted arrows
→ SHE reactions

- Non-Markov effects
- Quantum effects

hopping due to
residual interactions

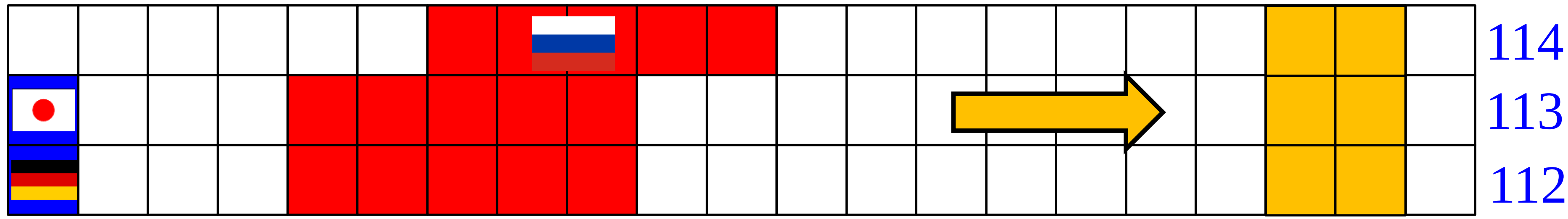
Another important issue: physics of neutron-rich nuclei



Yuri Oganessian

how to reach the island of stability?

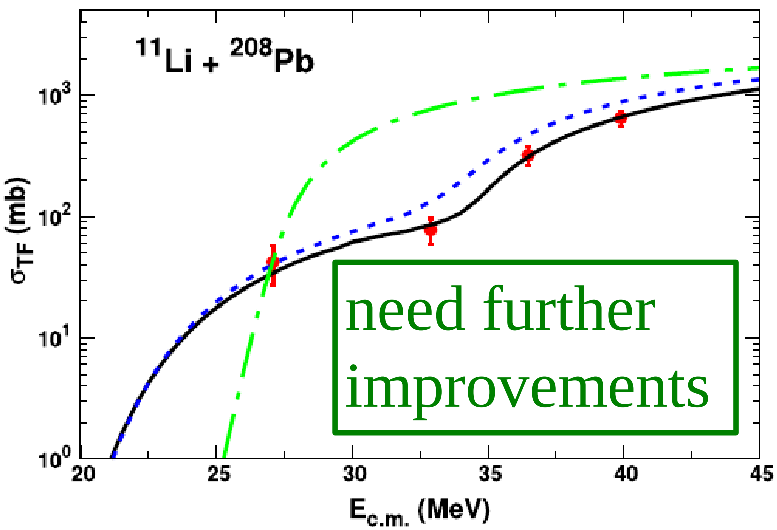
Fusion of neutron-rich nuclei



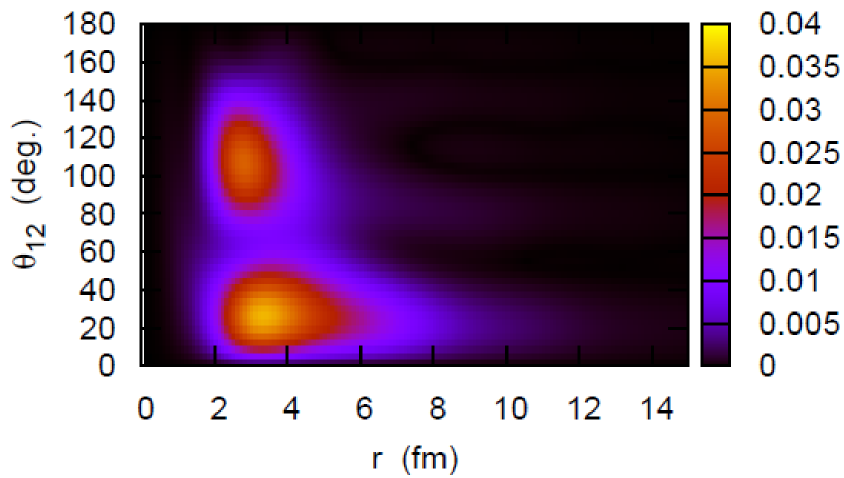
165 170 175 180

the island of stability

neutron-rich beams: indispensable→reaction dynamics?



