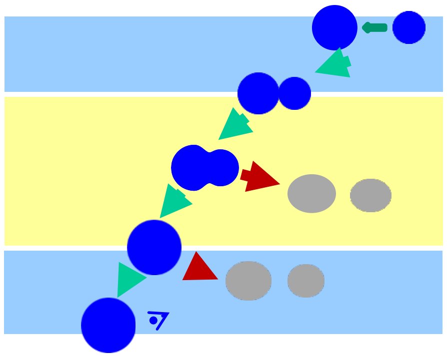
RIBF Users meeting 2016 2016.9.8

Theoretical challenges in fusion reactions relevant to superheavy elements

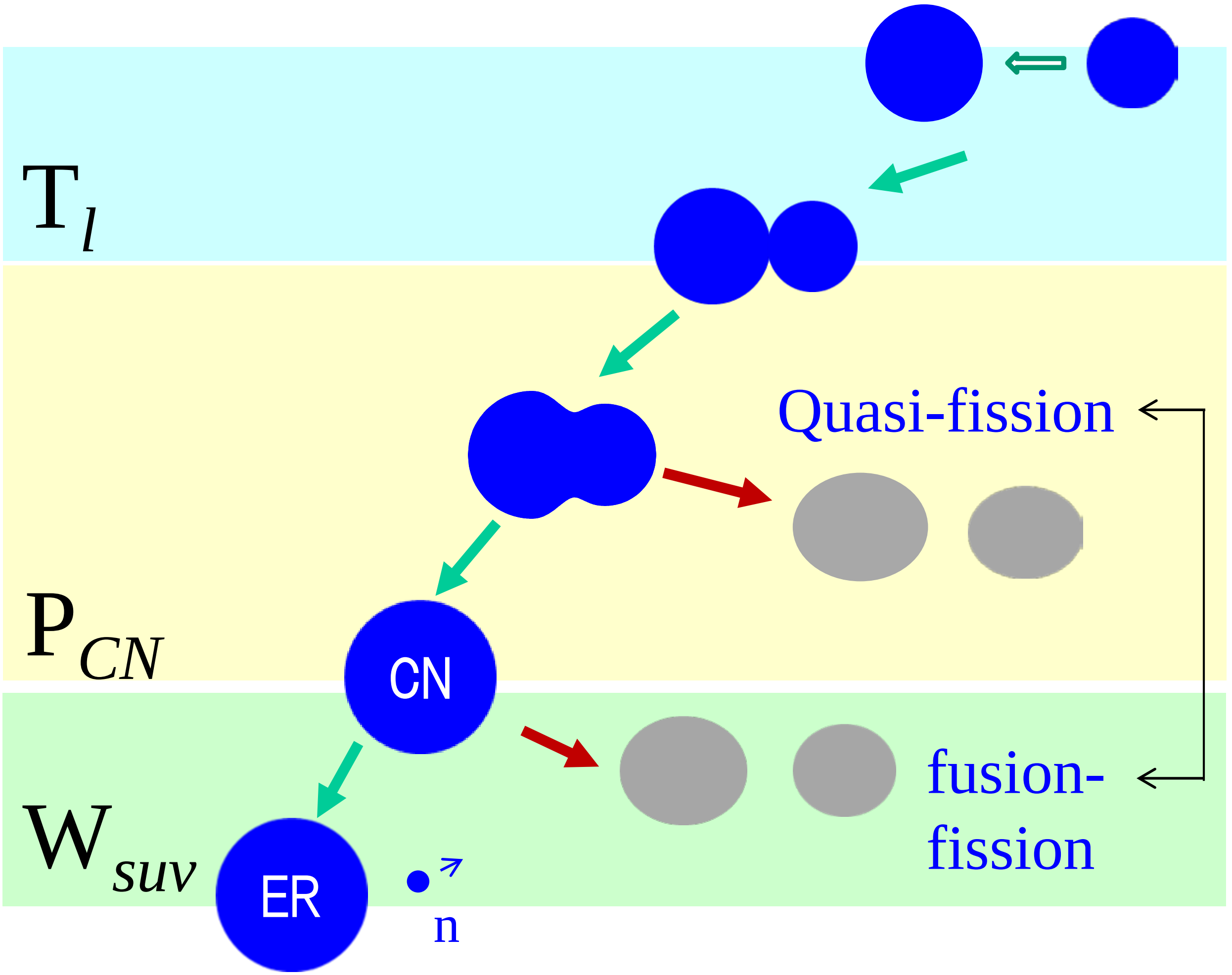
Kouichi Hagino
Tohoku University, Sendai, Japan

TOHOKU UNIVERSITY



1. Introduction: Fusion reactions for SHE
2. Approaching phase: coupled-channels method
3. Formation phase: Langevin method
4. Survival phase: statistical model
5. Towards Z=119-120 and island of stability

Introduction: Fusion reactions for SHE



CN = compound nucleus
ER = evaporation residue

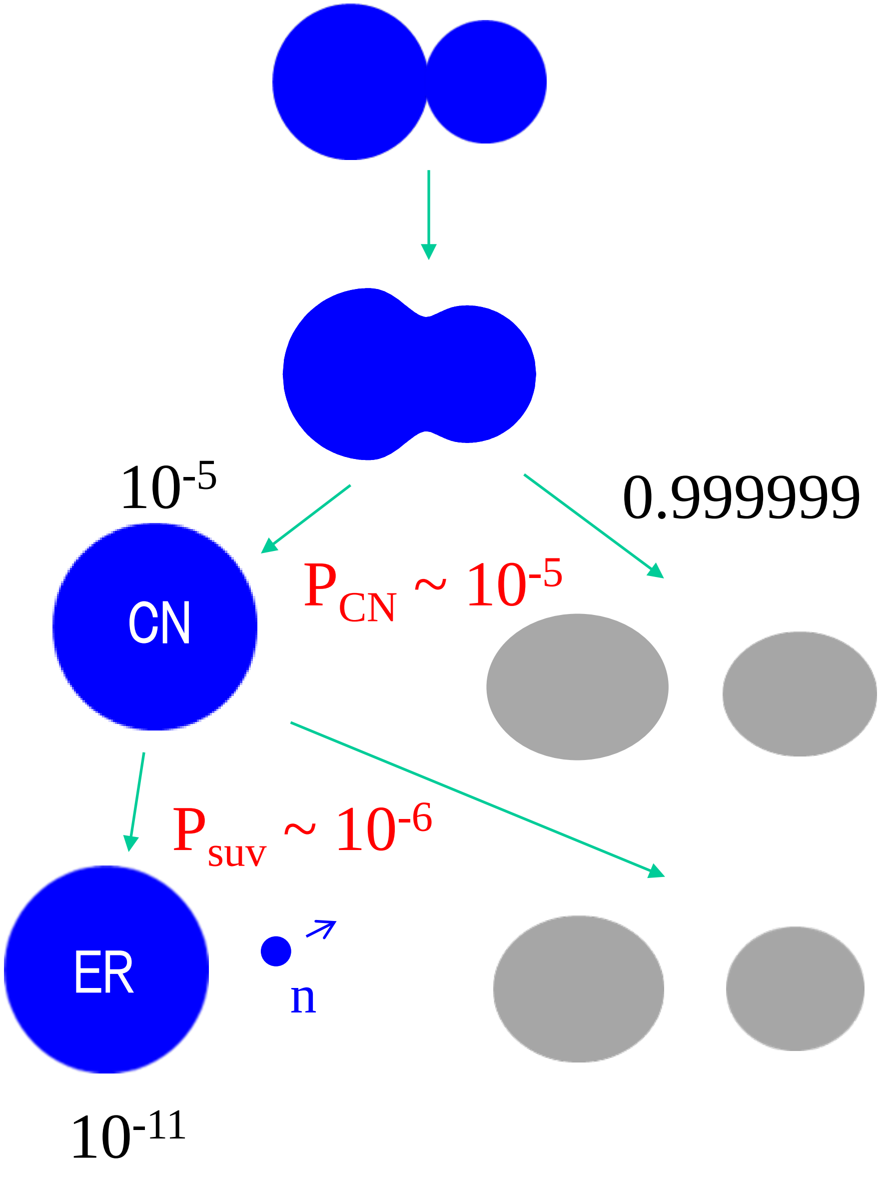
$$\sigma_{\mathrm{ER}}(E) = \frac{\pi}{k^2} \sum_{l} (2l+1) T_l(E)\, P_{\mathrm{CN}}(E,l)\, W_{\mathrm{suv}}(E^*,l)$$

formation of evaporation residues:
a very rare process

a small uncertainty in each process can be largely amplified

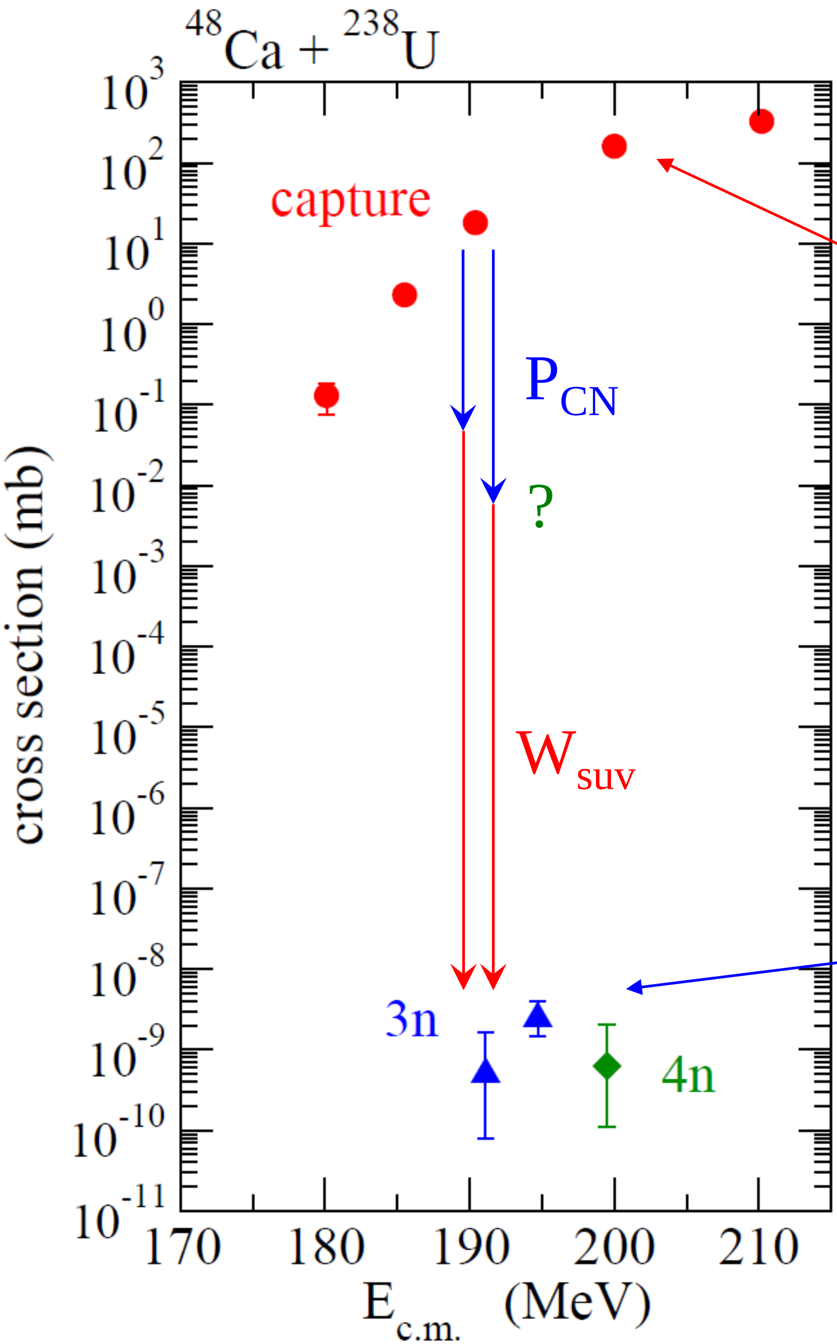
challenges: how to reduce theoretical uncertainties and make a reliable prediction

typical values for Ni+Pb reaction



another issue:

