NNPA
2018

NEW FRONTIERS IN NUCLEAR PHYSICS AND ASTROPHYSICS-1

28 May – 1 June 2018

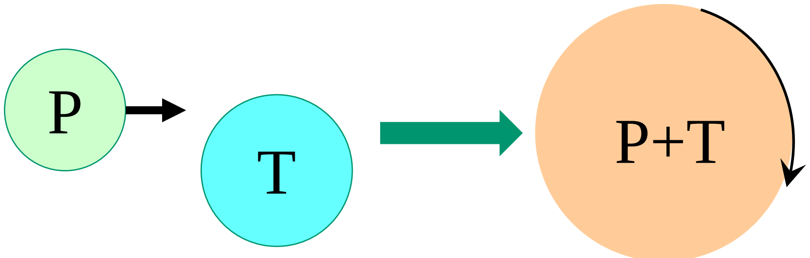
Heavy-ion fusion reactions for superheavy elements

Kouichi Hagino
Tohoku University, Sendai, Japan

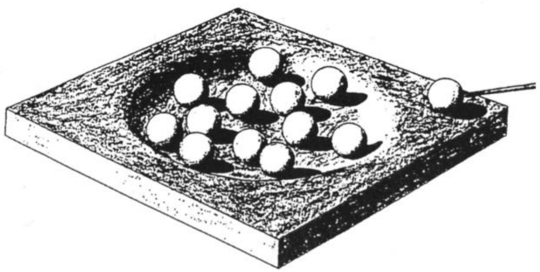
1. H.I. sub-barrier fusion reactions
2. Coupled-channels approach and barrier distributions
3. Application to superheavy elements
4. Hot fusion reactions of a deformed target
5. Summary and discussions

Recent review article:
K. Hagino and N. Takigawa, Prog. Theo. Phys.128 ('12)1061.

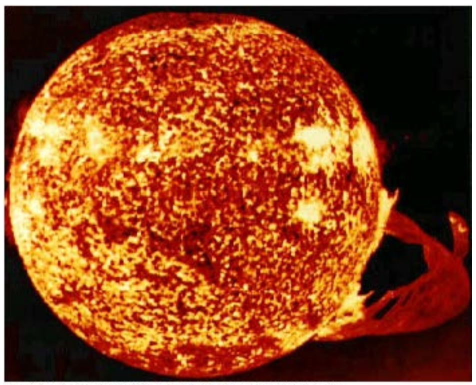
Fusion reactions: compound nucleus formation



compound nucleus

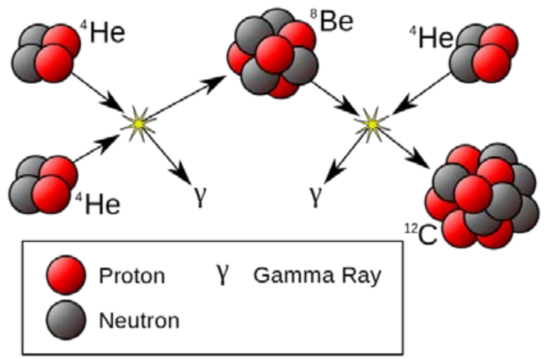


cf. Bohr '36

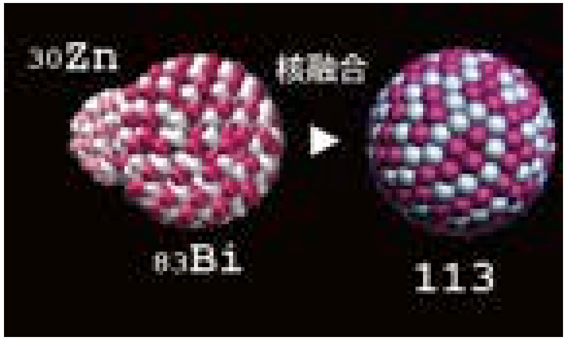


NASA, Skylab space station December 19, 1973, solar flare reaching 588 000 km off solar surface

energy production in stars



nucleosynthesis

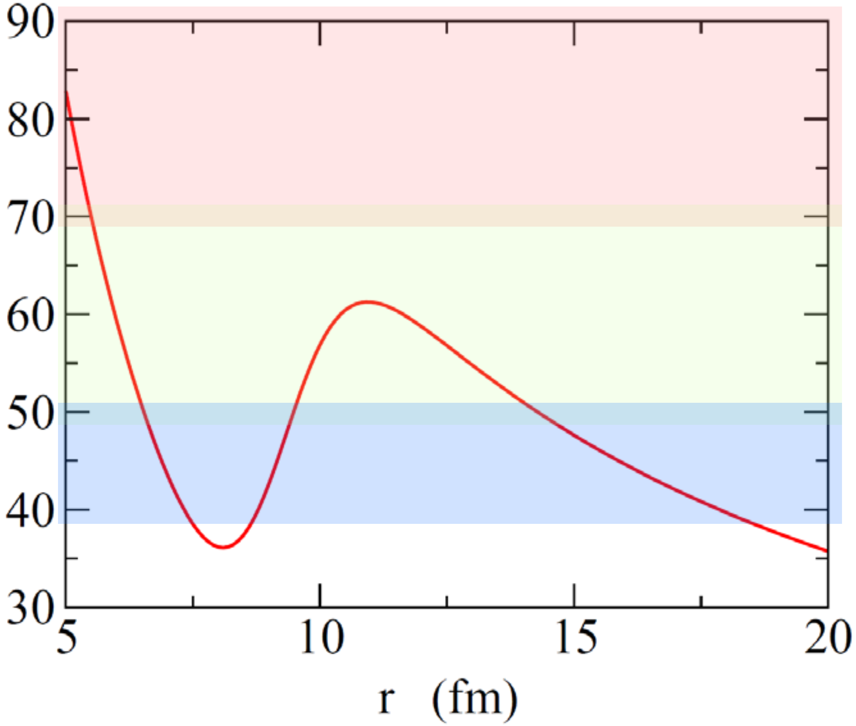


superheavy elements

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



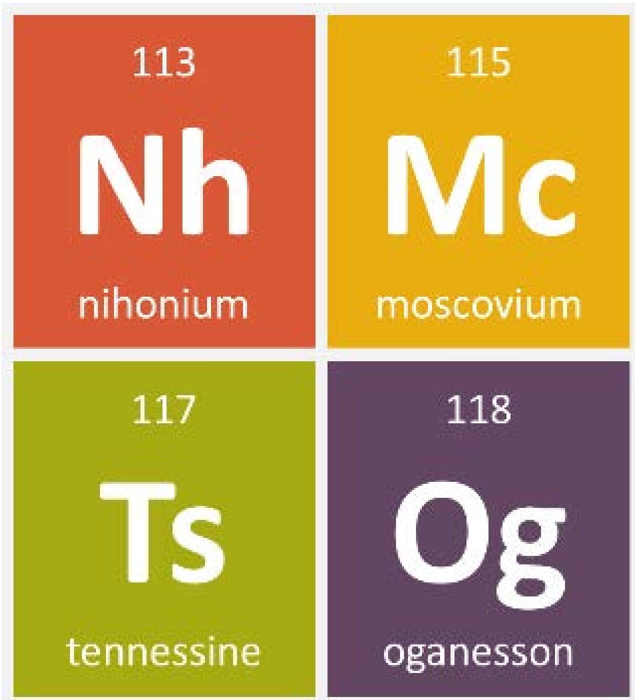
fusion reactions
in the sub-barrier energy region
$(|E - V_b| \lesssim 10\text{MeV})$

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

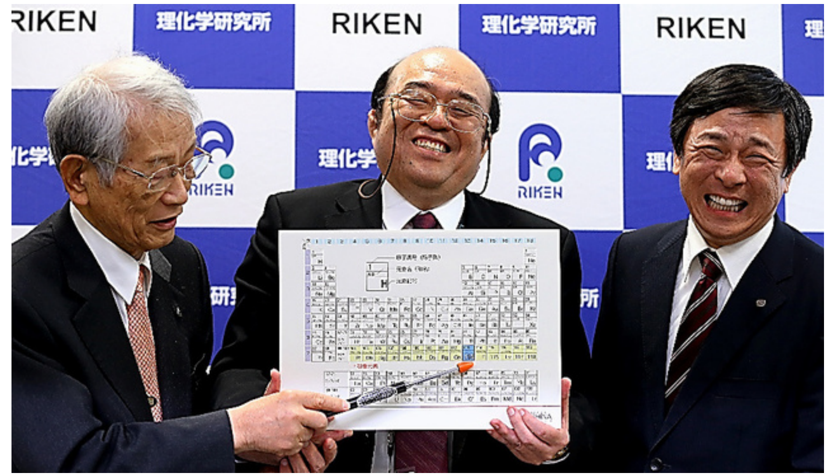
⇒ Coulomb barrier

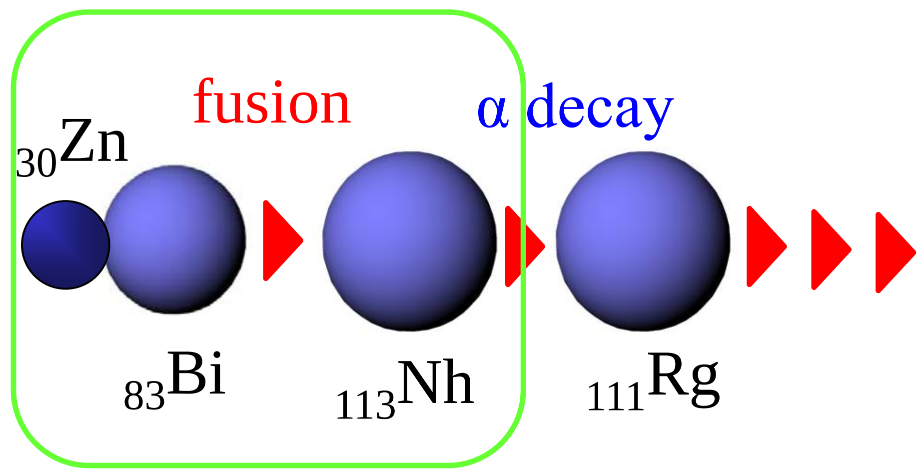
Why sub-barrier fusion?

two obvious reasons:



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?

two obvious reasons:

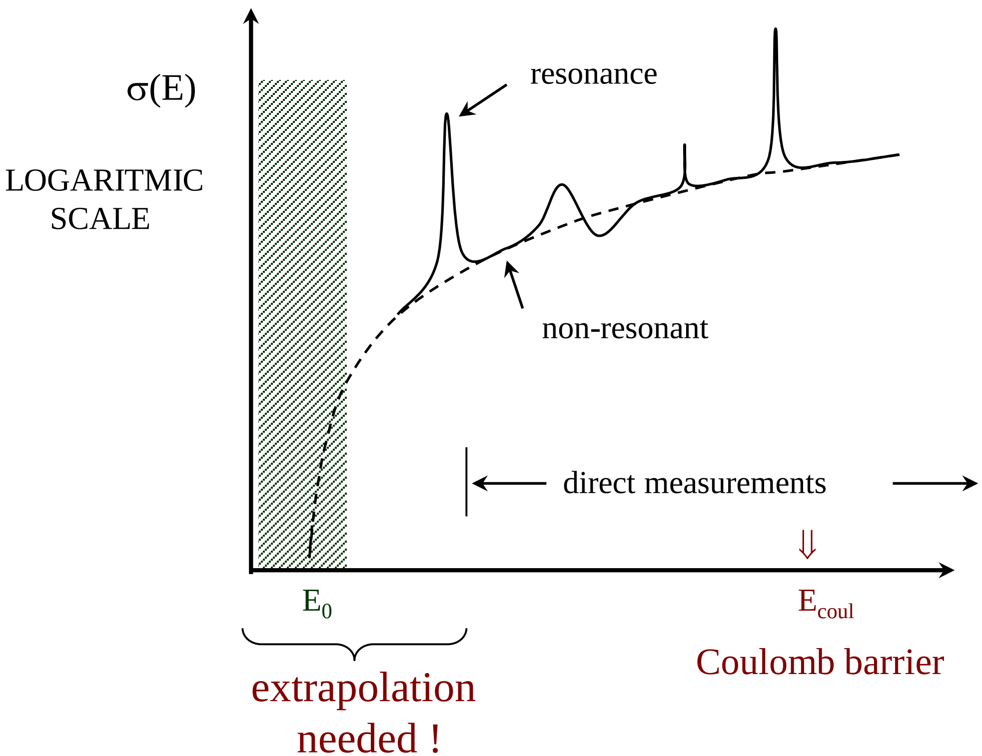
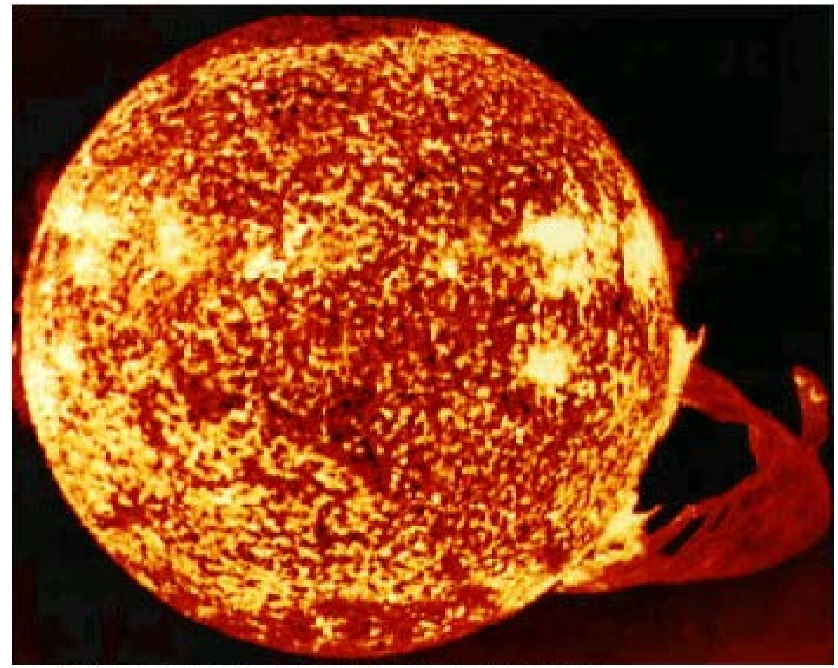


figure: M. Aliotta



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:

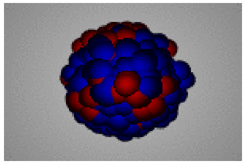
◆ reaction mechamism

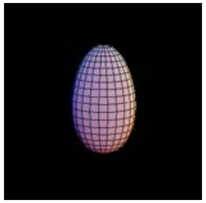
strong interplay between reaction and nuclear structure

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

◆ **many-particle tunneling**

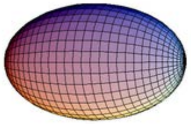
✓ many types of intrinsic degrees of freedom

