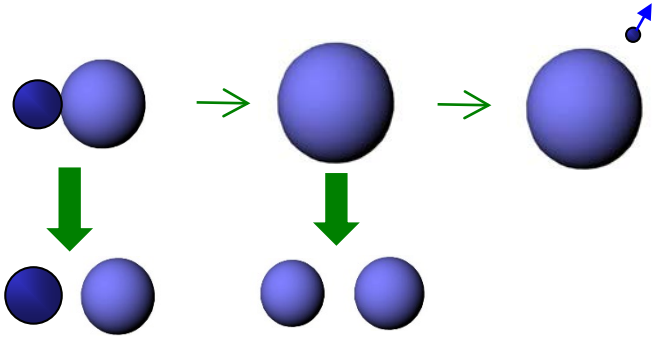
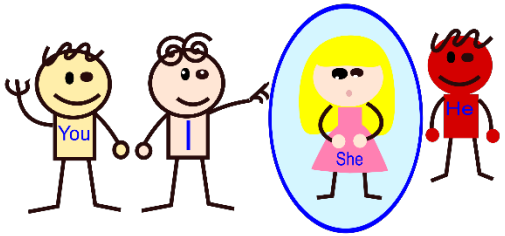
Mechanism of fusion reactions for superheavy elements

Kouichi Hagino

Tohoku University, Sendai, Japan





she

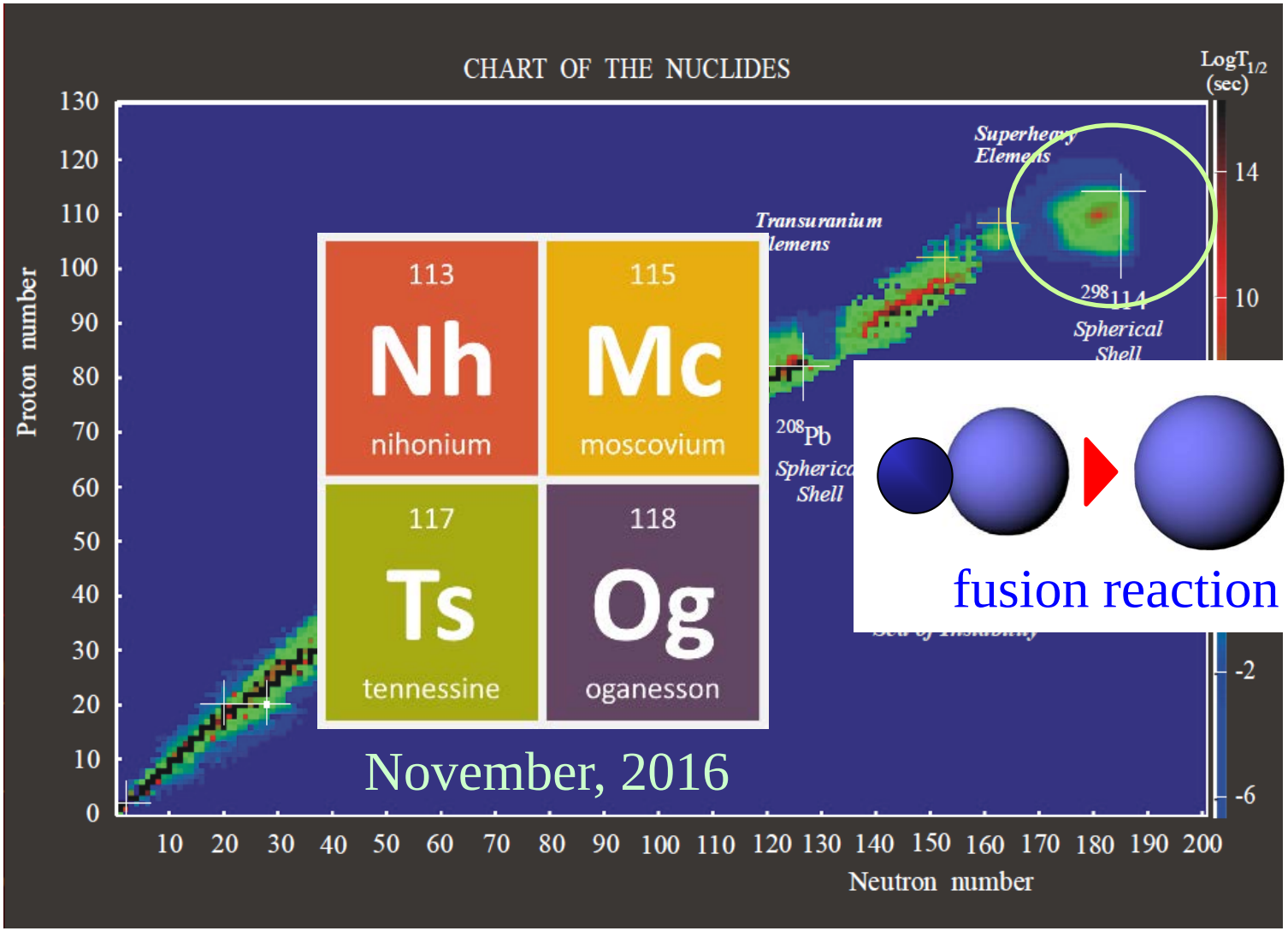
1. Heavy-ion fusion reactions for superheavy elements
2. Towards Z=119 and 120: role of a target deformation
3. Summary and discussions

The 5th joint meeting of the APS-DNP and JPS, Oct. 23-27, 2018, Kona, Hawaii, USA

