Fusion barrier distribution and superheavy elements (SHE)

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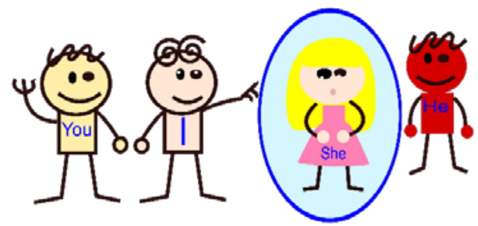
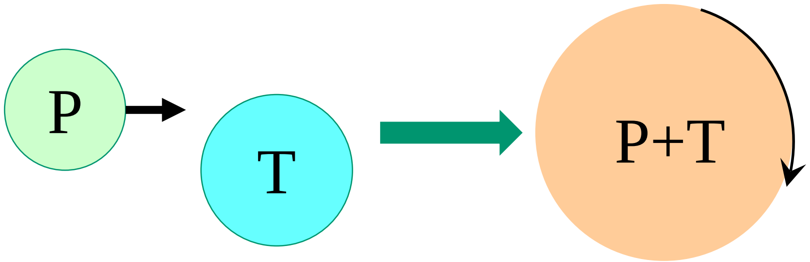


she quem é ela?

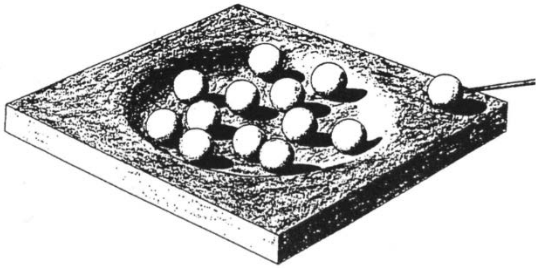
1. Heavy-ion sub-barrier fusion reactions
2. Coupled-channels approach and barrier distributions
3. Application to superheavy elements
4. Quantum friction
5. Summary

XLI Brazilian Meeting on Nuclear Physics, Maresias, Brazil, Sep. 2-6, 2018

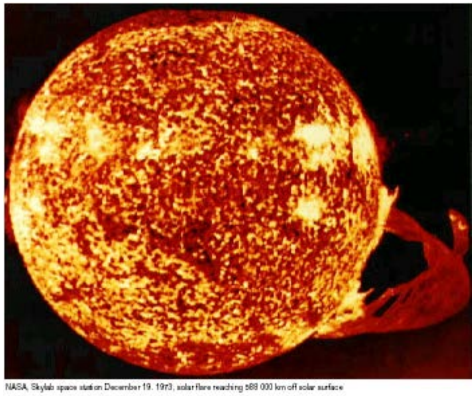
Fusion reactions: compound nucleus formation



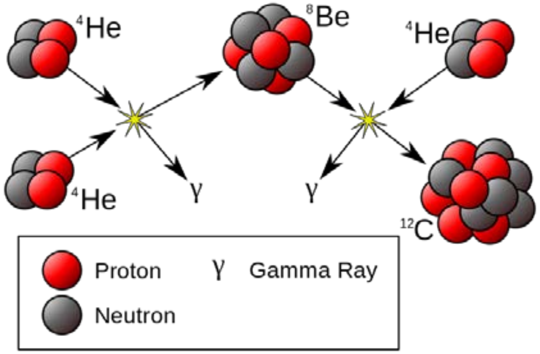
compound nucleus



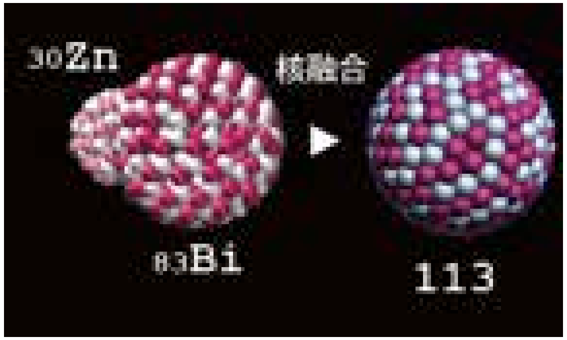
cf. Bohr '36



energy production in stars



nucleosynthesis

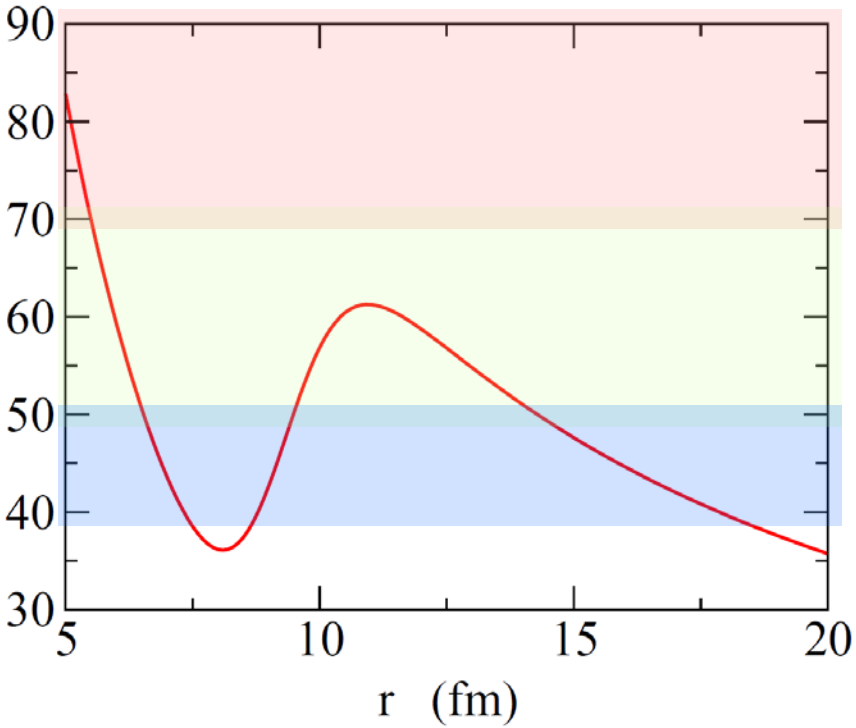


superheavy elements

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?

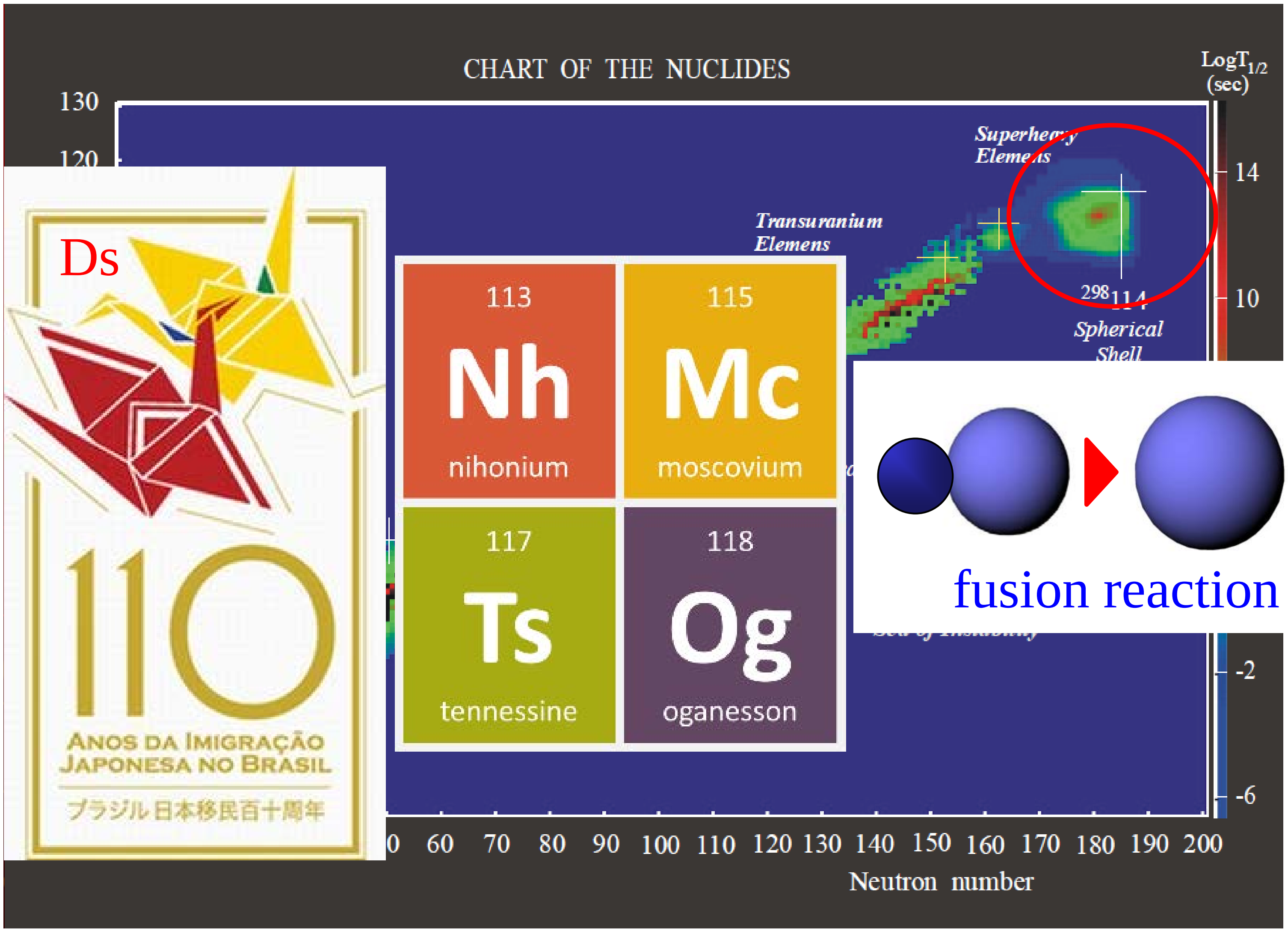
two obvious reasons:

i) Superheavy elements
ii) Nuclear Astrophysics

Fusion reactions for SHE

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?

two obvious reasons:

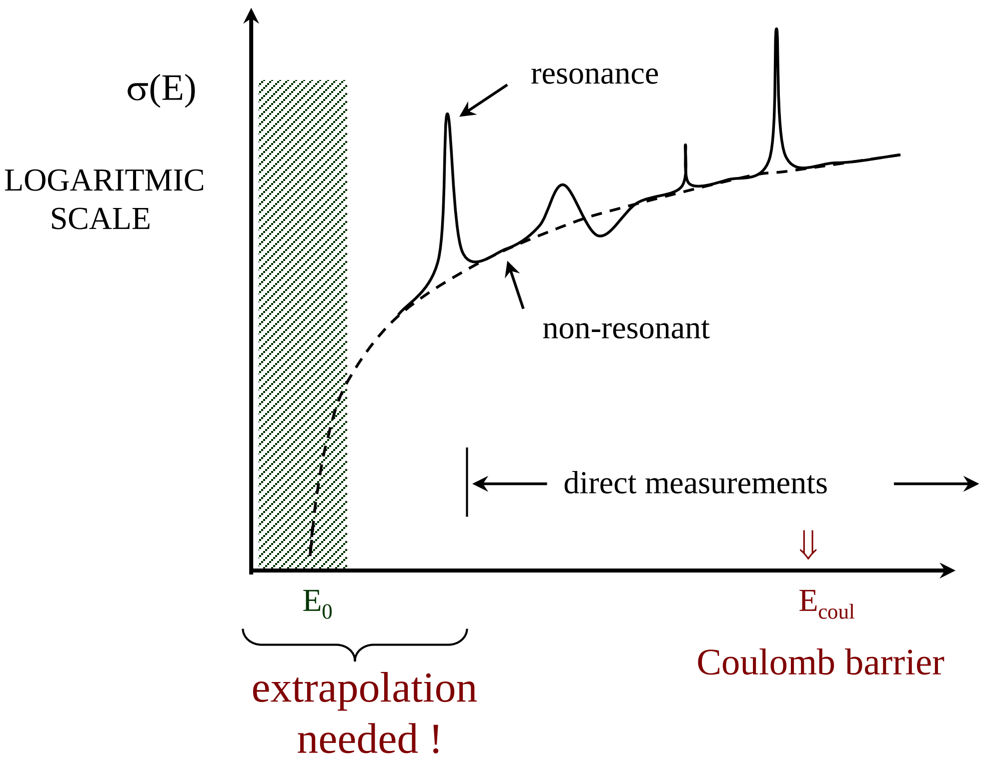
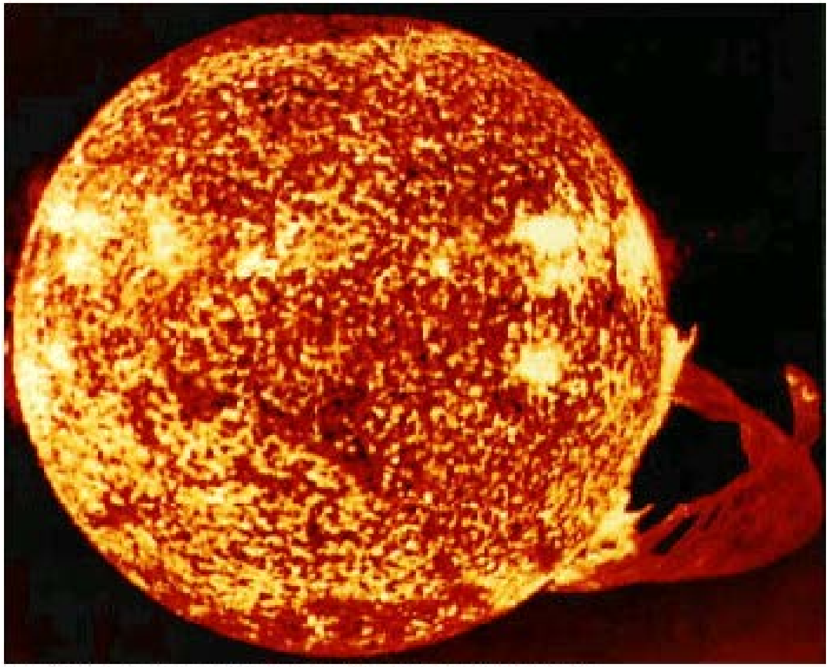