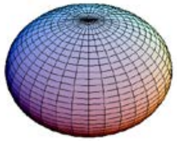




✓ energy dependence of tunneling probability

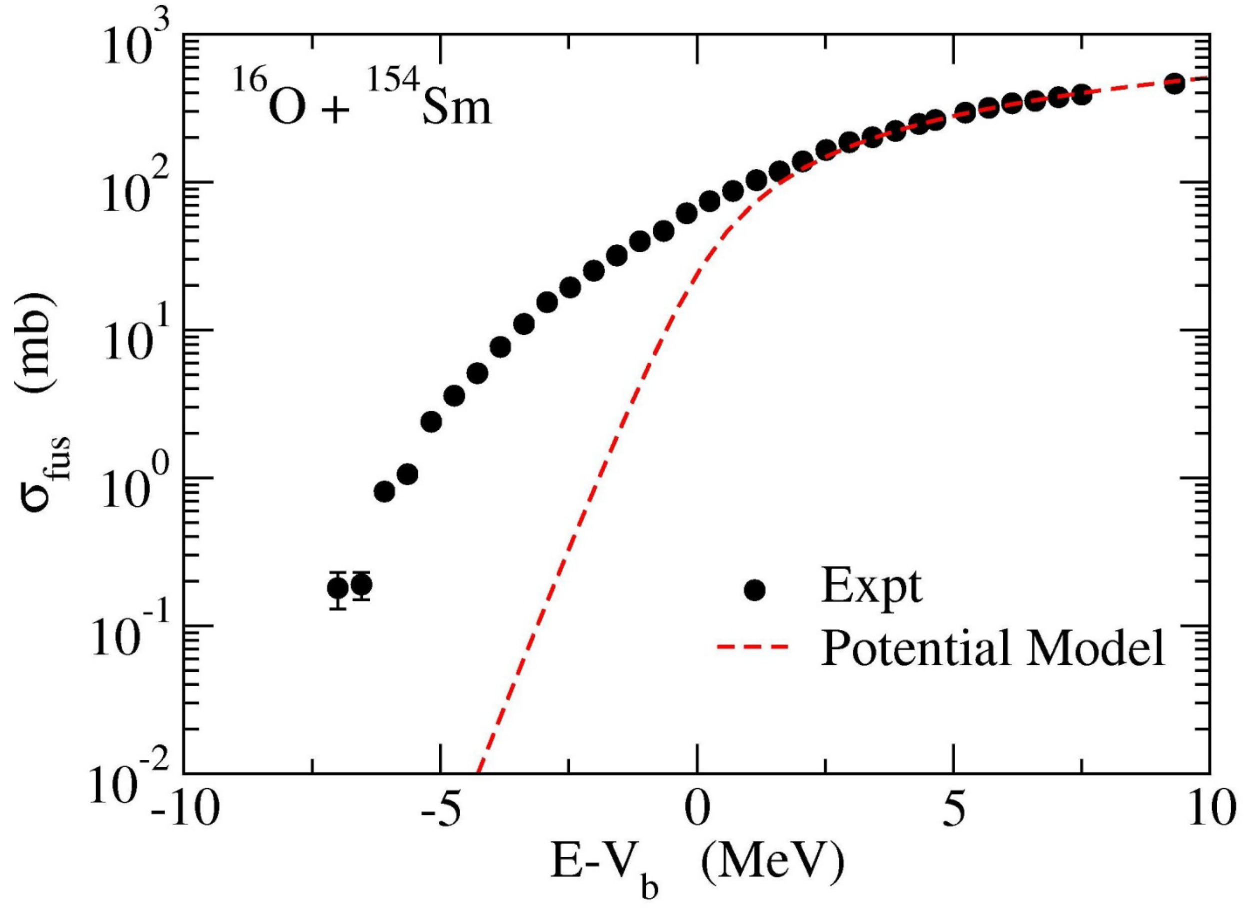
cf. alpha decay: fixed energy





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}

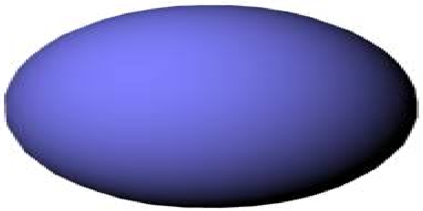


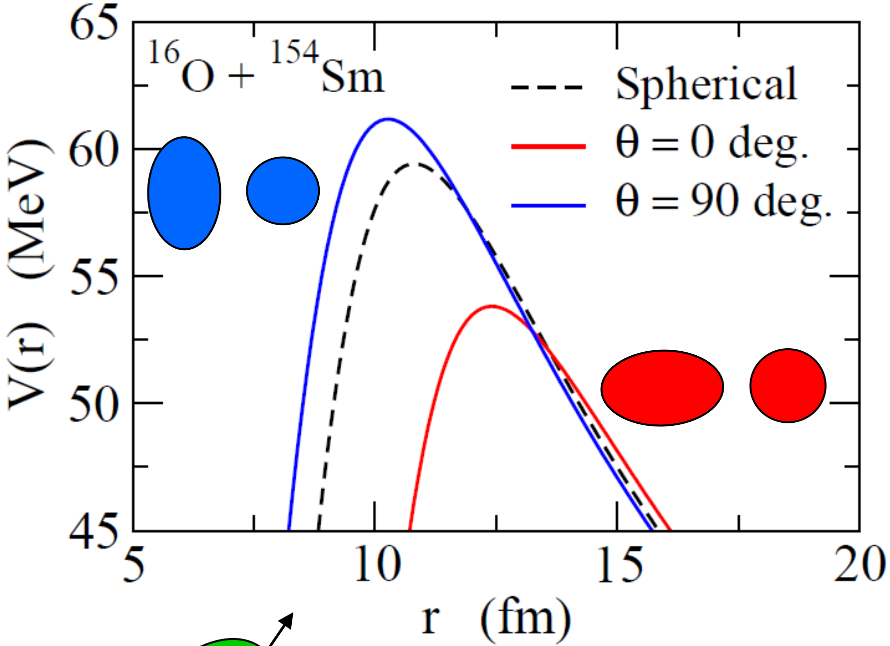
potential model: $V(r)$ + absorption

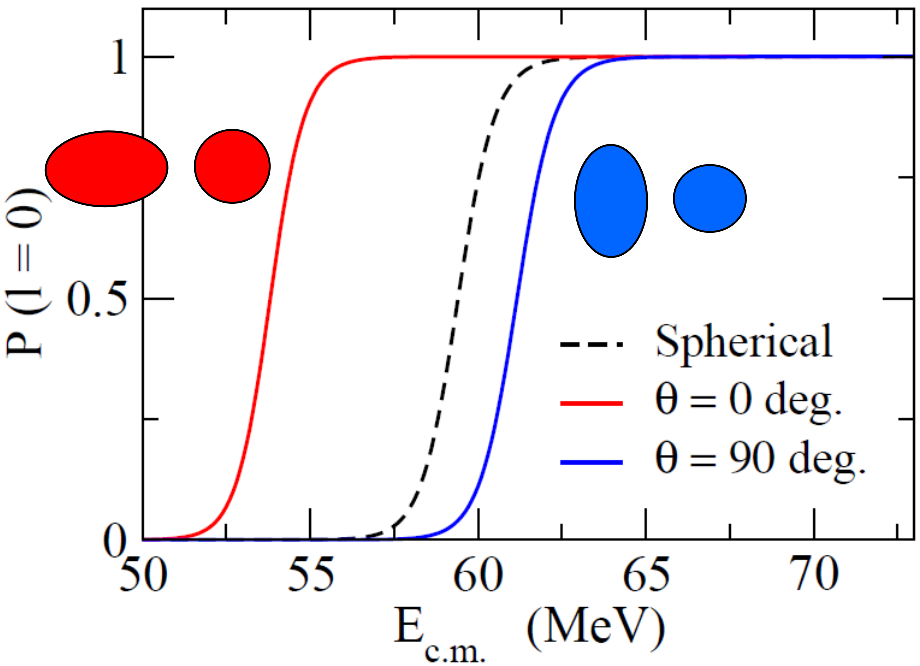
cf. seminal work:
R.G. Stokstad et al., PRL41('78) 465