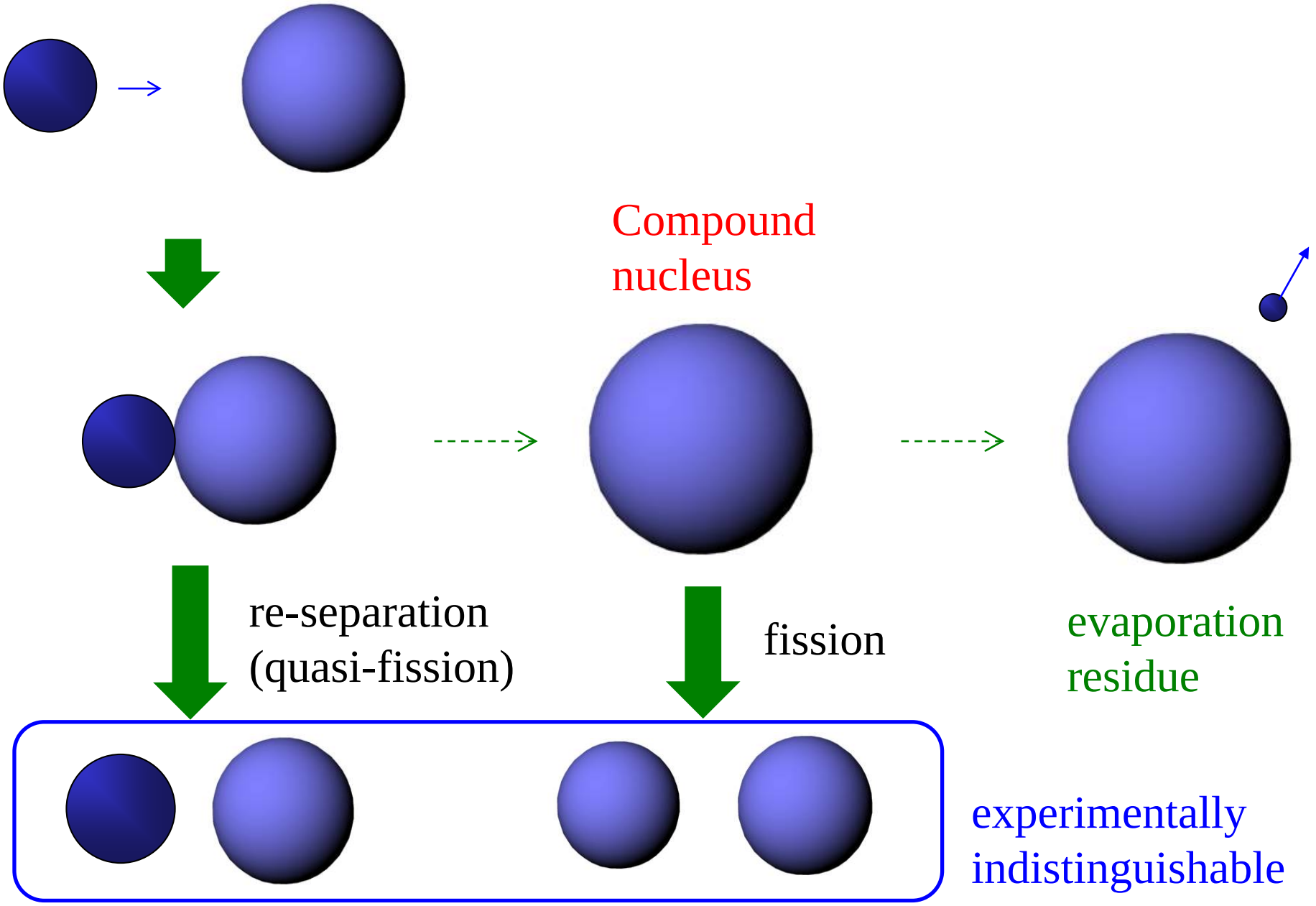
Fusion reactions for SHE

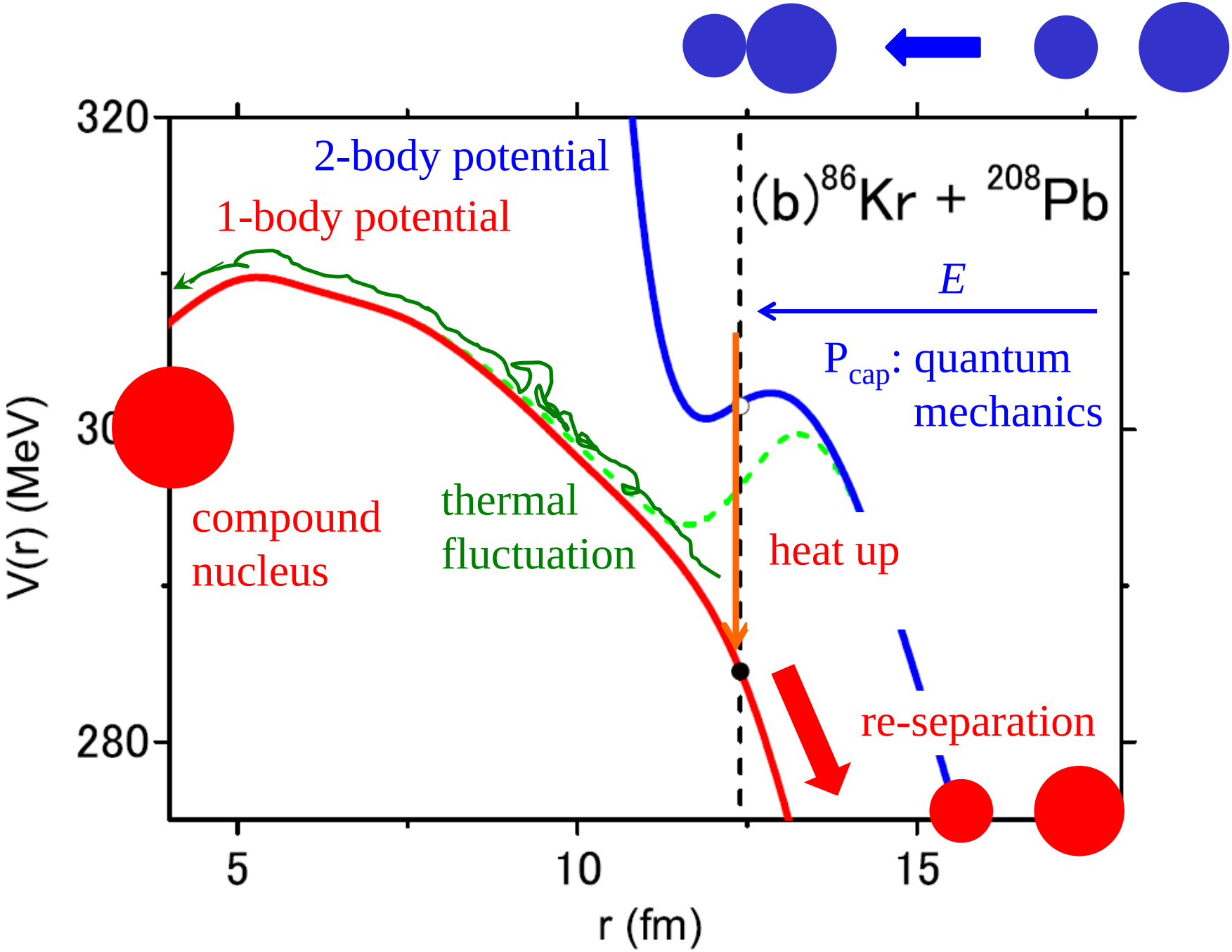
the island of stability around Z=114, N=184

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



Fusion for superheavy elements




320
280
5
10
15
r (fm)
V(r) (MeV)
2-body potential
1-body potential
(b)^{86}Kr + ^{208}Pb
E
P$_{cap}$: quantum mechanics
compound nucleus
thermal fluctuation
heat up
re-separation