figure: M. Aliotta



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

nuclear astrophysics
(nuclear fusion in stars)

cf. extrapolation of data

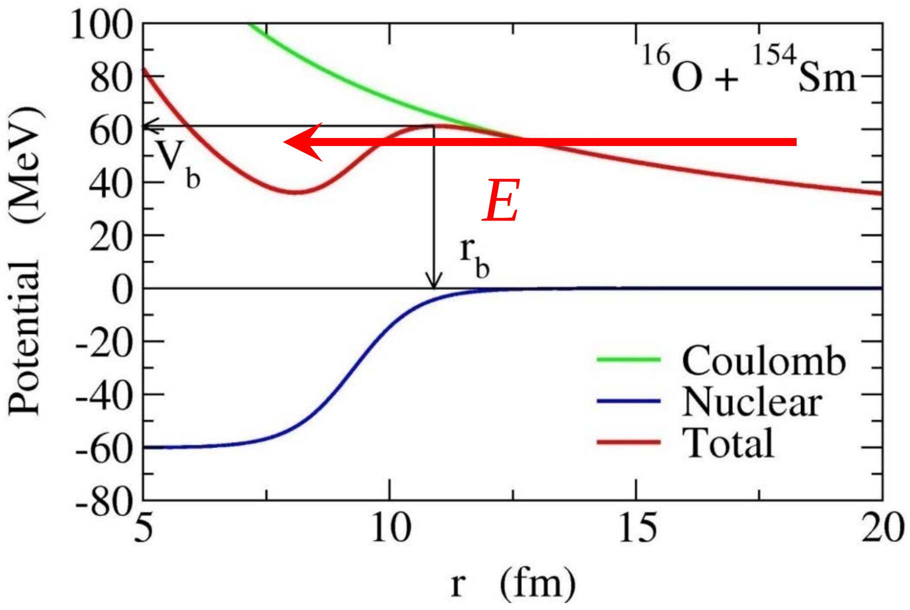
Why sub-barrier fusion?

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:

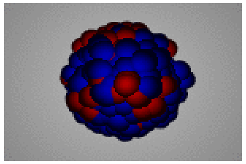
◆ reaction mechanism

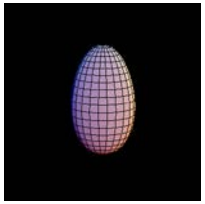
strong interplay between reaction and nuclear structure

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

◆ **many-particle tunneling**

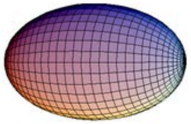
✓ many types of intrinsic degrees of freedom

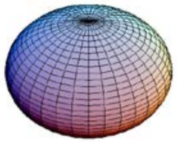




✓ energy dependence of tunneling probability

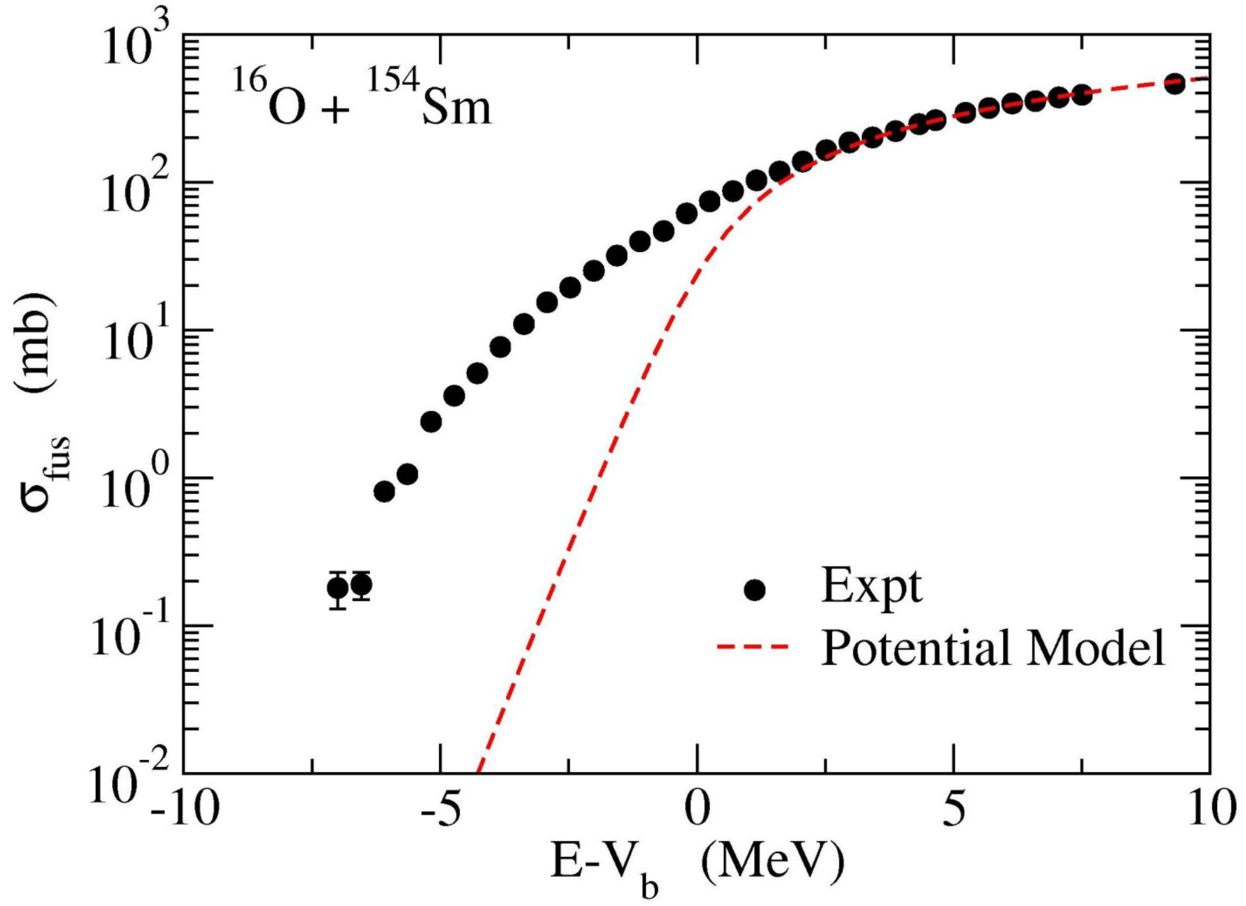
cf. alpha decay: fixed energy





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}

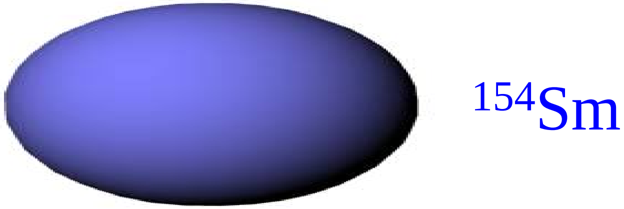


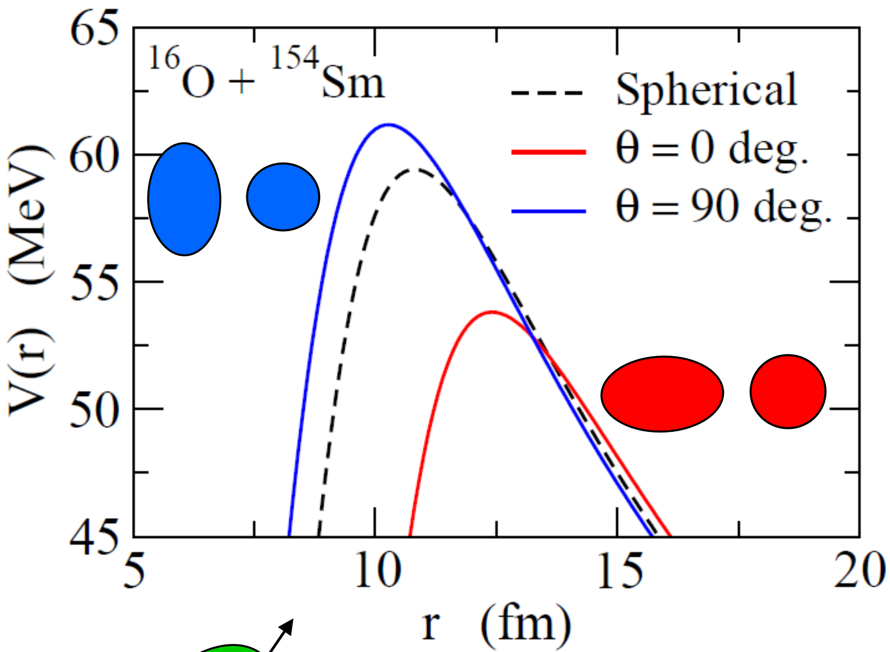
potential model: $V(r)$ + absorption

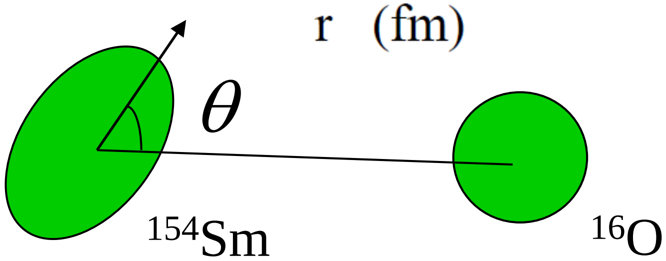
cf. seminal work:
R.G. Stokstad et al., PRL41('78) 465