no experimental data for P_{CN}



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

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

not available

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

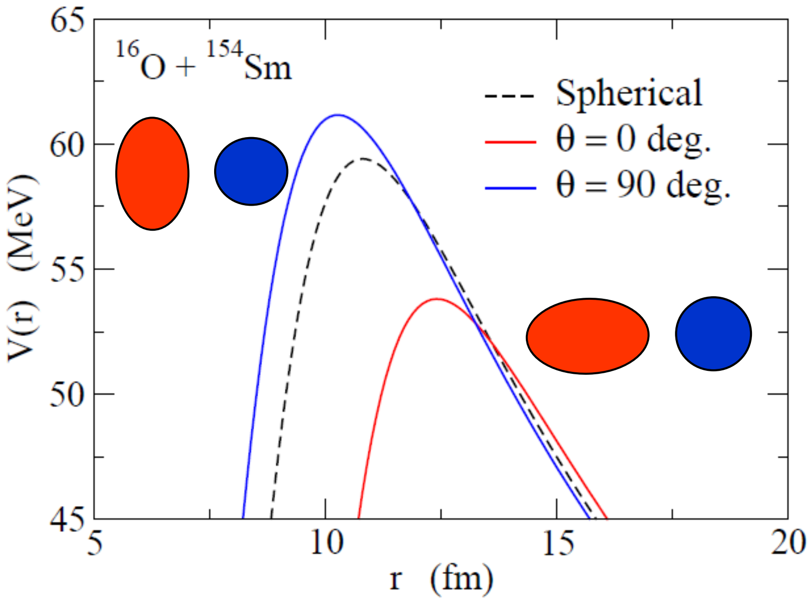
large uncertainties

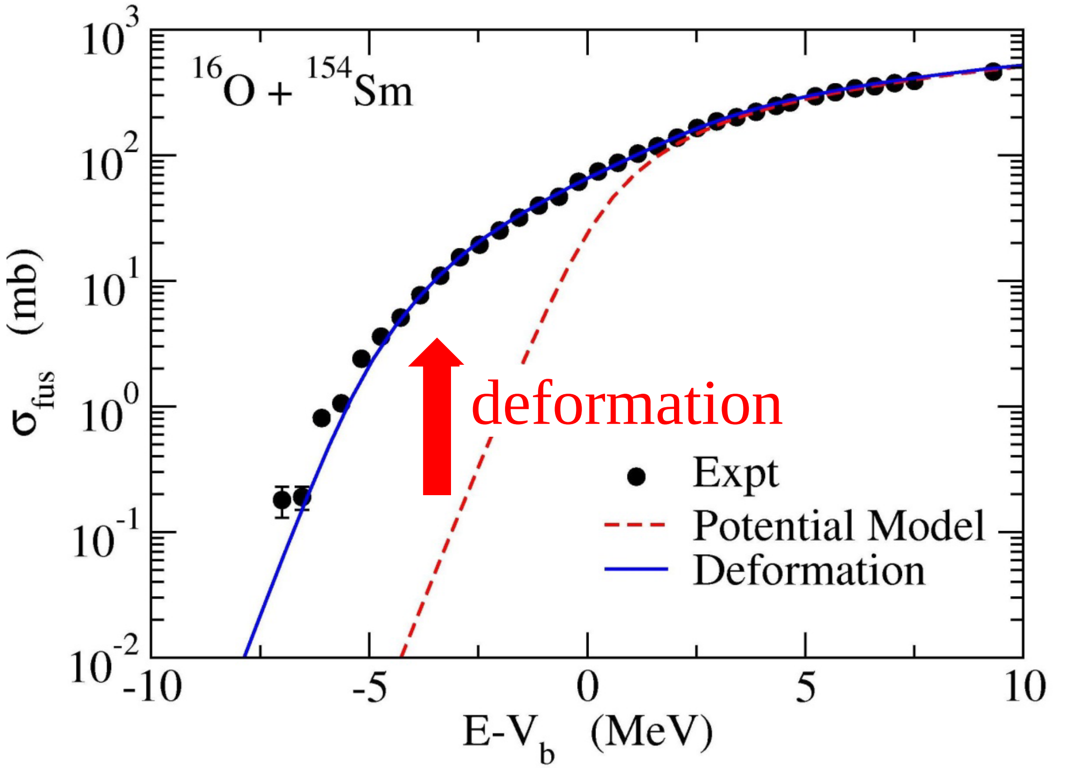
Approaching phase: coupled-channels method

Sub-barrier enhancement of capture cross sections

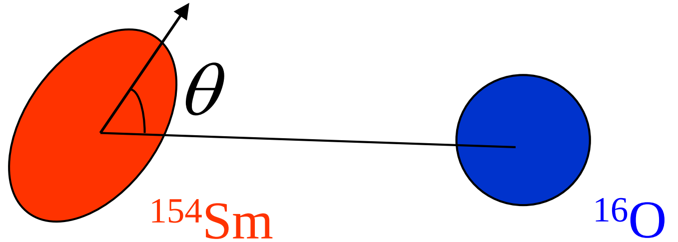
⟵ channel coupling effects

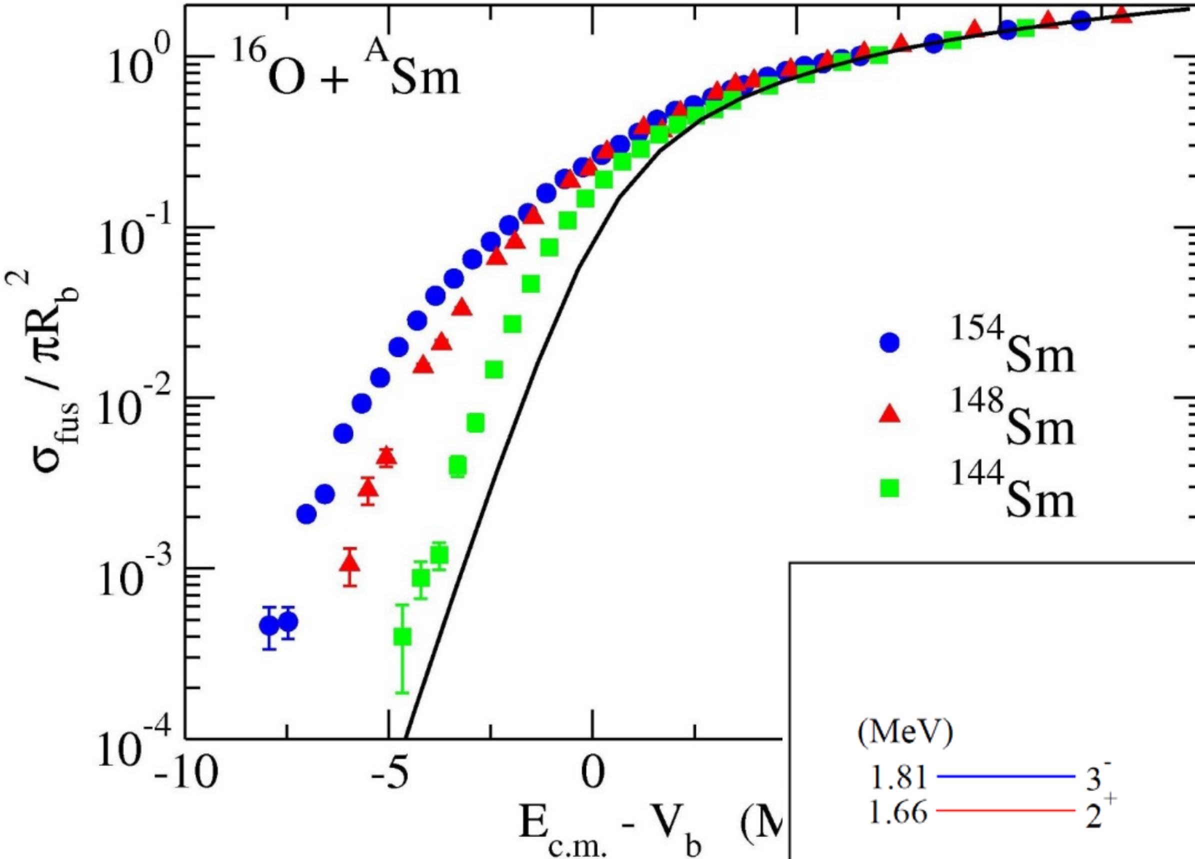
role of deformation

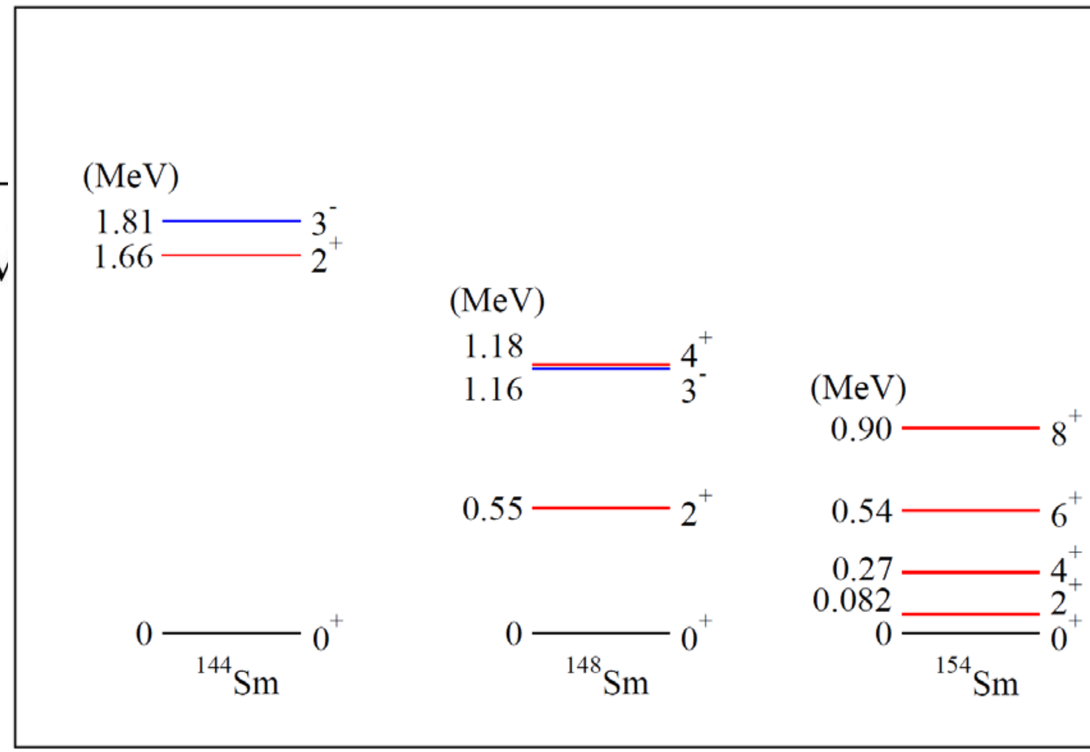




$$\sigma_{\rm cap}(E) = \int_0^1 d(\cos\theta)\sigma_{\rm cap}(E;\theta)$$







sub-barrier enhancement
in general

→ couplings to **low-lying collective motions**

⇩

coupled-channels method

K.H., N. Takigawa, PTP128 (‘12) 1061

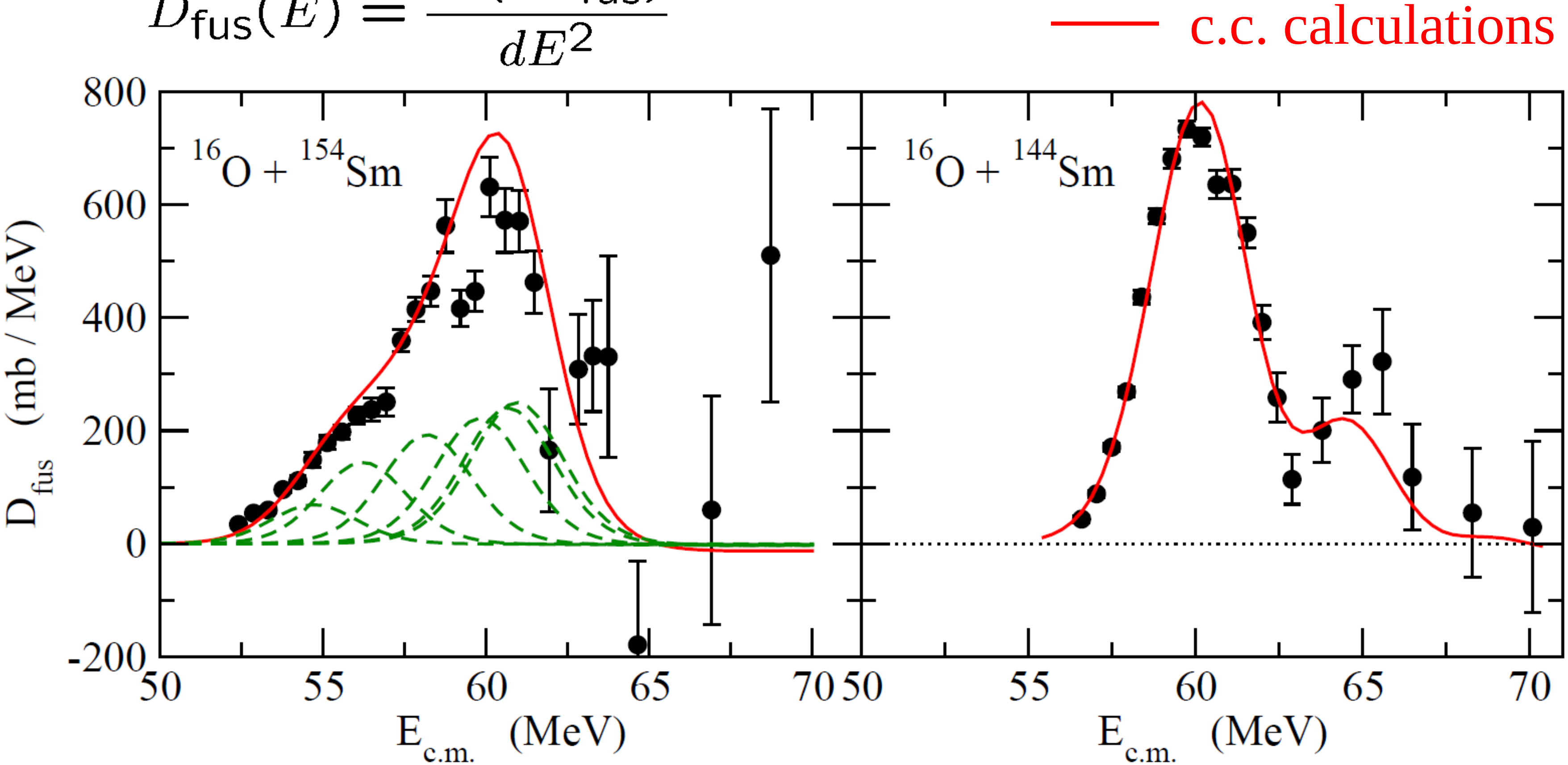
C.C. method: a standard tool for H.I. sub-barrier fusion reactions

CCFULL (K.H., N. Rowley, A.T. Kruppa, CPC123 (‘99) 143)

