Fusion barrier distribution and superheavy elements (SHE)

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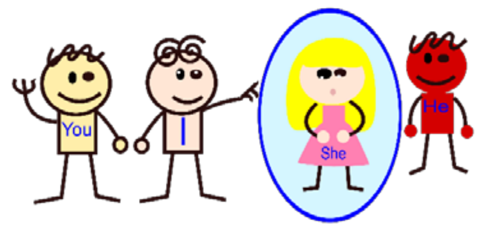
TOHOKU UNIVERSITY

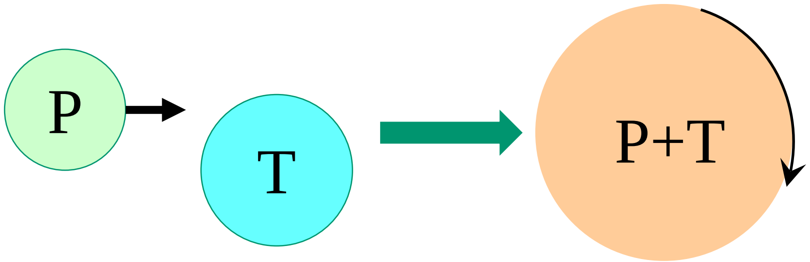


she 그녀는 누구입니까?

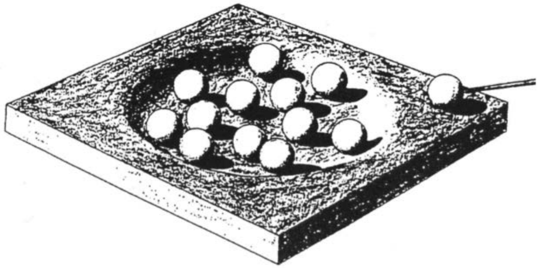
1. Heavy-ion sub-barrier fusion reactions
2. Coupled-channels approach and barrier distributions
3. Application to superheavy elements
4. Quantum friction
5. Summary

OMEG institute mini-workshop, Sep. 21, 2018, Soongsil Univeristy, Seoul, Korea

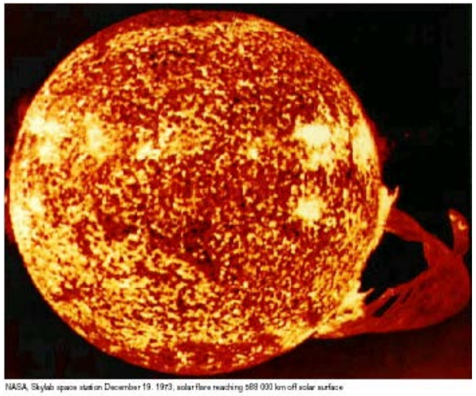
Fusion reactions: compound nucleus formation



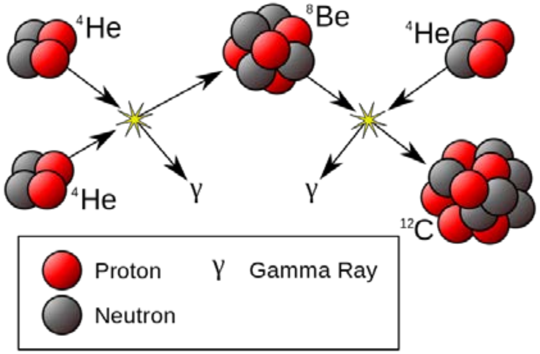
compound nucleus



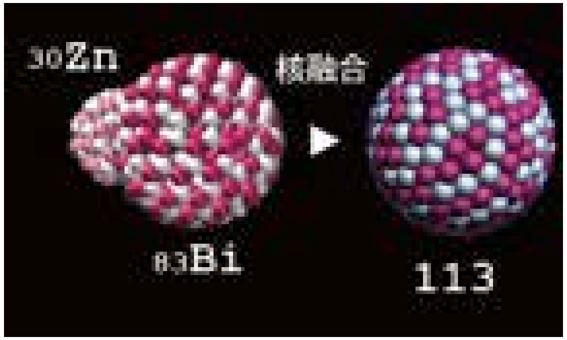
cf. Bohr '36



energy production in stars



nucleosynthesis

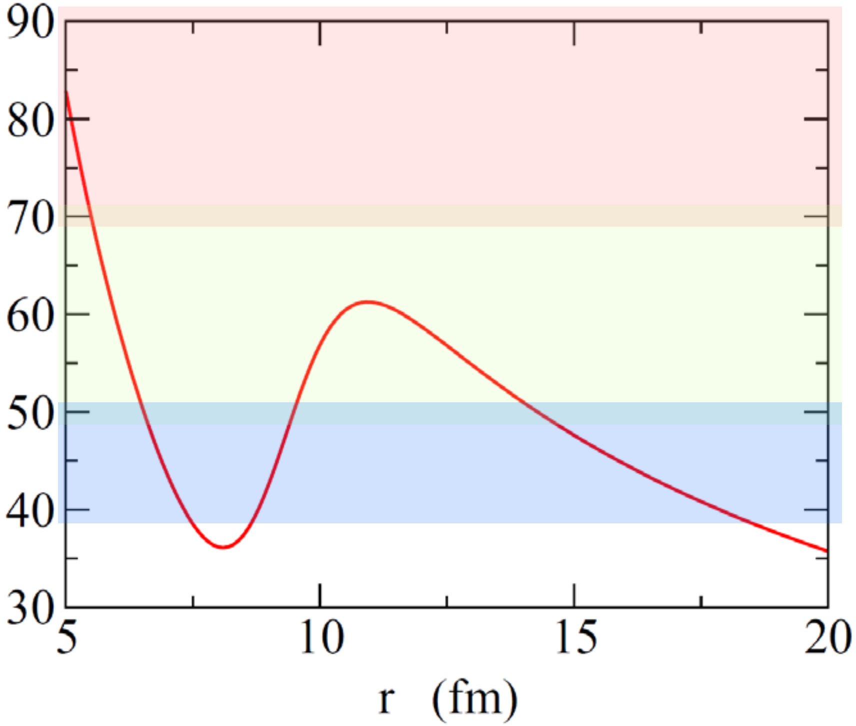


superheavy elements

Fusion and fission: large amplitude motions of quantum many-body systems with strong interaction

⟵ microscopic understanding: an ultimate goal of nuclear physics

Fusion reactions: compound nucleus formation



fusion reactions
in the sub-barrier energy region
$(|E - V_b| \lesssim 10\text{MeV})$

1. Coulomb force : long range, repulsive
2. Nuclear force : short range, attractive

→ Coulomb barrier

Why sub-barrier fusion?

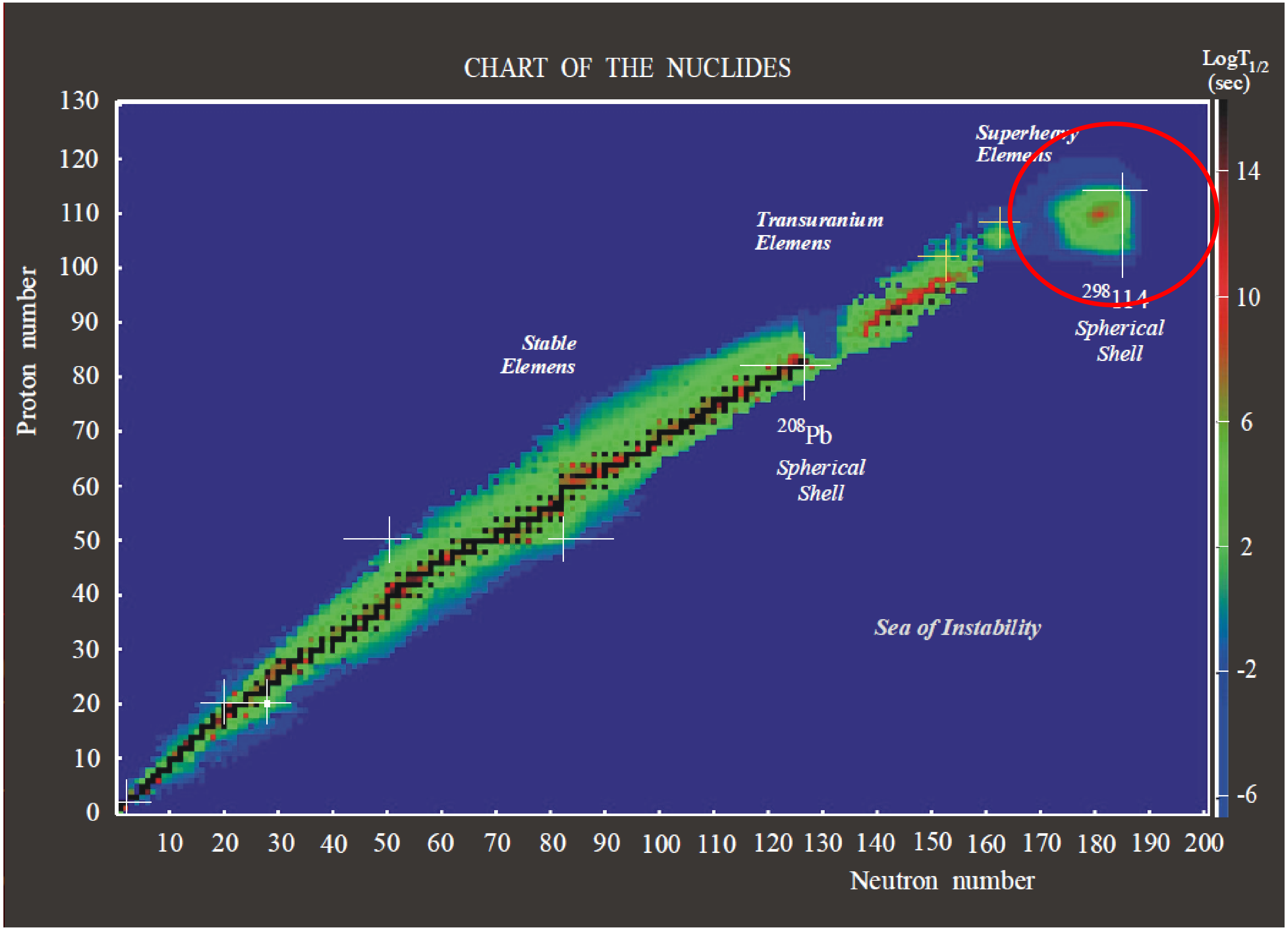
two obvious reasons:

i) Superheavy elements
ii) Nuclear Astrophysics

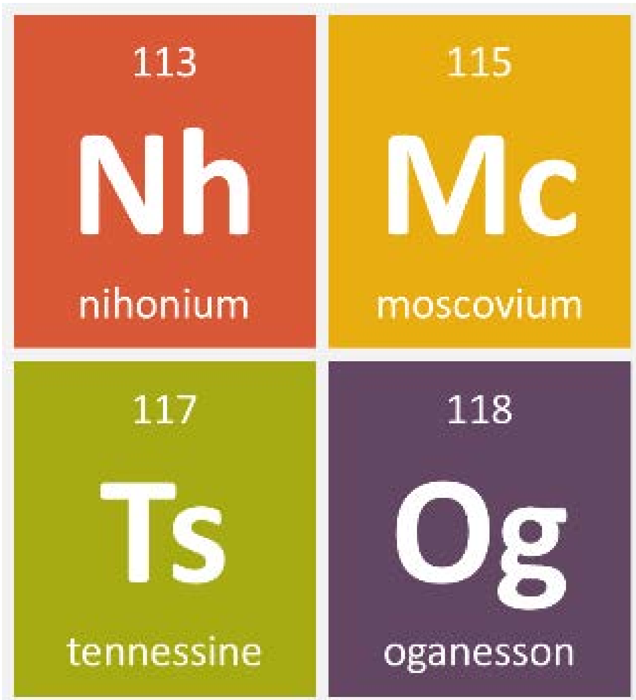
Why sub-barrier fusion?

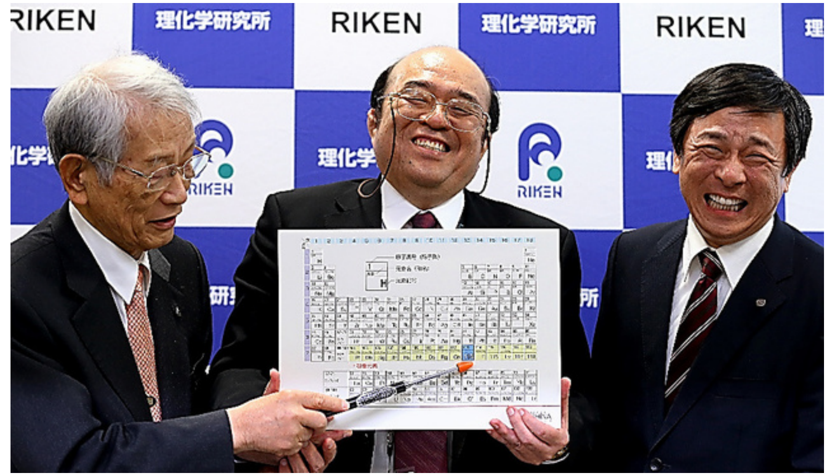
island of stability around Z=114, N=184

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

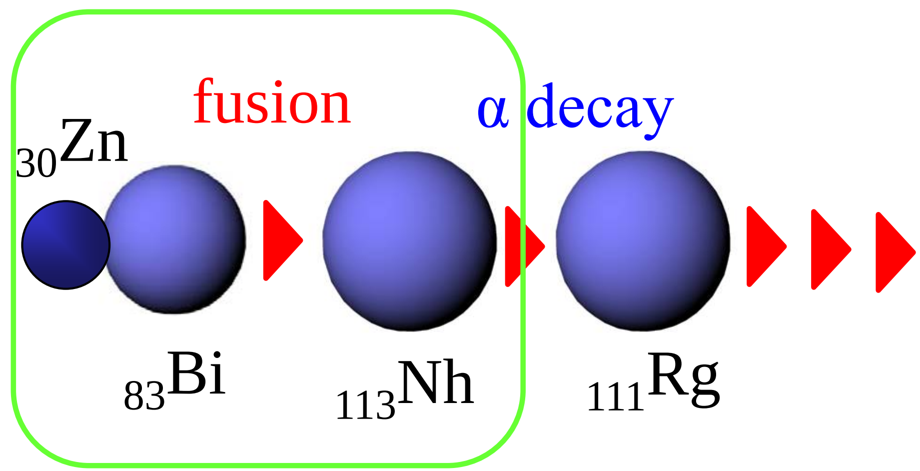


Why sub-barrier fusion?





