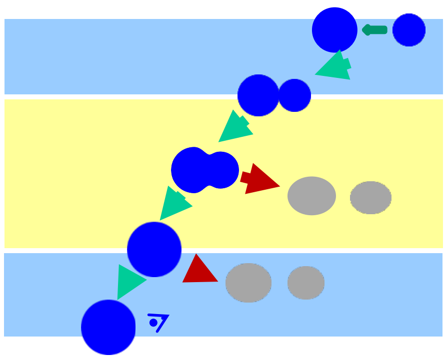
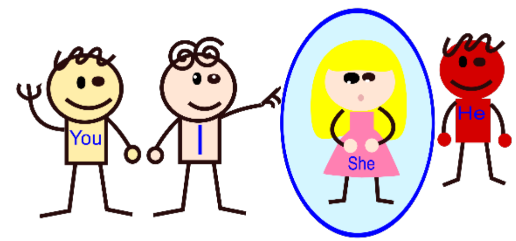
Capture barrier distributions and superheavy elements

Kouichi Hagino

Tohoku University, Sendai, Japan





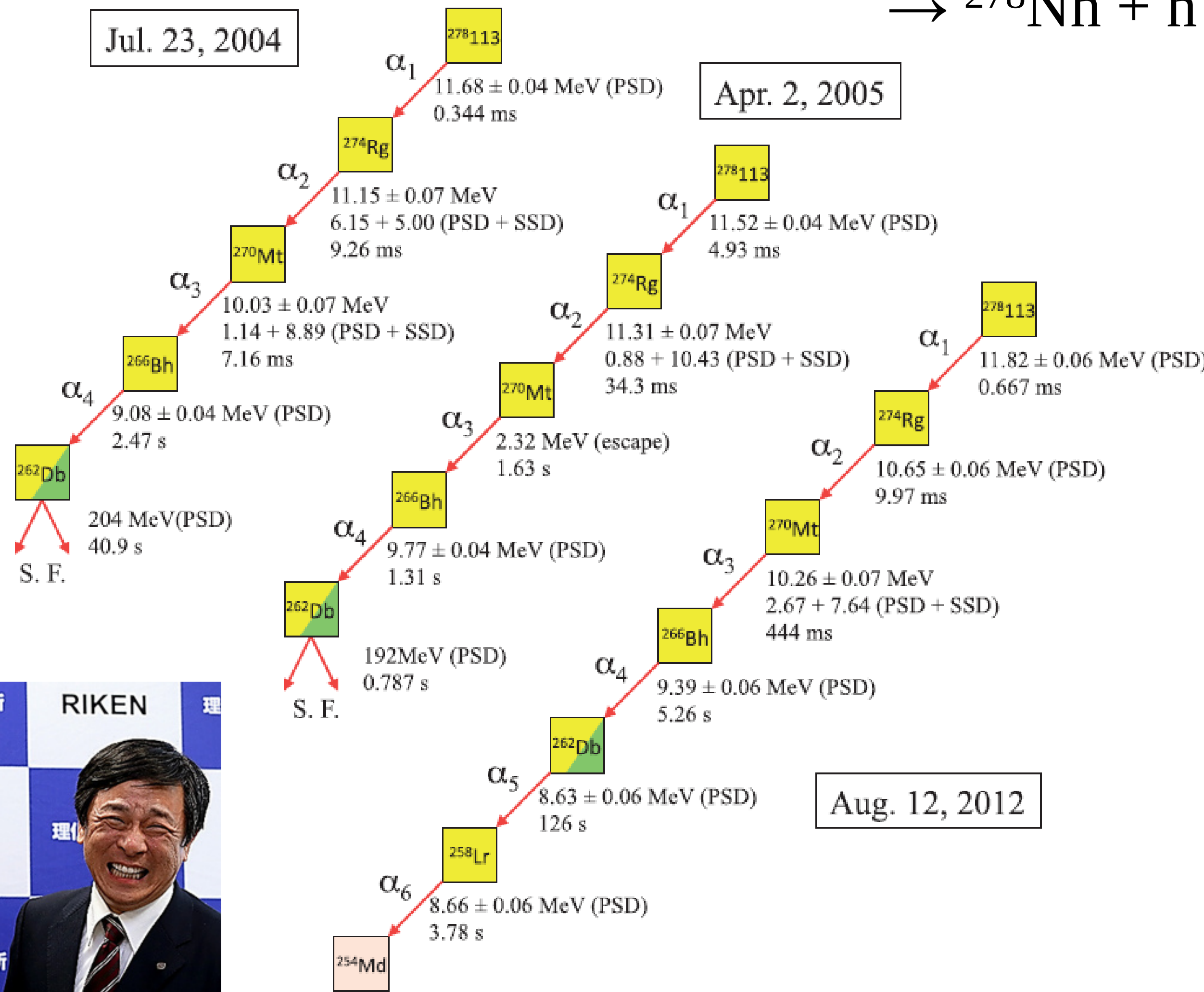
she

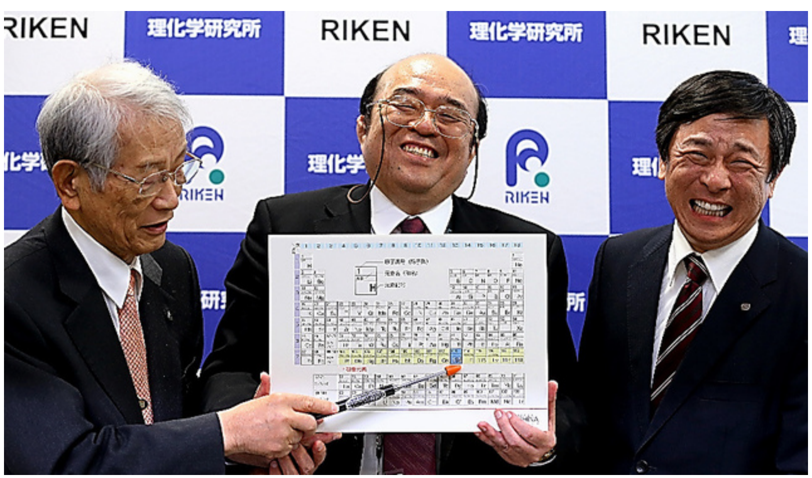
1. Introduction: Fusion reactions for SHE
2. Role of deformation in capture reactions
3. Barrier distribution and C.C. analysis
4. Summary

New element 113: Nihonium

$$^{70}Zn + {}^{209}Bi \rightarrow {}^{279}Nh^* \rightarrow {}^{278}Nh + n$$

November, 2016

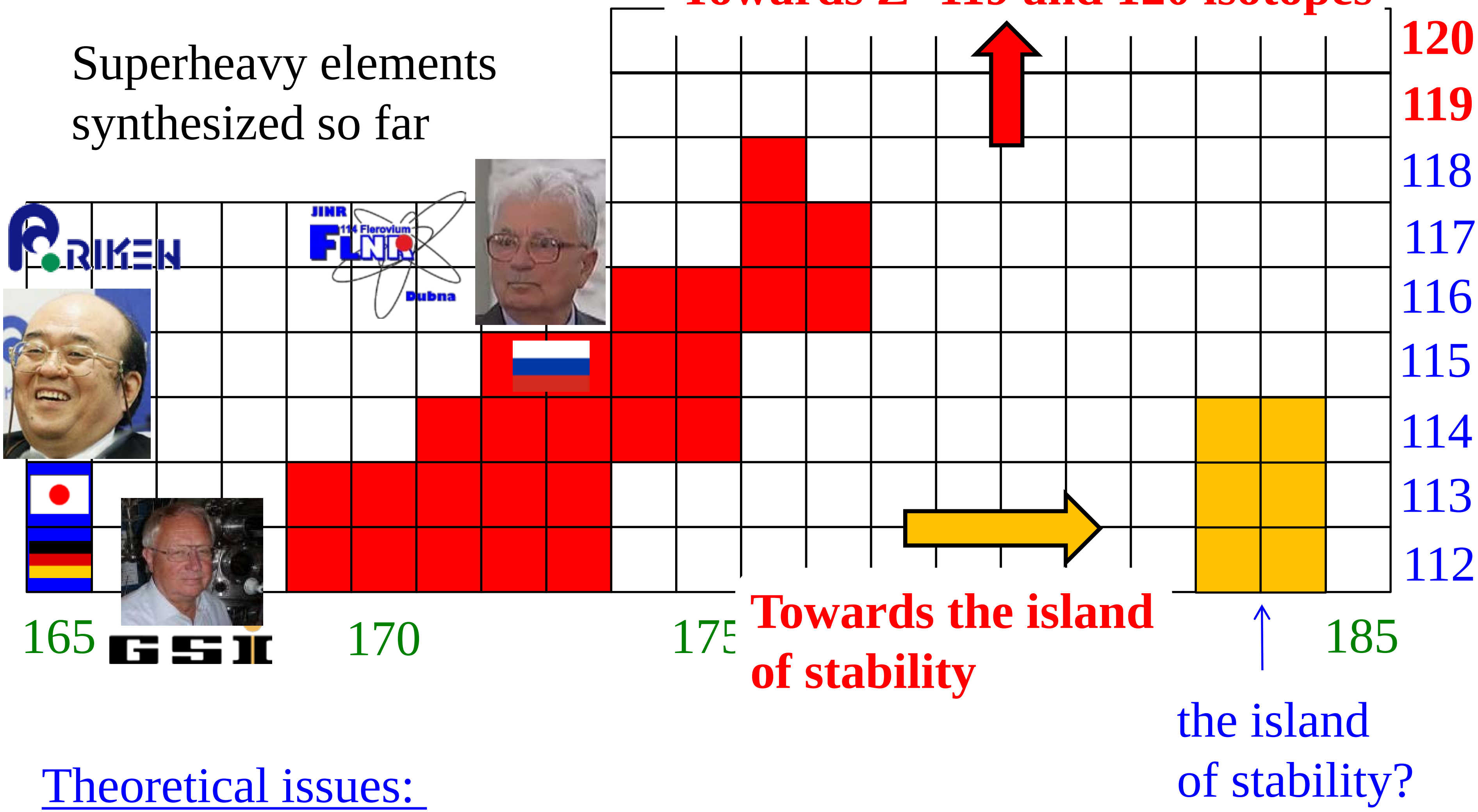




Morimoto-san's talk

Future directions

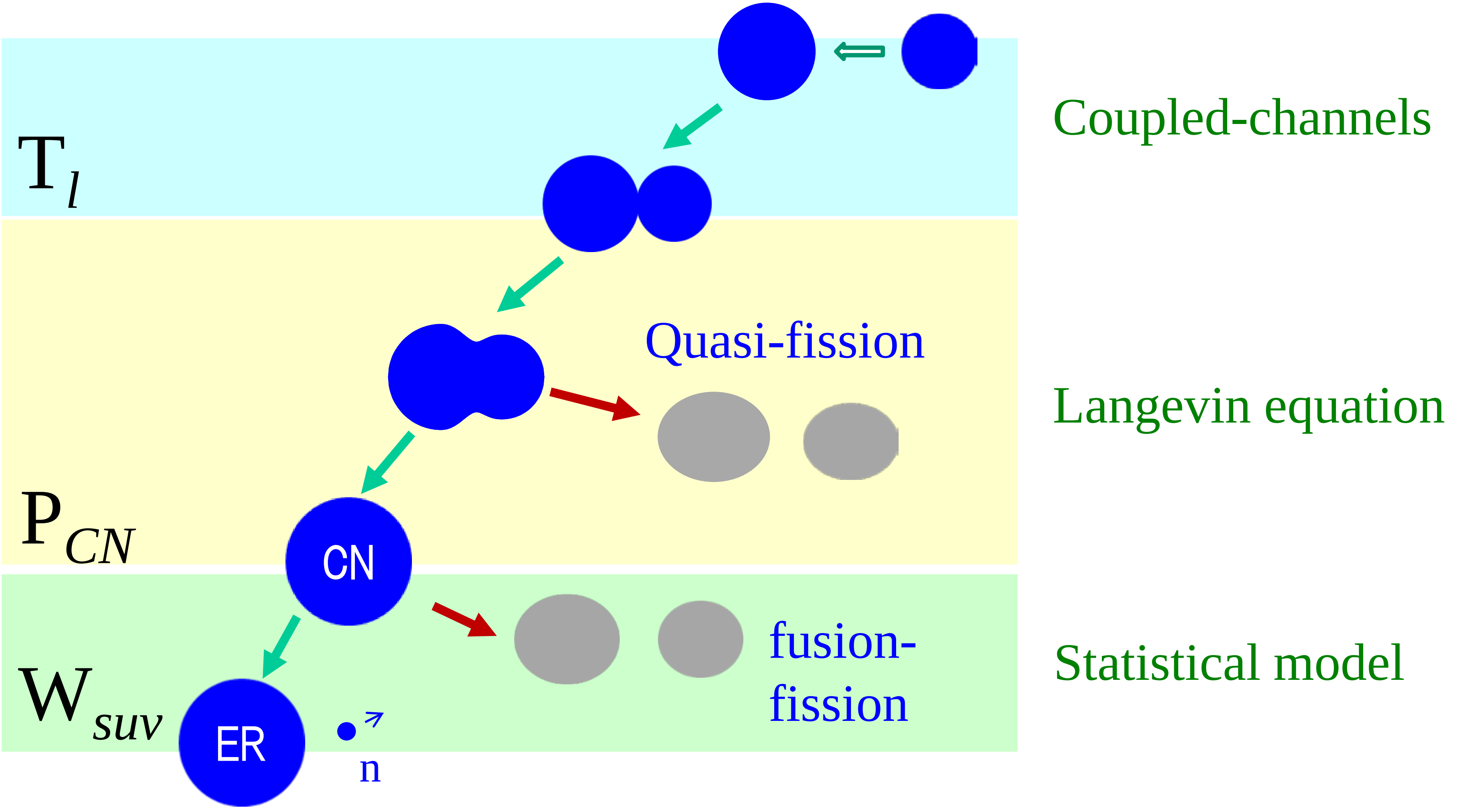
Superheavy elements synthesized so far



Theoretical issues:

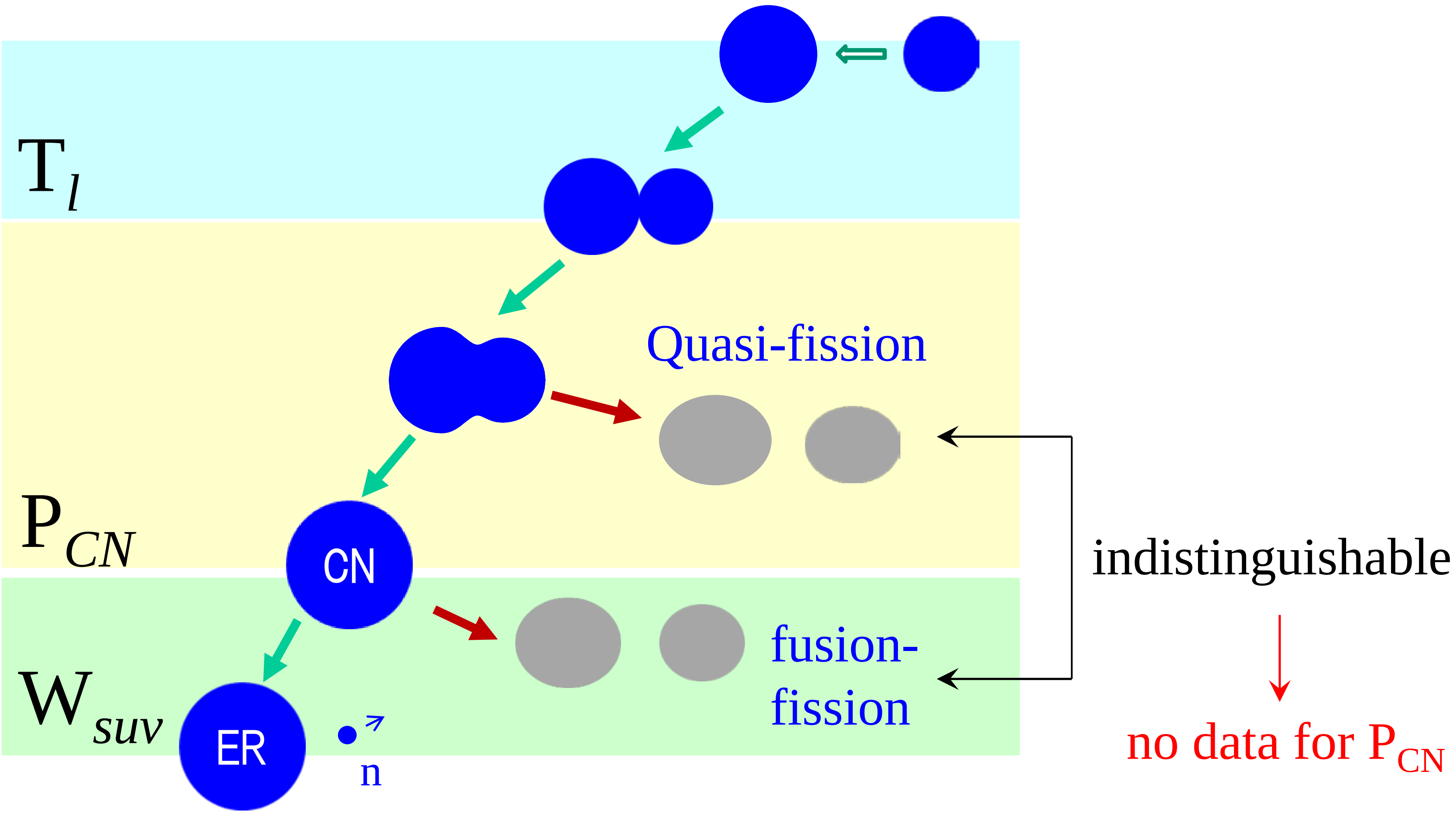
- to understand the reaction dynamics
- to make a reliable theoretical prediction for fusion cross sections