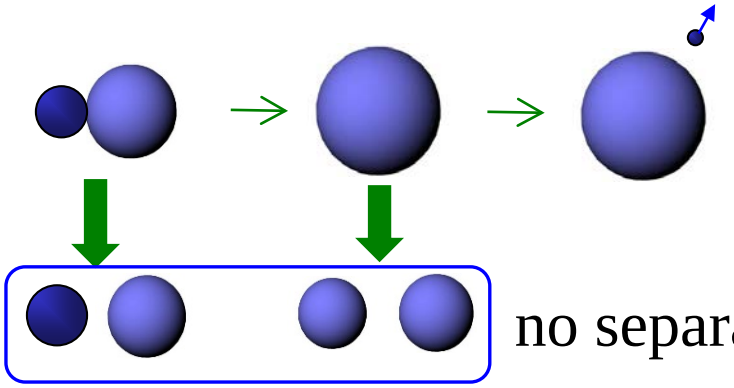
Fusion for superheavy elements

ER formation : a very rare process

→ large theoretical uncertainties

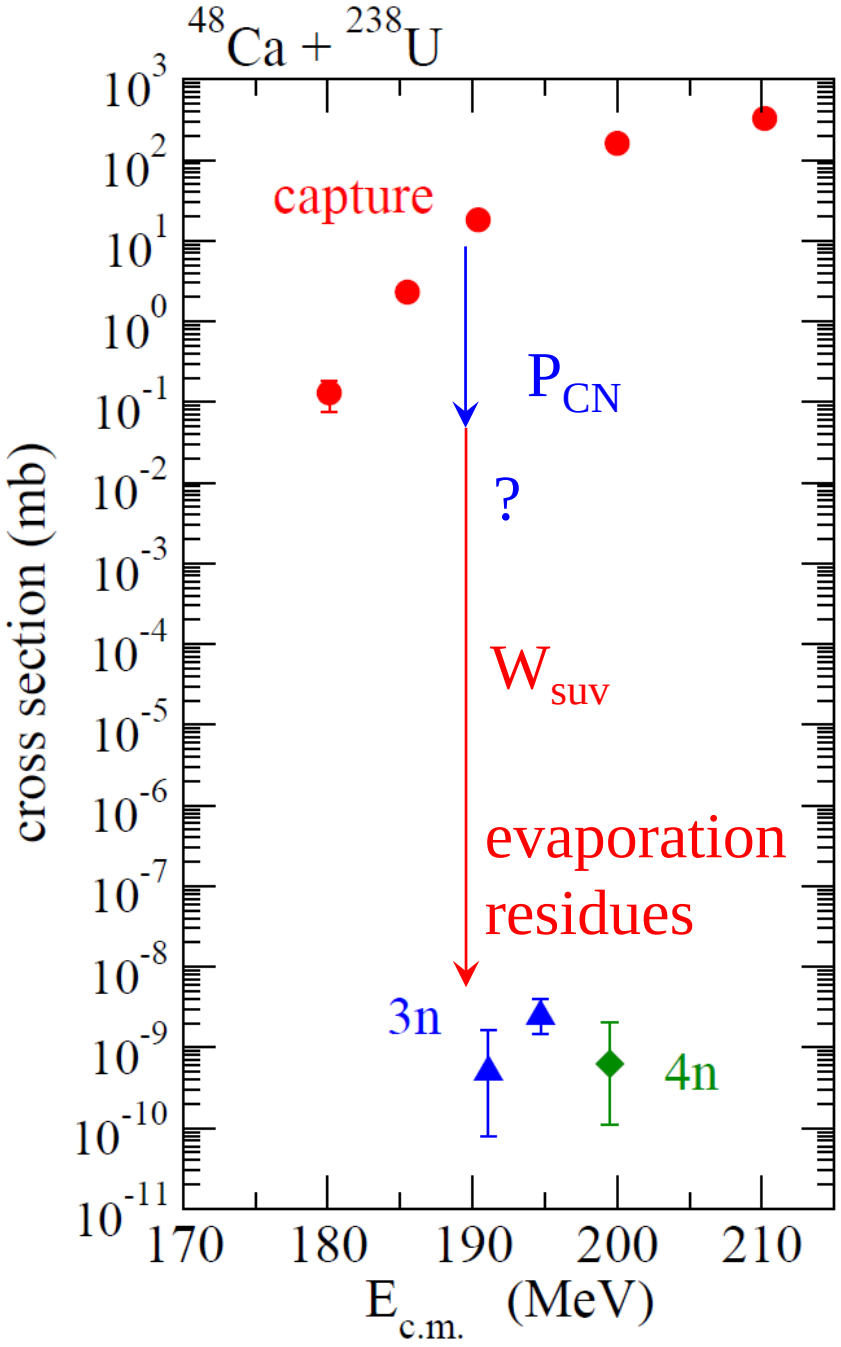
✓ no data for σ_{CN}

→ P_{CN} x W_{suv} only



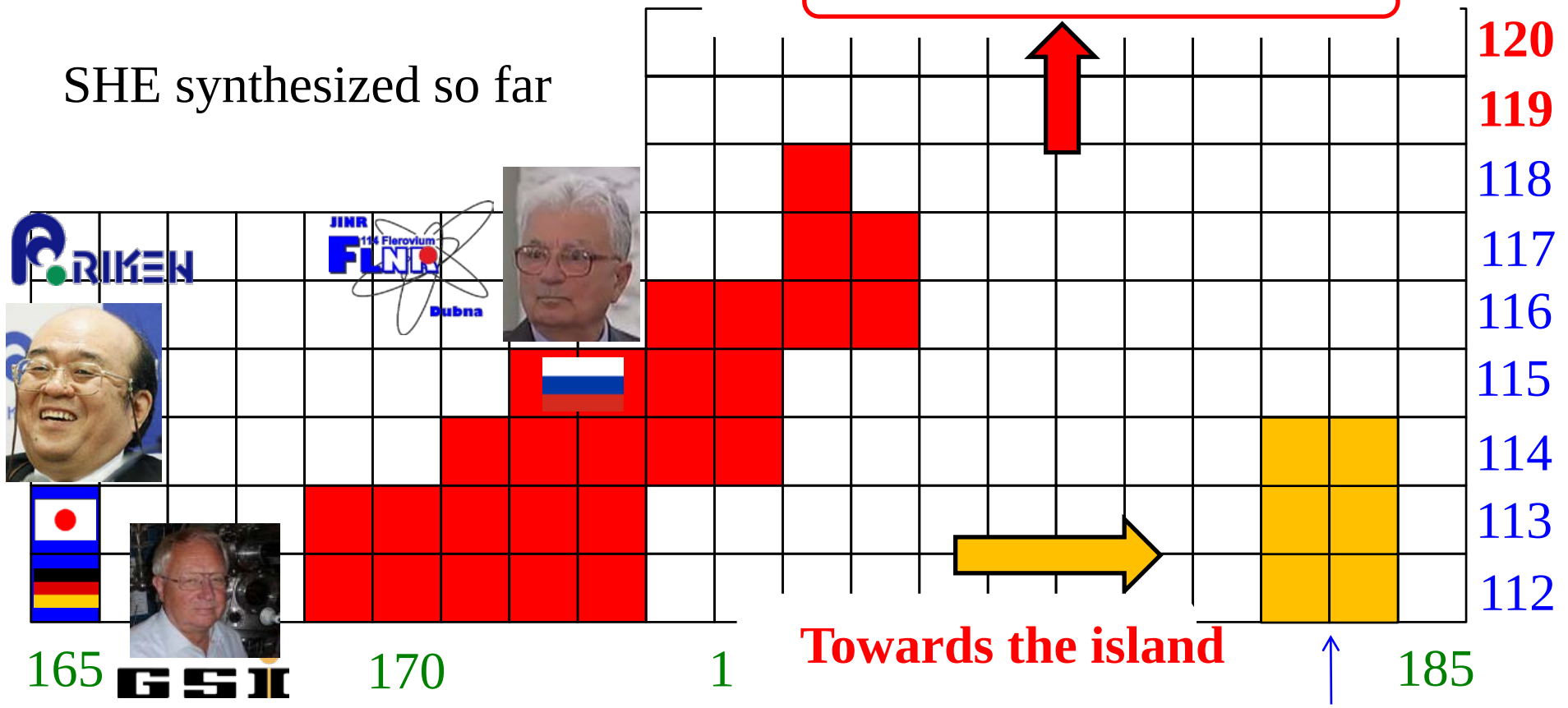
no separation

a big challenge:
to reduce theoretical uncertainties
and make reliable predictions



Future directions

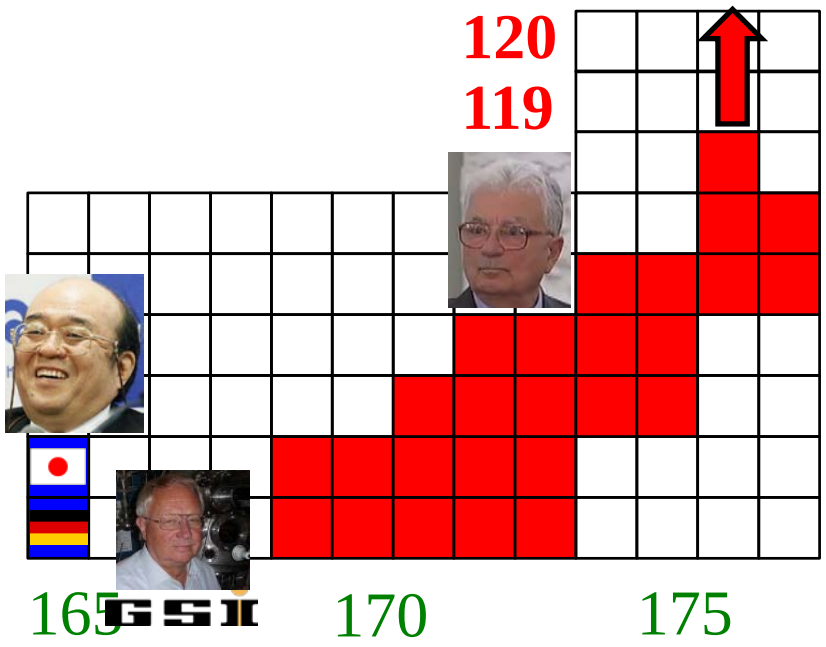
SHE synthesized so far

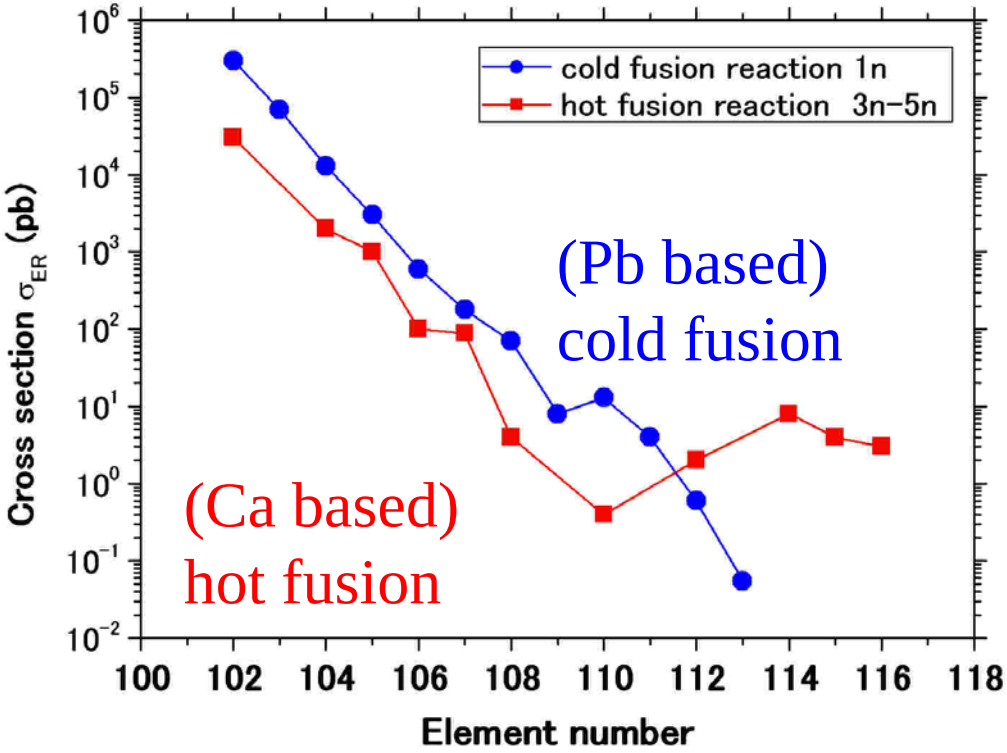


Theoretical issues:

- Reaction dynamics
- Reliable predictions for cross sections

Synthesis of Z=119 and 120 with hot fusion reactions





- hot fusion: ^{48}Ca + actinide nucleus

  Dubna: ^{48}Ca + ^{249}Cf ($\beta_2 = 0.235$) → $^{297-x}$Og (Z=118) + xn

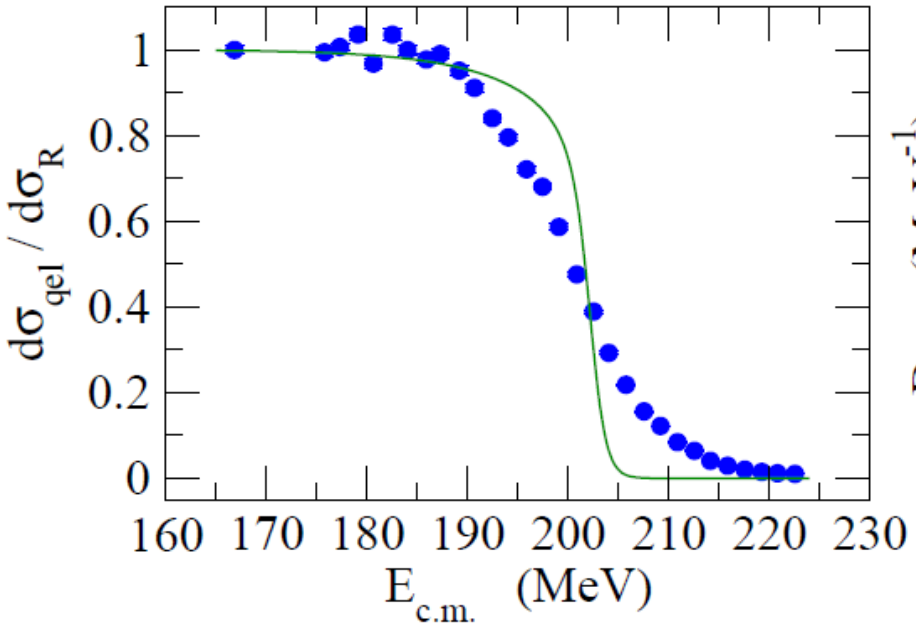
  role of nuclear deformation?

