Heavy-ion fusion reactions: quantum tunneling with many degrees of freedom and superheavy elements

Kouichi Hagino
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Tsunenaga Hasekura

Sendai
→ Roma
(1613-1615)

Newe Zeyttung/auß der Inſel Japonien.

Retract vnd Contrafähung der vier Jüngling vnd Königklichen Geſandten auß Japon/wie
ſie zu Mayland den 25. Julij ankommen/vnd den 3. Auguſti von dannen wider verruckt.

CONtrafähung der vier Jüngling vnd Geſandten auß Japon/mit namen Mancius/Julianus/Martinus/vnd Michael/ſo den 23. Martij des 1585. Jars/im Namen vnd an ſtat Franciſci Königs in Bungen/Prothaſij Königs in Arimania/vnnd Bartholomei Hertzogs zu Omura zu Rom ſich Bäpſtlicher Hayligkeit/beneben der heyligen Kirchen Gottes vnderworffen. Vnd nach dem ſie Neaples/Venedig/vnd Mayland beſucht/durch Hiſpanien wider haimbwartz gezogen ſein/ſampt einem Prieſter der Societet IESV, P. N. Meſchita genant/der ſie im Chriſtlichen Glauben vnderwiſen/vnd die drey Jar/ſo ſie auß Japon biß gehn Rom/auff Waſſer vnd Lande jhr Raiß zugebracht/das gelayt geben. Deren die zwen erſten auß Fürſtlichem Geſchlecht von Omura/die andern zwen ſonſt von hohem vnd ſehr Altem Adel geborn. Alle vier aber von Natur/wie es jr Lands art mit bringt/gar Sinnreiche/Hochverſtendige/vnd vber die maß wolkündige Leut/Wie an mehr orten von jrer Nation in gemein/vnd von diſen vier ſonderbar geſchriben wirdt.

Getruckt zu Augſpurg/durch
Michael Manger.

Anno, M. D. LXXXVI.

4 Japanese boys came to Padova from Kyushu in 1585 (after Roma and Firenze).

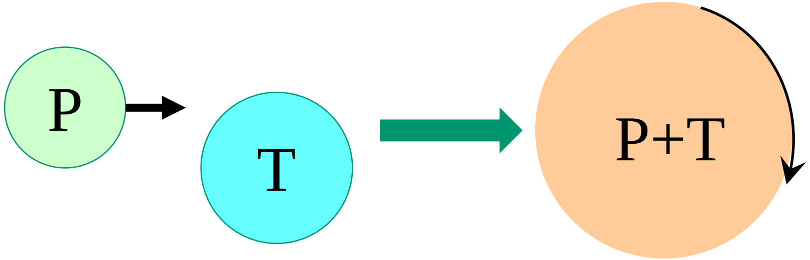
Heavy-ion fusion reactions: quantum tunneling with many degrees of freedom and superheavy elements

Kouichi Hagino
Tohoku University

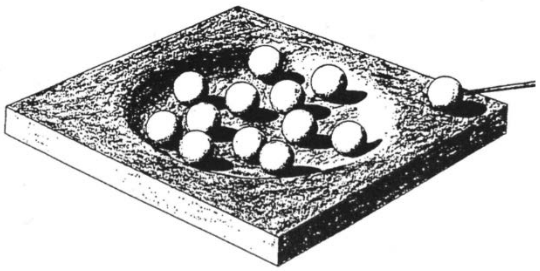
1. H.I. fusion reactions: why are they interesting?
2. Coupled-channels approach
3. Future perspectives: superheavy elements

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

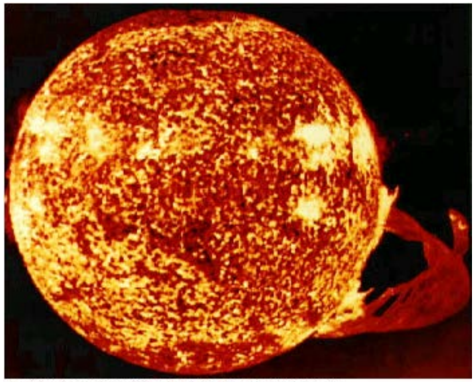
Fusion reactions: compound nucleus formation