Fusion reactions for SHE

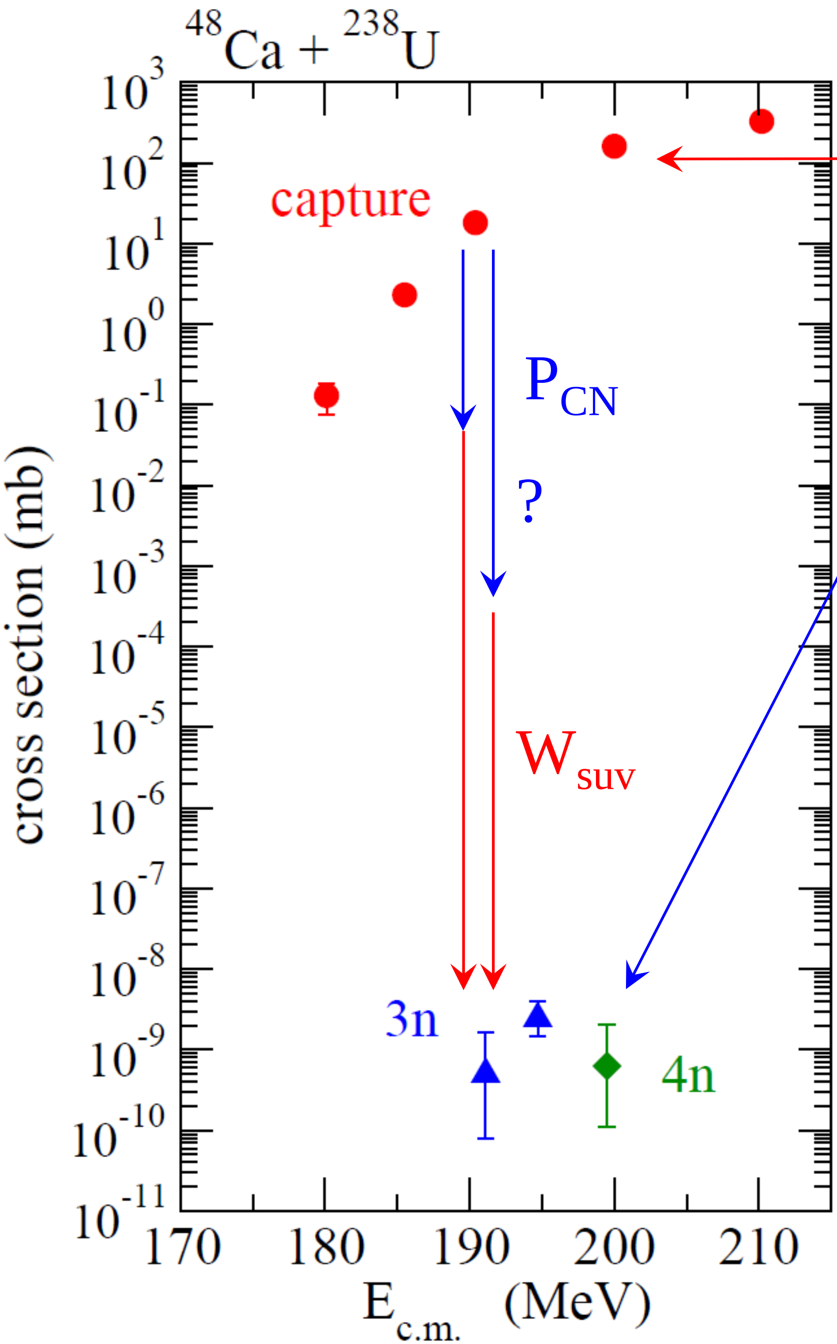


$$\sigma_{\mathrm{ER}}(E) = \frac{\pi}{k^2} \sum_l (2l+1) T_l(E)\, P_{\mathrm{CN}}(E,l)\, W_{\mathrm{suv}}(E^*,l)$$

Fusion reactions for SHE



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



no experimental data for P_{CN}

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

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

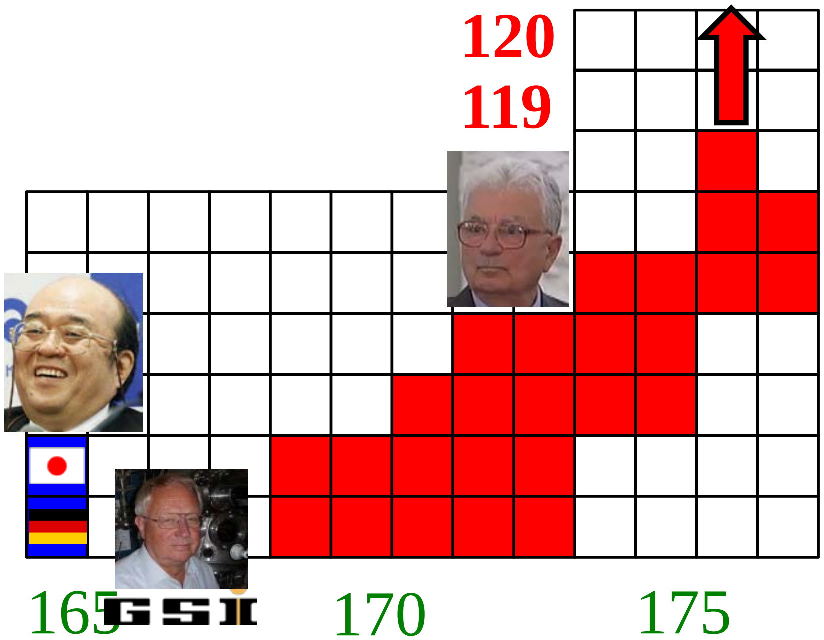
large uncertainties

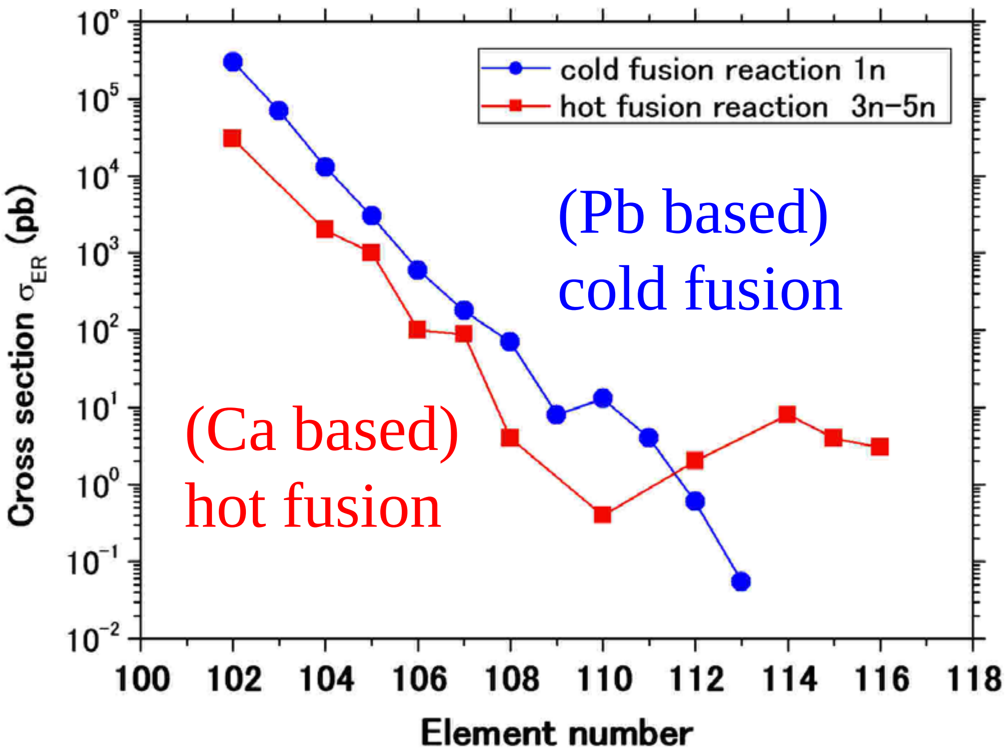
challenges
: reduction of theoretical uncertainties

a good understanding of the reaction dynamics

Hot fusion for Z = 119 and 120

Towards Z=119 and 120 isotopes



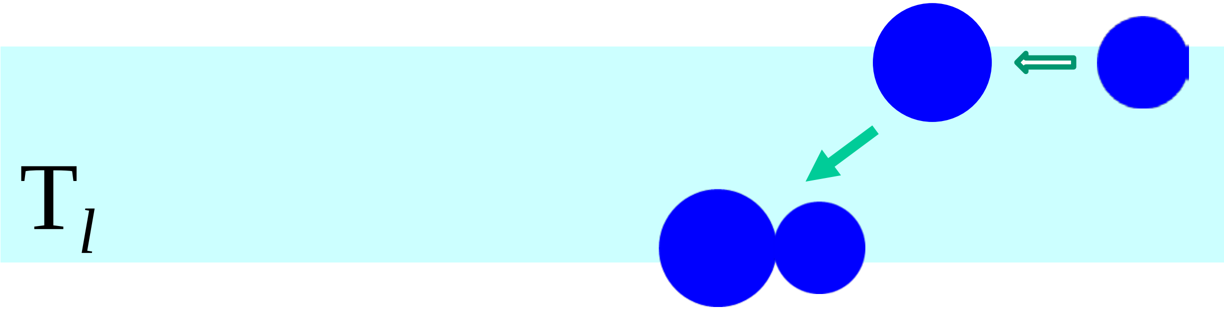


hot fusion: ^{48}Ca + actinide targets

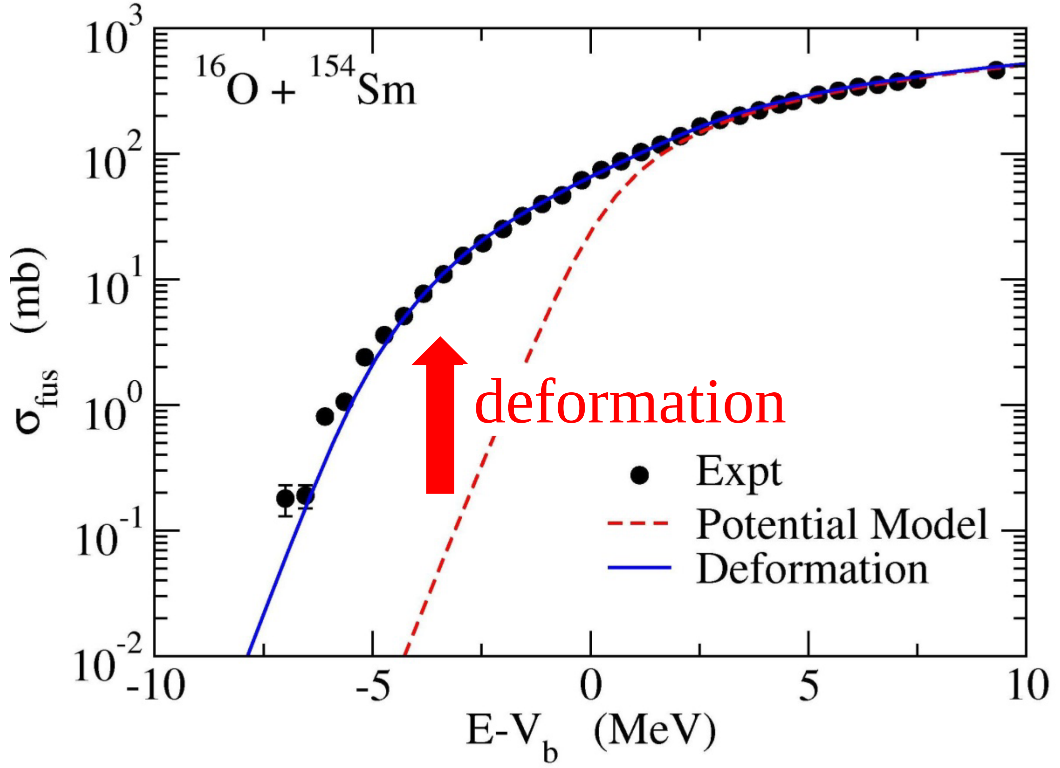
Dubna: ^{48}Ca + ^{249}Cf (β_2 = 0.235) $\longrightarrow$ $^{297-x}$Og (Z=118) + xn

role of deformation?