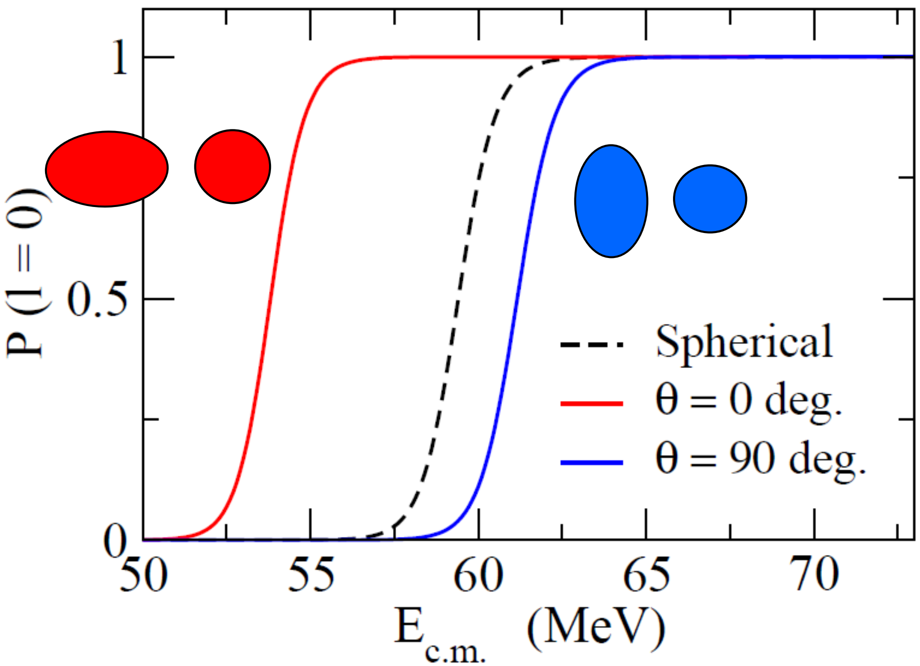
Effects of nuclear deformation

^{154}Sm : a typical deformed nucleus



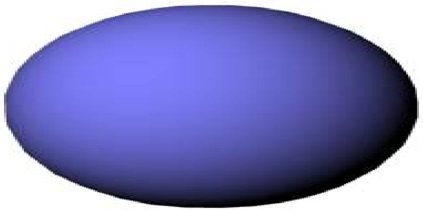




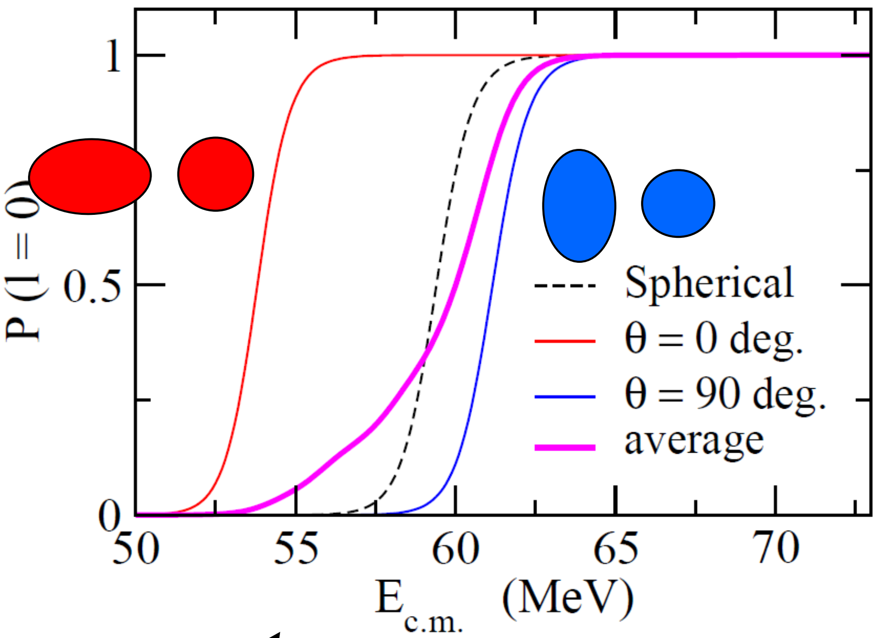


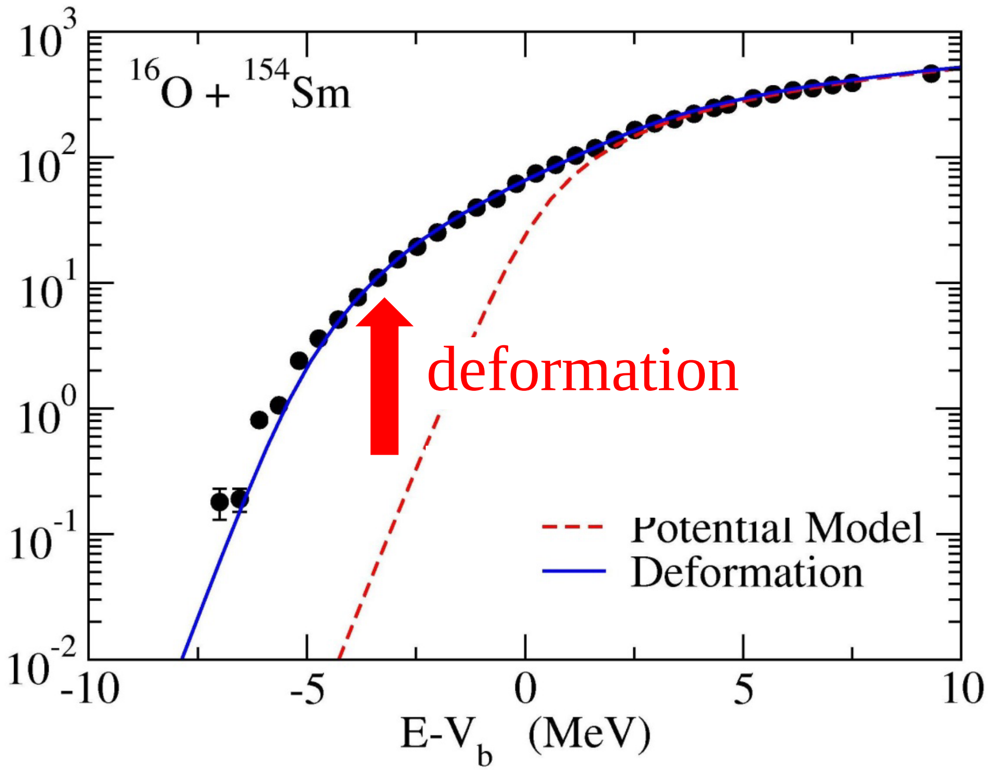
Effects of nuclear deformation

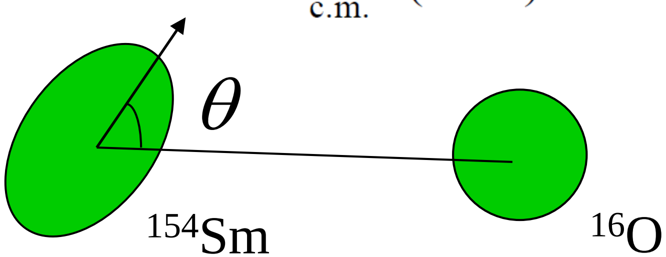
^{154}Sm : a typical deformed nucleus



^{154}Sm

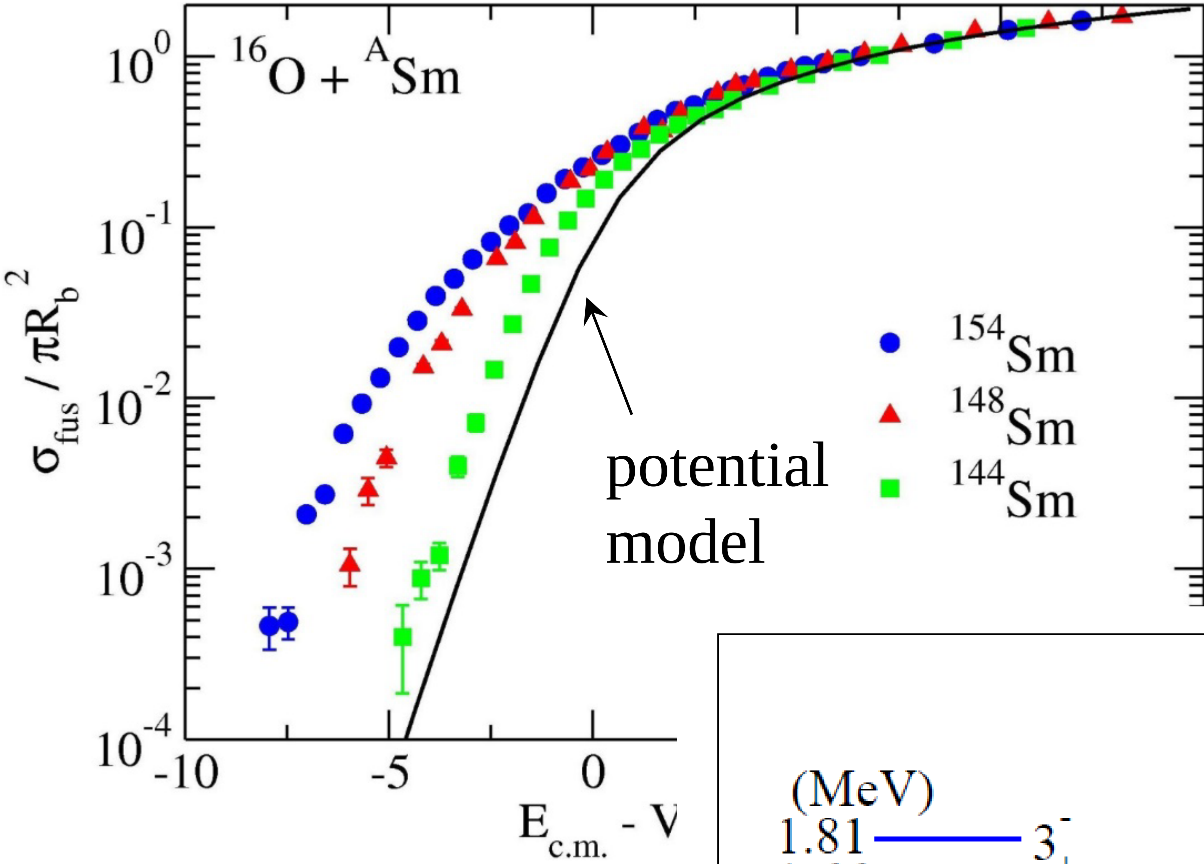




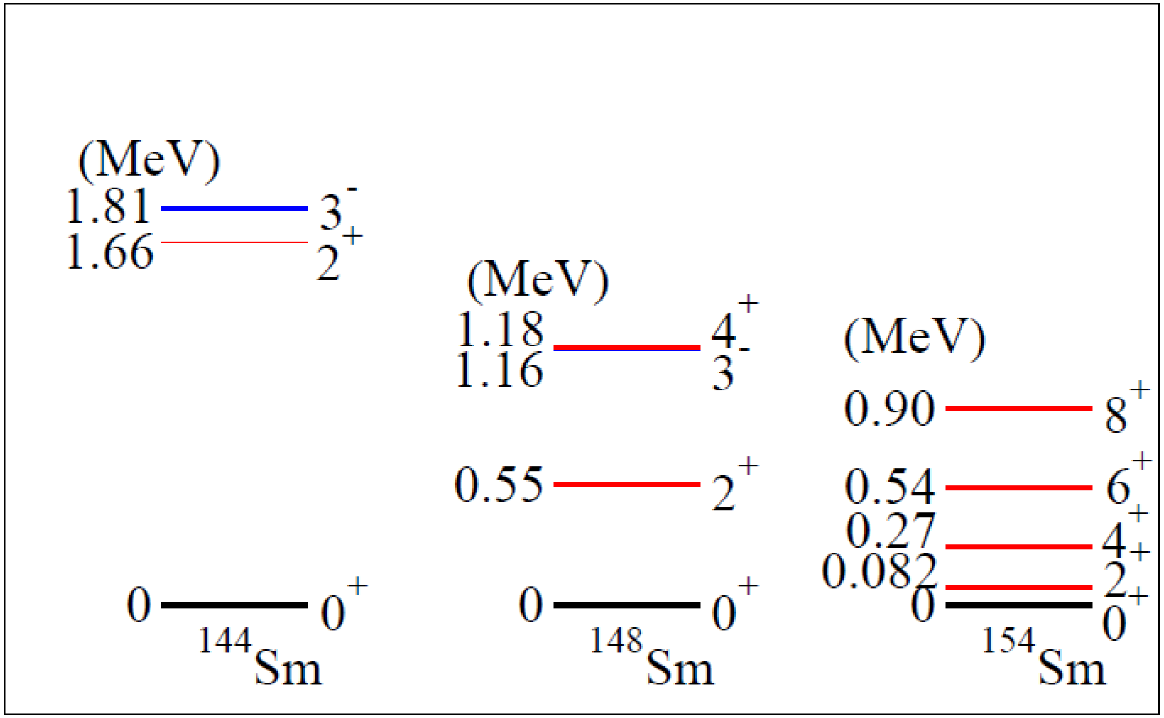


$$\sigma_{\rm fus}(E) = \int_0^1 d(\cos\theta)\sigma_{\rm fus}(E;\theta)$$

Fusion: strong interplay between nuclear structure and reaction



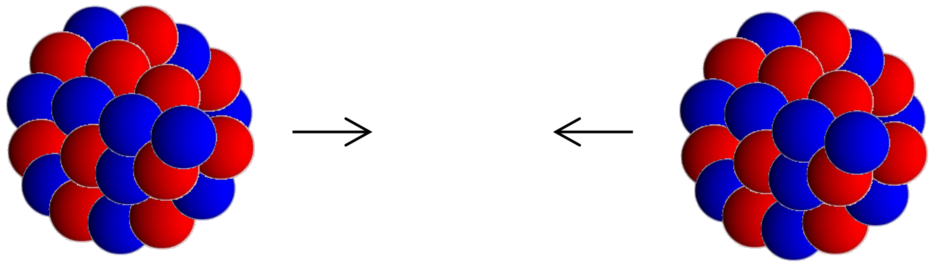
enhancement of fusion cross sections
: a general phenomenon



strong correlation with nuclear spectrum
→ coupling assisted tunneling

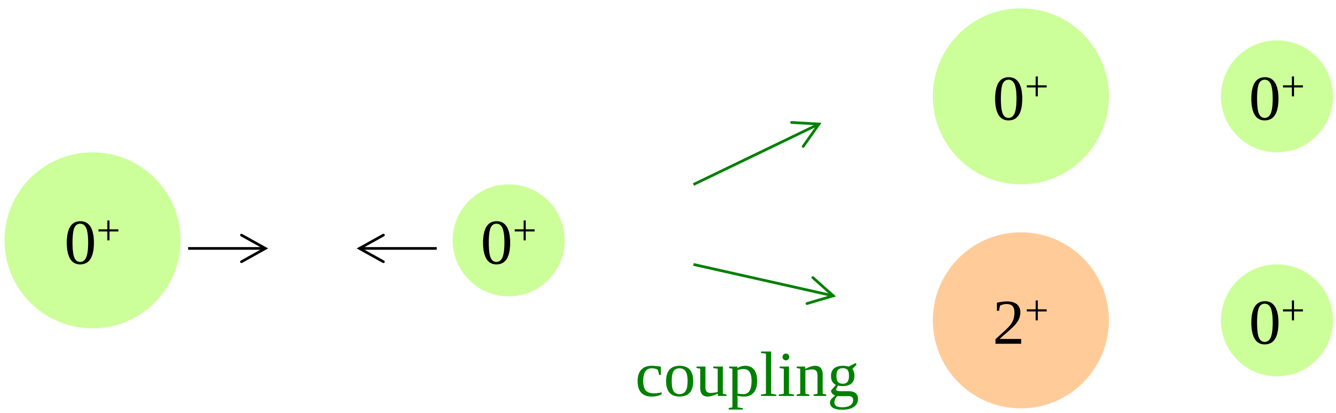
Coupled-channels method: a quantal scattering theory with excitations

