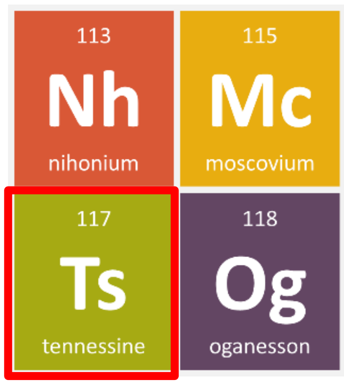
Open issues in physics of SHE and fission : nuclear reaction perspectives



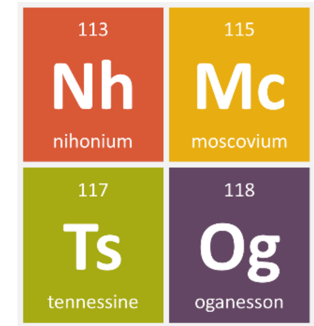
Kouichi Hagino
Kyoto University

1. Introduction: fusion for superheavy elements
2. Theoretical issues in the Langevin approach
3. Towards a microscopic description to induced fission
4. Summary

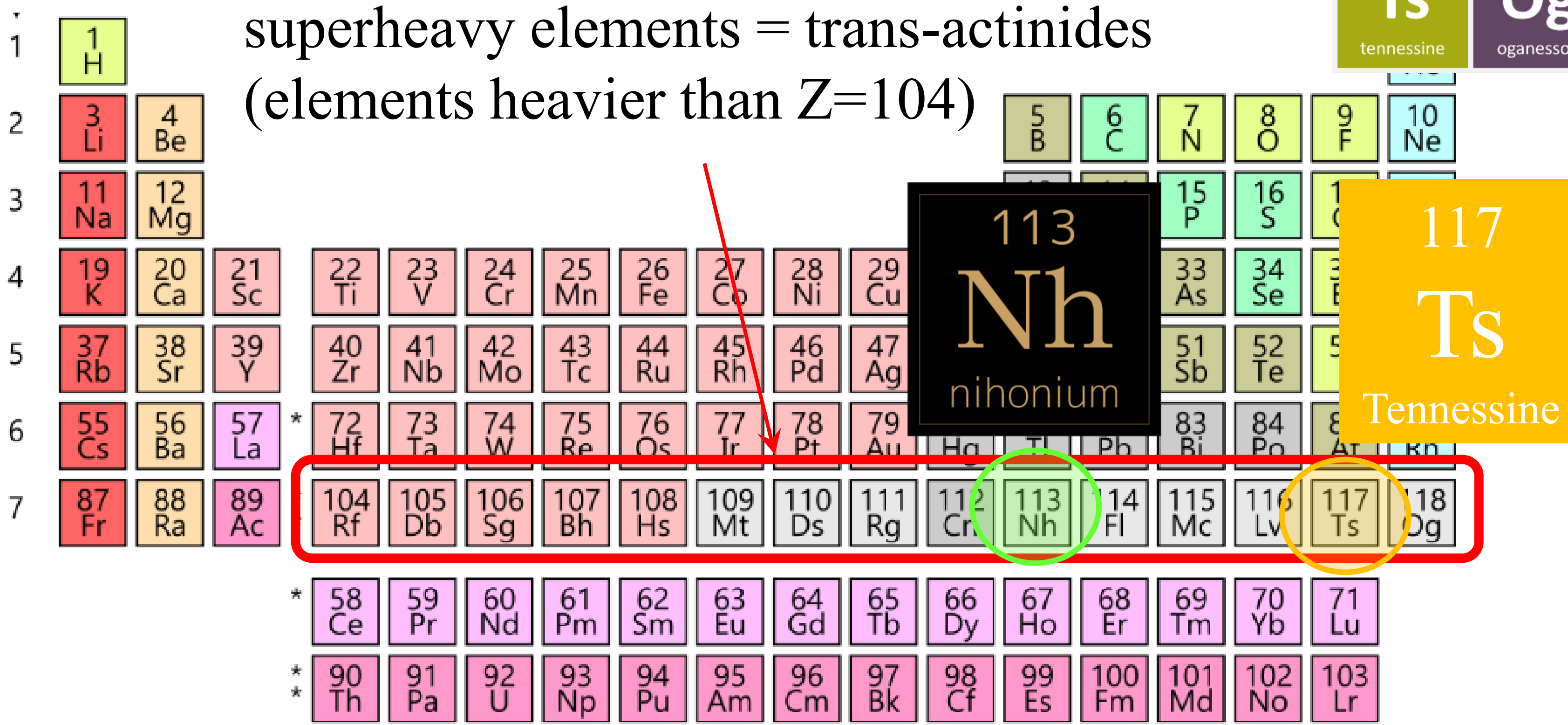
A seminar at University of Tennessee, September 30, 2025

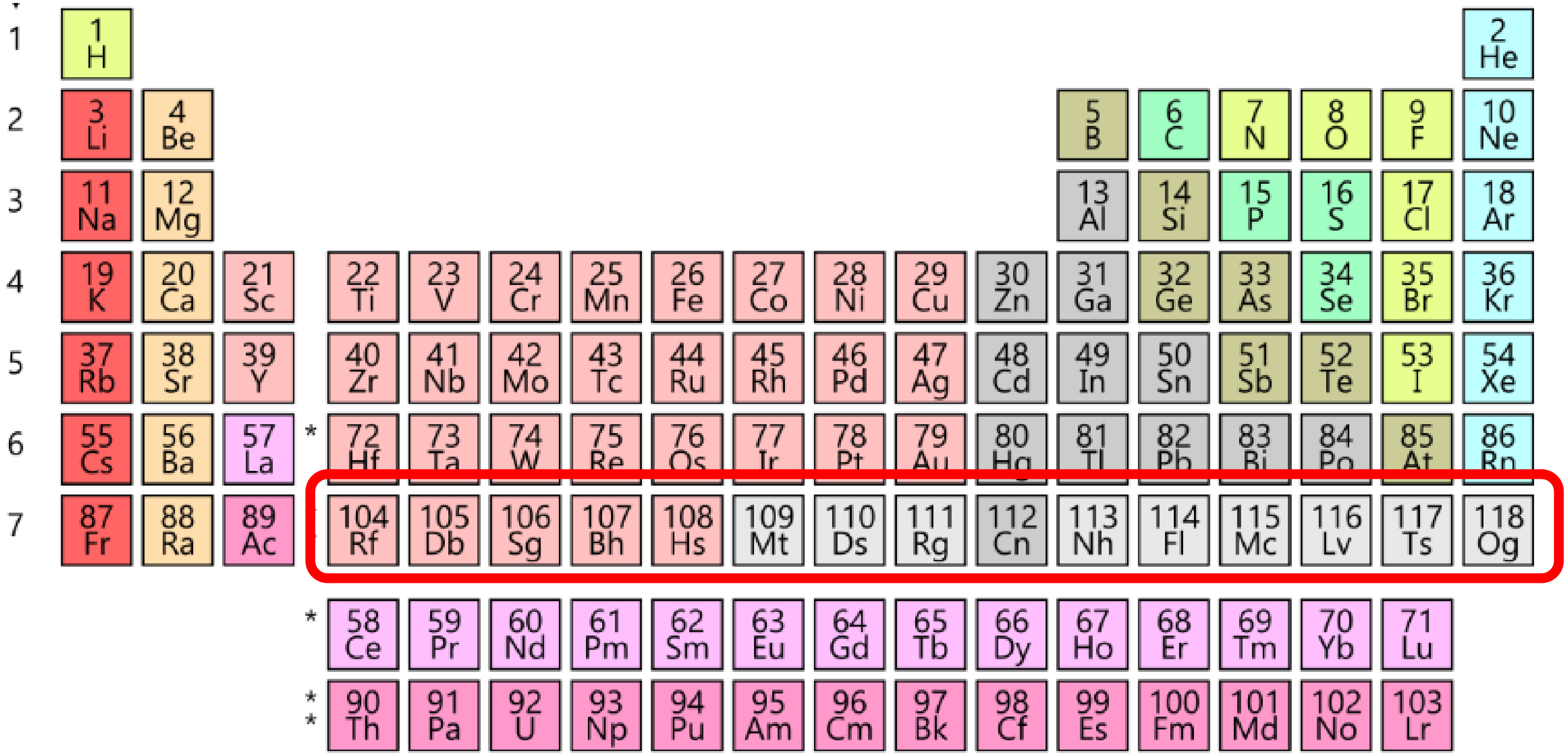
who is SHE?

who is SHE?



superheavy elements = trans-actinides
(elements heavier than Z=104)



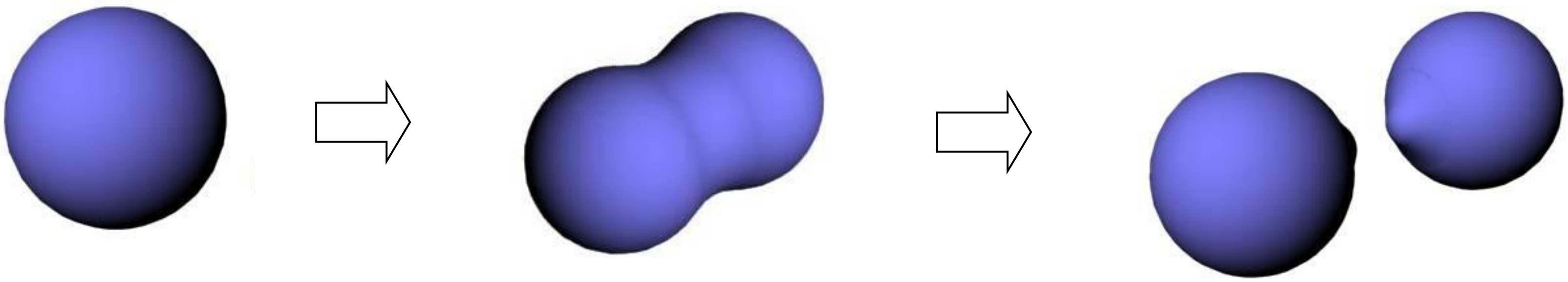


Interests in physics and chemistry of superheavy elements

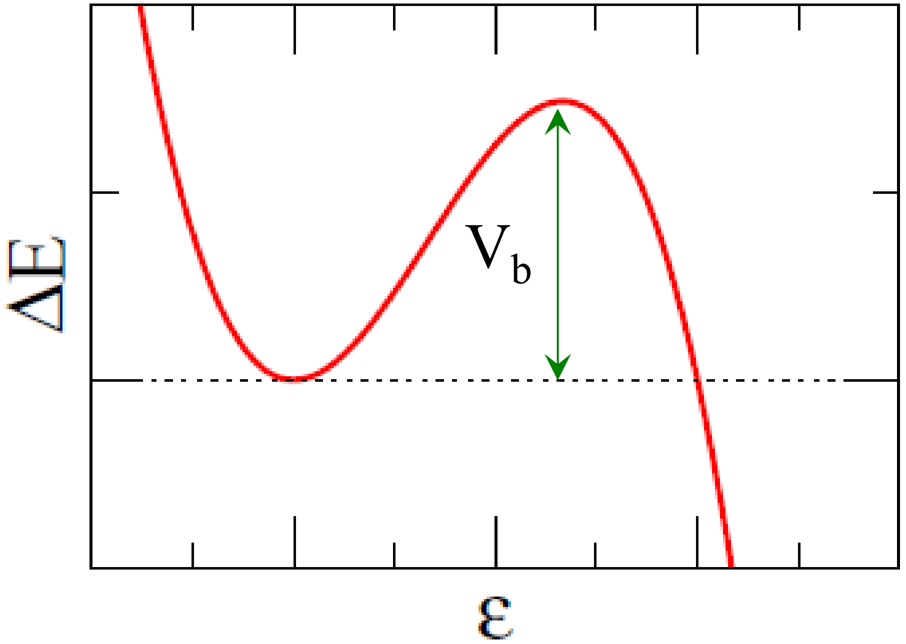
- what is the heaviest element? → atomic property
- what is the double magic nucleus next to ^{208}Pb? → nuclear property
- should the periodic table be changed or not? → chemical property
- how do superheavy elements influence the r-process nucleosynthesis?
  → astrophysics

what determines the limit of existence of elements?

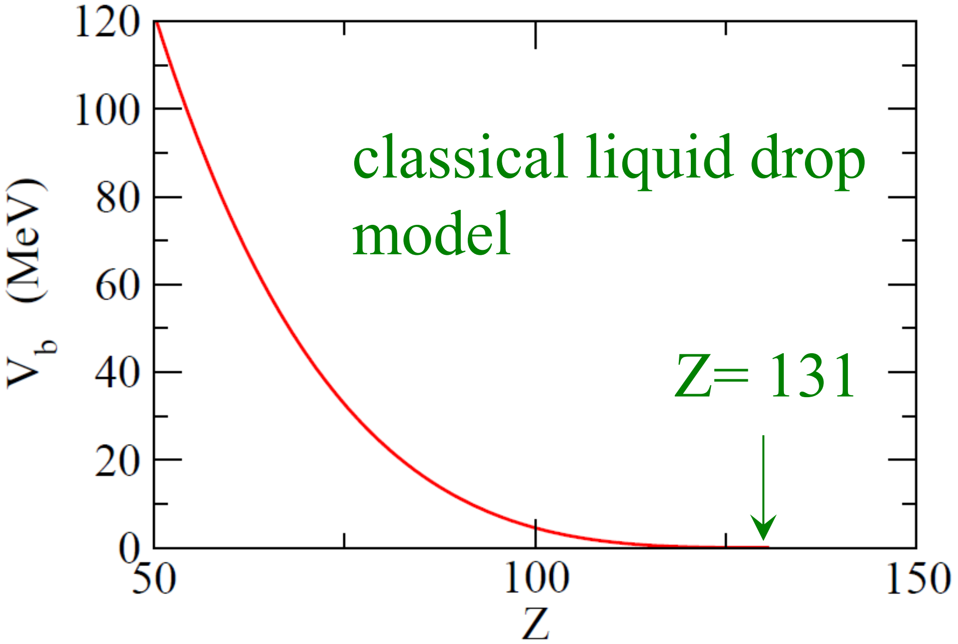
heavy nuclei $\rightarrow$ unstable against fission