Role of deformation in capture cross sections

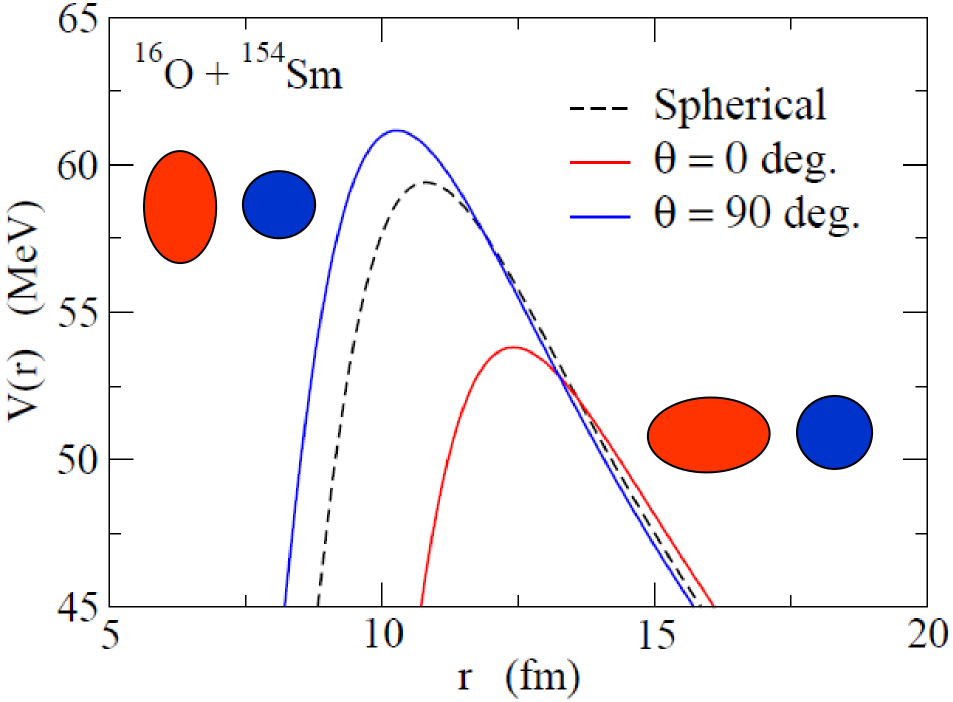


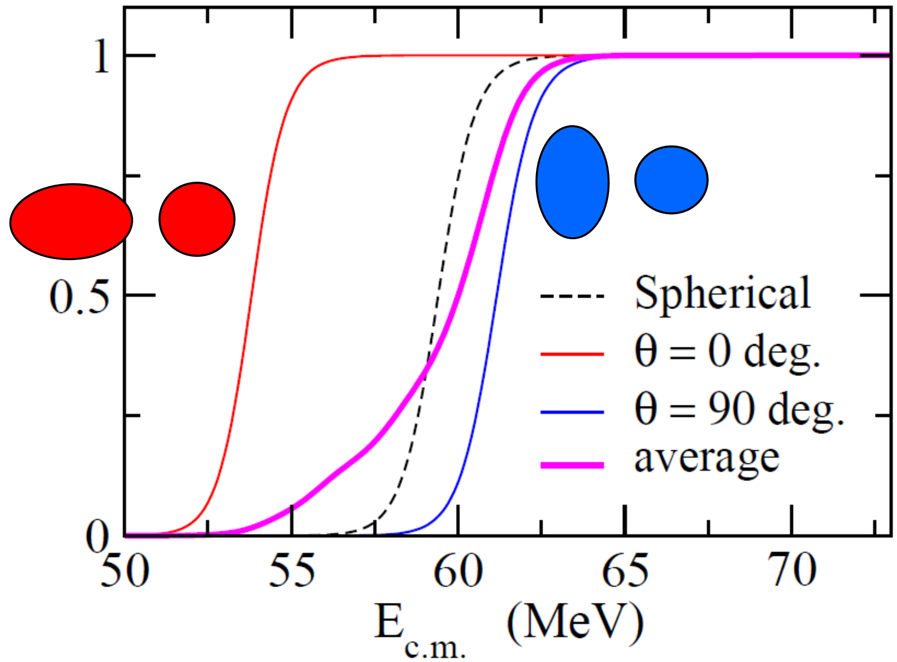
Sub-barrier enhancement of capture cross sections



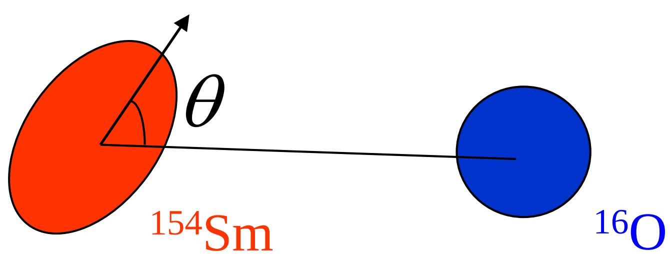
Role of deformation in capture cross sections

Sub-barrier enhancement of capture cross sections





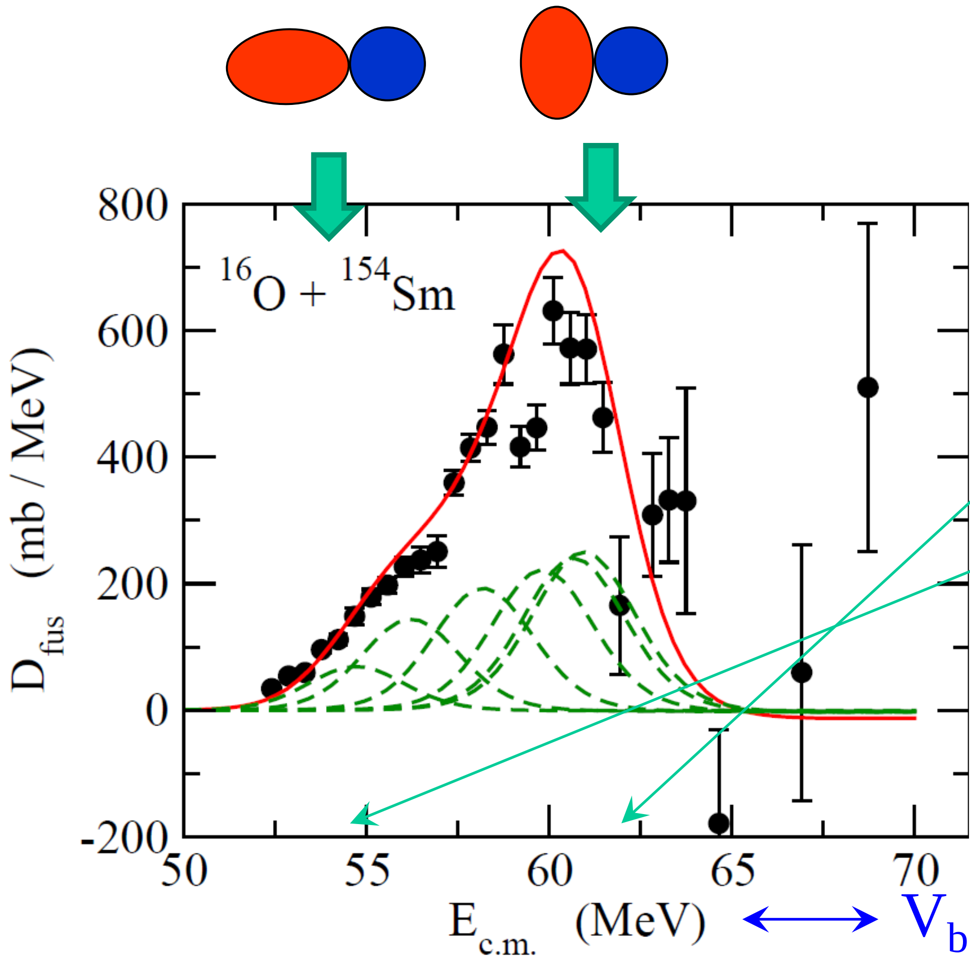
$$\sigma_{\rm cap}(E) = \int_0^1 d(\cos\theta)\sigma_{\rm cap}(E;\theta)$$

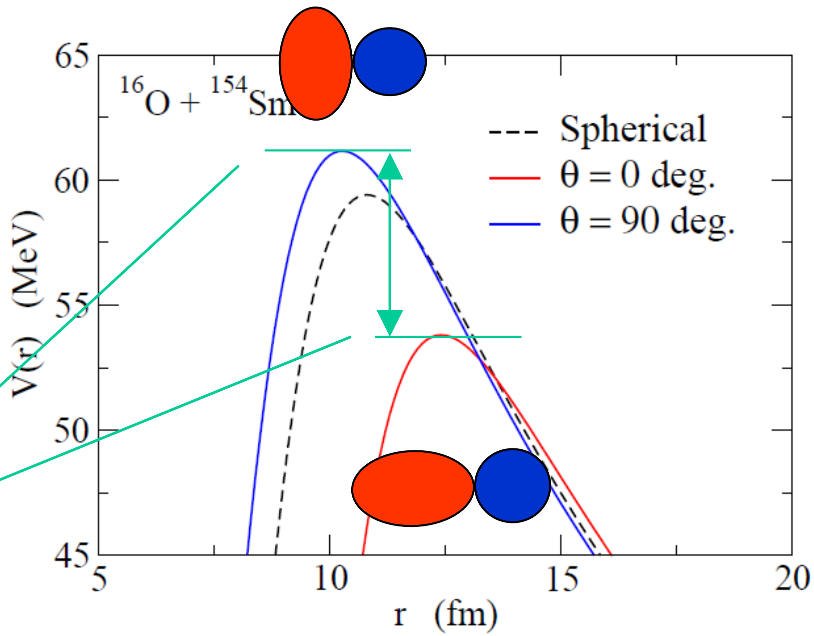


K.H., N. Takigawa, PTP128 ('12) 1061

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

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





⟷ V_b

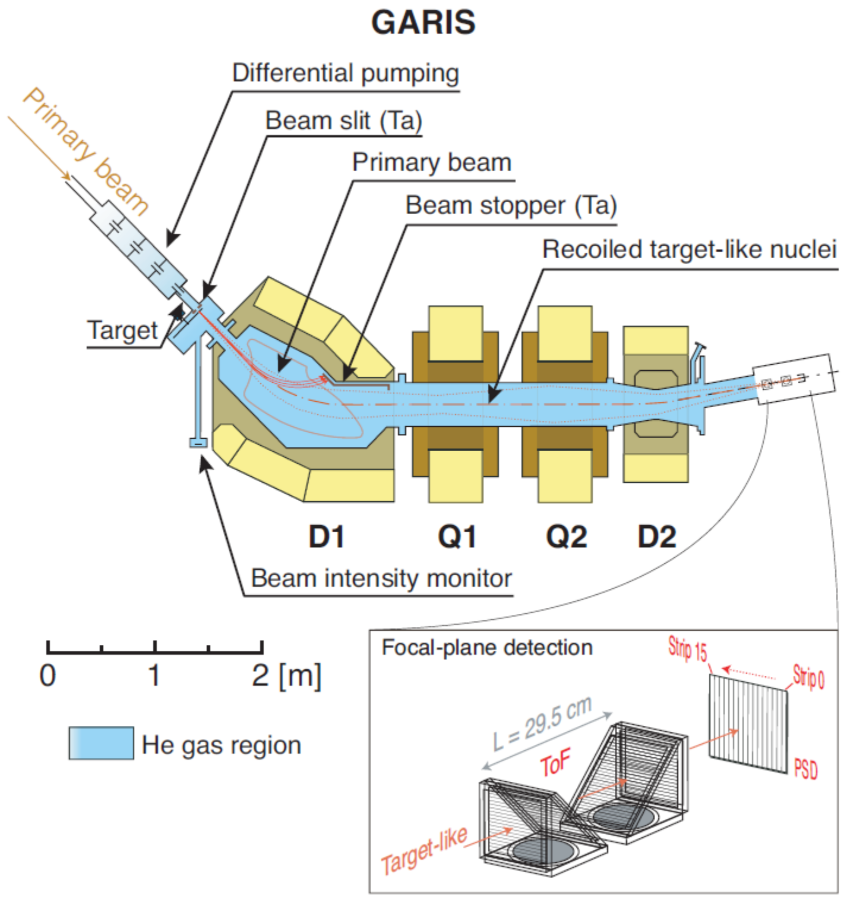
Data: J.R. Leigh et al., PRC52 ('95) 3151

a nice tool to understand the reaction dynamics

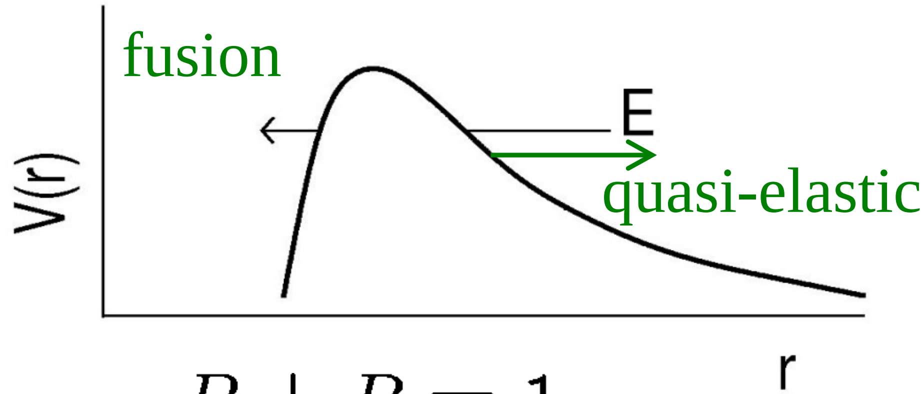
K.H., N. Takigawa, PTP128 ('12) 1061

Measurements of barrier distributions with GARIS

T. Tanaka, Y. Narikiyo, K. Morita, K. Fujita, D. Kaji,
K. Morimoto, ..., K.H., J. of Phys. Soc. Japan (JPSJ), in press.



Quasi-elastic barrier distribution



$$P + R = 1$$

- a sum of elastic, inelastic, and transfer

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

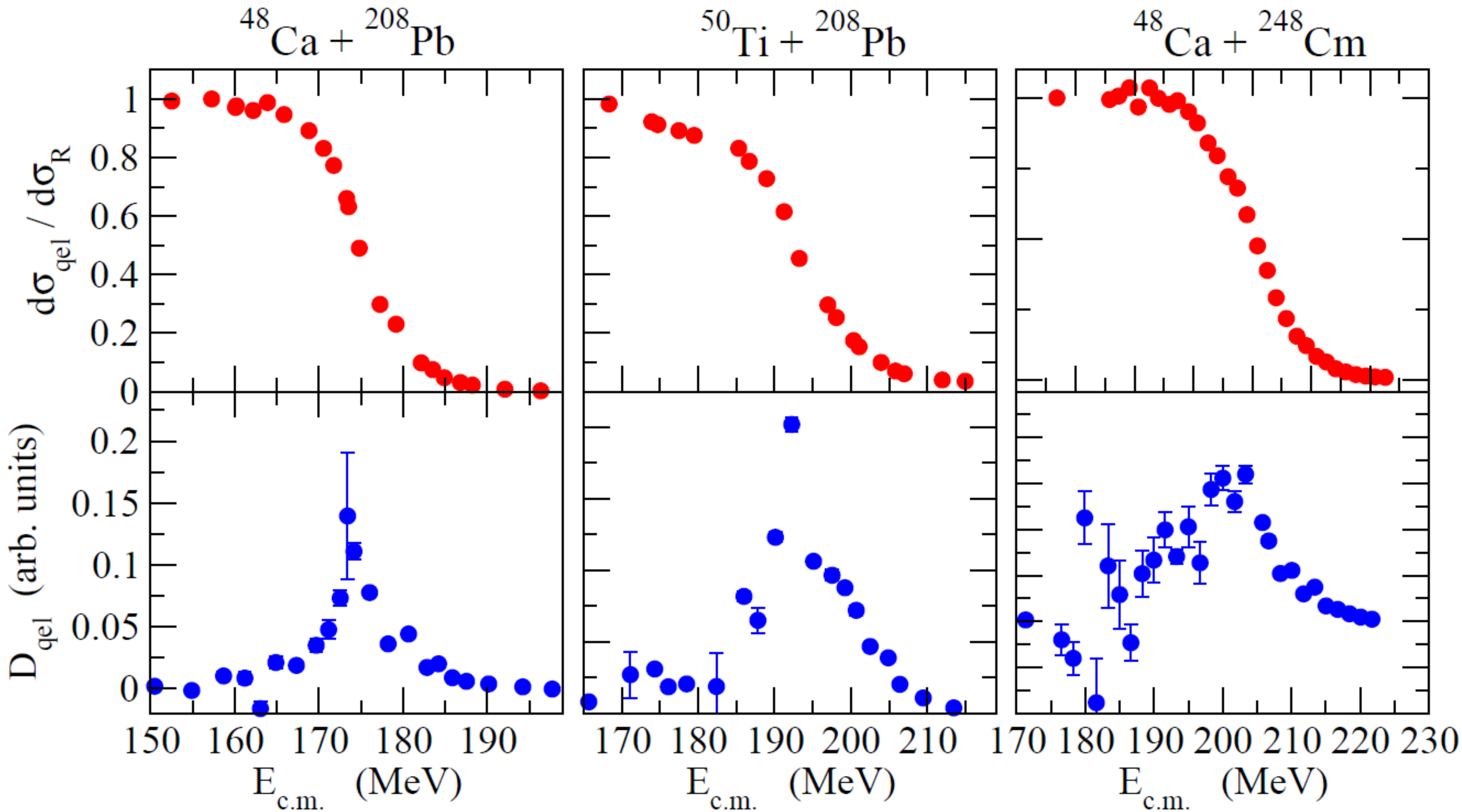
K.H. and N. Rowley, PRC69 (’04) 054610

Measurements of barrier distributions with GARIS

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

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

T. Tanaka et al., K.H., JPSJ, in press.



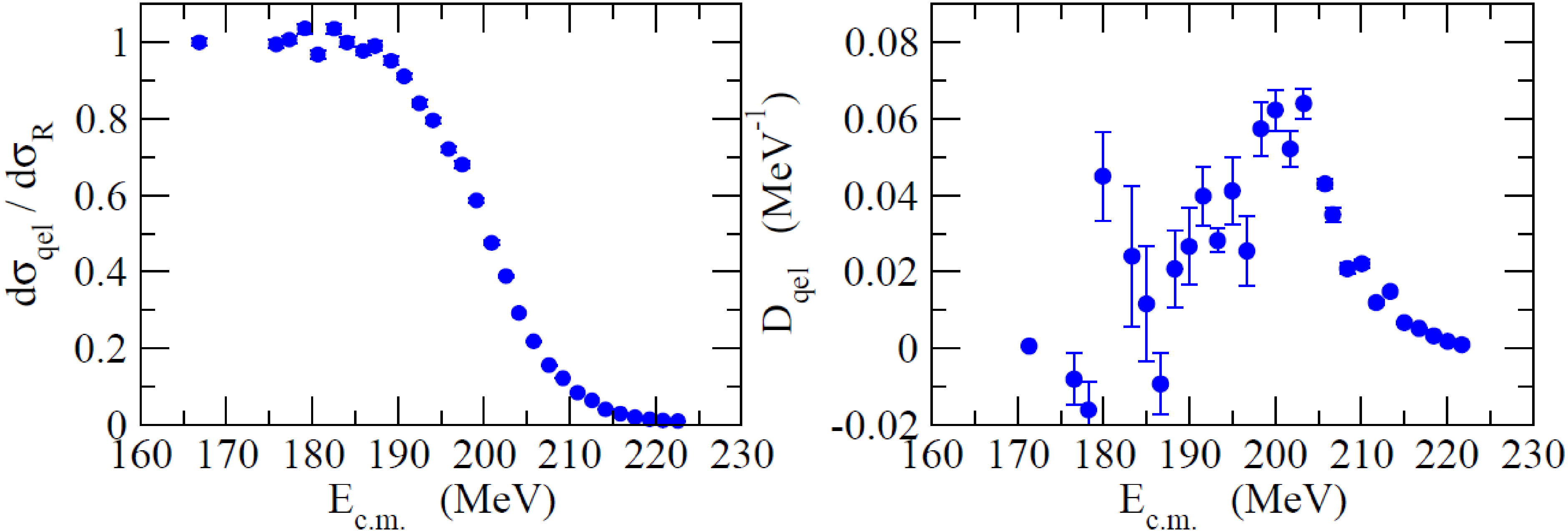
Analysis for a hot fusion reaction $^{48}Ca + ^{248}Cm$