November, 2016



superheavy elements

cf. ^{209}Bi (^{70}Zn,n) ^{278}Nh

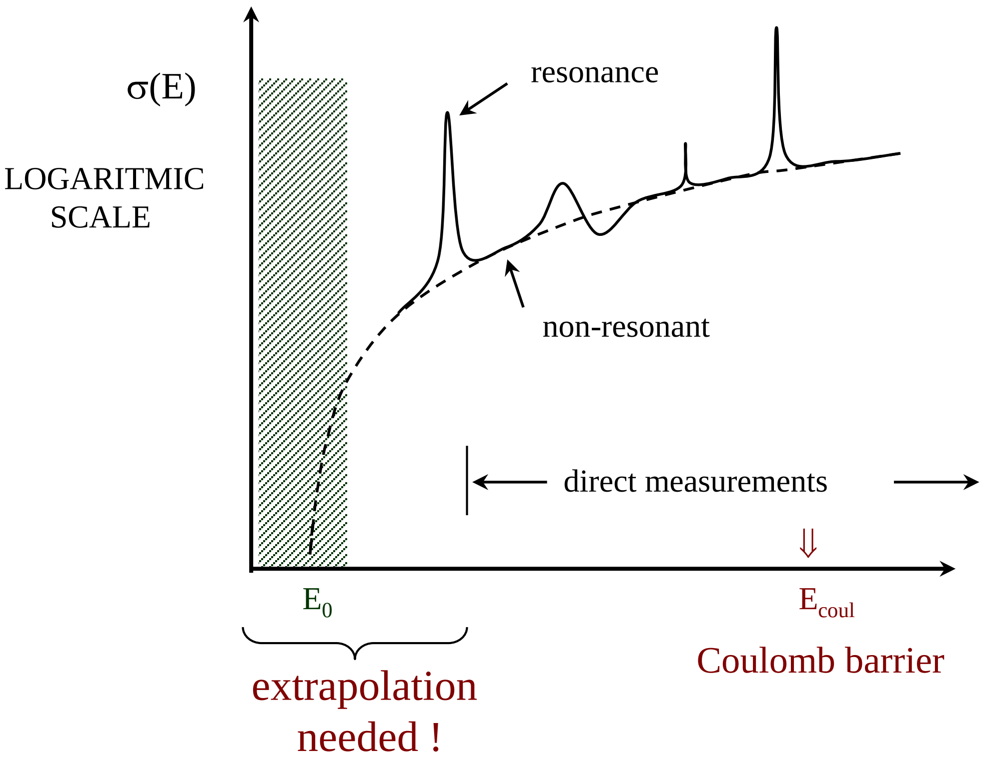
$V_B \sim 260$ MeV

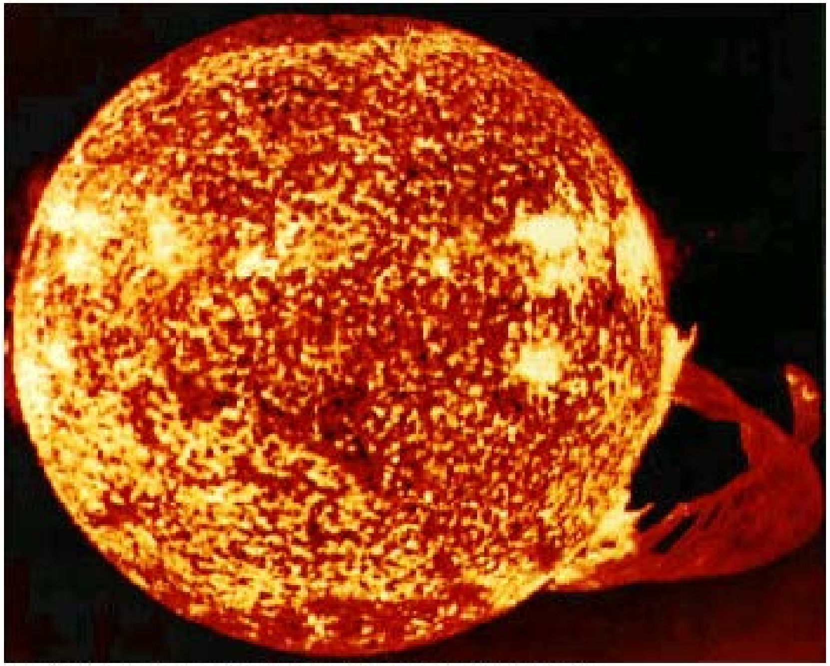
$E_{cm}^{(exp)} \sim 262$ MeV

Why sub-barrier fusion?

nuclear astrophysics (nuclear fusion in stars)

cf. extrapolation of data





NASA, Skylab space station December 19, 1973, solar flare reaching 588 000 km off solar surface

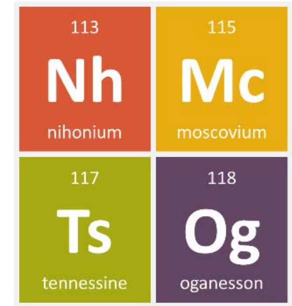
figure: M. Aliotta

Why sub-barrier fusion?

Two obvious reasons:

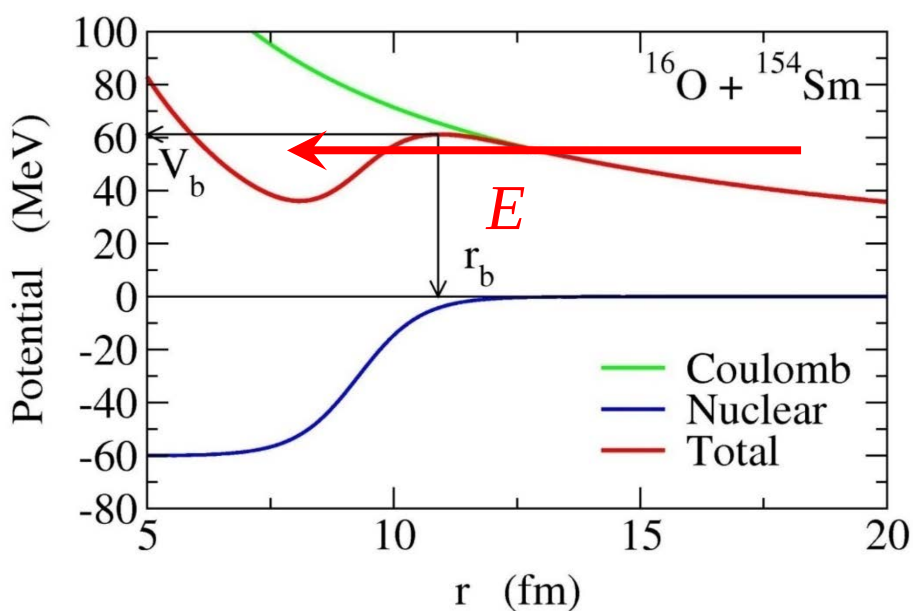
✓discovering new elements (SHE)

✓nuclear astrophysics (fusion in stars)



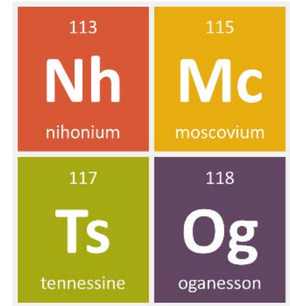
Other reasons:

◆ **many-particle tunneling**



Why sub-barrier fusion?

Two obvious reasons:



✓discovering new elements (SHE)
✓nuclear astrophysics (fusion in stars)

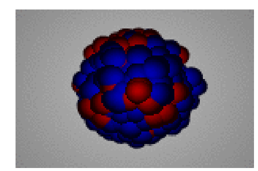
Other reasons:

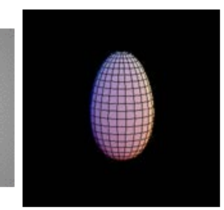
◆ reaction mechanism

strong interplay between reaction and nuclear structure

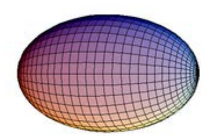
cf. high *E* reactions: much simpler reaction mechanism

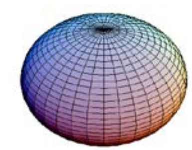
◆ **many-particle tunneling**





✓ many types of intrinsic degrees of freedom





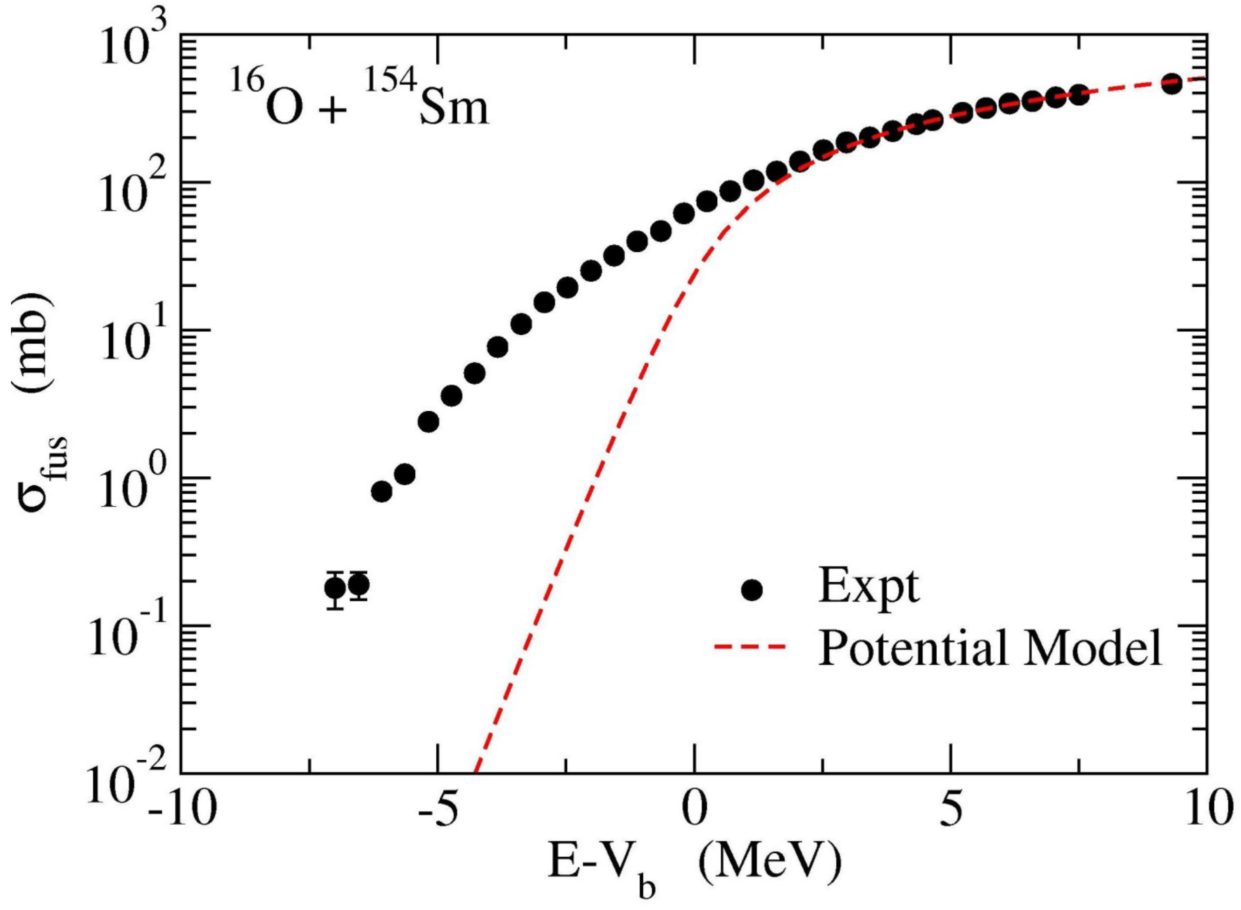
✓ energy dependence of tunneling probability

cf. alpha decay: fixed energy

H.I. fusion reaction = an ideal playground to study quantum tunneling with many degrees of freedom

Discovery of large sub-barrier enhancement of σ_{fus}

potential model: $V(r)$ + absorption

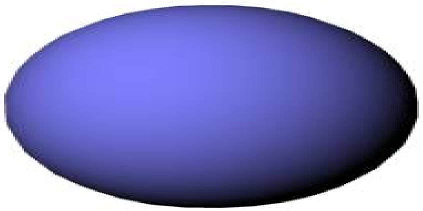


cf. seminal work:

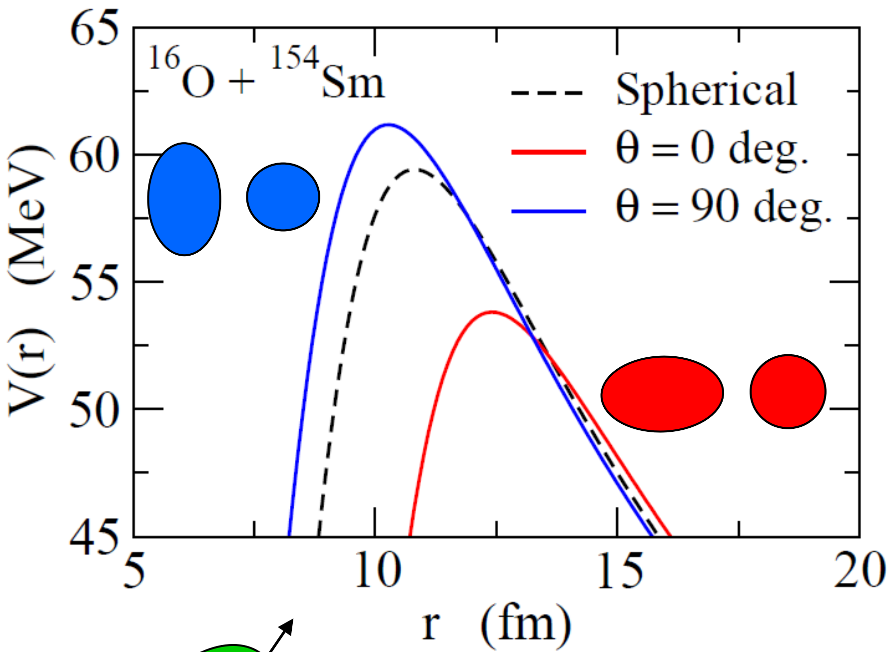
R.G. Stokstad et al., PRL41('78) 465

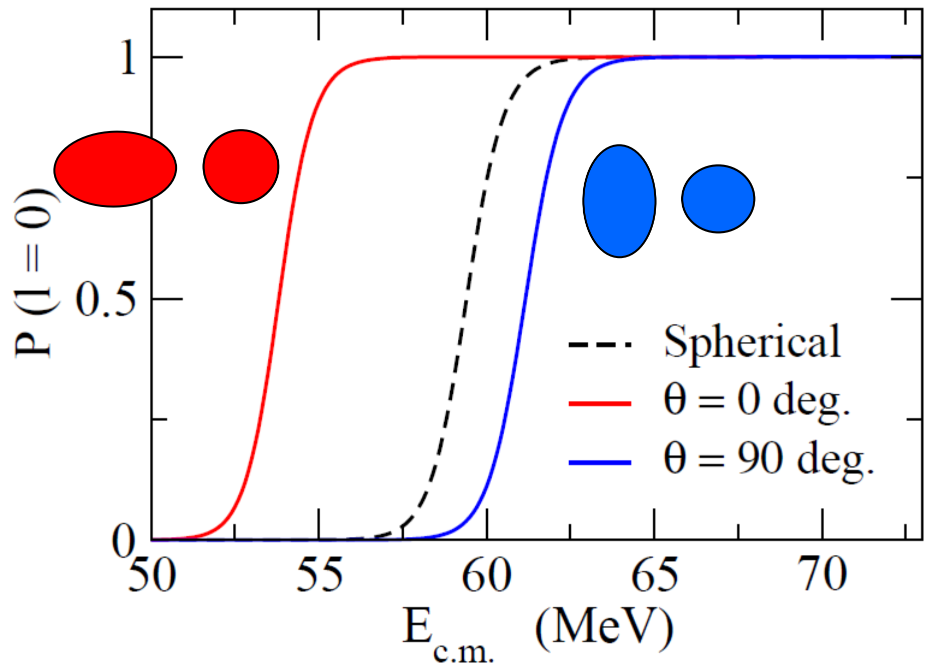
Effects of nuclear deformation

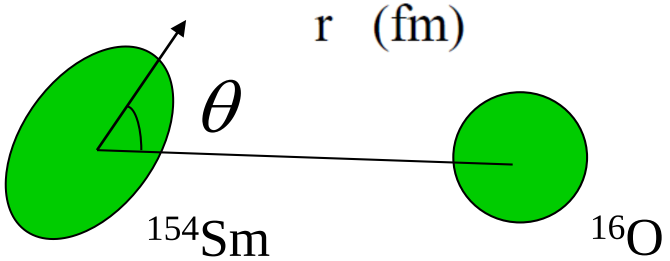
^{154}Sm : a typical deformed nucleus



^{154}Sm

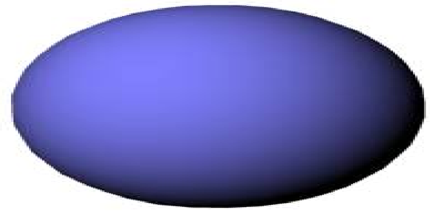




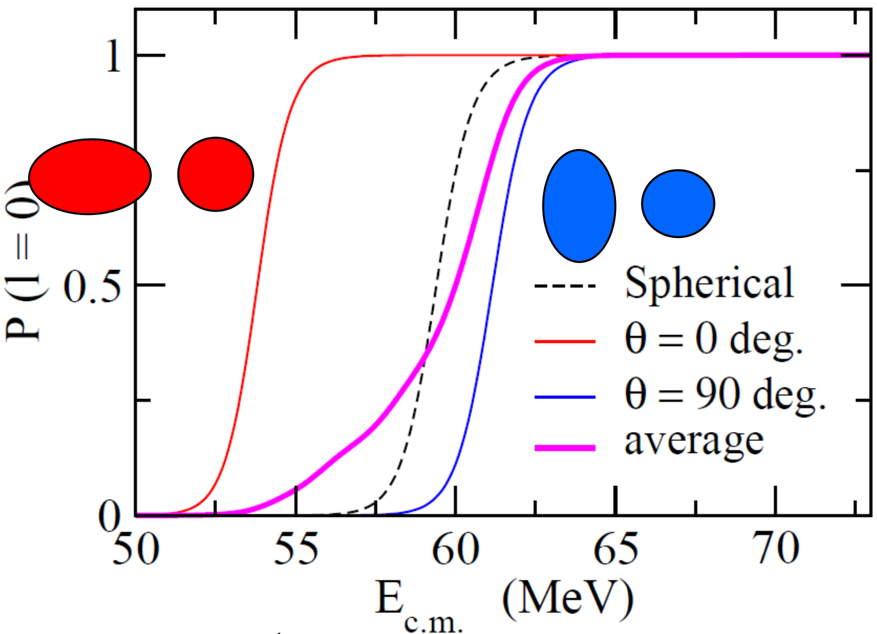


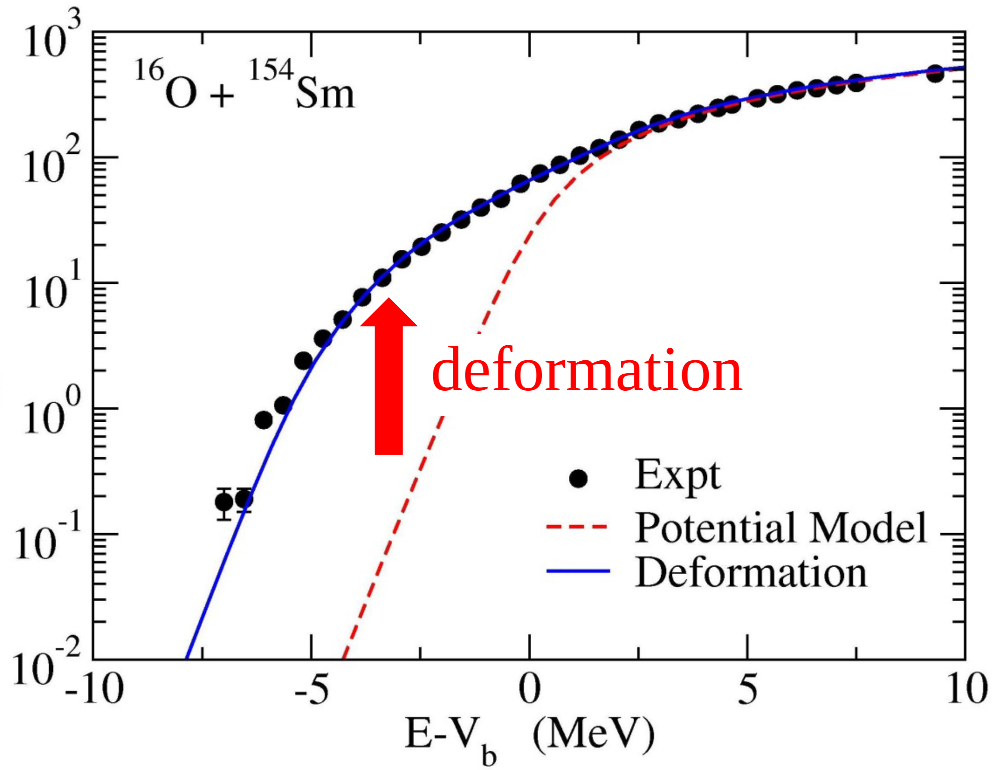
Effects of nuclear deformation

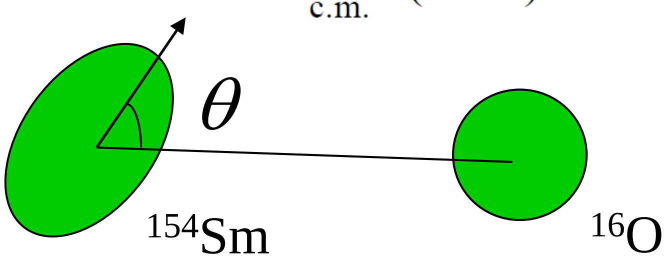
^{154}Sm : a typical deformed nucleus



^{154}Sm

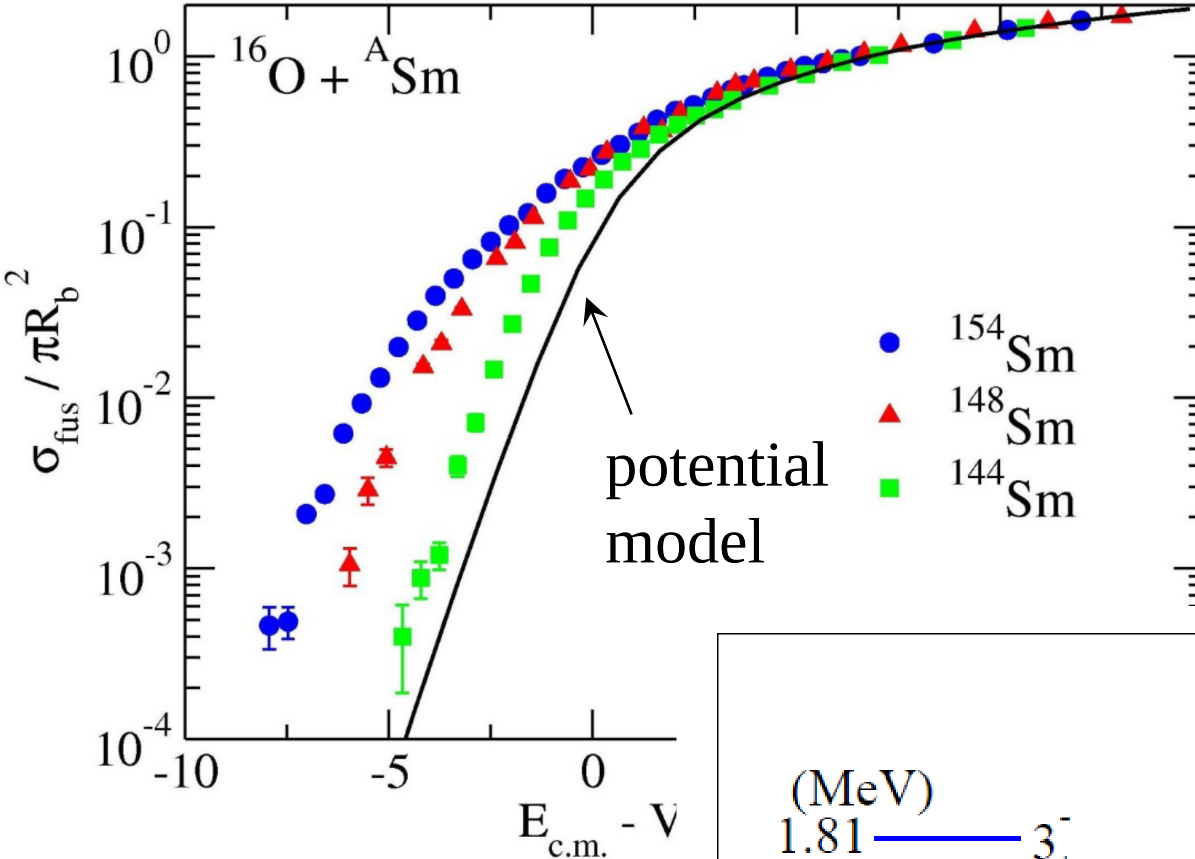






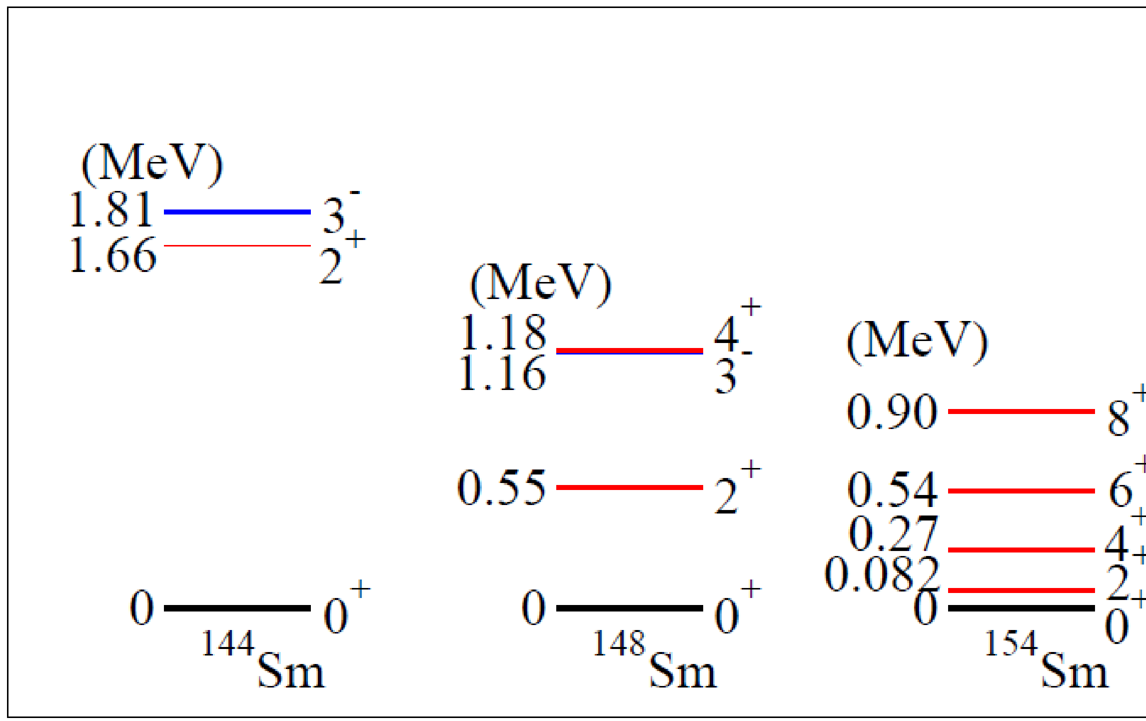
$$\sigma_{\text{fus}}(E) = \int_0^1 d(\cos\theta)\sigma_{\text{fus}}(E;\theta)$$