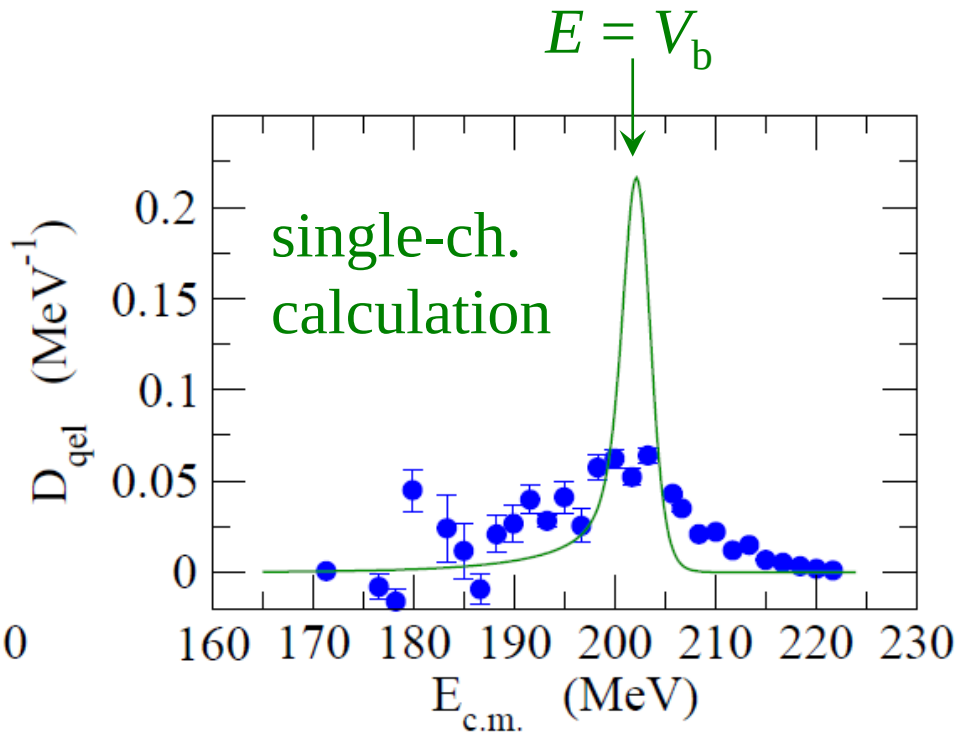
- Z=119, 120: ^{48}Ca → $^{50}_{22}$Ti, $^{51}_{23}$V, $^{54}_{24}$Cr

  How much will cross sections be altered? (still an open question)

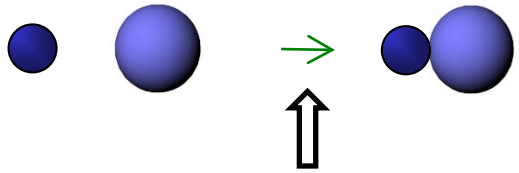
Role of deformation: Barrier distribution measurement with GARIS

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





T.Tanaka et al., JPSJ87 (‘18) 014201



B.D.

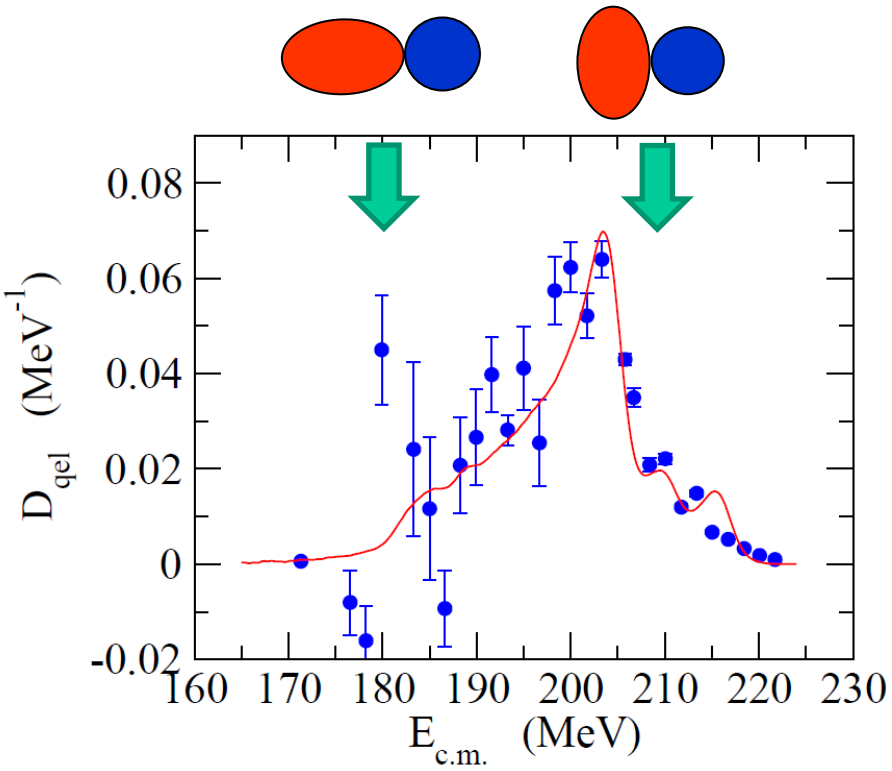
cf. Tanaka’s talk on Sat.

$$D_{\mathrm{qel}}(E) = -\frac{d}{dE}\left(\frac{\sigma_{\mathrm{qel}}(E,\pi)}{\sigma_R(E,\pi)}\right)$$

K.H. and N. Rowley, PRC69 ('04) 054610

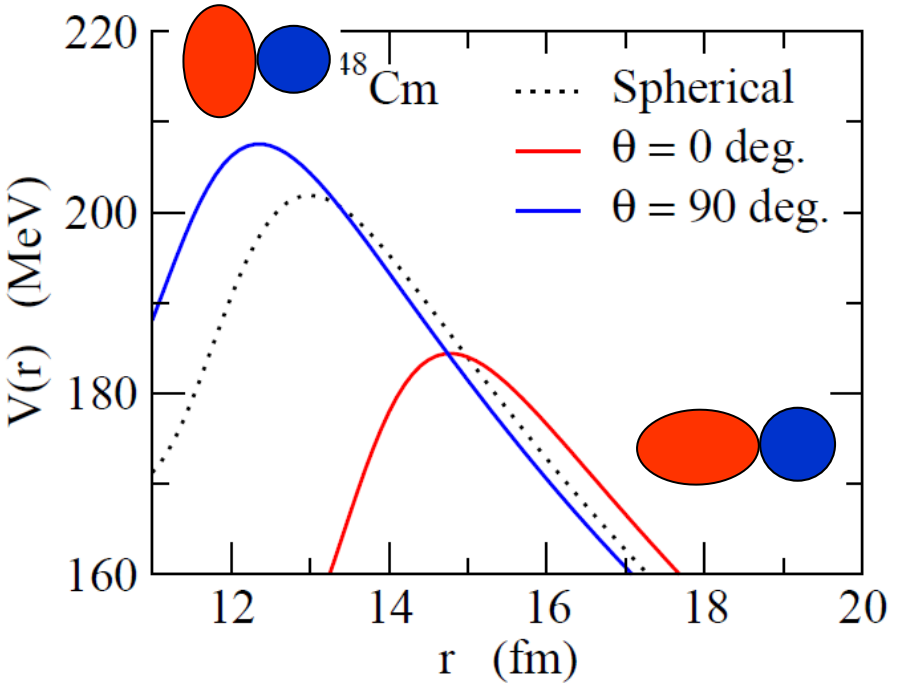
a distribution of the barrier heights due to channel coupling effects

Coupled-channels calculations (T. Tanaka and K.H.)



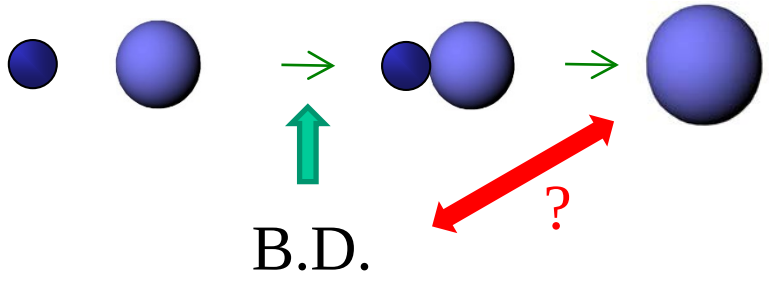
T.Tanaka et al., JPSJ87 (‘18) 014201

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

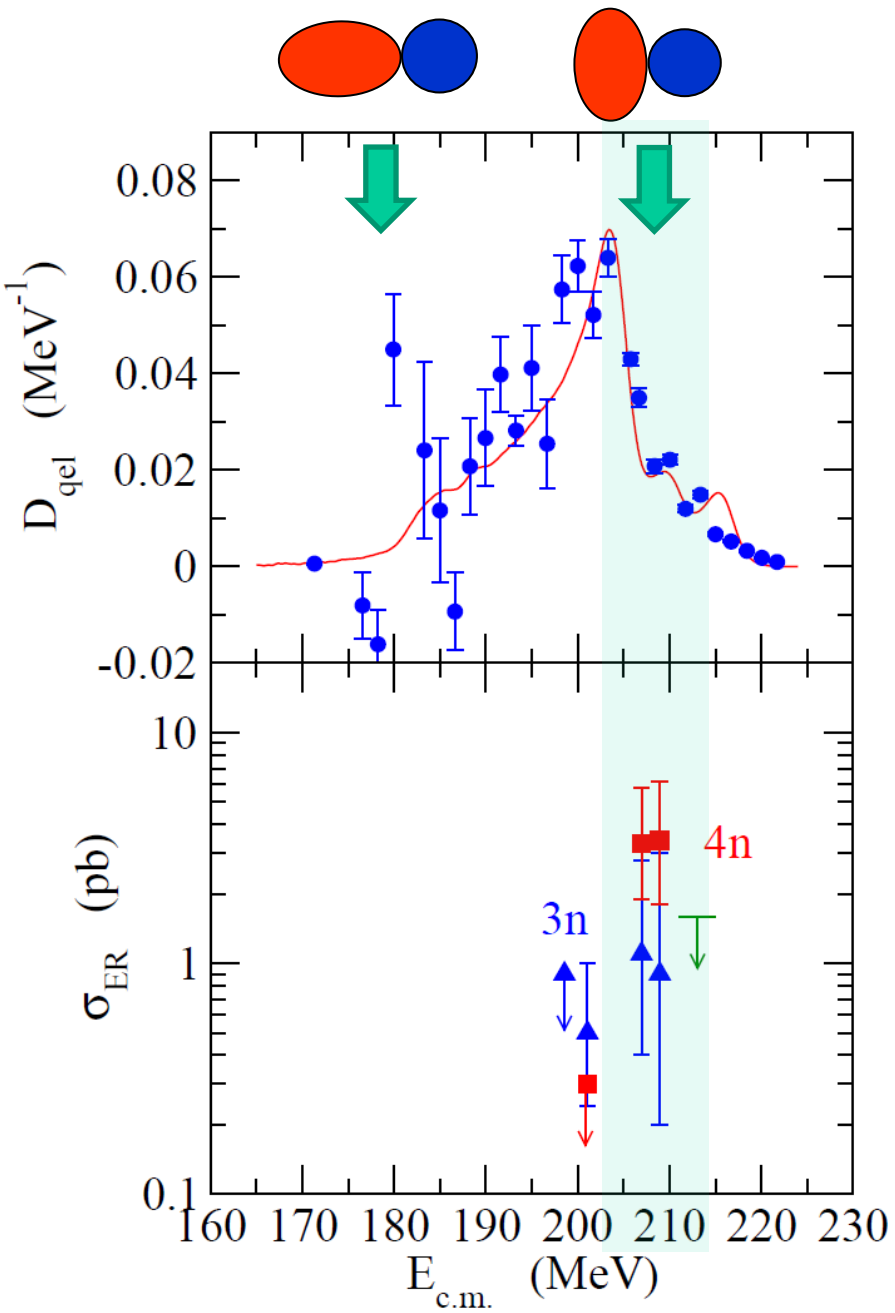


- ✓ ^{248}Cm deformation
- ✓ ^{48}Ca (oct. vib.)
- ✓ 1n transfer

the next question:

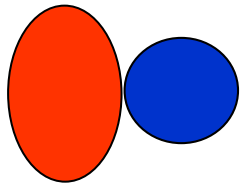


Connection to the ER cross sections

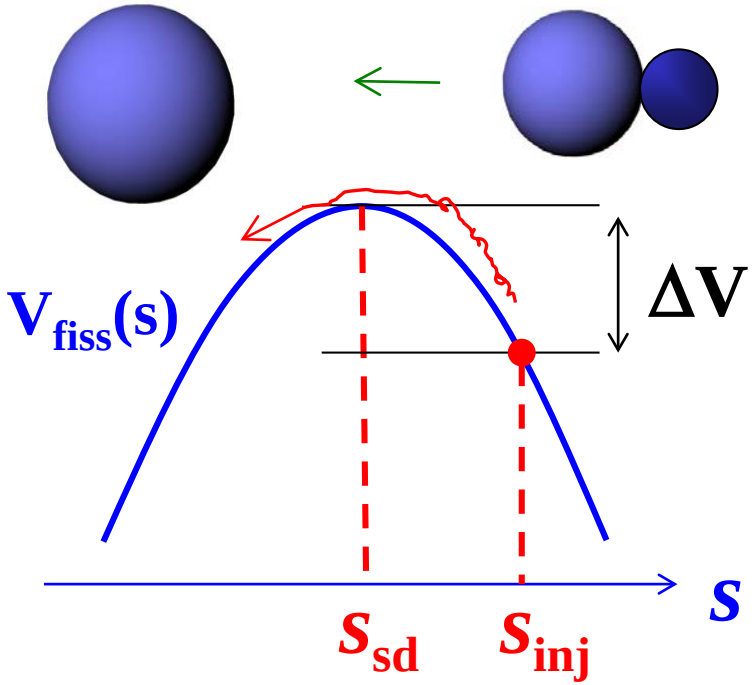


$^{48}Ca + {}^{248}Cm \rightarrow {}^{296}_{116}Lv^{*}$

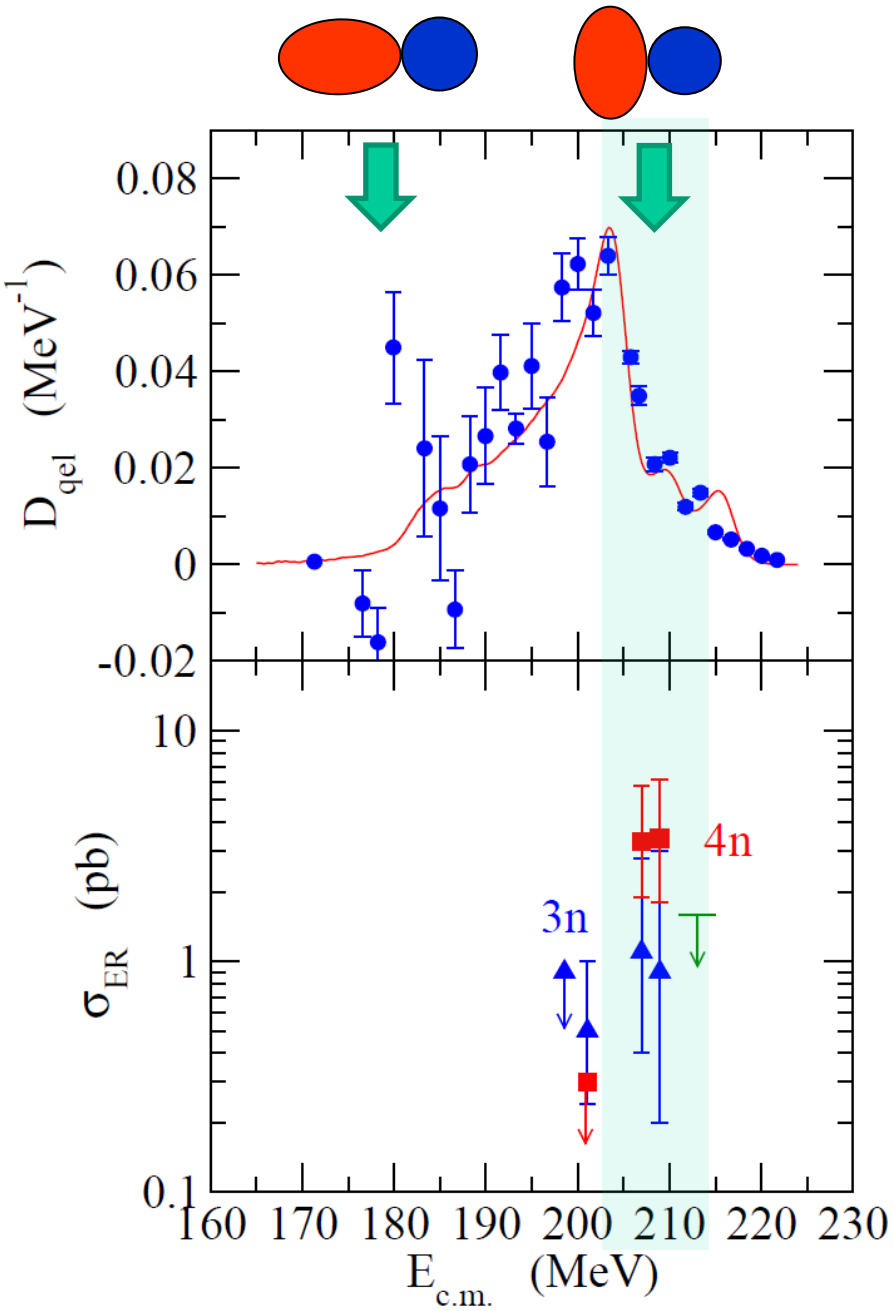
notion of compactness:
D.J. Hinde et al., PRL74 (‘95) 1295