K.H. and T. Tanaka (2017)
(T. Tanaka et al., K.H., JPSJ in press)

$$^{48}\mathrm{Ca} + ^{248}\mathrm{Cm}\ (\beta_2 = 0.297,\ \beta_4 = 0.04) \rightarrow {}^{296}_{116}\mathrm{Lv}^*$$

[β_2 and β_4 from P. Moller]

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



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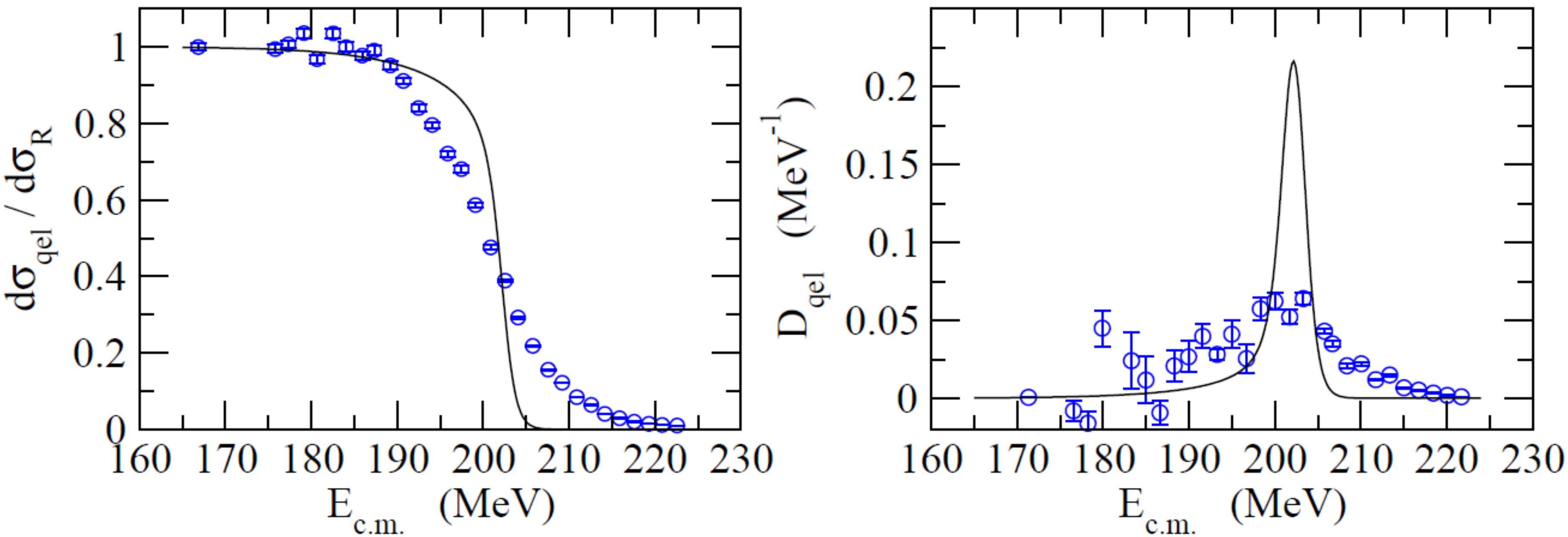
single-channel calculation (spherical ^{248}Cm)



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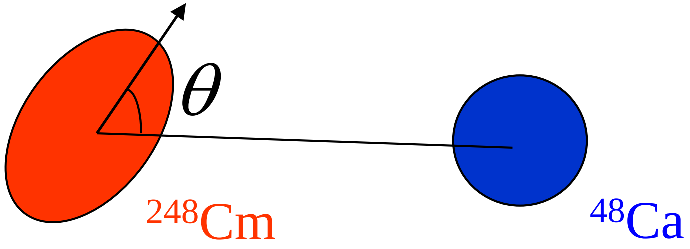
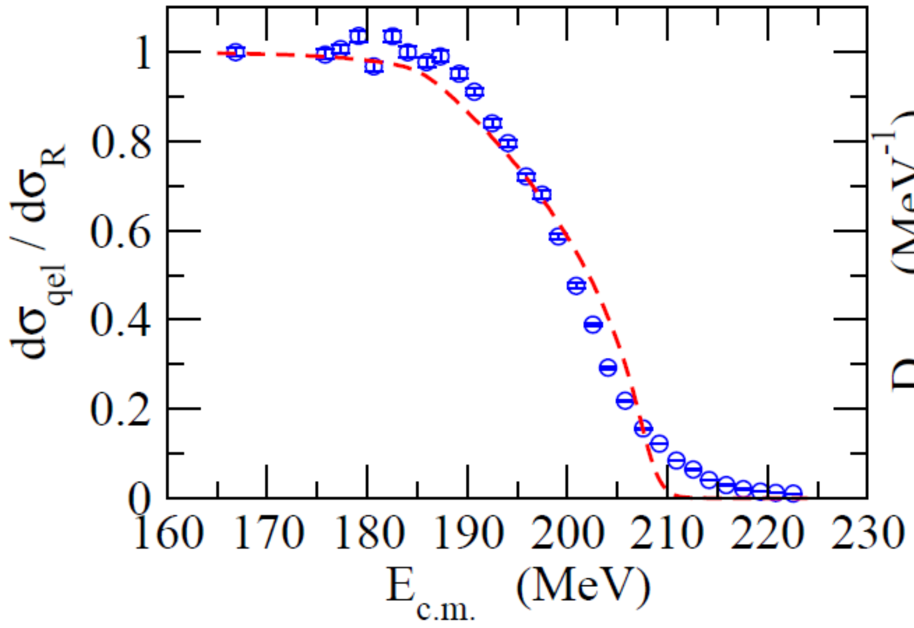
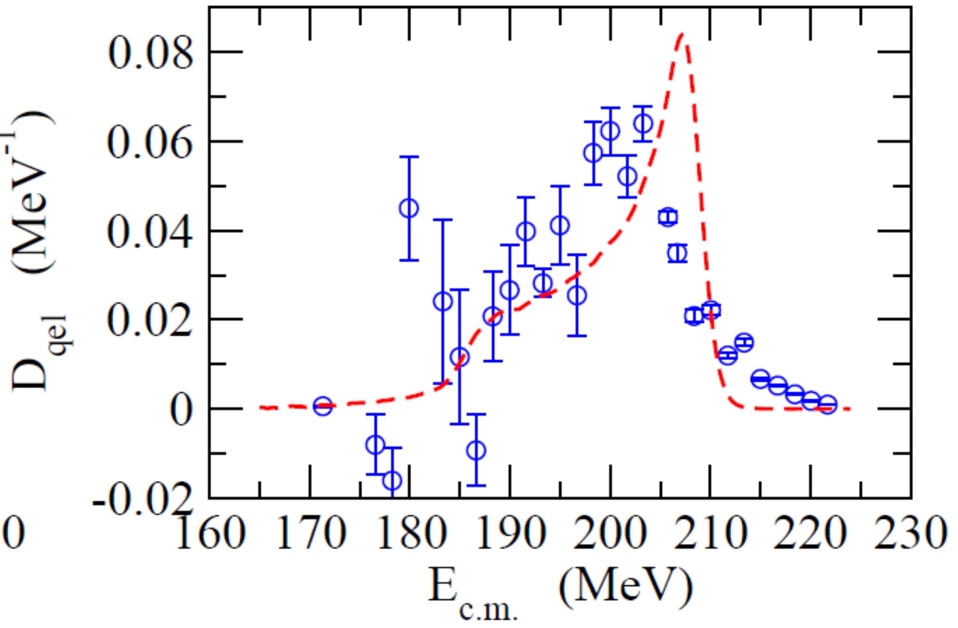
$$\frac{d\sigma_{\rm qel}}{d\Omega} = \int_0^1 d(\cos\theta)\left(\frac{d\sigma_{\rm el}}{d\Omega}\right)_\theta$$







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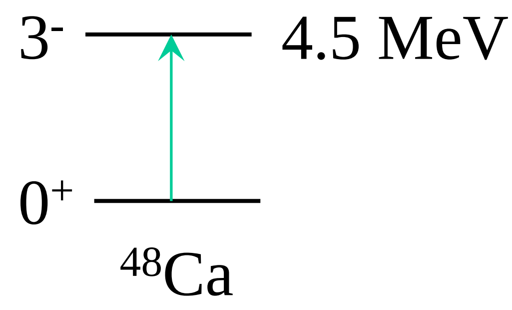