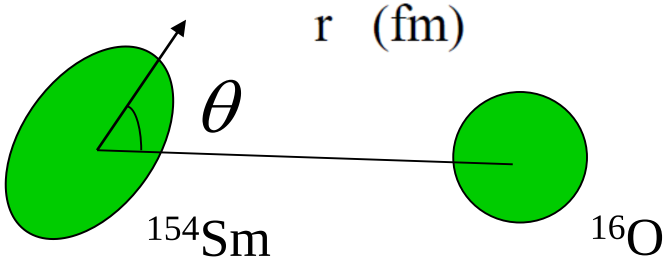
Effects of nuclear deformation

^{154}Sm : a typical deformed nucleus



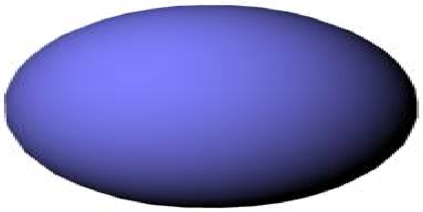




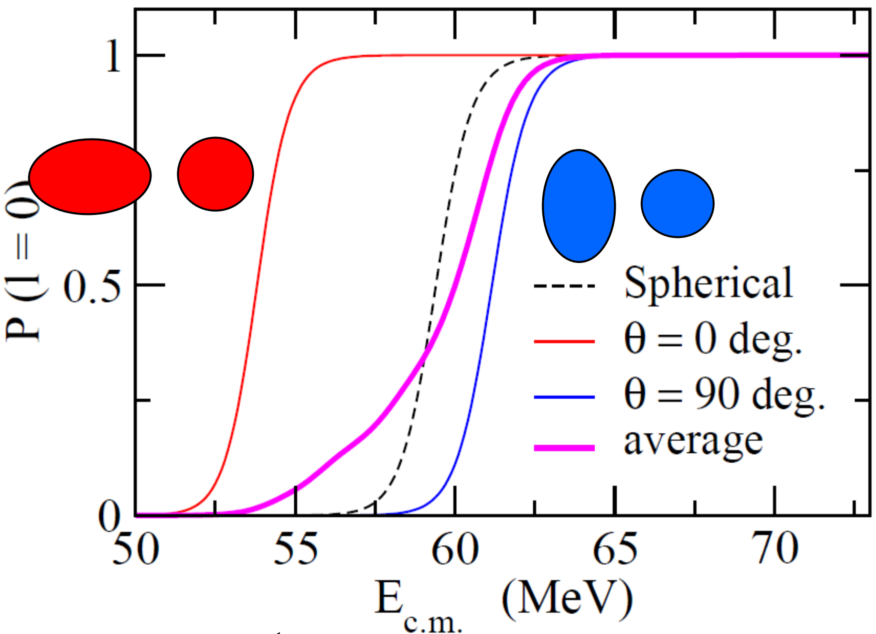


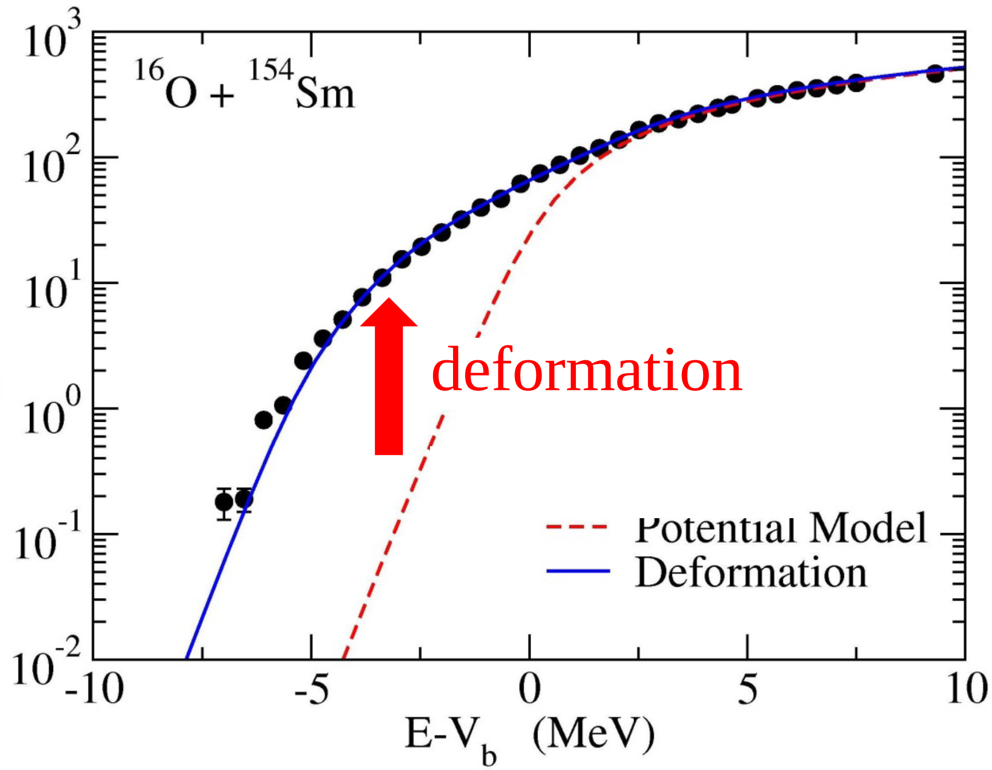
Effects of nuclear deformation

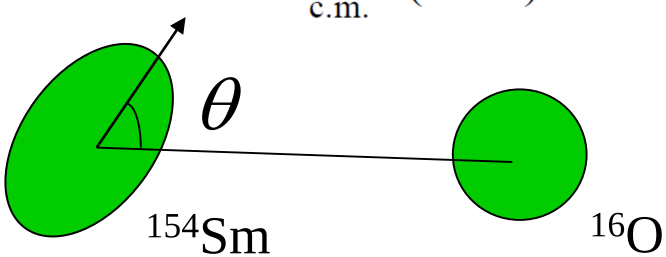
^{154}Sm : a typical deformed nucleus



^{154}Sm

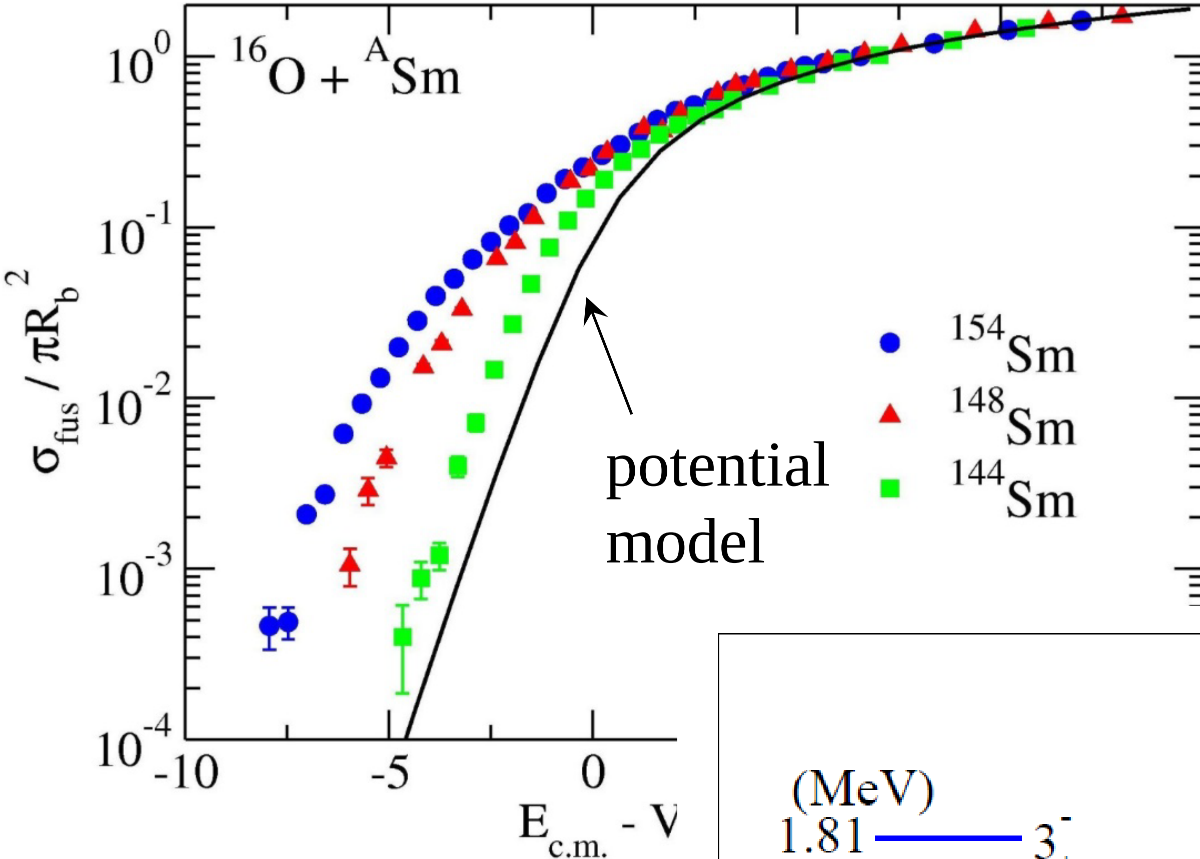




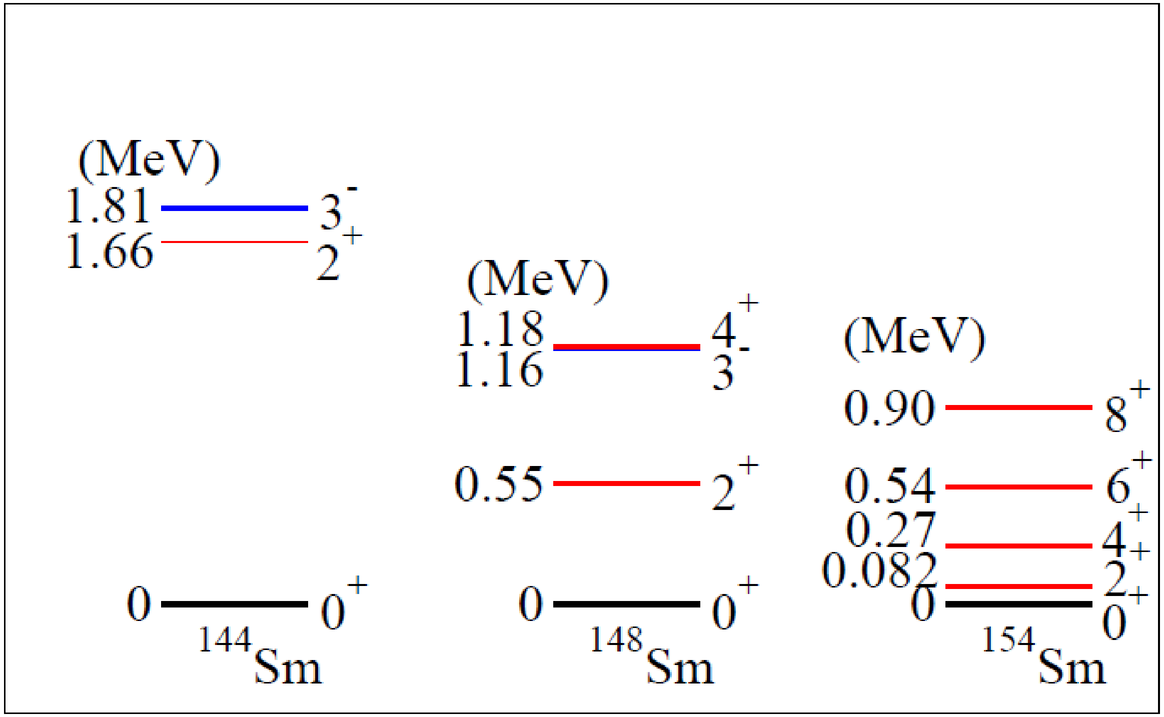


$$\sigma_{\mathrm{fus}}(E) = \int_0^1 d(\cos\theta)\sigma_{\mathrm{fus}}(E;\theta)$$

Fusion: strong interplay between nuclear structure and reaction



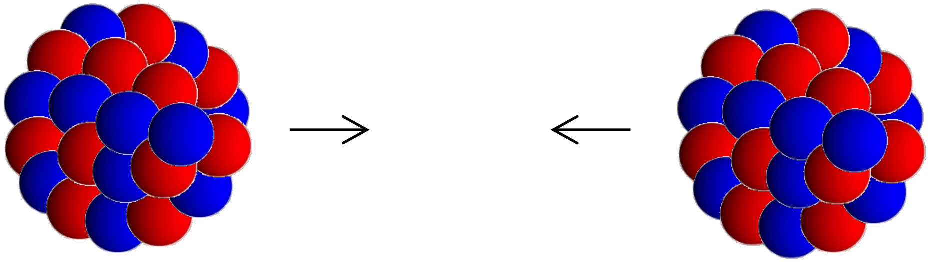
enhancement of fusion cross sections
: a general phenomenon



strong correlation with nuclear spectrum
→ coupling assisted tunneling

Coupled-channels method: a quantal scattering theory with excitations

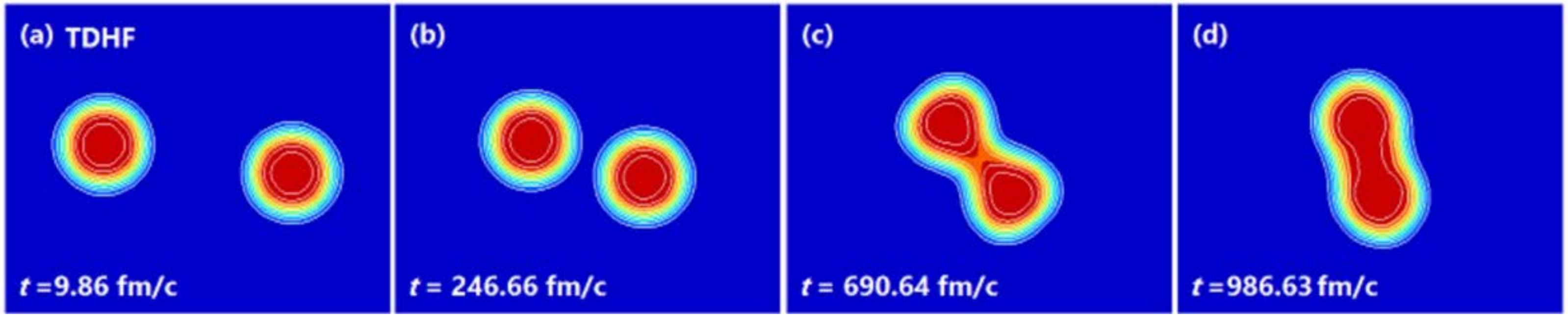
many-body problem



still very challenging

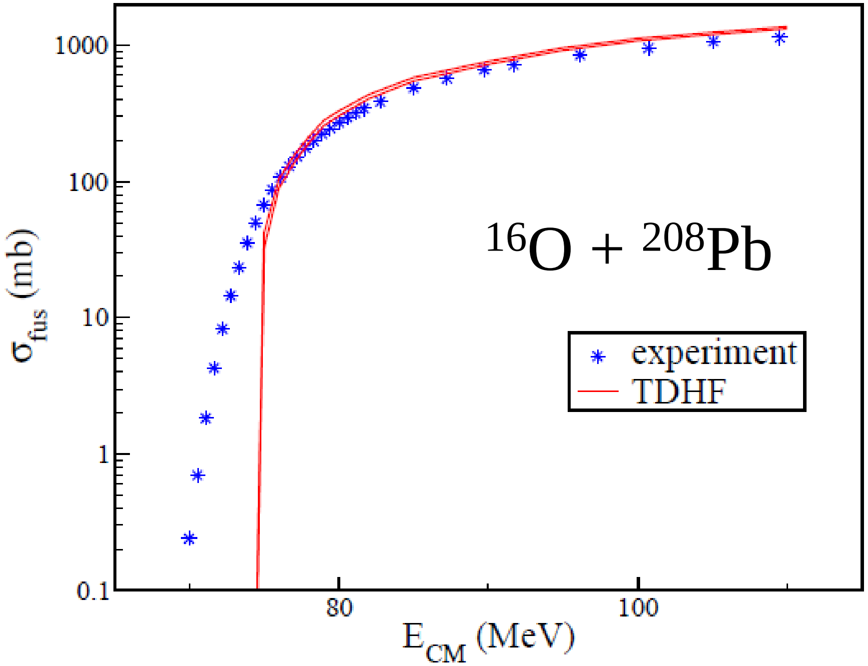
TDHF simulation

TDHF = Time Dependent Hartree-Fock



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

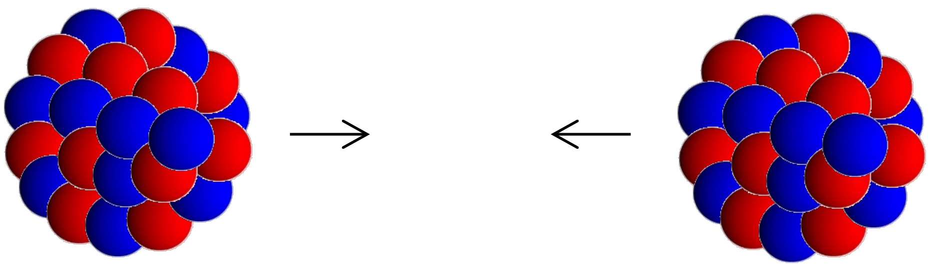
“ab-initio”, but no tunneling



C. Simenel,
EPJA48 (’12) 152

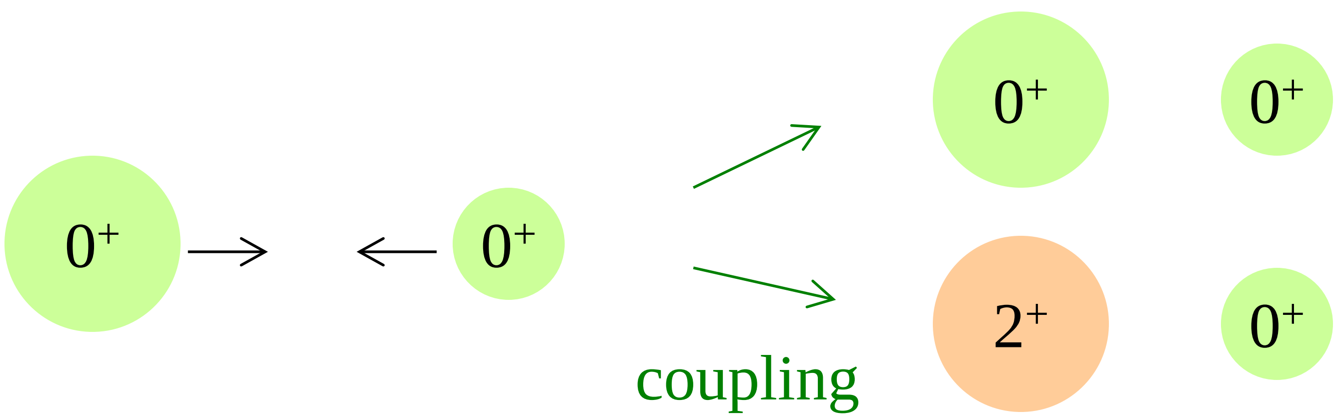
Coupled-channels method: a quantal scattering theory with excitations

many-body problem



still very challenging

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



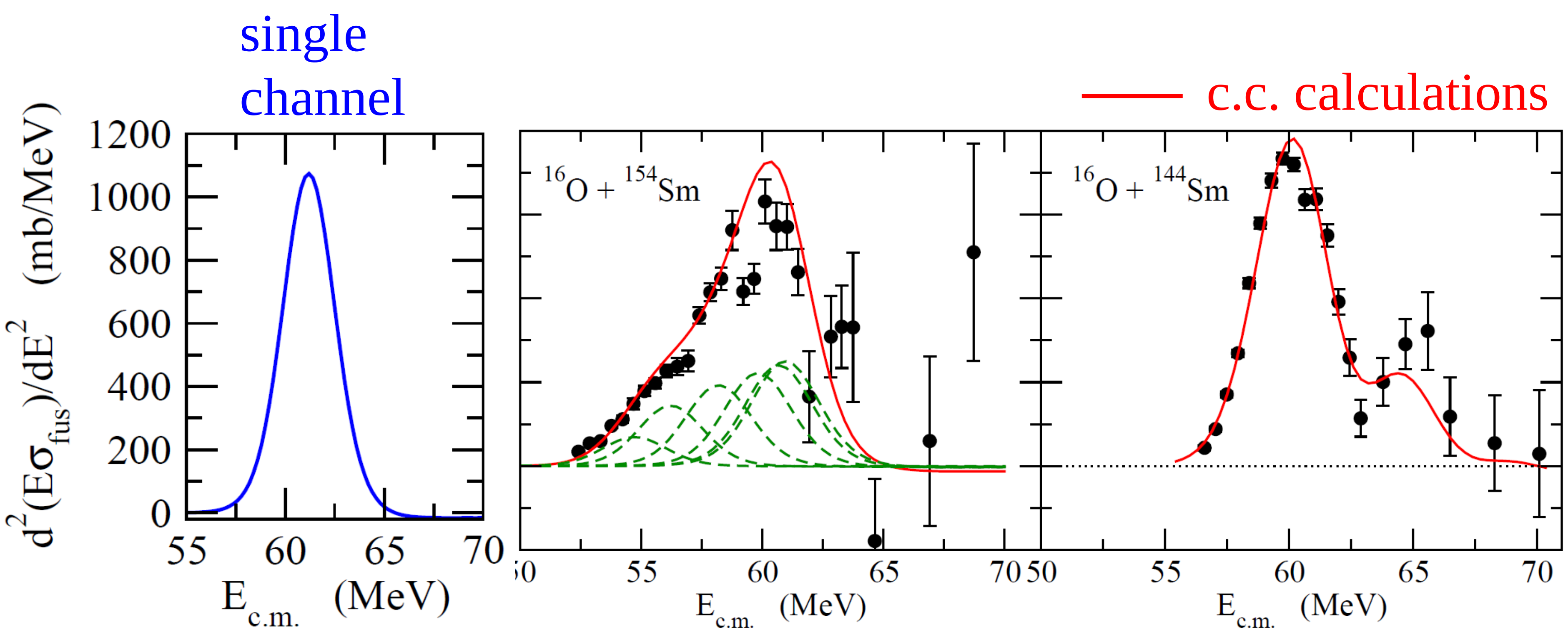
scattering theory with excitations

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)]