K.-S. Choi, K. Hagino et al., Phys. Lett. B780 ('18) 455



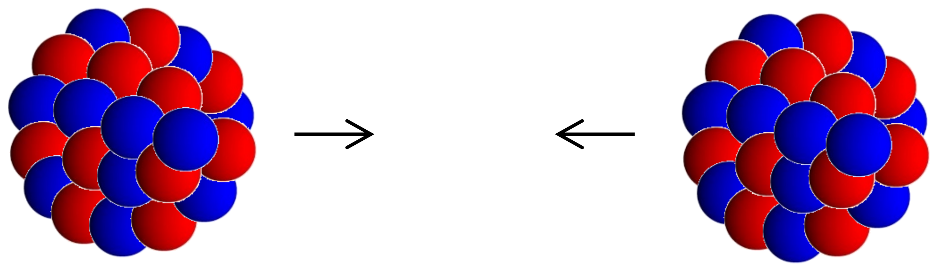
K.H. and H. Sagawa, PRC72('05)044321

good understandings of the structure of neutron-rich nuclei is also important

Complexity in Heavy-ion reactions

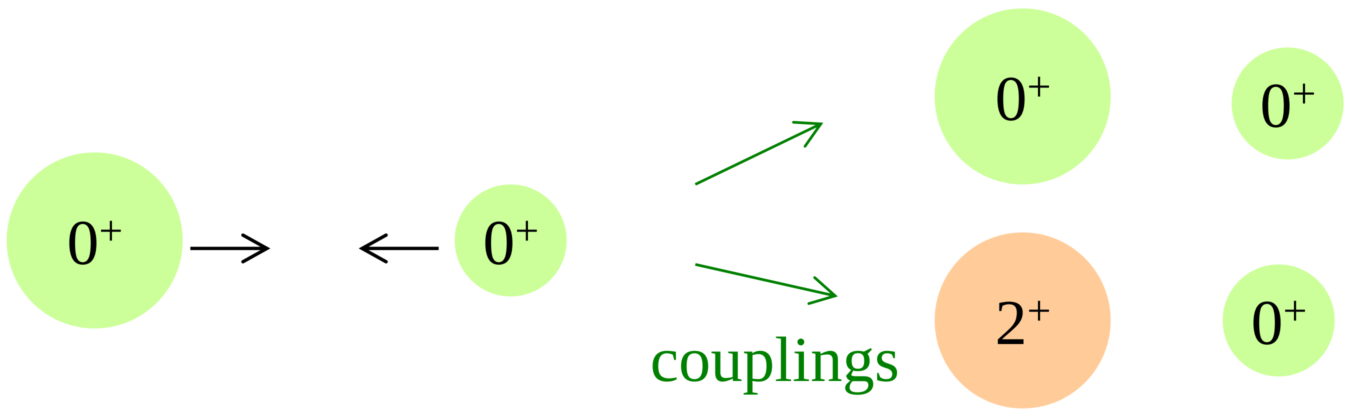
in connection to the recent exp. results of ANU

Many-body treatment



Still difficult at low energies
cf. many-particle tunneling

→ a two-body treatment with a few excitation channels
(the coupled-channels approach)