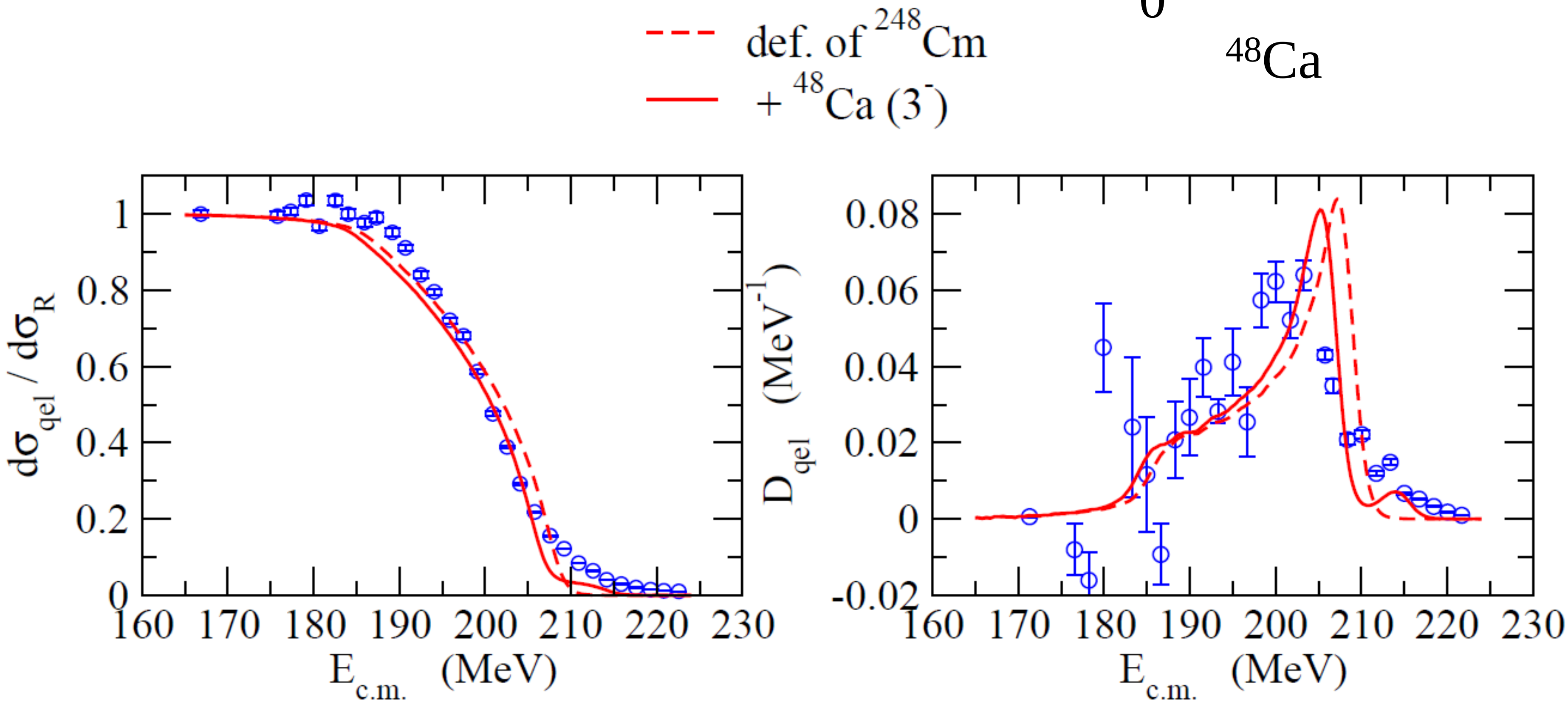

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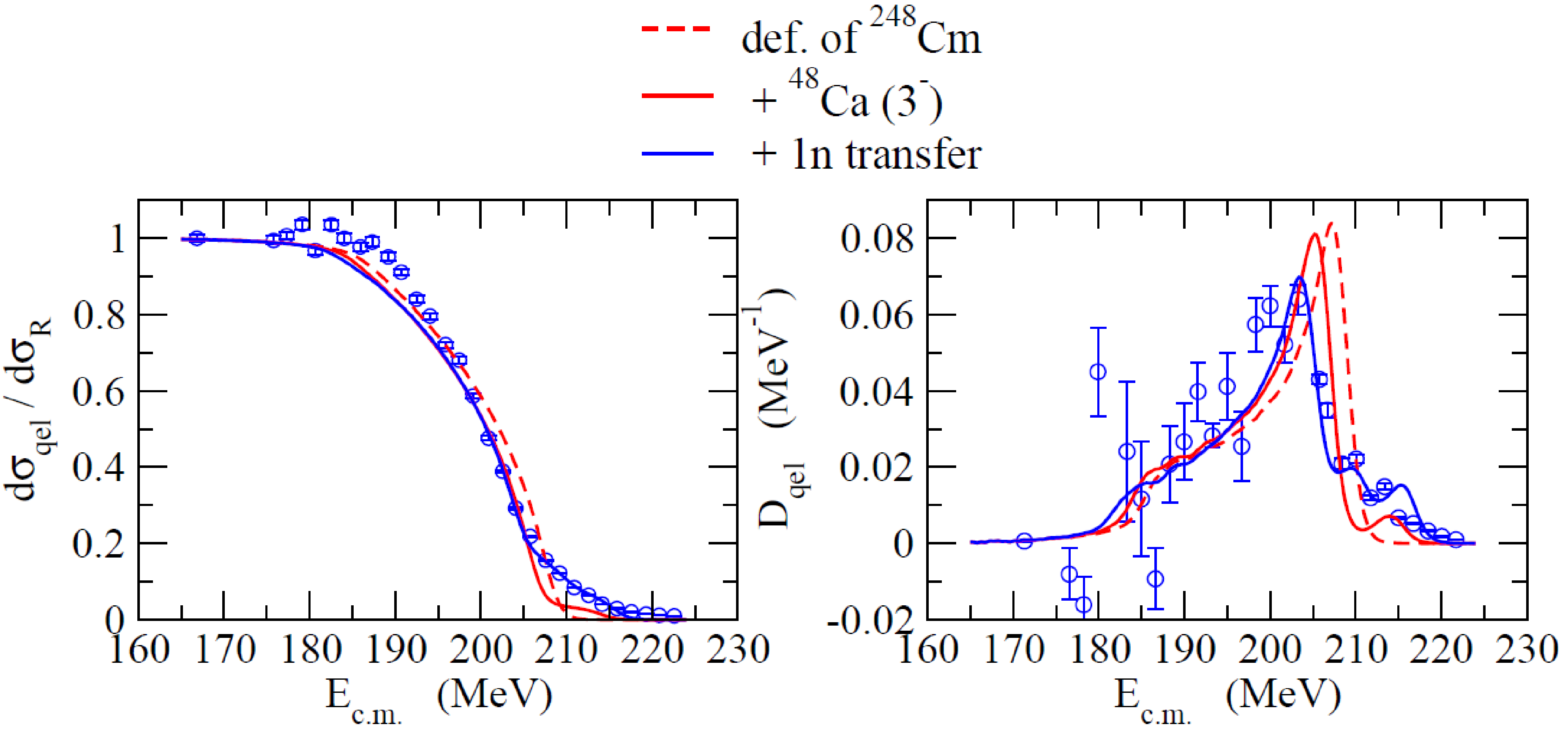
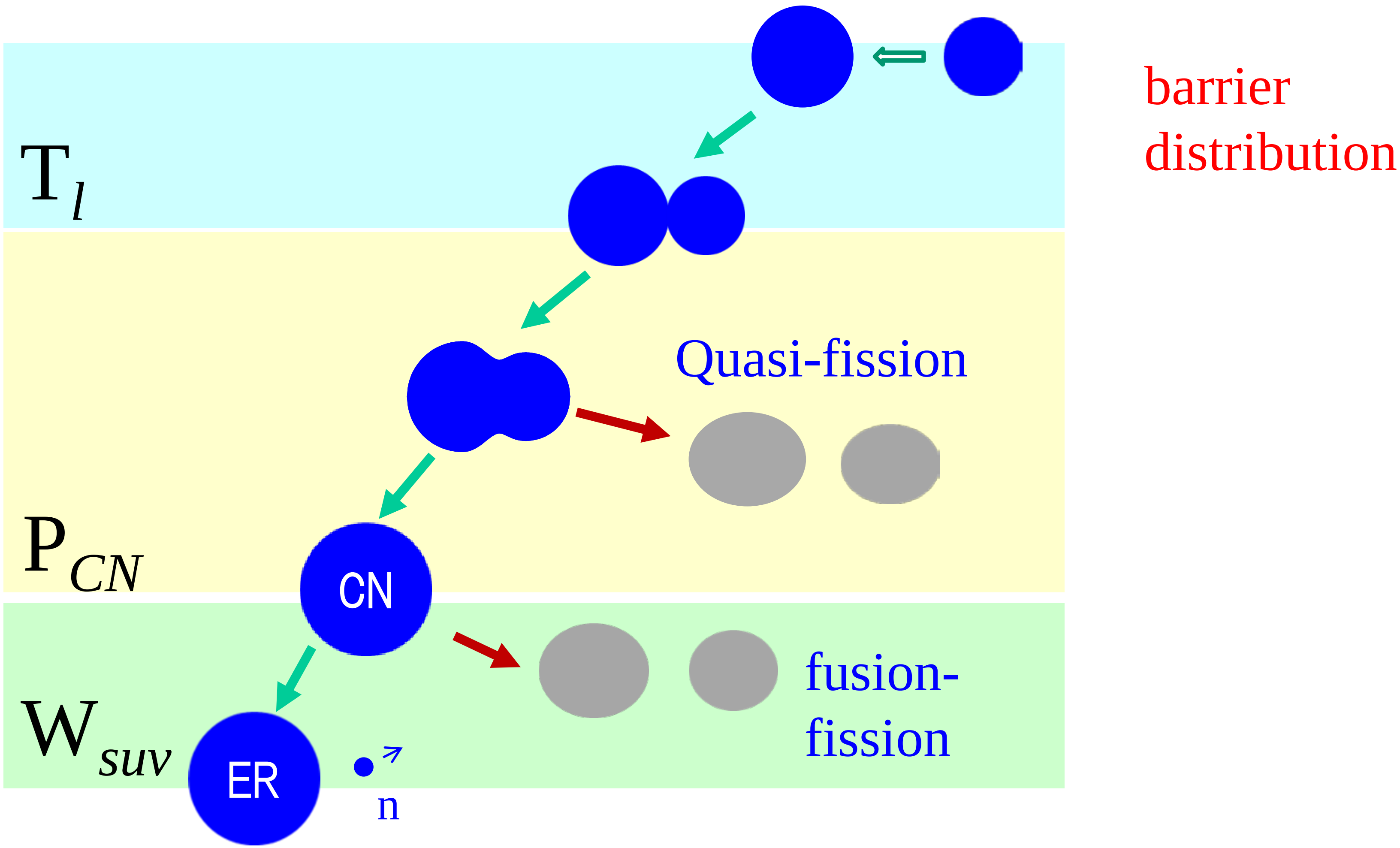
1n transfer

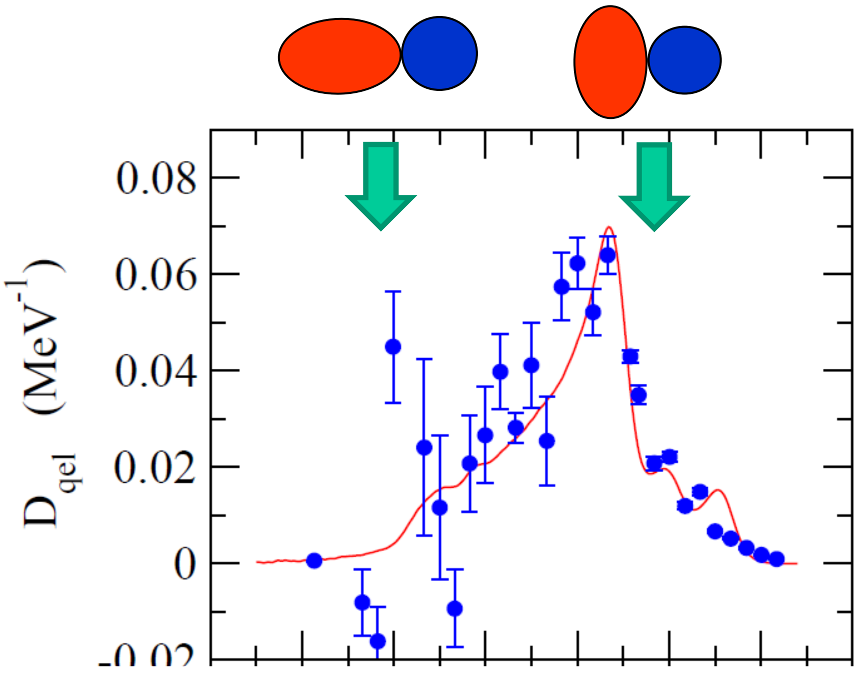
$$^{48}Ca + ^{248}Cm \rightarrow {}^{49}Ca + {}^{247}Cm\ (Q_{gg} = -1.06\ MeV)$$



Connection to the ER cross sections



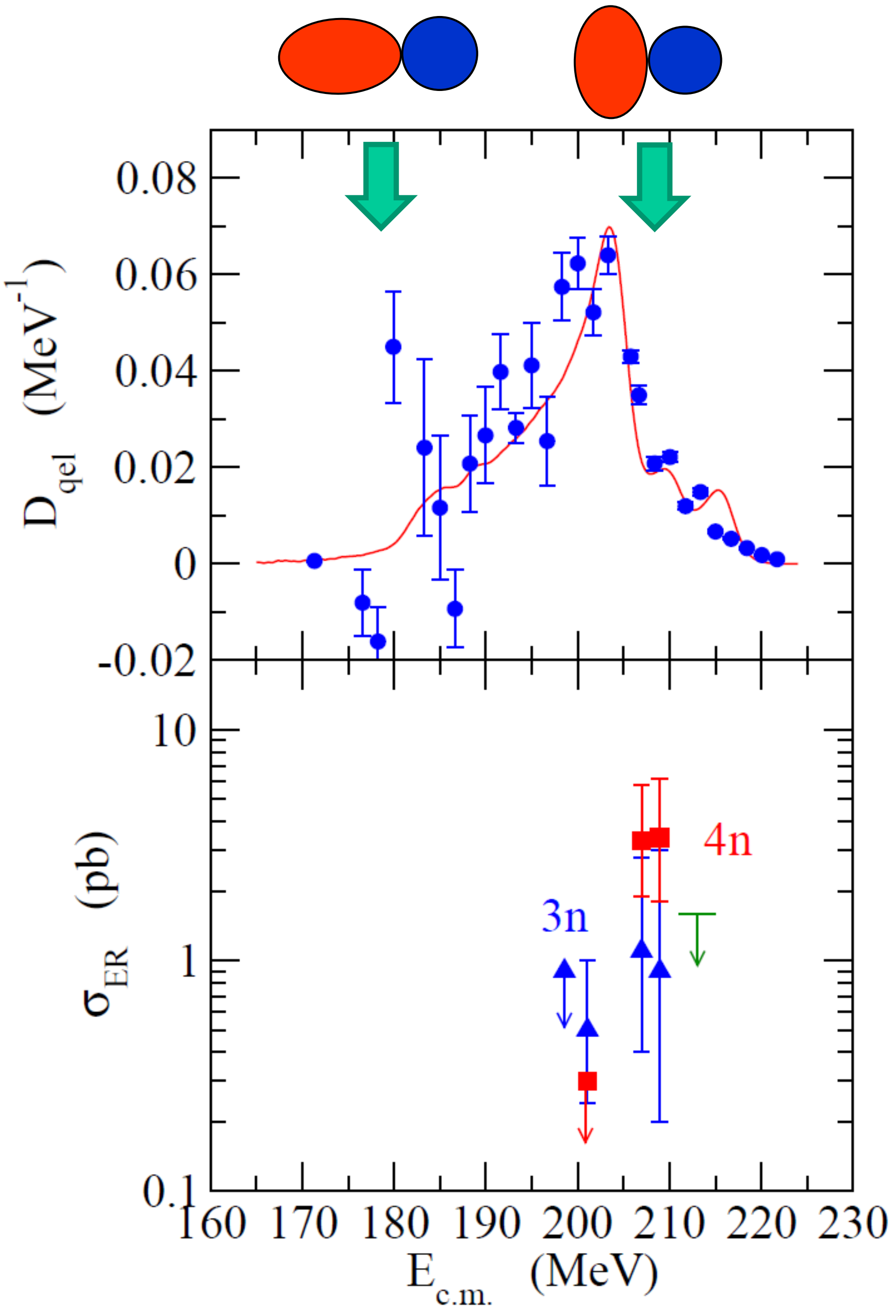
Connection to the ER cross sections



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

Connection to the ER cross sections

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



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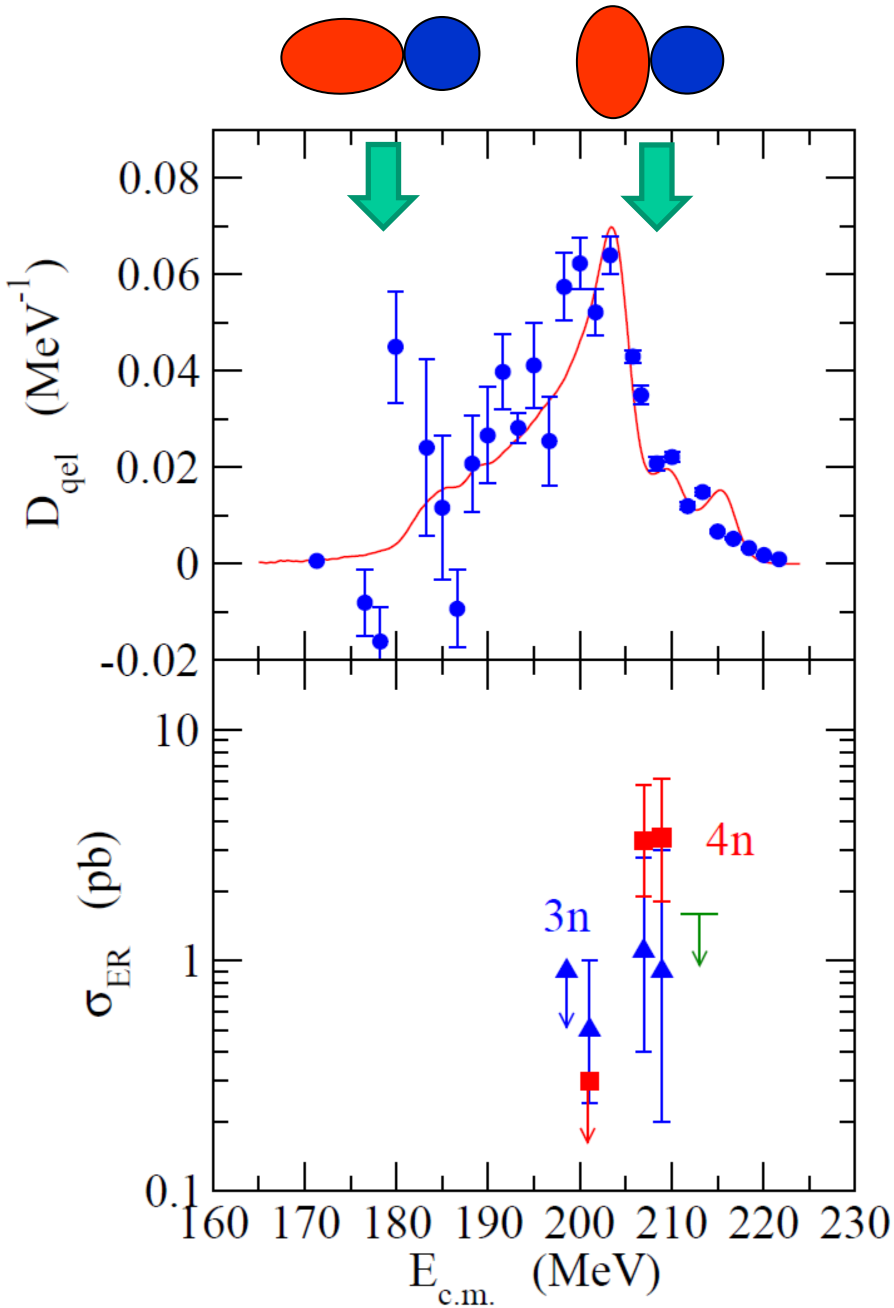
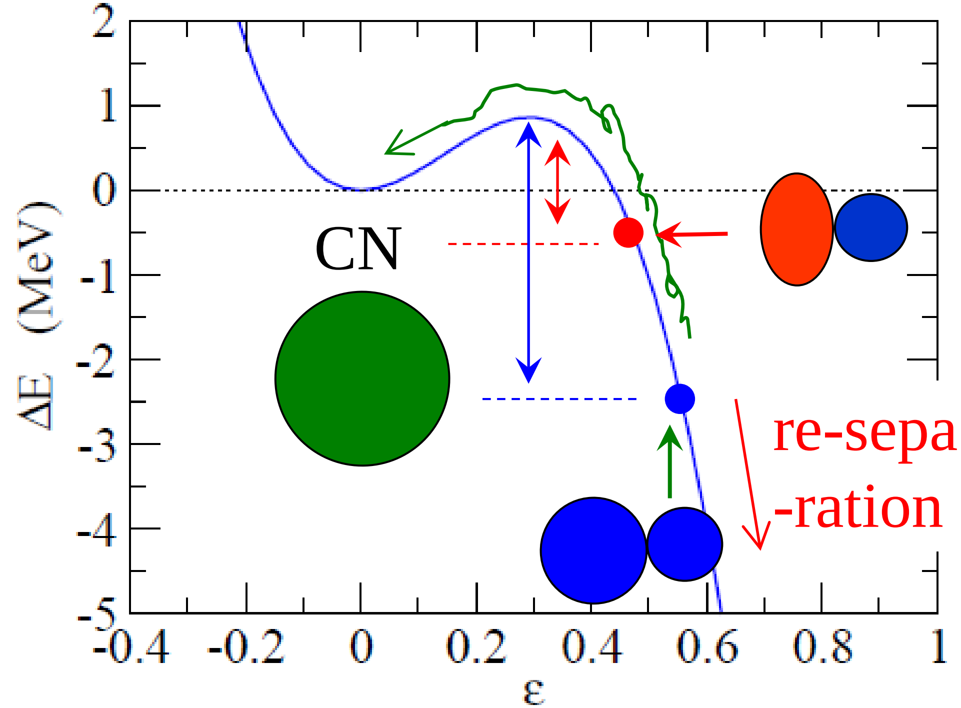
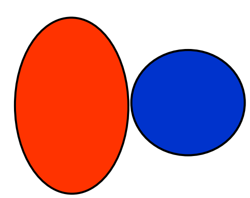