many-body problem



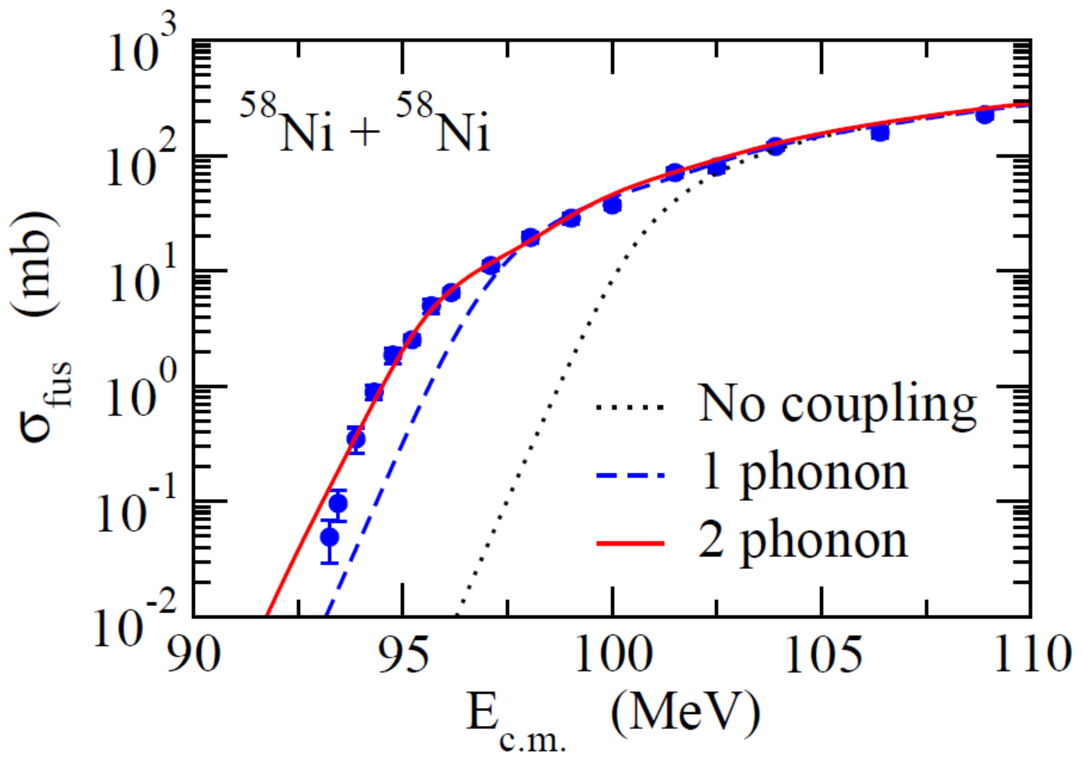
still very challenging

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

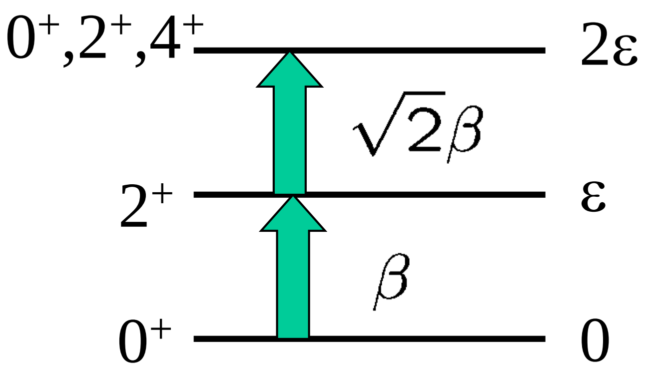


scattering theory with excitations

An example of coupled-channels calculation



simple harmonic oscillator



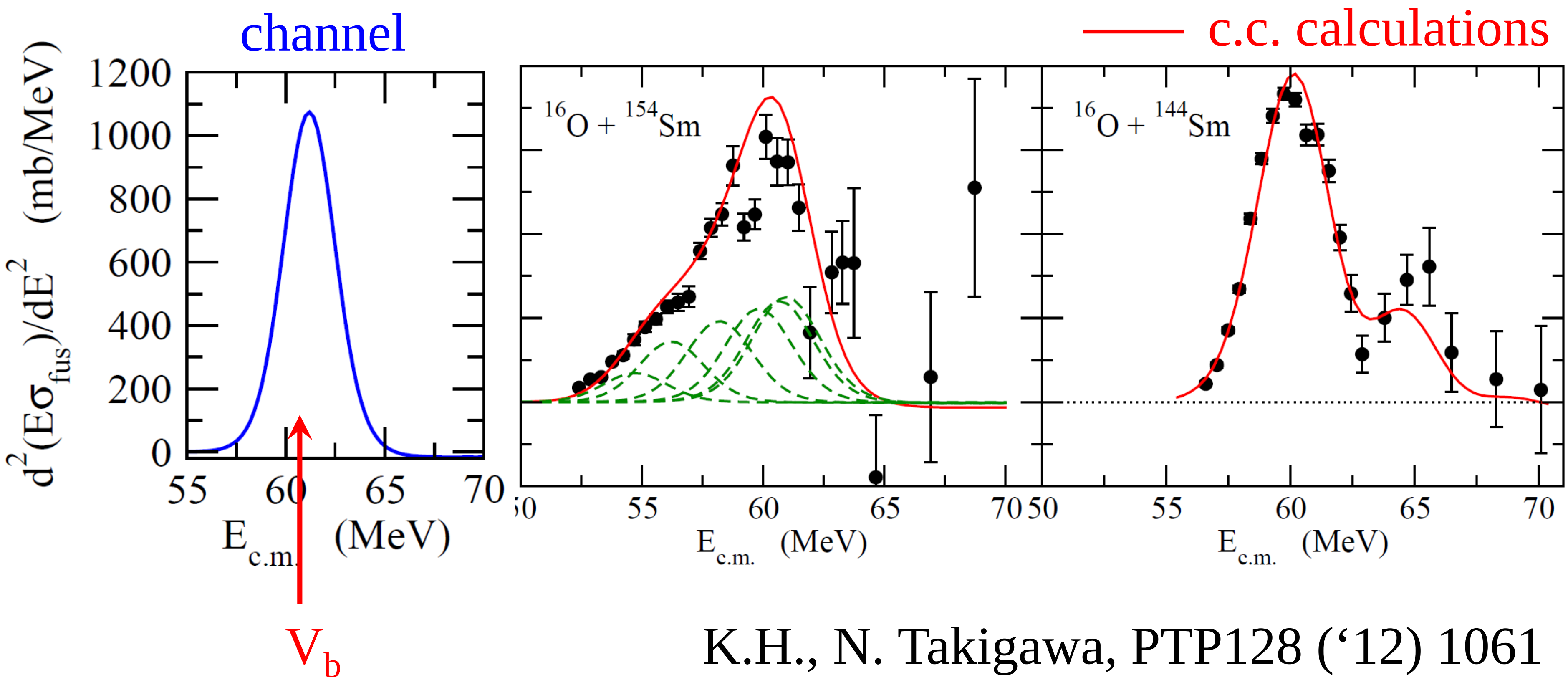
C.C. approach: a standard tool for sub-barrier fusion reactions

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

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

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

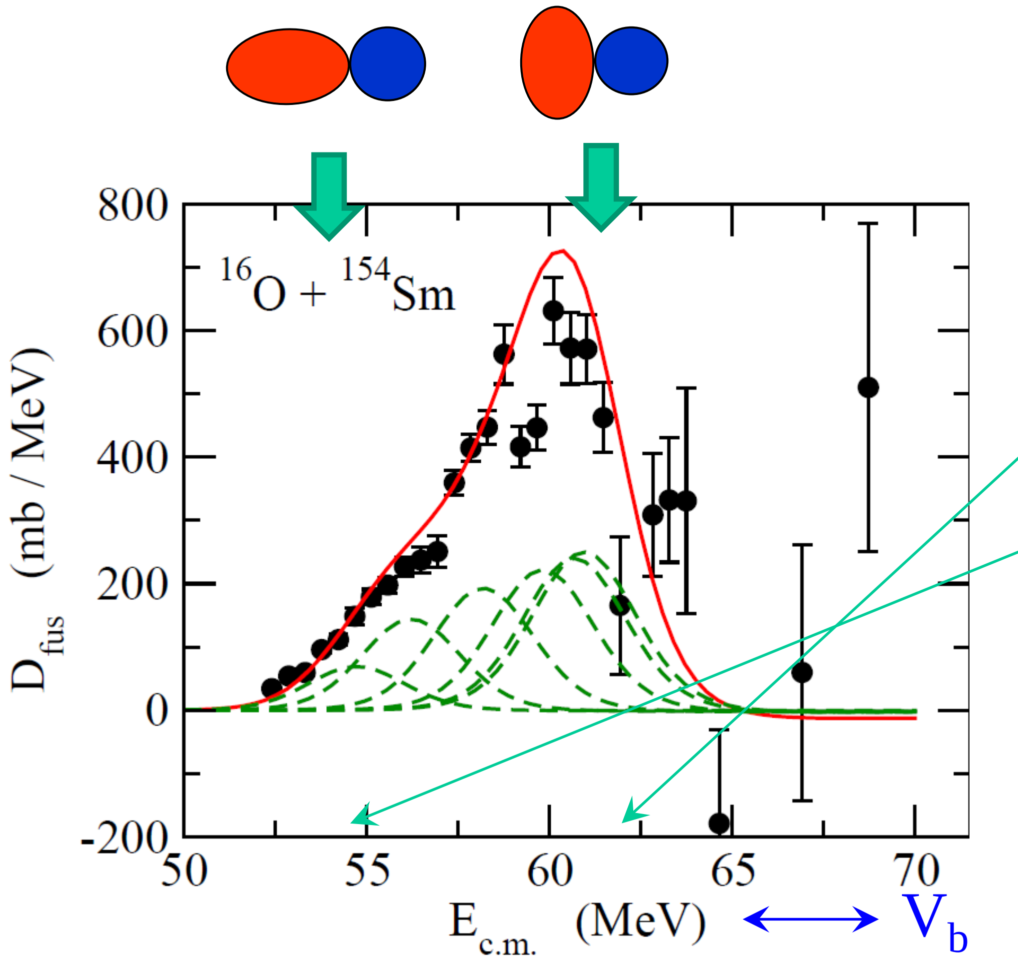
single channel

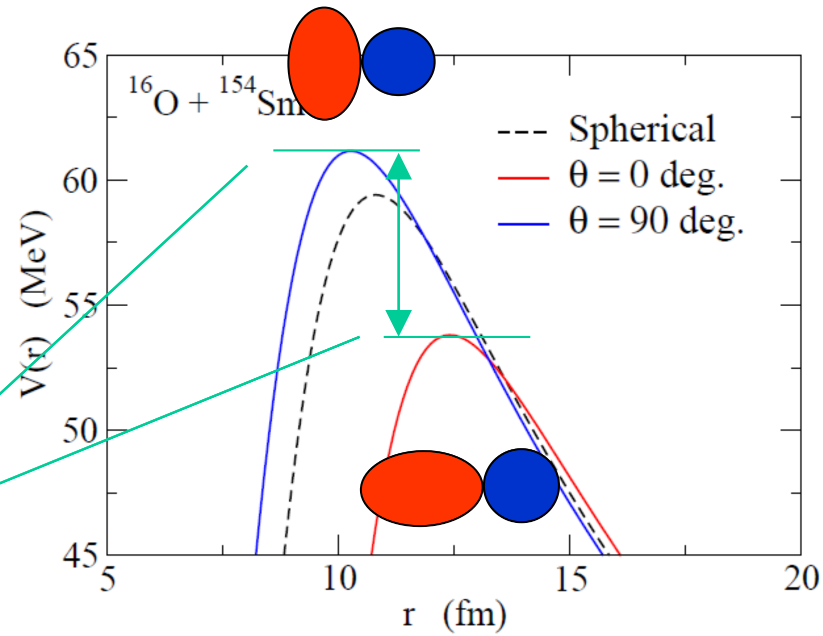


K.H., N. Takigawa, PTP128 (‘12) 1061

✓ 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

a nice tool to understand the reaction dynamics

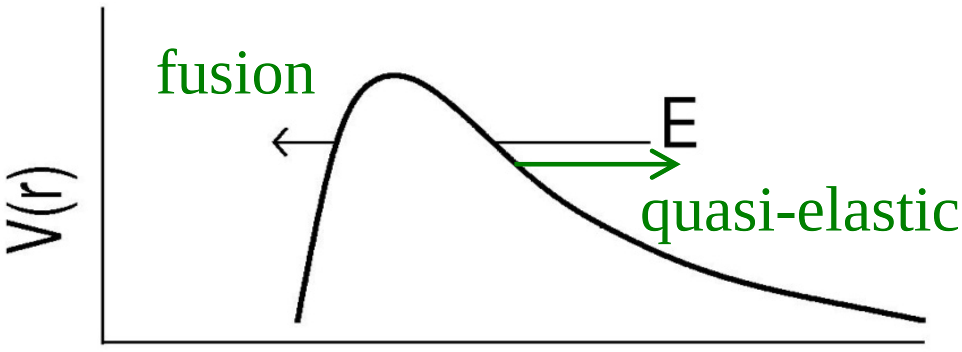
K.H., N. Takigawa, PTP128 ('12) 1061

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

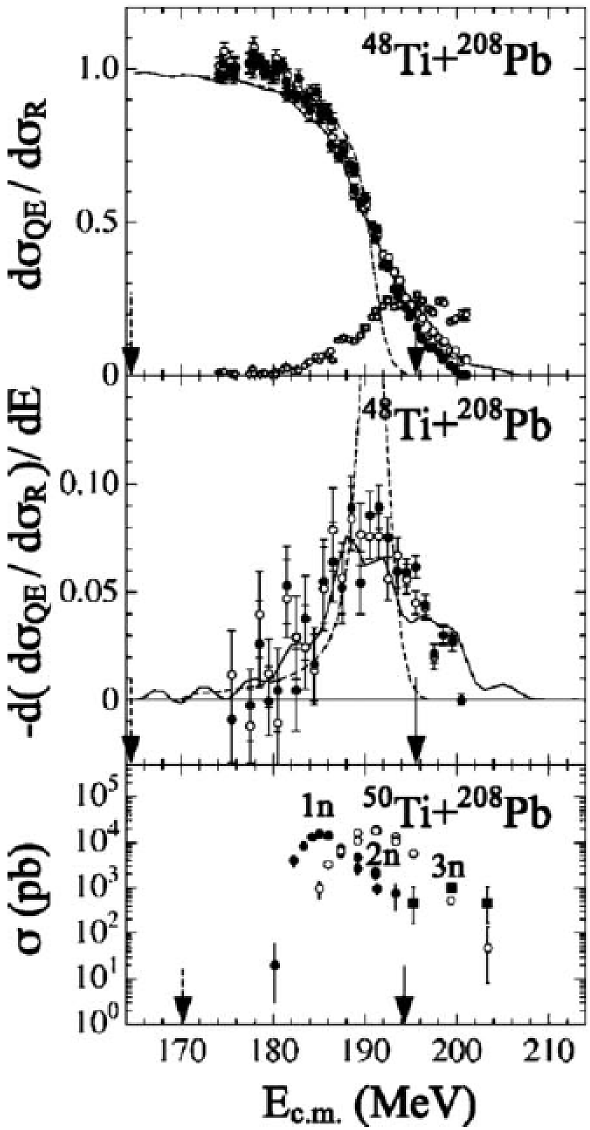
Quasi-elastic barrier distribution

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

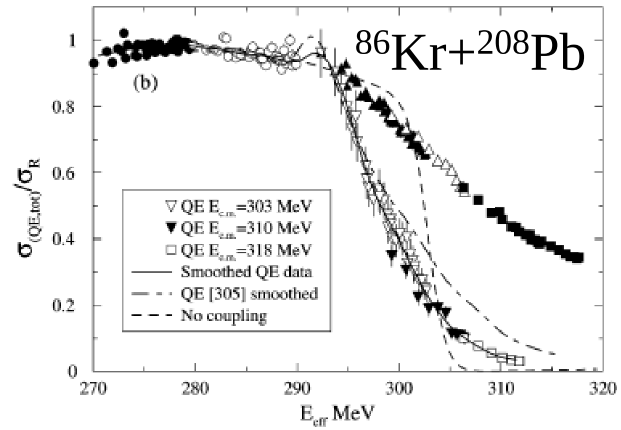
H. Timmers et al., NPA584('95)190
K.H. and N. Rowley, PRC69('04)054610