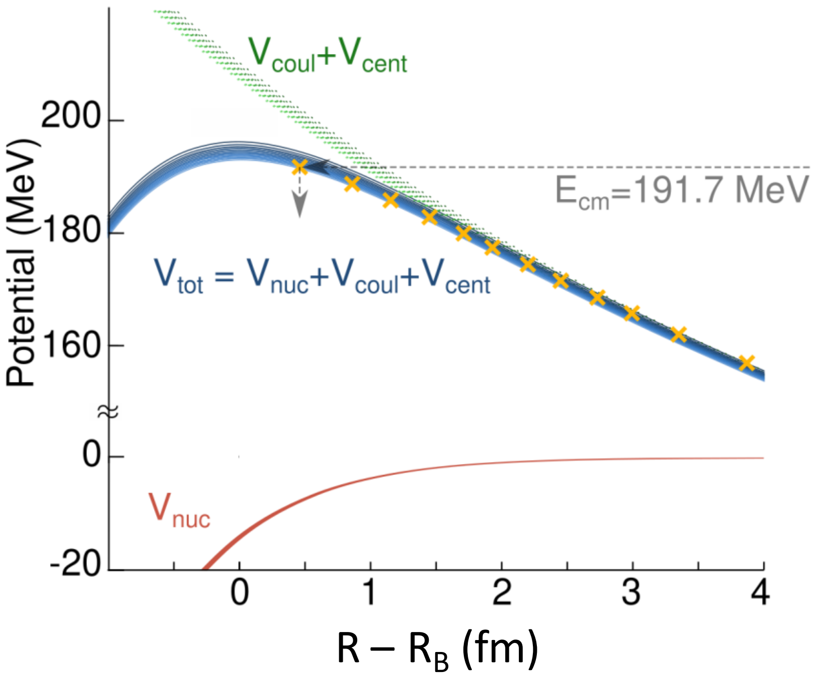
K. Hagino, K. Ogata, and A.M. Moro, PPNP125, 103951 (2022)

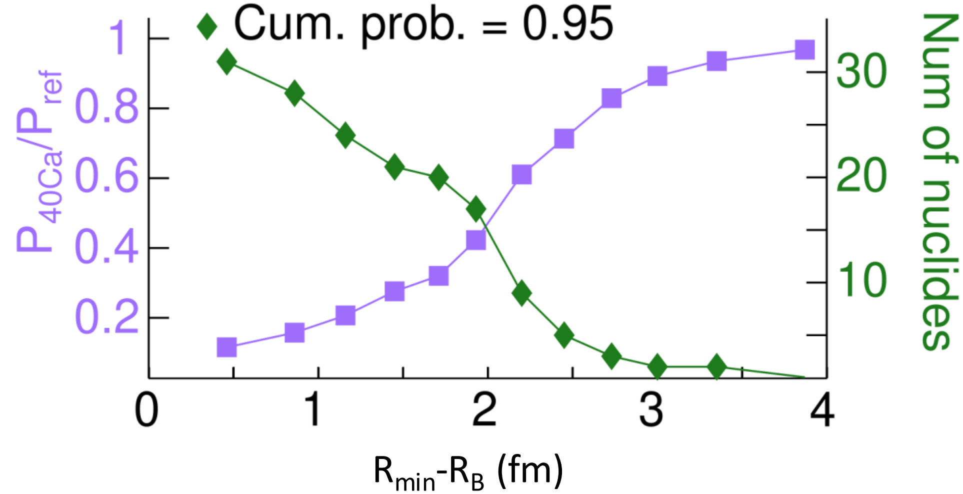
Complexity in Heavy-ion reactions

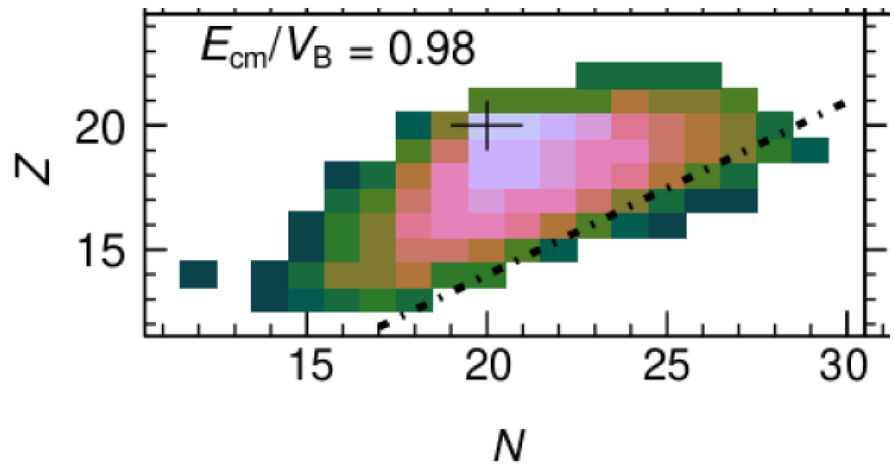
In reality, this might be too simple….