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



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

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

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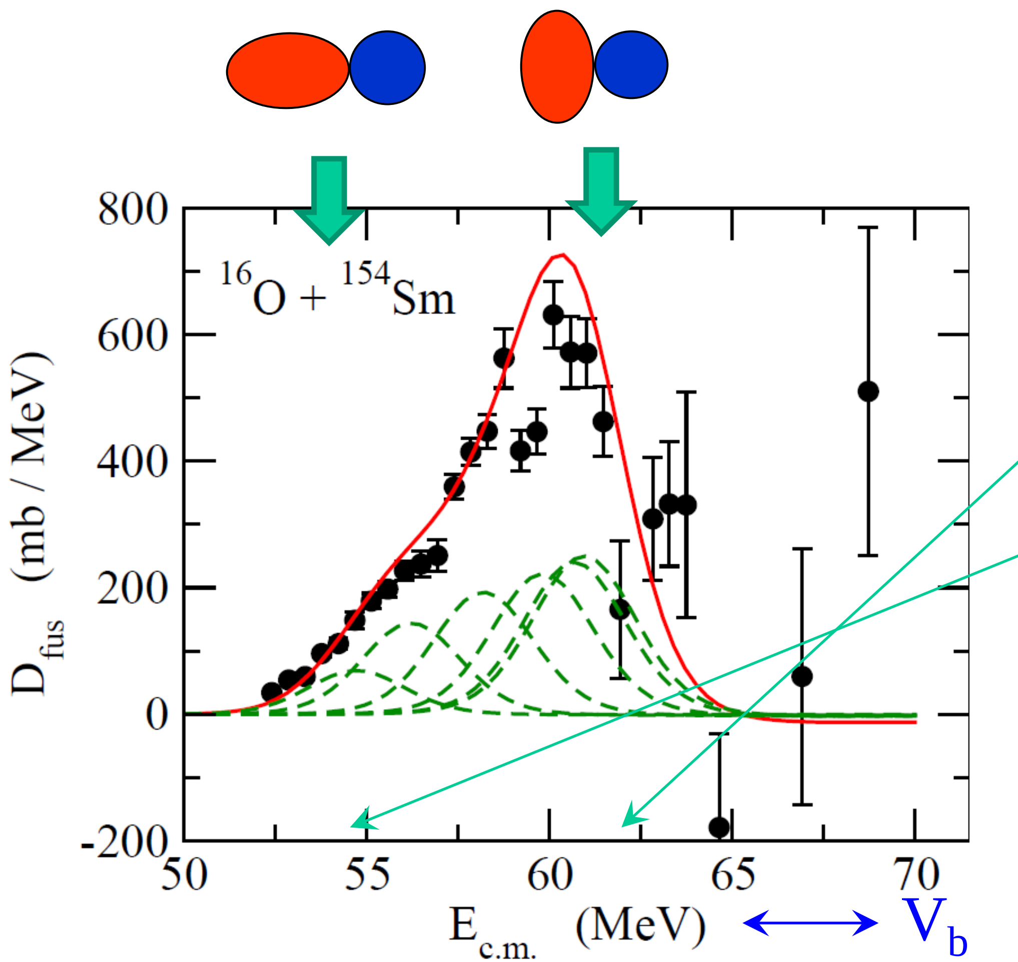
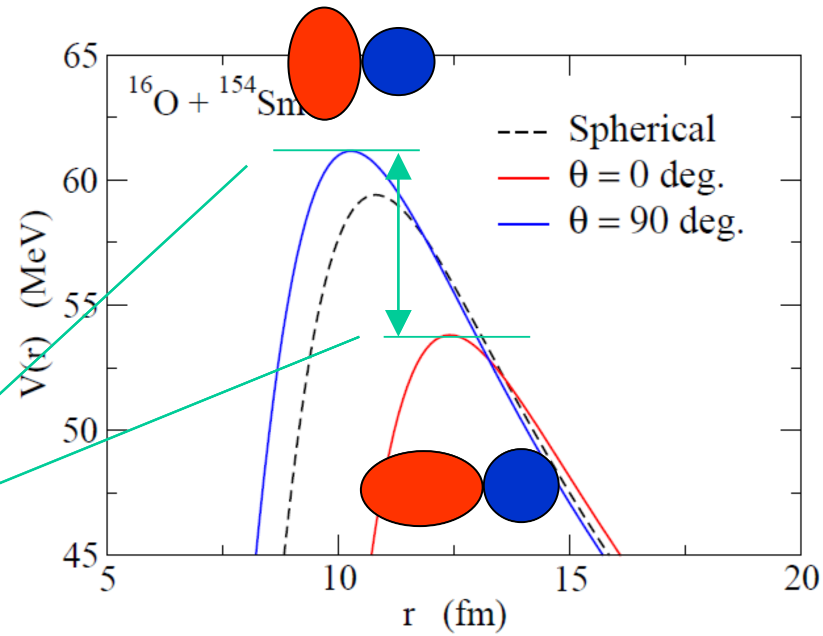




Data: J.R. Leigh et al.,
PRC52 (‘95) 3151

a nice tool to understand the reaction dynamics

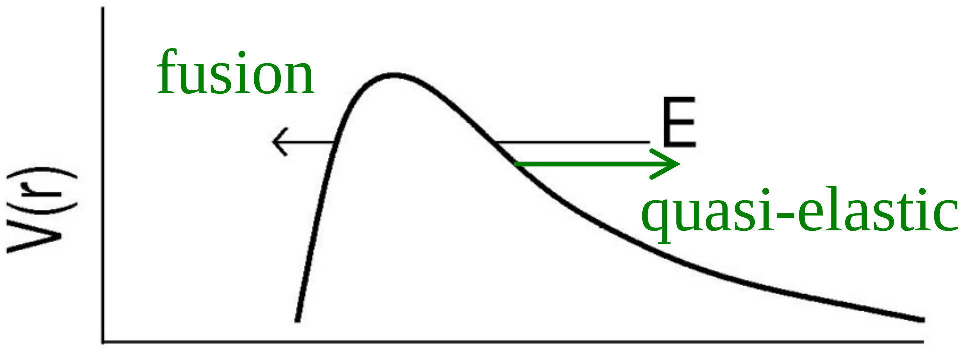
K.H., N. Takigawa, PTP128 (‘12) 1061

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

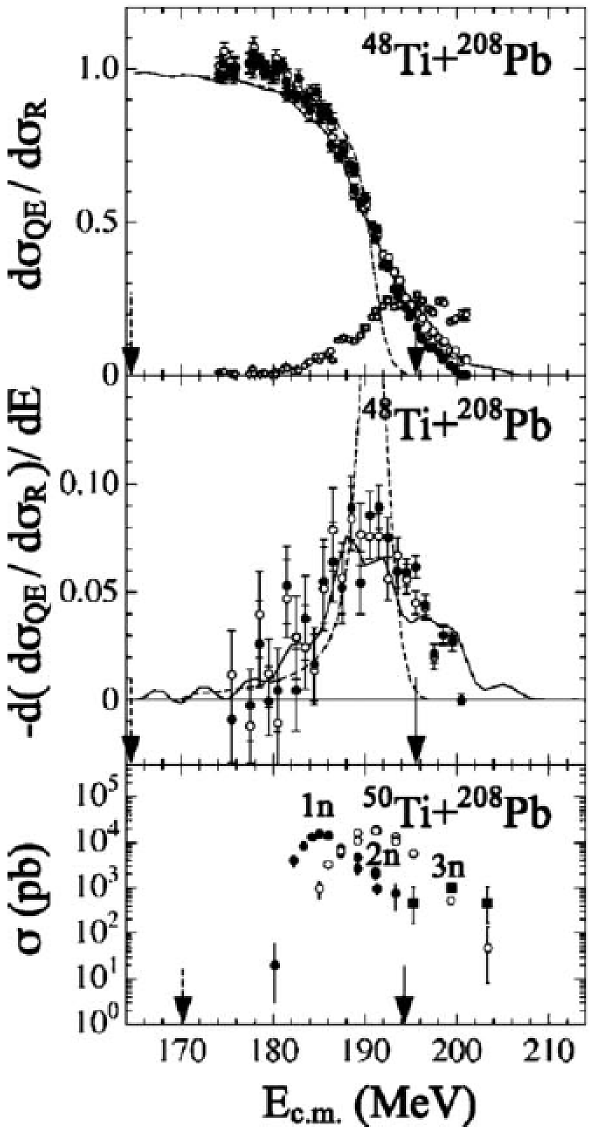
- a sum of elastic, inelastic, and transfer
- easier to measure than capture

Quasi-elastic barrier distribution

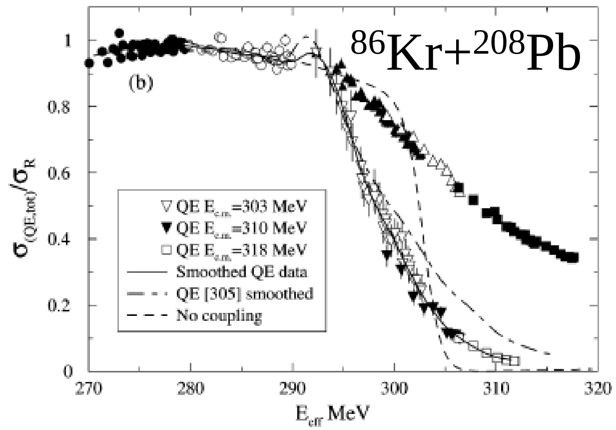
$$D_{\rm qel}(E) = -\frac{d}{dE}\left(\frac{\sigma_{\rm qel}(E,\pi)}{\sigma_R(E,\pi)}\right)$$

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

previous attempts

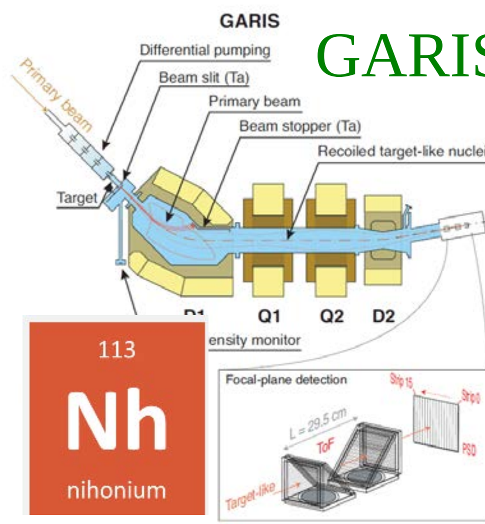


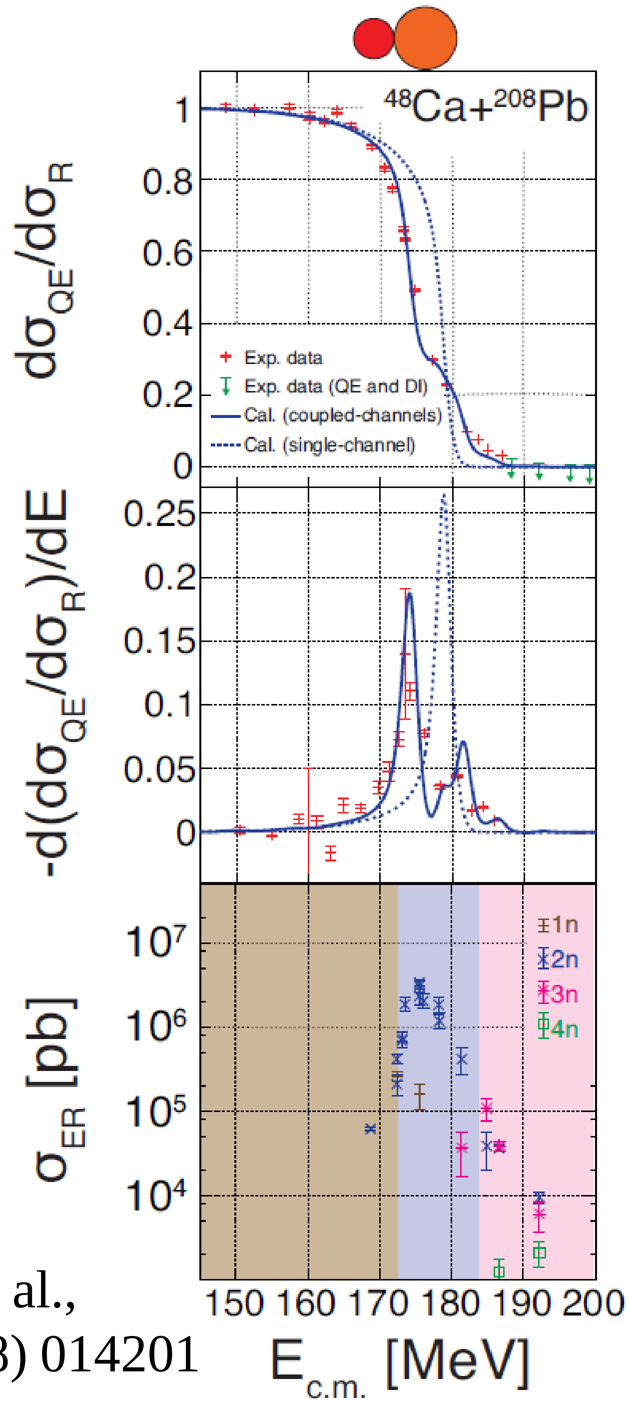
S. Mitsuoka et al.,
PRL99 ('07) 182701



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

GARIS





T. Tanaka et al.,
JPSJ 87 ('18) 014201

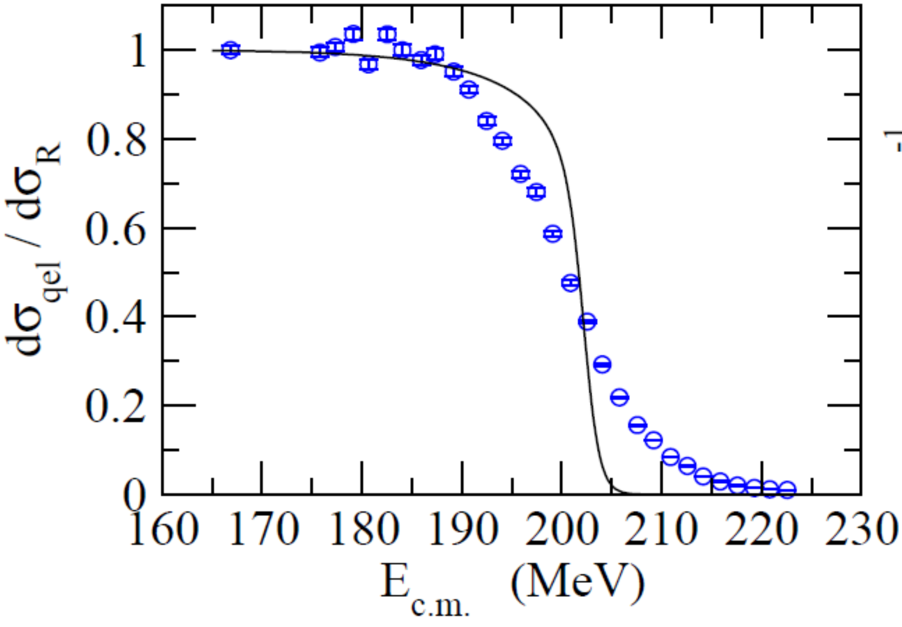
Analysis for a hot fusion reaction $^{48}Ca + ^{248}Cm$