Fusion: strong interplay between nuclear structure and reaction



enhancement of fusion cross sections

: a general phenomenon

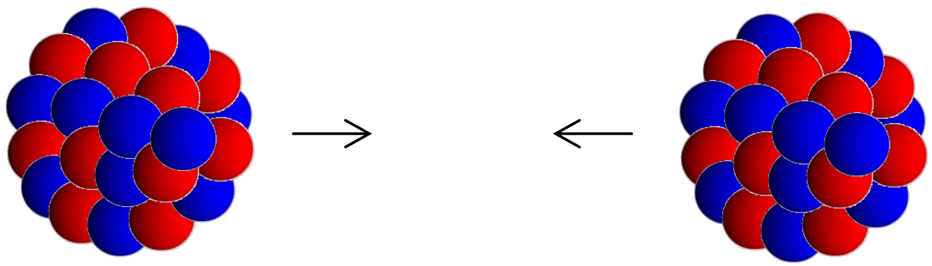


strong correlation with nuclear spectrum

→ coupling assisted tunneling

Coupled-channels method: a quantal scattering theory with excitations

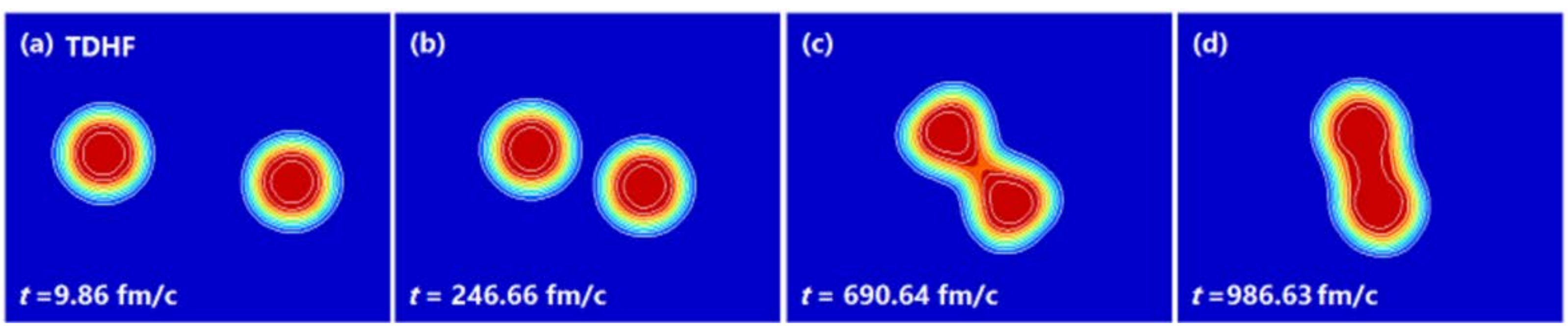
many-body problem



still very challenging

TDHF simulation

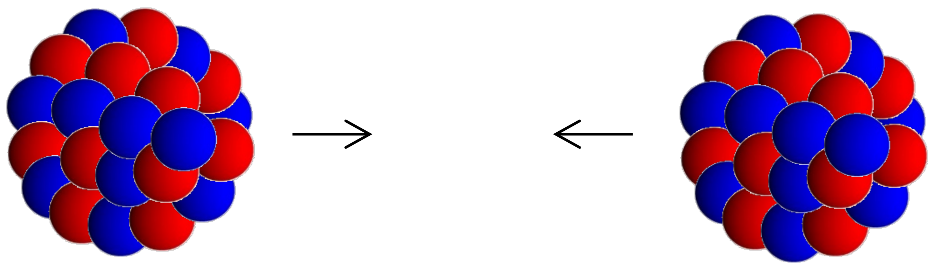
TDHF = Time Dependent Hartree-Fock



S. Ebata, T. Nakatsukasa, JPC Conf. Proc. 6 (‘15) 020056

Coupled-channels method: a quantal scattering theory with excitations

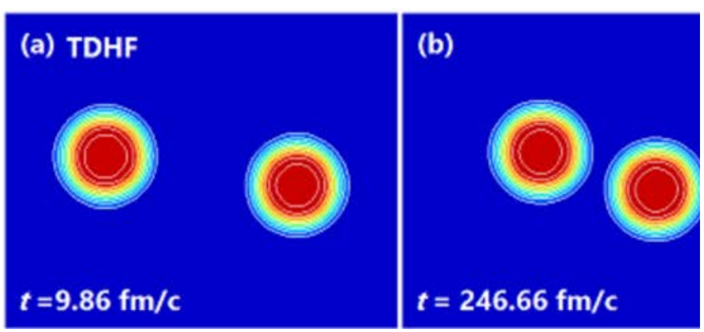
many-body problem



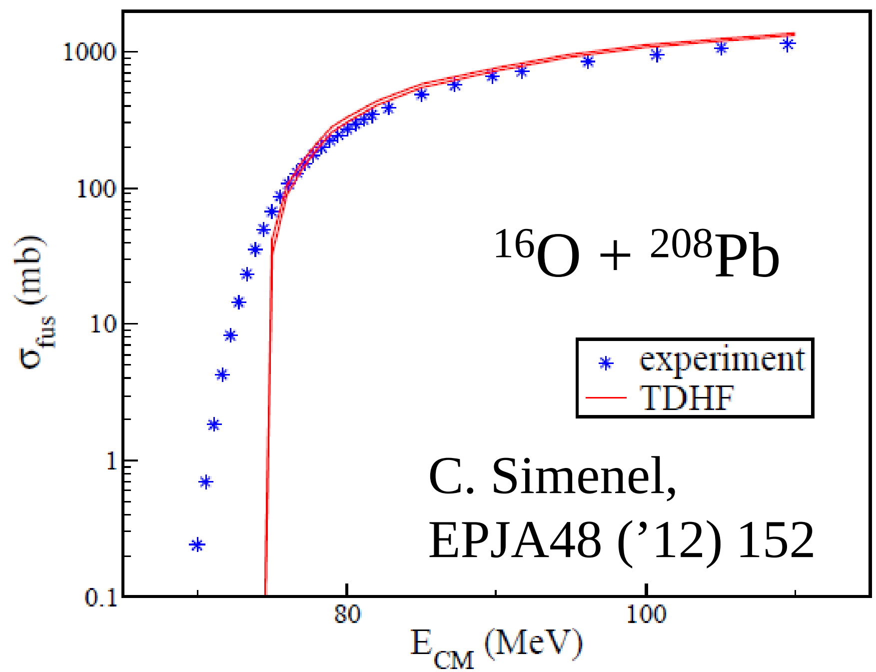
still very challenging

“ab-initio”, but no tunneling

TDHF simulation



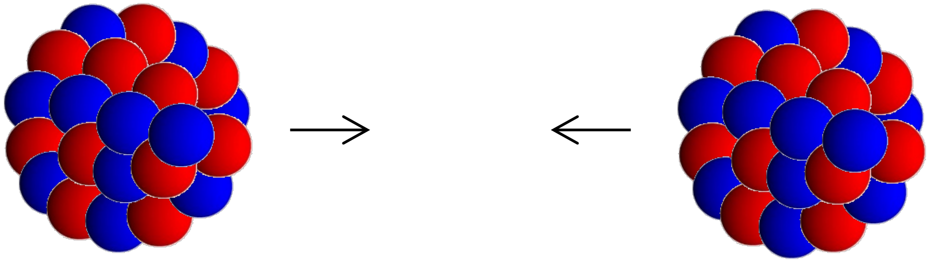
S. Ebata, T. Nakatsukasa, JPC C



C. Simenel,
EPJA48 (’12) 152

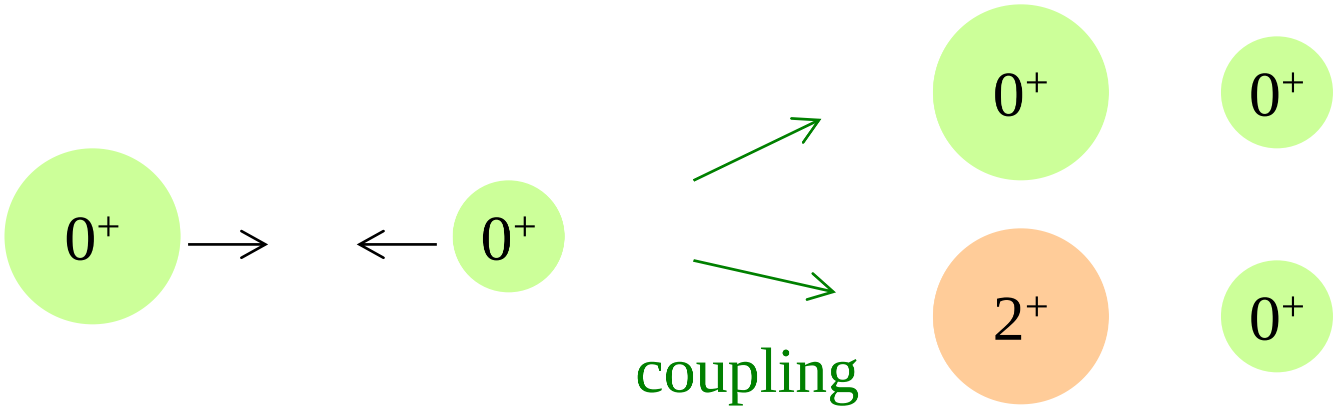
Coupled-channels method: a quantal scattering theory with excitations

many-body problem



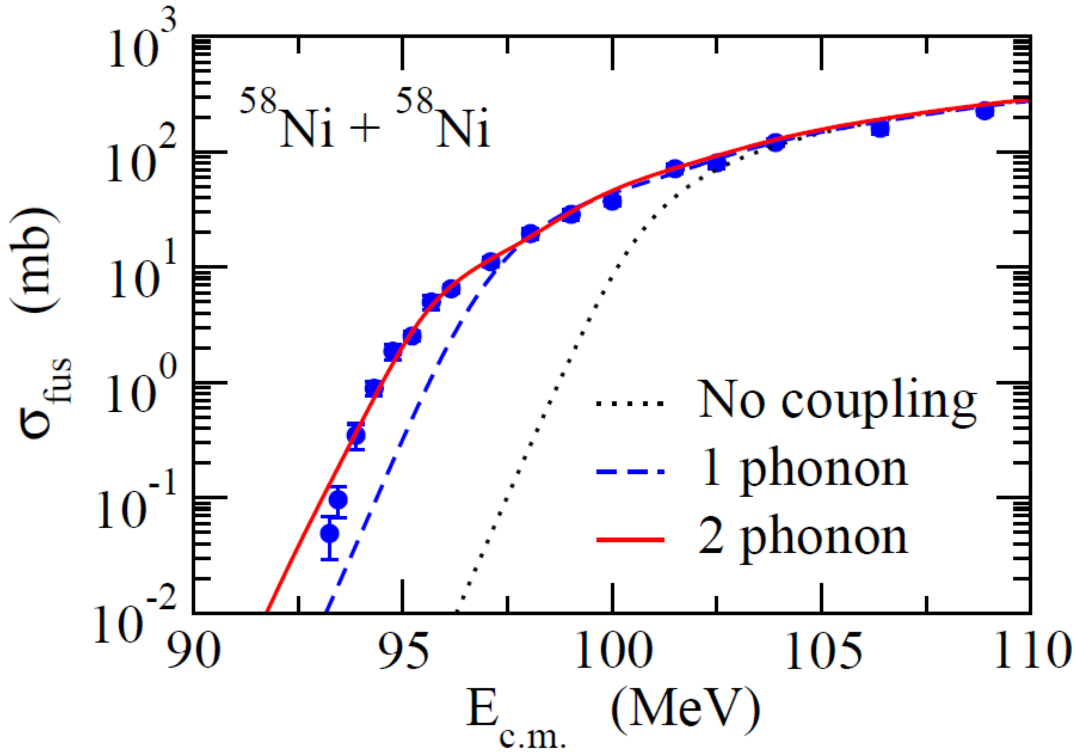
still very challenging

two-body problem, but with excitations
(coupled-channels approach)

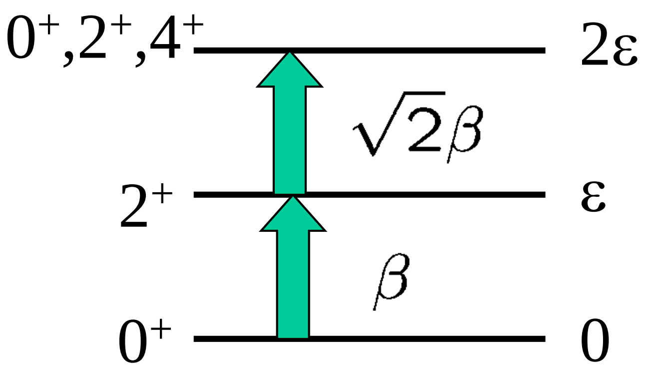


scattering theory with excitations

An example of coupled-channels calculation



simple harmonic oscillator

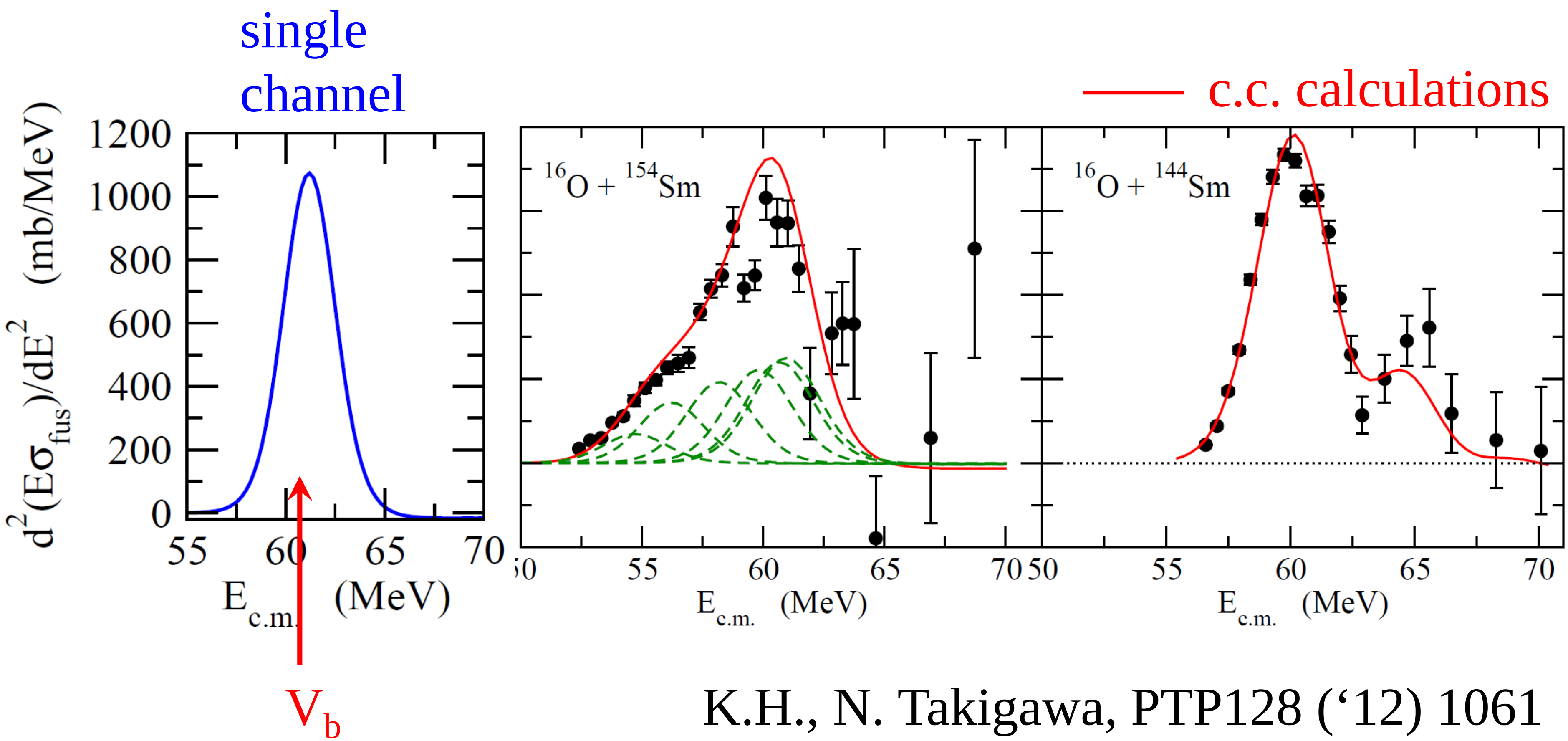


C.C. approach: a standard tool for sub-barrier fusion reactions

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

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

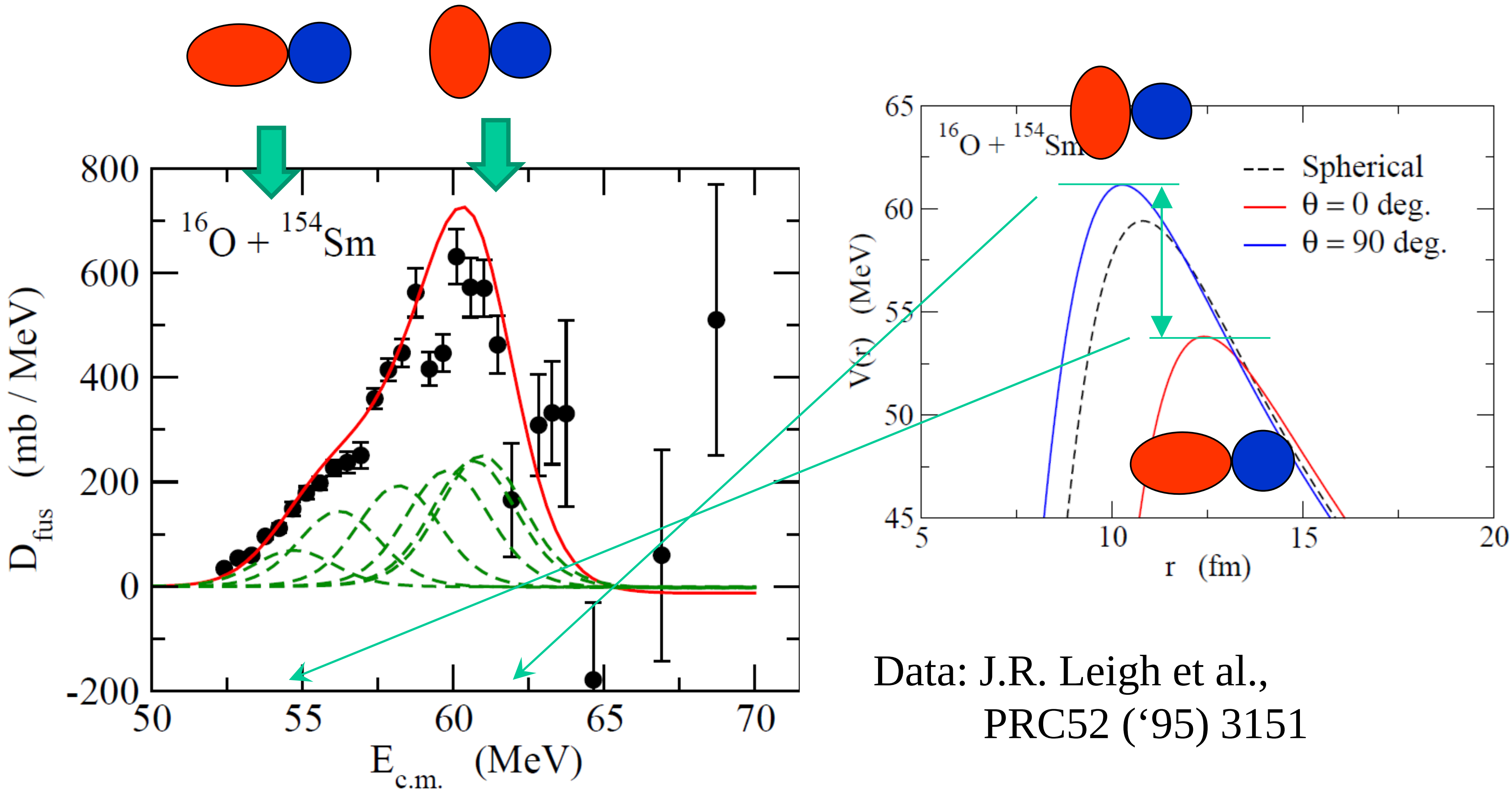
$$D_{\rm fus}(E) = \frac{d^2(E\sigma_{\rm fus})}{dE^2} \propto \frac{dP_{l=0}}{dE}$$



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

geometrical interpretation → a nice tool to understand the reaction dynamics

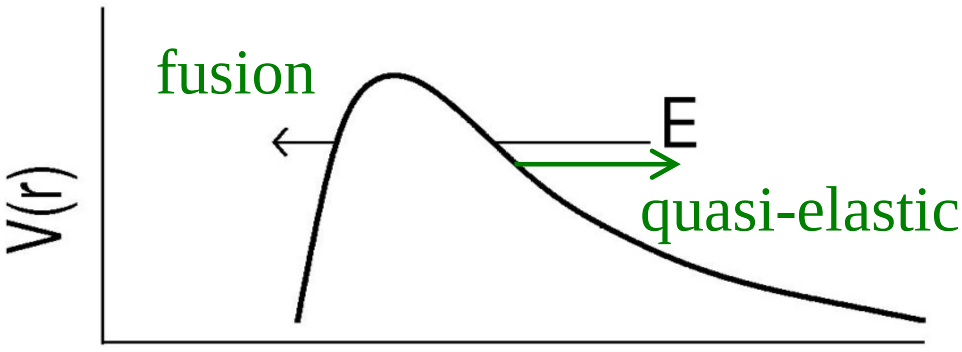
K.H., N. Takigawa, PTP128 ('12) 1061

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

hot fusion reactions

^{48}Ca + actinide target → SHE

= deformation → reaction dynamics with barrier distributions?