K.J. Cook (ANU) et al., Nature Communications 14, 7988 (2023)

^{40}Ca + ^{208}Pb





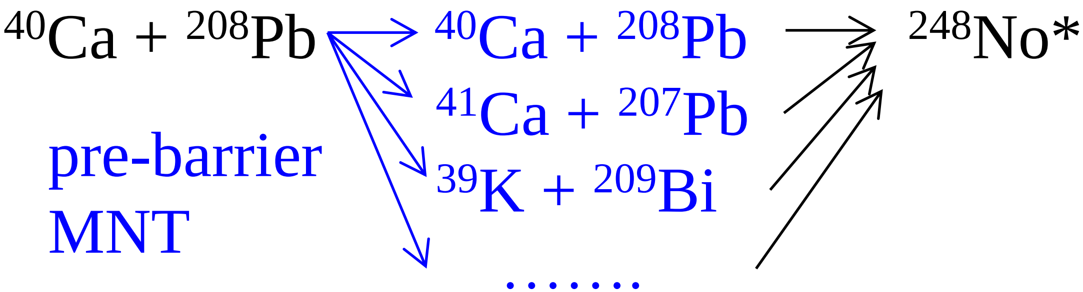


backward flux at θ_{lab}=115 deg. with different energies

large probability of pre-barrier MNT

Complexity in Heavy-ion reactions

an implication to SHE reactions

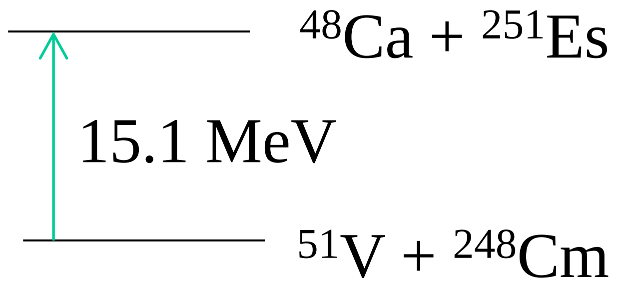


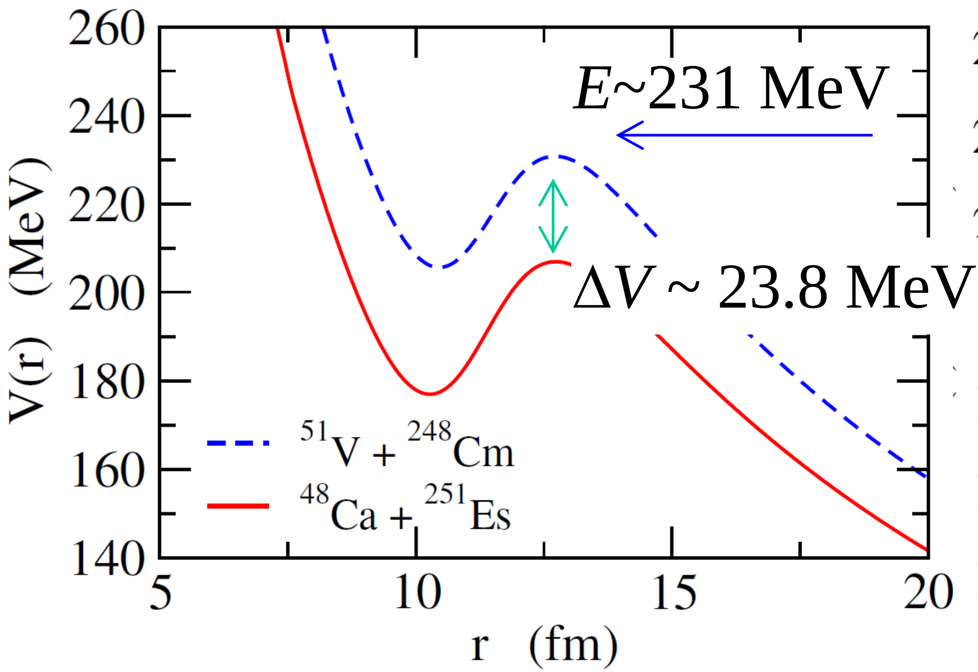
$$\sigma_{\rm CN} \sim \underbrace{\sum_k w_k\, \sigma_{\rm cap}(Z_k, N_k, E_k^*)}_{\text{TDHF+Projection?}}\, \underbrace{P_{\rm CN}(Z_k, N_k, E_k^*)}_{\text{Langevin?}}$$