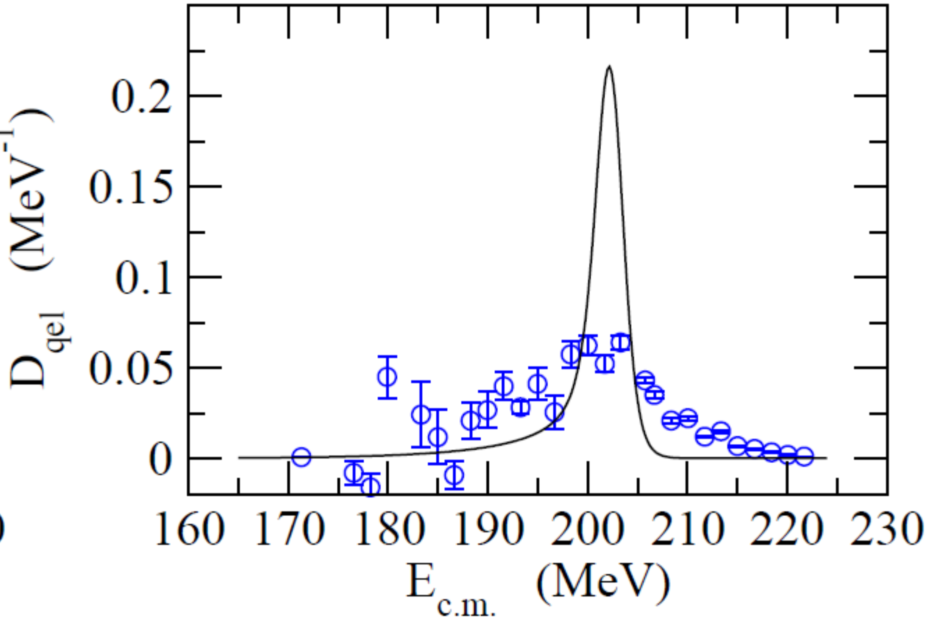
K.H. and T. Tanaka (2017)
(T. Tanaka et al., JPSJ 87 ('18) 014201)

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

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

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





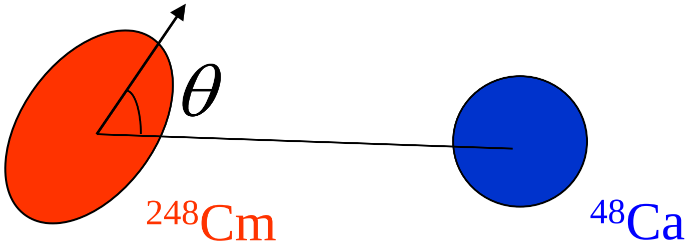
Analysis for a hot fusion reaction ^{48}Ca + ^{248}Cm

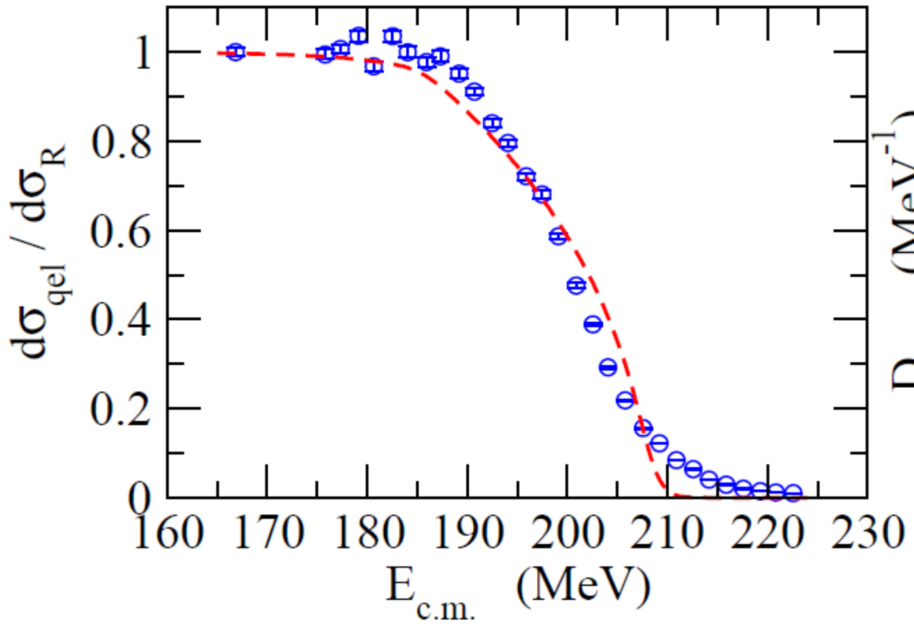
K.H. and T. Tanaka (2017)

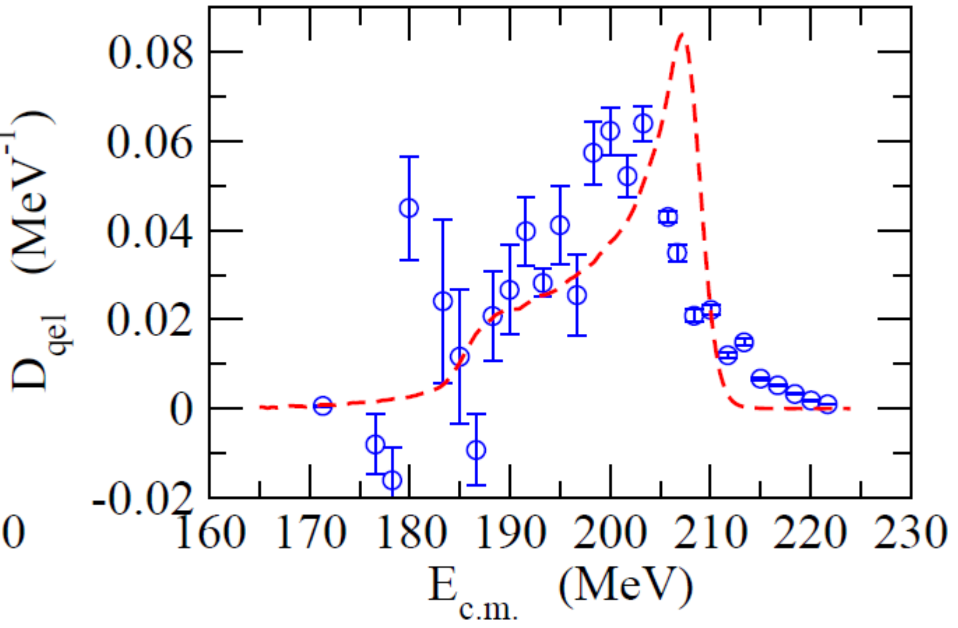
$^{48}\mathrm{Ca} + ^{248}\mathrm{Cm}\ (\beta_2 = 0.297,\ \beta_4 = 0.04) \rightarrow ^{296}_{116}\mathrm{Lv}^*$

[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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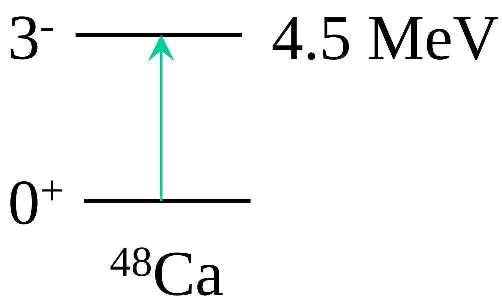
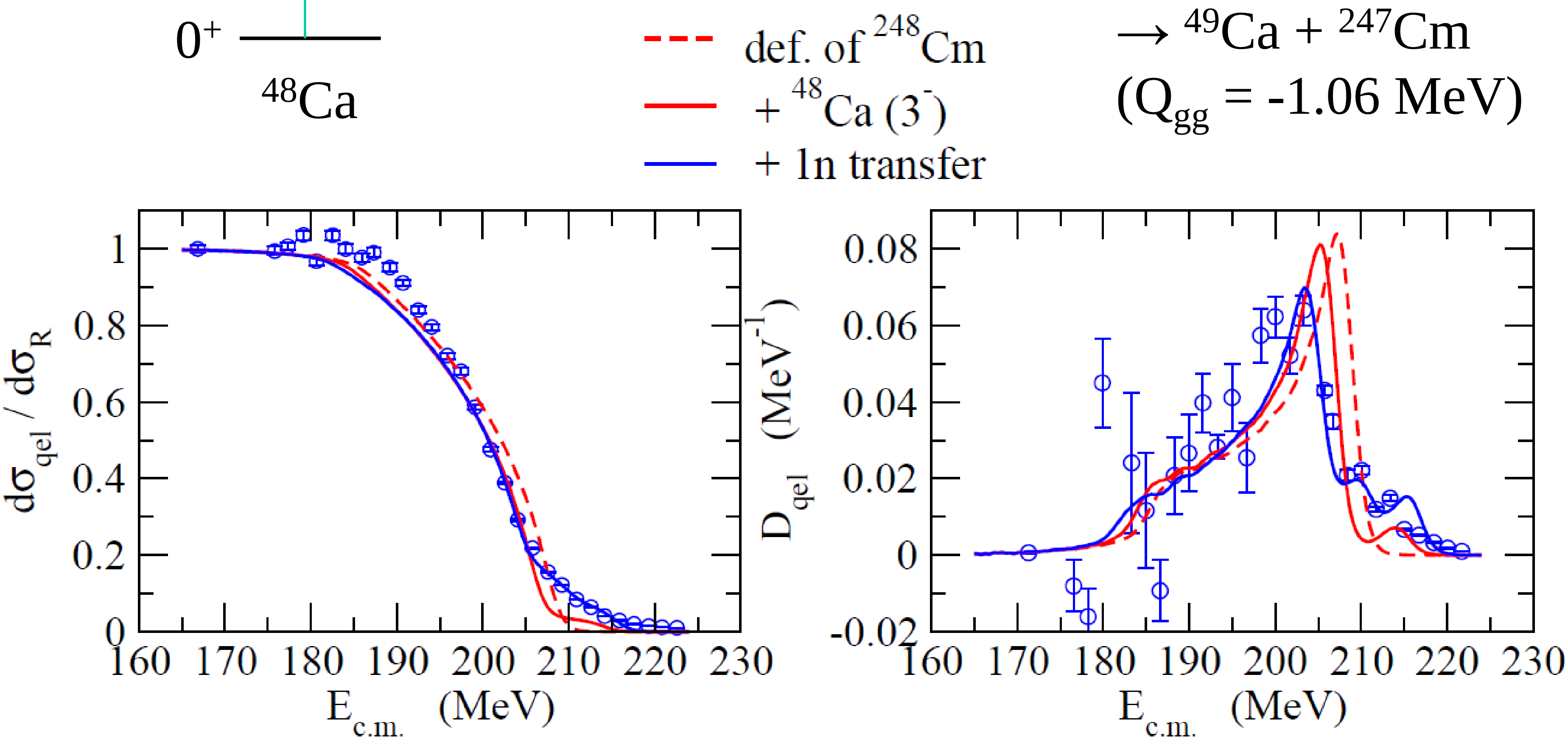