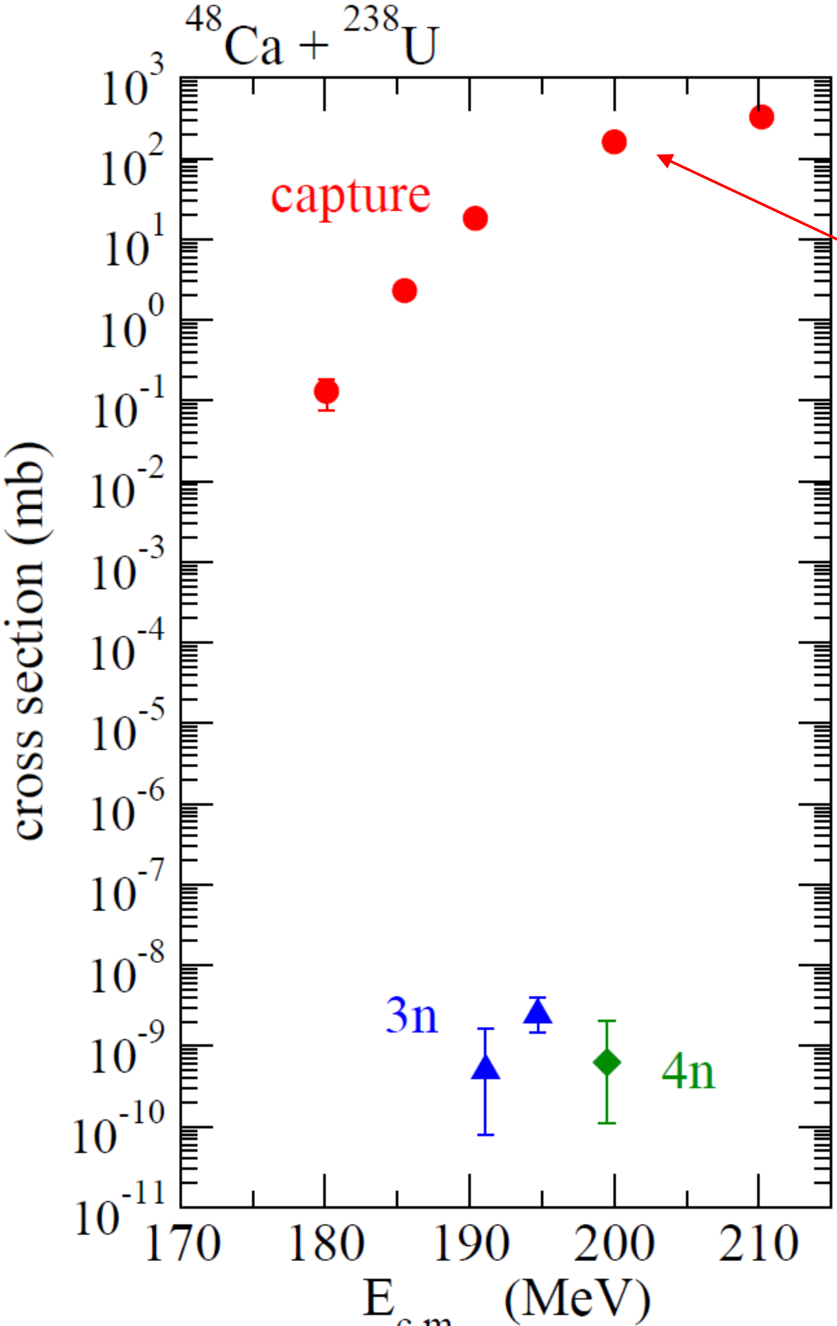
cf. Coulomb excitations: important for SHE

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

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



K.H., N. Takigawa, PTP128 (‘12) 1061



Experimental data exist for σ_{cap}

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

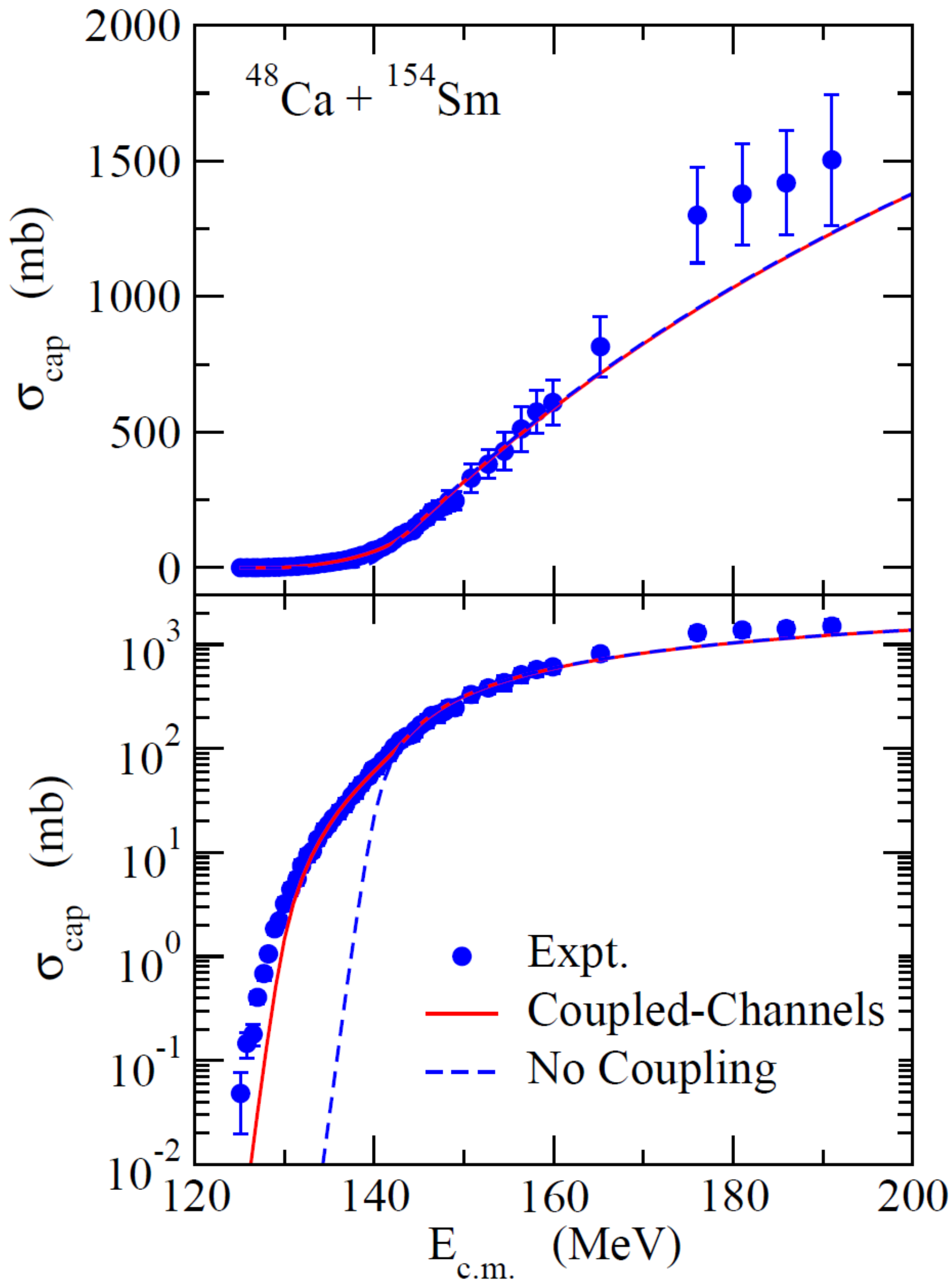
inputs for C.C. calculations

i) inter-nucleus potential

fit to exp. data for capture

ii) intrinsic motions

collective model
(rigid rotor / harmonic vibrators)



calculations with CCFULL

$^{48}Ca + ^{154}Sm$ (rot: up to 16^+)

$\sigma_{exp} \longrightarrow \sigma_{cc} \longrightarrow T_l(E)$

* enhancement at very low energies → transfer process

Recent development: CCFULL + nuclear structure

inputs for C.C. calculations

i) inter-nucleus potential

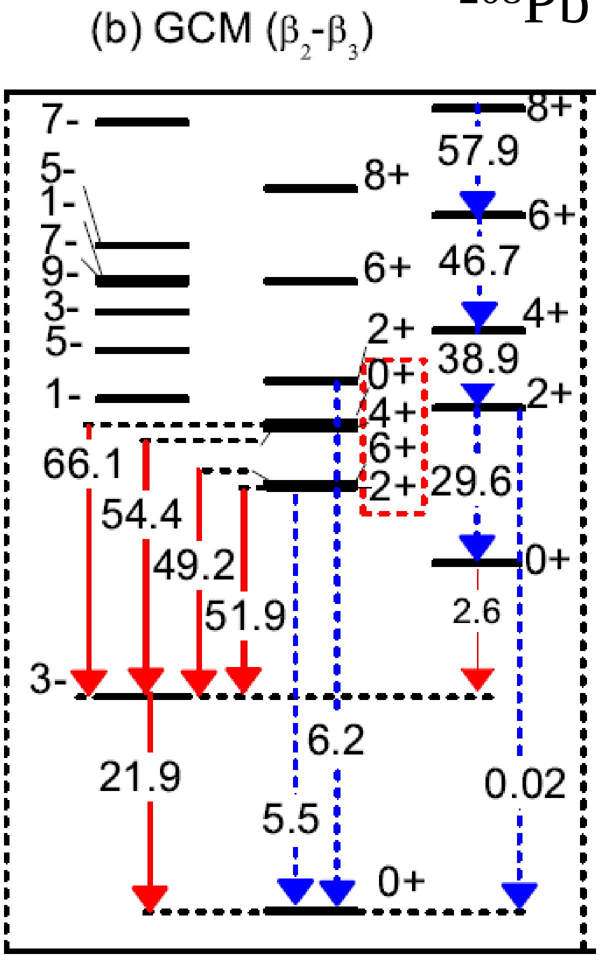
fit to exp. data for capture

ii) intrinsic motions

collective model
(rigid rotor / harmonic vibrators)

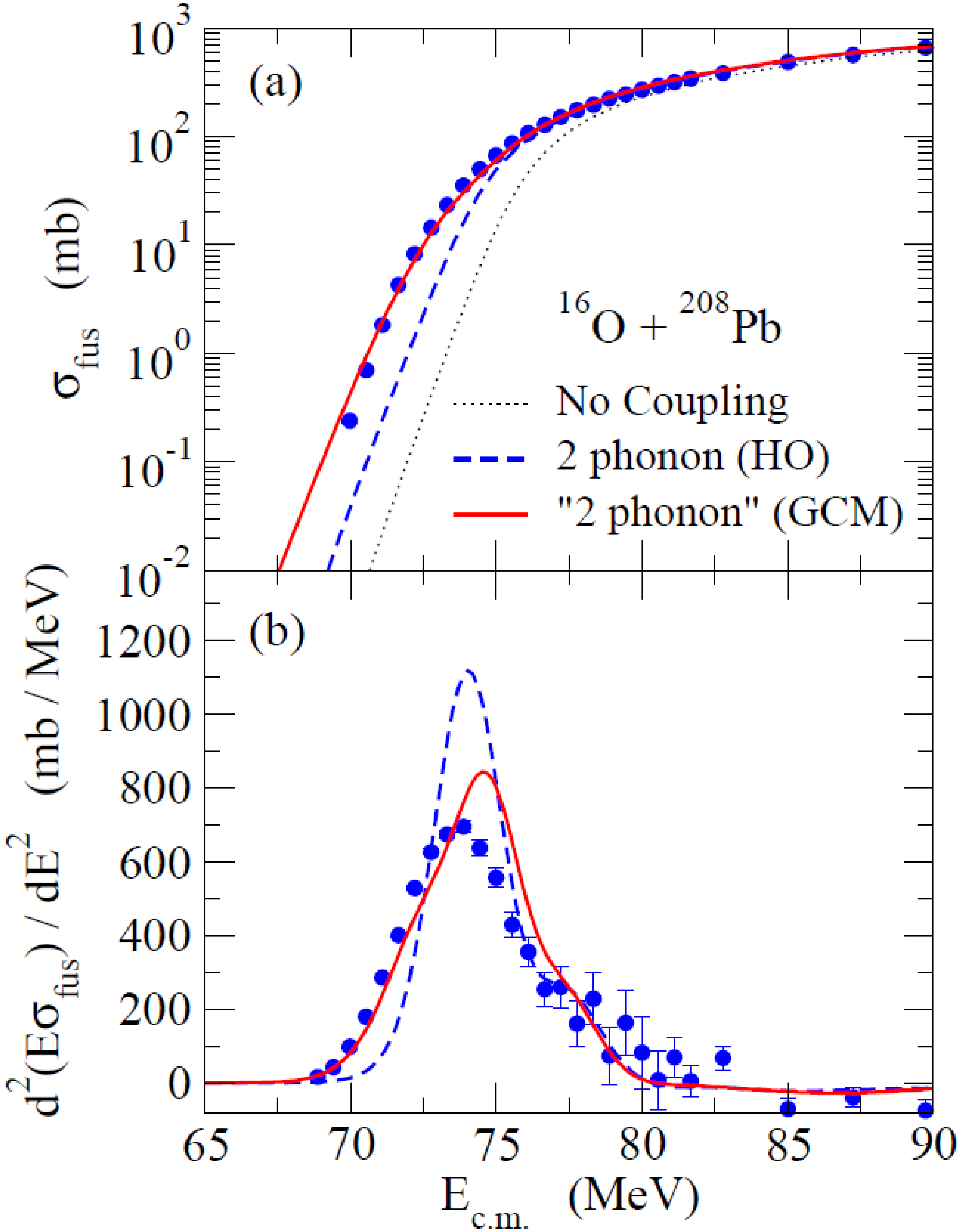
CCFULL
+ nuclear structure calculations
(GCM, Shell Model, IBM…..)