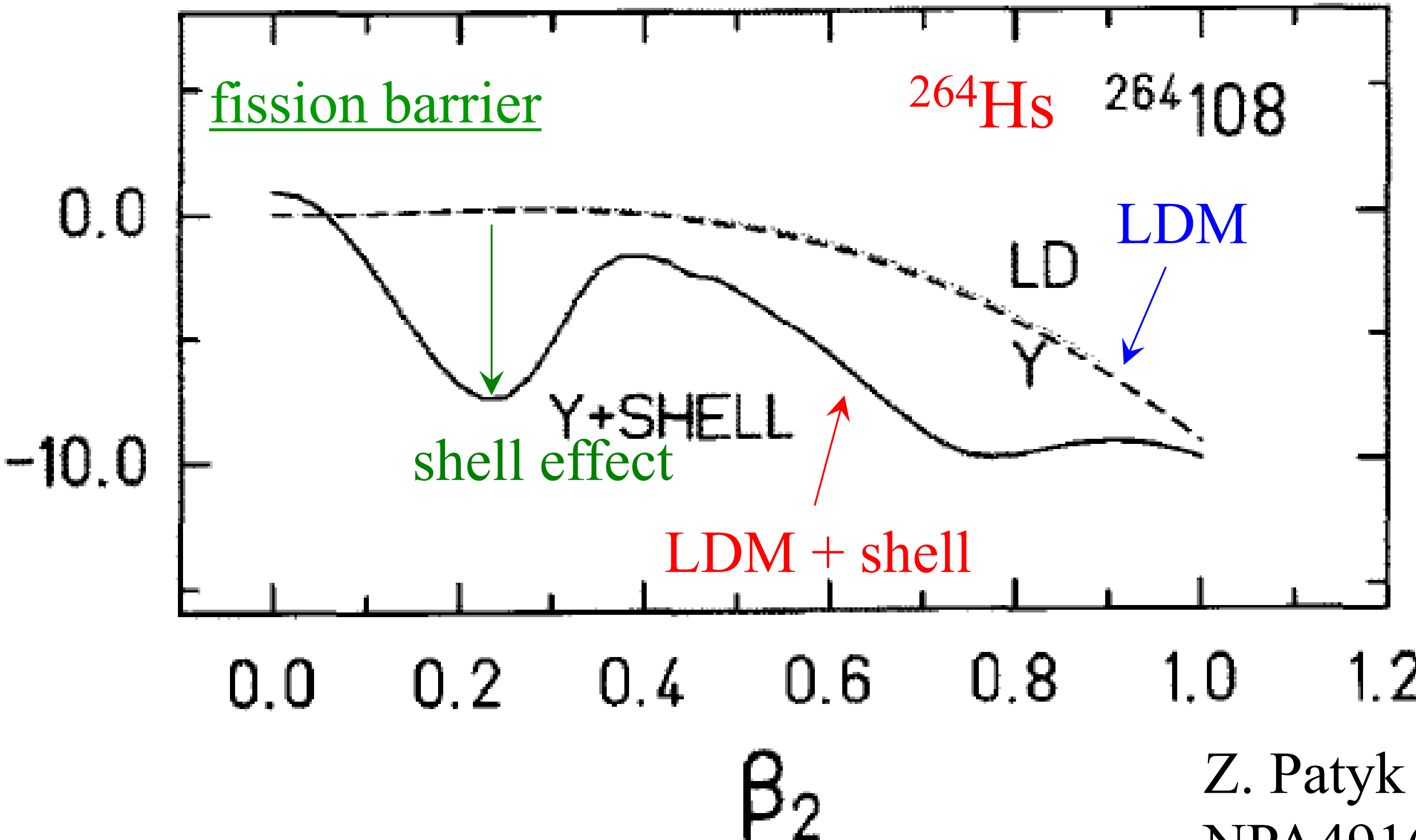
fission barrier



barrier height



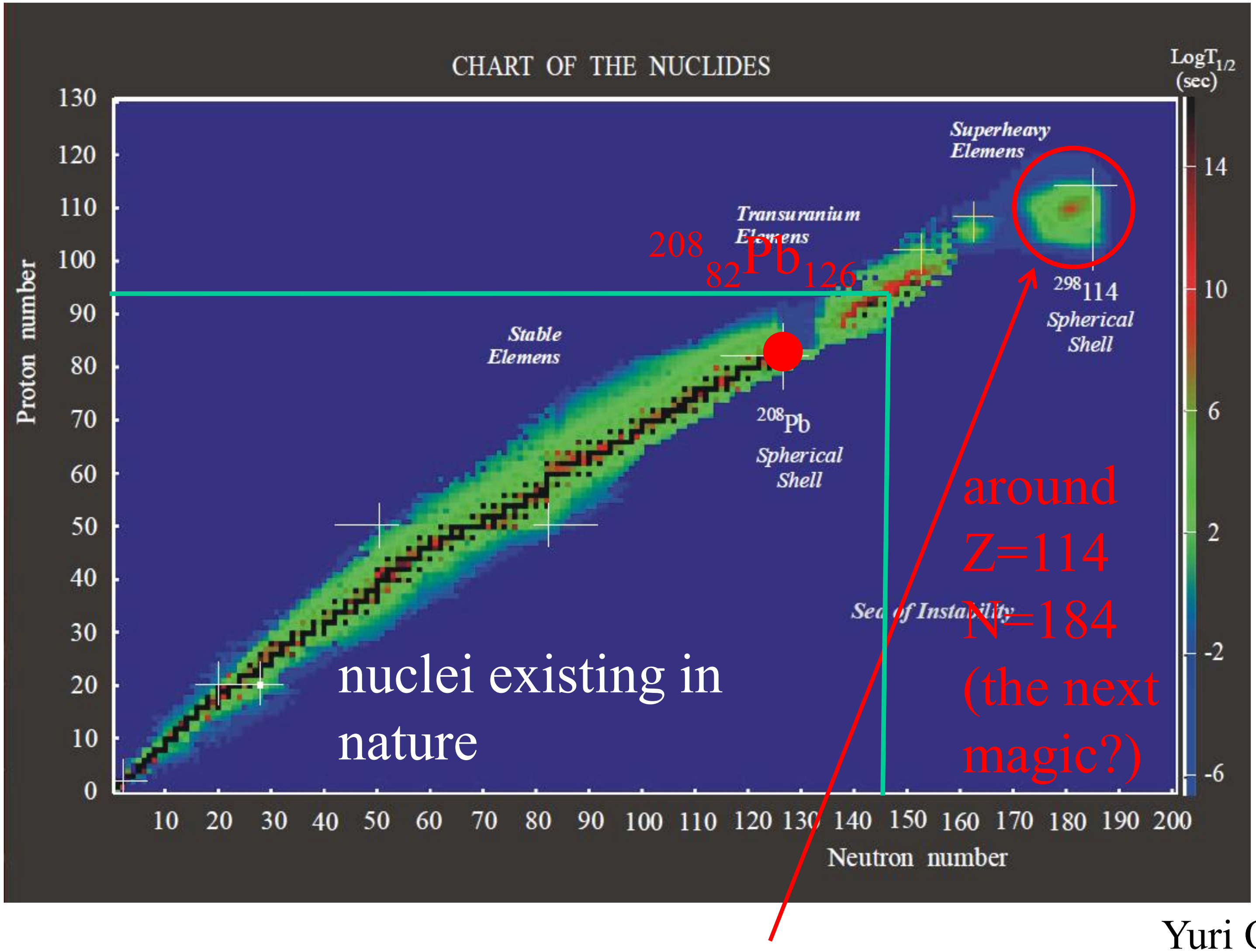
what determines the limit of existence of elements?



Z. Patyk et al.,
NPA491(‘89) 267

QM shell effect (magic numbers) raises B_{fiss} and stabilizes a nucleus

Superheavy elements (the island of stability)



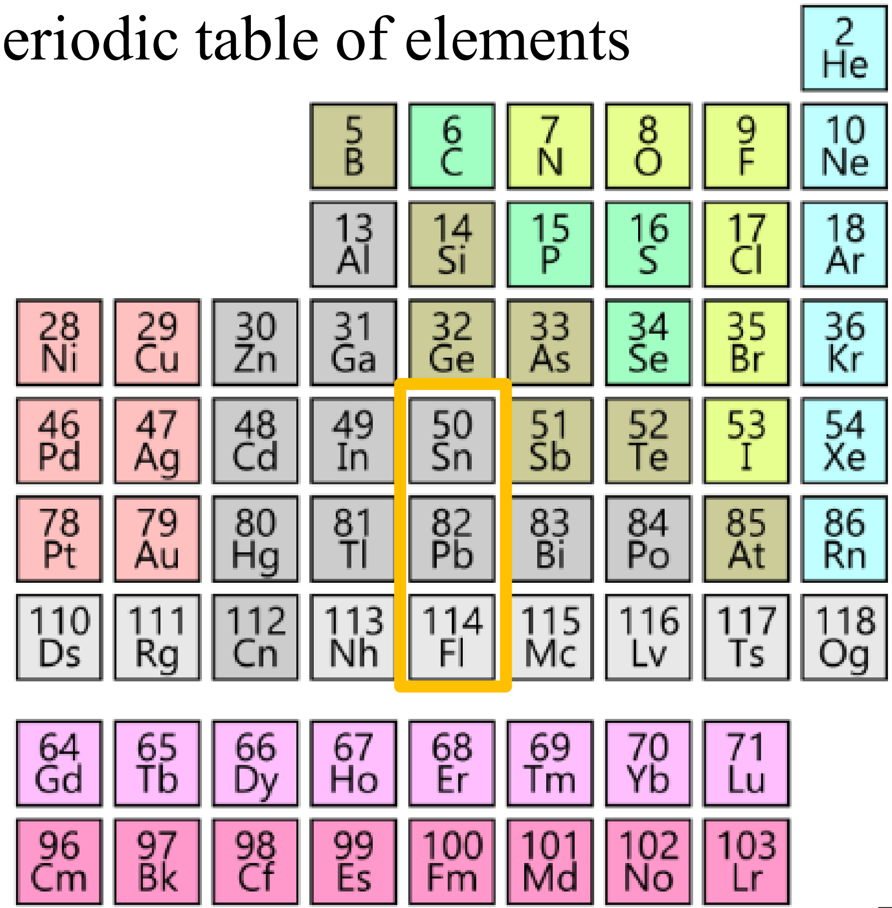
Yuri Oganessian

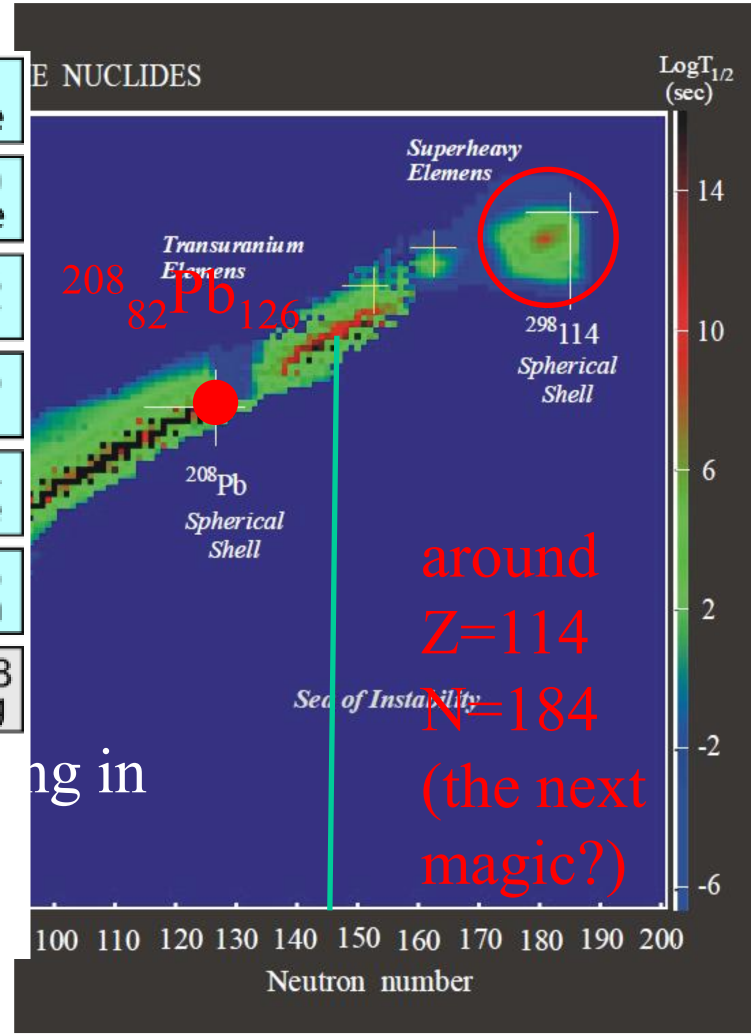
long-lived with $10^{3\text{-}5}$ years

W.D. Myers and W.J. Swiatecki (1966), A. Sobiczewski et al. (1966)

Superheavy elements (the island of stability)

periodic table of elements



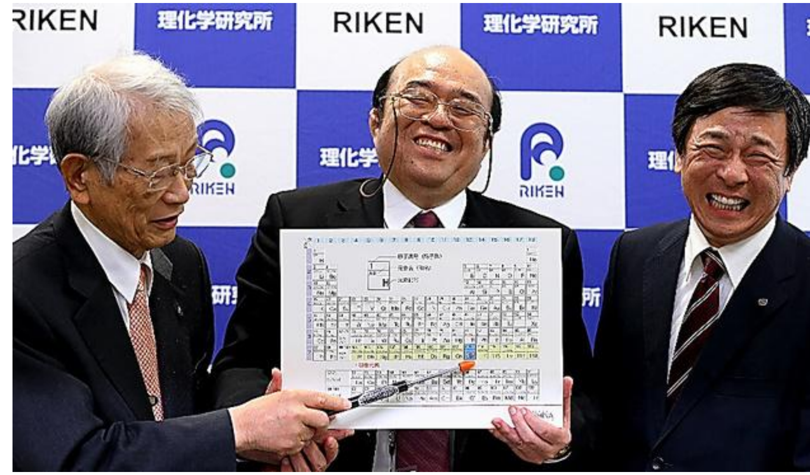


Y. Maeno, K. Hagino, and T. Ishiguro, Found. of Chem. 23, 201 (2021).

Yuri Oganessian

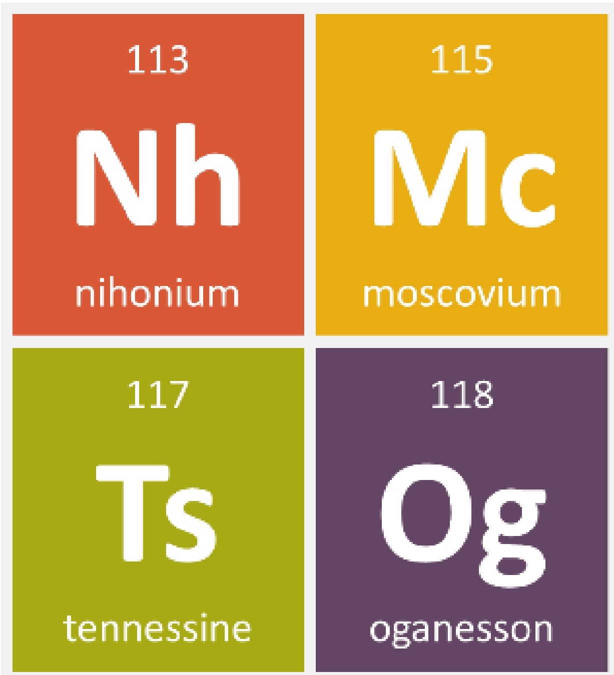
the nuclear magic numbers are in the same column!