E. Crema et al., PRC88 ('13) 044616

previous attempts

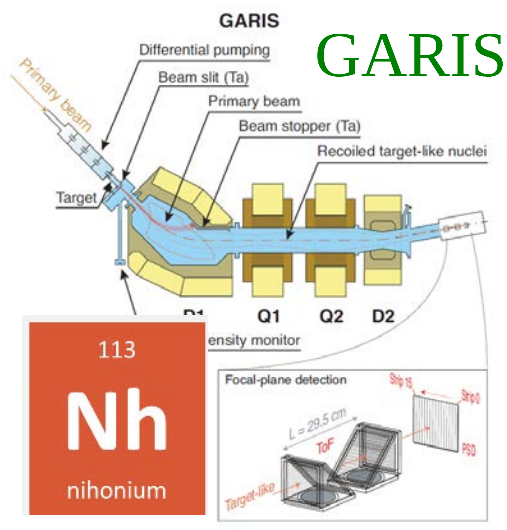


S. Mitsuoka et al.,
PRL99 (‘07) 182701

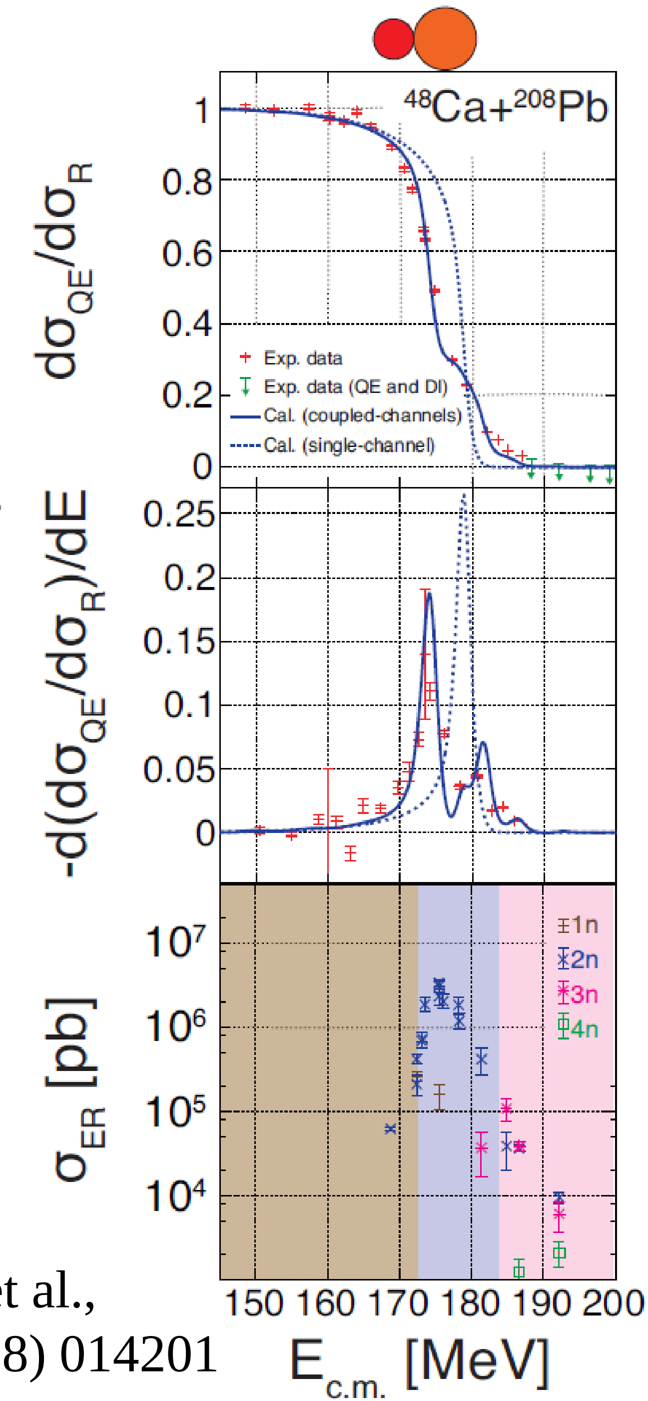


S.S. Ntshangase et al.,
PLB651 (‘07) 27

GARIS



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



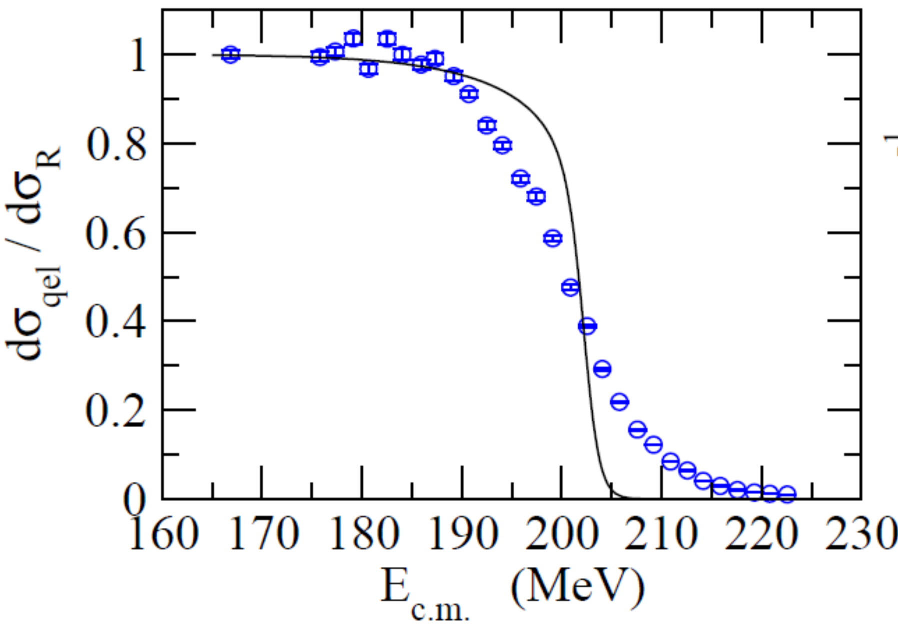
C.C. analysis for a hot fusion reaction ^{48}Ca + ^{248}Cm

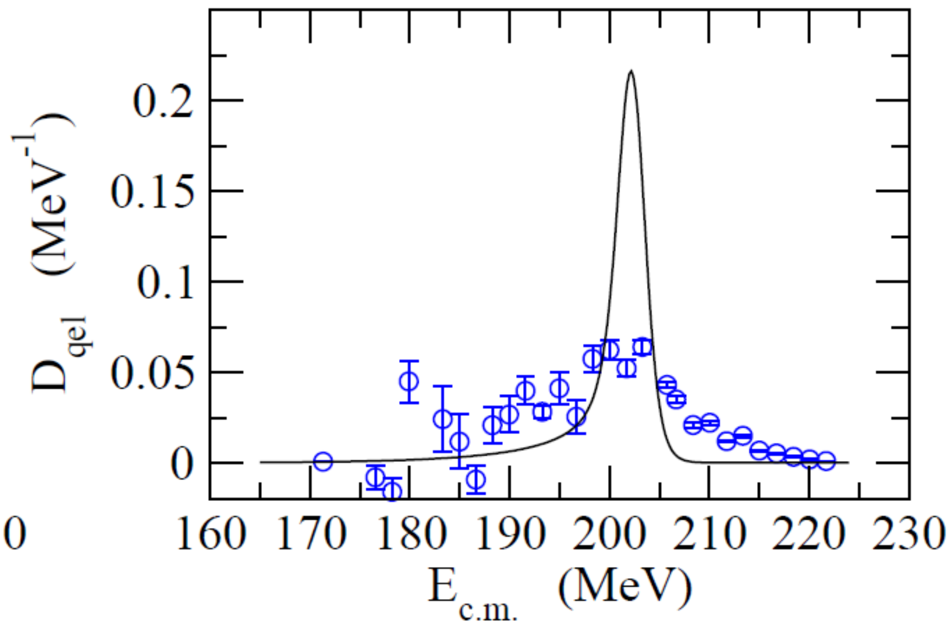
K.H. and T. Tanaka (2017)
(T. Tanaka et al., JPSJ 87 ('18) 014201)

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

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

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





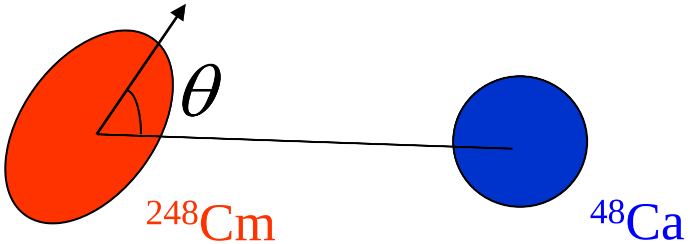
C.C. analysis for a hot fusion reaction ^{48}Ca + ^{248}Cm

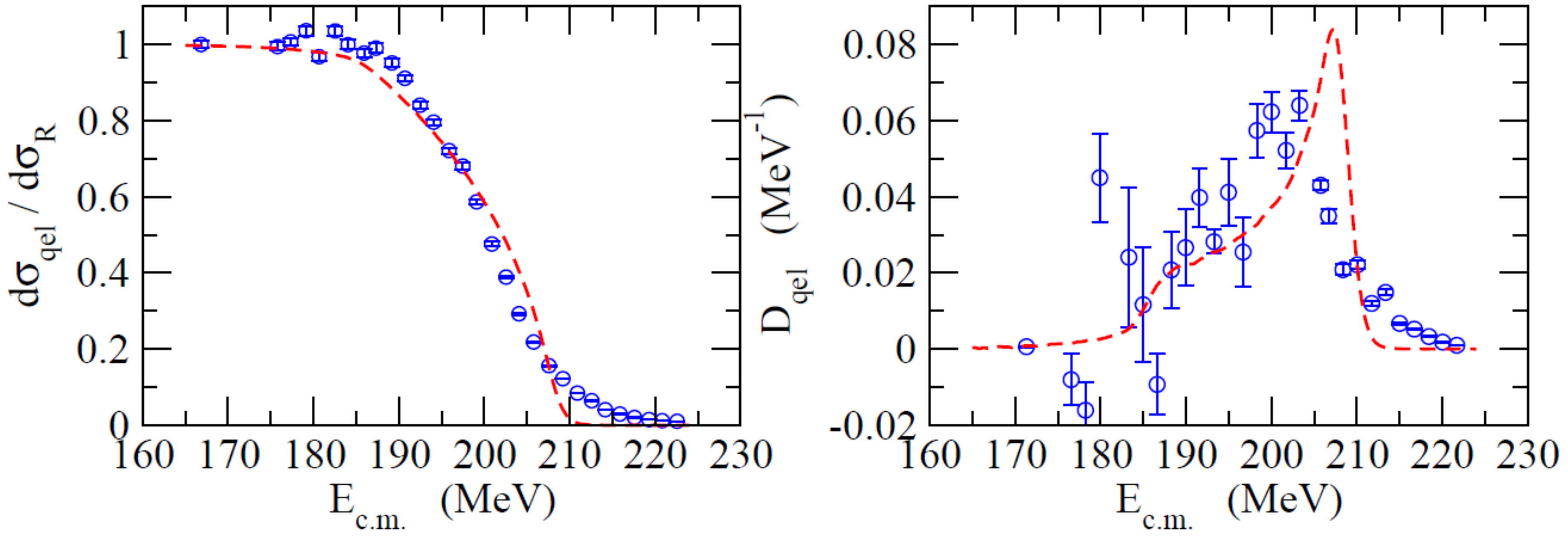
K.H. and T. Tanaka (2017)

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

[β_2 and β_4 from P. Moller]