1n transfer

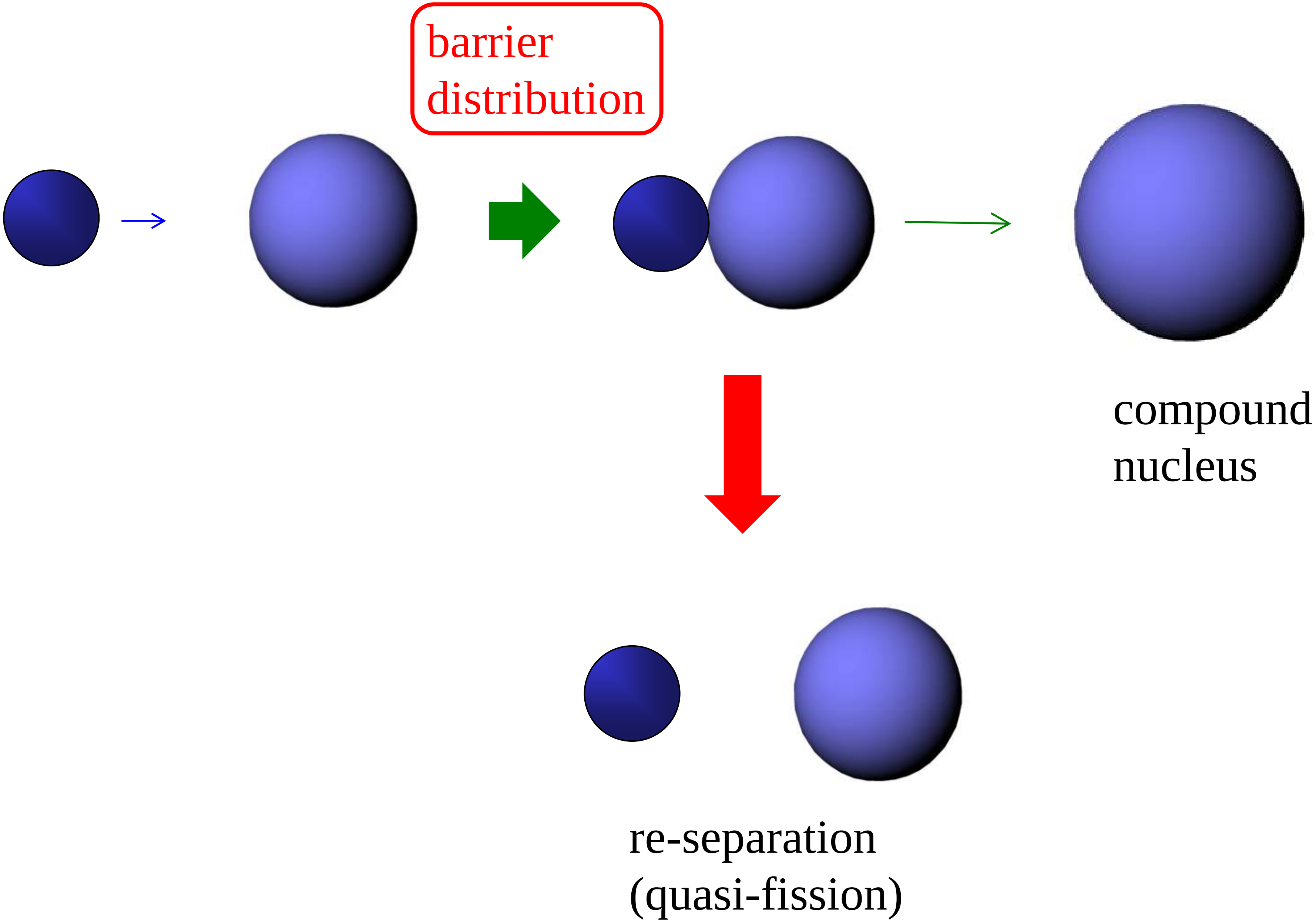
$^{48}Ca + ^{248}Cm$

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

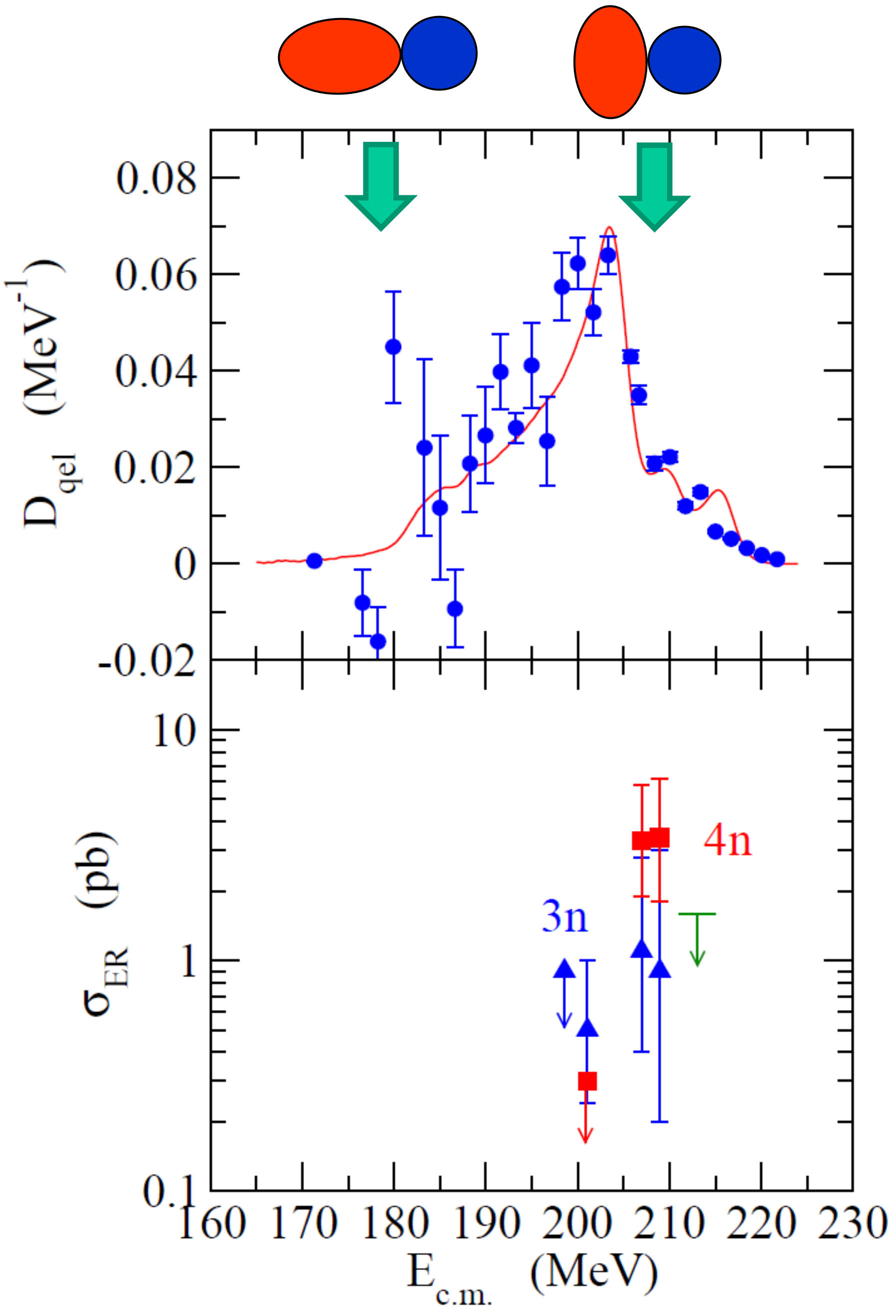
$(Q_{gg} = -1.06\ MeV)$



Connection to the ER cross sections

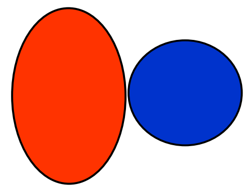


Connection to the ER cross sections



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

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



= more compact at the touching
→ favorable for CN

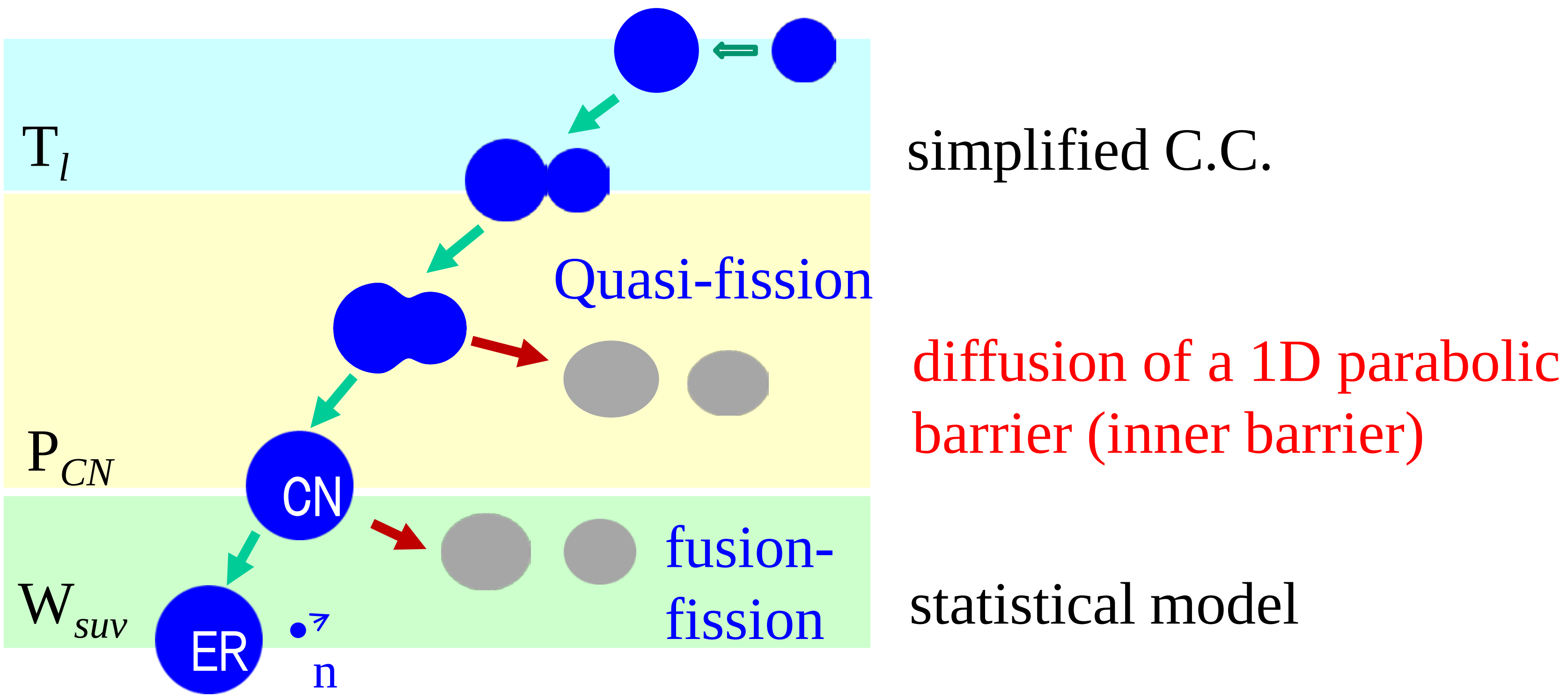
Extension of the fusion-by-diffusion model

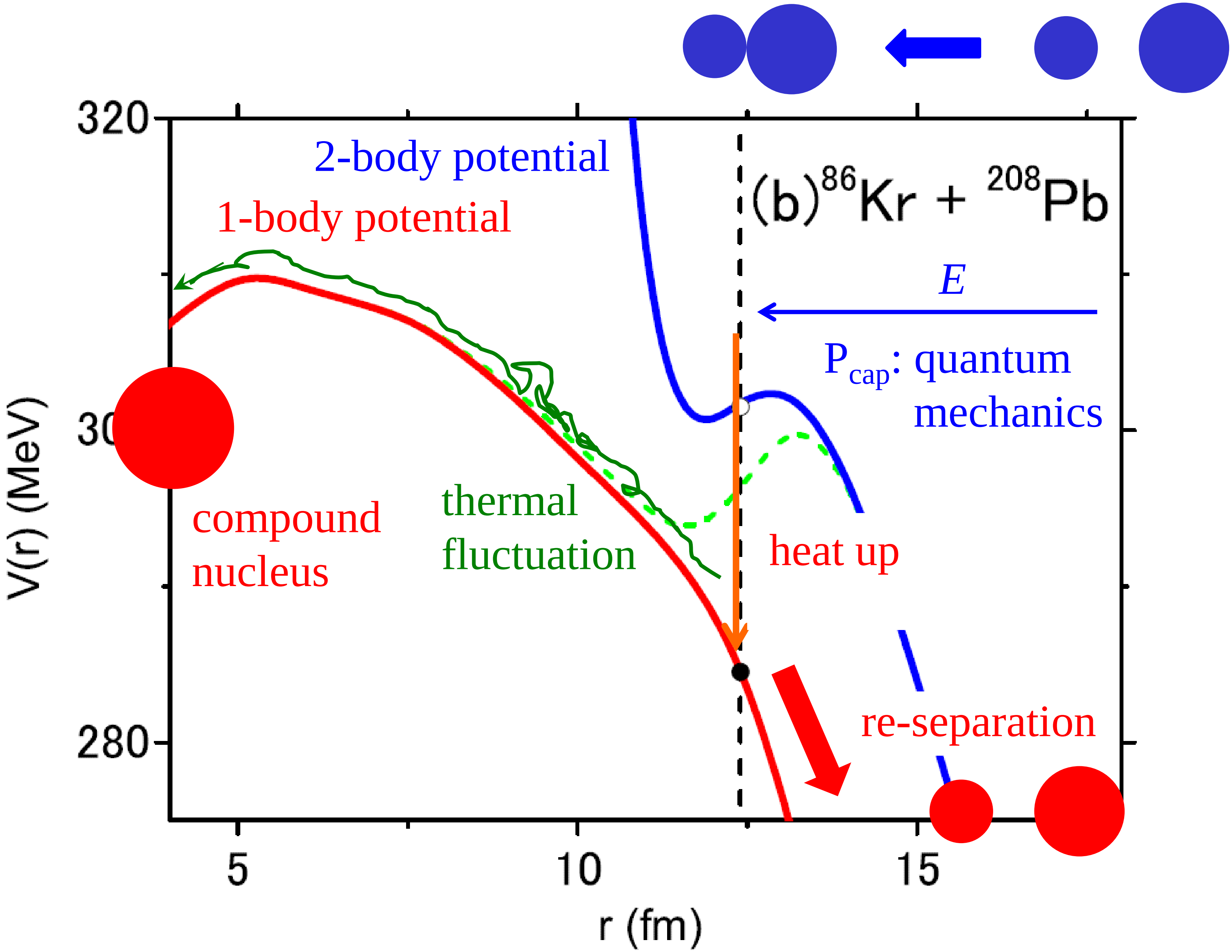
K.H., arXiv: 1803.02036

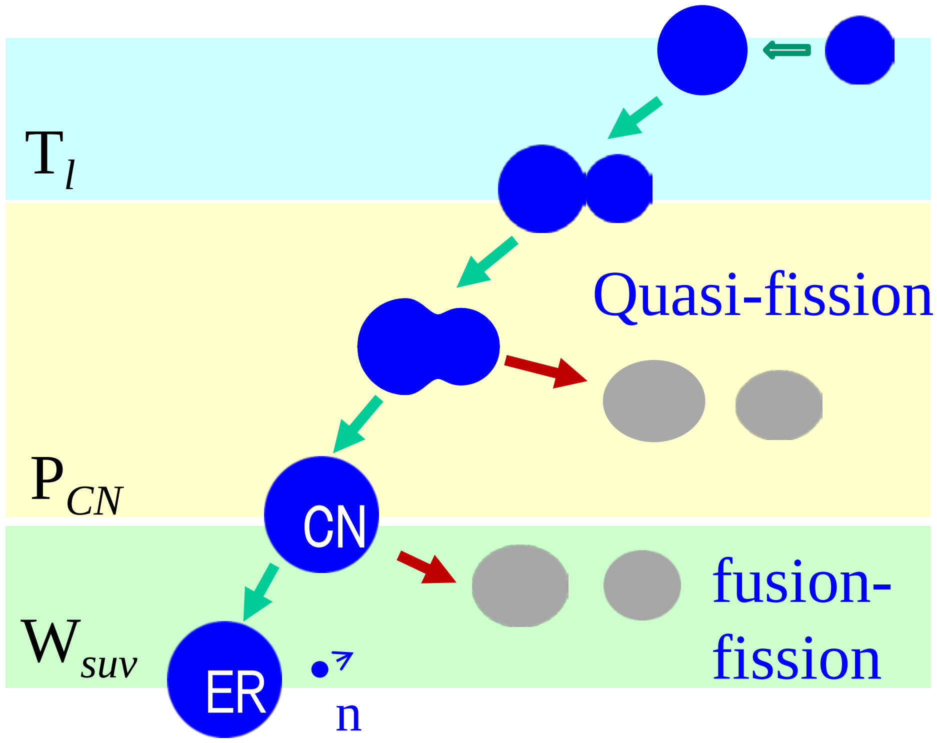
Fusion-by-diffusion model

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

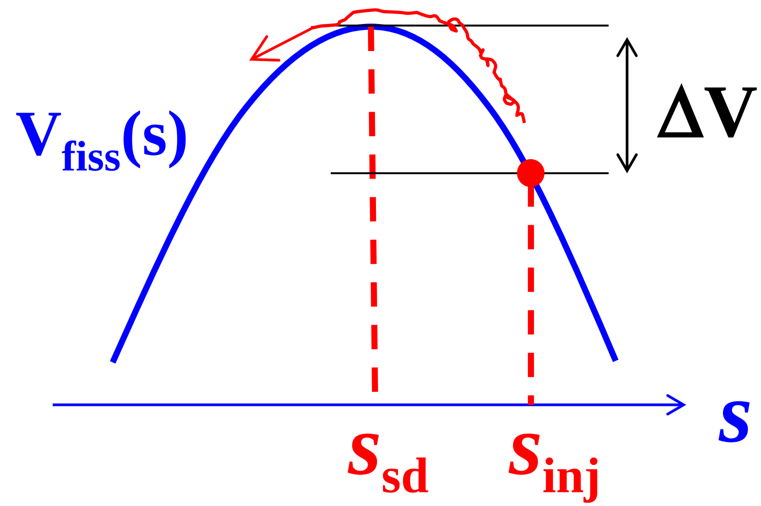
PRC71 (‘05) 014602




2-body potential
1-body potential
(b) $^{86}Kr + ^{208}Pb$
E
P_{cap}: quantum mechanics
compound nucleus
thermal fluctuation
heat up
re-separation
320
300
280
5
10
15
V(r) (MeV)
r (fm)