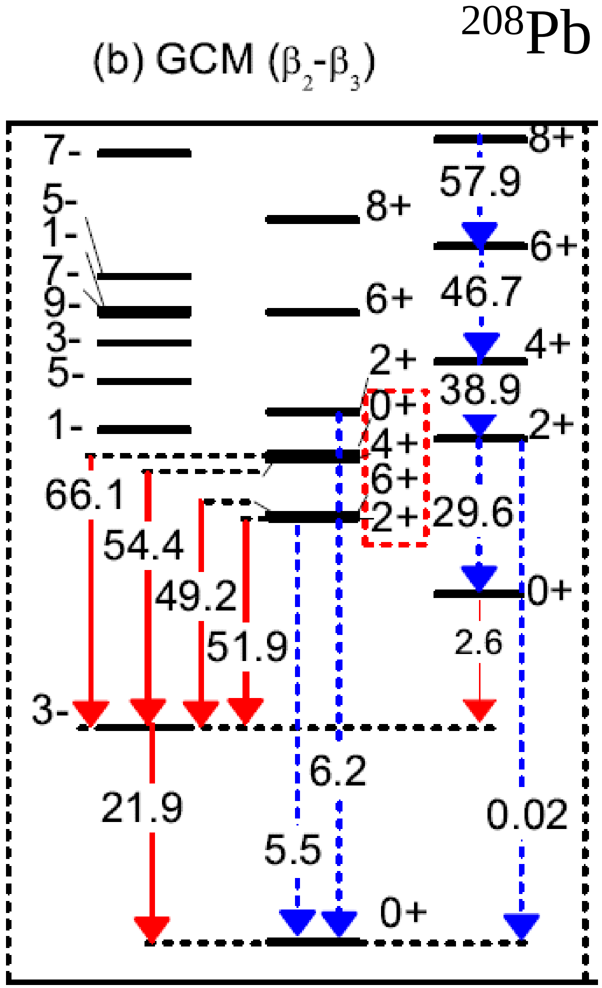
^{208}Pb



J.M. Yao and K.H.,
PRC94 (‘16) 11303(R)

GCM + CCFULL





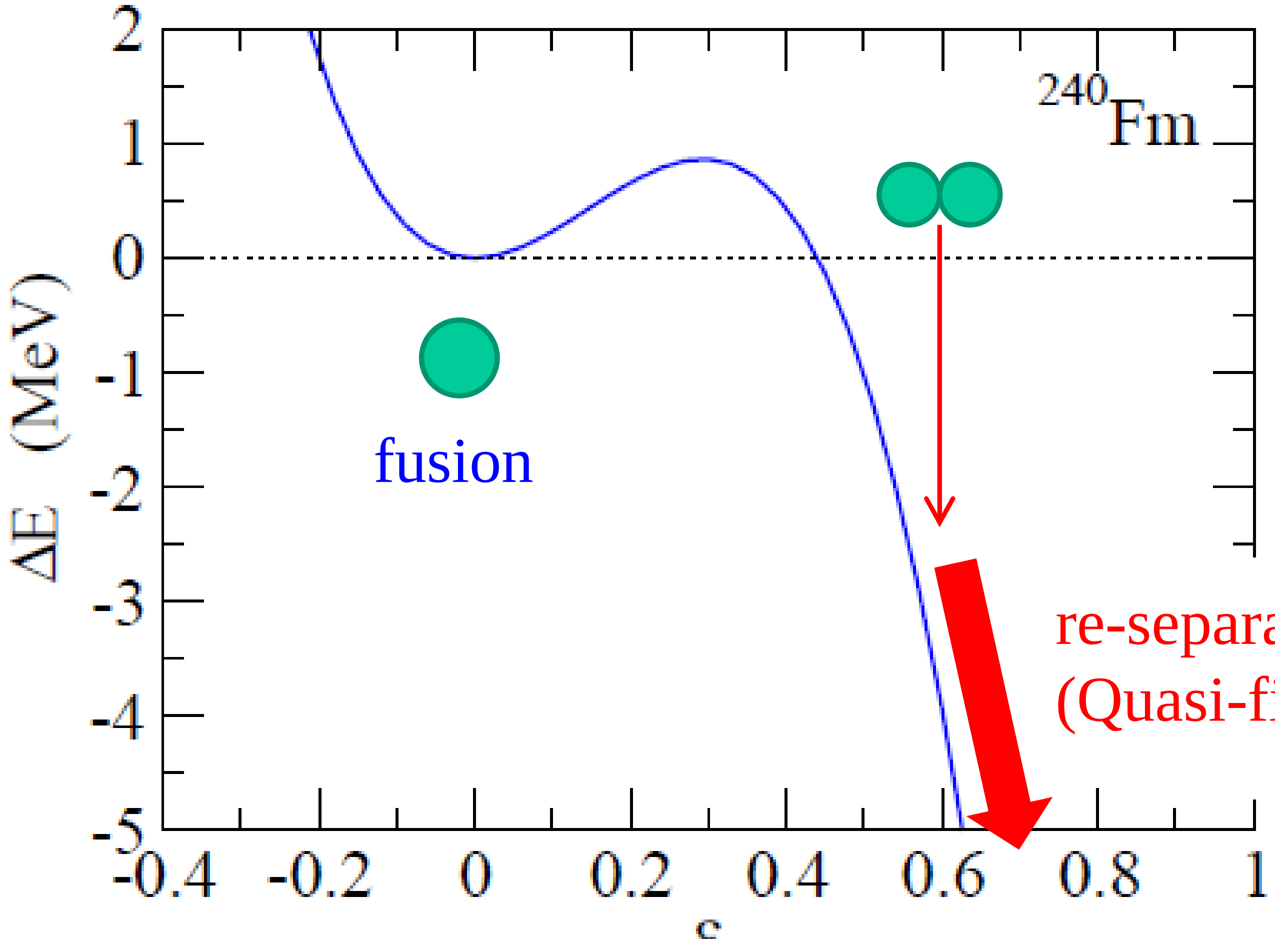
J.M. Yao and K.H., PRC94 ('16) 11303(R)

Formation phase: Langevin method

Fission barrier (Liquid Drop Model)

touching point:
outside the fission barrier

$^{120}_{50}Sn + ^{120}_{50}Sn \rightarrow ^{240}_{100}Fm$



(deformation)

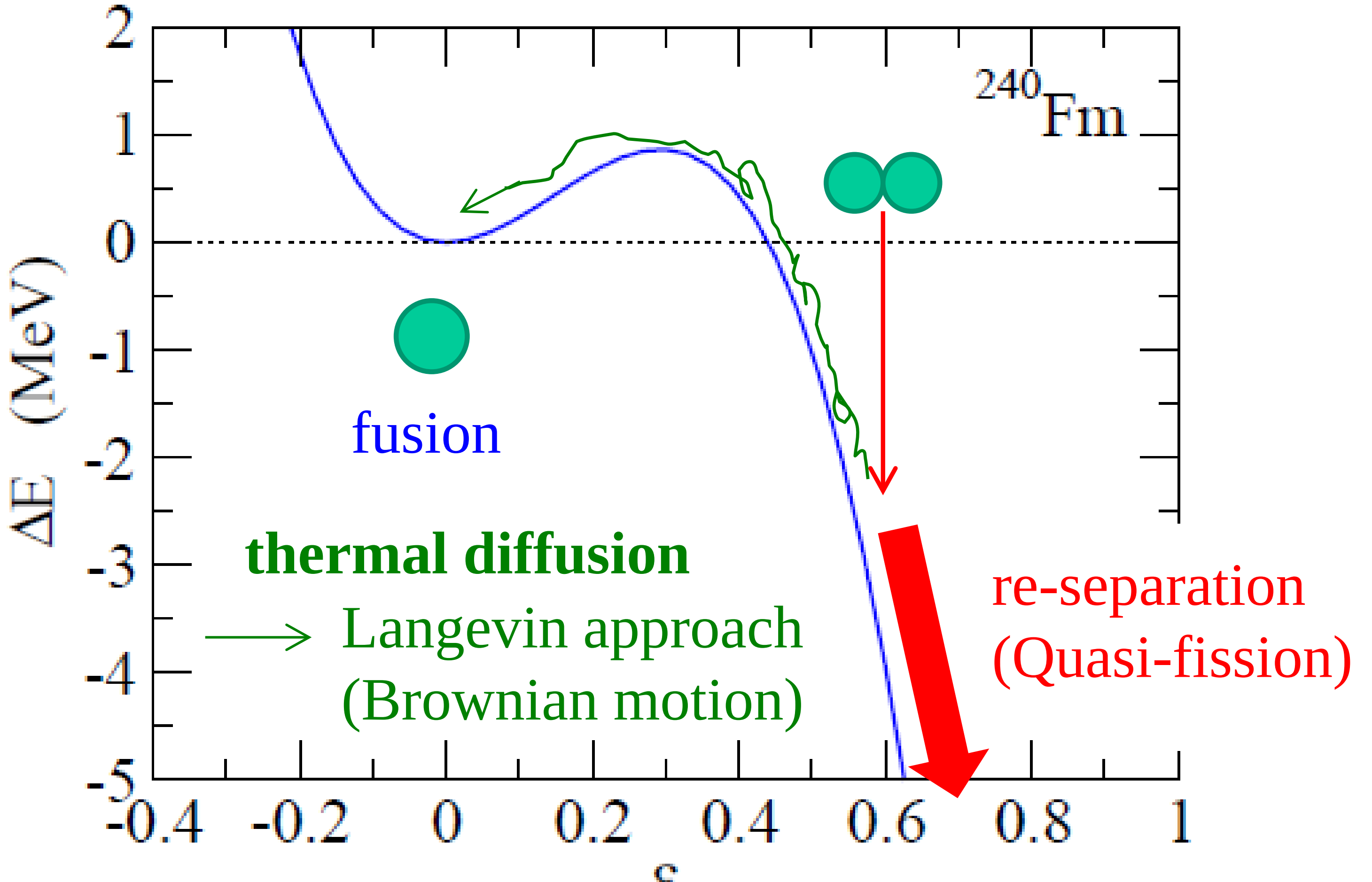
$\varepsilon_{touch} \sim 0.587$

Formation phase: Langevin method

Fission barrier (Liquid Drop Model)

touching point:
outside the fission barrier

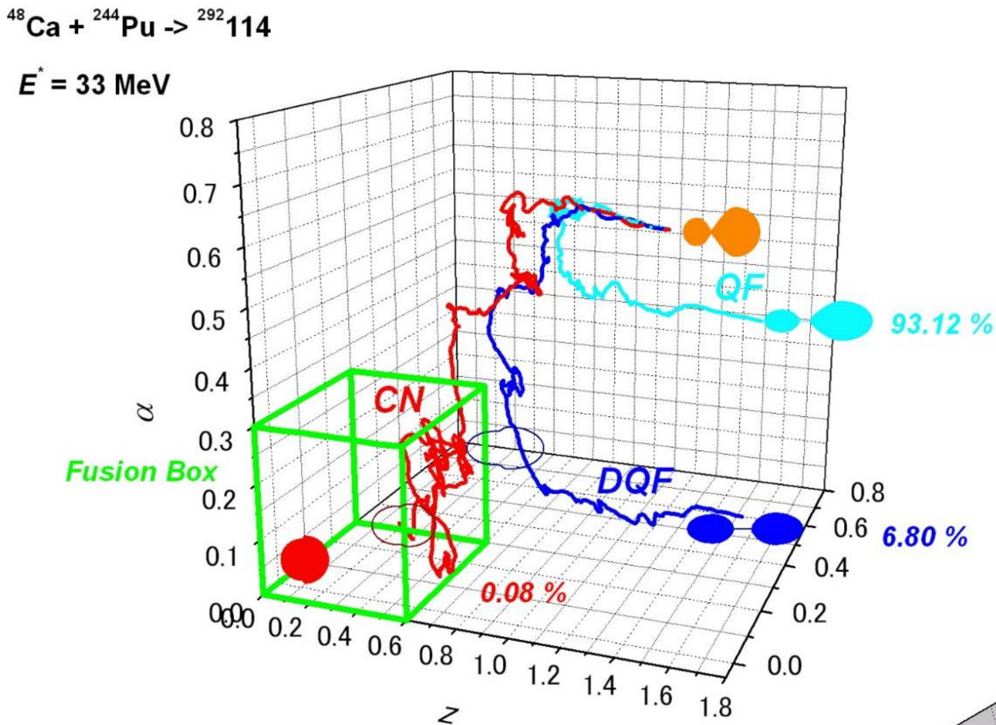
$^{120}_{50}Sn + ^{120}_{50}Sn \rightarrow ^{240}_{100}Fm$



(deformation)

$\varepsilon_{touch} \sim 0.587$

Langevin approach

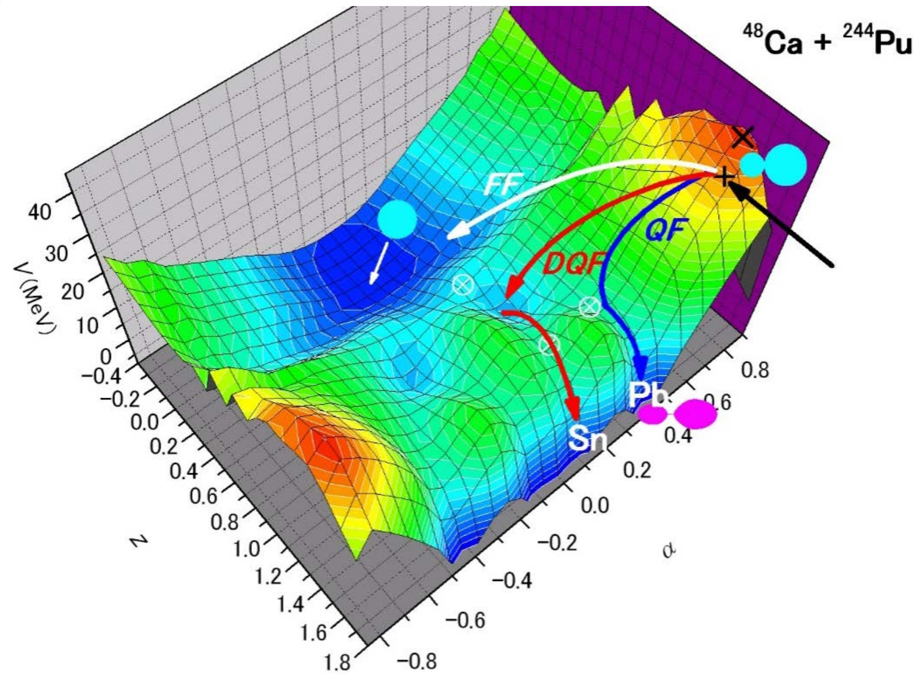


multi-dimensional extension of:

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

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

q:
- internuclear separation (*z*)
- deformation (δ)
- mass asymmetry (α) of the two fragments