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





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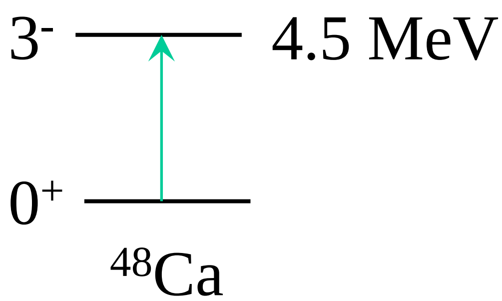
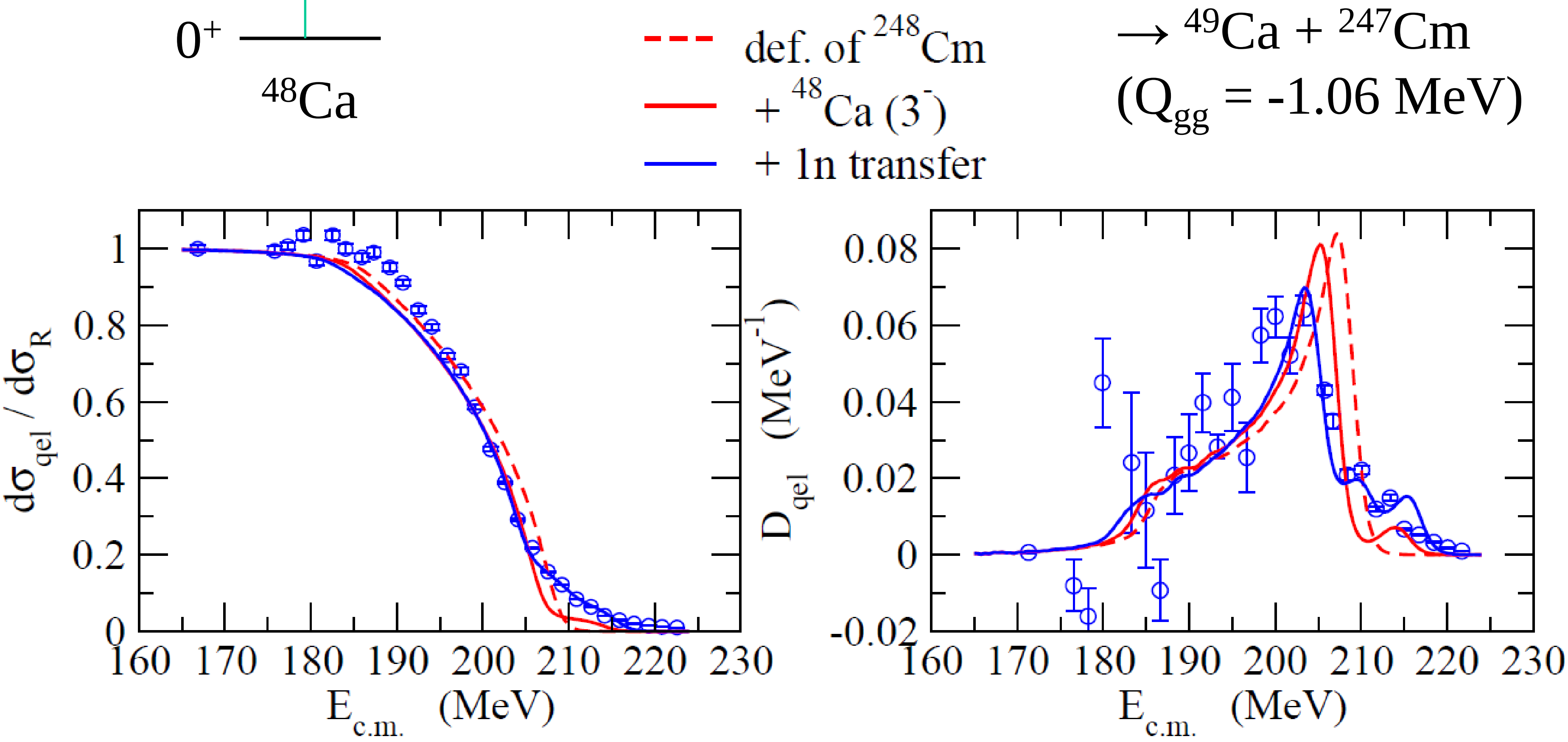
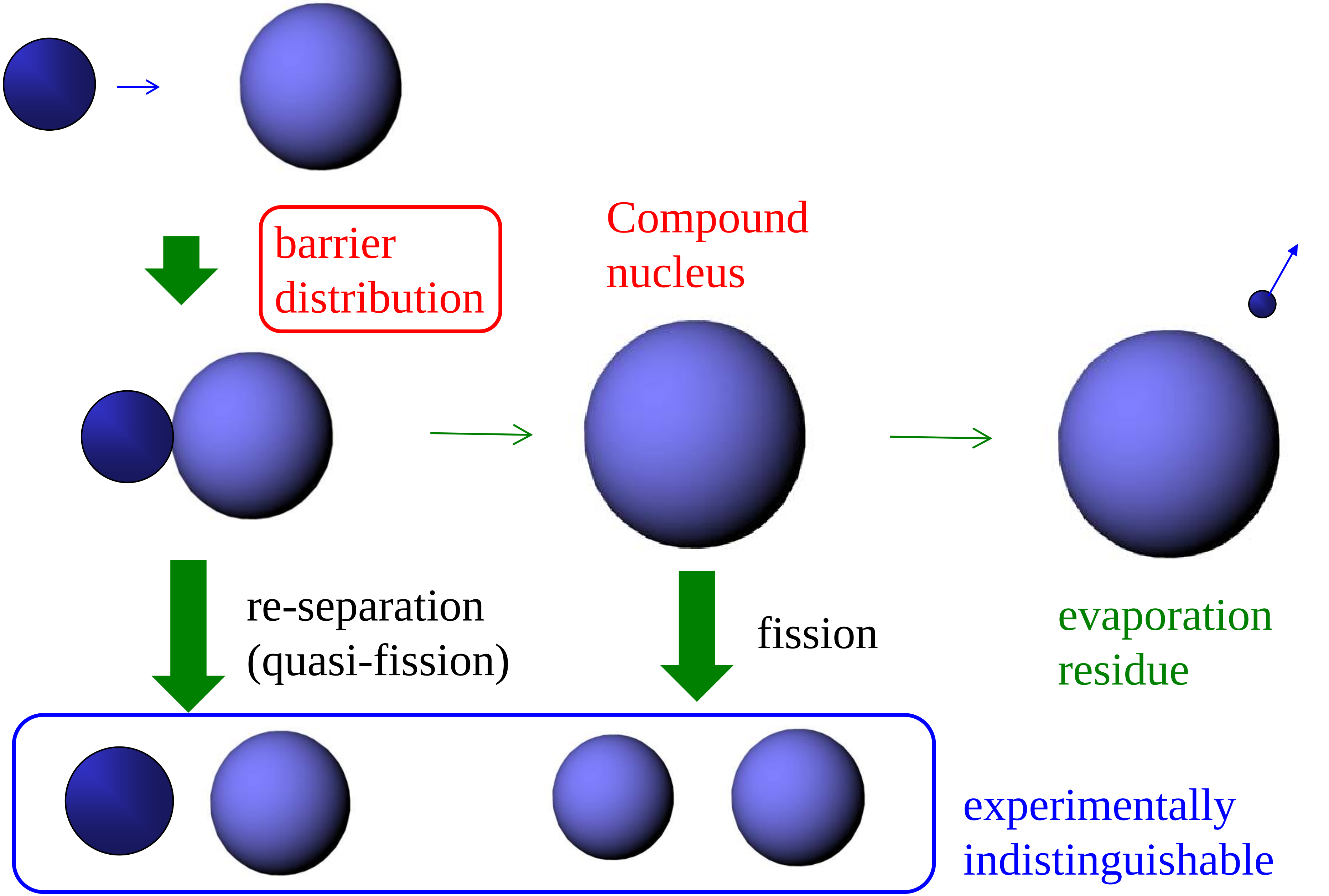


1n transfer

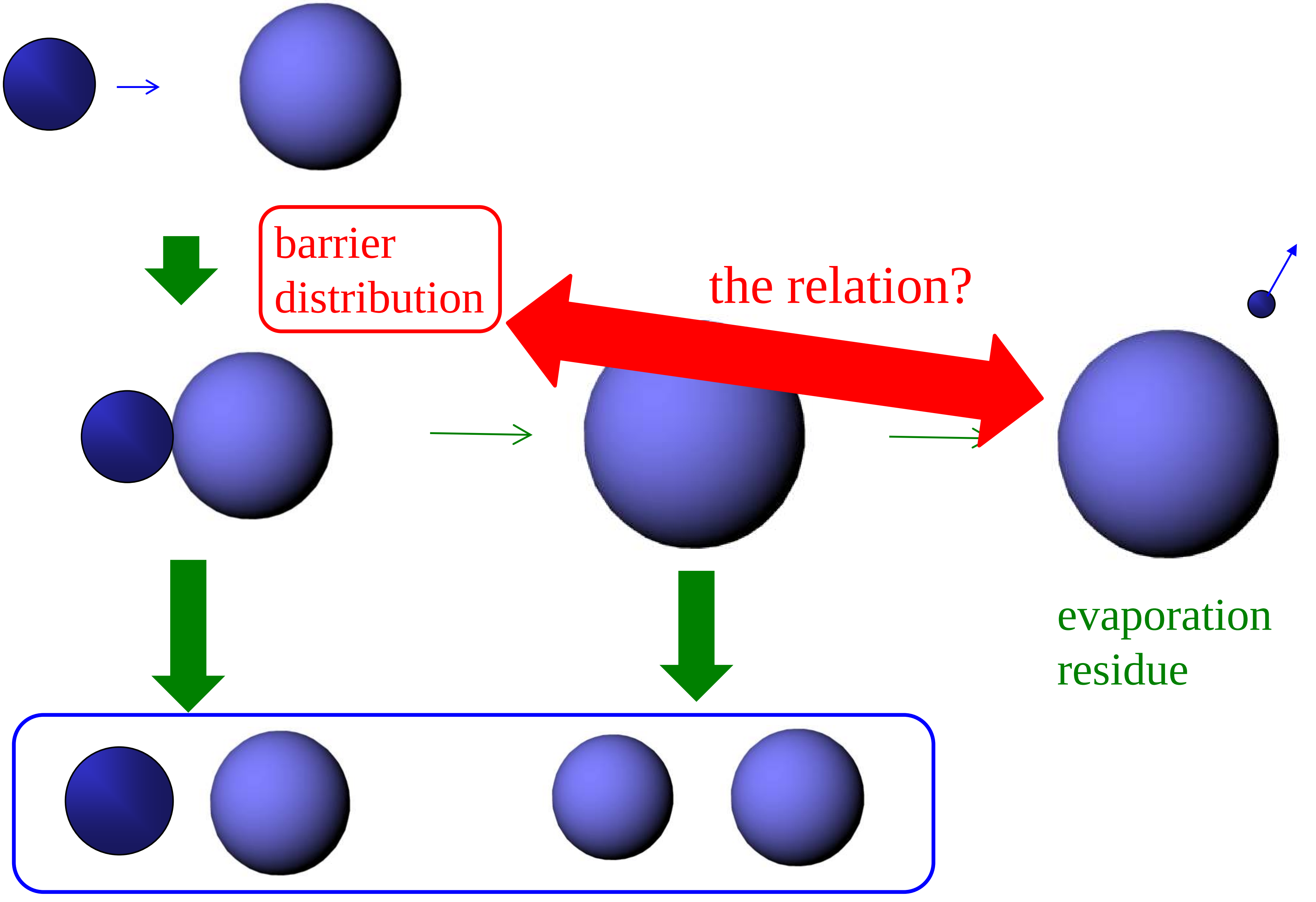
^{48}Ca + ^{248}Cm
$\rightarrow$ ^{49}Ca + ^{247}Cm
(Q_{gg} = -1.06 MeV)