Fusion reactions for SHE

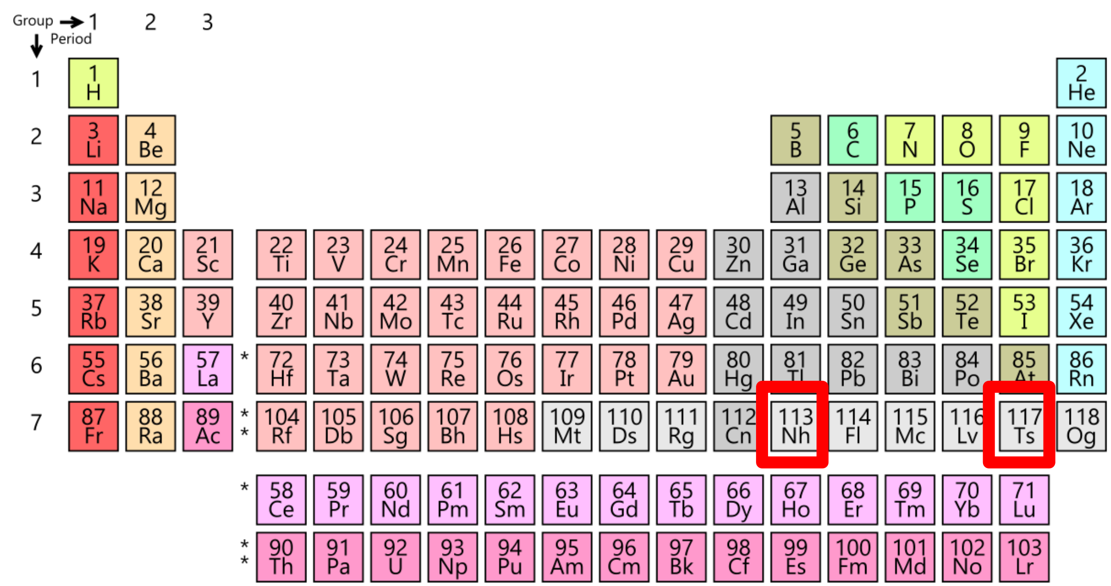


the element 113: Nh

the element 117: Ts

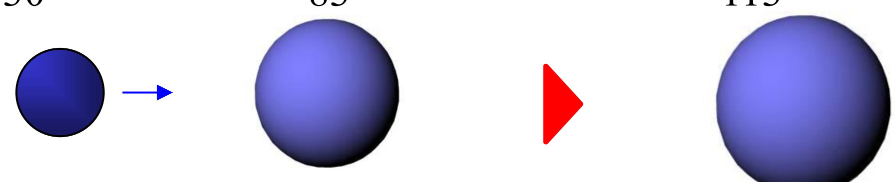


November, 2016



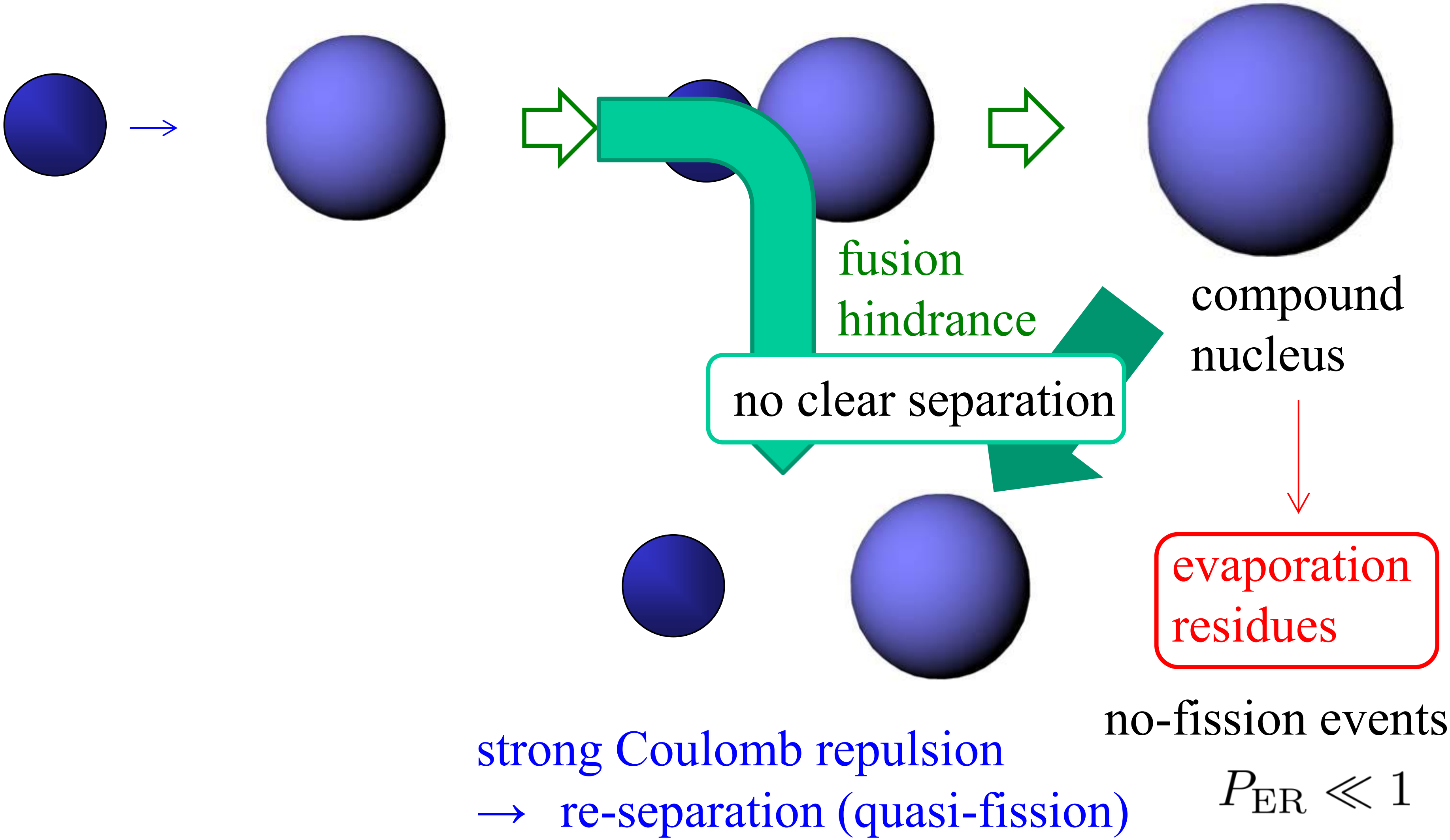
Wikipedia

$^{70}_{30}\mathrm{Zn}$ $^{209}_{83}\mathrm{Bi}$ $^{279}_{113}\mathrm{Nh}^{*}$

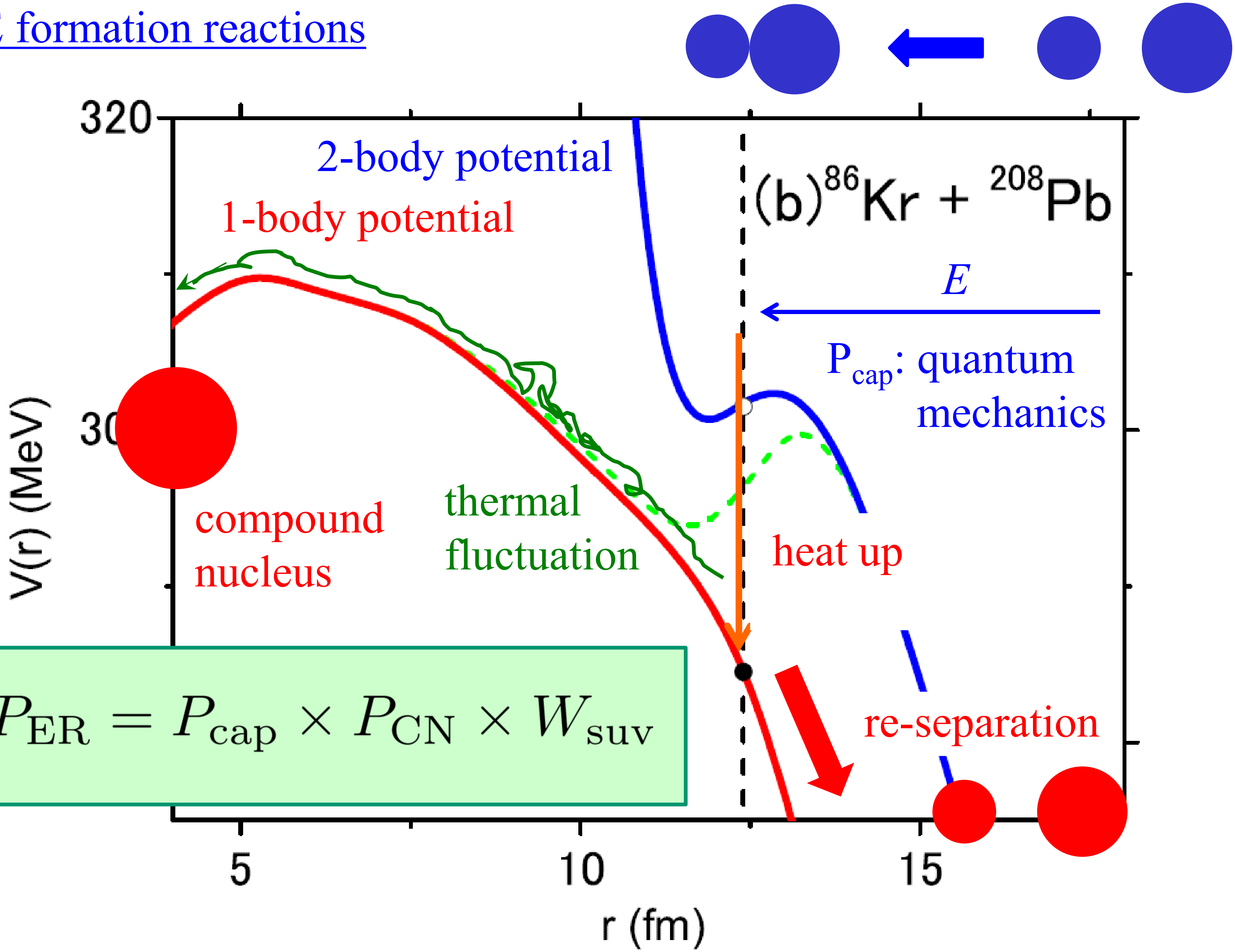


Heavy-ion fusion reaction

Fusion for SHE: fusion hindrance

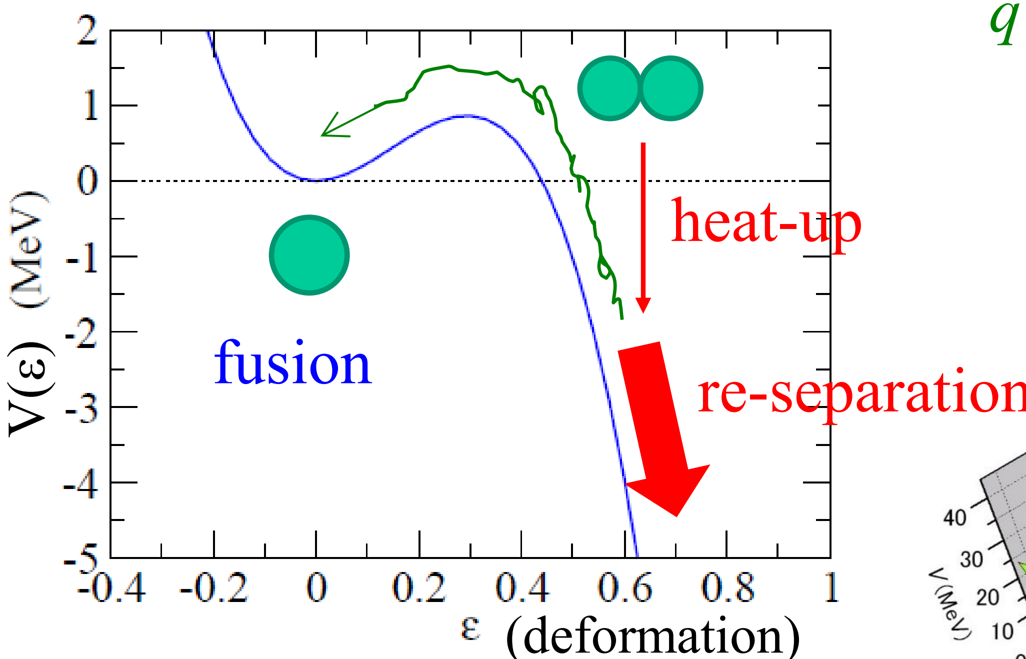


SHE formation reactions



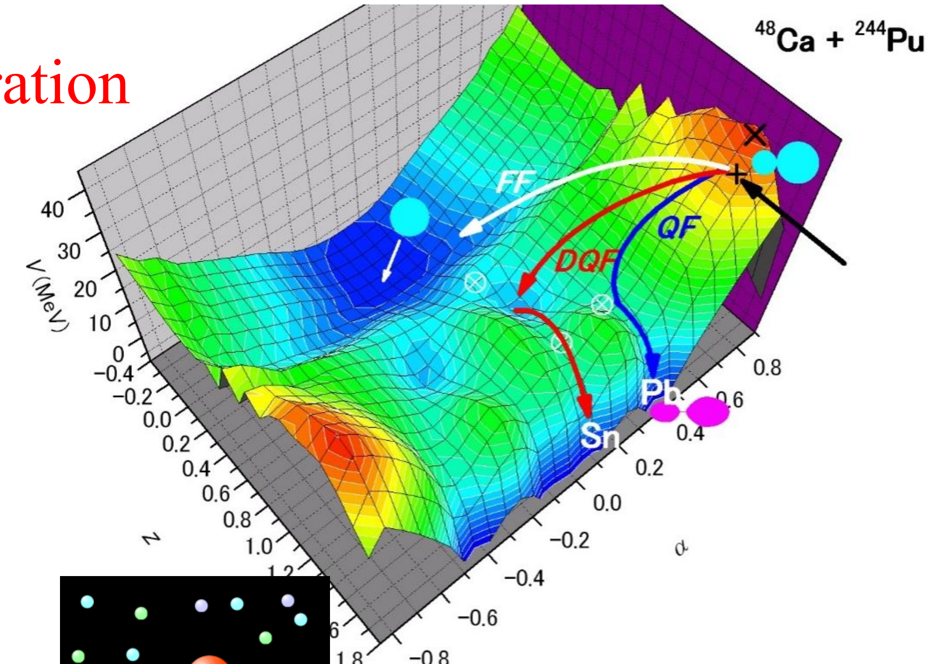
$$P_{\rm ER} = P_{\rm cap} \times P_{\rm CN} \times W_{\rm suv}$$

Langevin approach



multi-dimensional extention

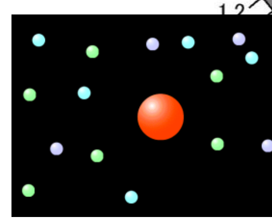
q: ▪internuclear separation,
▪deformation,
▪asymmetry of the two fragments



thermal fluctuation

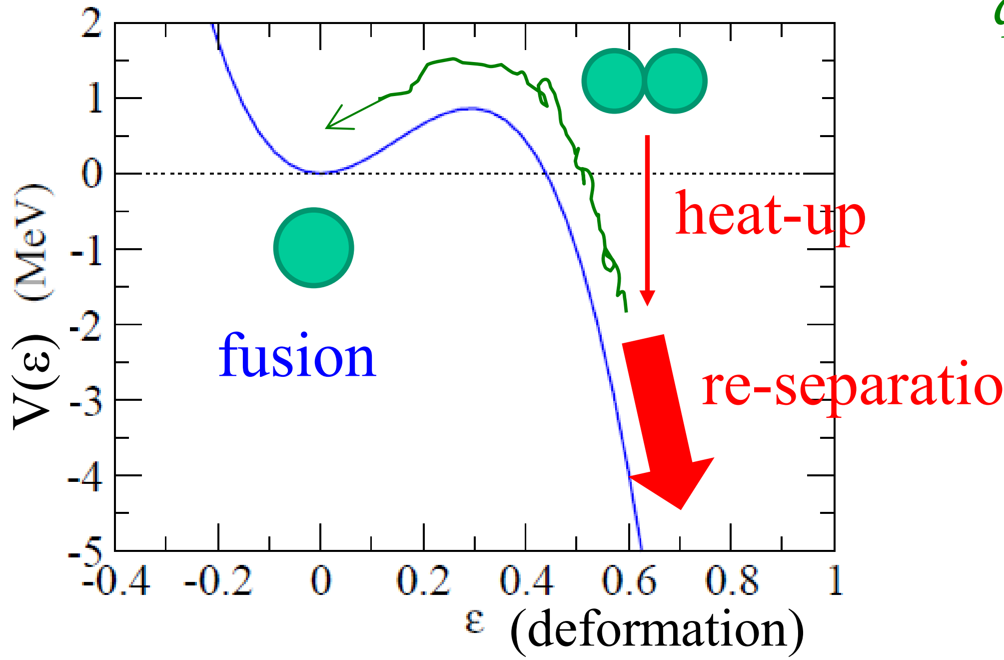
⟶ Langevin method
(Brownian method)

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



γ: friction coefficient
$R(t)$: random force

Langevin approach



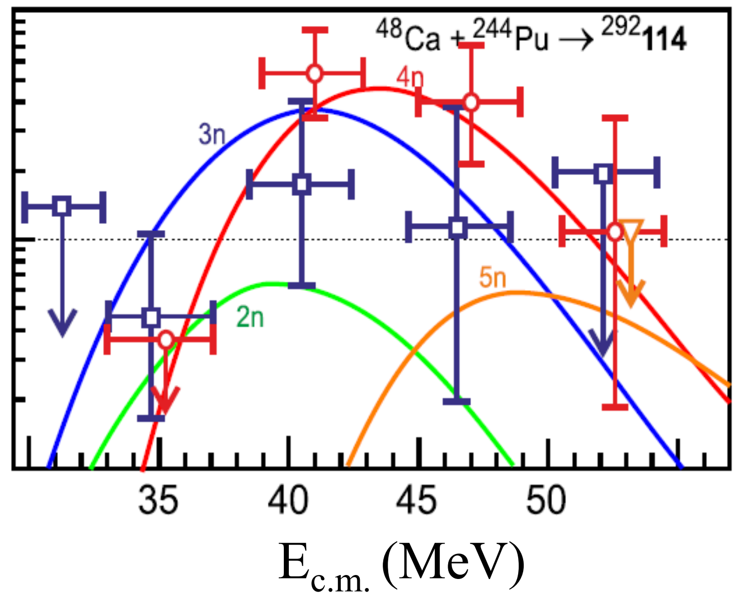
thermal fluctuation

$\longrightarrow$ Langevin method (Brownian method)