$$P + R = 1$$

Quasi-elastic scattering
: reflected flux at the barrier

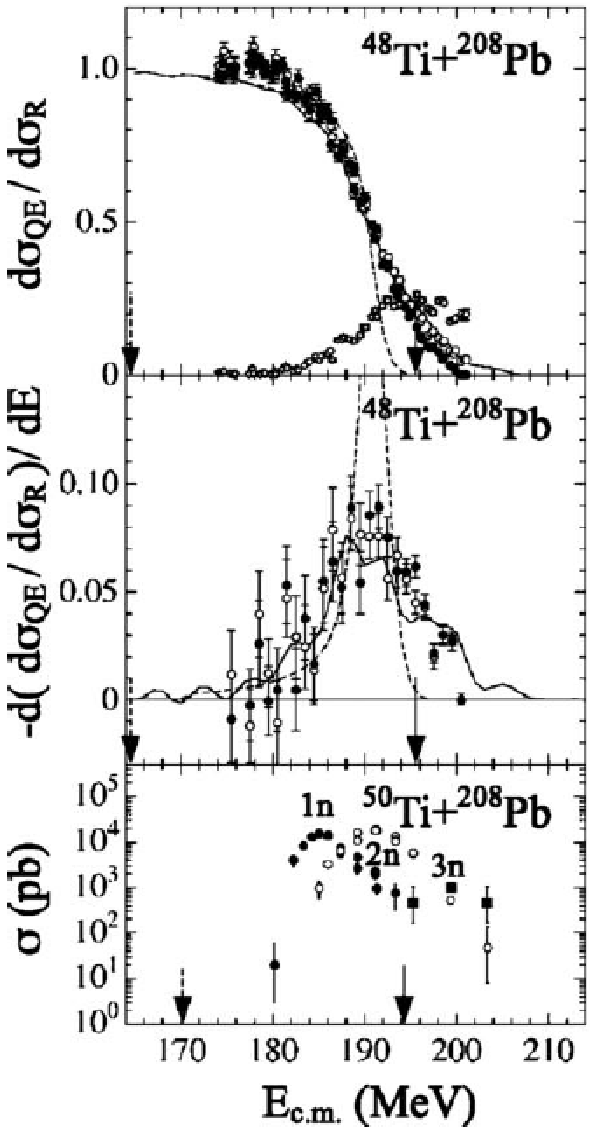
- a sum of elastic, inelastic, and transfer
- easier to measure than capture

Quasi-elastic barrier distribution

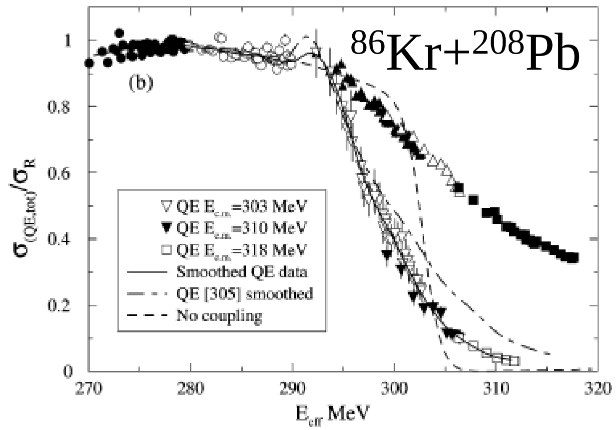
$$\boxed{D_{\rm qel}(E) = -\frac{d}{dE}\left(\frac{\sigma_{\rm qel}(E,\pi)}{\sigma_R(E,\pi)}\right)}$$

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

previous attempts

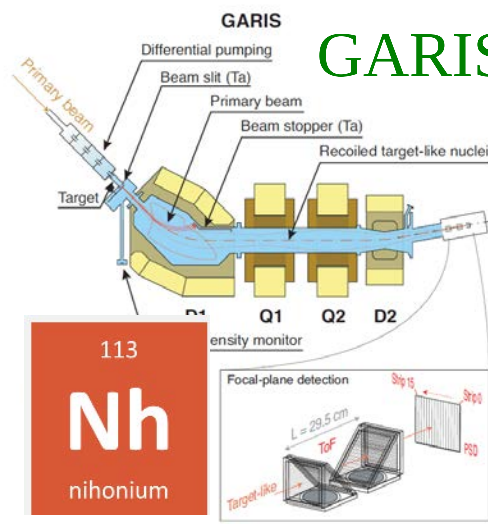


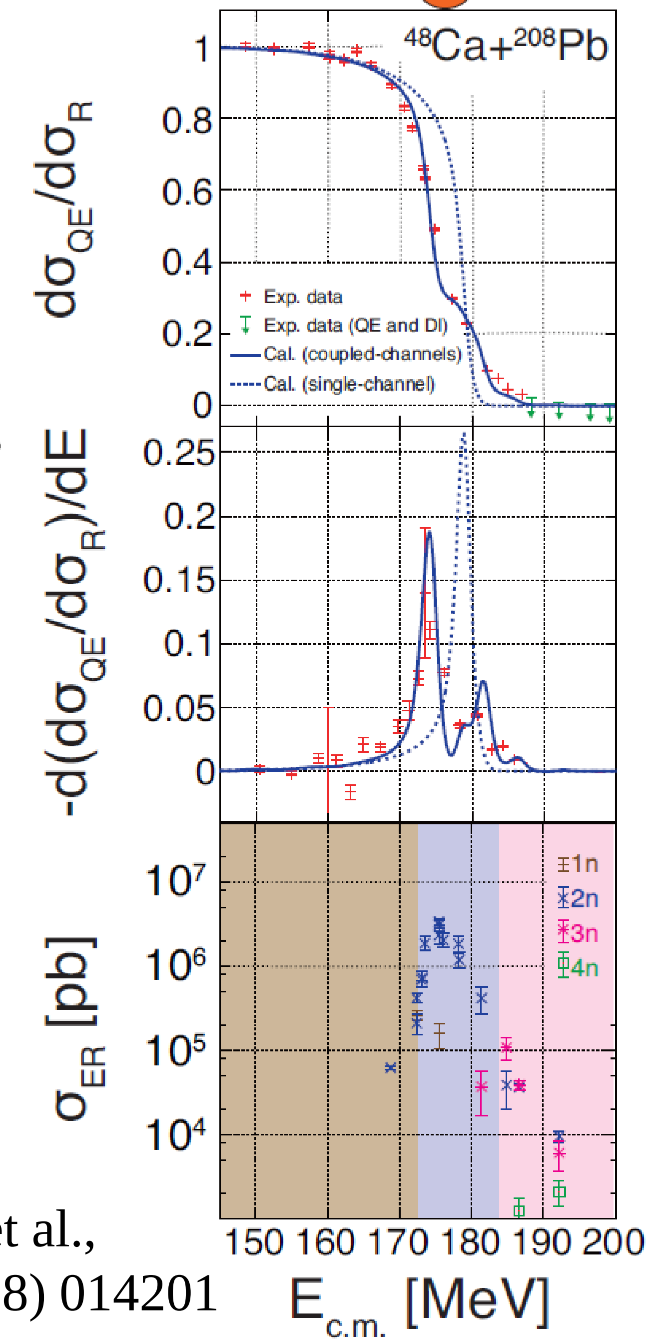
S. Mitsuoka et al.,
PRL99 (‘07) 182701



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

GARIS





T. Tanaka et al.,
JPSJ 87 (‘18) 014201

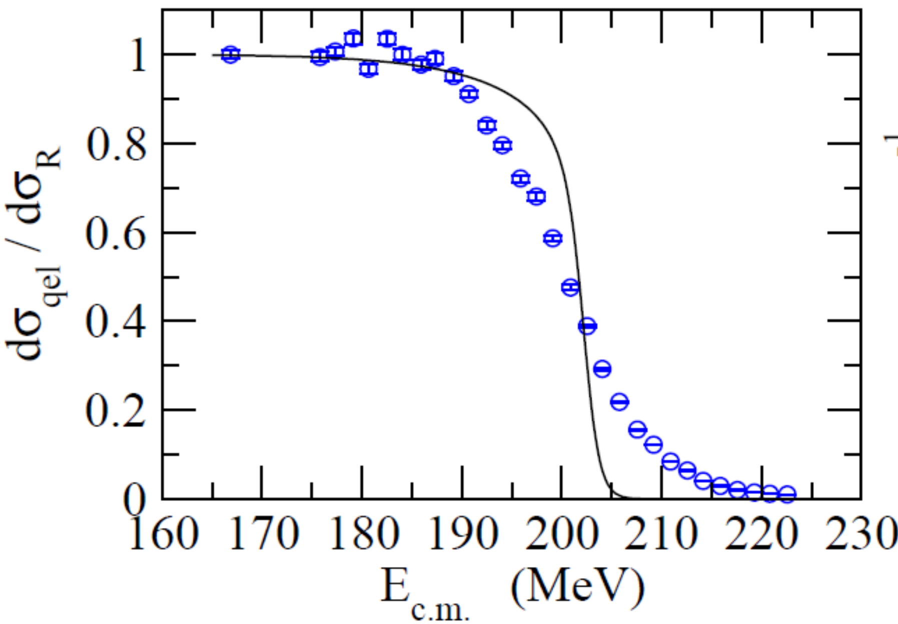
C.C. analysis for a hot fusion reaction $^{48}Ca + {}^{248}Cm$

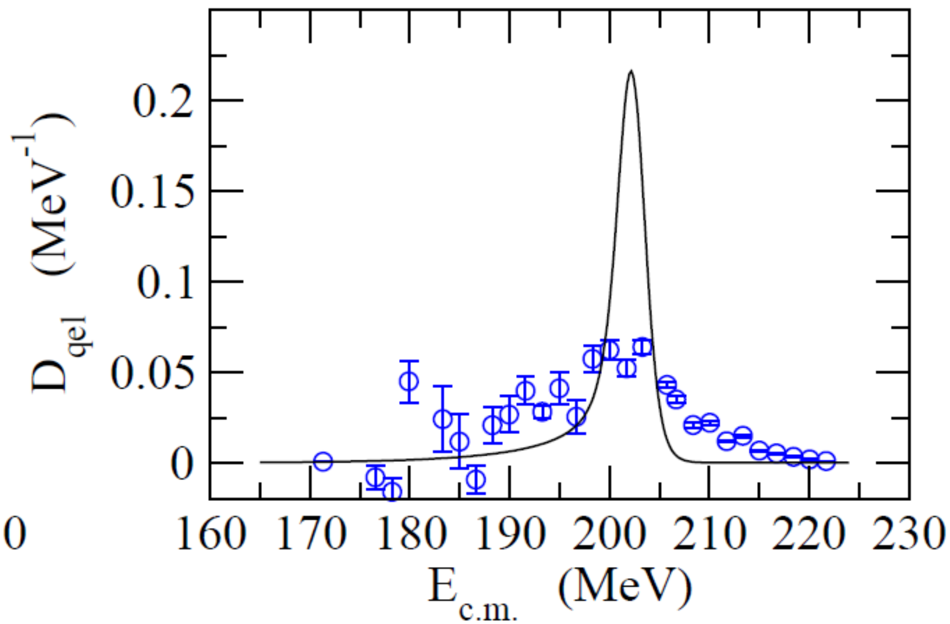
K.H. and T. Tanaka (2017)
(T. Tanaka et al., JPSJ 87 ('18) 014201)

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

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

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





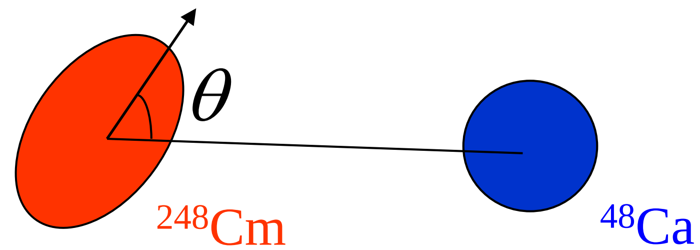
C.C. analysis for a hot fusion reaction ^{48}Ca + ^{248}Cm

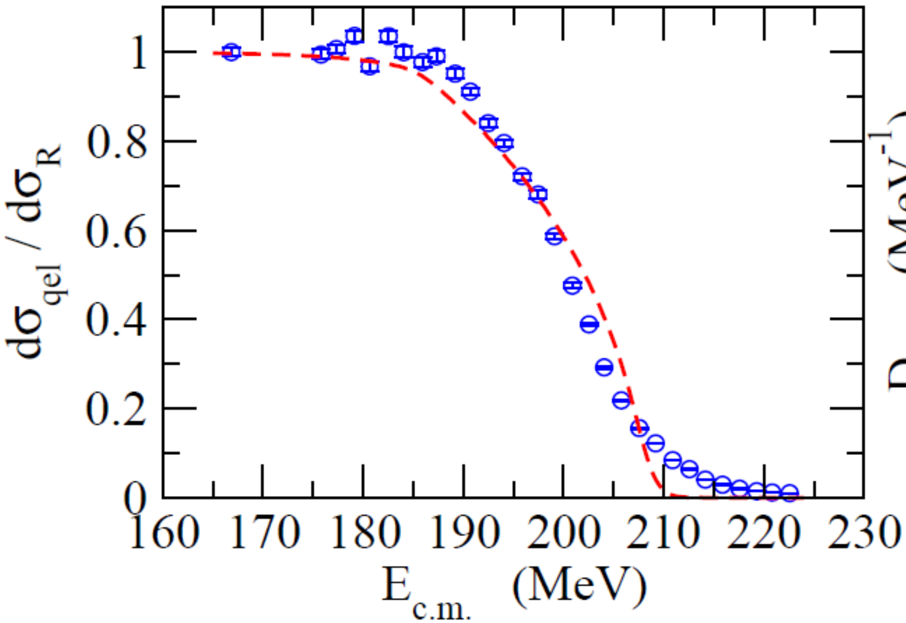
K.H. and T. Tanaka (2017)

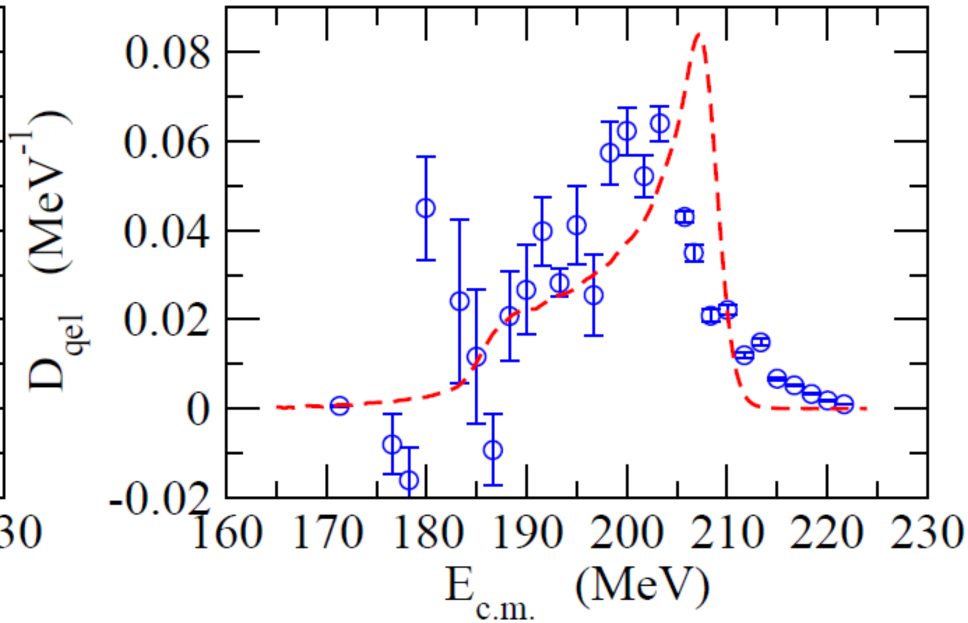
$$^{48}\mathrm{Ca} + {}^{248}\mathrm{Cm}\ (\beta_2 = 0.297,\ \beta_4 = 0.04) \rightarrow {}^{296}_{116}\mathrm{Lv}^*$$