Connection to the ER cross sections

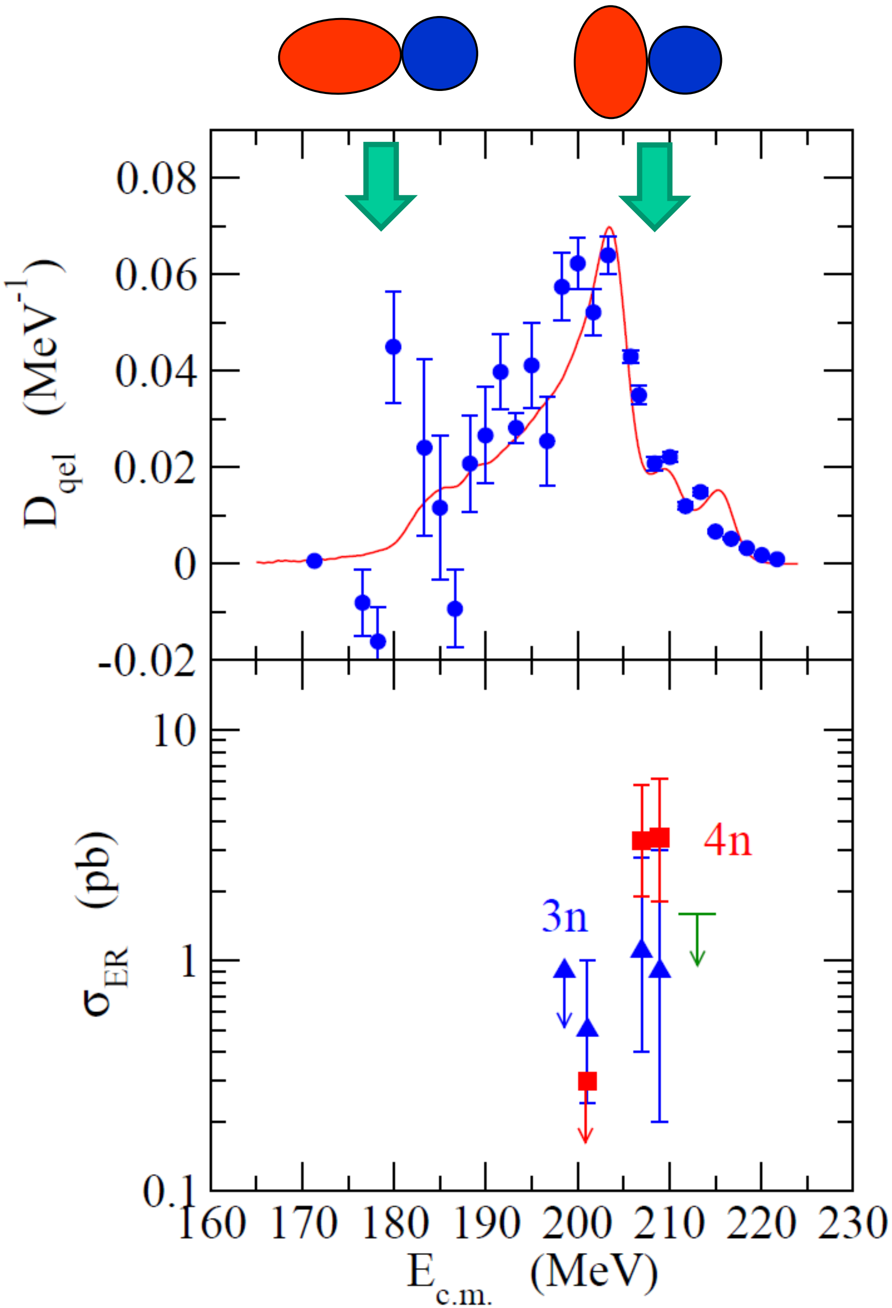


Connection to the ER cross sections

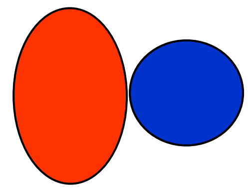


Connection to the ER cross sections

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



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



= more compact at the touching
→ favorable for CN

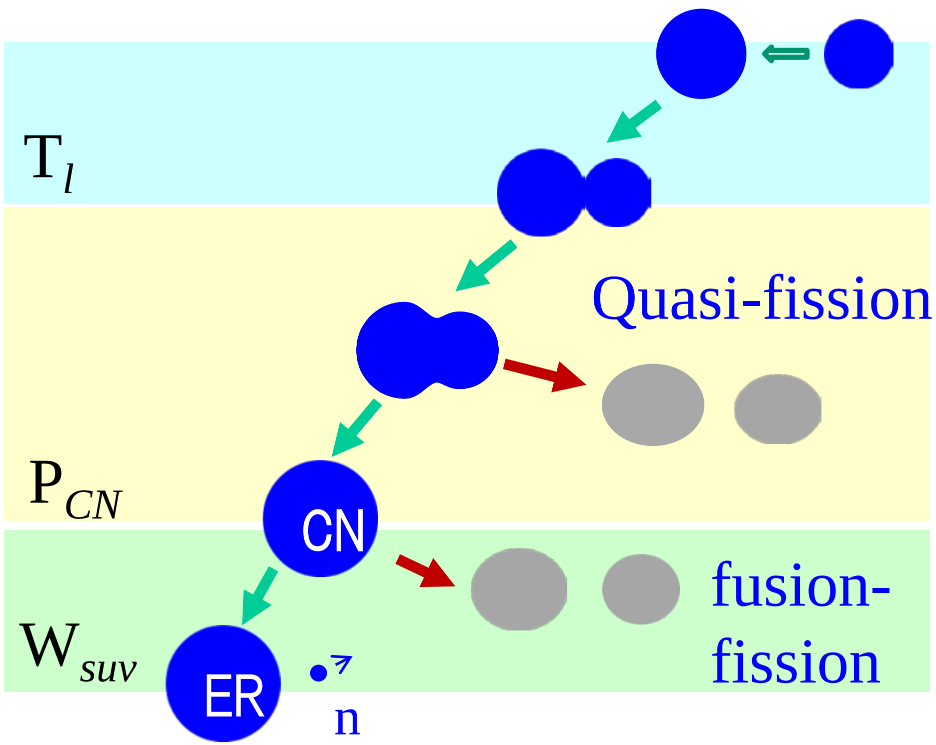
Extension of the fusion-by-diffusion model

K.H., PRC98 (‘18) 014607

Fusion-by-diffusion model

W.J. Swiatecki et al., Acta Phys. Pol. B34 (‘03) 2049

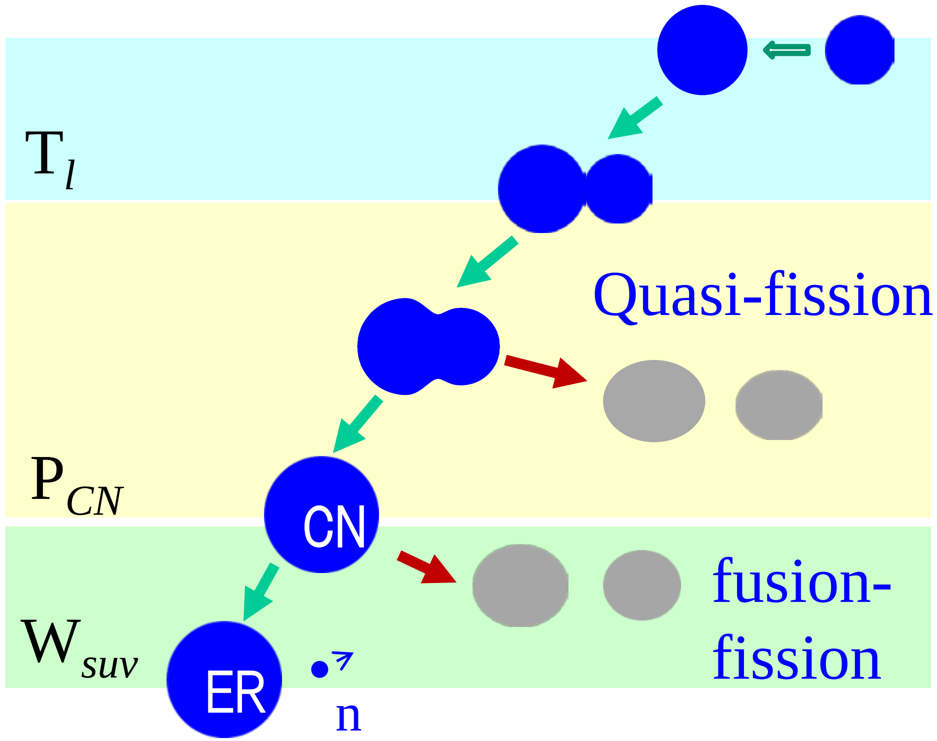
PRC71 (‘05) 014602



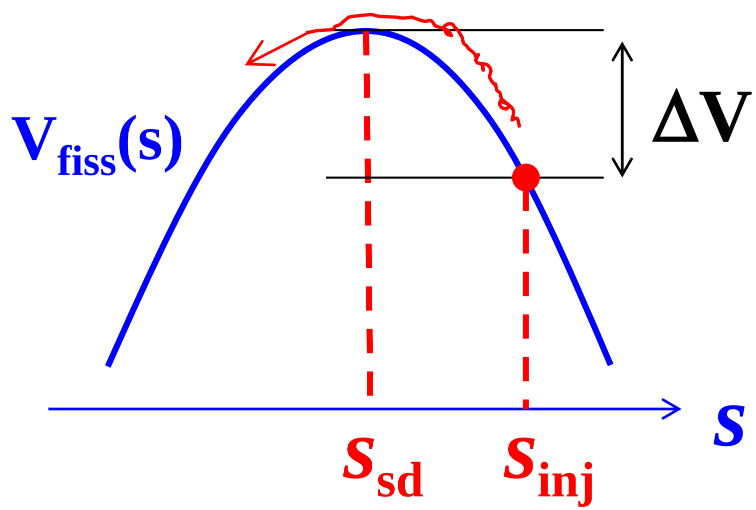
simplified C.C.

diffusion of a 1D parabolic barrier (inner barrier)

statistical model

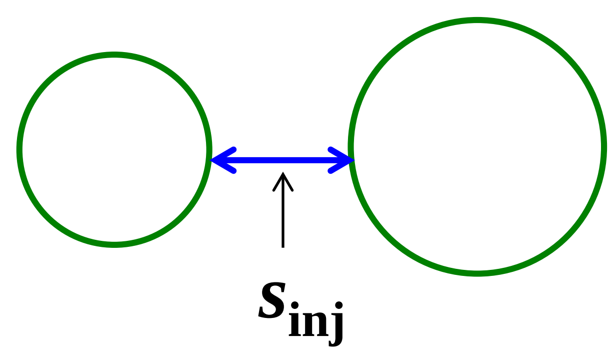


diffusion of a 1D parabolic barrier



Langevin in the overdamped limit:

$$P_{\mathrm{CN}}(E) = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{\Delta V}{T}\right)\right]$$



W.J. Swiatecki et al.,
PRC71 (‘05) 014602

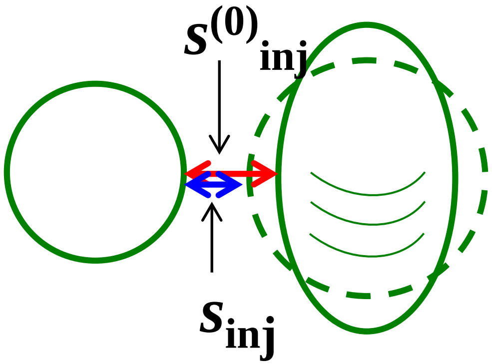
Extension of the fusion-by-diffusion model

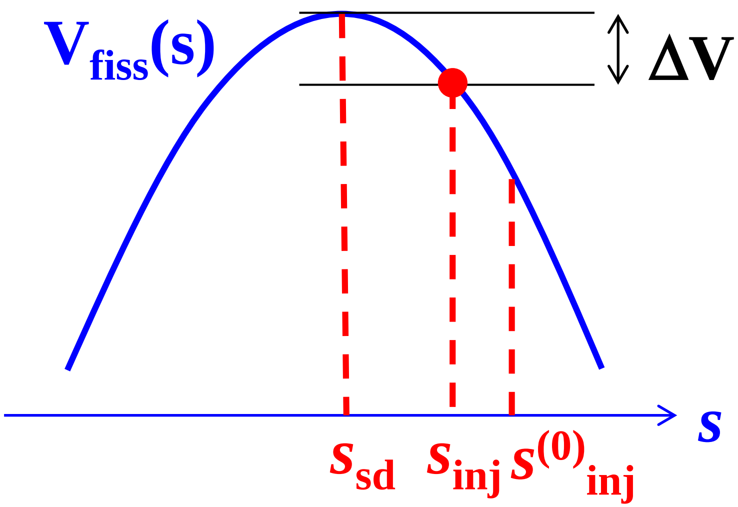
K.H., PRC98 ('18) 014607

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

$$P_{\mathrm{CN}}(E,\theta) = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{\Delta V(\theta)}{T(\theta)}\right)\right]$$

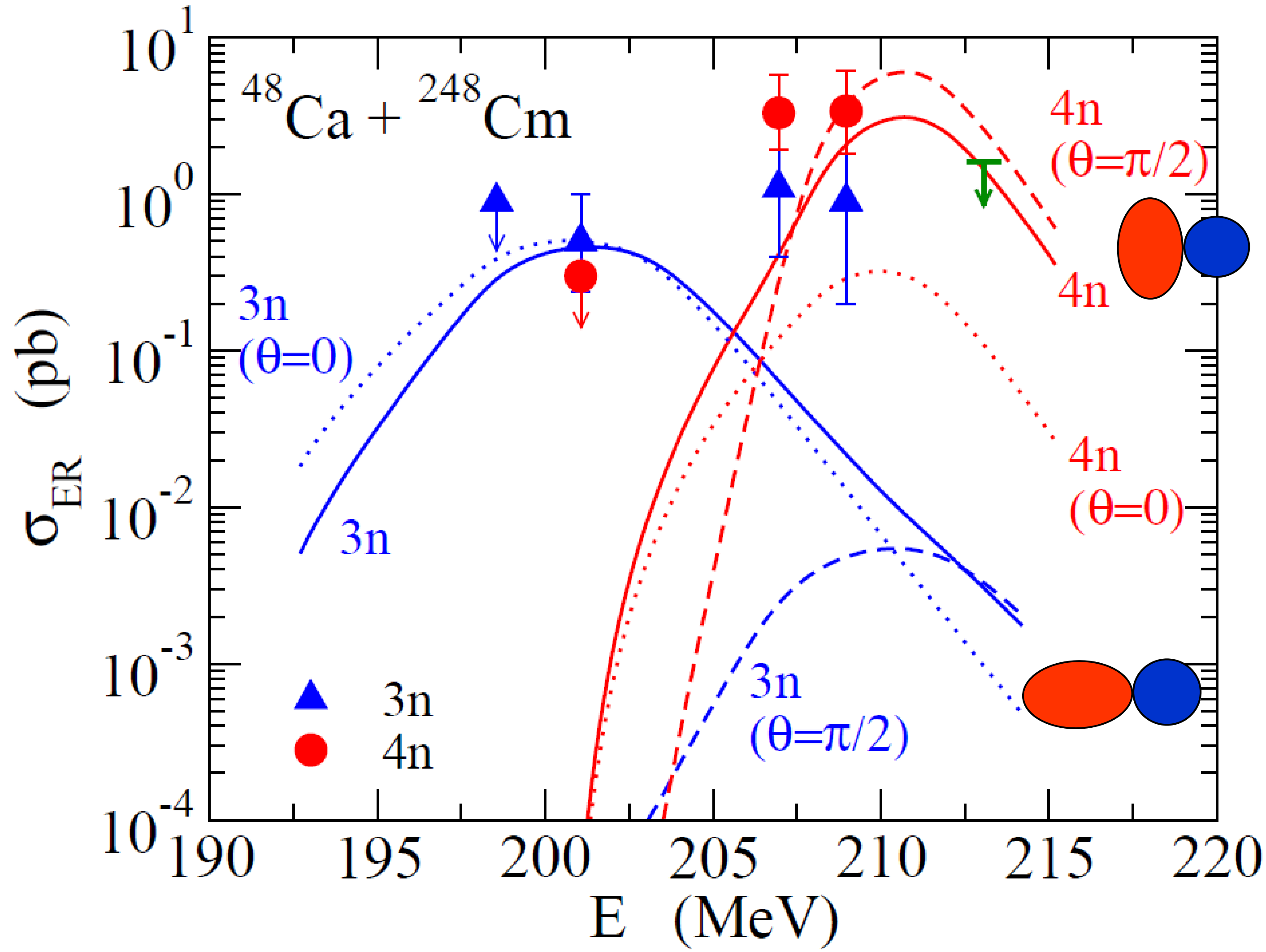
θ = π/2 (side collision)