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

multi-dimensional extention

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

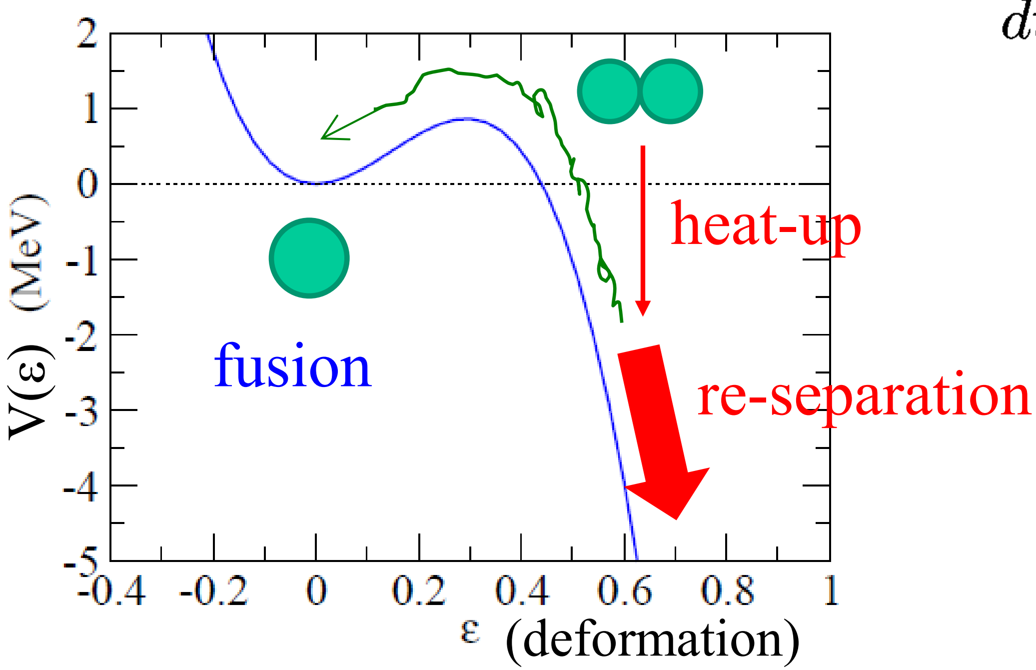


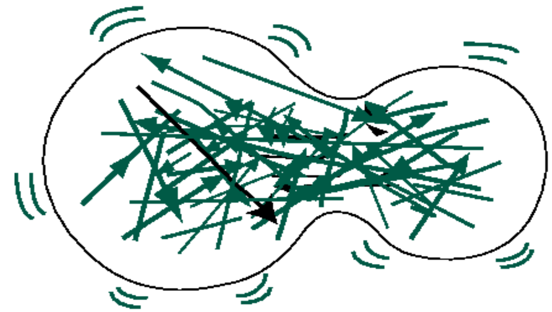
V.I. Zagrebaev and W. Greiner (2015)

successful,
at least phenomenologically

Langevin approach

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





nuclear intrinsic d.o.f.
: internal environment

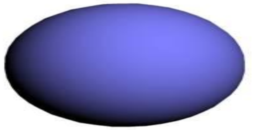
→ open quantum systems

Theoretical issues

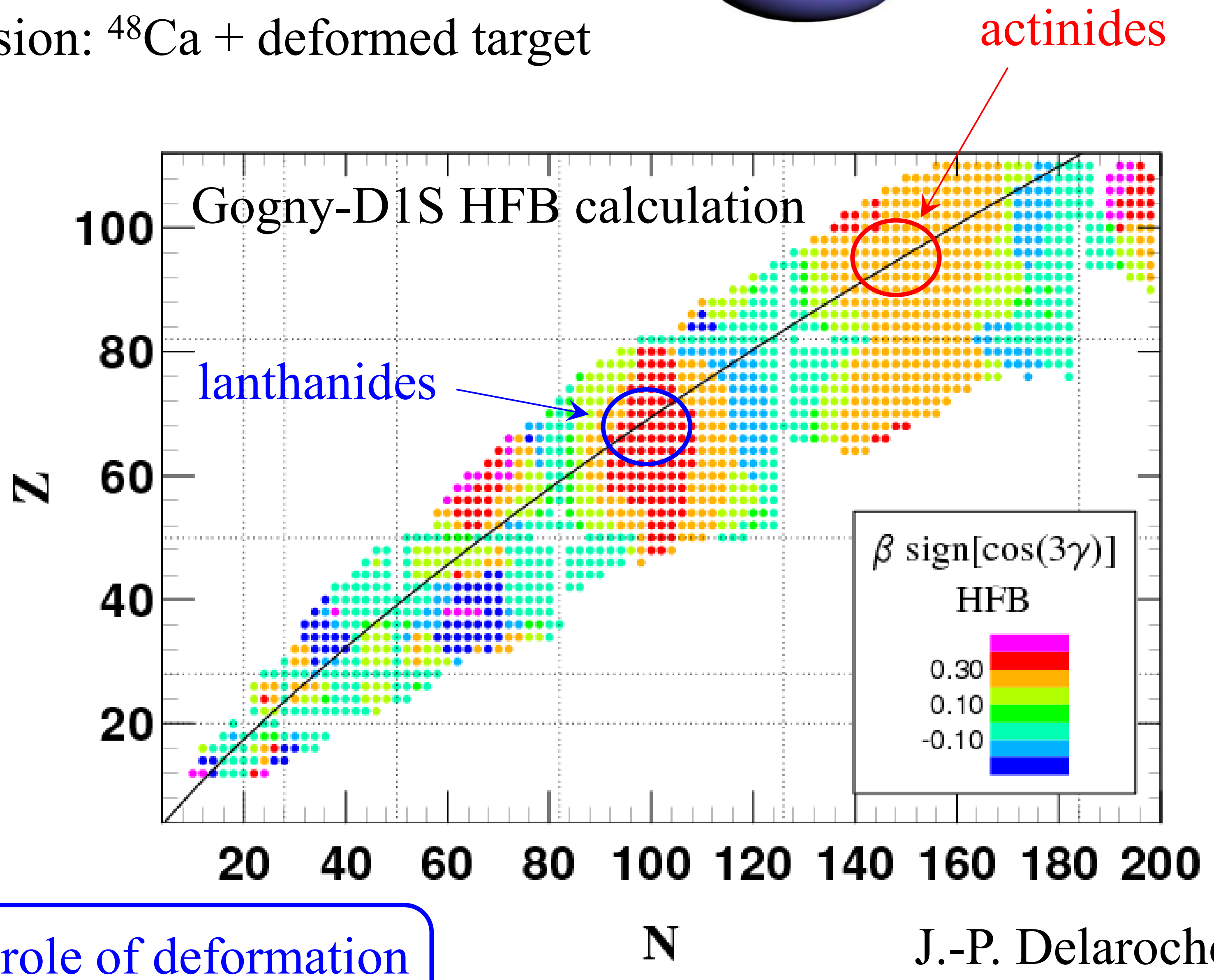
✓how to thermaize? mechanisms?
✓is thermal equilibrium OK?
✓Is Markovian approximation OK?
✓quantum effects?

➡ ▪a quantal theory for friction
▪a microscopic approach

Another issue: Nuclear Deformation



hot fusion: ^{48}Ca + deformed target

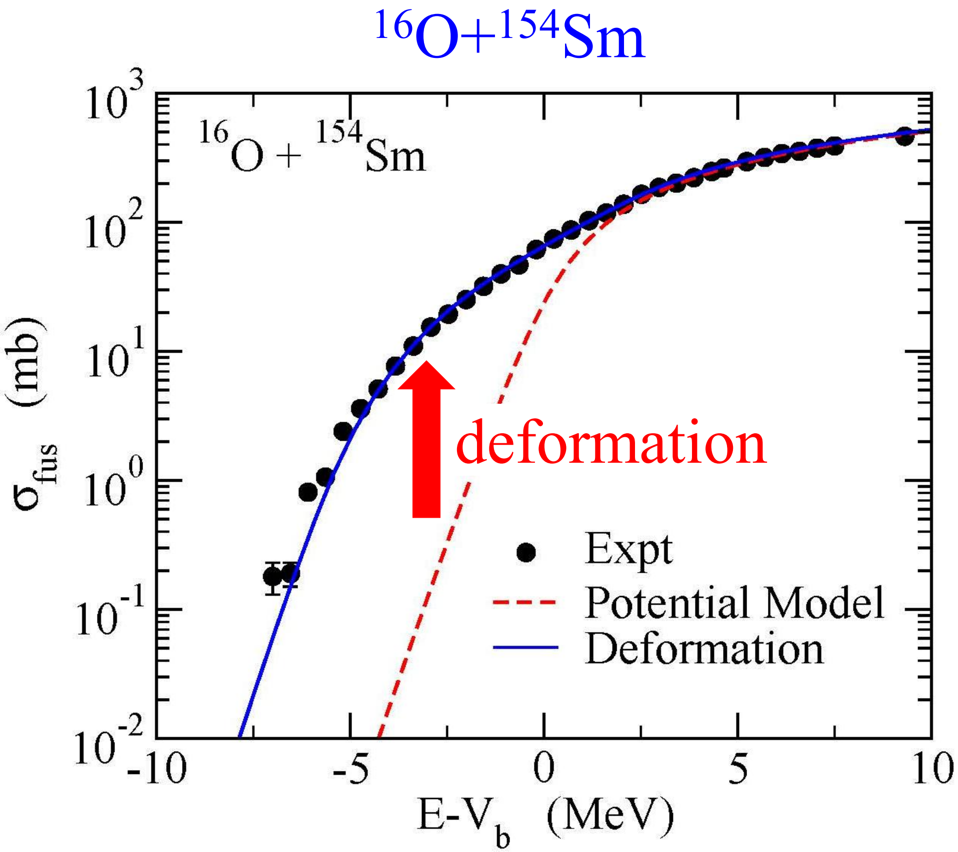


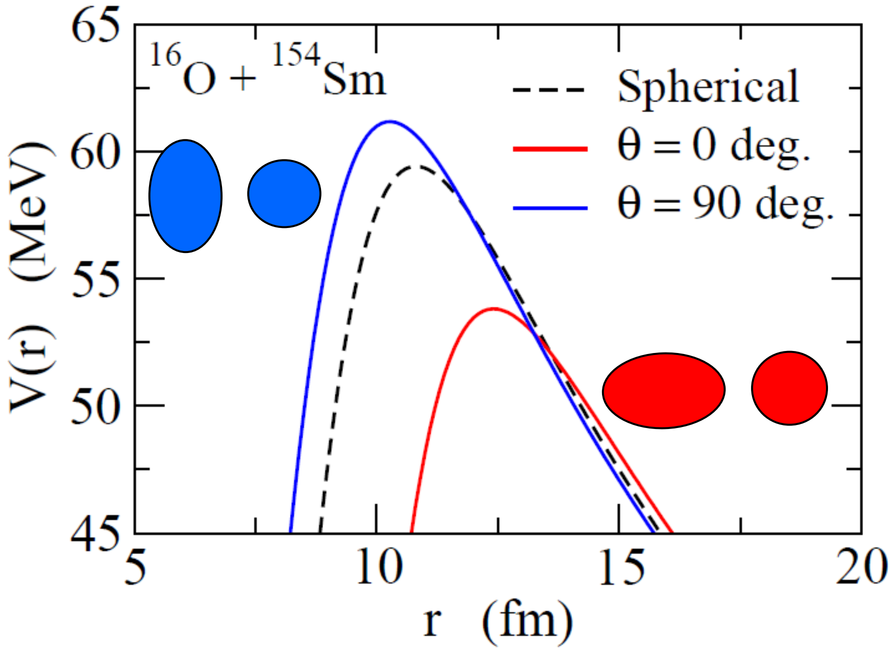
the role of deformation
in heavy-ion reactions?

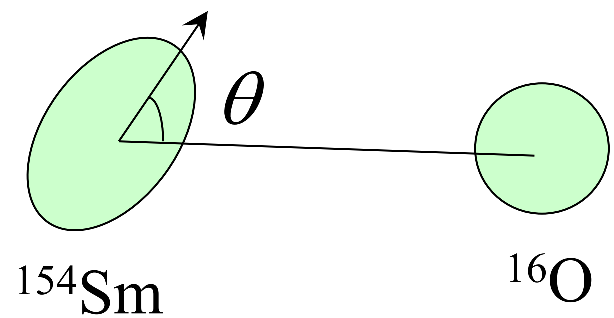
J.-P. Delaroche et al.,
PRC81 ('10) 014303

Nuclear deformation and barrier distribution

Nuclear deformation → a large sub-barrier enhancement of fusion cross sections

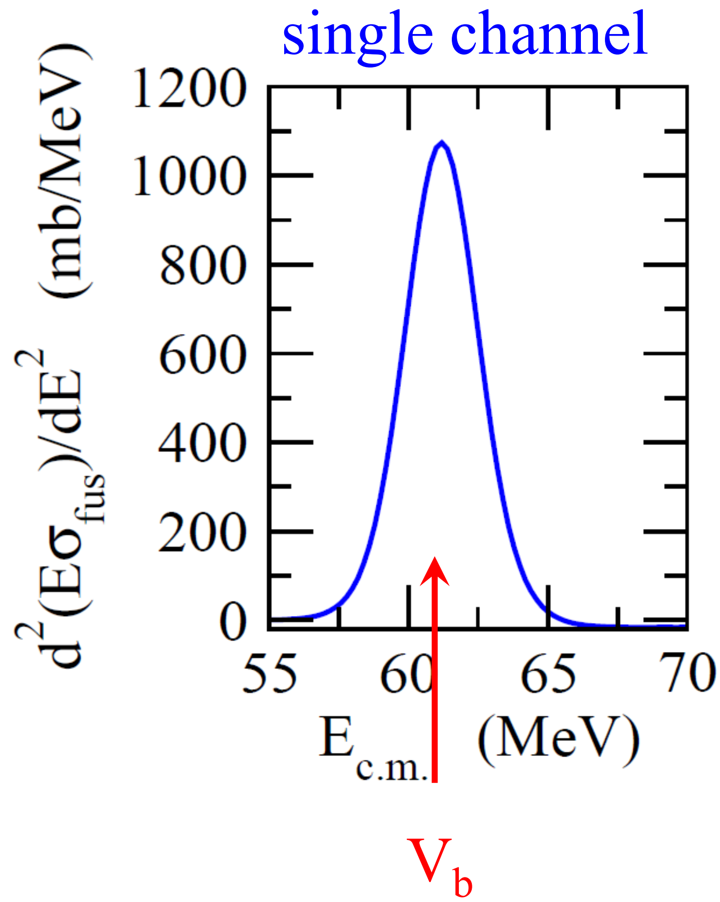






Fusion barrier distribution [Rowley, Satchler, Stelson, PLB254('91)]

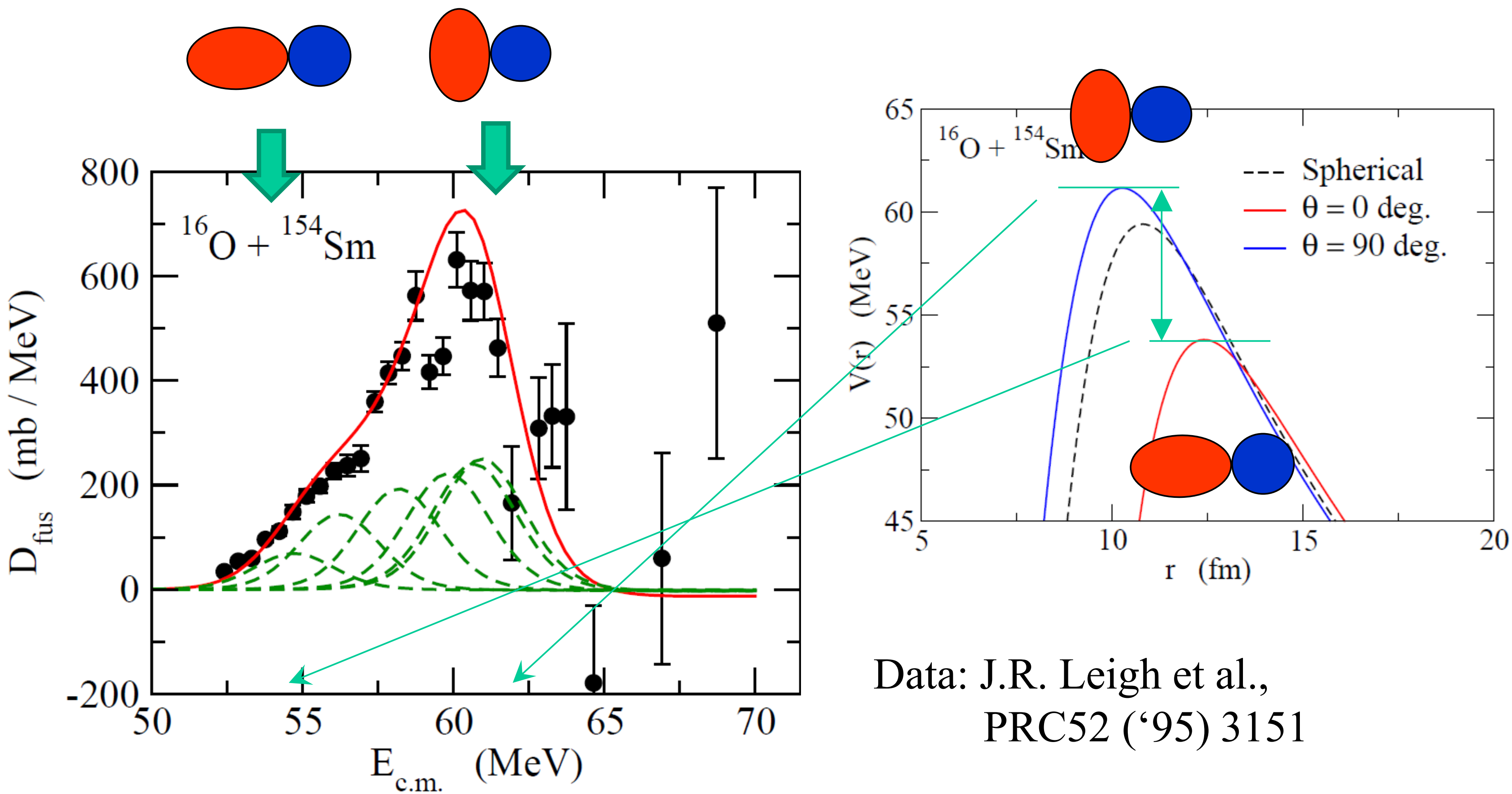
$$\boxed{D_{\mathrm{fus}}(E) = \frac{d^2(E\sigma_{\mathrm{fus}})}{dE^2}} \propto \frac{dP_{l=0}}{dE}$$