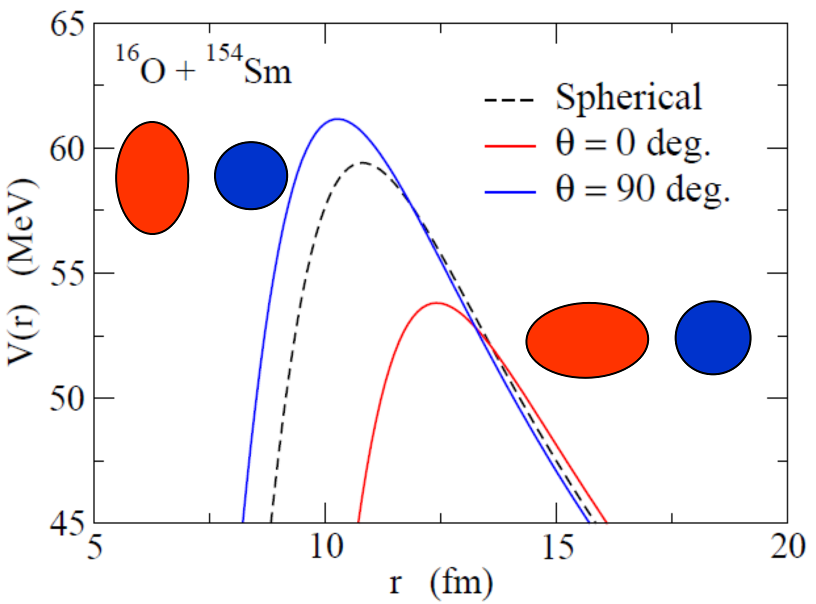


✓ Y. Aritomo et al.
✓ Zagrebaev-Greiner

extension to deformed systems

hot fusion: actinide targets

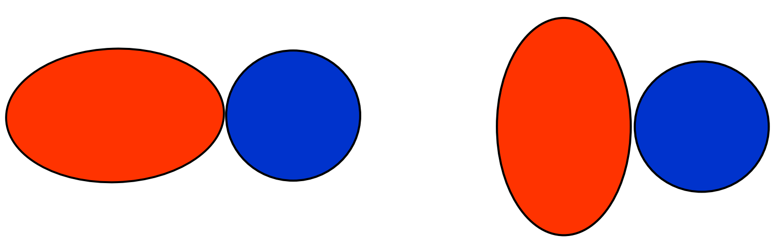
Dubna: ^{48}Ca + ^{249}Cf (β_2 = 0.235) $\rightarrow$ $^{297-x}$Og (Z=118) + xn



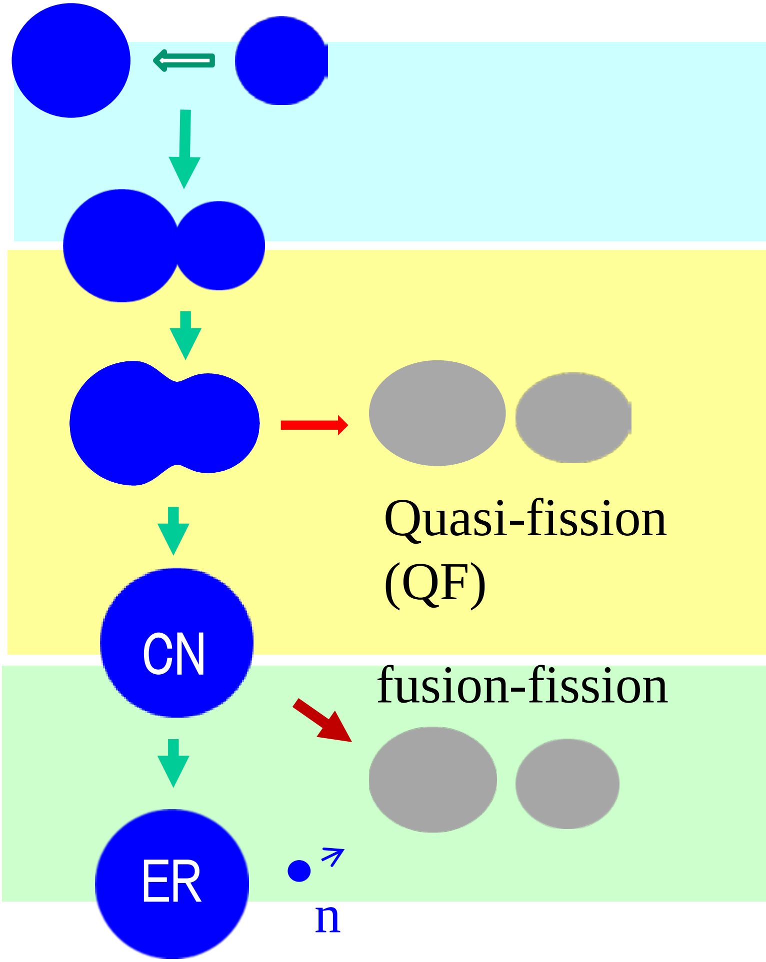
$$\sigma_{\rm cap}(E) = \int_0^1 d(\cos\theta)\sigma_{\rm cap}(E;\theta)$$

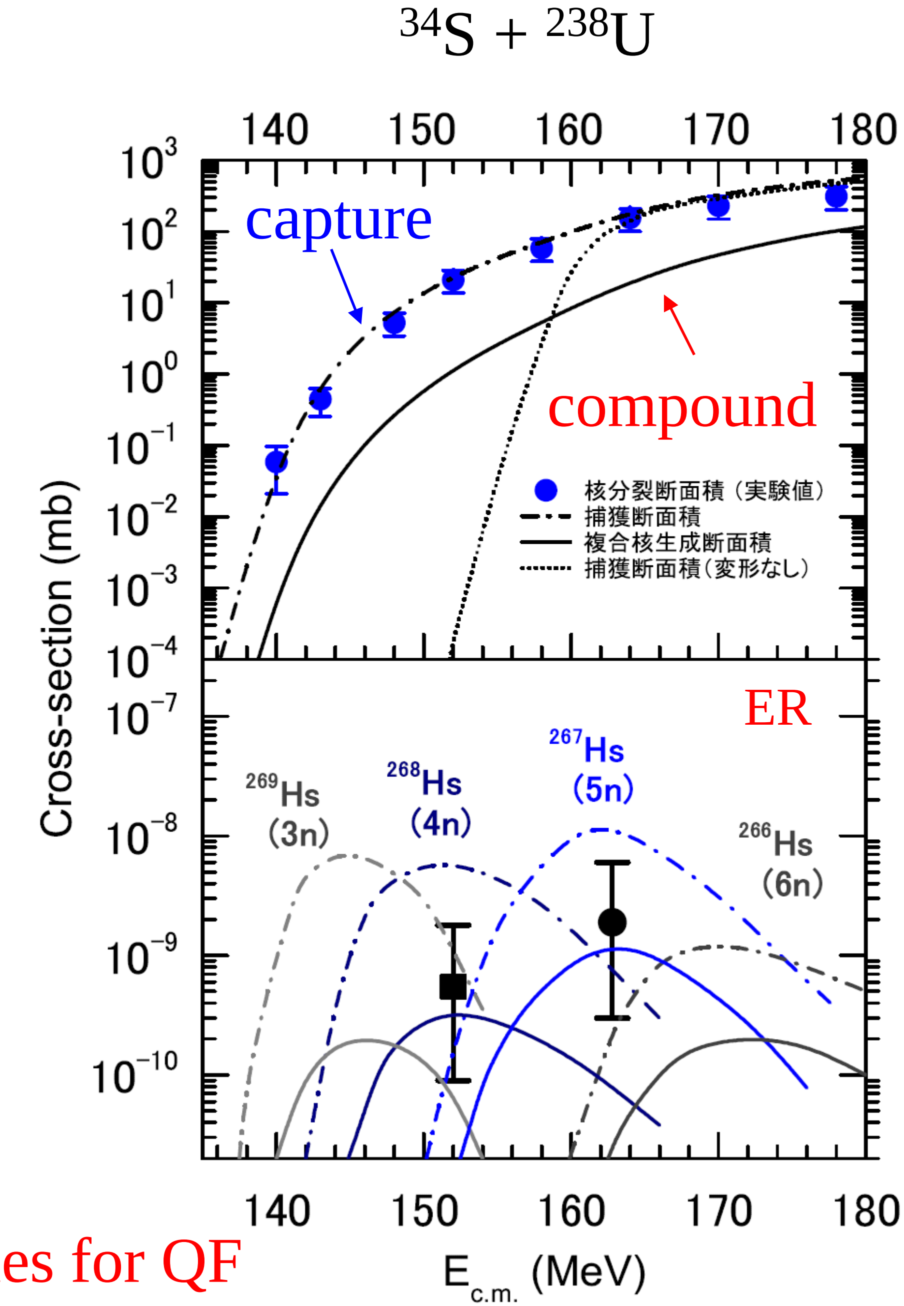
$$\sigma_{\rm ER}(E) = \int_0^1 d(\cos\theta)\sigma_{\rm ER}(E;\theta)$$