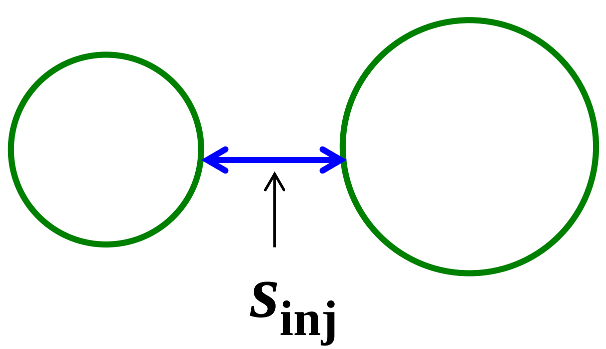


diffusion of a 1D parabolic barrier



Langevin in the overdamped limit:

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



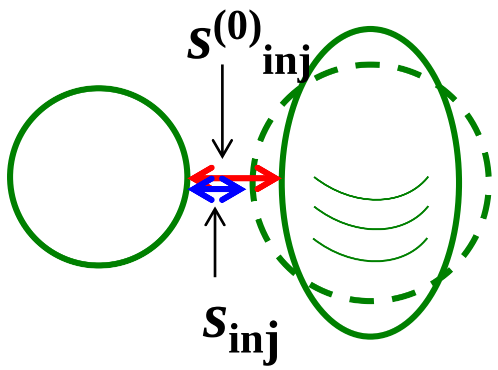
Extension of the fusion-by-diffusion model

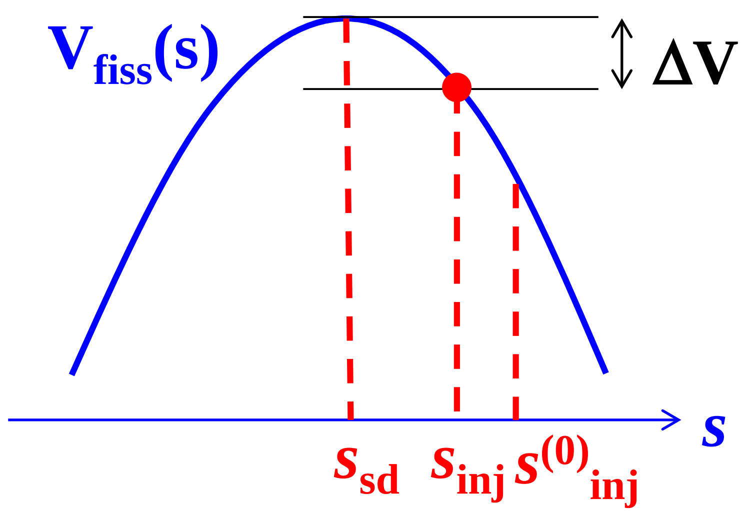
K.H., arXiv: 1803.02036

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

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

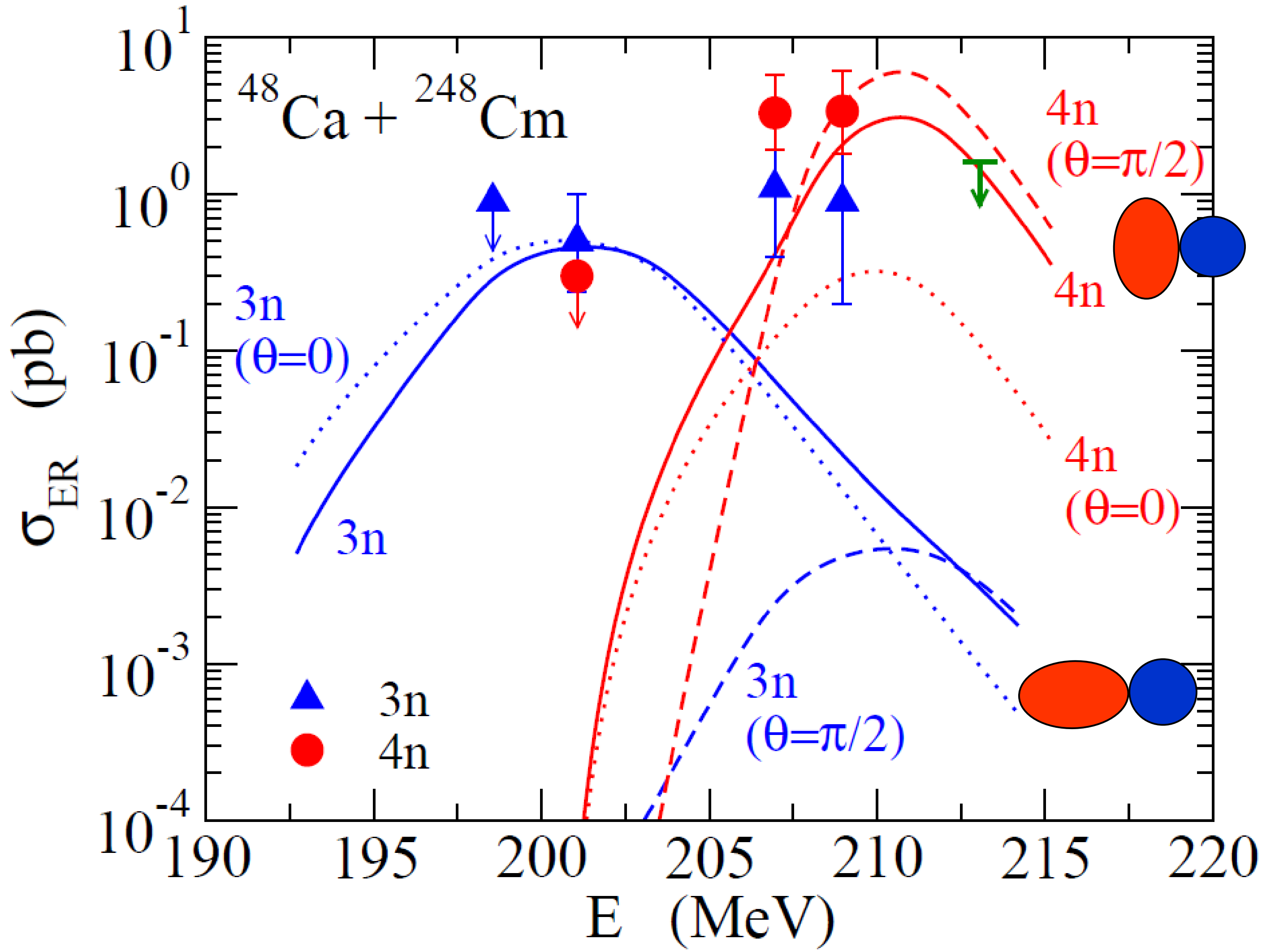
θ = π/2 (side collision)



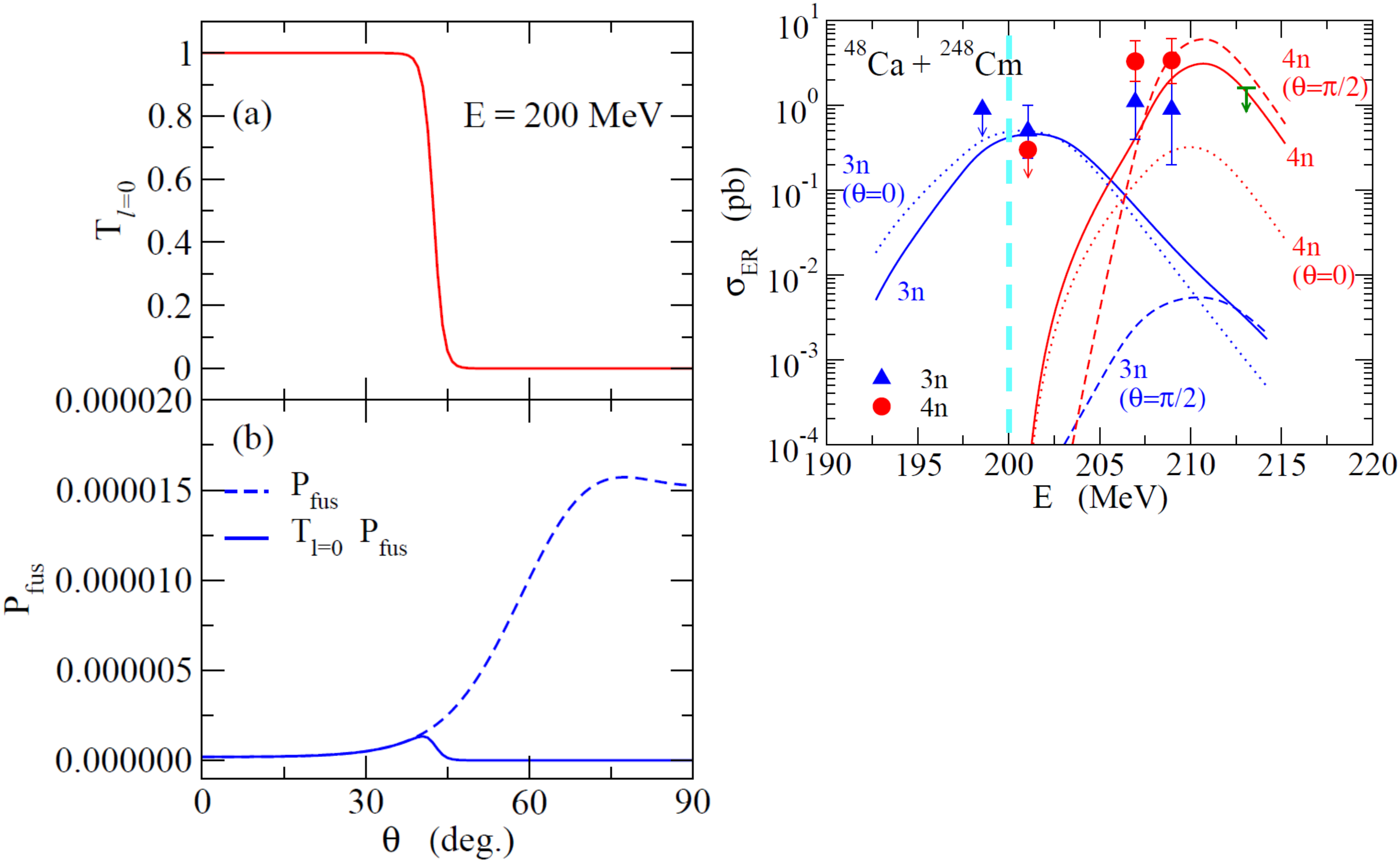


Extension of the fusion-by-diffusion model

K.H., arXiv: 1803.02036



$$\sigma_{\mathrm{ER}}(E) = \frac{\pi}{k^2} \sum_l (2l+1) \int_0^1 d\cos\theta \, T_l(E,\theta) P_{\mathrm{fus}}(E,l,\theta) W_{\mathrm{sur}}(E^*,l)$$



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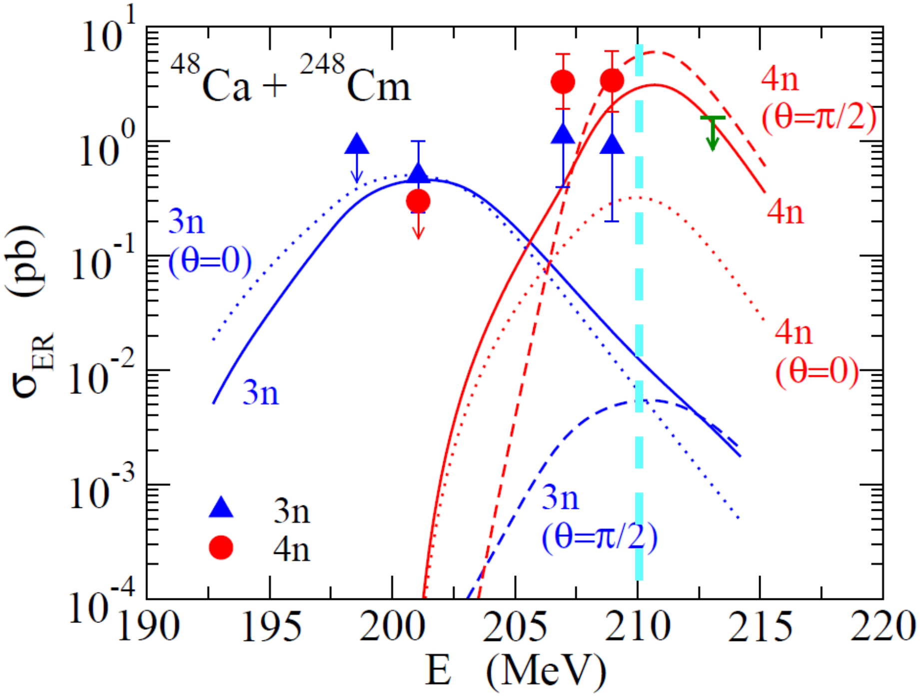
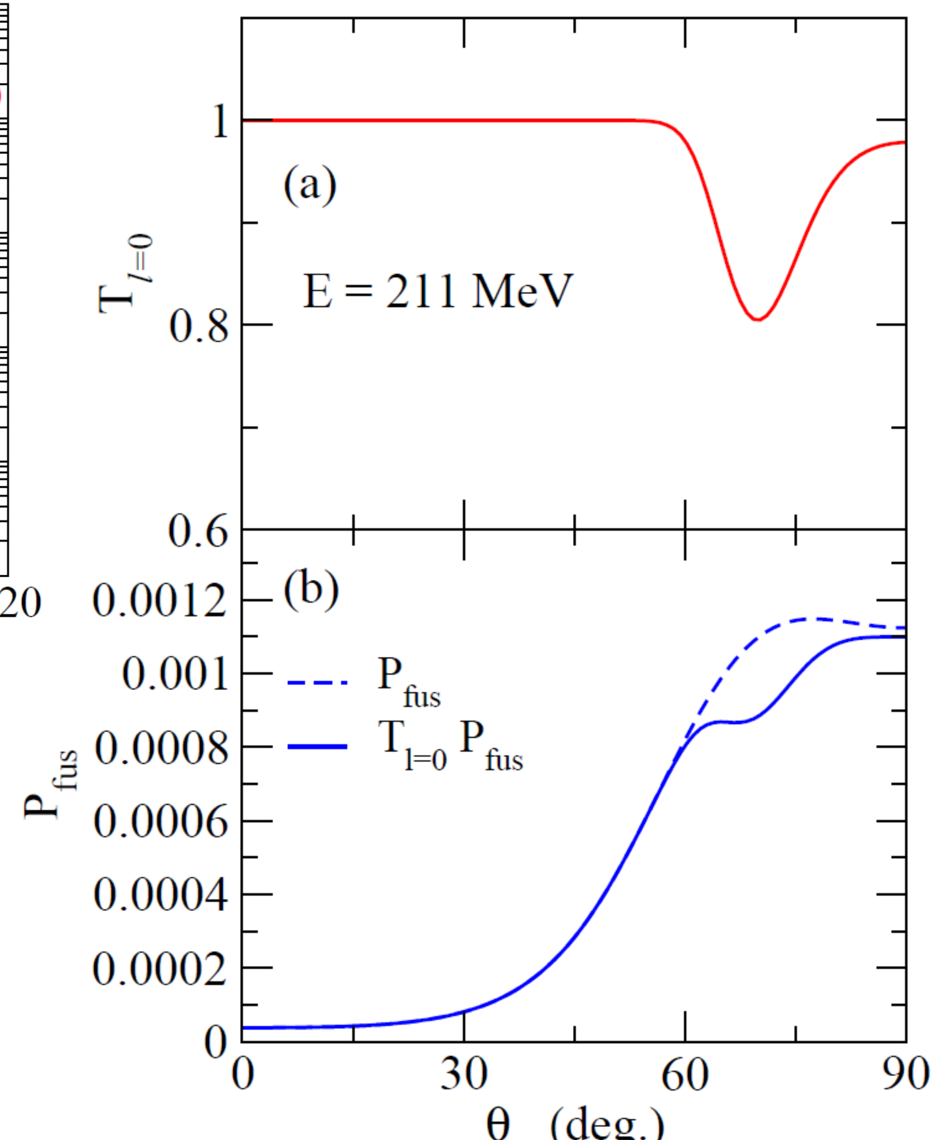