K.H., N. Takigawa, PTP128 ('12) 1061

✓ Fusion barrier distribution (Rowley, Satchler, Stelson, PLB254('91))

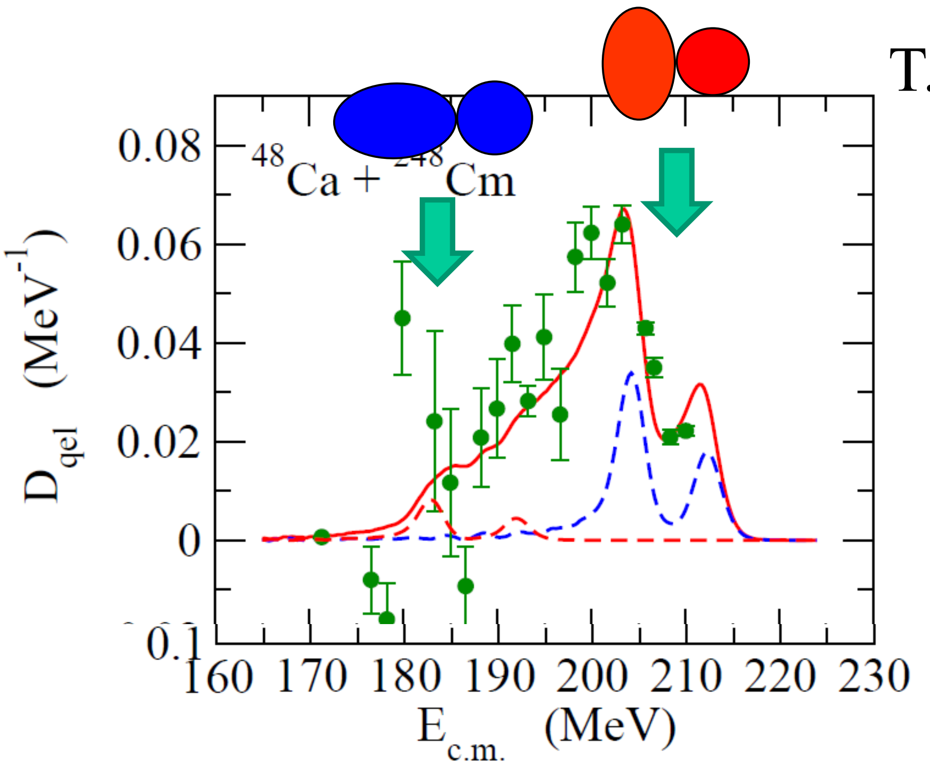
$$D_{\text{fus}}(E) = \frac{d^2(E\sigma_{\text{fus}})}{dE^2}$$



Data: J.R. Leigh et al., PRC52 ('95) 3151

can be used to identify the side/tip collisions

Application to hot fusion reactions



$^{48}Ca + {}^{248}Cm \rightarrow {}^{296}_{116}Lv^*$

T. Tanaka,..., K.H., et al.,
JPSJ 87 ('18) 014201
PRL124 ('20) 052502

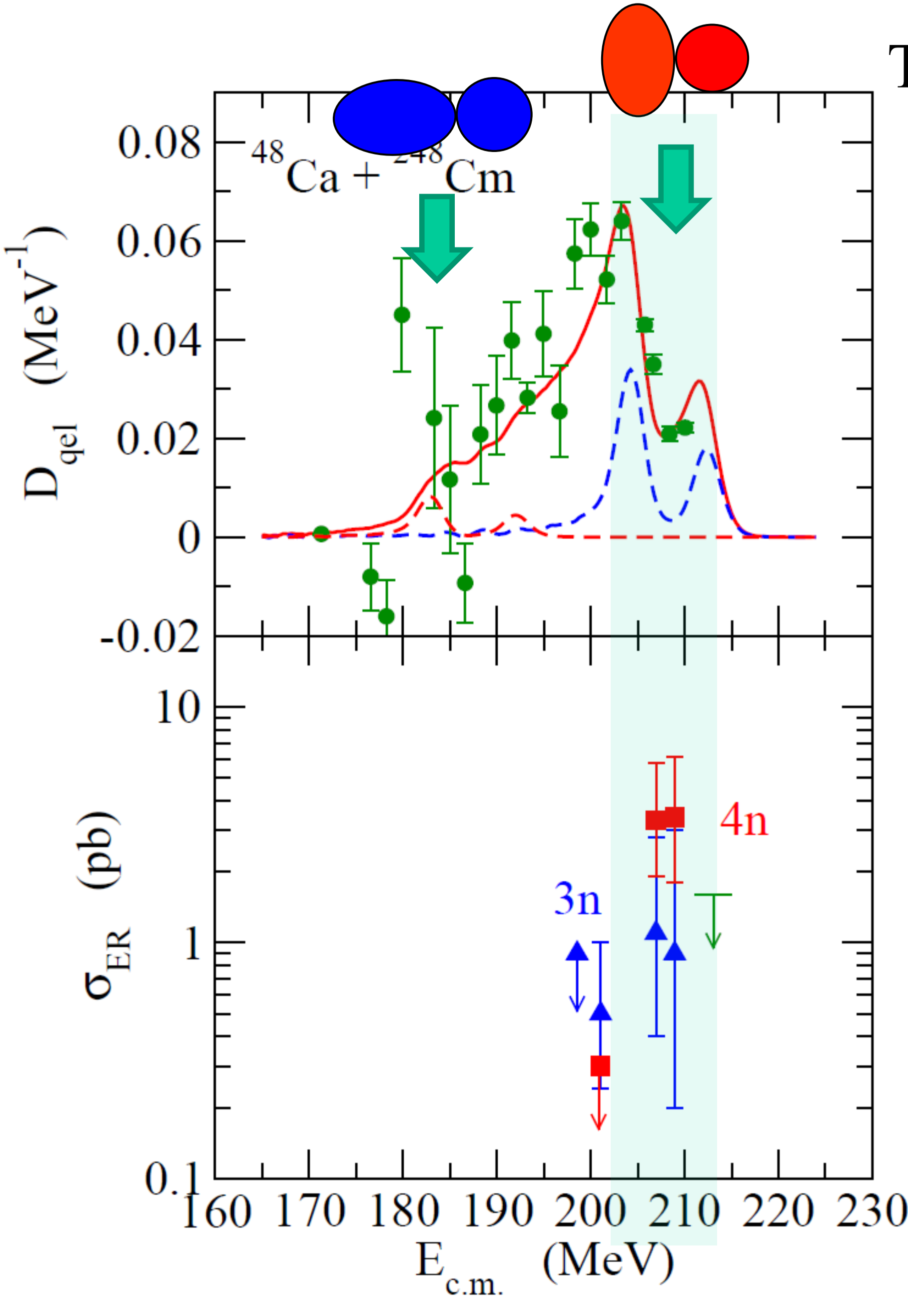
capture barrier distribution

$^{51}V + {}^{248}Cm \rightarrow {}^{299}119^*$

M. Tanaka et al.,
JPSJ91, 084201 (2022)

Application to hot fusion reactions

$^{48}Ca + ^{248}Cm \rightarrow {}^{296}_{116}Lv^*$

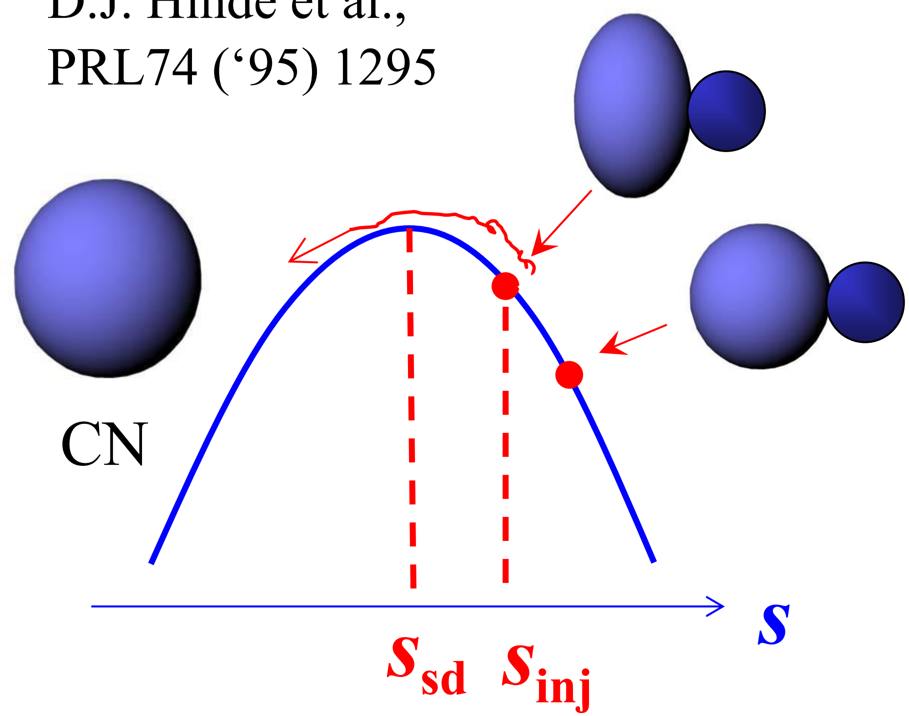


T. Tanaka,…, K.H., et al.,
JPSJ 87 ('18) 014201
PRL124 ('20) 052502

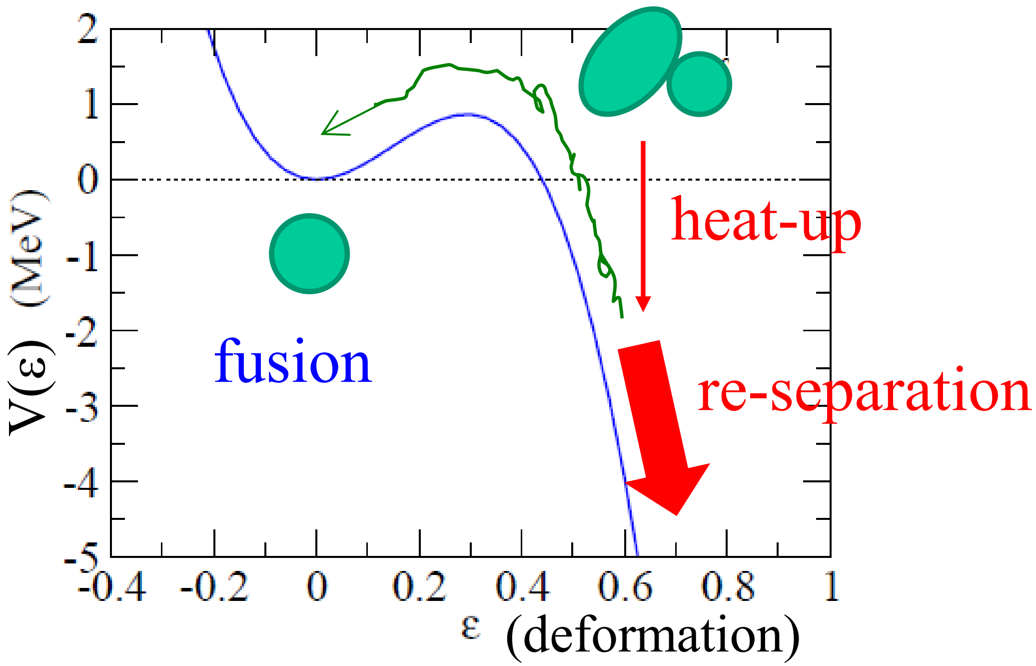
capture barrier distribution

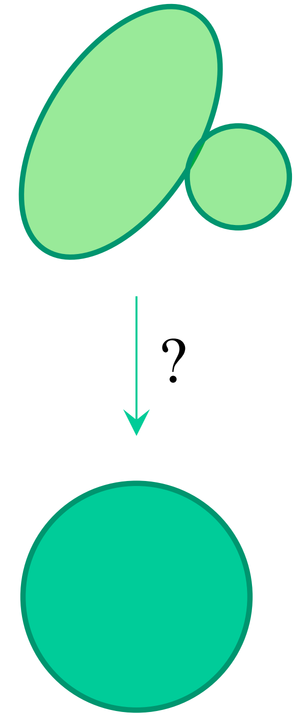
cf. notion of compactness:

D.J. Hinde et al.,
PRL74 ('95) 1295



open problems





- how is the shape evolved to a compound nucleus?
- Deformation: a quantum effect

  how does the deformation disappear during heat-up?

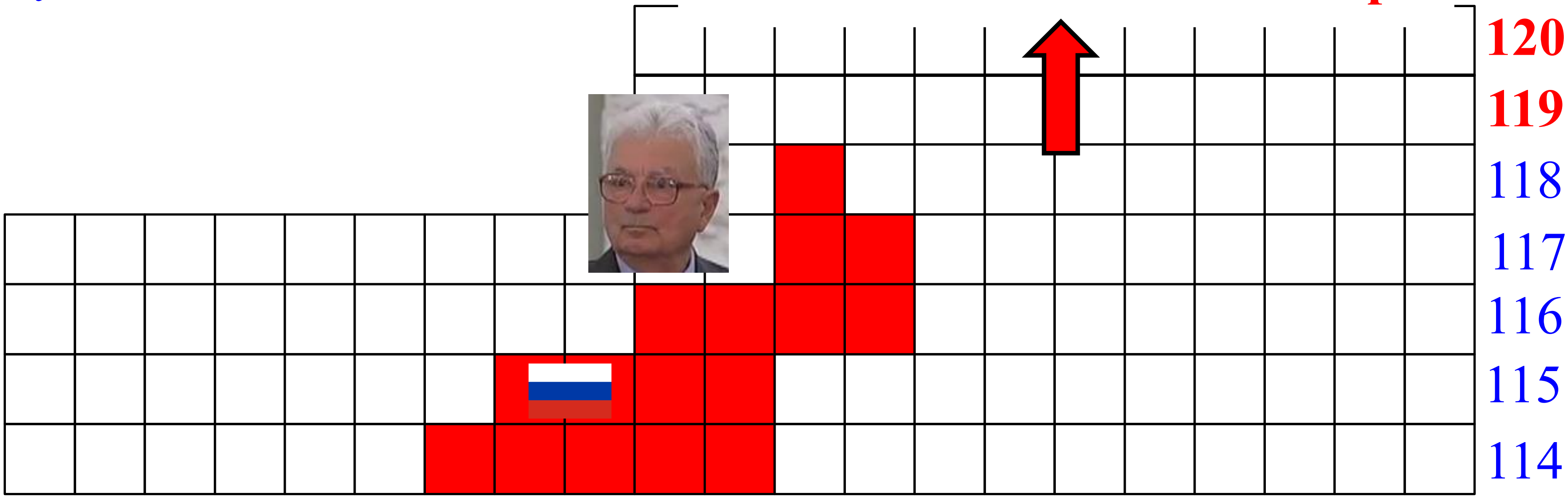
quantum friction/open quantum systems

cf. M. Tokieda and K.H., Ann. of Phys. 412 ('20) 168005.