[β_2 and β_4 from P. Moller]

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



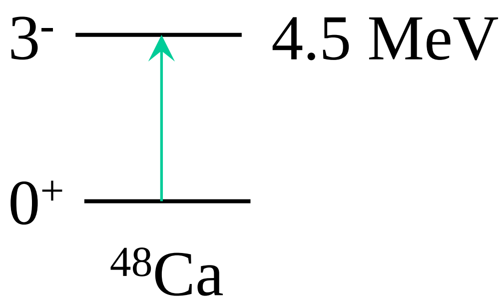




C.C. analysis for a hot fusion reaction $^{48}Ca + ^{248}Cm$

K.H. and T. Tanaka (2017)

$$^{48}Ca\,(3^-) + ^{248}Cm\,(\beta_2 = 0.297,\ \beta_4 = 0.04) \rightarrow {}^{296}_{116}Lv^*$$

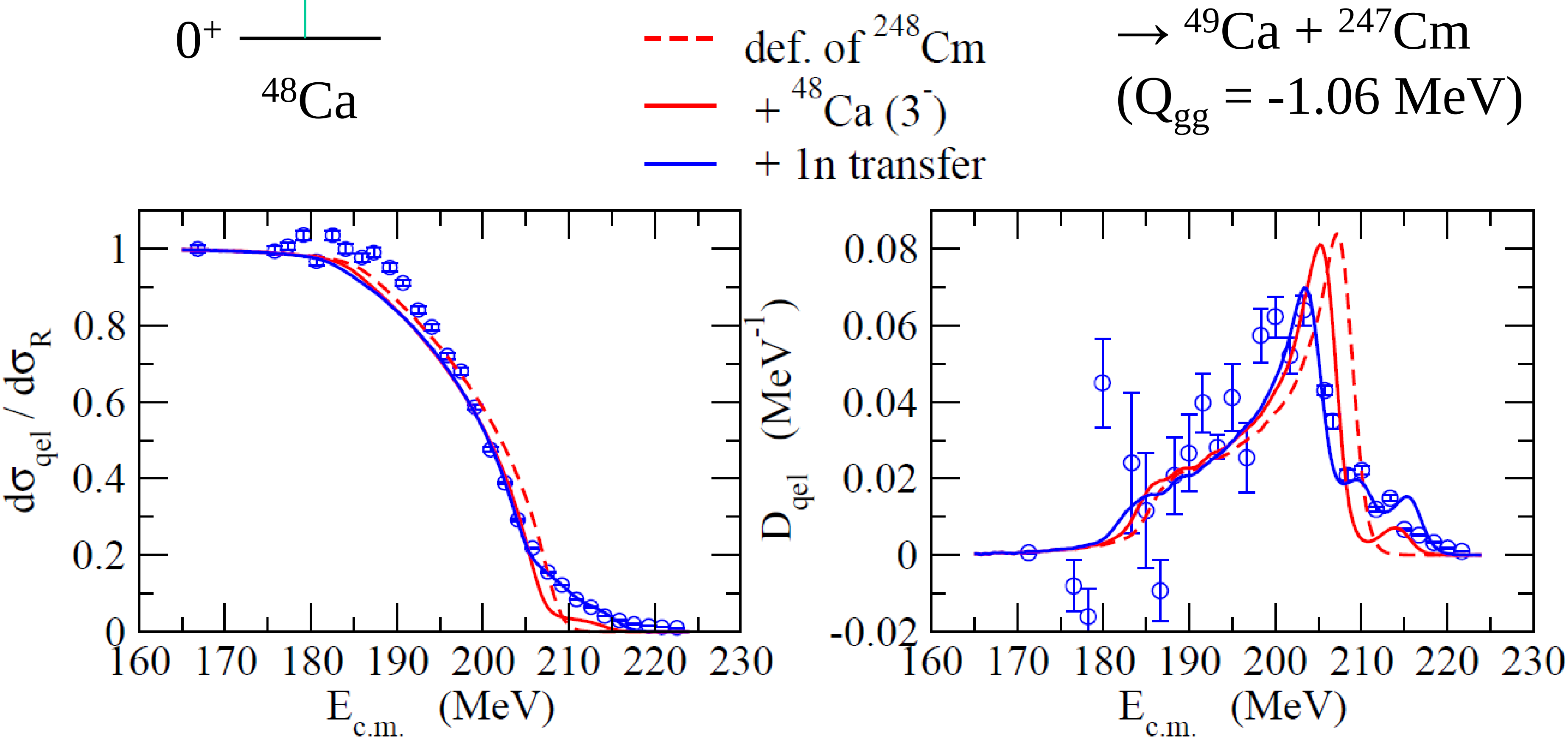


1n transfer

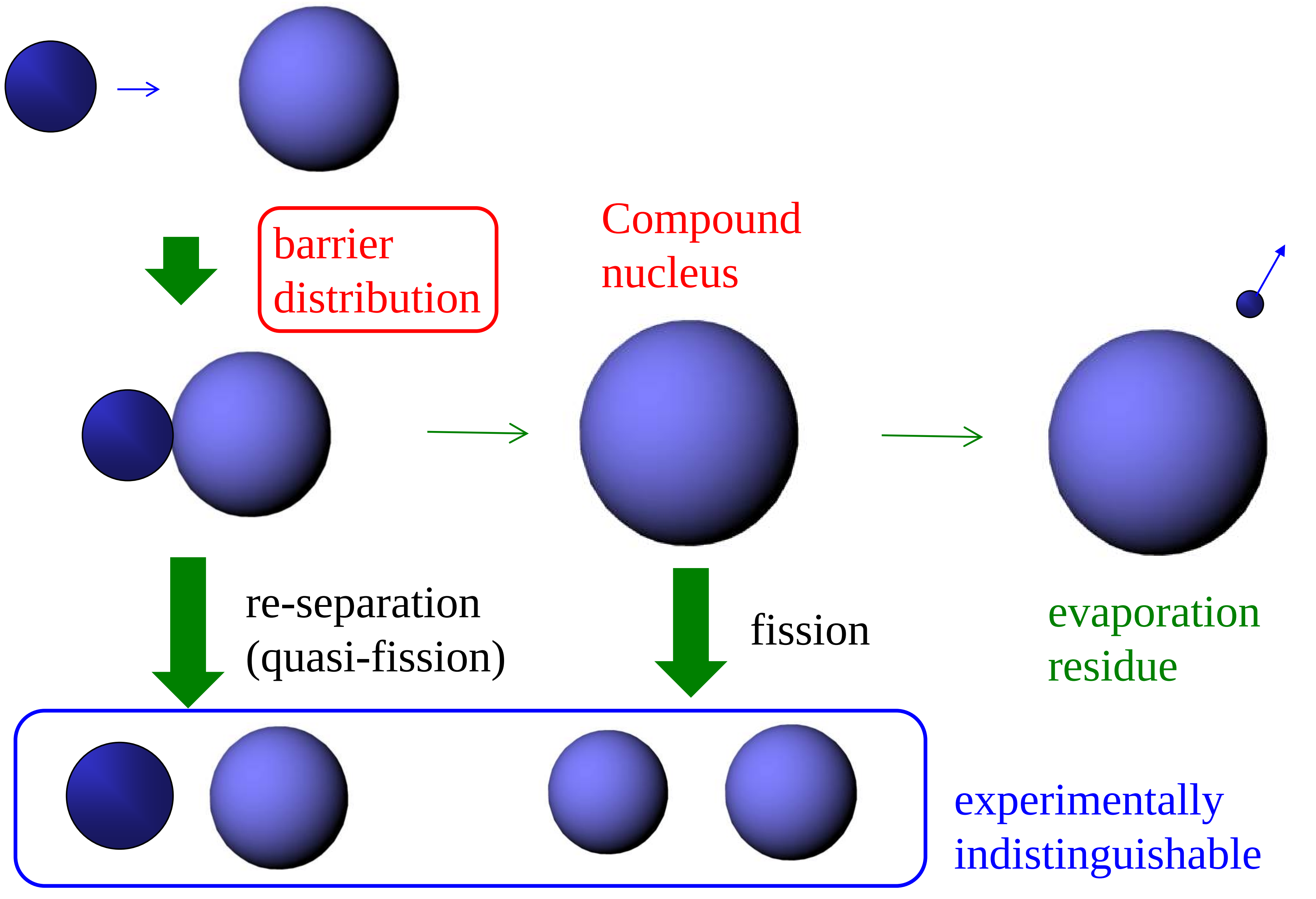
$^{48}Ca + ^{248}Cm$

$\rightarrow {}^{49}Ca + ^{247}Cm$

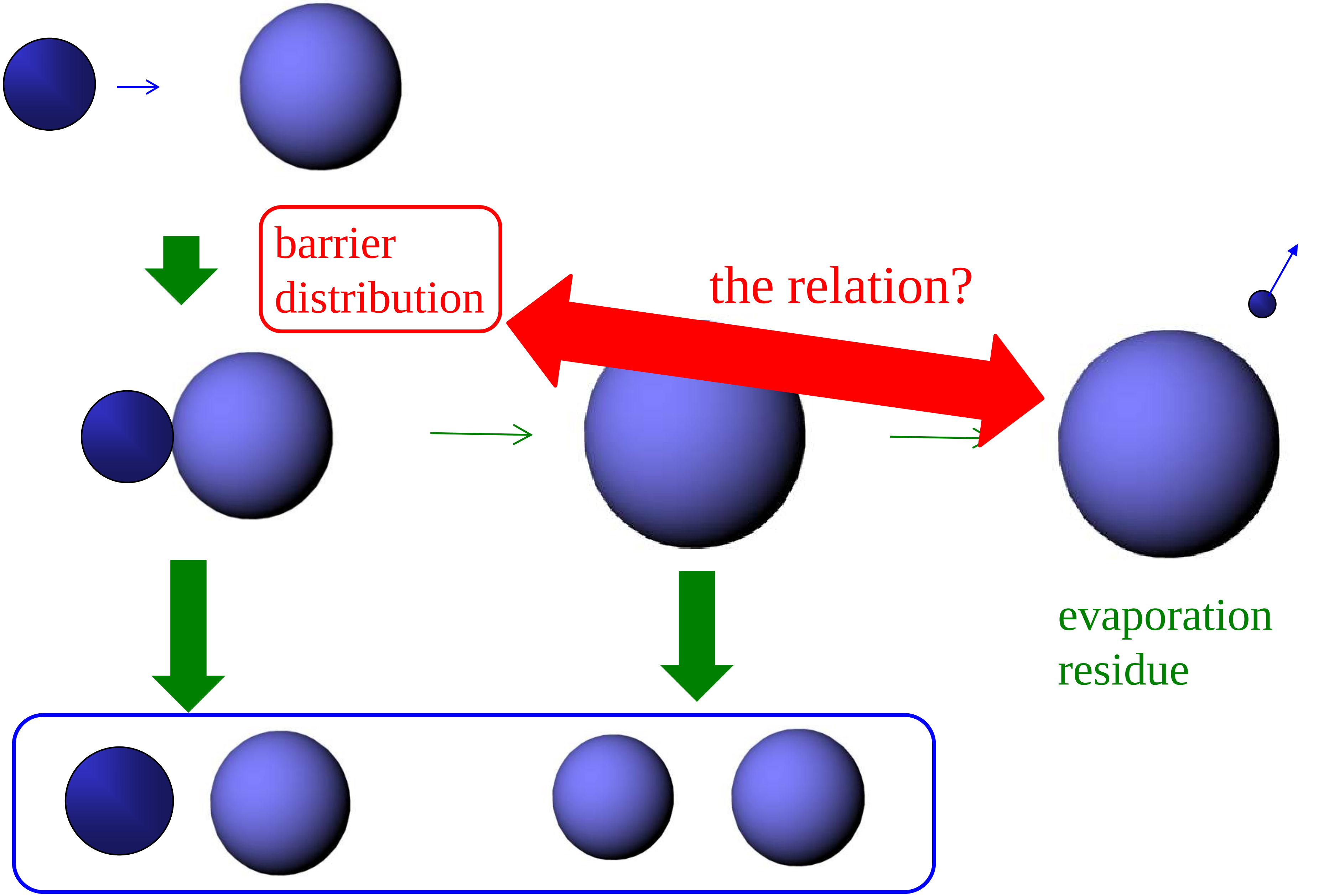
$(Q_{gg} = -1.06$ MeV)