= more compact at the touching
→ favorable for CN

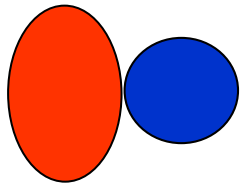


Connection to the ER cross sections

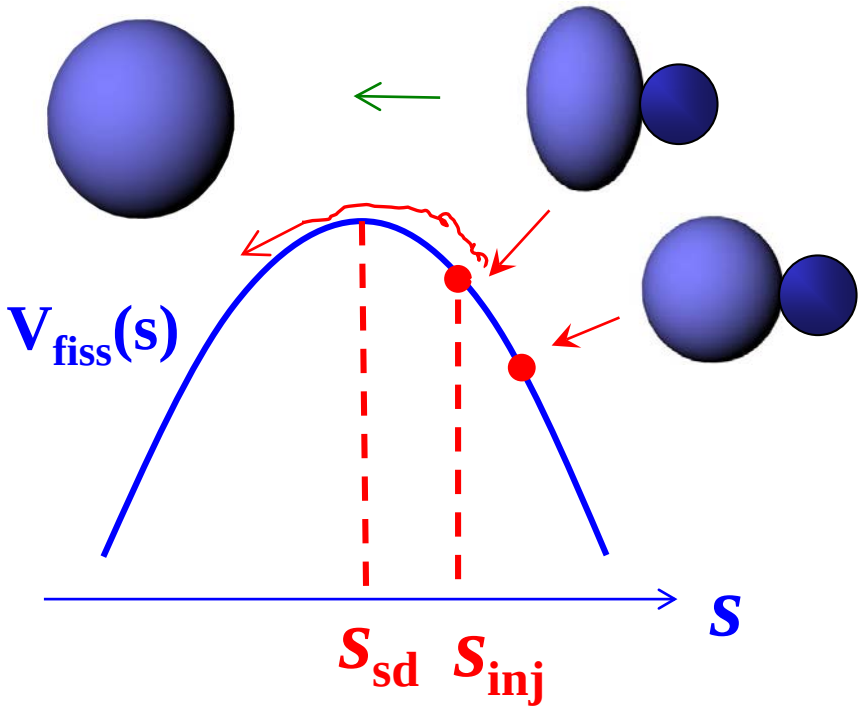


$^{48}Ca + {}^{248}Cm \rightarrow {}^{296}_{116}Lv^{*}$

notion of compactness:
D.J. Hinde et al., PRL74 (‘95) 1295

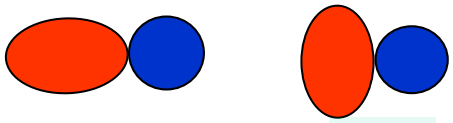


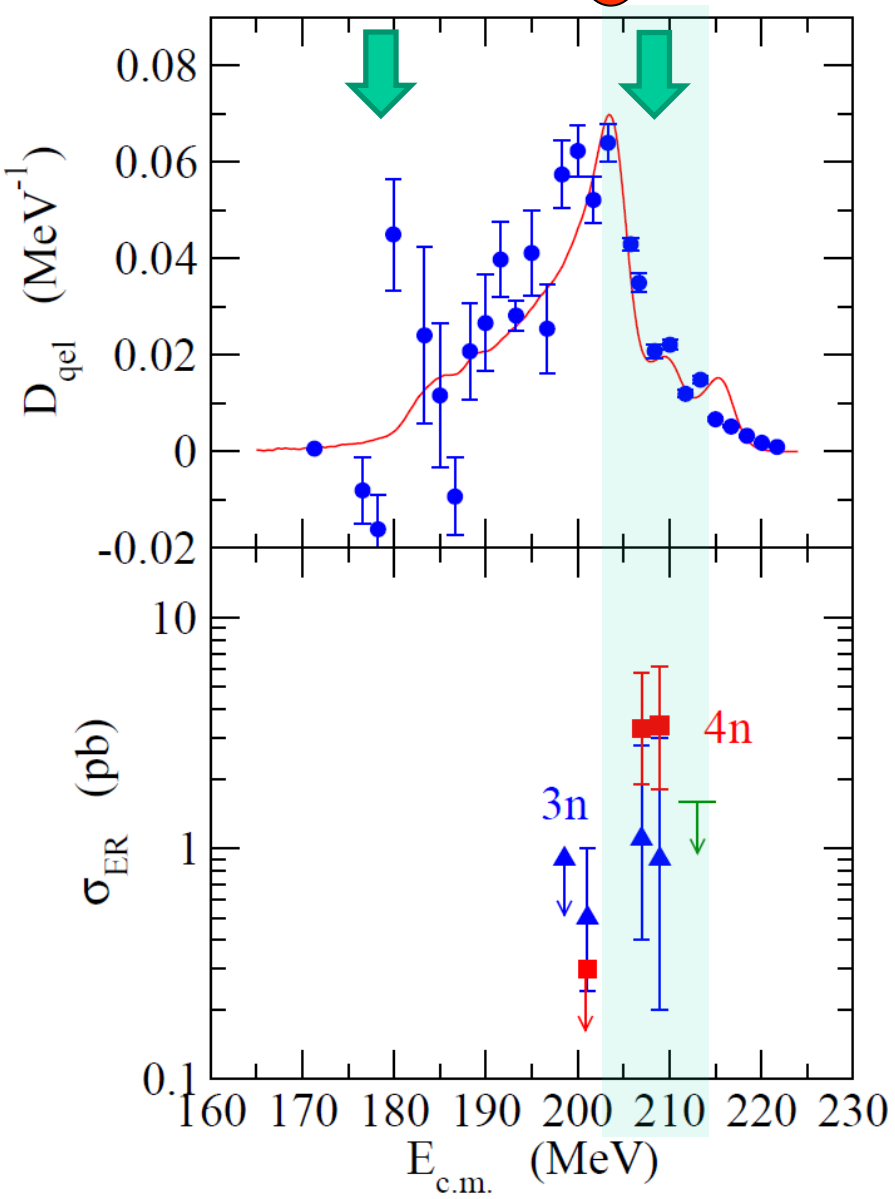
= more compact at the touching
→ favorable for CN



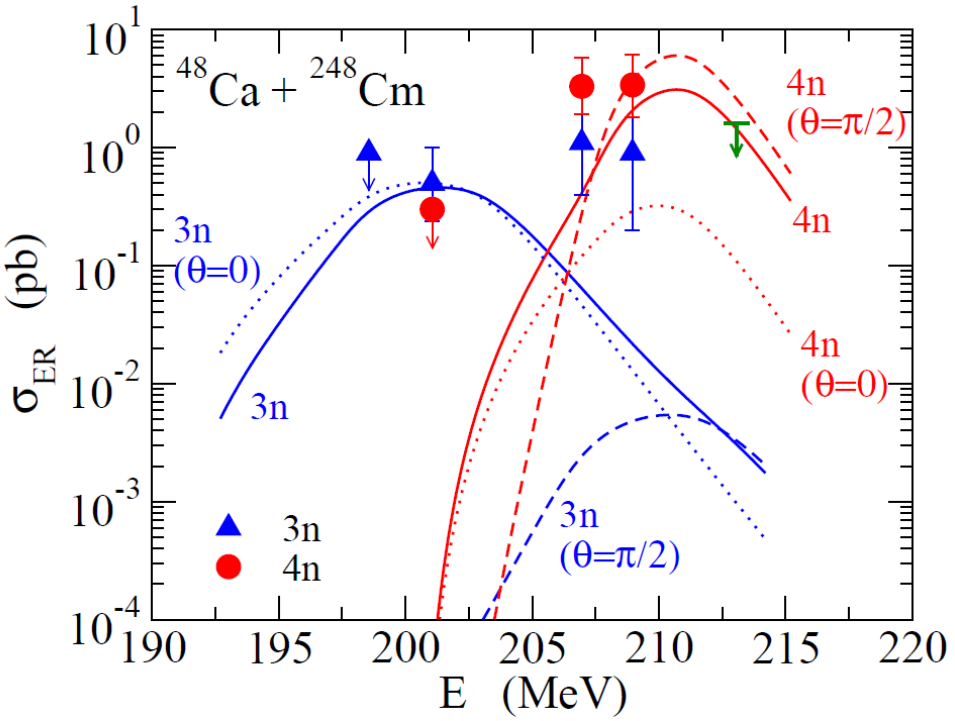
Connection to the ER cross sections

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





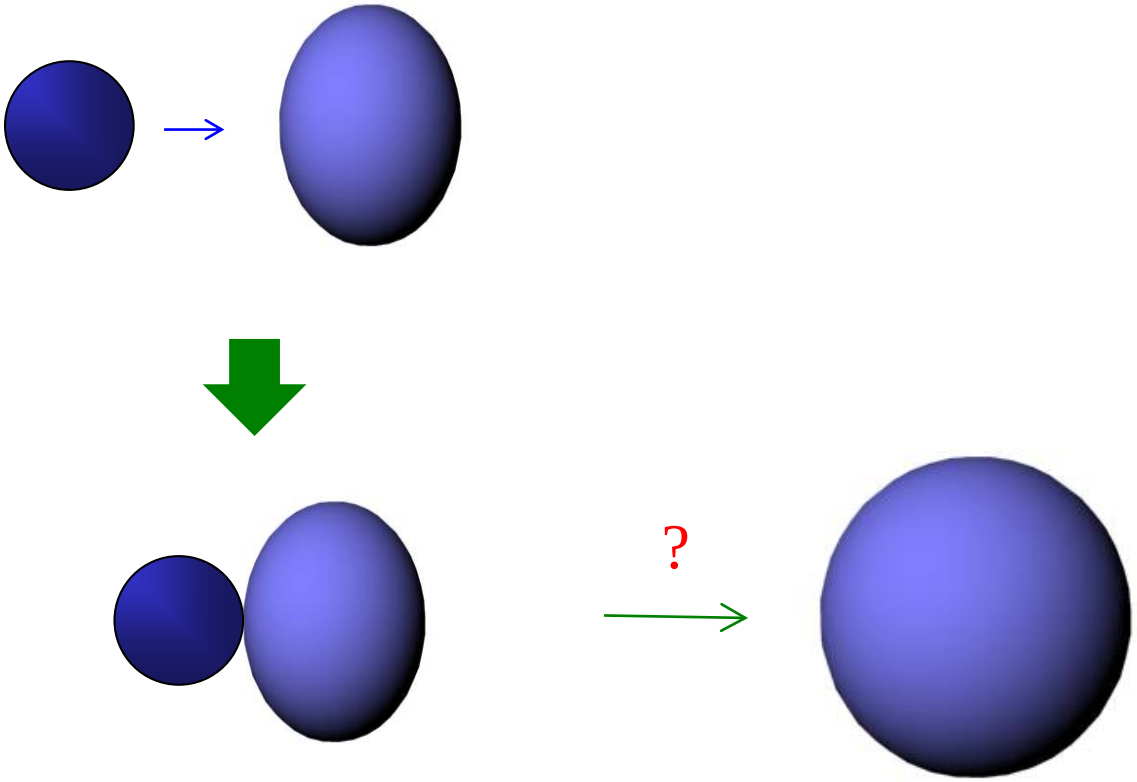
fusion-by-diffusion model



K.H., PRC98 (‘18) 014607

T.Tanaka et al., JPSJ87 (‘18) 014201

A more challenging problem



heat up

→ disappearance of quantum effects
(shell effect and deformation)

quantum theory for friction

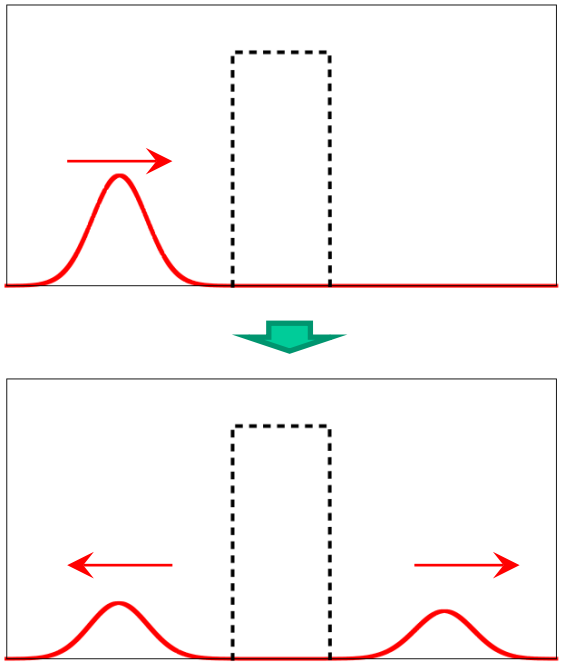
Quantum friction classical eq. of motion $\dot{p} = -V'(x) - \gamma p$