compound
nucleus

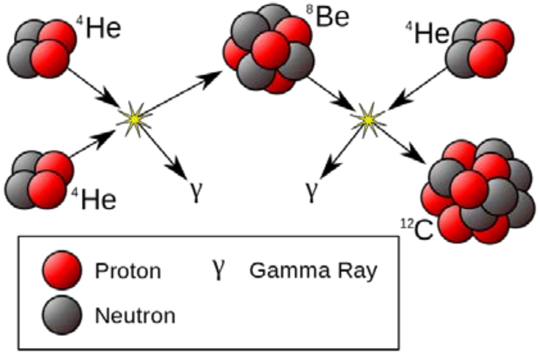


cf. Bohr ‘36

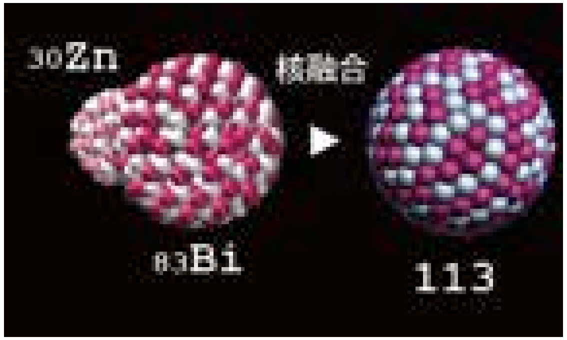


NASA, Skylab space station December 19, 1973, solar flare reaching 588 000 km off solar surface

energy production
in stars (Bethe ‘39)