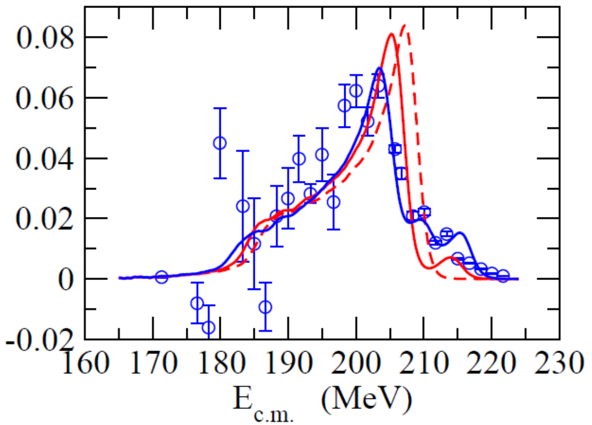


Summary and discussions

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

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

Quantum friction

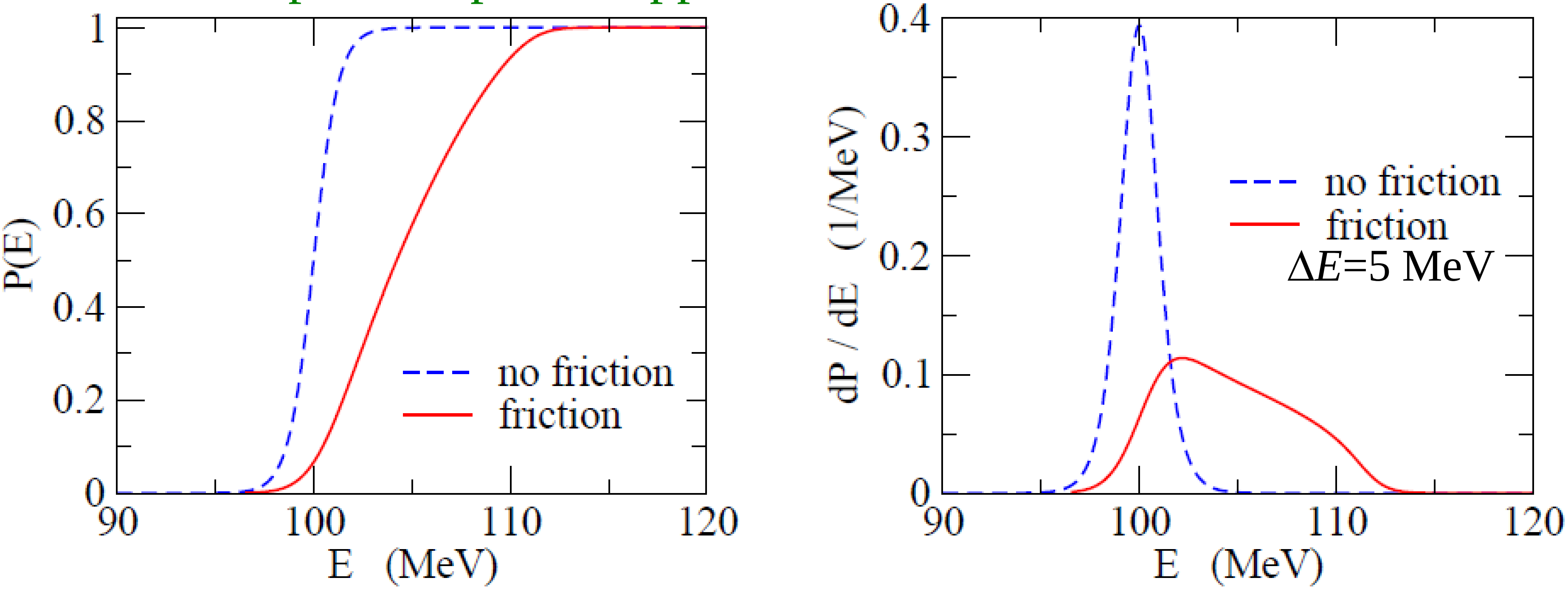
classical eq. of motion $\dot{p} = -V'(x) - \gamma p$

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

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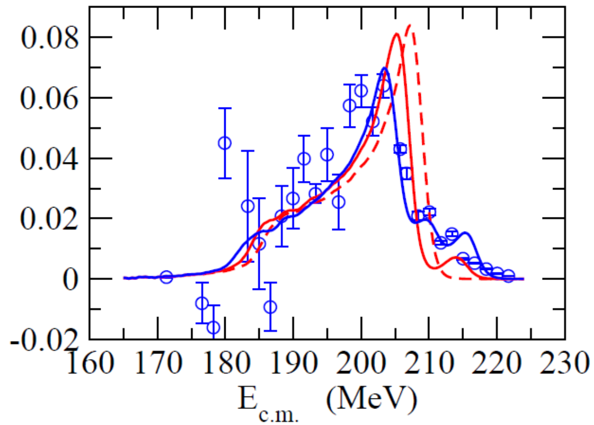


more data coming soon

➢ Open problems

✓ reaction dynamics?

quantum theory for friction

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

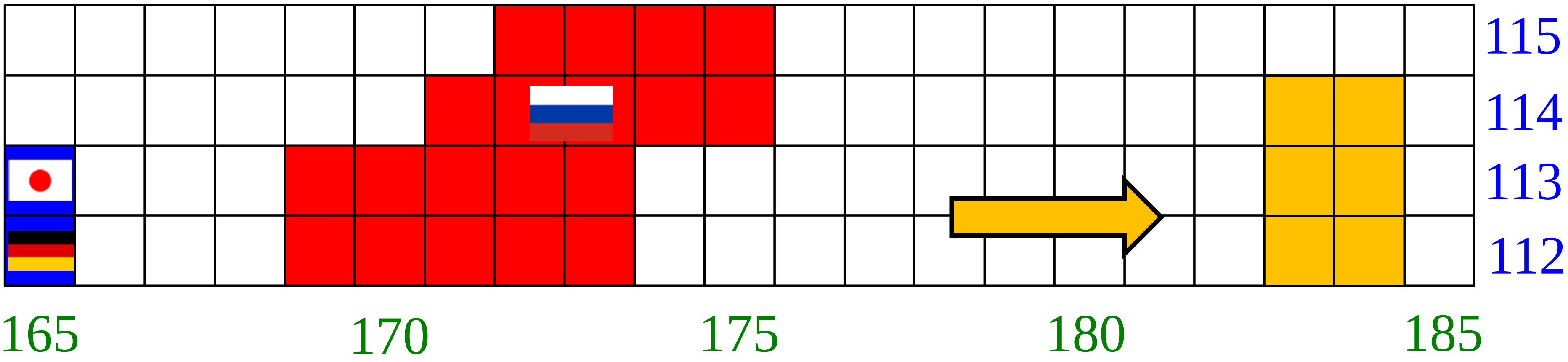
✓ shape evolution with a deformed target?

how does the deformation disappear during heat-up?

✓ towards island of stability

reaction dynamics with neutron-rich beams?

Towards the island of stability



neutron-rich beams: indispensable

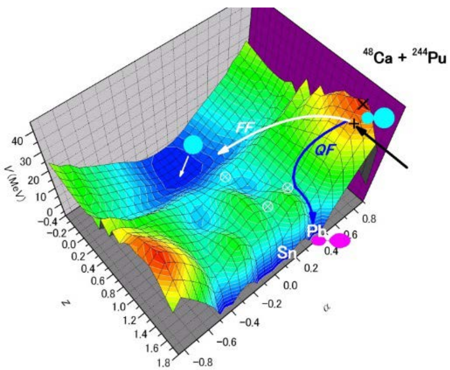
- ➢ how to deal with low beam intensity?
- ➢ reaction dynamics of neutron-rich beams?
  - ✓ capture: role of breakup and (multi-neutron) transfer?
  - ✓ diffusion: neutron emission during a shape evolution?
  - ✓ survival: validity of the statistical model?

structure of exotic nuclei

more studies are required

formation of SHE

reaction dynamics

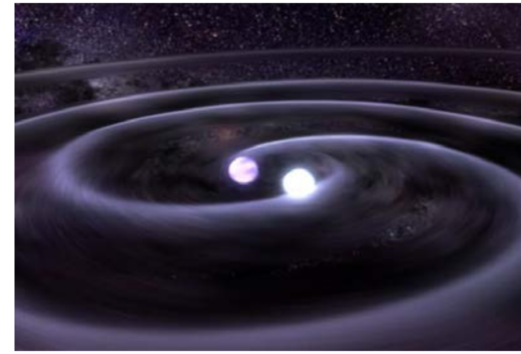


structure of SHE

chemistry of SHE

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	

the origin of (S)HE



Nuclear Physics
(RIBF/FRIB)
Astrophysics

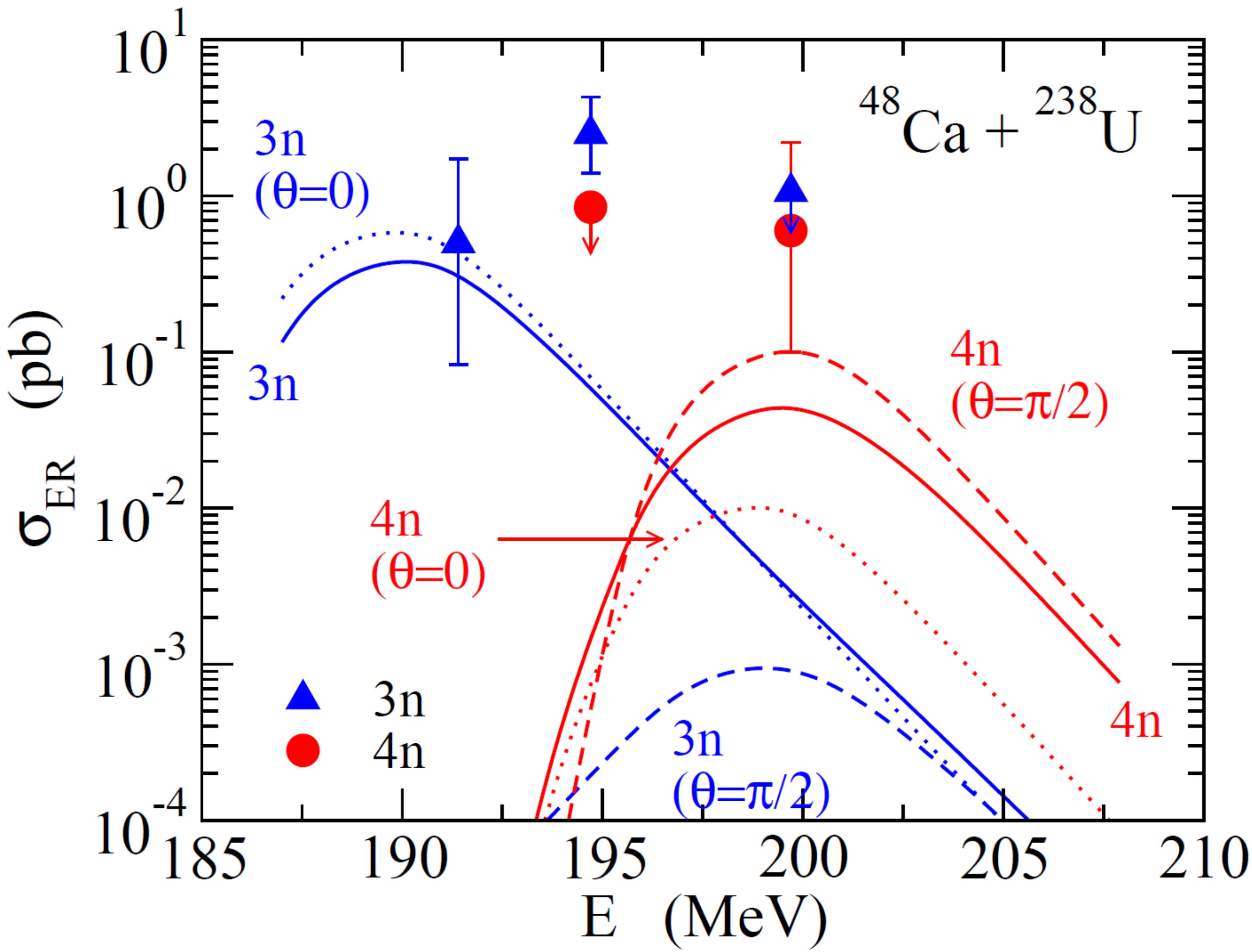
interdisciplinary SHE science

with physics, chemistry, and astronomy

FUSION20

November 16-20, 2020
Shizuoka, Japan

Kouichi Hagino (co-chair) Tohoku University
Katsuhisa Nishio (co-chair) JAEA



^{48}Ca + ^{238}U
3n
(θ=0)
3n
4n
(θ=π/2)
4n
(θ=0)
4n
3n
(θ=π/2)
3n
4n
σ_{ER} (pb)
E (MeV)