$$R_{\rm touch}(\theta) = R_p + R_T(1+\beta_2 Y_{20}(\theta))$$



Y. Aritomo, K.H., K. Nishio, S. Chiba,
PRC85('12)044614



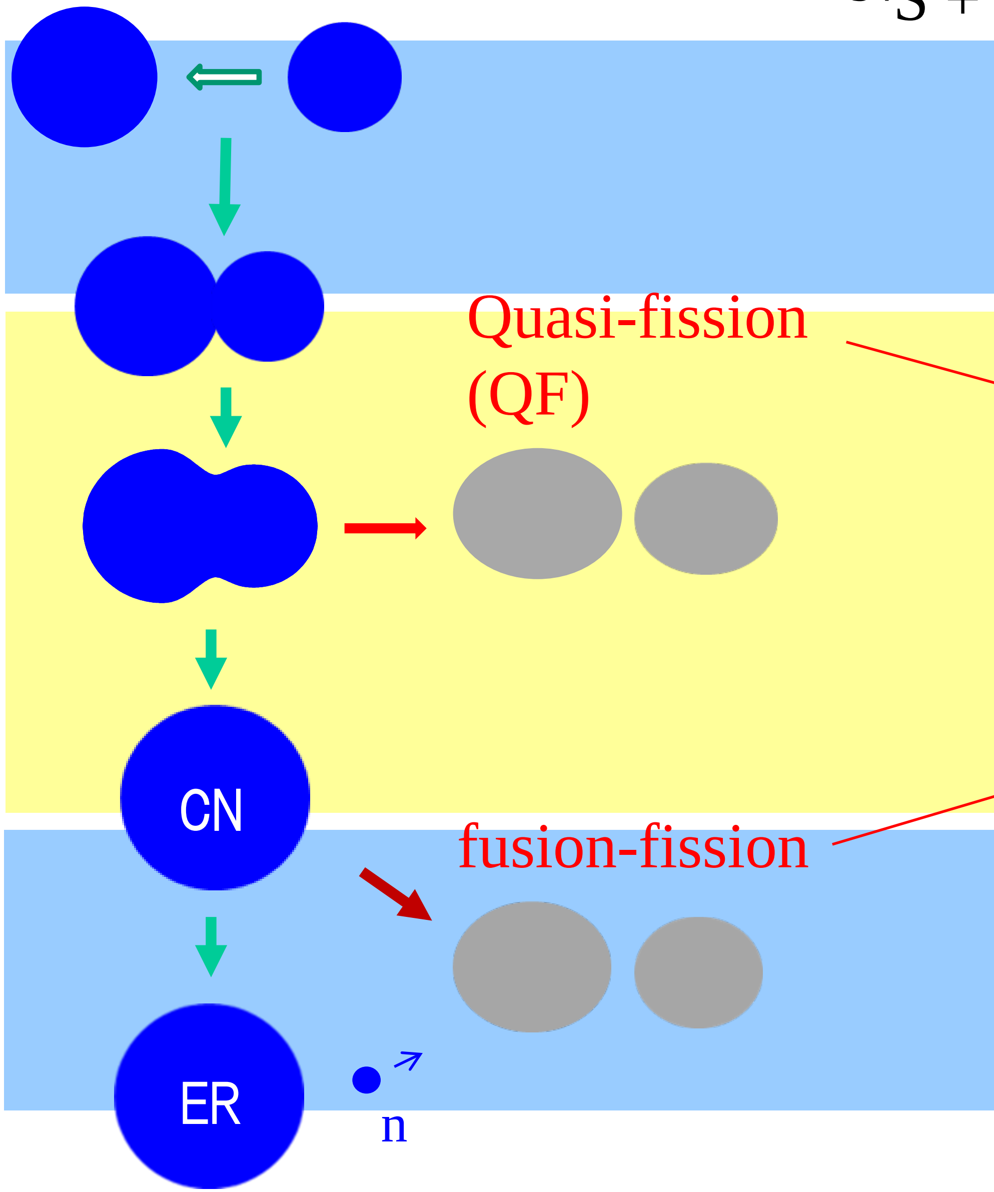


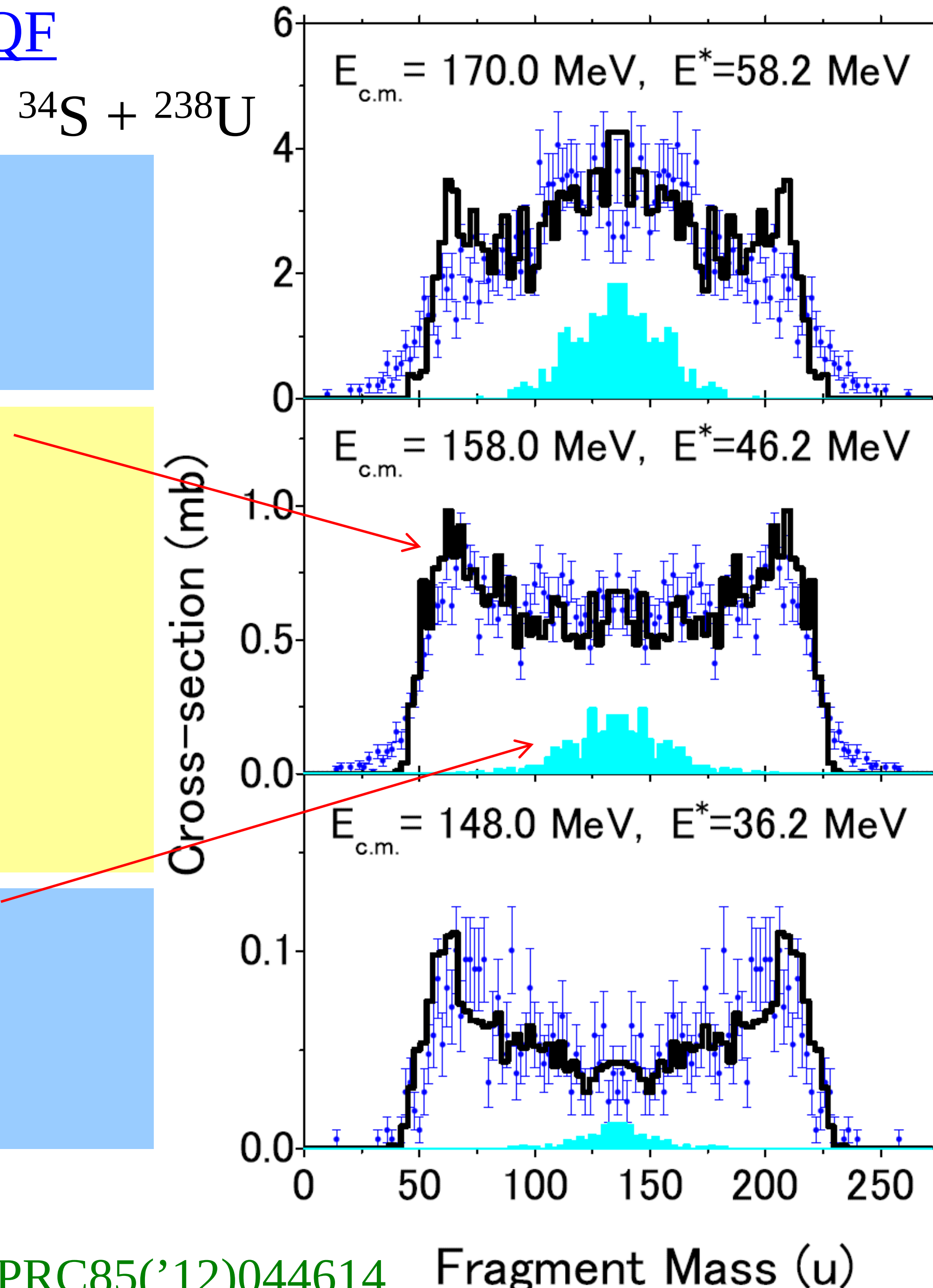
No data for σ_{CN}

→ important to check whether the model reproduces other quantities for QF

Y. Aritomo, K.H., K. Nishio, S. Chiba, PRC85('12)044614

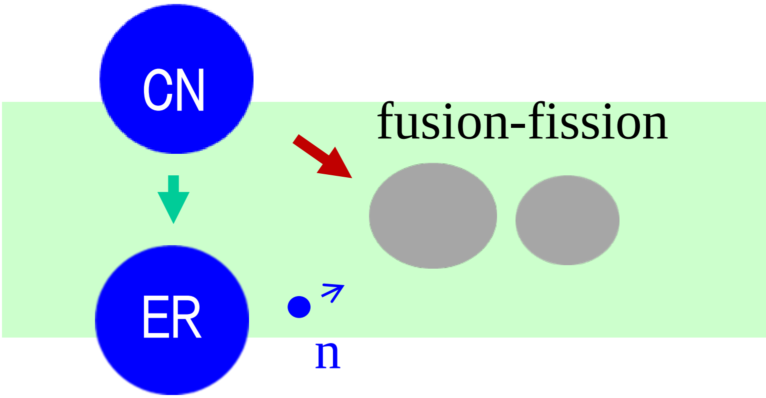
fragment mass distribution for QF





Y. Aritomo, K.H., K. Nishio, S. Chiba, PRC85('12)044614

Survival phase: statistical model



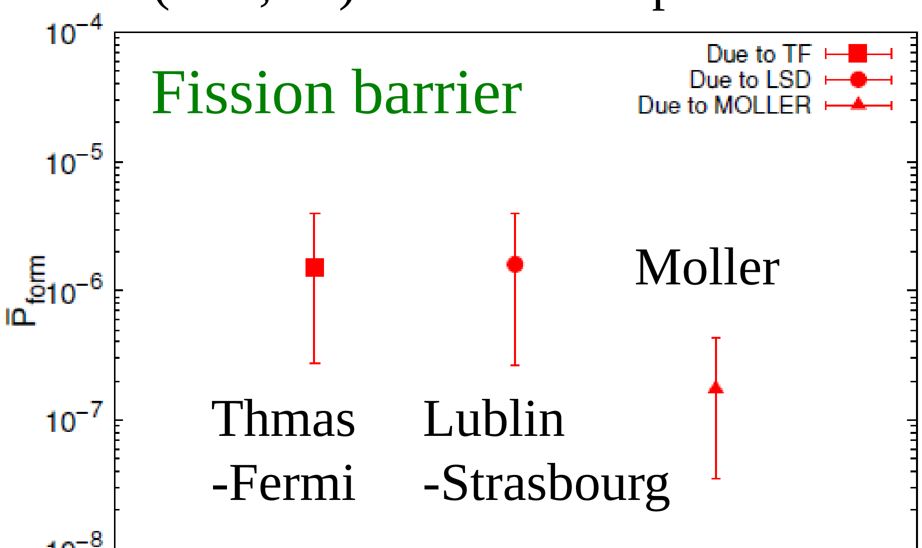
statistical model

$$\frac{\Gamma_n}{\Gamma_f} \sim \frac{\int_0^{E^*-S_n} d\epsilon\, \rho_{A-1}(E^* - S_n - \epsilon)}{\int_0^{E^*-B_f} d\epsilon\, \rho_f(E^* - B_f - \epsilon)}$$

method well established, but too many parameters/model dependence

B_f, level densities, friction…..

^{208}Pb (^{58}Fe, 1n) ^{265}Hs at the optimum energy

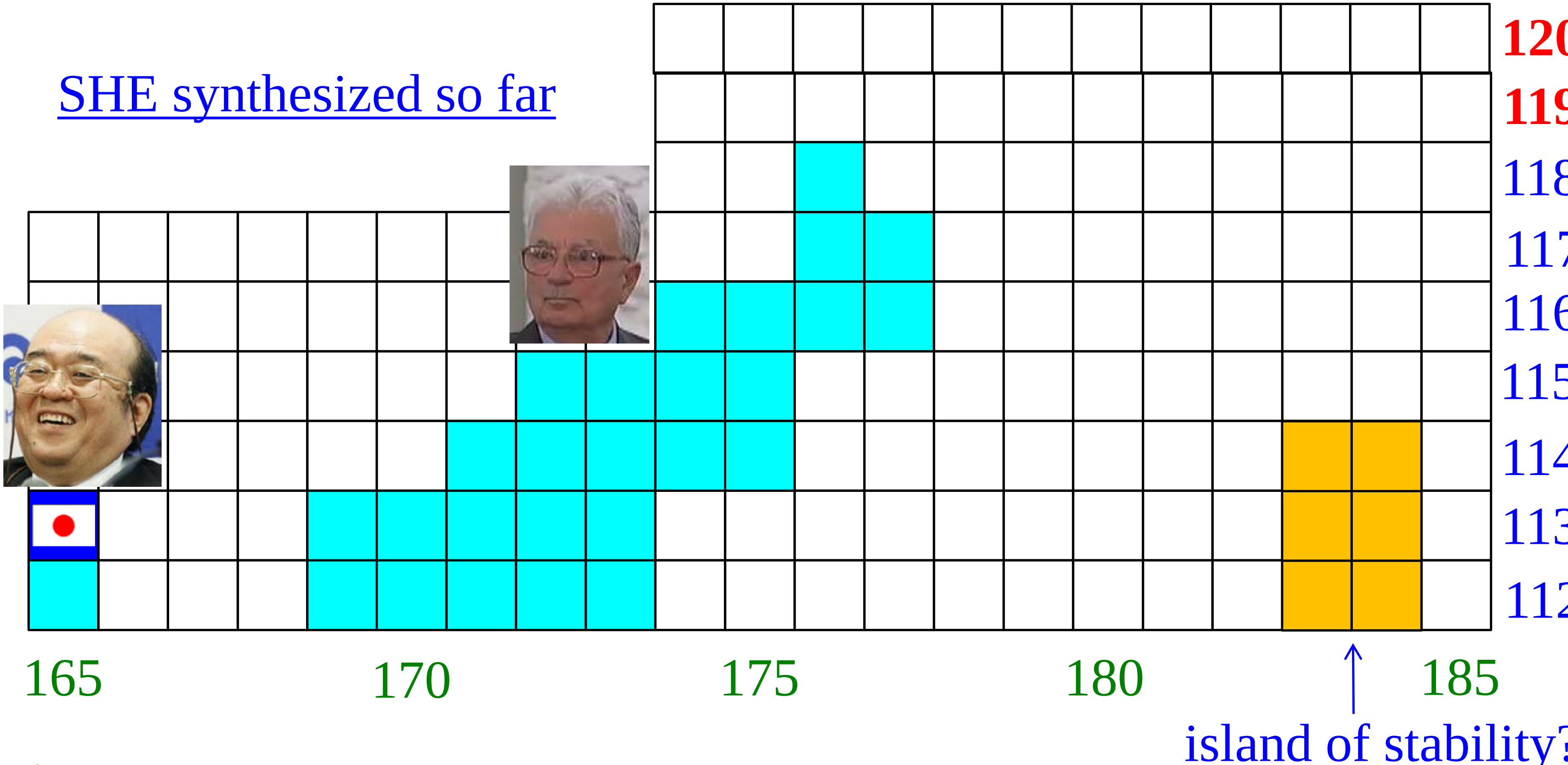


$$\langle P_{\text{form}} \rangle = \frac{\sigma_{\text{ER}}^{(exp)}}{\frac{\pi}{k^2} \sum_l (2l+1) W(E^*)}$$

KEWPIE2

H. Lu, D. Boilley, Y. Abe, and C. Shen, preprint.

Towards Z=119-120 and island of stability



- Towards Z=119 and 120 superheavy elements

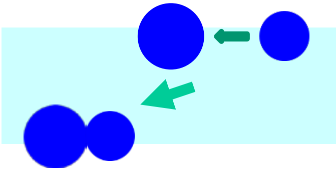
  ^{48}Ca projectile (hot fusion) → $^{50}_{22}$Ti, $^{51}_{23}$V, $^{54}_{24}$Cr projectiles etc.

- Towards island of stability

  neutron-rich beams: indispensable

Theoretical challenges towards Z=119-120 and island of stability

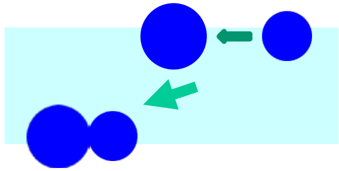
1. Approaching phase



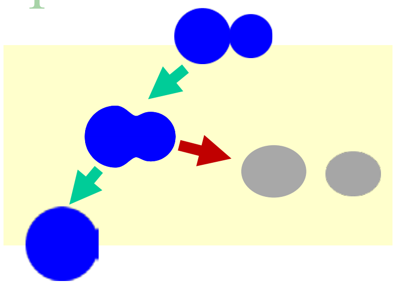
- ✓ coupled-channels for stable nuclei: well established
- ✓ still challenging: breakup and multi-nucleon transfer processes
- ✓ barrier distribution → Bayesian statistics

Theoretical challenges towards Z=119-120 and island of stability

1. Approaching phase



- ✓ coupled-channels for stable nuclei: well established
- ✓ still challenging: breakup and multi-nucleon transfer processes
- ✓ barrier distribution → Bayesian statistics

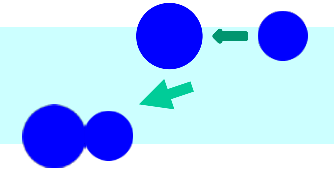


2. Formation phase

- ✓ Langevin approach
- ✓ challenge: remove the restriction of $\delta_1 = \delta_2$ (4-dim. Langevin)
  → important for Ti, V, Cr induced fusion
- ✓ neutron emissions during the shape evolution
- ✓ a change in the potential surface due to the neutron emissions

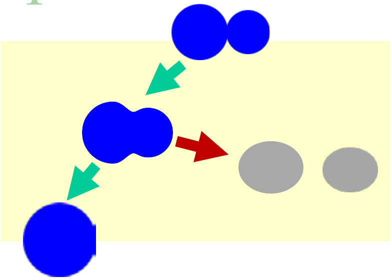
Theoretical challenges towards Z=119-120 and island of stability

1. Approaching phase



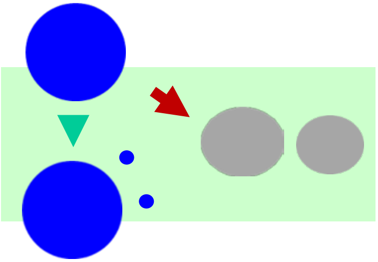
- ✓ coupled-channels for stable nuclei: well established
- ✓ still challenging: breakup and multi-nucleon transfer processes
- ✓ barrier distribution → Bayesian statistics

2. Formation phase



- ✓ Langevin approach
- ✓ challenge: remove the restriction of $\delta_1 = \delta_2$ (4-dim. Langevin)
  → important for Ti, V, Cr induced fusion
- ✓ neutron emissions during the shape evolution
- ✓ a change in the potential surface due to the neutron emissions

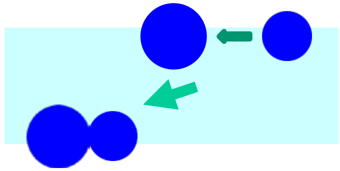
3. Survival phase



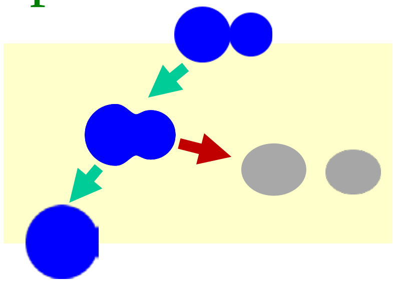
- ✓ statistical model
- ✓ many parameters (B_f, level density,….)
- ✓ difficult for an absolute value, but how about relative quantities?