Coupled-channels approach to the Caldeira-Leggett model

Synthesis of Z=119 and 120

Towards Z=119 and 120 isotopes



hot fusion reactions with ^{48}Ca:

$$^{48}_{20}Ca + {}_{99}Es \rightarrow 119$$
$$^{48}_{20}Ca + {}_{100}Fm \rightarrow 120$$

short lived →not available with sufficient amounts

$$\boxed{^{48}Ca \rightarrow {}^{50}_{22}Ti,\ {}^{51}_{23}V,\ {}^{54}_{24}Cr \text{ projectiles}}$$

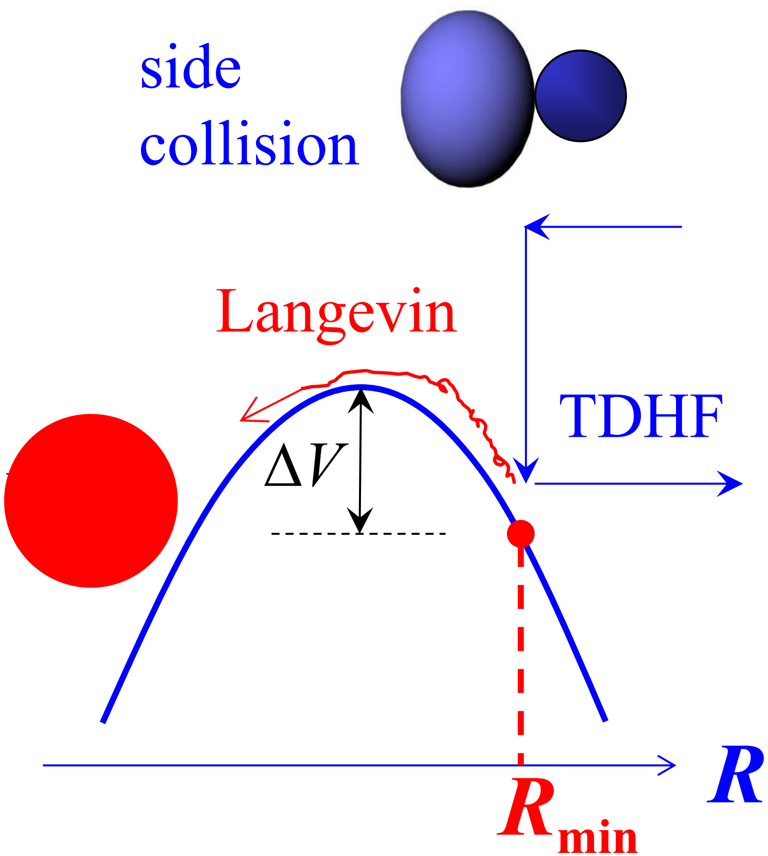
closed shell → open shells

how much will cross sections be affected?

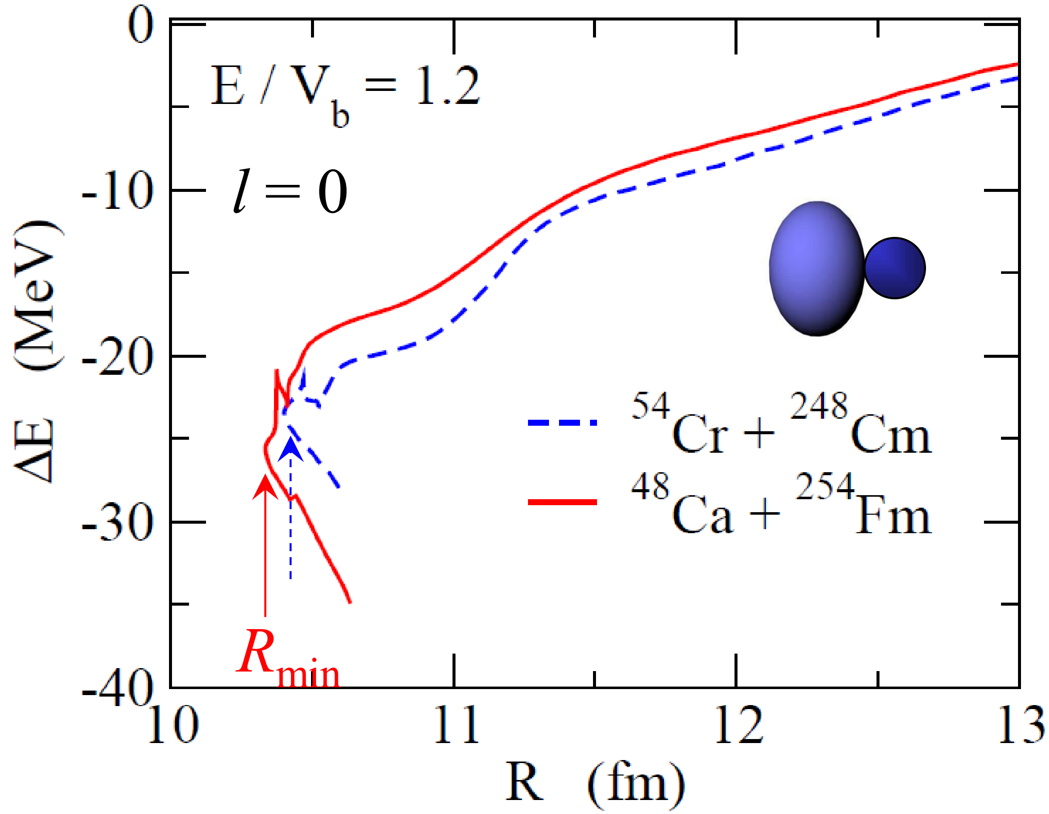
TDHF + Langevin approach

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

SUGGESTION



$^{54}Cr + ^{248}Cm \rightarrow \ ^{302}120$
$^{48}Ca + ^{254}Fm \rightarrow \ ^{302}120$



→ Langevin caluclation

New model for fusion for SHE: TDHF + Langevin approach

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

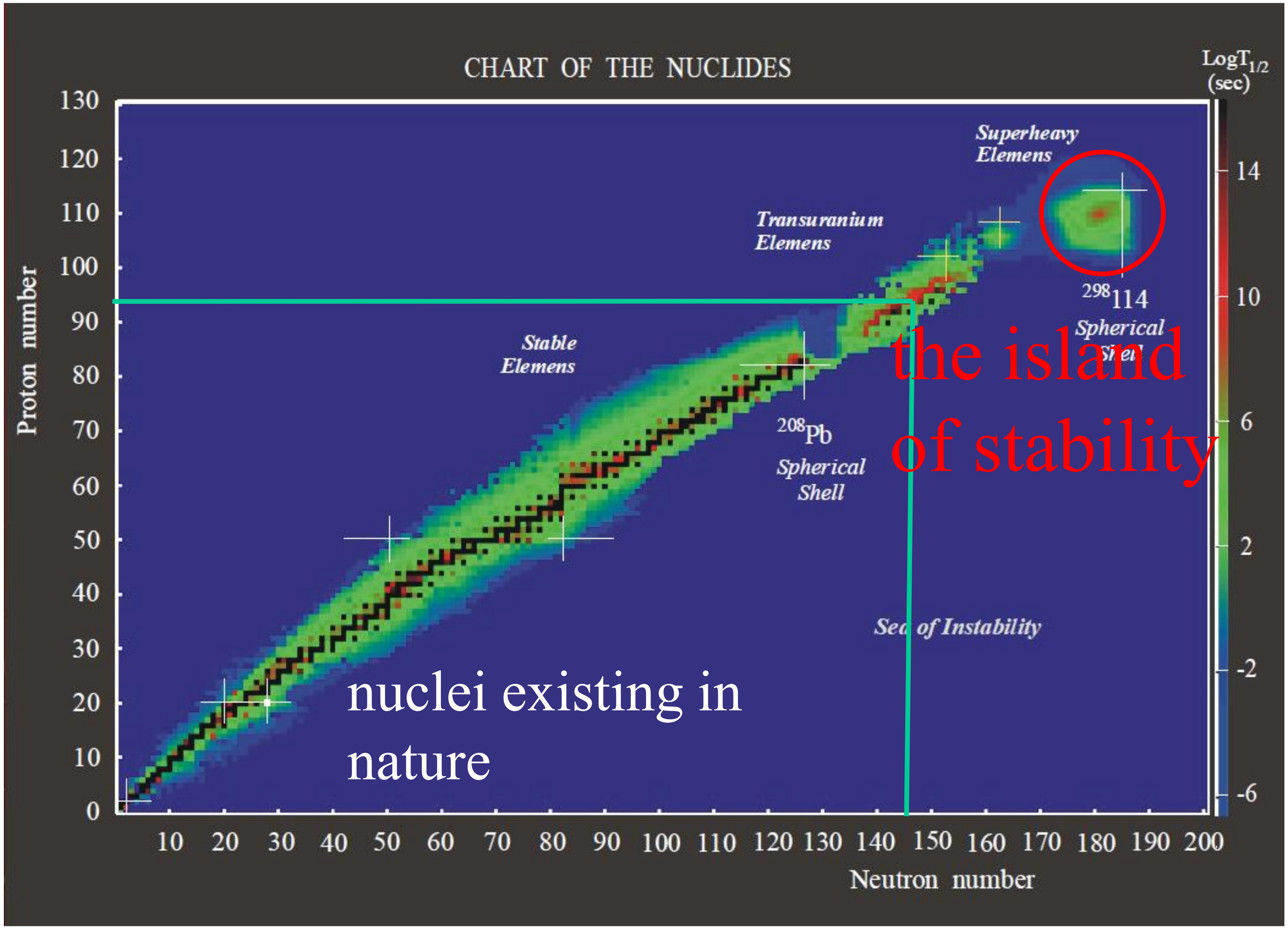
how special is ^{48}Ca ?

System	CN	E^* (MeV)	$R_{\min}$ (fm)	$P_{\rm CN}$ ($\times 10^4$)	$W_{\rm sur}$ ($\times 10^9$)	$P_{\rm CN}\,W_{\rm sur}$ ($\times 10^{13}$)
^{48}Ca + ^{254}Fm	^{302}120	29.0	12.93	1.72	176	302
^{54}Cr + ^{248}Cm	^{302}120	33.2	13.09	1.89	1.31	2.47
^{51}V + ^{249}Bk	^{300}120	37.0	12.94	3.95	0.117	0.461
^{48}Ca + ^{257}Fm	^{305}120	30.5	12.94	2.49	0.729	1.82

similar $P_{\rm CN}$

no special role of ^{48}Ca in the entrance channel

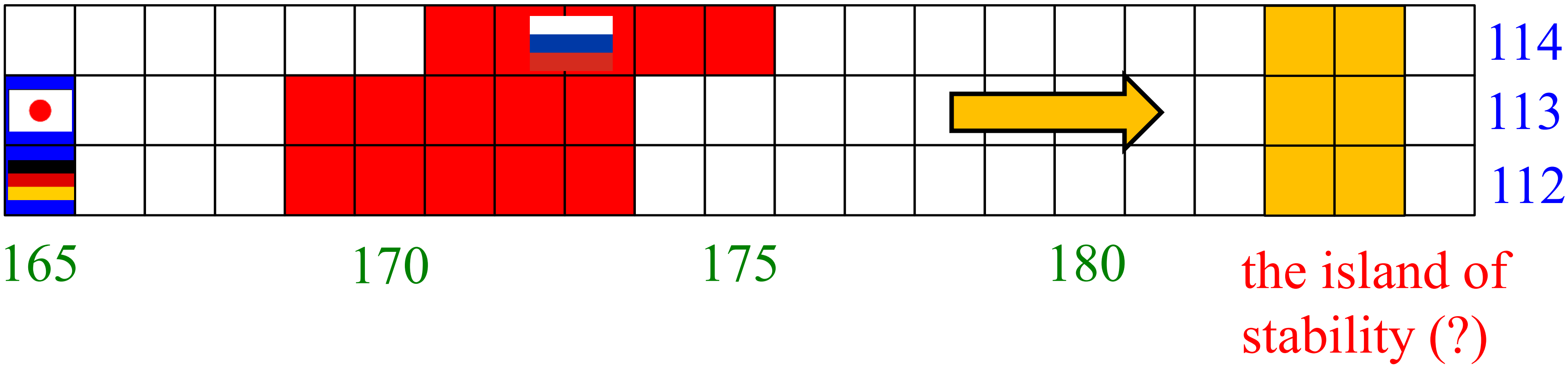
Another important issue: physics of neutron-rich nuclei



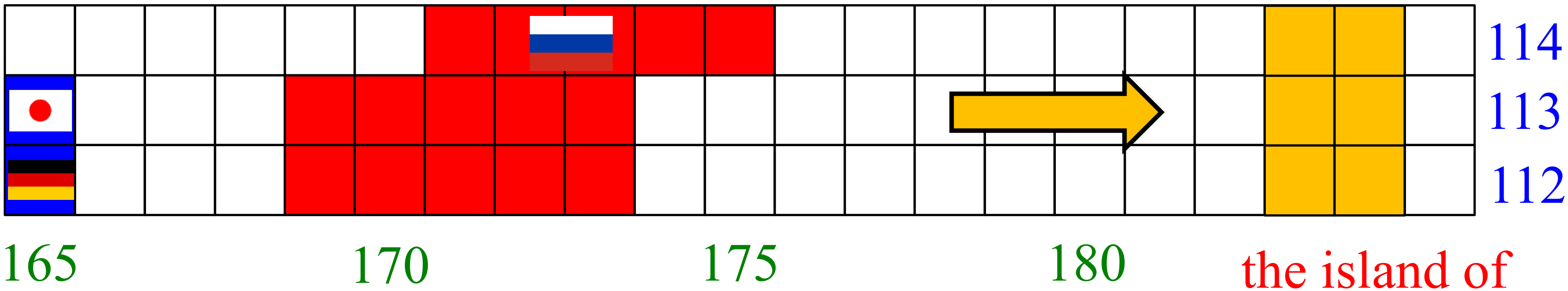
Yuri Oganessian

how to reach the island of stability?

Fusion of unstable nuclei



Fusion of unstable nuclei



the island of stability (?)

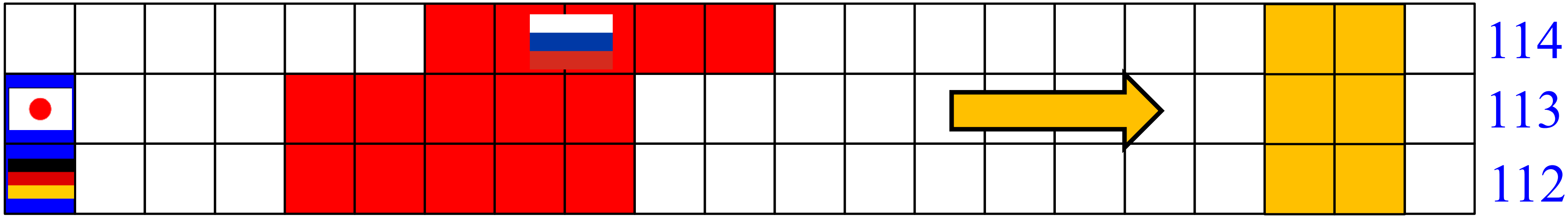
neutron-rich beams: indispensable

- how to deal with low beam intensity?
- reaction dynamics of neutron-rich beams?
  - ✓ capture: effects of breakup and multi-neutron transfer?
  - ✓ diffusion: neutron emission during a shape evolution?
  - ✓ survival: validity of the statistical model?

structure of exotic nuclei

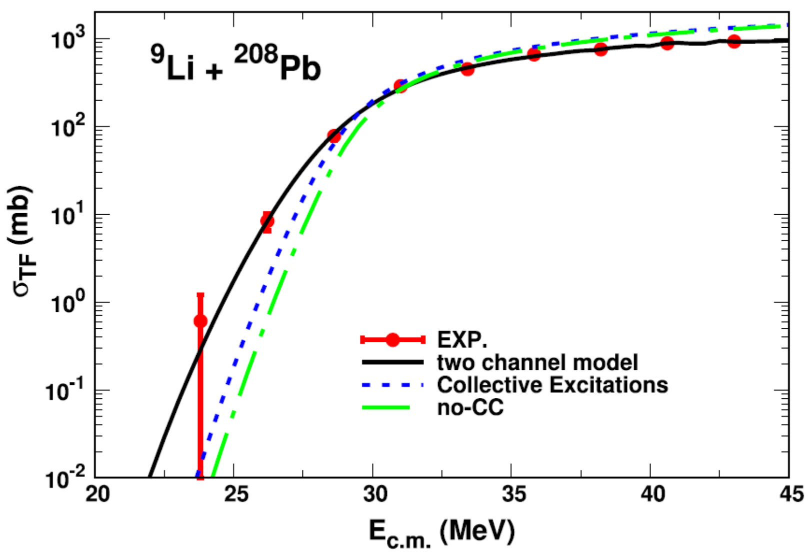
more studies are required

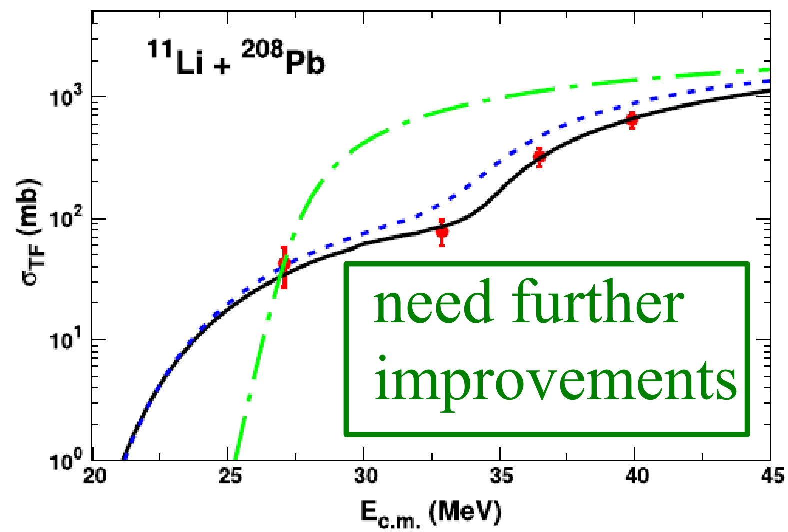
Fusion of unstable nuclei



neutron-rich beams: indispensable
→reaction dynamics?