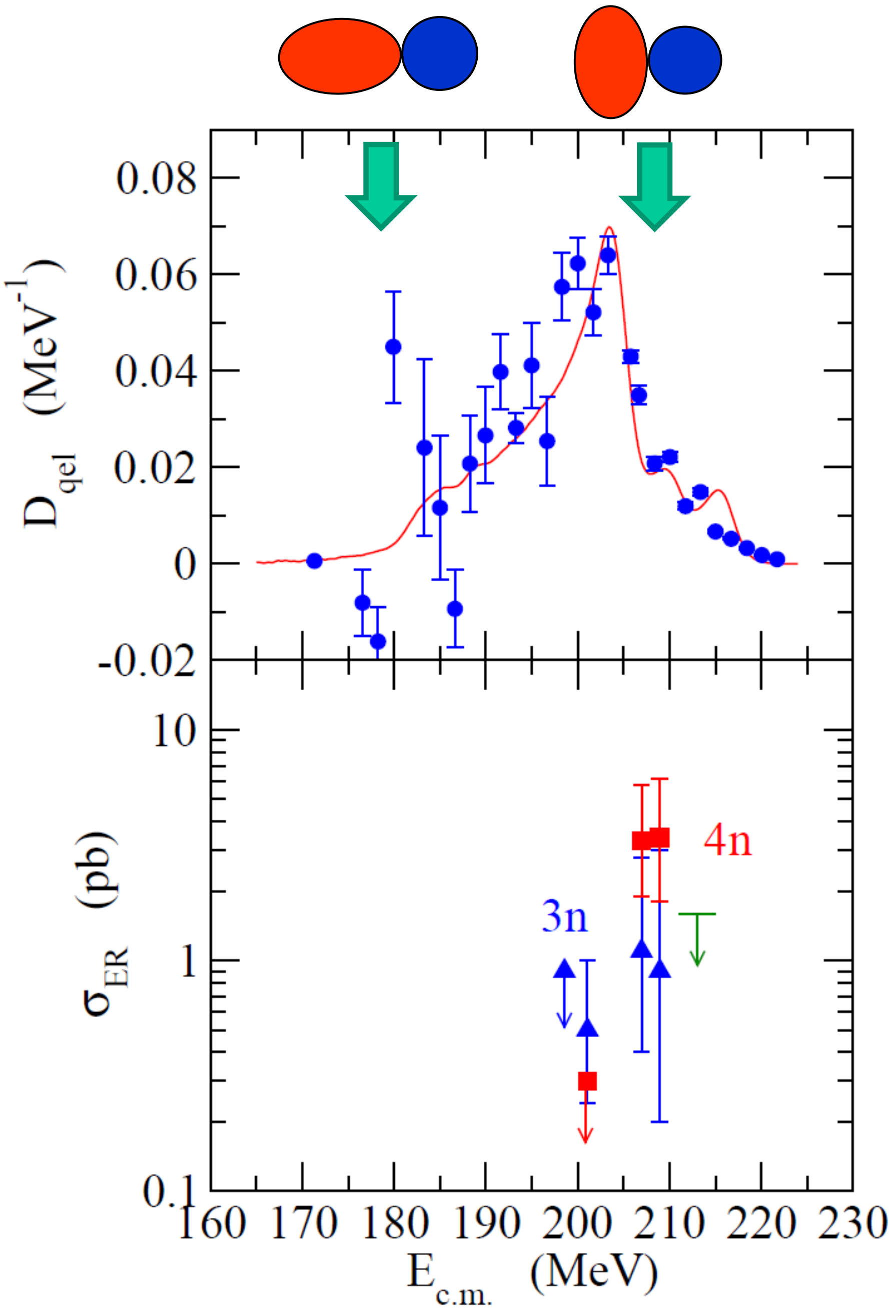
Connection to the ER cross sections



Connection to the ER cross sections

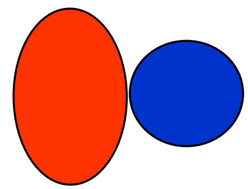


Connection to the ER cross sections

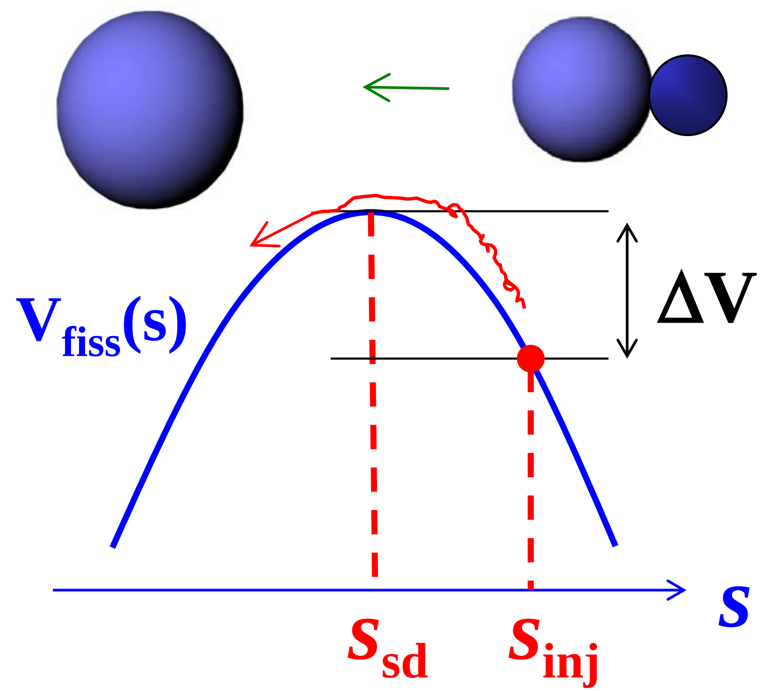


$^{48}Ca + ^{248}Cm \rightarrow ^{296}_{116}Lv^*$

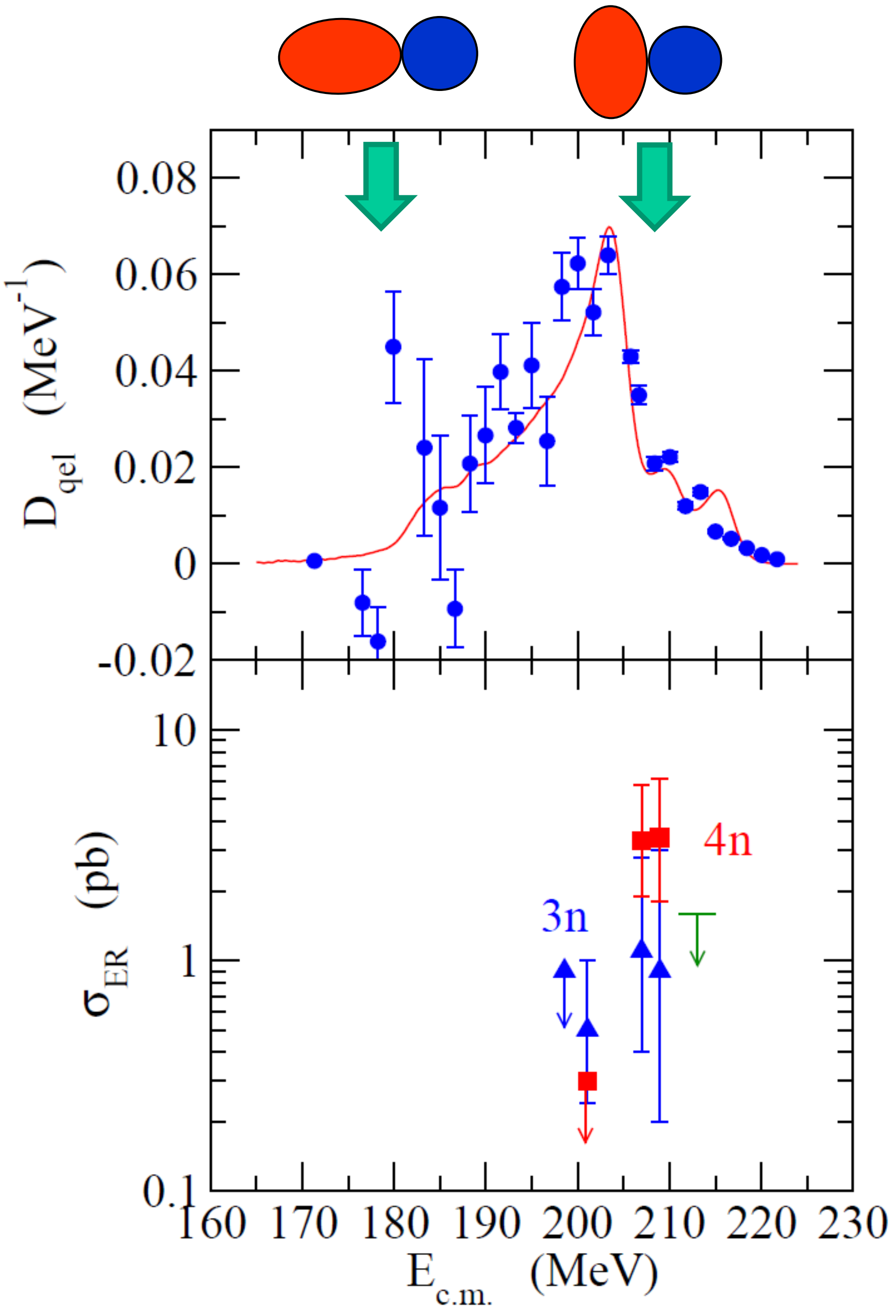
notion of compactness:
D.J. Hinde et al., PRL74 ('95) 1295



= more compact at the touching
→ favorable for CN

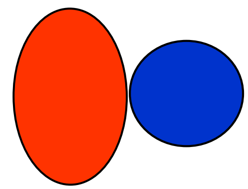


Connection to the ER cross sections

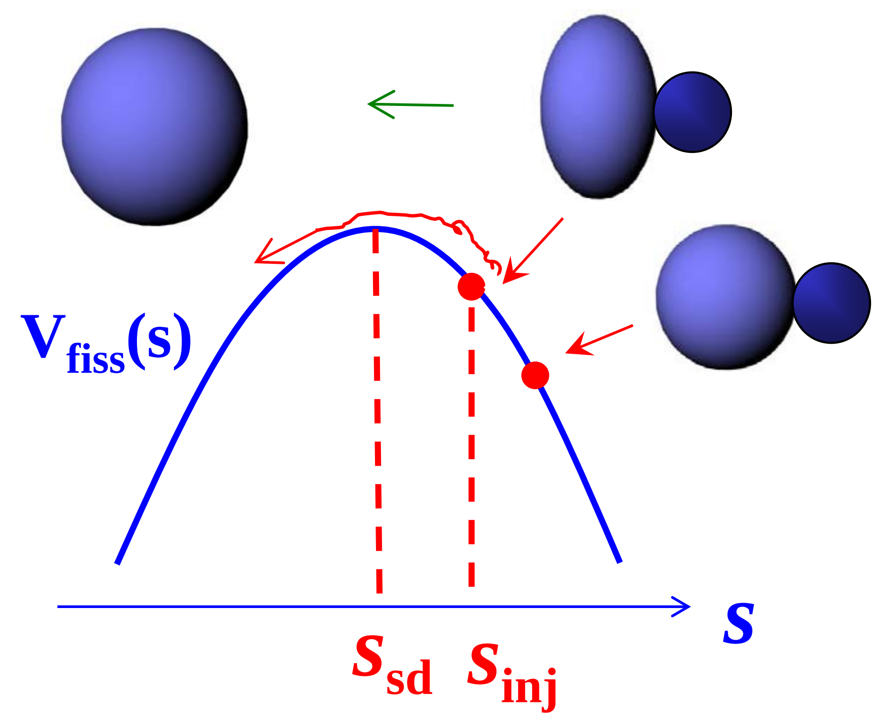


$^{48}Ca + ^{248}Cm \rightarrow ^{296}_{116}Lv^*$

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



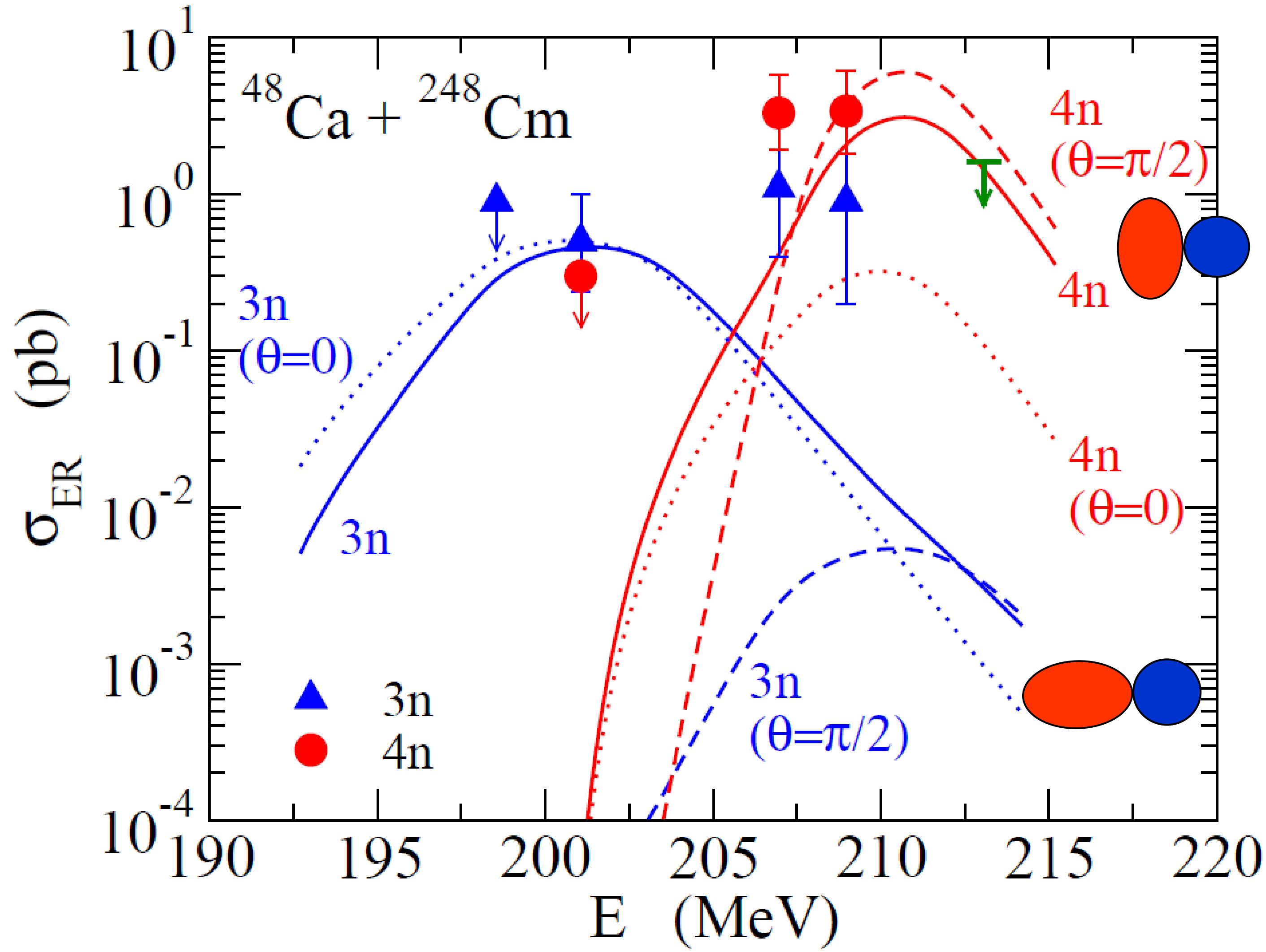
= more compact at the touching
→ favorable for CN



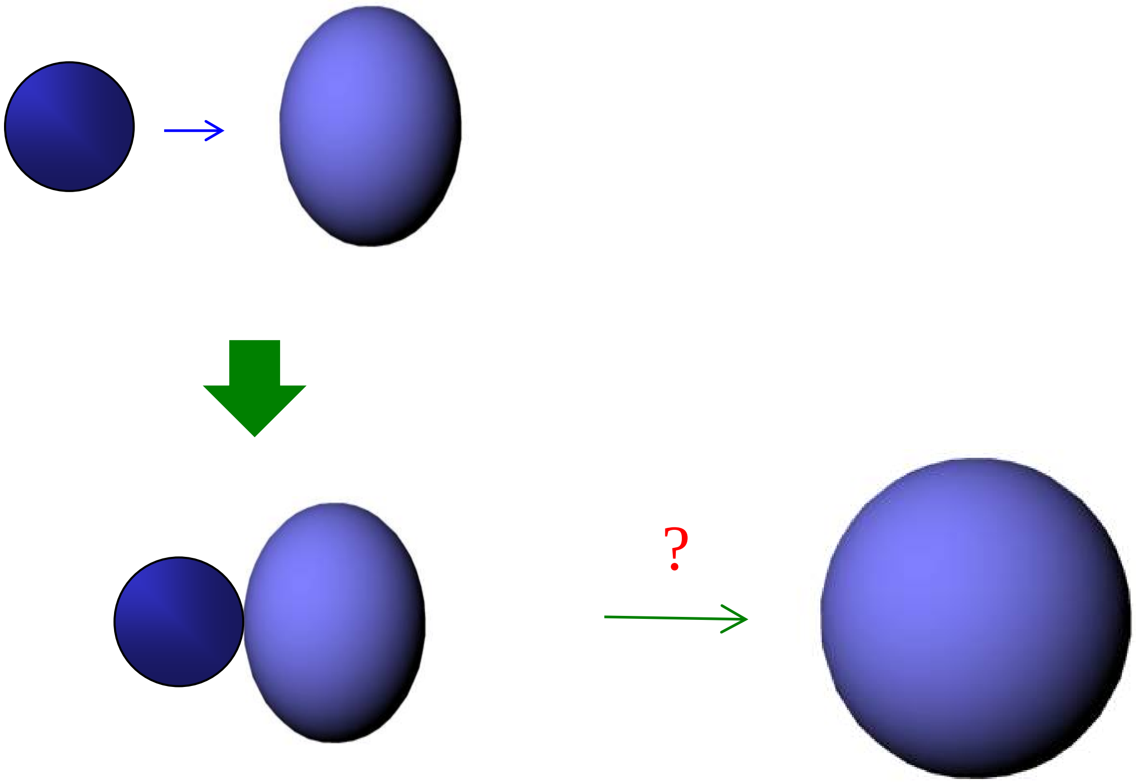
Role of deformation in formation of evaporation redidues

K.H., PRC98 ('18) 014607

extended fusion-by-diffusion model



A more challenging problem



heat up

disappearance of quantum effects
(shell effect and deformation)

quantum theory for friction

Quantum friction

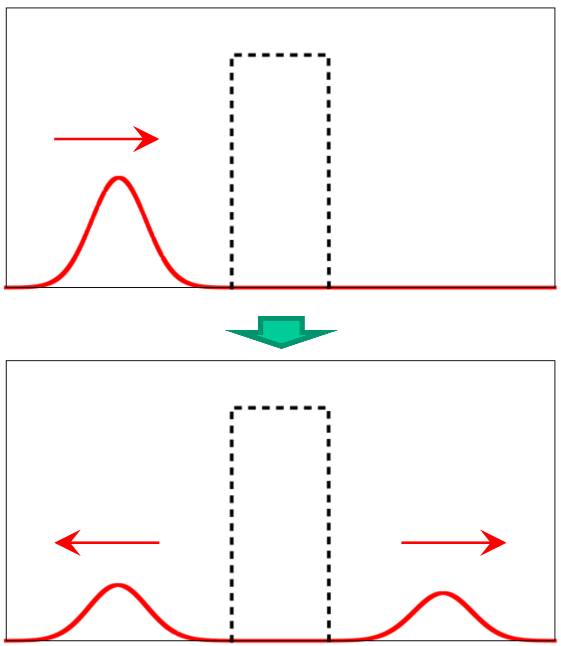
classical eq. of motion $\dot{p} = -V'(x) - \gamma p$