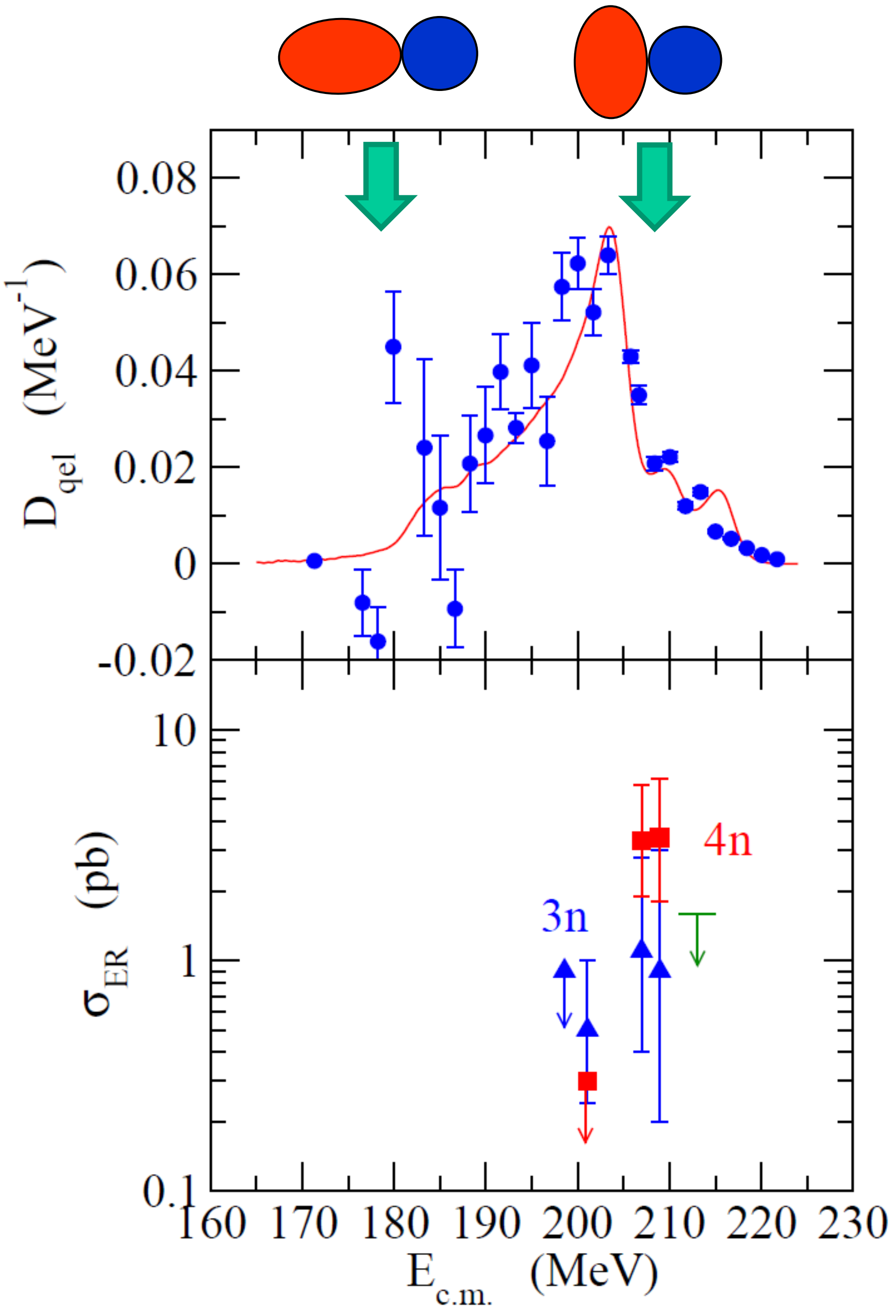
notion of compactness:
D.J. Hinde et al., PRL74 ('95) 1295





= more compact at the touching
→ lower barrier height

Connection to the ER cross sections



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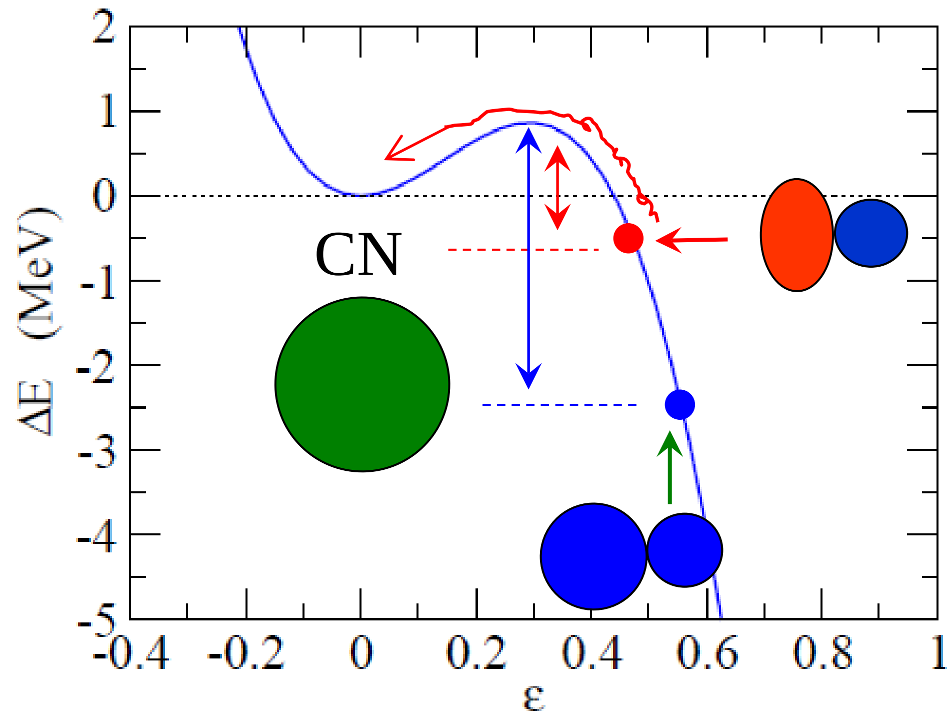
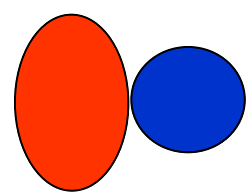
D.J. Hinde et al., PRL74 ('95) 1295

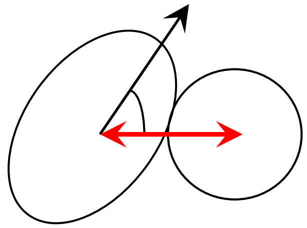




= more compact at the touching
→ lower barrier height

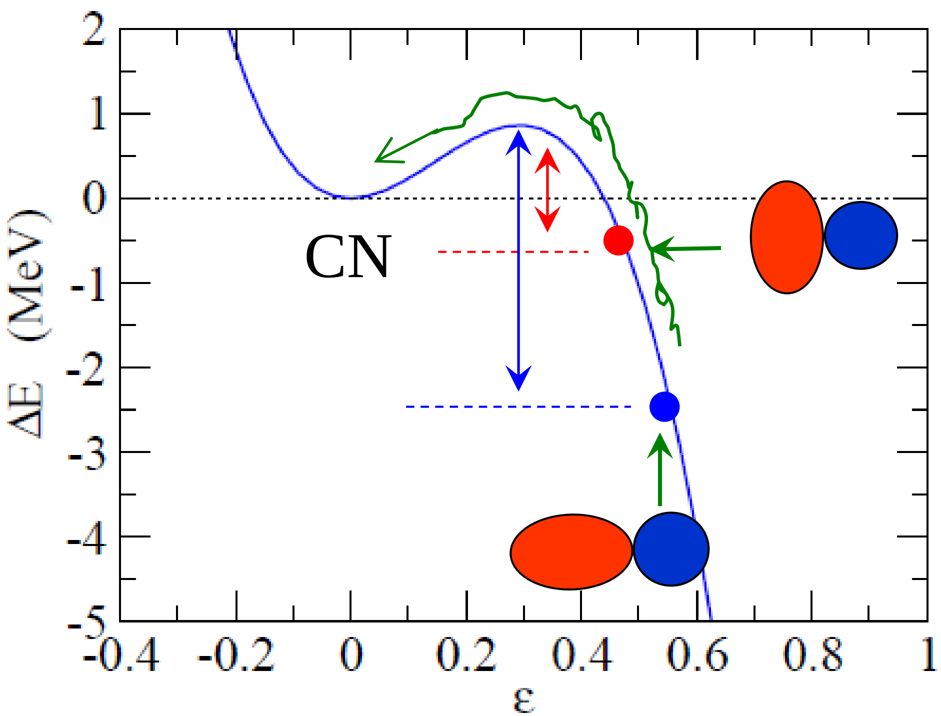
Connection to the ER cross sections

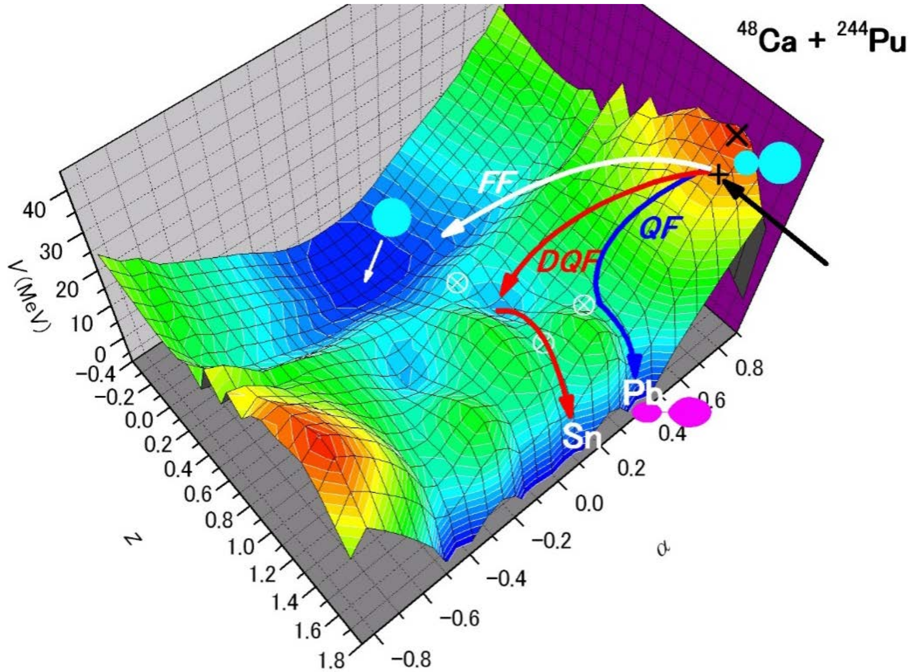
the initial (injection) point of a Langevin calculation:



$s_{inj}(\theta)$

$$s_{\mathrm{inj}}(\theta) = s_0 + \sum_\lambda R_T \beta_\lambda Y_{\lambda 0}(\theta)$$

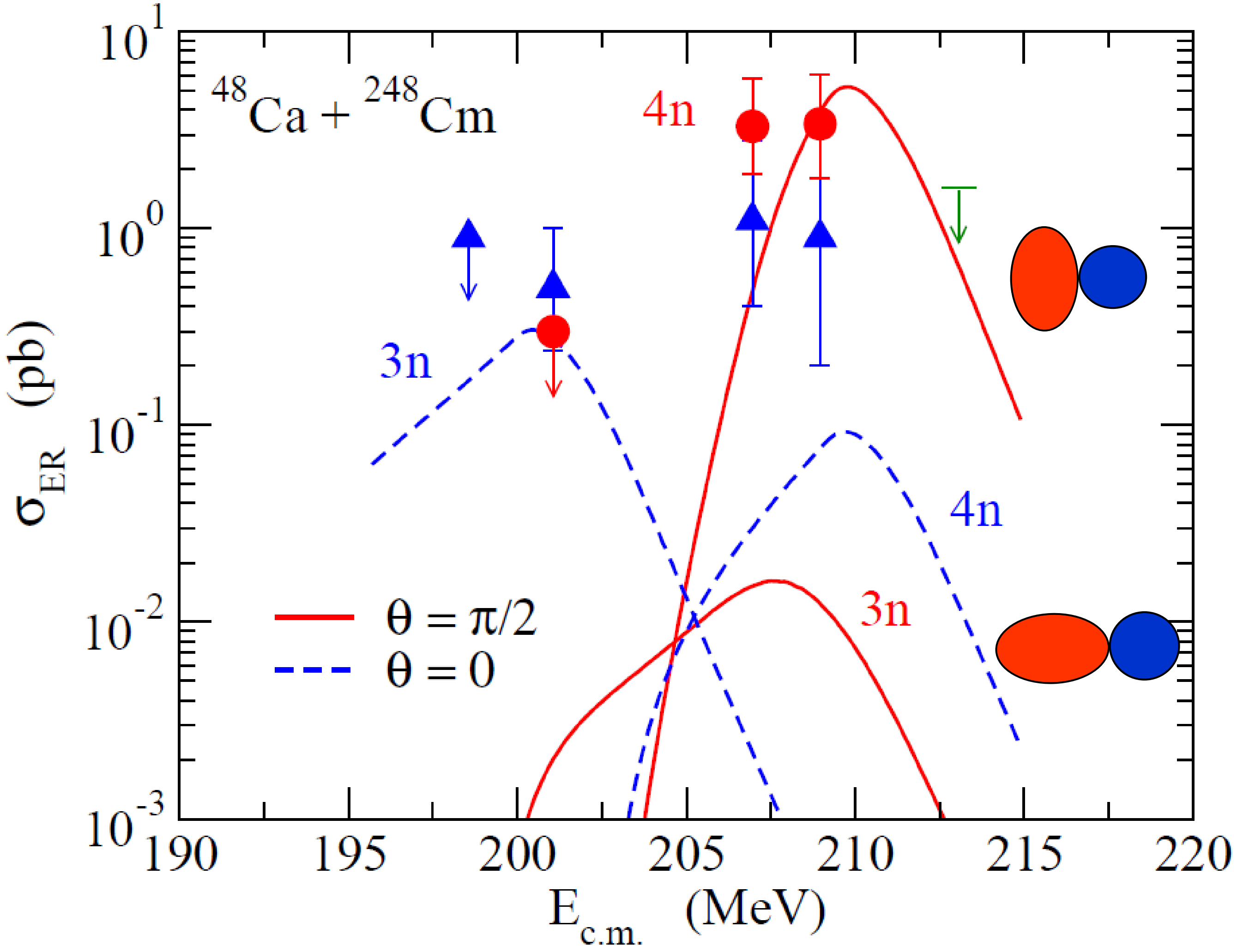




Y. Aritomo, K.H., K. Nishio,
S. Chiba, PRC85 ('12) 044614

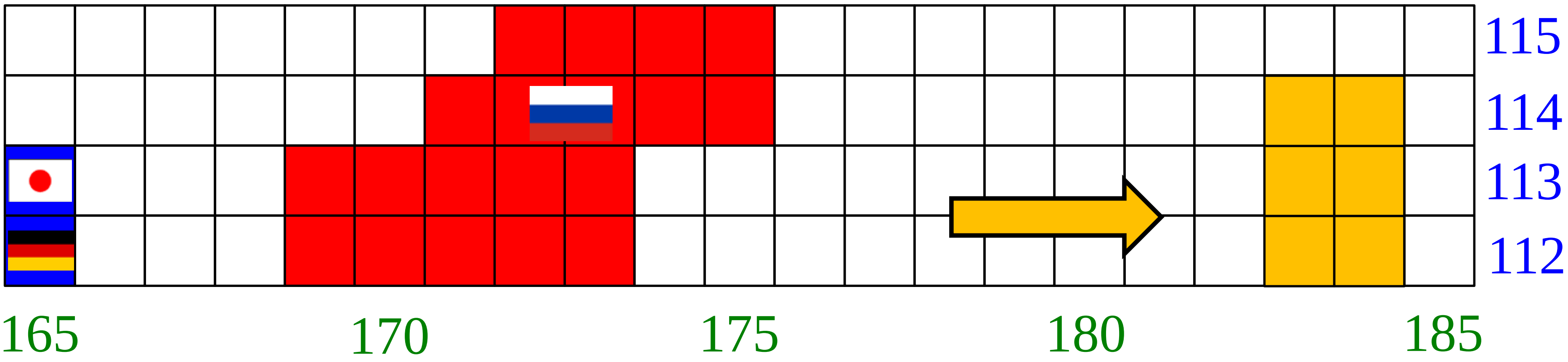
role of orientation angle in ER cross sections

Fusion-by-diffusion model (Swiatecki) + deformation



K.H., in preparation

Towards the island of stability



neutron-rich beams: indispensable

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

structure of exotic nuclei

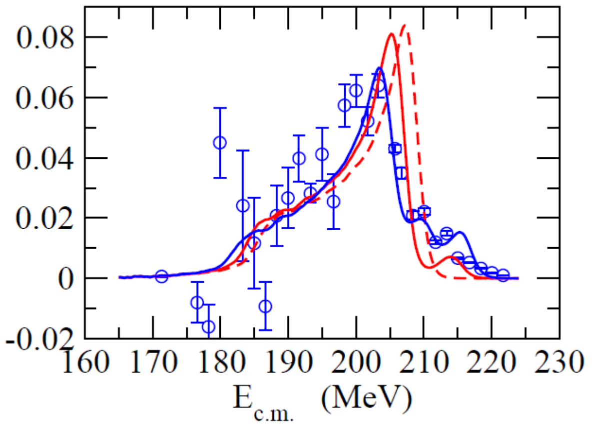
more studies are required

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

➢ Open problems

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

how much cross sections will be altered?