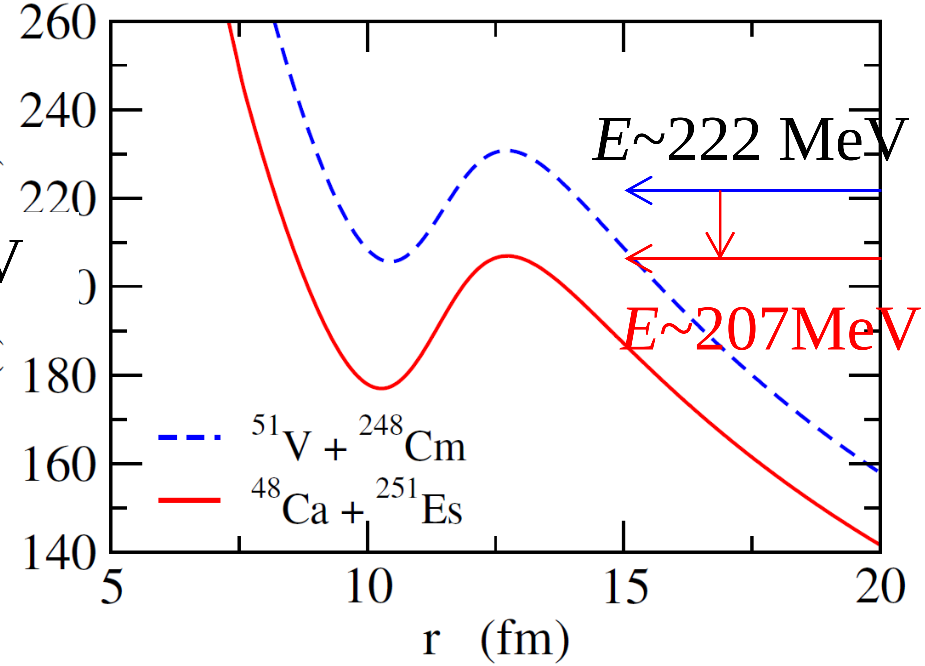
cf. K. Sekizawa and K.H., PRC99 (2019) 051602(R)

Example: $^{51}V + ^{248}Cm$ reaction

$$^{51}V + ^{248}Cm \rightarrow ^{48}Ca + ^{251}Es - 15.1\ \mathrm{MeV}$$







Very rough estimate: $\Delta E \sim 9$ MeV $\leftarrow \sim S_n$

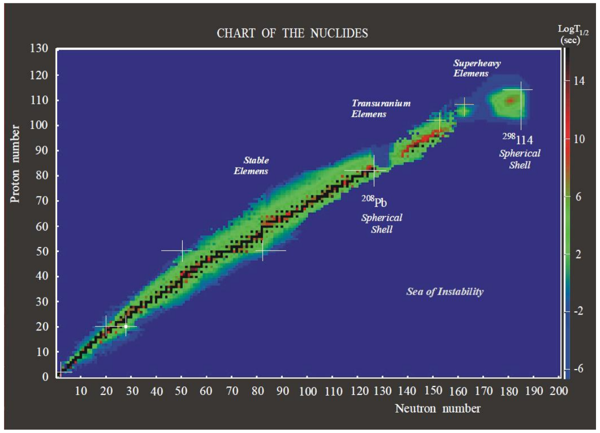
$\rightarrow$ this mechanism may be important if $P_{tr} > \Gamma_n / \Gamma_f$

Exp. plan: Satoshi Sakaguchi @ Kyushu University

Summary

open quantum systems (OQS)

- SHE
- the island of stability



✓how to thermaize? mechanisms?
✓is thermal equilibrium OK?
✓Is Markovian approximation OK?
✓quantum effects?

→ a microscopic description for fusion/fission

✓Deformation?
✓Fusion of unstable nuclei