nucleosynthesis

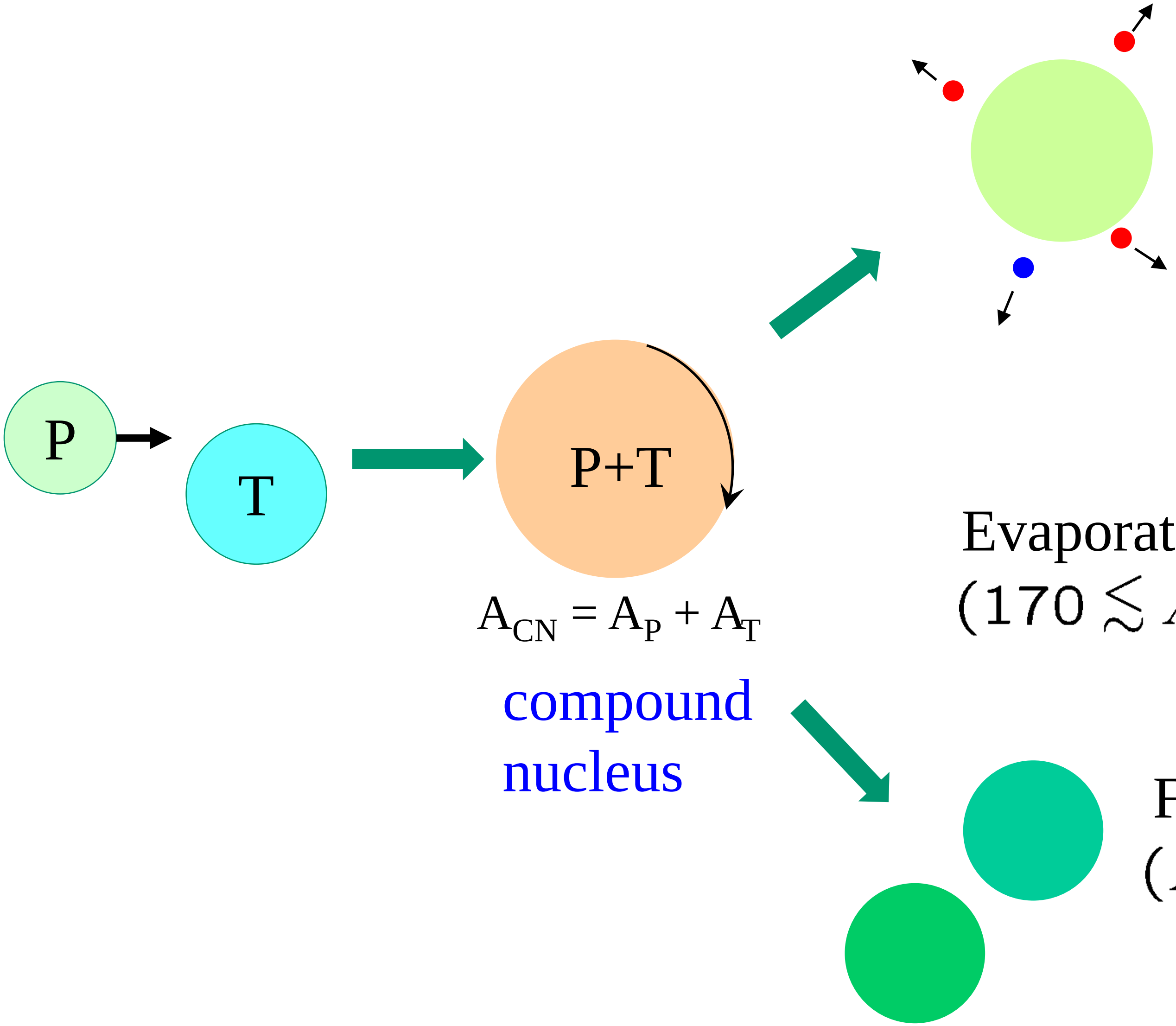


superheavy elements

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



$A_{CN} = A_P + A_T$

compound
nucleus

Evaporation
$(A_{\mathrm{CN}} \lesssim 170)$

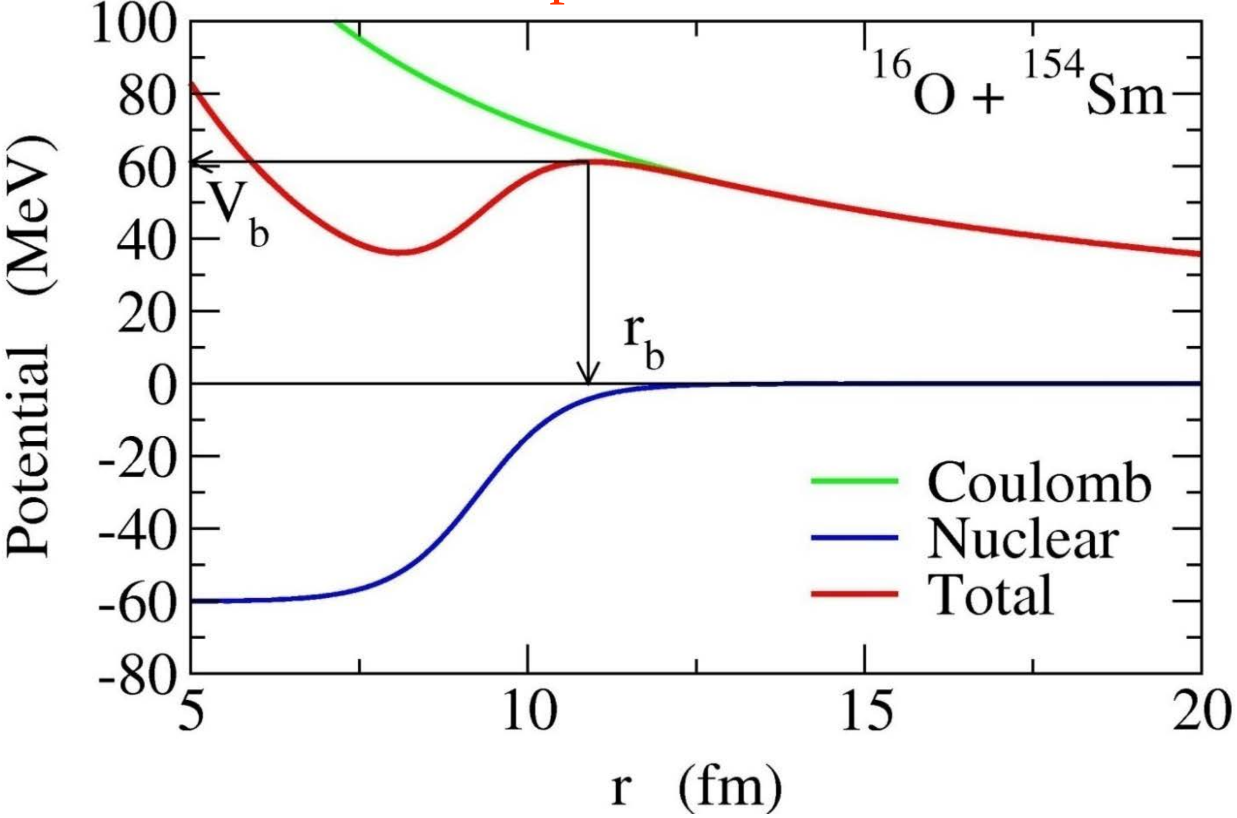
n,p,α emissions
γ decay

Evaporation + Fission
$(170 \lesssim A_{\mathrm{CN}} \lesssim 220)$

Fission
$(A_{\mathrm{CN}} \gtrsim 220)$

cf. superheavy
elements

Inter-nucleus potential



Two interactions:

1. Coulomb force
   long range repulsion
2. Nuclear force
   short range attraction

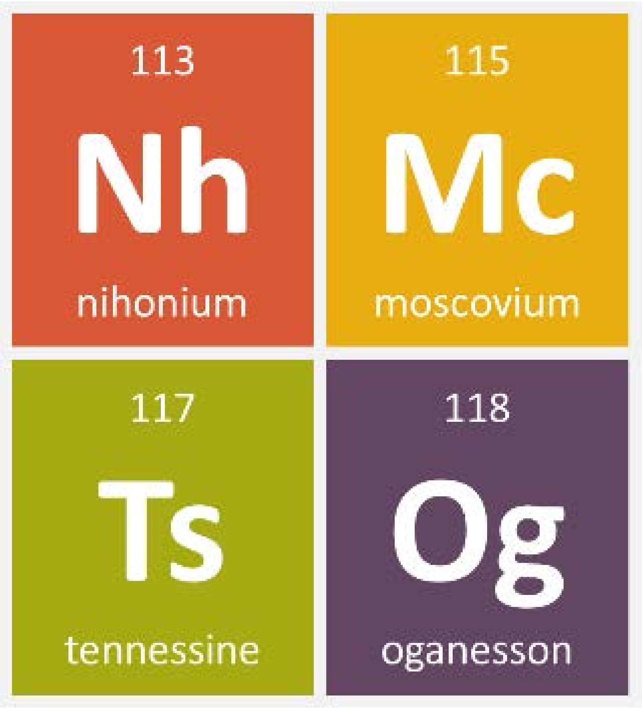
⇓

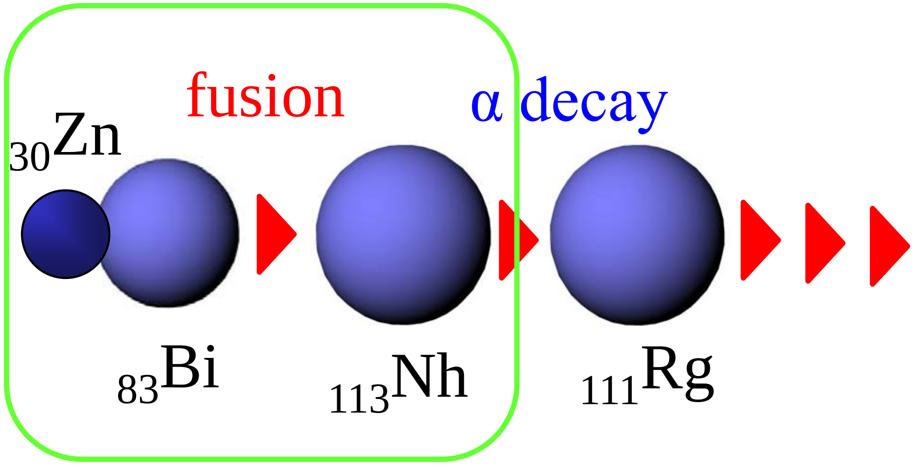
<u>potential barrier</u>
due to a cancellation
between the two
(Coulomb barrier)

- •Above-barrier energies
- ➡ •Sub-barrier energies
  (energies around the Coulomb barrier)
- •Deep sub-barrier energies

Why sub-barrier fusion?

two obvious reasons:





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:

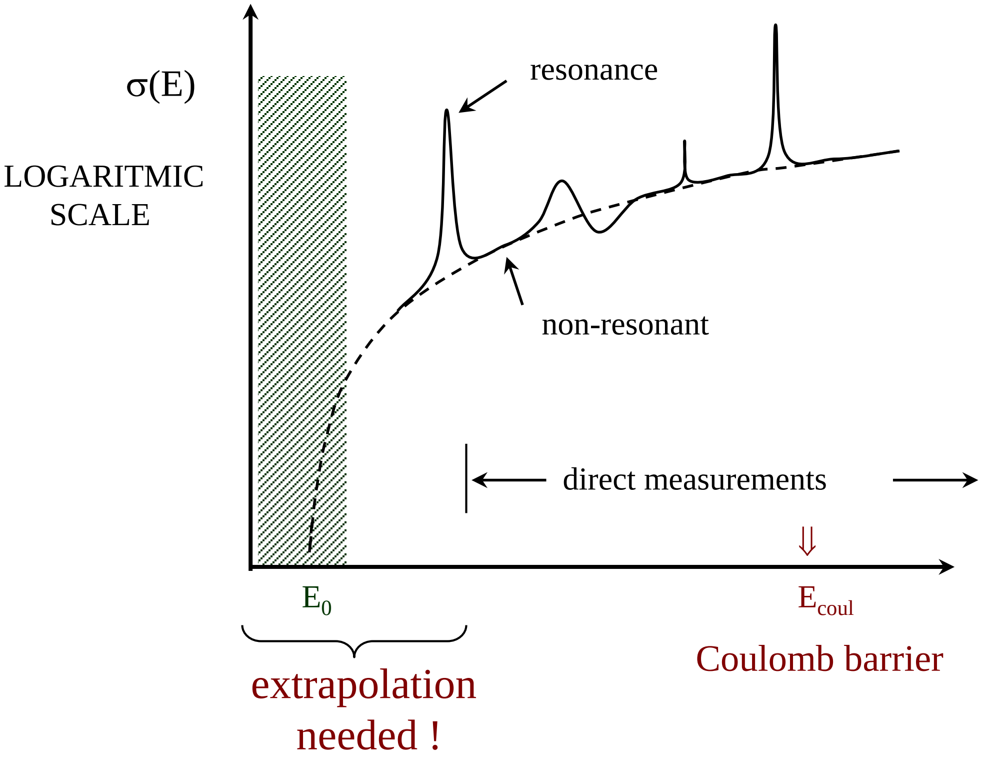
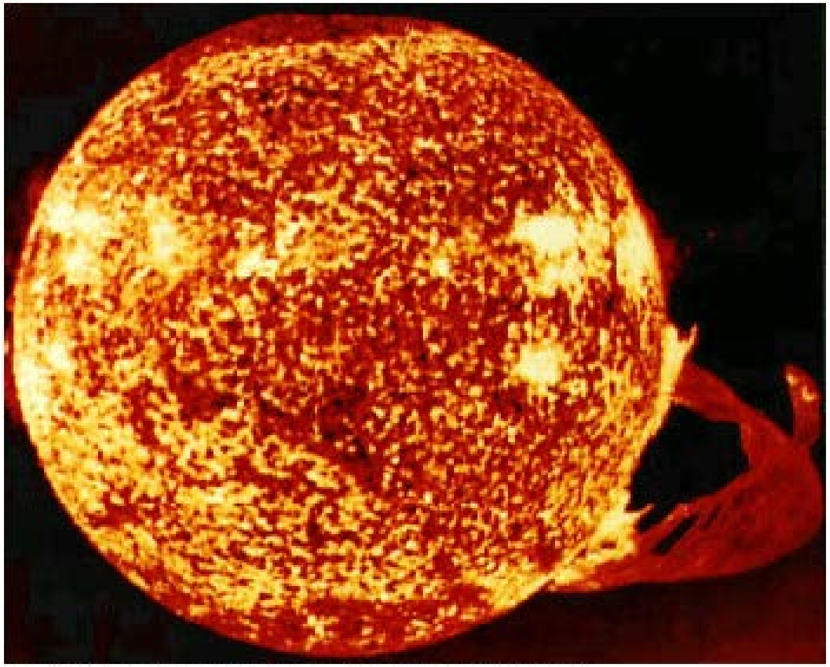


figure: M. Aliotta



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:

✓superheavy elements ✓ nuclear astrophysics

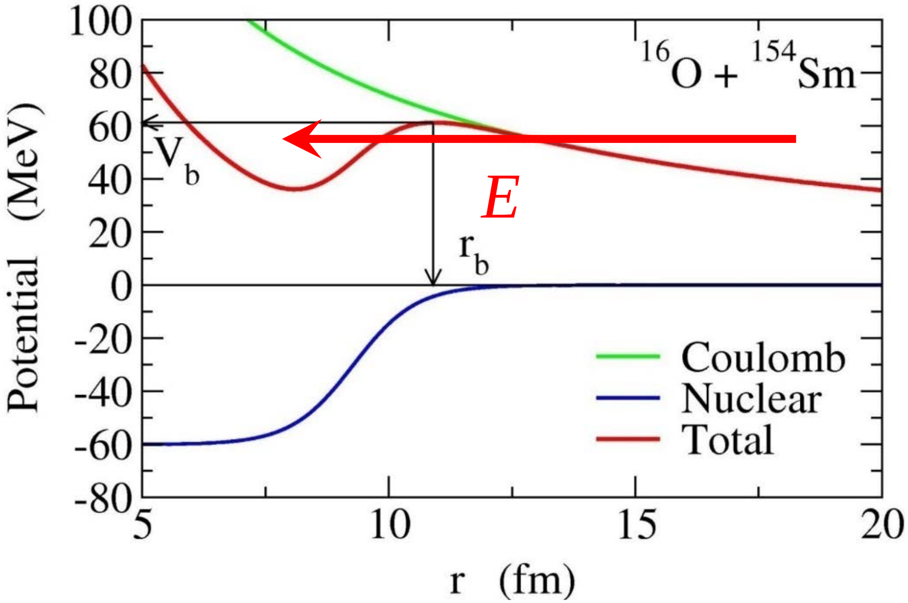
other reasons:

✓reaction dynamics

strong interplay between reaction and structure

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

✓many-particle tunneling



Why sub-barrier fusion?

two obvious reasons:

✓superheavy elements ✓ nuclear astrophysics

other reasons:

✓reaction dynamics

strong interplay between reaction and structure

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

✓many-particle tunneling

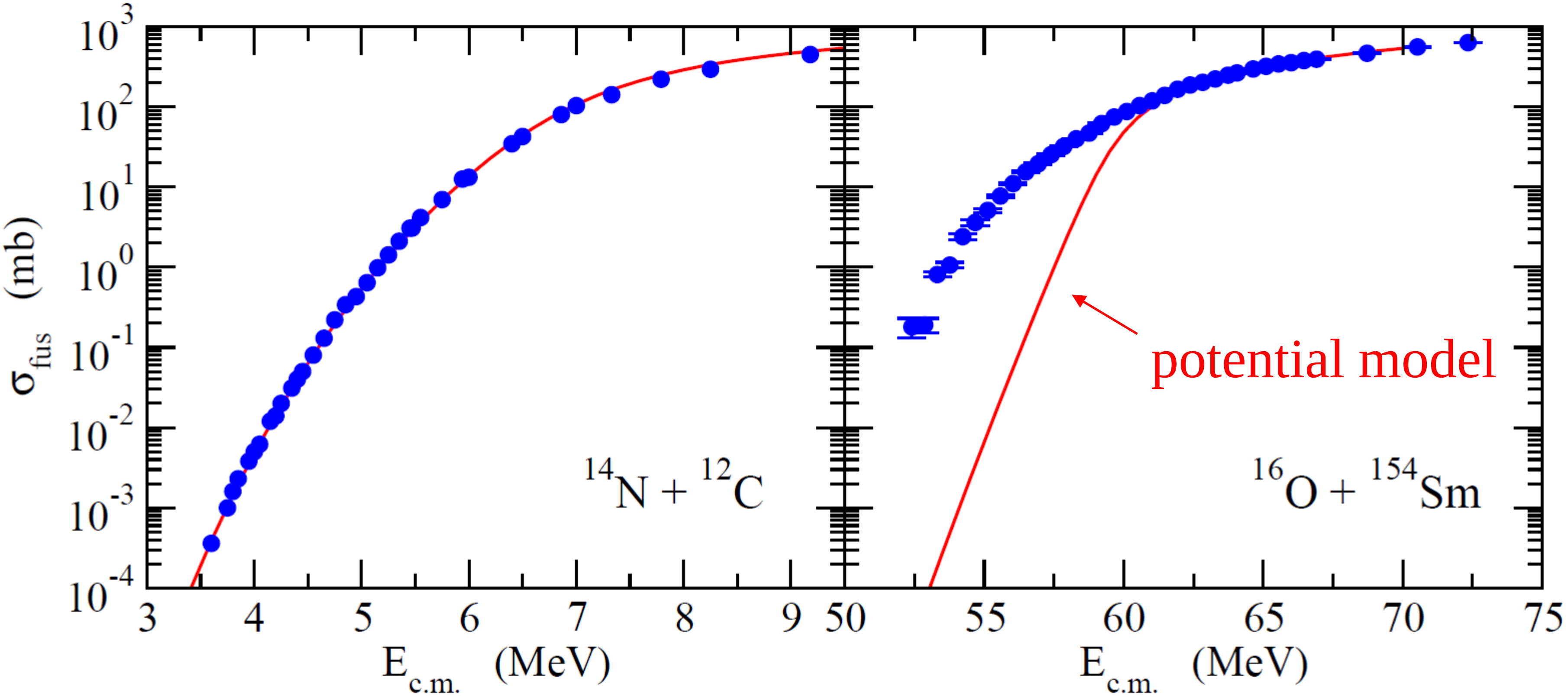
- many types of intrinsic degrees of freedom
  (several types of collective vibrations,
  deformation with several multipolarities)
- energy dependence of tunneling probability
  cf. alpha decay: fixed energy