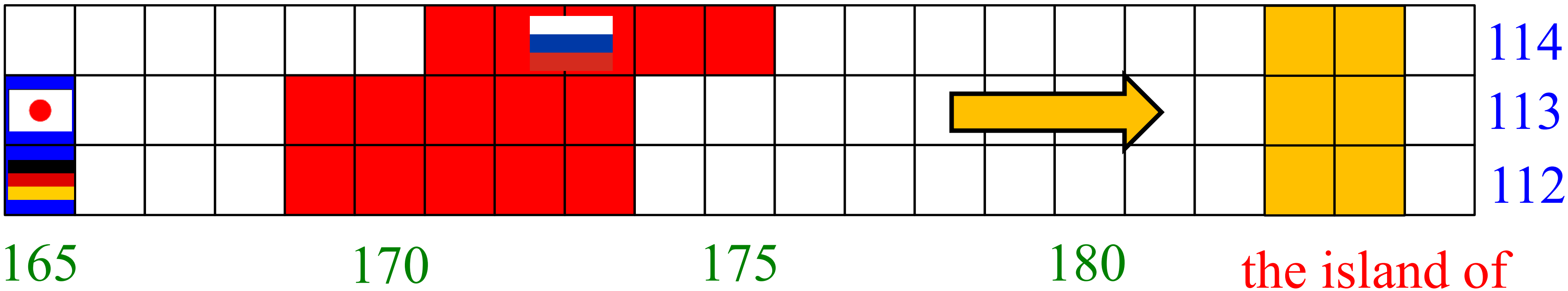
K.-S. Choi, K. Hagino et al.,
Phys. Lett. B780 ('18) 455





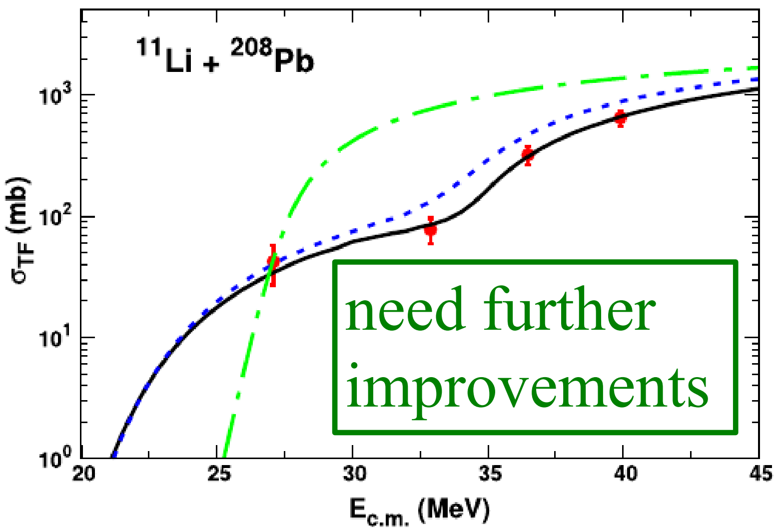
simultaneous explanation for ^{9}Li+^{208}Pb and ^{11}Li+^{208}Pb with:
^{11}Li+^{208}Pb ⟷ ^{9}Li+^{210}Pb ⟷ ^{7}Li+^{212}Pb transfer couplings

Fusion of unstable nuclei

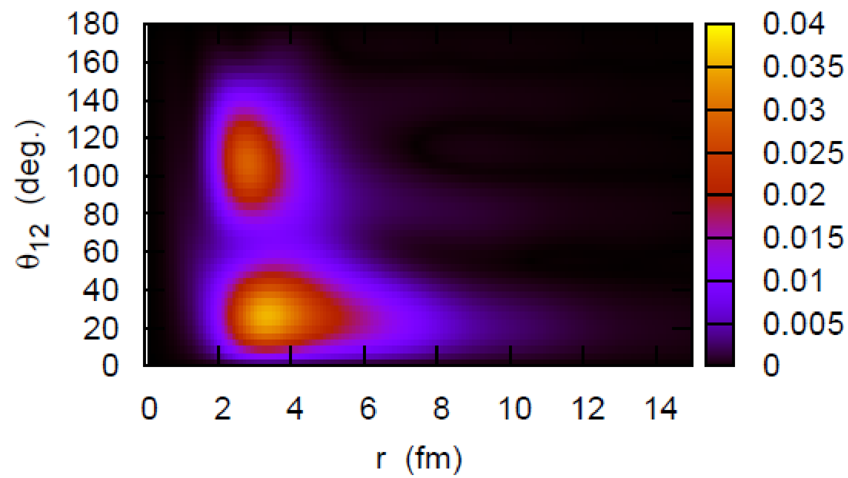


the island of stability

neutron-rich beams: indispensable→reaction dynamics?



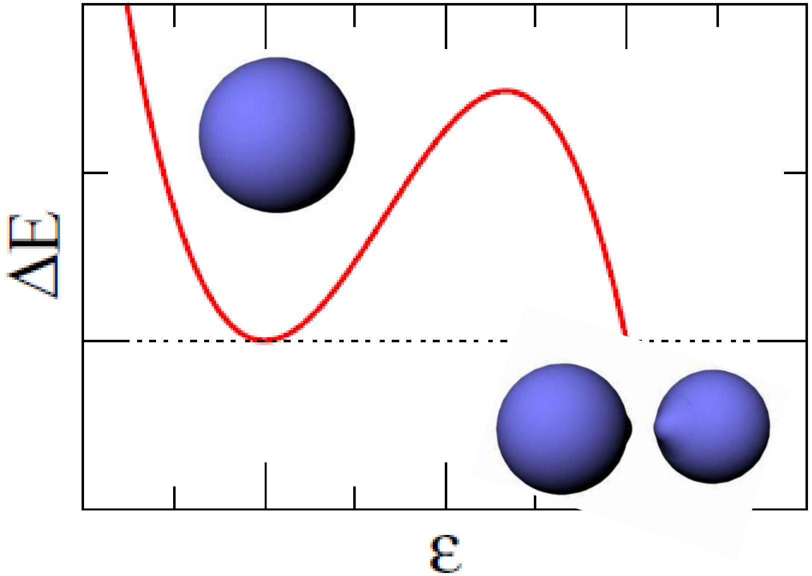
K.-S. Choi, K. Hagino et al., Phys. Lett. B780 ('18) 455



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

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

A related big theoretical challenge: nuclear fission

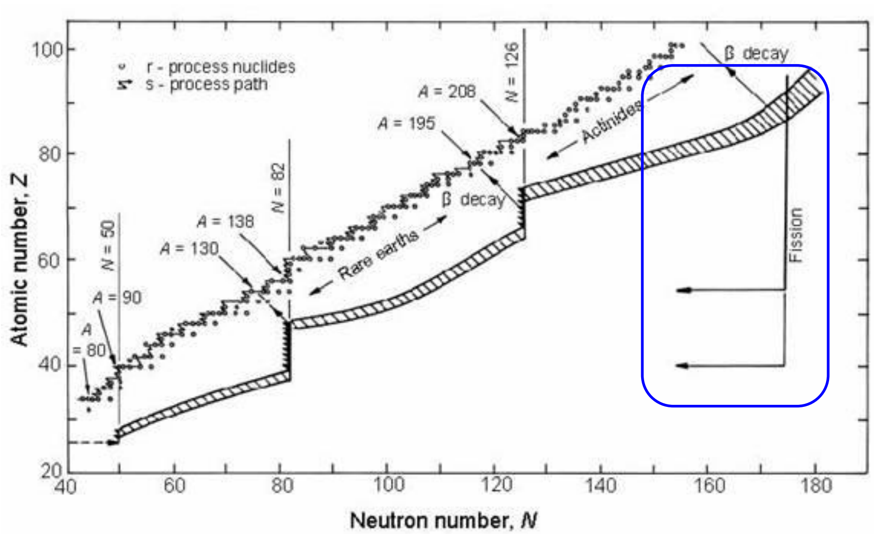


How well can one describe nuclear fission microscopically?

G.F. Bertsch and K.H., Phys. Rev. C107, 044615 (2023).
K. Uzawa and K.H., Phys. Rev. C110, 014321 (2024).

Why is a microscopic theory for fission important?

- ➢ r-process nucleosynthesis



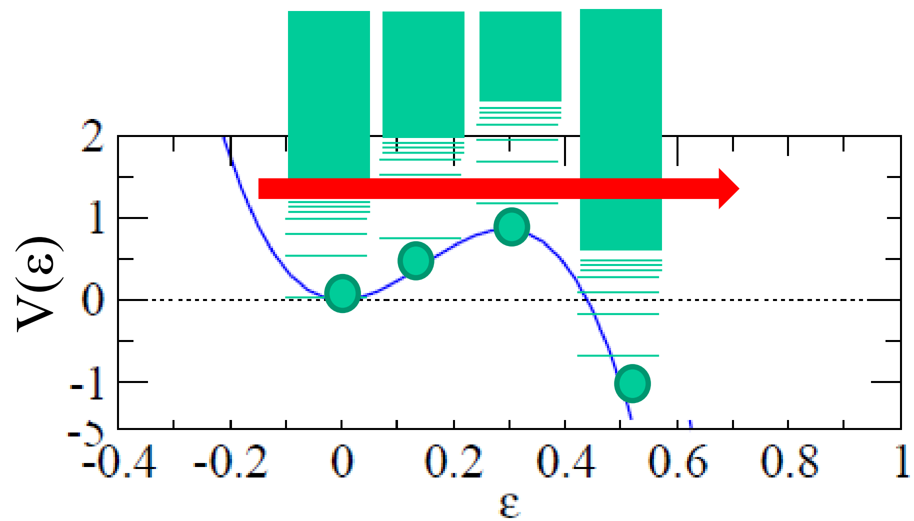
(neutron induced) fission of neutron-rich nuclei

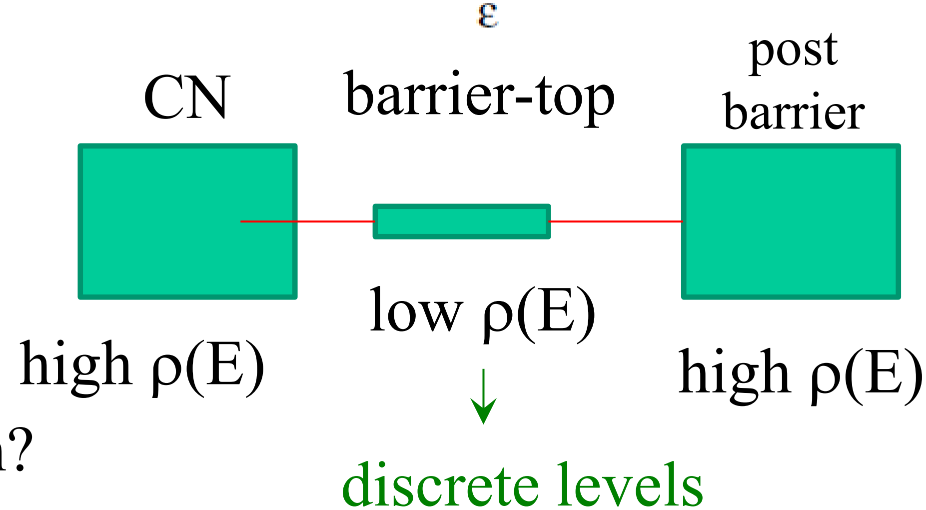
→ low E^* and low $\rho(E^*)$

✓ Validity of statistical models?

✓ Validity of the Langevin approach?

- ➢ barrier-top fission



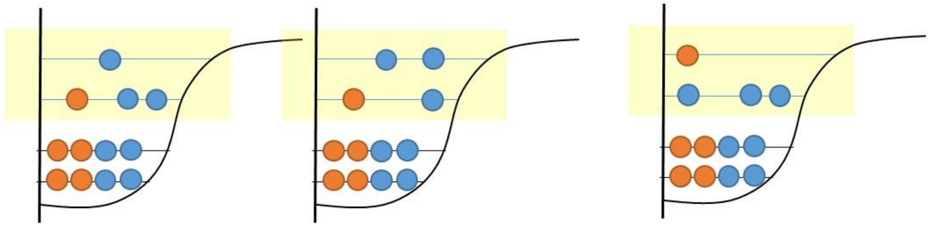


How to connect to a many-body Hamiltonian?

Shell model approach?

A similar approach for nuclear fission?

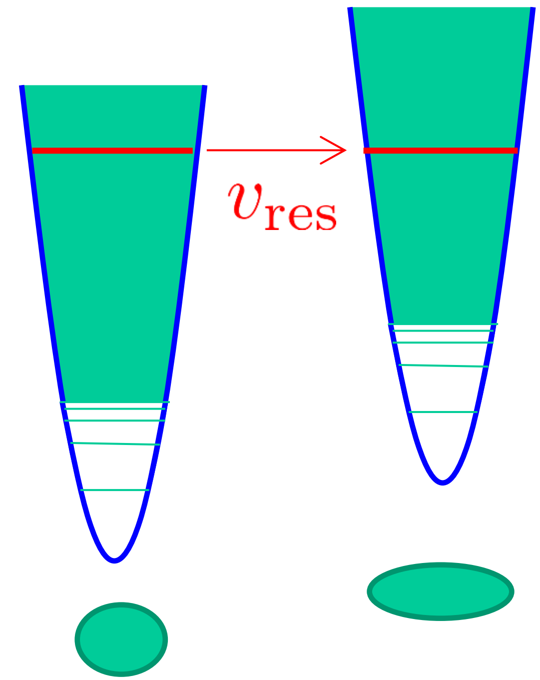
Shell model



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

Figure: Noritaka Shimizu (Tsukuba)

many-particle many-hole configurations in a mean-field potential
→mixing by residual interactions