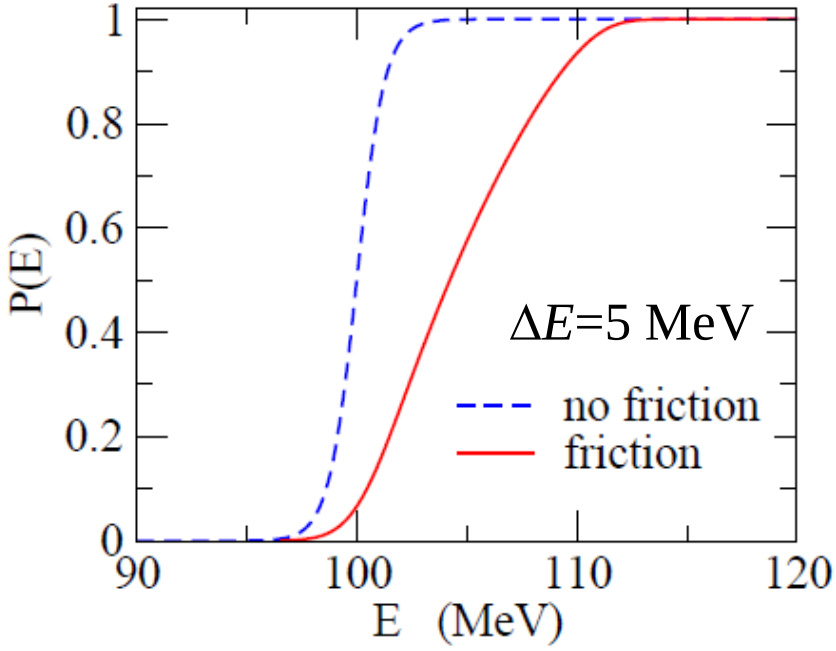
a quantization: Kanai model E. Kanai, PTP 3 (1948) 440

$$H = \frac{p^2}{2m} + V(x) \rightarrow \frac{\pi^2}{2m} e^{-\gamma t} + e^{\gamma t} V(x) \qquad (\pi = e^{\gamma t} p)$$

$$\longrightarrow \quad \frac{d}{dt}\langle p \rangle = -\langle V'(x) \rangle - \gamma \langle p \rangle$$

time-dep. wave packet approach

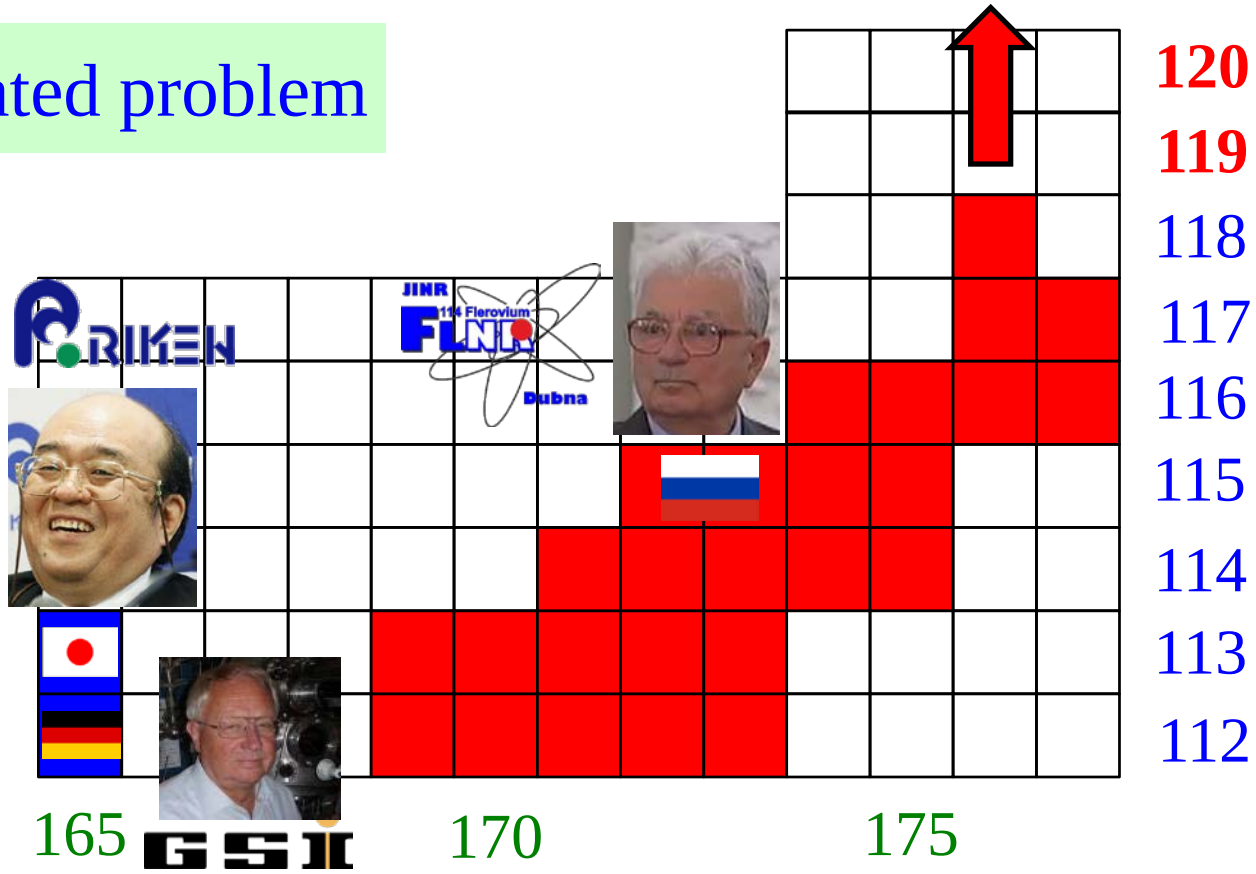




M. Tokieda and K.H., PRC95 (‘17) 054604

Tokieda’s talk on Saturday (Nuclear Reactions-1)

A related problem



hot fusion reaction:

$$^{48}_{20}\mathrm{Ca} + \cancel{^{254}_{99}\mathrm{Es}} \rightarrow {}^{302}119$$

not available with sufficient amount

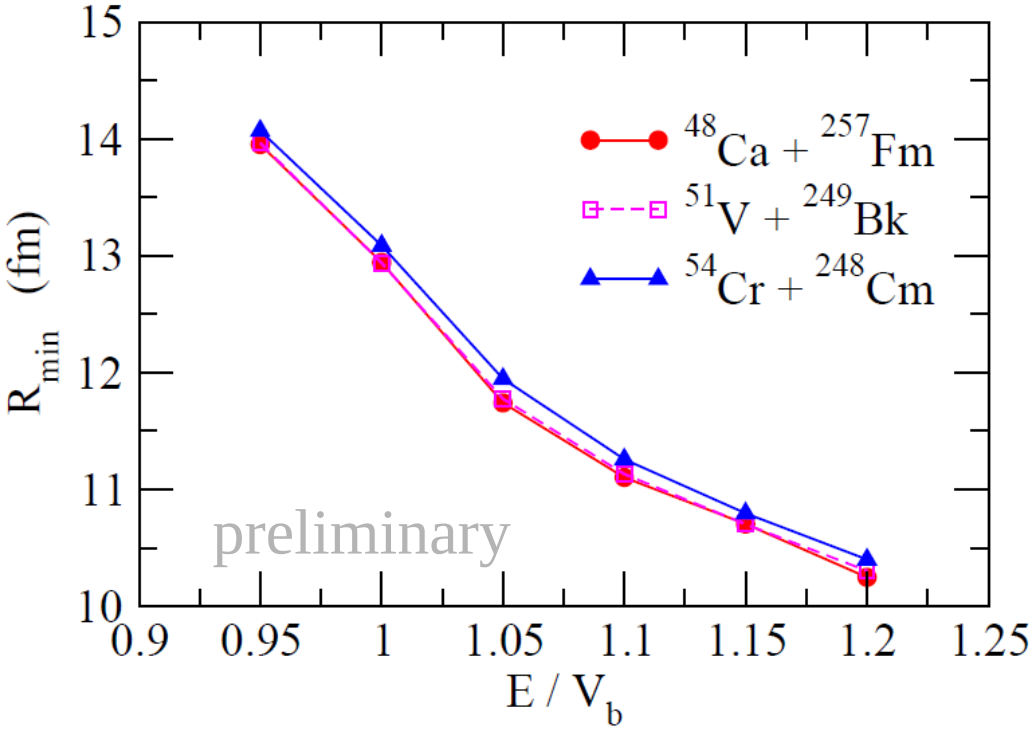
$$^{51}_{23}\mathrm{V} + {}^{248}_{96}\mathrm{Cm} \rightarrow {}^{299}119 \text{ etc.}$$

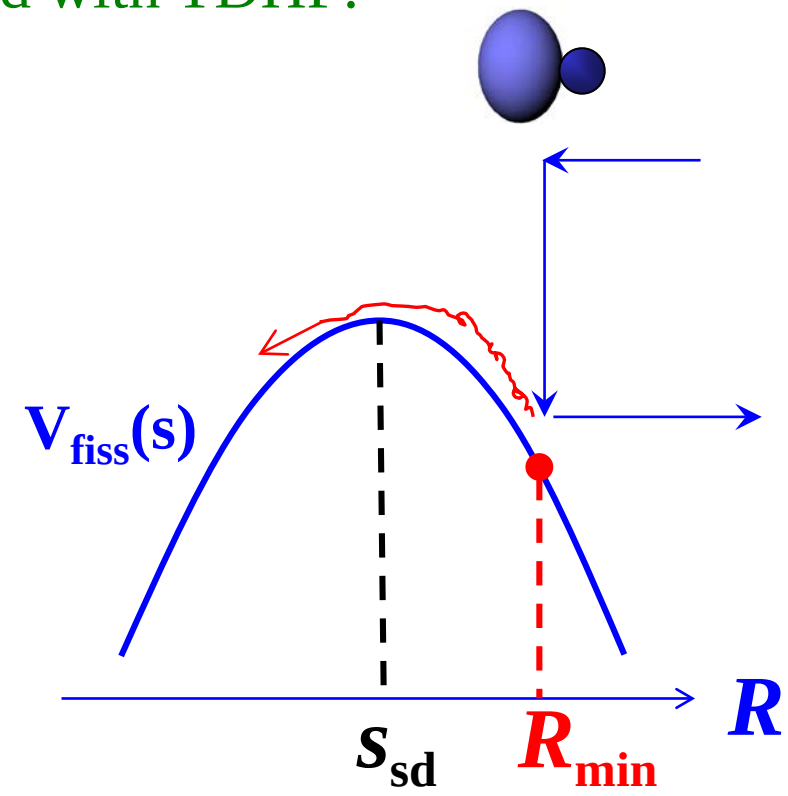
how much will fusion cross sections be influenced?