✓ shape evolution with a deformed target?

how does the deformation disappear during heat-up?

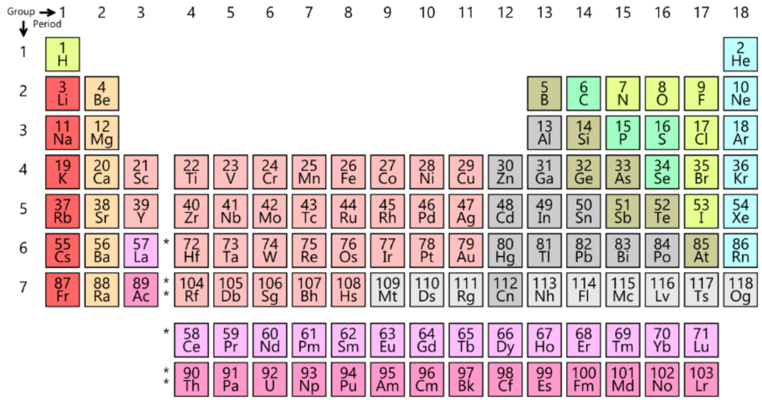
cf. Nakatsukasa-san's conjecture?

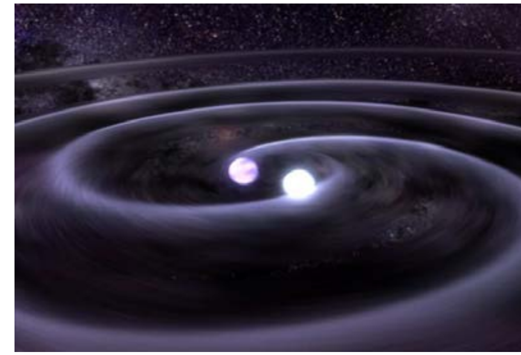
✓ reaction dynamics with neutron-rich nuclei?

formation of SHE

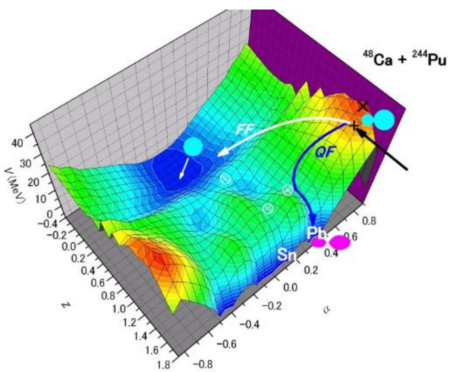
chemistry of SHE

the origin of (S)HE





reaction dynamics



Nuclear Physics (RIBF)
Astrophysics

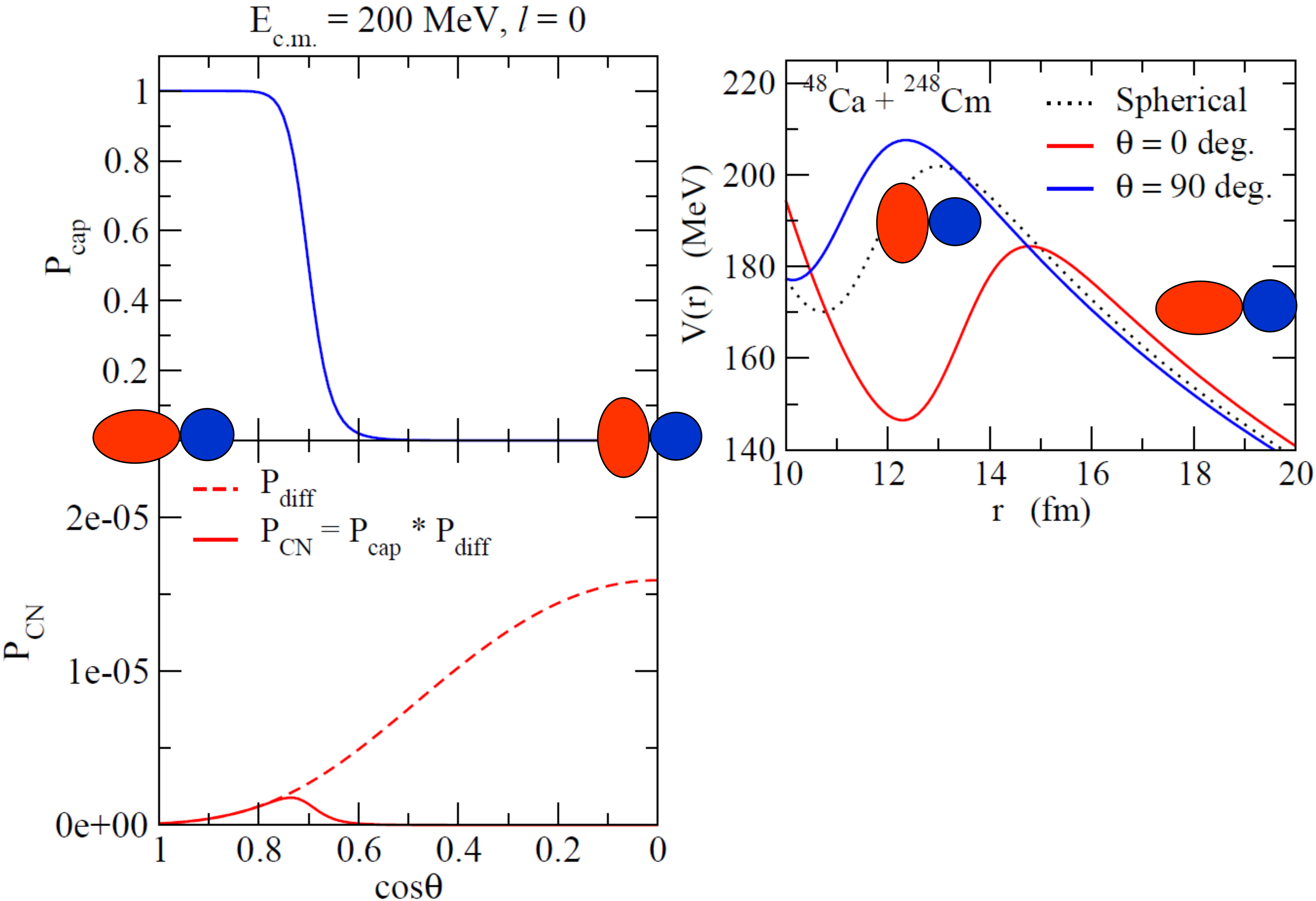
sessions in this morning

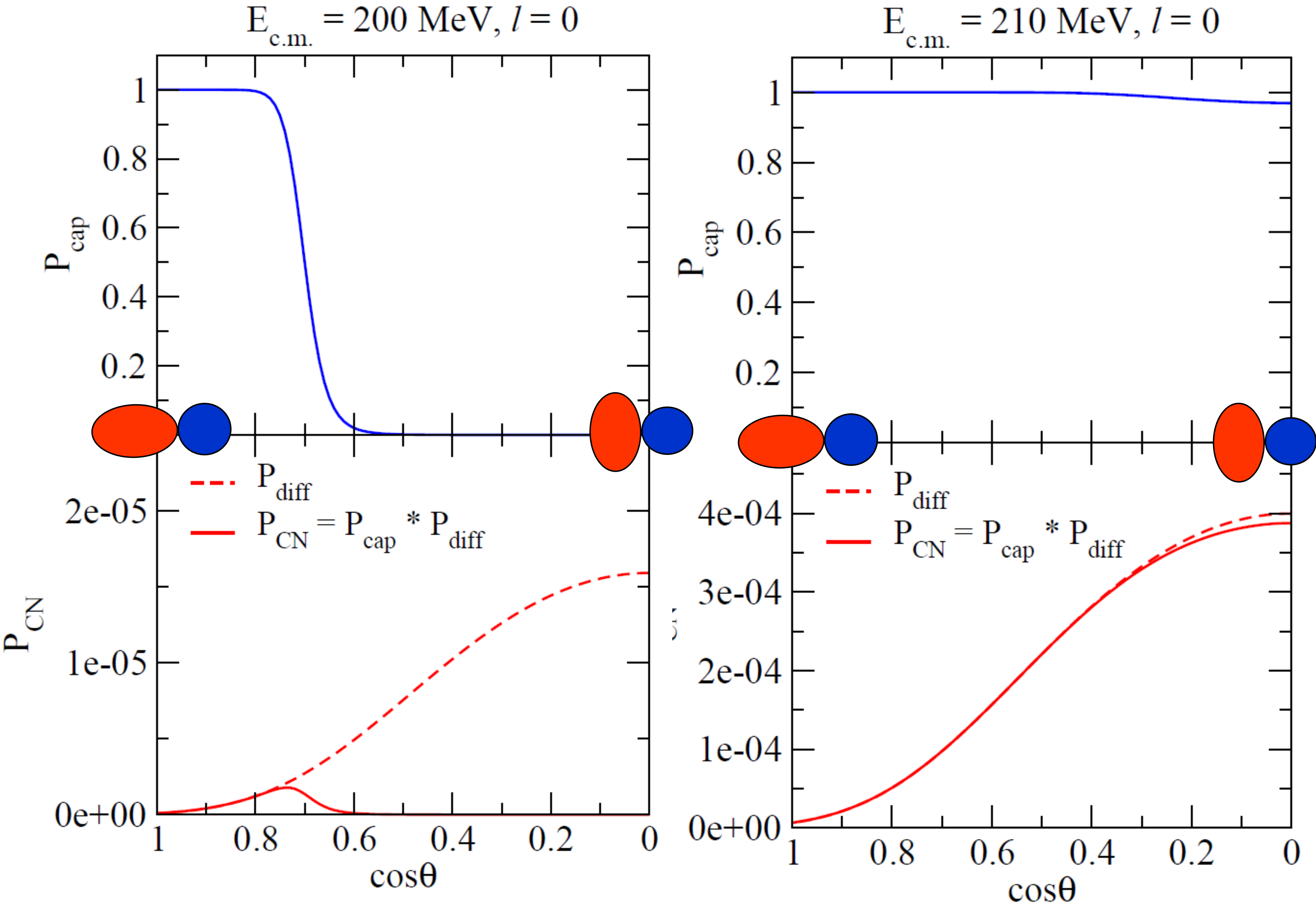
structure of SHE

Haba-san's talk

<u>interdisciplinary SHE science</u>

with physics, chemistry, and astronomy


E_c.m. = 200 MeV, l = 0
P_cap
1
0.8
0.6
0.4
0.2
P_diff
P_CN = P_cap * P_diff
P_CN
2e-05
1e-05
0e+00
1
0.8
0.6
0.4
0.2
0
cosθ
48Ca + 248Cm
Spherical
θ = 0 deg.
θ = 90 deg.
V(r) (MeV)
220
200
180
160
140
10
12
14
16
18
20
r (fm)



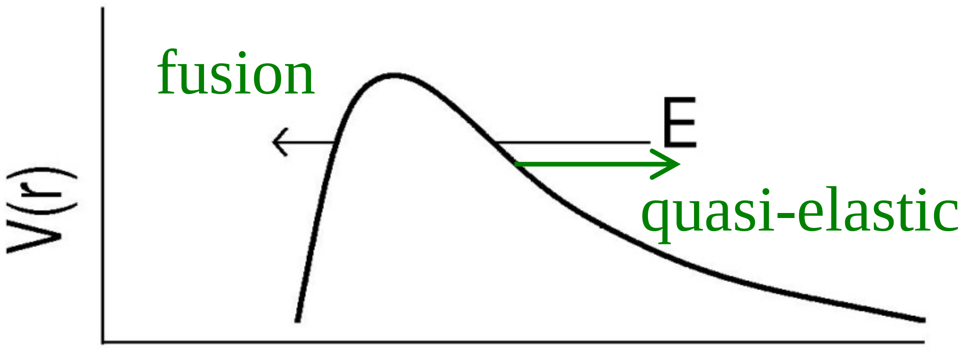
E c.m. = 200 MeV, l = 0
E c.m. = 210 MeV, l = 0
P cap
P CN
P diff
P CN = P cap * P diff
1
0.8
0.6
0.4
0.2
0
2e-05
1e-05
0e+00
4e-04
3e-04
2e-04
1e-04
cosθ

Recent application to SHE : Quasi-elastic B.D.

hot fusion reactions

^{48}Ca + actinide nucleus → SHE

= deformation ⇨ reaction dynamics with barrier distributions?



$$P + R = 1$$

Quasi-elastic scattering
: reflected flux at the barrier

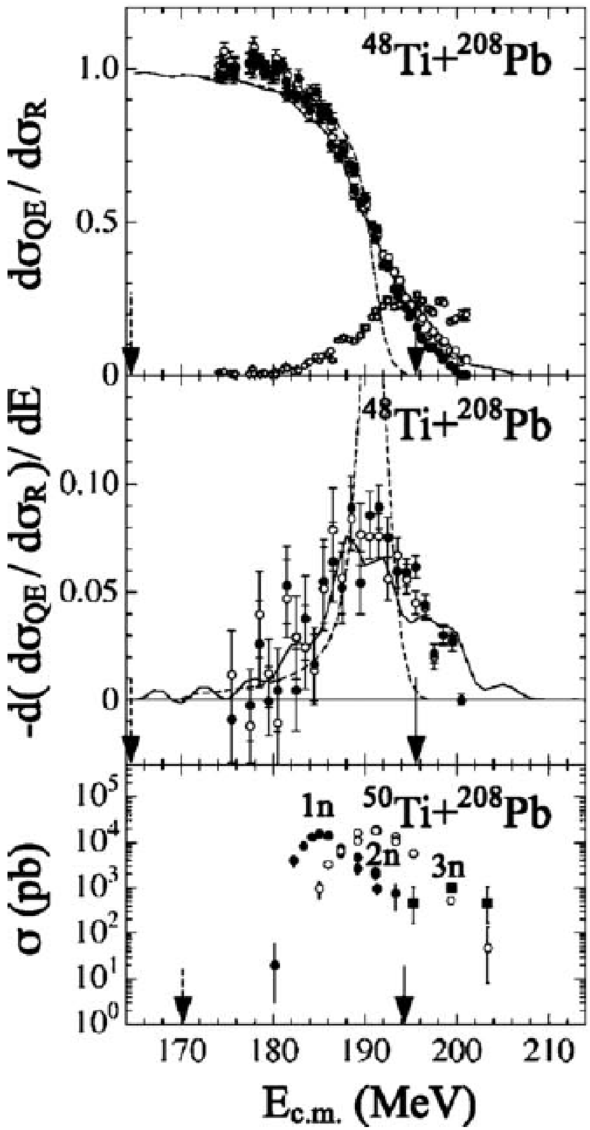
- a sum of elastic, inelastic, and transfer
- easier to measure than capture