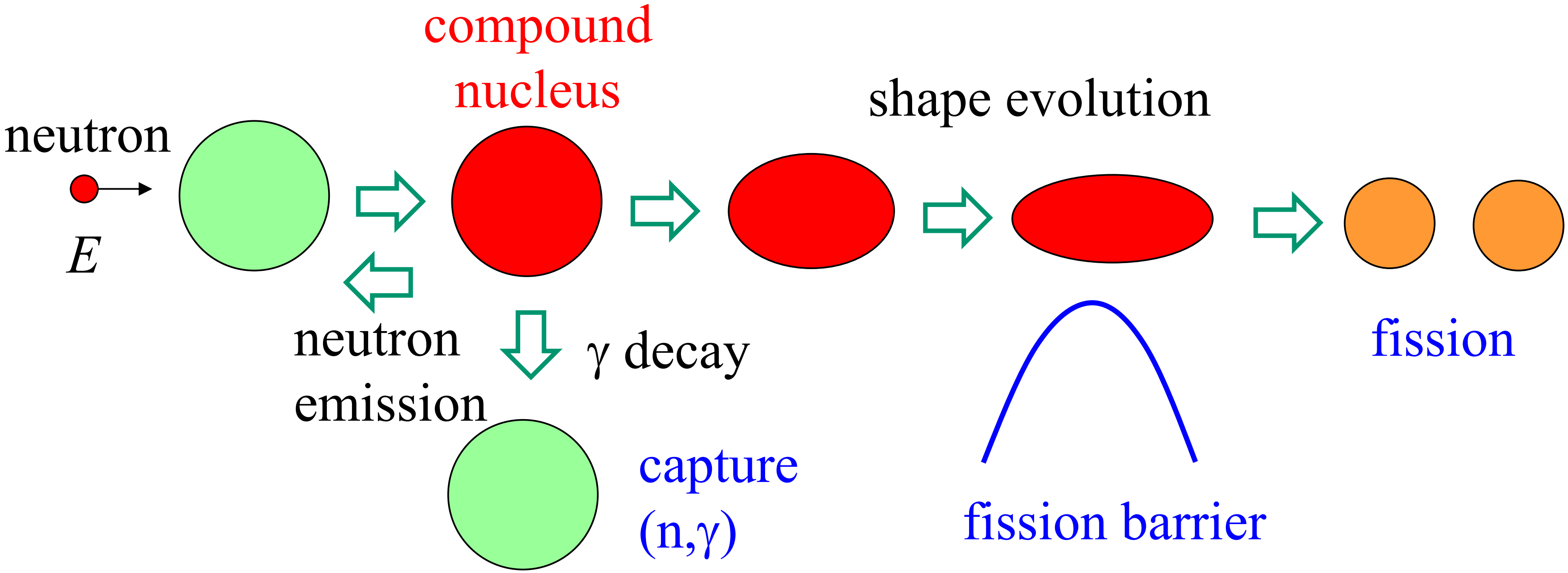


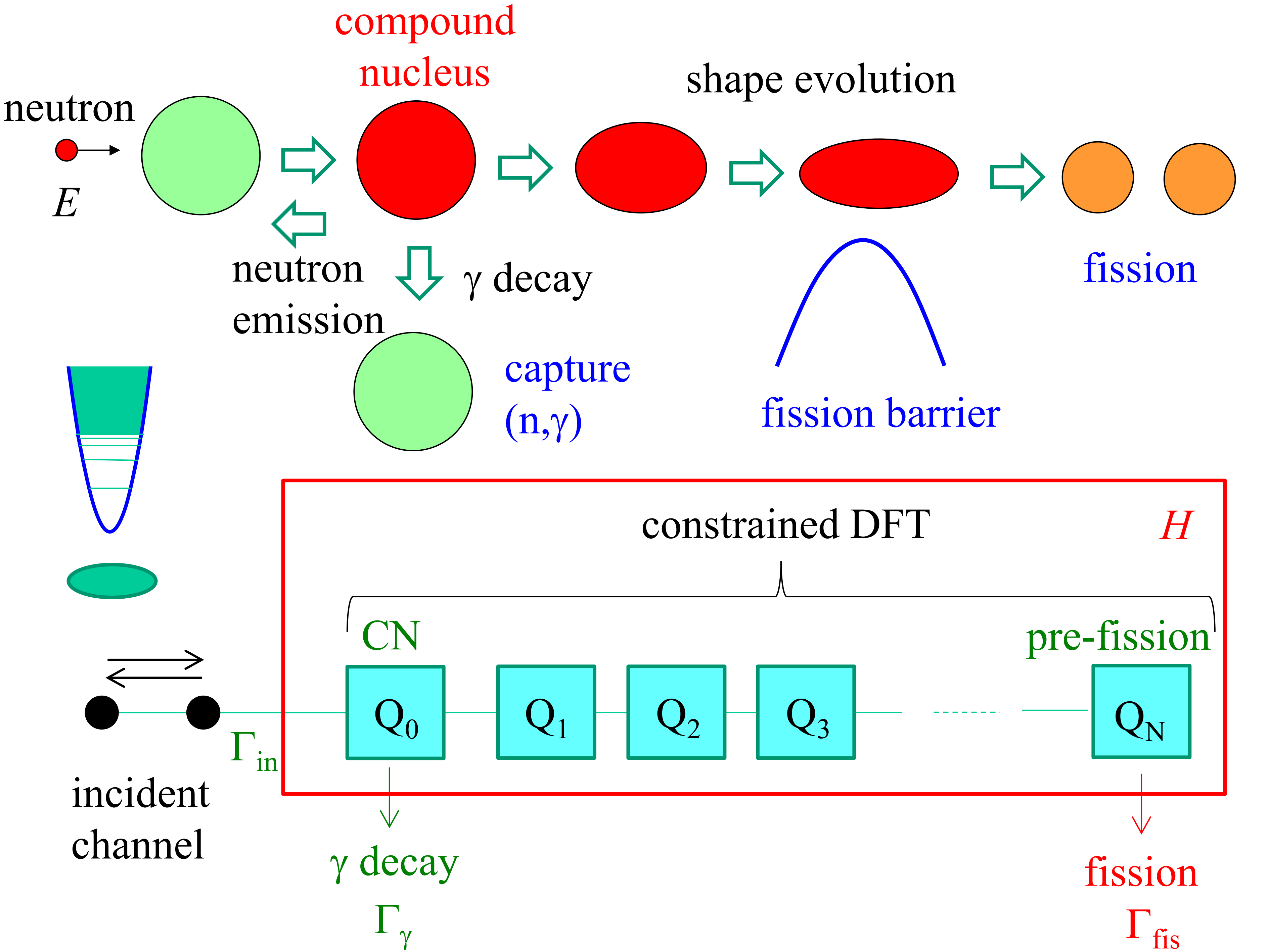
- Many-body configurations in a MF pot. for each shape
- hopping due to res. int.

→ shape evolution

a good connection to nuclear reaction theory

fission problem





compound
nucleus
neutron
E
shape evolution
neutron
emission
γ decay
capture
(n,γ)
fission barrier
fission
constrained DFT
H
CN
pre-fission
Q0
Q1
Q2
Q3
QN
Γin
incident
channel
γ decay
Γγ
fission
Γfis

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

G.F. Bertsch and K.H., Phys. Rev. C107, 044615 (2023).
K. Uzawa and K.H., Phys. Rev. C110, 014321 (2024).

dim.

=1000	2520	9794	15088	11577	2774	2940	3021
GOE	Q = 18b	23b	29b	34b	39b	46b	51b

$\Gamma_{\rm cap}$

3150	2196	3752	2871	4420	1000
57b	62b	67b	74b	79b	GOE

$\Gamma_{\rm fis}$

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

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

Fluctuations of fission width

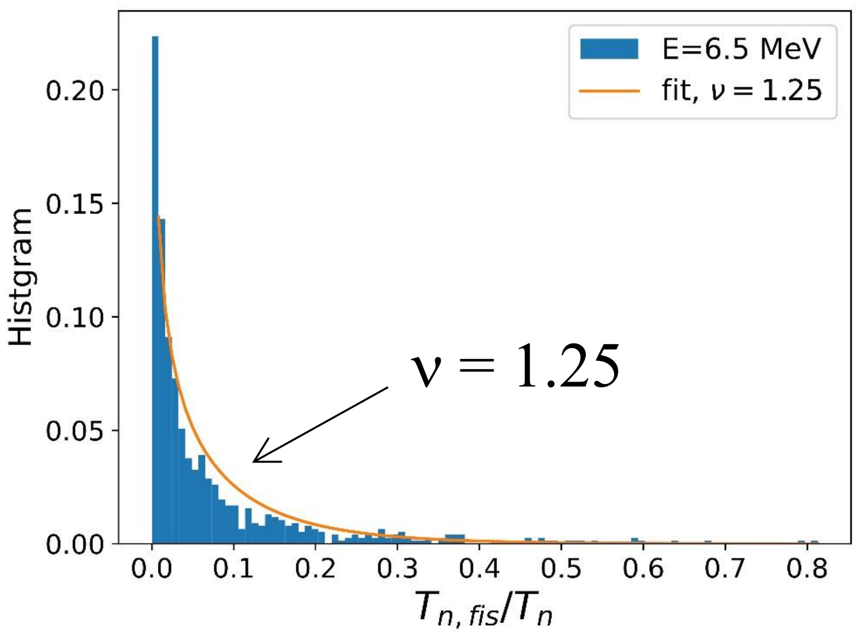
K. Uzawa and K.H., Phys. Rev. C110, 014321 (2024).

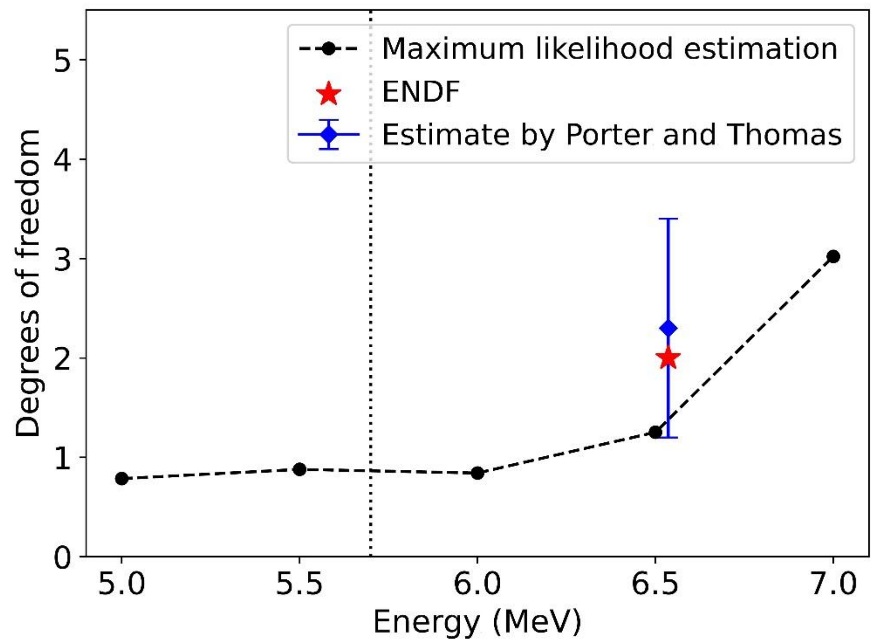
chi-square distribution:

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

ν: # of d.o.f.

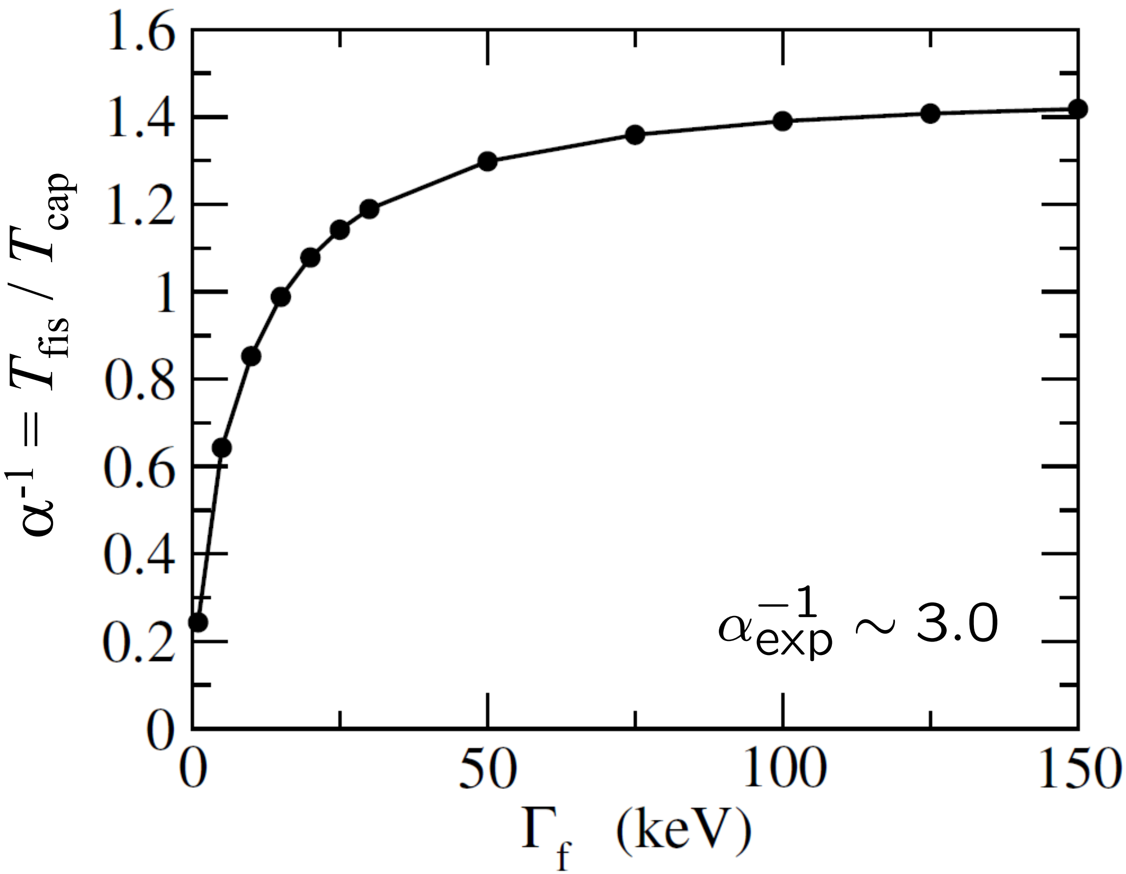
(ν=1: the PT distribution)





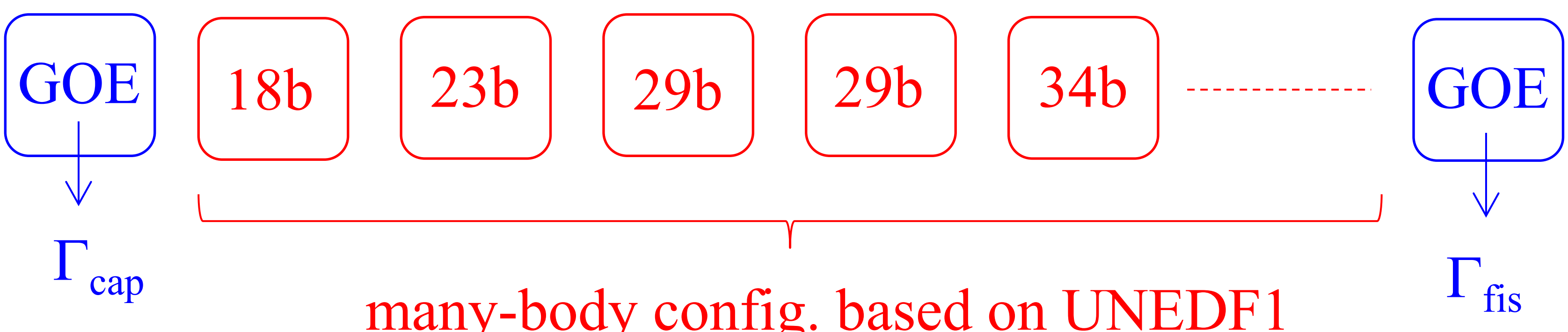
a small number of d.o.f. for induced fission ← transition state theory

insensitivity property



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

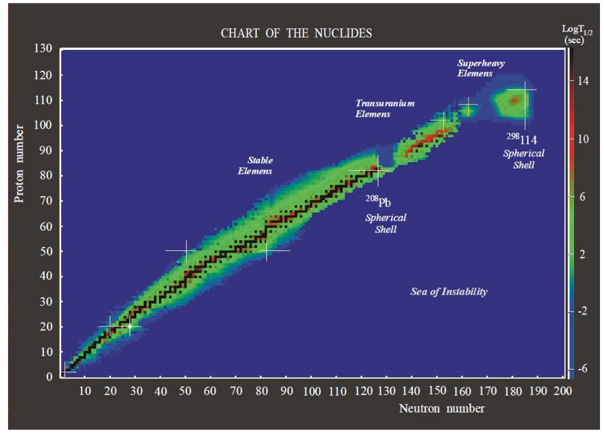
K.H. and G.F. Bertsch, JPSJ 93, 064003 (2024).



Summary

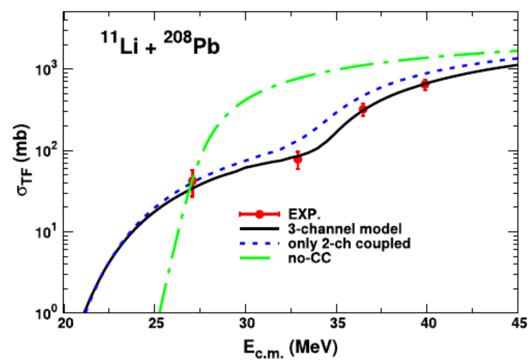
Physics of SHE

- SHE
- the island of stability
- fission

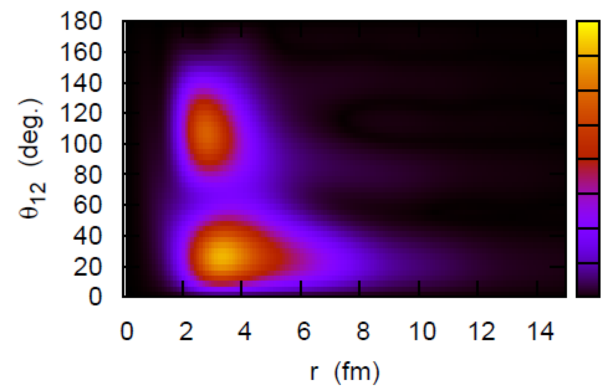


open quantum systems (OQS)

Reactions of n-rich nucl.



Structure of n-rich nucl.



SHE + neutron-rich nuclei + OQS → new direction

A big challenge: a microscopic descrption for SHE and fission