TDHF+Langevin approach

K. Sekizawa, Y. Aritomo, and K.H., a work in progress

the distance of closest approach estimated with TDHF:





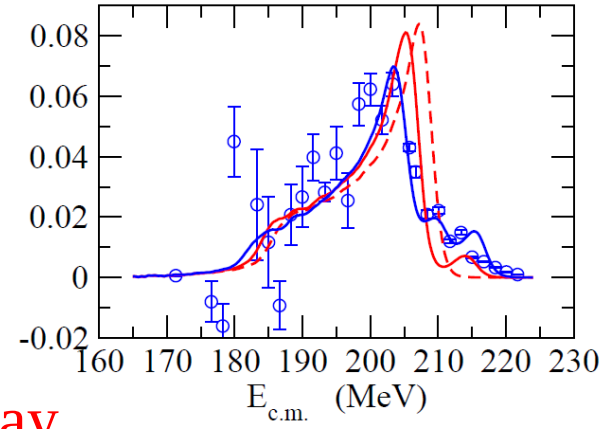
input to Langevin calculations

comparison between ^{48}Ca- and ^{51}V-induced reations (on going)

Summary

Reaction dynamics for SHE formation reactions

- Recent measurement of barrier distributions with GARIS
  - ✓ $^{48}Ca + ^{248}Cm$
  - ✓ coupled-channels analysis
  - ✓ notion of compactness: ER formation with side collisions



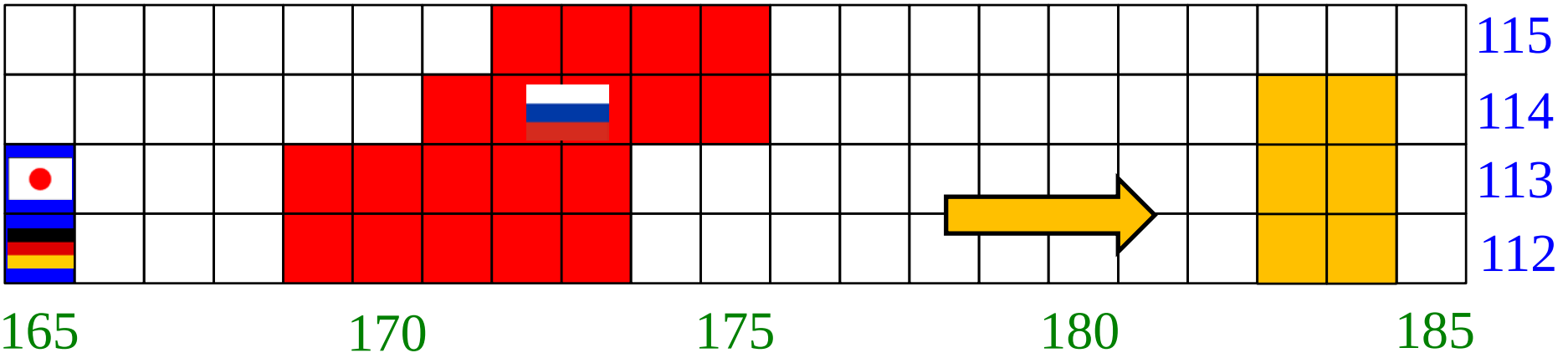
more data coming soon

cf. T. Tanaka's talk on Saturday (Nuclear Reactions -1)

- Open problems
  - ✓ reaction dynamics? → quantum theory for friction
  - ✓ shape evolution with a deformed target?

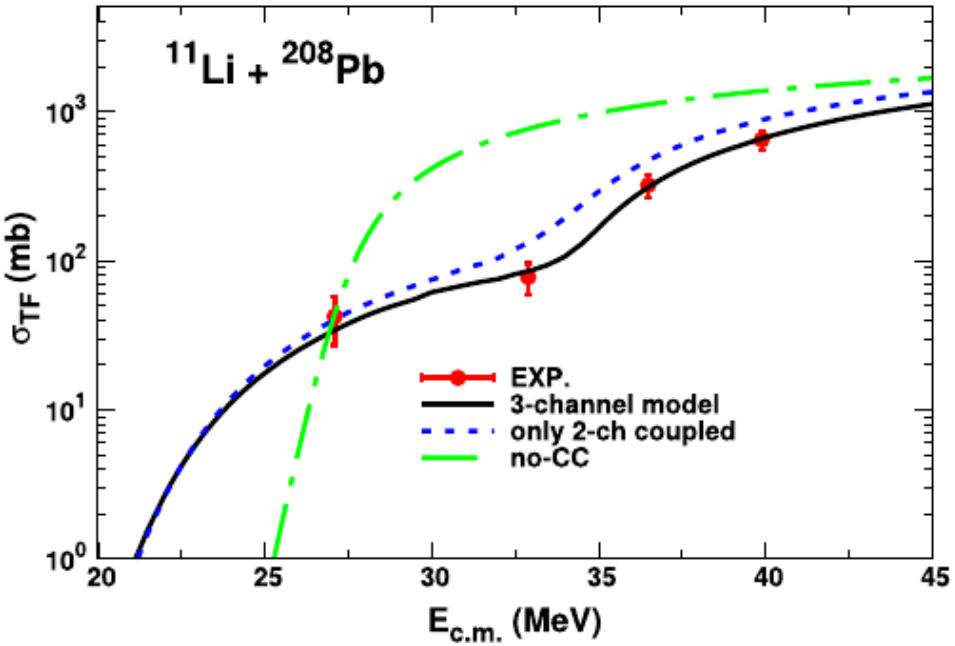
    how does the deformation disappear during heat-up?
  - ✓ towards island of stability

Towards the island of stability



neutron-rich beams: indispensable

→ reaction dynamics with neutron-rich beams?



more studies are needed

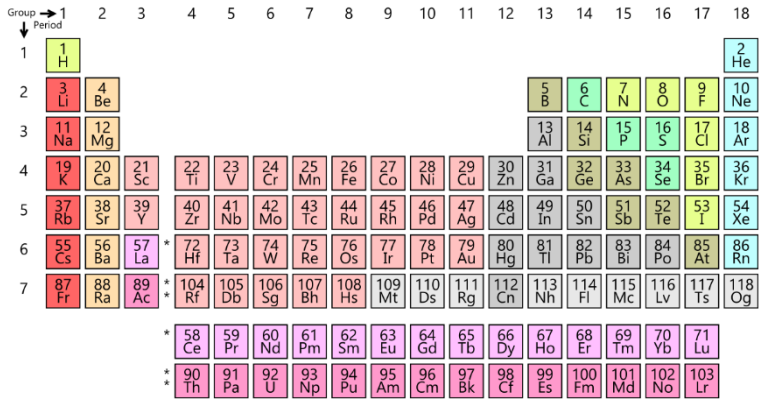
K.-S. Choi, M.-K. Cheoun, W.Y. So, K.H., and K.S. Kim, PLB780 (‘18) 455.

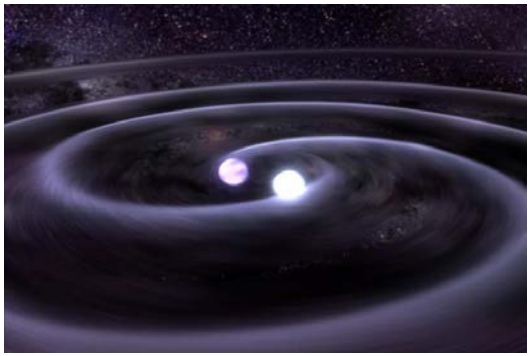
SHE as an interdisciplinary sicence

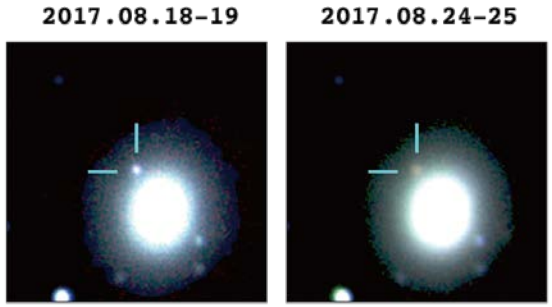
formation of SHE

chemistry of SHE

the origin of (S)HE







heavy-ion fusion reactions

2019 IYPT

International Year of the Periodic Table of Chemical Elements

r-process nucleosynthesis

✓ fission

SHE: quantum many-body systems with a strong Coulomb field

→ comprehensive understanding of SHE