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

Large enhancement of fusion cross sections

Potential model: *V*(*r*) + absorption

$$\boxed{\sigma_{\rm fus} = \frac{\pi}{k^2}\sum_l (2l+1)(1-|S_l|^2)}$$

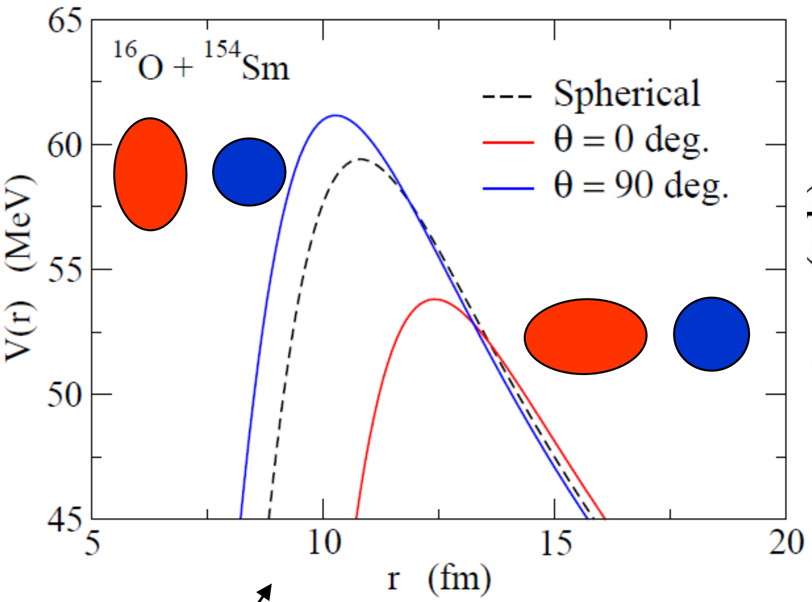


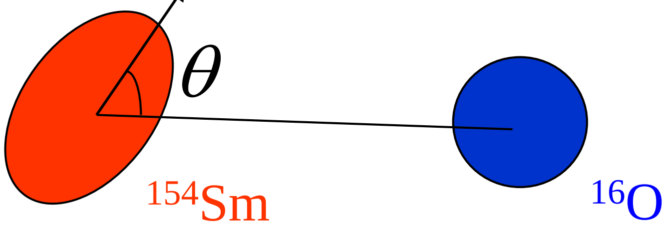
cf. seminal work:
R.G. Stokstad et al., PRL41('78) 465