Theoretical challenges towards Z=119-120 and island of stability

1. Approaching phase



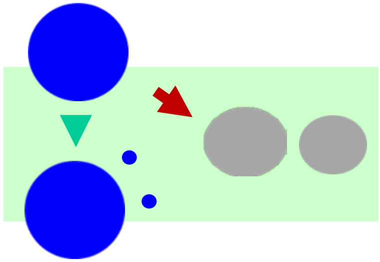
- ✓ coupled-channels for stable nuclei: well established
- ✓ still challenging: breakup and multi-nucleon transfer processes
- ✓ barrier distribution → Bayesian statistics



2. Formation phase

- ✓ Langevin approach
- ✓ challenge: remove the restriction of $\delta_1 = \delta_2$ (4-dim. Langevin)
  → important for Ti, V, Cr induced fusion
- ✓ neutron emissions during the shape evolution
- ✓ a change in the potential surface due to the neutron emissions

3. Survival phase



- ✓ statistical model
- ✓ many parameters (B_f, level density,….)
- ✓ difficult for an absolute value, but how about relative quantities?

need continuous efforts both from theory and experiment

Bayesian approach to sub-barrier fusion

$$D_{\rm exp}(E) = \sum_{i=1}^{K} w_k D_0(E; B_k, s_k)$$

optimize K, w_k, B_k, s_k
in order to reproduce data

↓

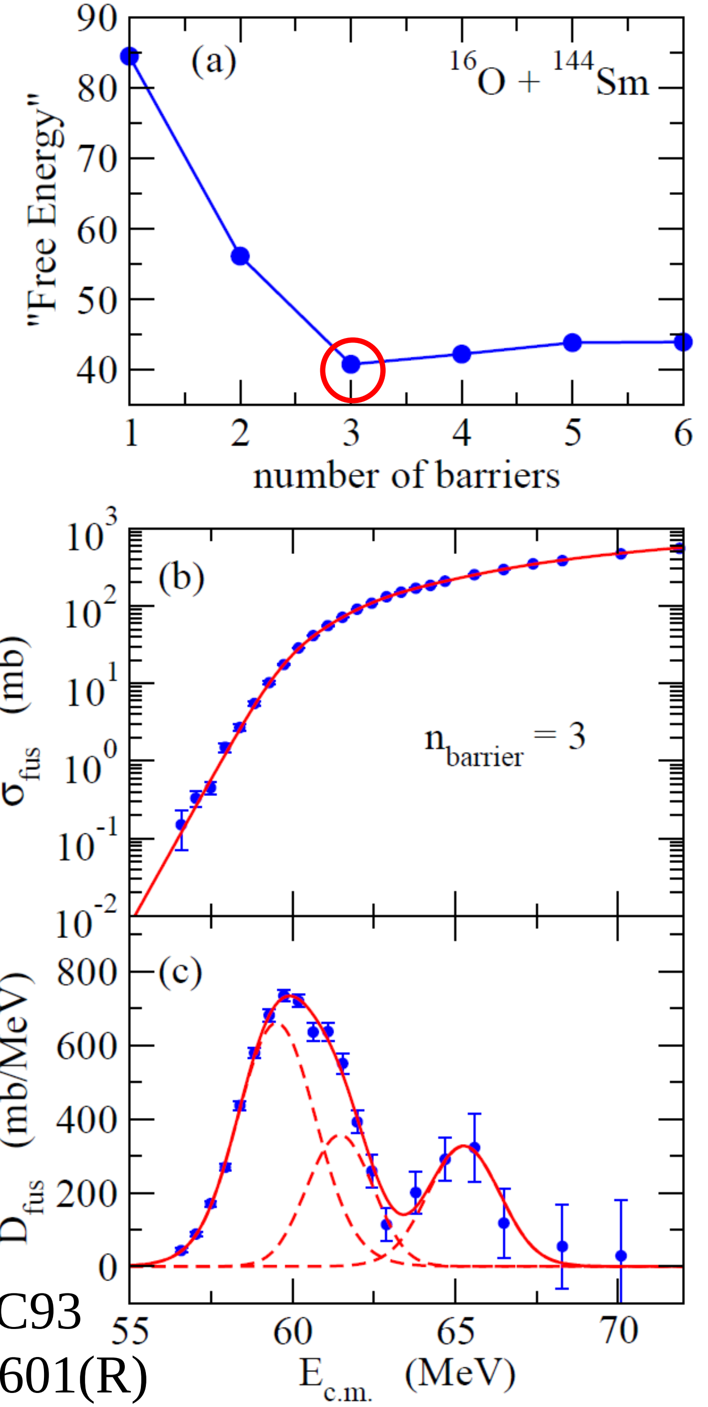
problem: how to fix K (# of barrier)?
(over-fitting)

↓

Guidline for K using the Bayesian spectrum deconvolution

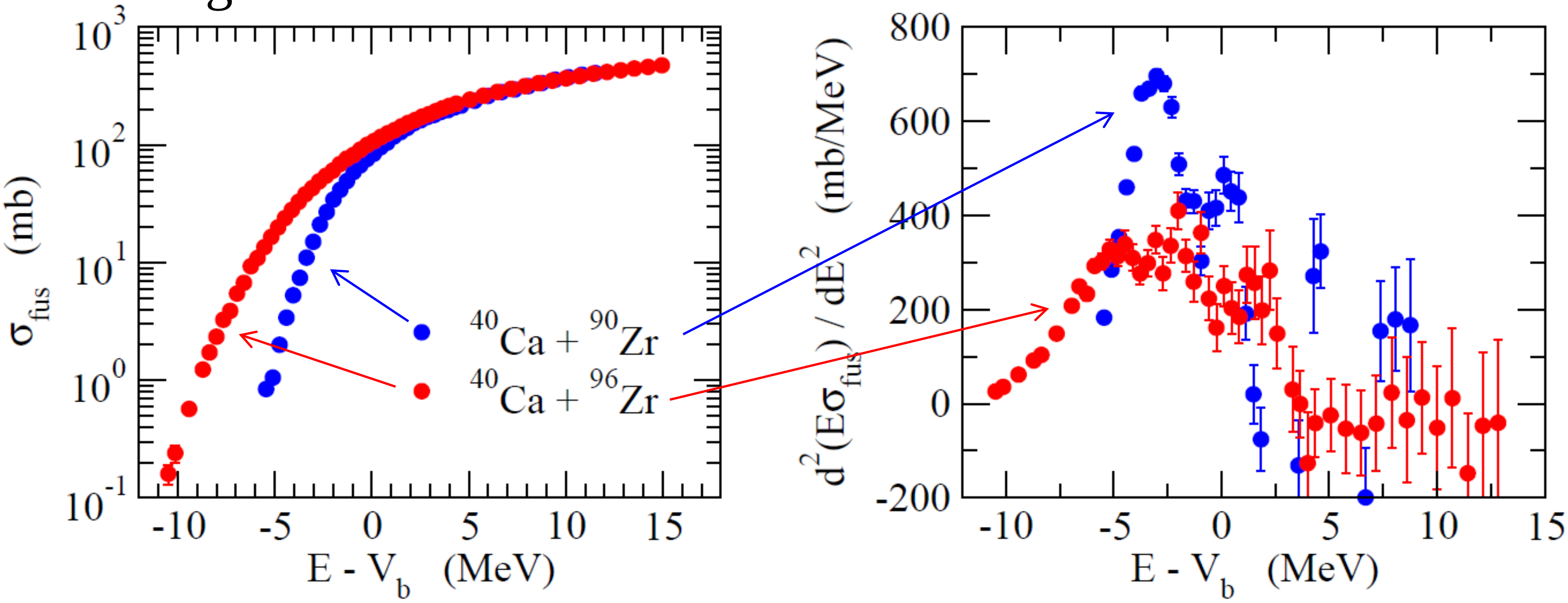
→ extraction of T_l from barrier distribution

K.H., PRC93 ('16) 061601(R)



Role of multi-neutron transfer process in subbarrier fusion

Legnaro data for $^{40}Ca + ^{90,96}Zr$



H. Timmers et al., NPA633('98)421

$^{40}Ca + ^{96}Zr$

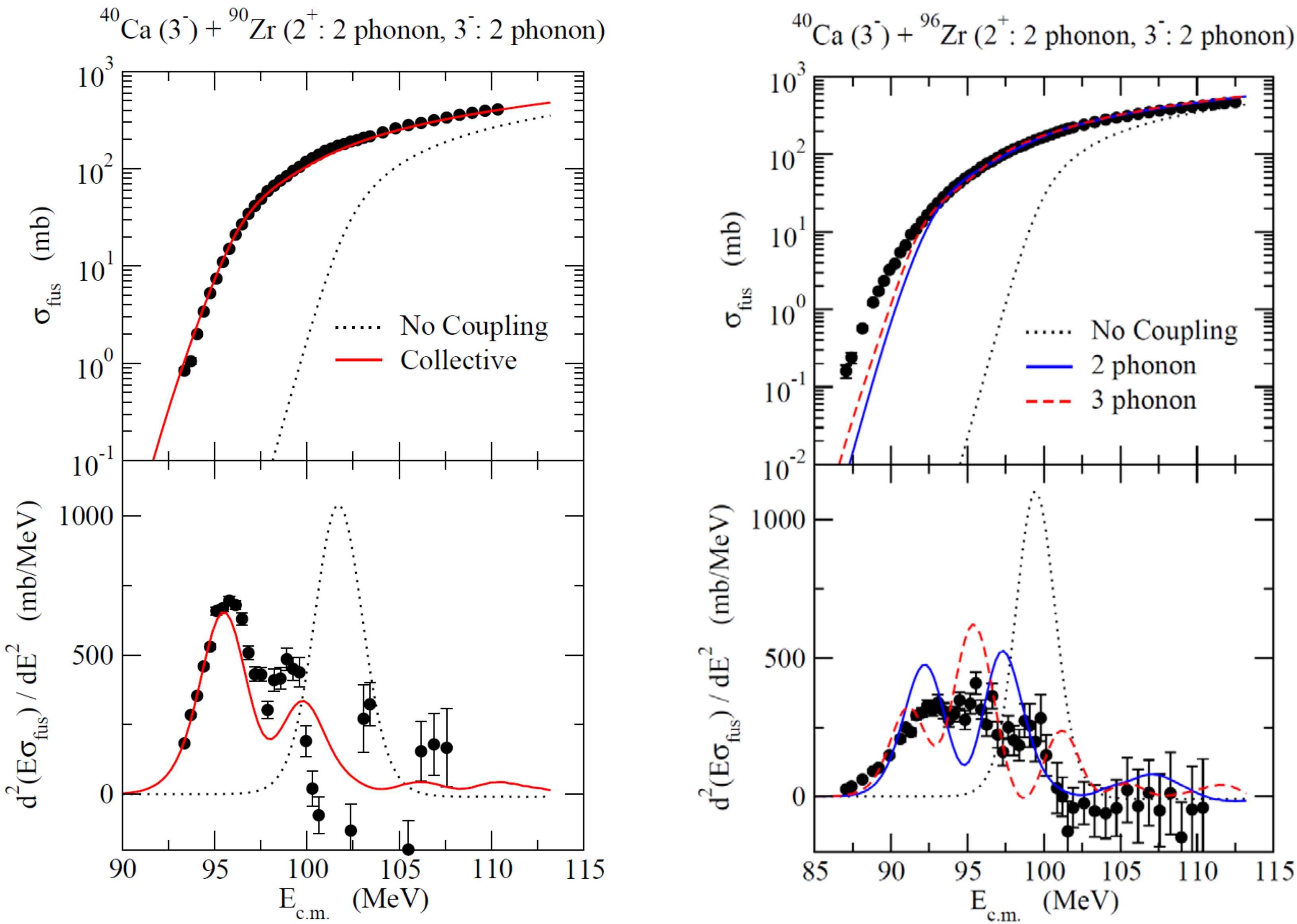
- more enhancement of fusion cross sections
- flatter barrier distribution

✓stronger octupole collectivity
✓multi-neutron transfer process

stronger octupole collectivity in ^{96}Zr

^{90}Zr: $B(E3: 3^-_1 \rightarrow 0^+) = 29.1$ W.u., $E_{3-} = 2.748$ MeV

^{96}Zr: $B(E3: 3^-_1 \rightarrow 0^+) = 52.7$ W.u., $E_{3-} = 1.897$ MeV



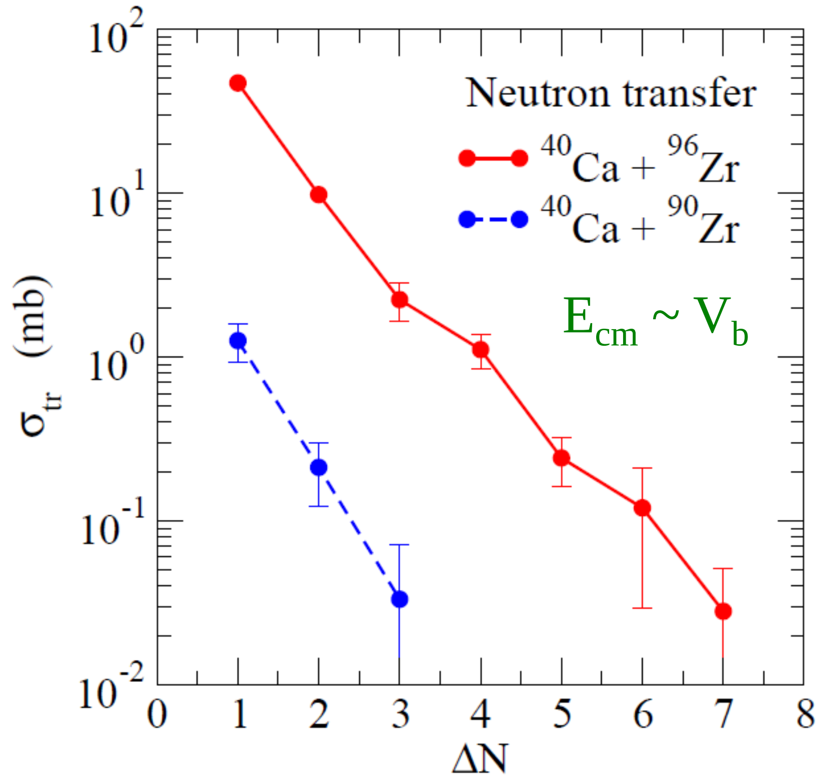
Q-values for multi-neutron transfer channels

Q_{gg} (MeV)