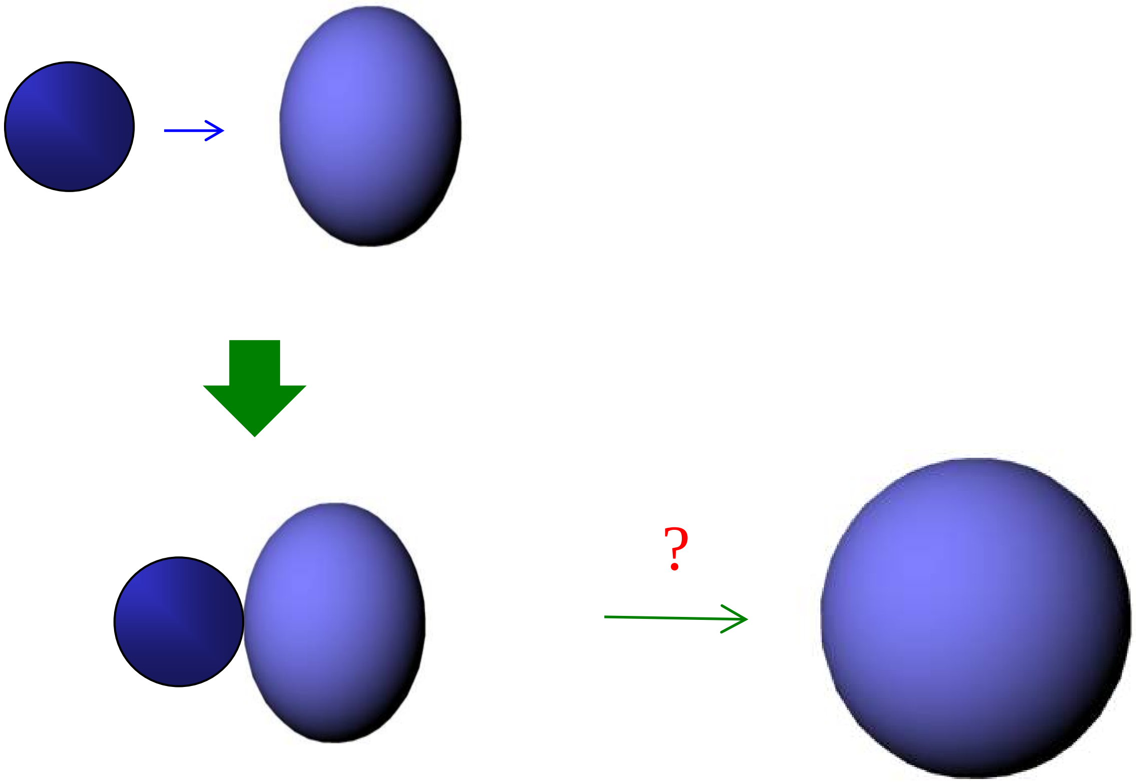


Extension of the fusion-by-diffusion model

K.H., PRC98 ('18) 014607



A more challenging problem



heat up

→ disappearance of quantum effects
(shell effect and deformation)

quantum theory for friction

Quantum friction

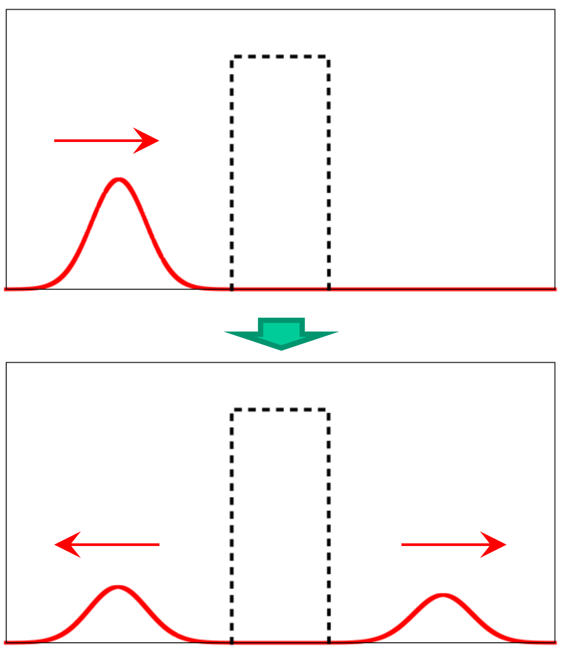
classical eq. of motion $\dot{p} = -V'(x) - \gamma p$

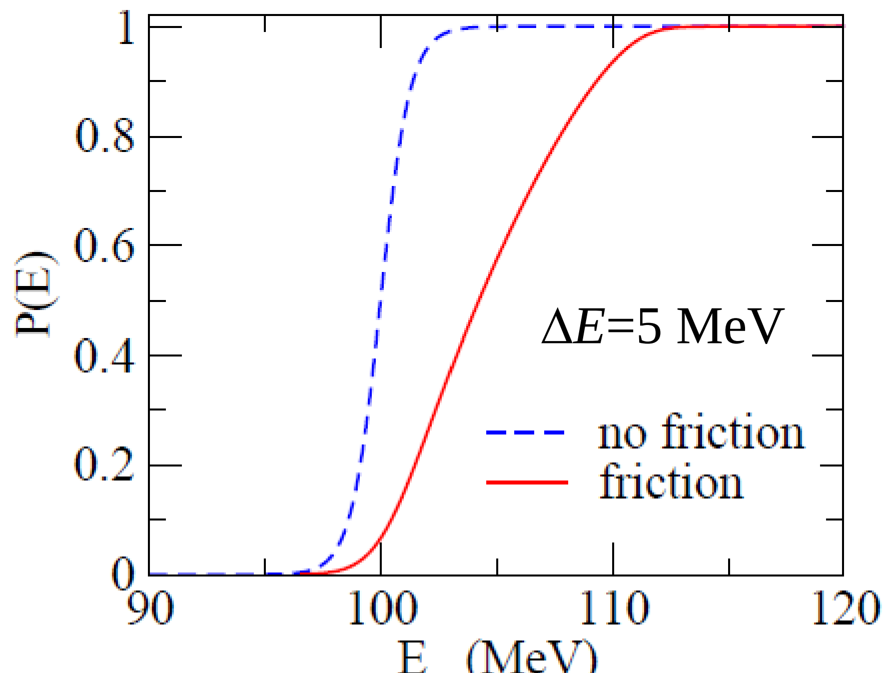
a quantization: Kanai model E. Kanai, PTP 3 (1948) 440)

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

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

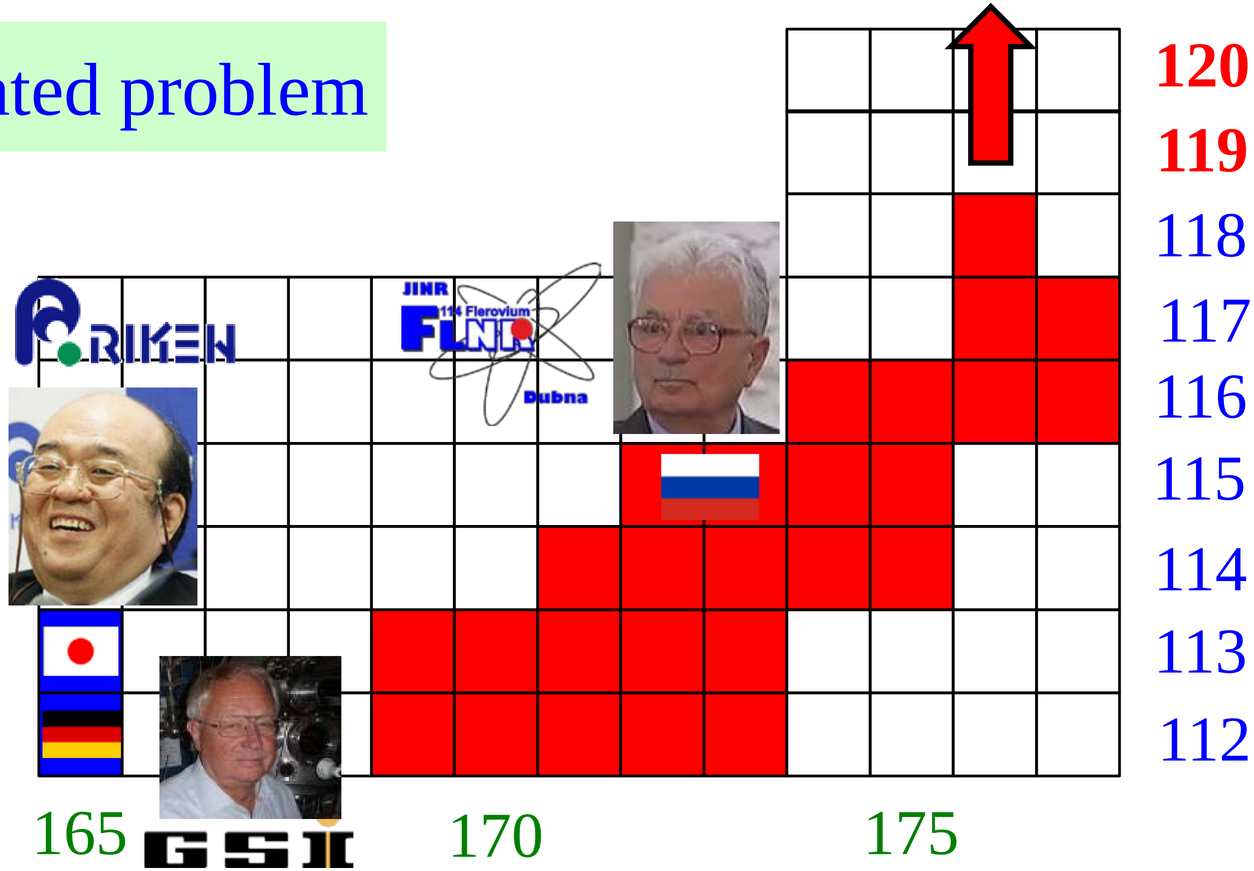
time-dep. wave packet approach





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

A related problem



hot fusion reaction:

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

not available with sufficient amount

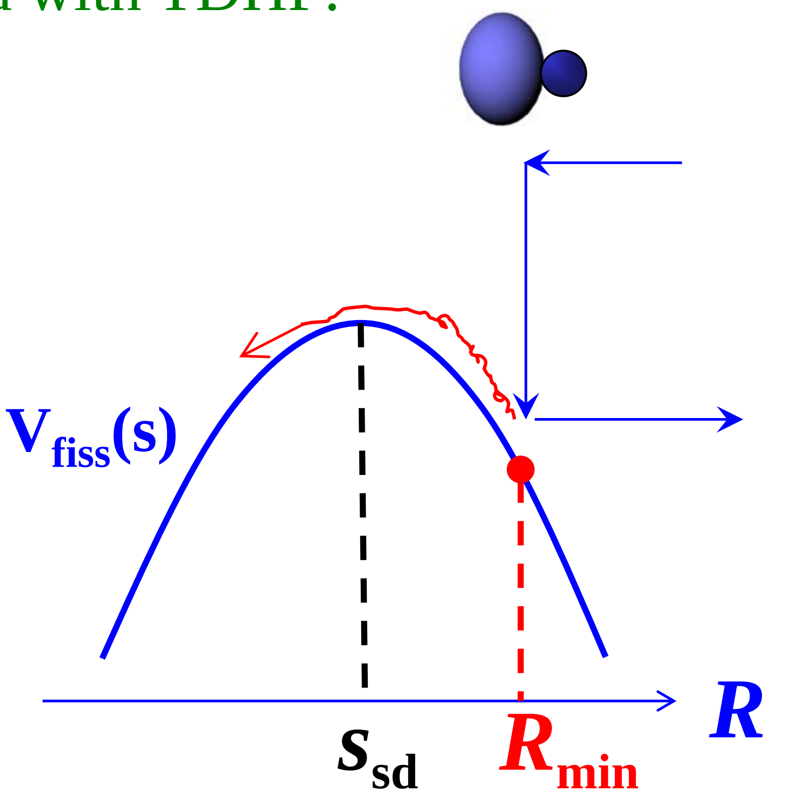
$$^{51}_{23}\mathrm{V} + {}^{248}_{96}\mathrm{Cm} \rightarrow {}^{299}119 \text{ etc.}$$

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:



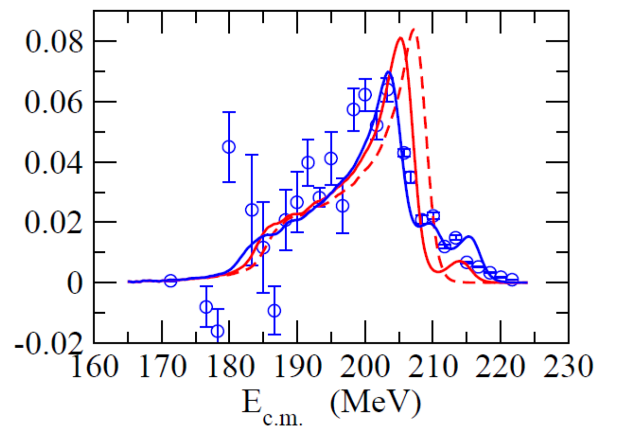
➡ input to Langevin calculations

➡ 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

    reaction dynamics with <u>neutron-rich</u> beams?

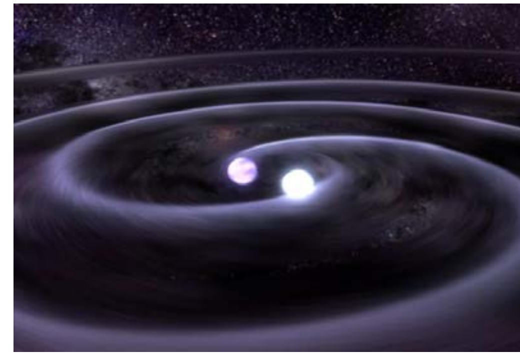
cf. Felipe Canto’s talk

formation of SHE

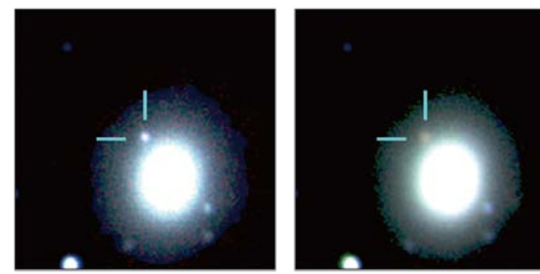
chemistry of SHE

the origin of (S)HE

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La *	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac **	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
			**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	



2017.08.18–19 2017.08.24–25



heavy-ion fusion reactions

International Year
of the Periodic Table
of Chemical Elements

r-process nucleosynthesis

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

→ comprehensive understanding of SHE