Quasi-elastic barrier distribution

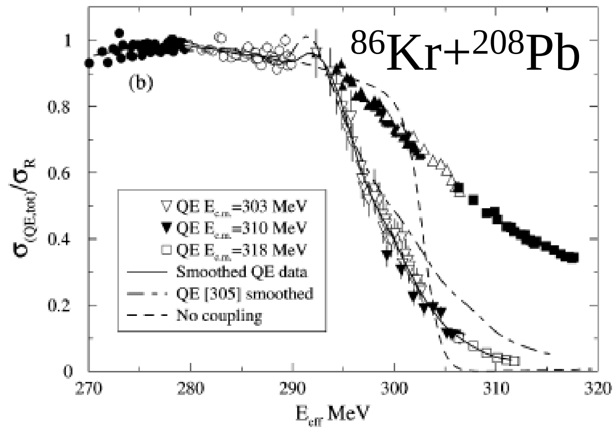
$$D_{\rm qel}(E) = -\frac{d}{dE}\left(\frac{\sigma_{\rm qel}(E,\pi)}{\sigma_R(E,\pi)}\right)$$

H. Timmers et al., NPA584('95)190
K.H. and N. Rowley, PRC69('04)054610

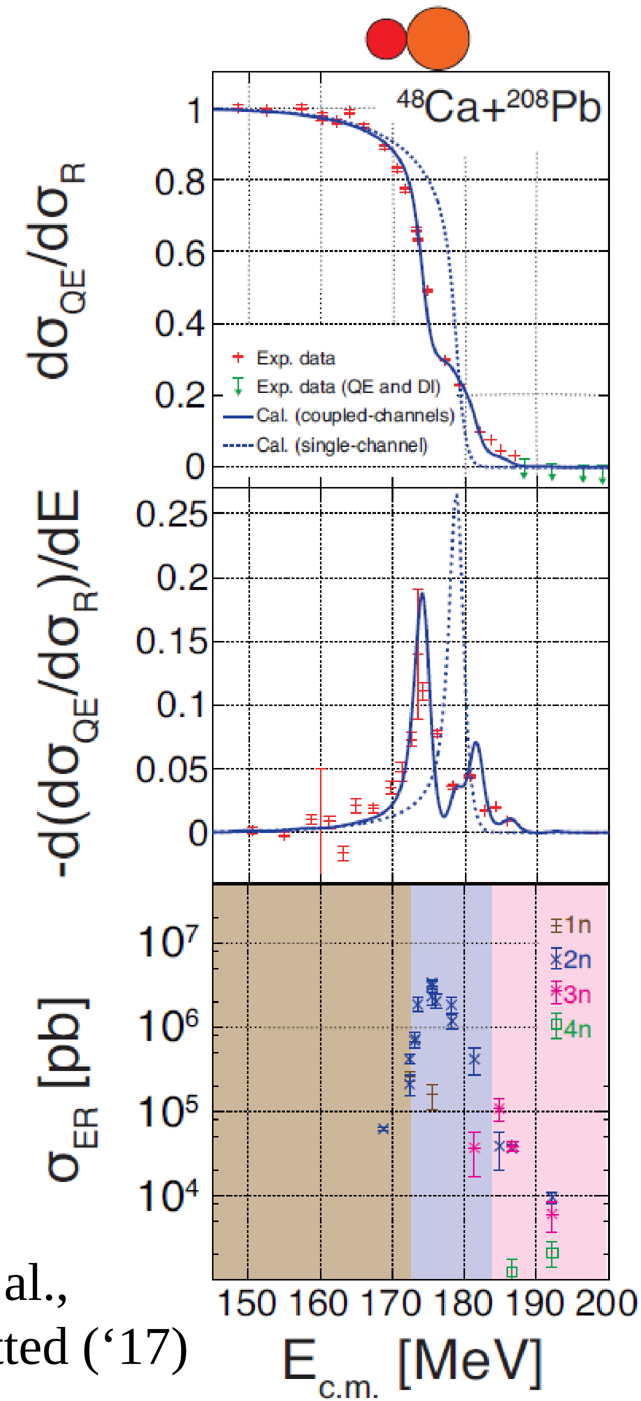
previous attempts



S. Mitsuoka et al., PRL99 (‘07) 182701

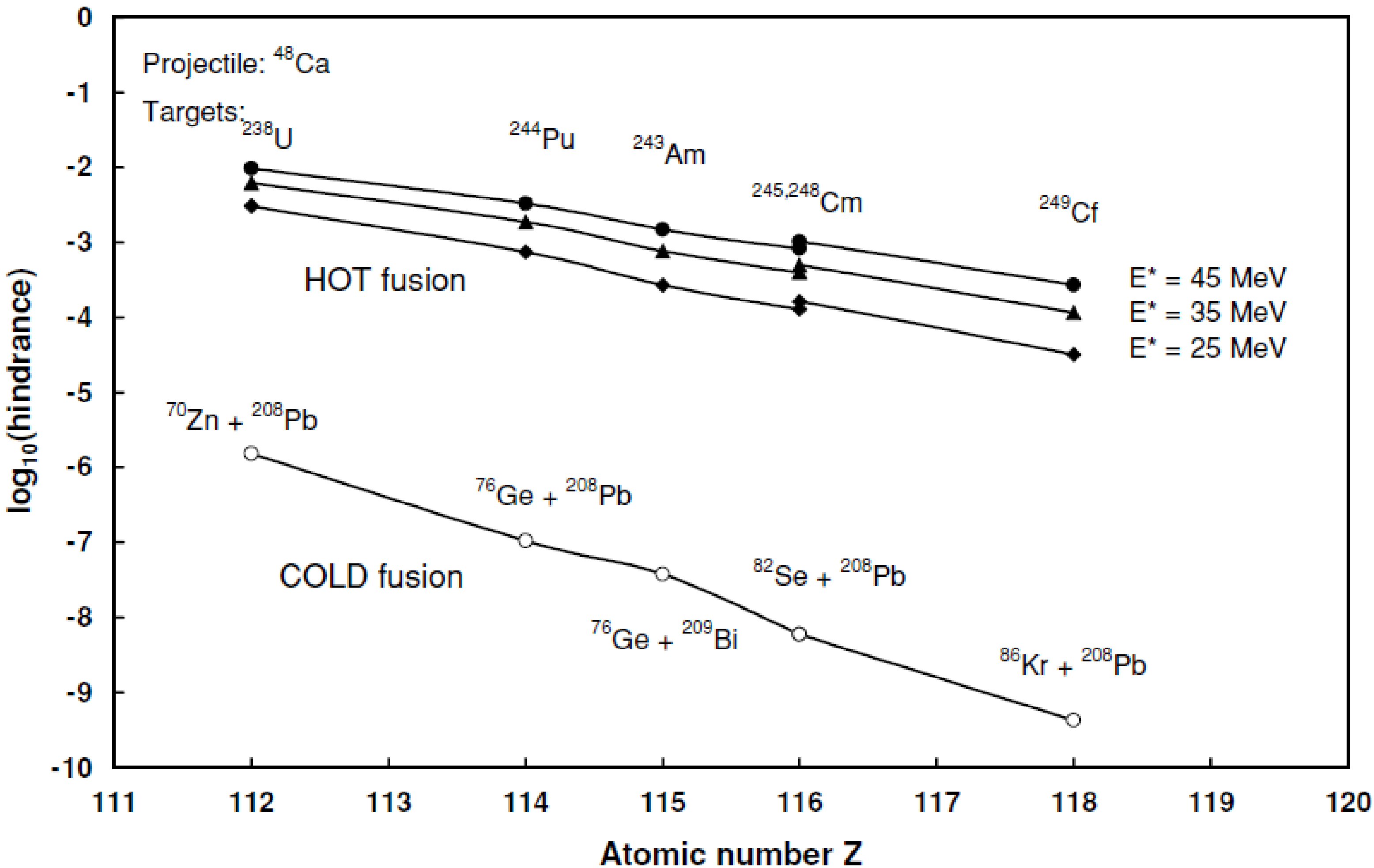


S.S. Ntshangase et al., PLB651 (‘07) 27



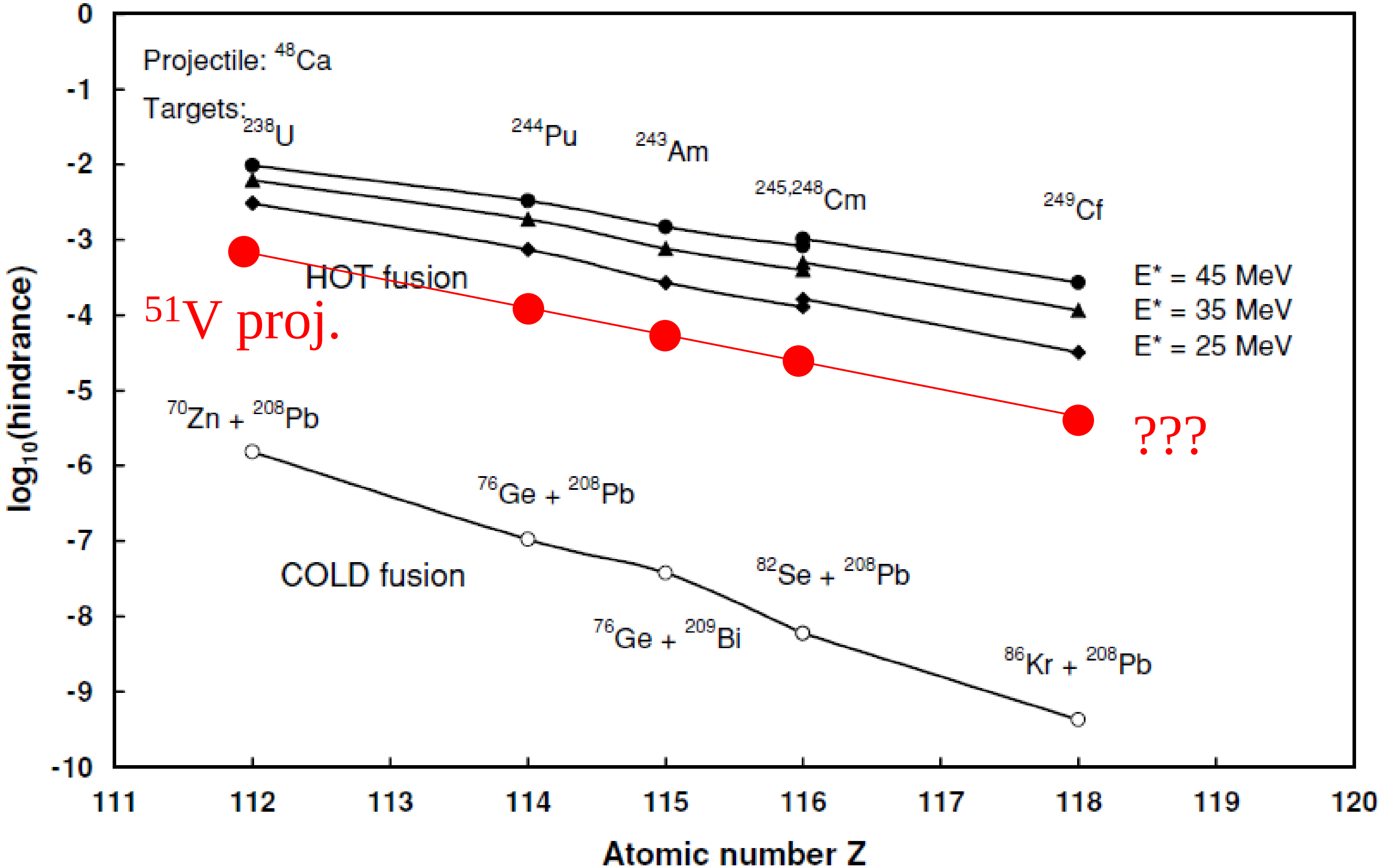
T. Tanaka et al., JPSJ, submitted (‘17)

fusion-by-diffusion model



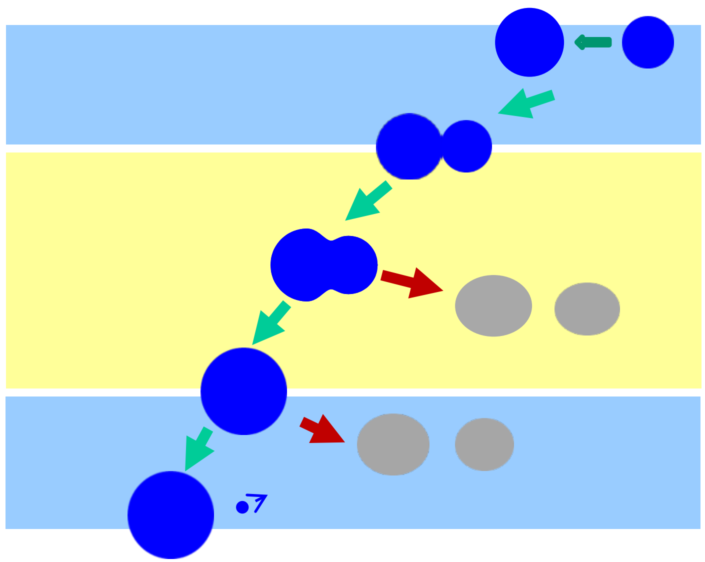
W.J. Swiatecki, K. Siwek-Wilczynska, and J. Wilczynski, PRC71 ('05) 014602

fusion-by-diffusion model



W.J. Swiatecki, K. Siwek-Wilczynska, and J. Wilczynski, PRC71 ('05) 014602

Super-heavy nuclei



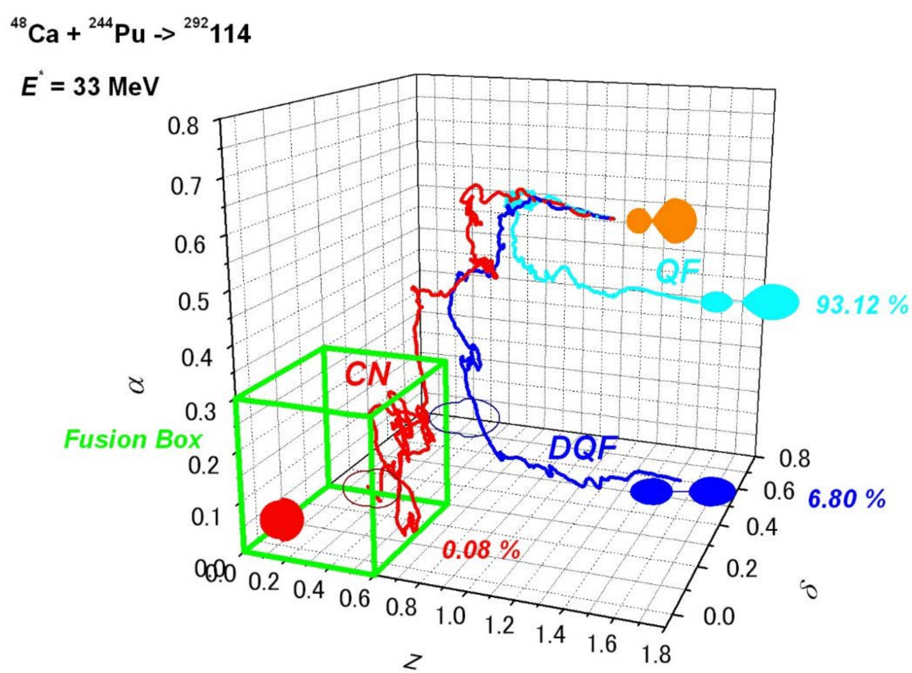
coupled-channels method

Langevin approach

V.I. Zagrebaev and W. Greiner, NPA944('15)257

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

statistical model



Evap. resid. cross section (pb)