	^{40}Ca + ^{90}Zr	^{40}Ca + ^{96}Zr
+1n	-3.61	+0.51
+2n	-1.44	+5.53
+3n	-5.86	+5.24
+4n	-4.17	+9.64
+5n	-9.65	+8.42
+6n	-9.05	+11.62

cf. Q_{gg} (-1n) = -8.45 MeV for ^{40}Ca+^{90}Zr

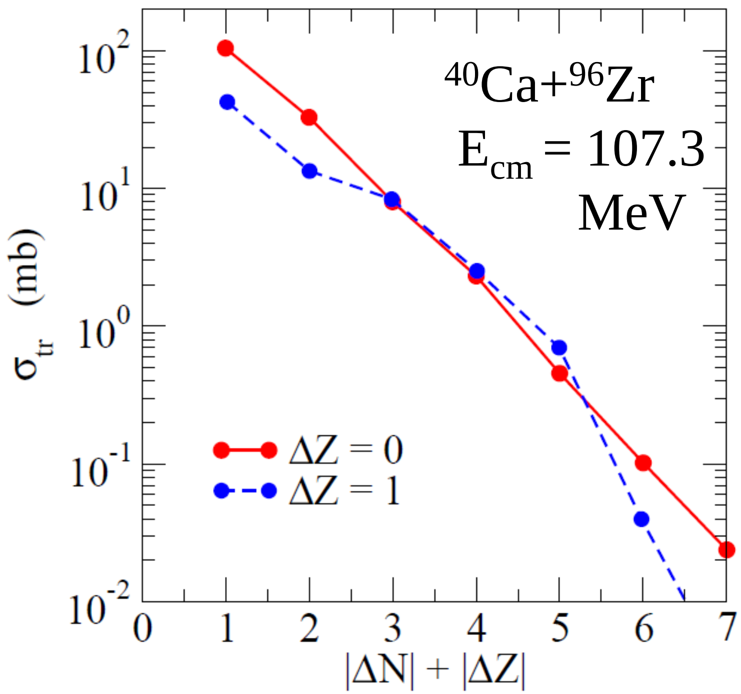
Experimental data for total transfer cross sections



G. Montagnoli et al.,
J. of Phys. G23('97)1431

New simple model

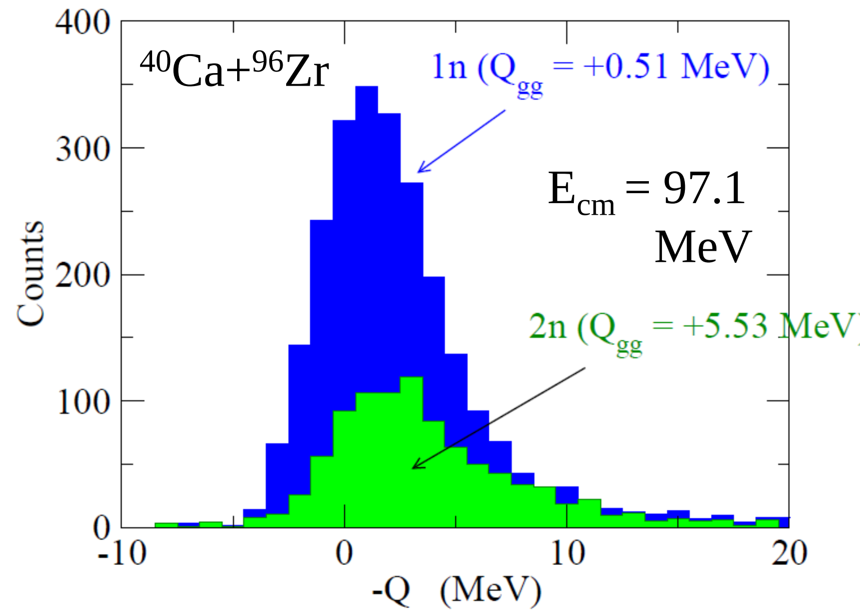
1. Neutron transfer chain only



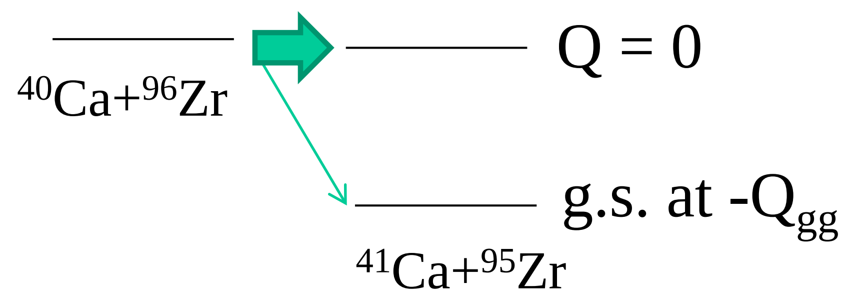
S. Szilner et al., PRC76('07)024604

proton transfer: less strongly coupled to the entrance channel

2. Approximate Q-value distribution



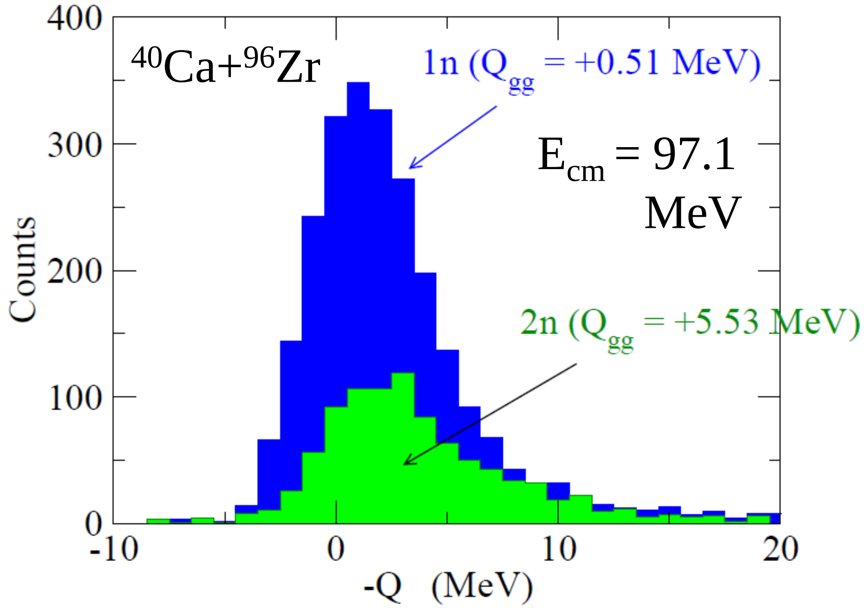
L. Corradi et al., PRC84('11)034603
(Recent data with PRISMA)



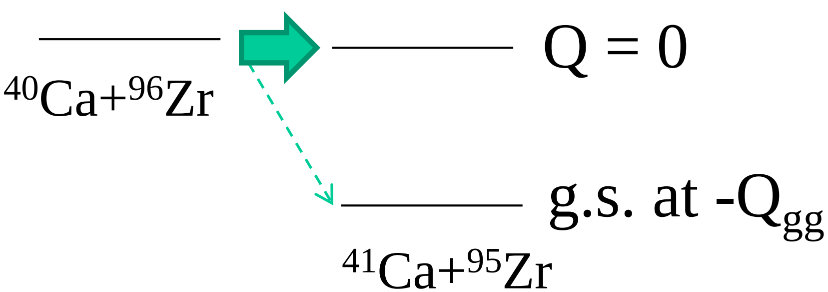
Q-value matching

→ put all the strength to a single state at Q=0

2. Approximate Q-value distribution



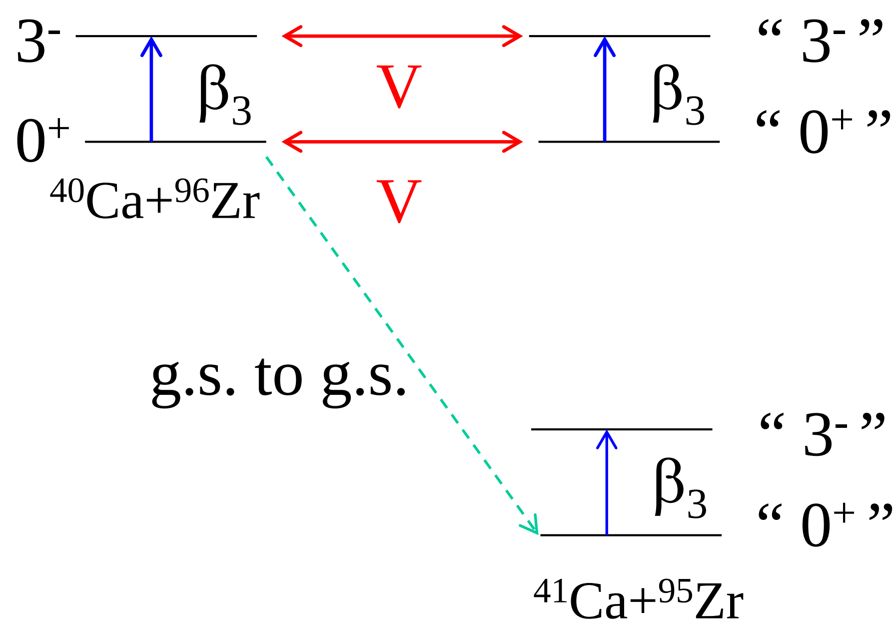
L. Corradi et al., PRC84('11)034603
(Recent data with PRISMA)



Q-value matching

→ put all the strength
to a single state at Q=0

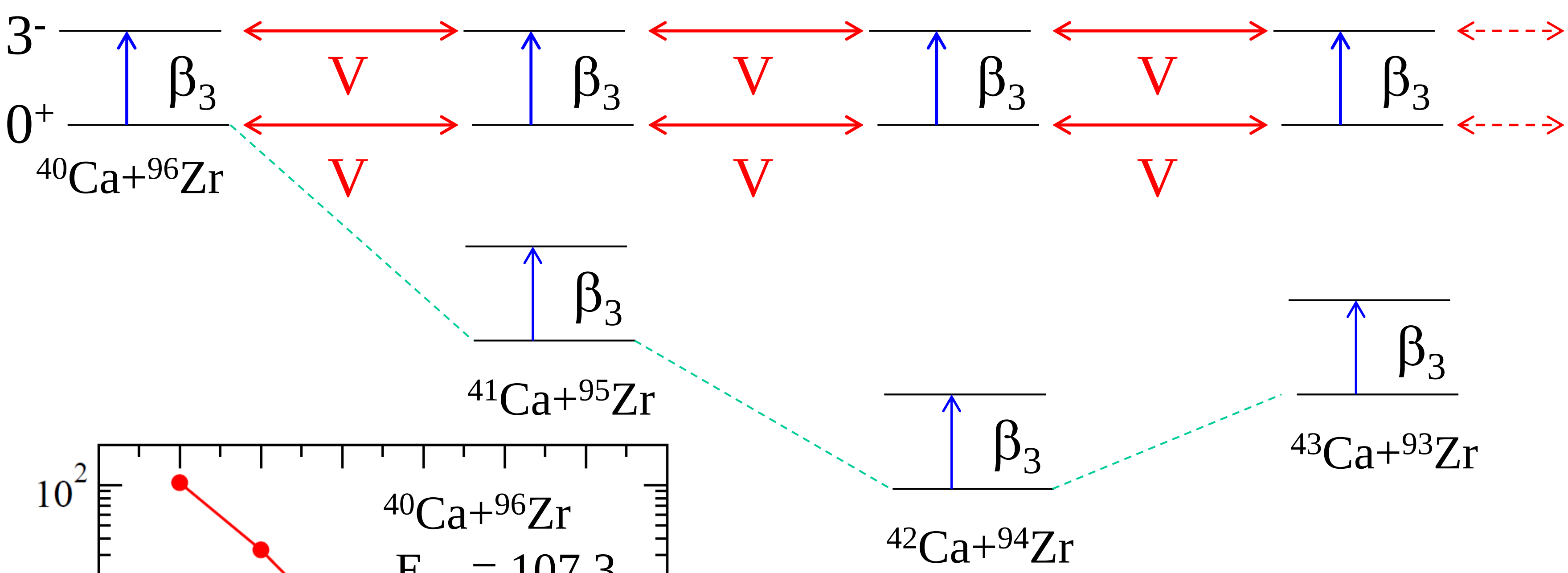
3. Same coupling scheme for inelastic excitations

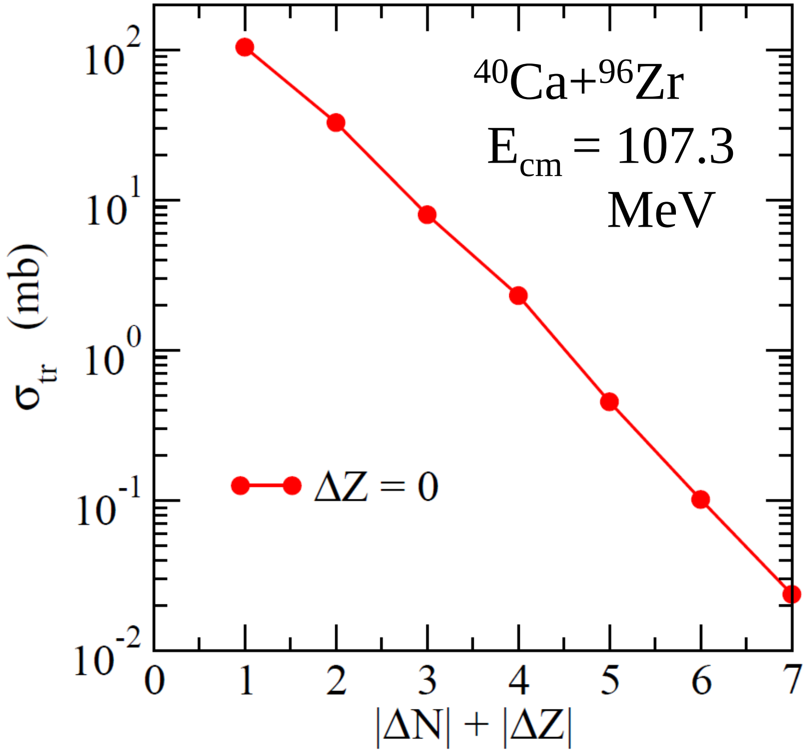


Brink-Axel hypothesis

constant coupling approximation
for transfer

4. Sequential coupling to each transfer partition with the same strength





Brink-Axel hypothesis

experimental data:

$$\frac{\sigma_{\Delta N}}{\sigma_{\Delta N-1}} \sim const.$$

S. Szilner et al., PRC76('07)024604