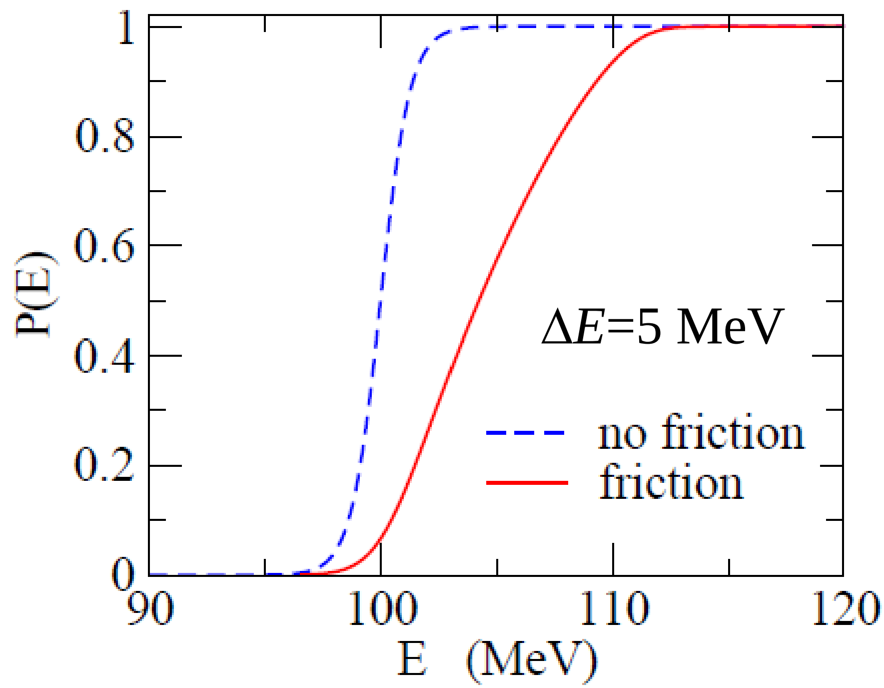
a quantization: Kanai model E. Kanai, PTP 3 (1948) 440)

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

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

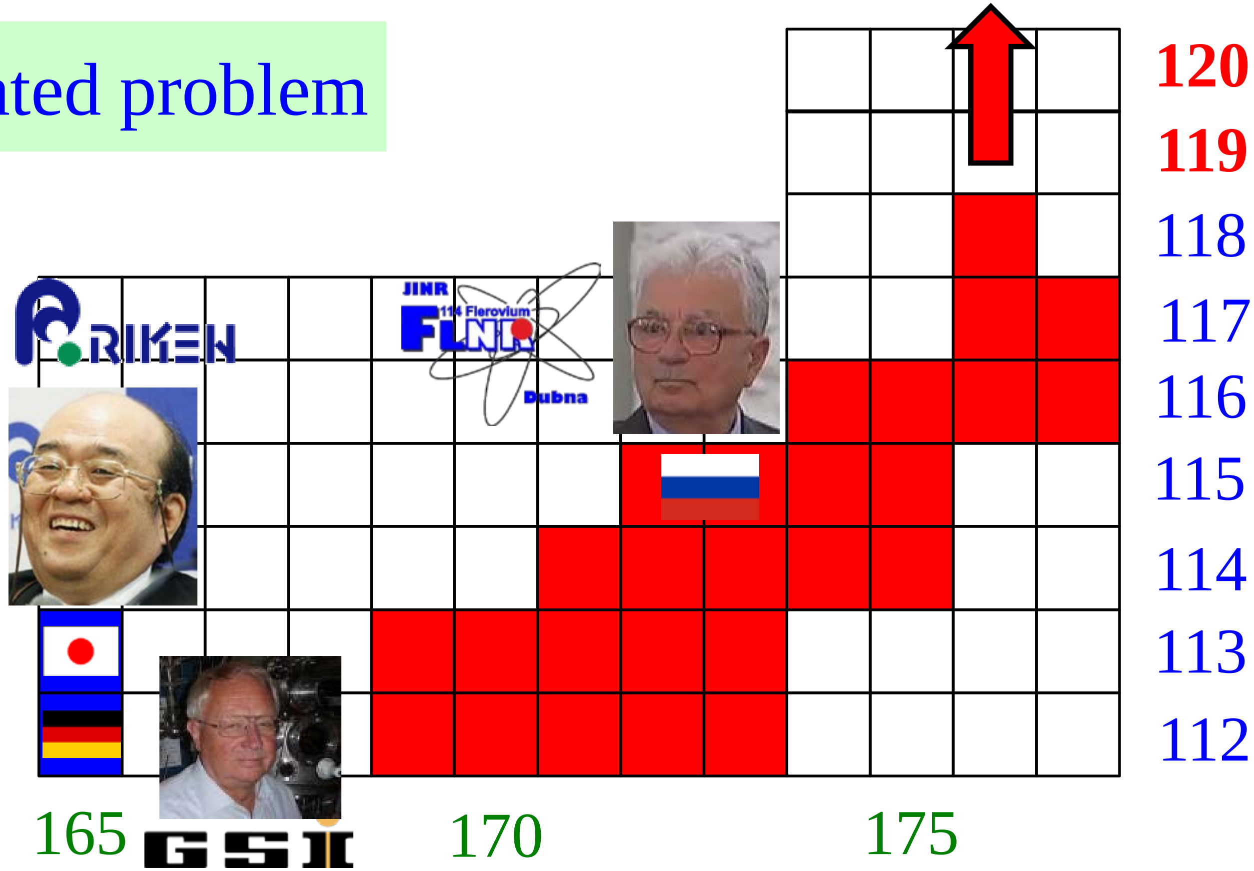
time-dep. wave packet approach





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

A related problem



hot fusion reaction:

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

not available with sufficient amount

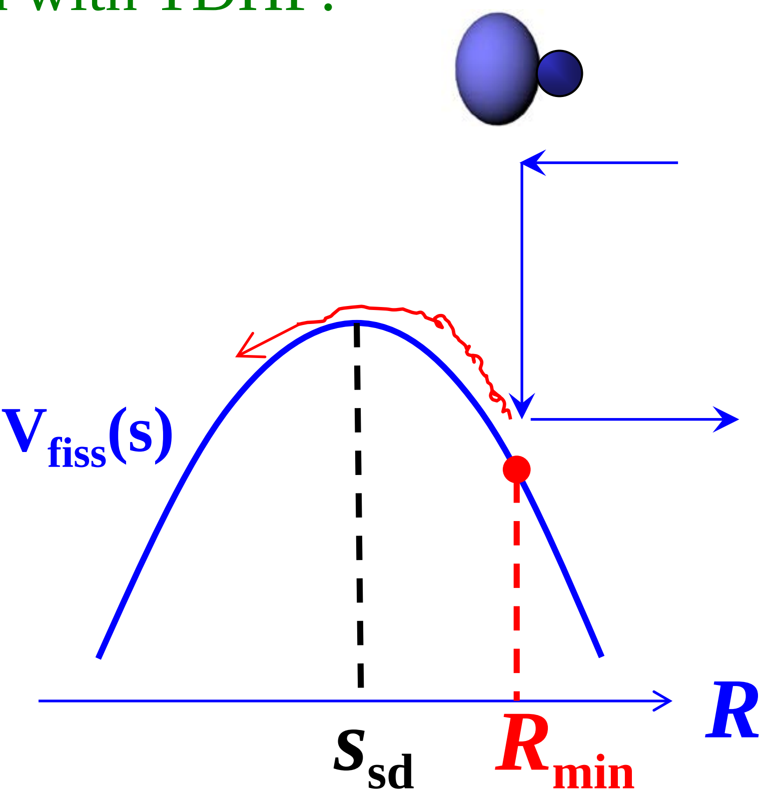
$$ {}^{51}_{23}\mathrm{V} + {}^{248}_{96}\mathrm{Cm} \rightarrow {}^{299}119 \text{ etc.} $$

how much will fusion cross sections be influenced?

TDHF+Langevin approach

K. Sekizawa and K. Hagino, a work in progress

the distance of closest approach estimated with TDHF:



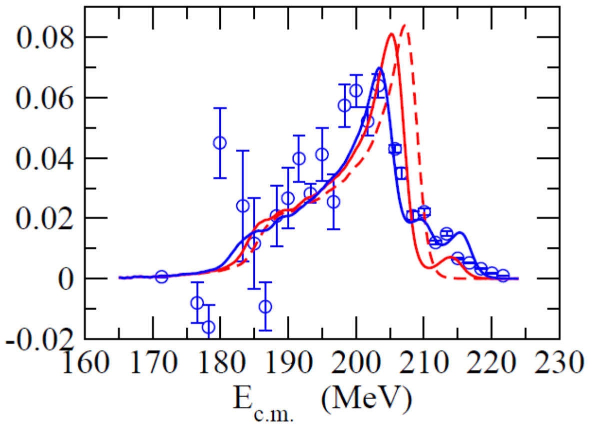
→ input to Langevin calculations

→ 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

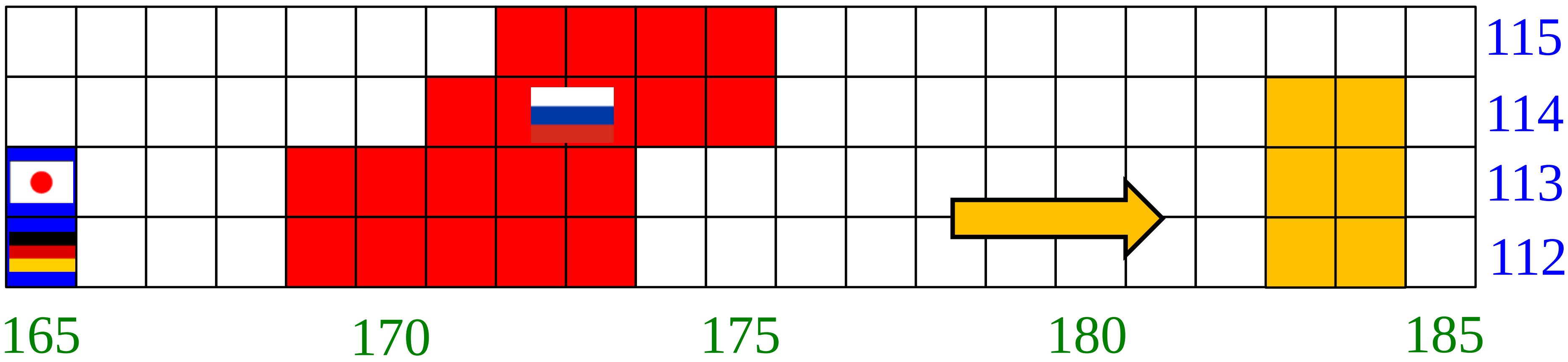


more data coming soon

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

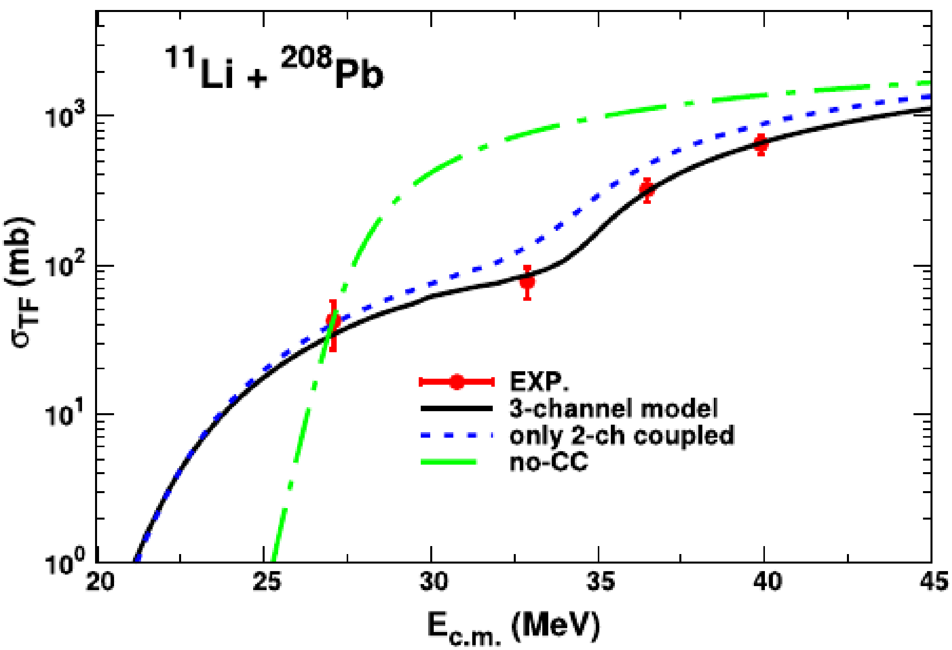
    how does the deformation disappear during heat-up?
  - ✓ towards island of stability

Towards the island of stability



neutron-rich beams: indispensable

→ reaction dynamics with neutron-rich beams?



more studies are needed

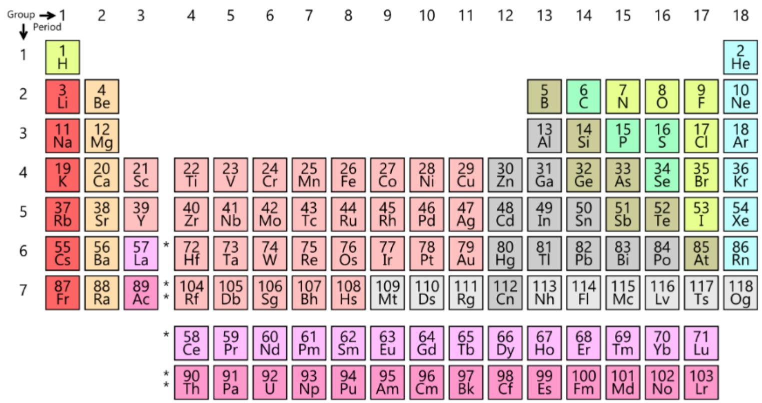
K.-S. Choi, M.-K. Cheoun, W.Y. So, K.H., and K.S. Kim, PLB780 ('18) 455.

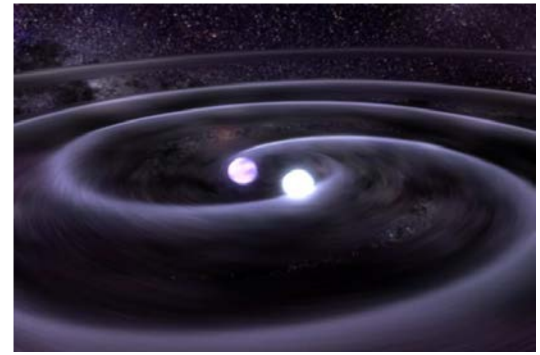
SHE as an interdisciplinary sicence

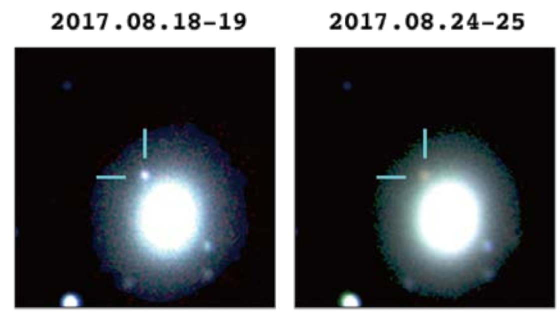
formation
of SHE

chemistry of SHE

the origin of (S)HE







heavy-ion fusion
reactions

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

감사합니다

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