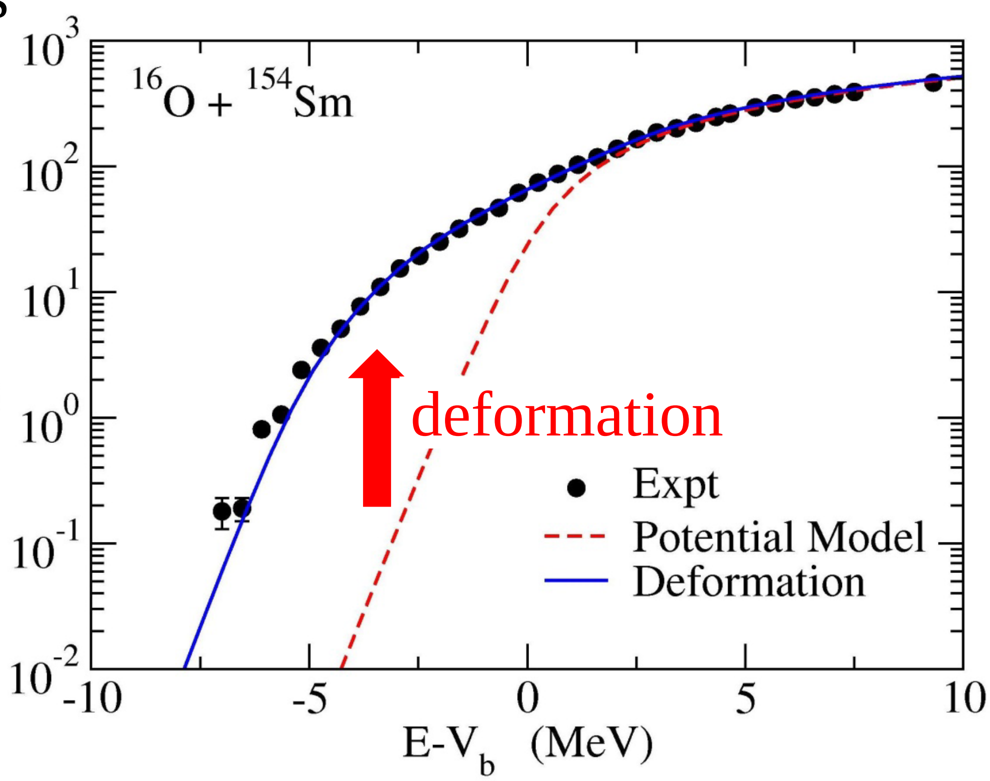
Effects of nuclear deformation

^{154}Sm : a typical deformed nucleus

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



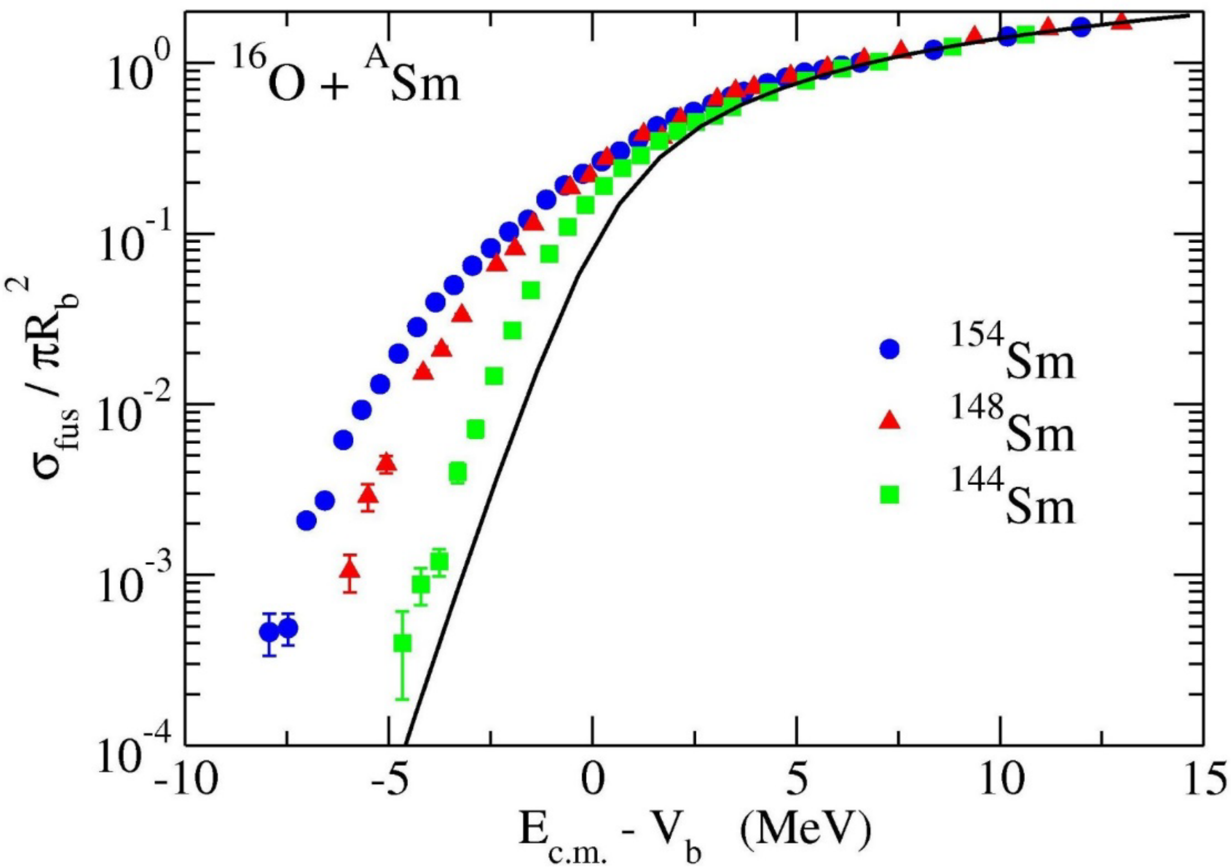




Fusion: strong interplay between nuclear structure and reaction

* Sub-barrier enhancement also for non-deformed targets:

couplings to low-lying collective excitations → coupling assisted tunneling



$^{16}O + {}^{A}Sm$

$\sigma_{fus} / \pi R_b^2$

$E_{c.m.} - V_b$ (MeV)

● ^{154}Sm

▲ ^{148}Sm

■ ^{144}Sm

10^{0}

10^{-1}

10^{-2}

10^{-3}

10^{-4}

-10

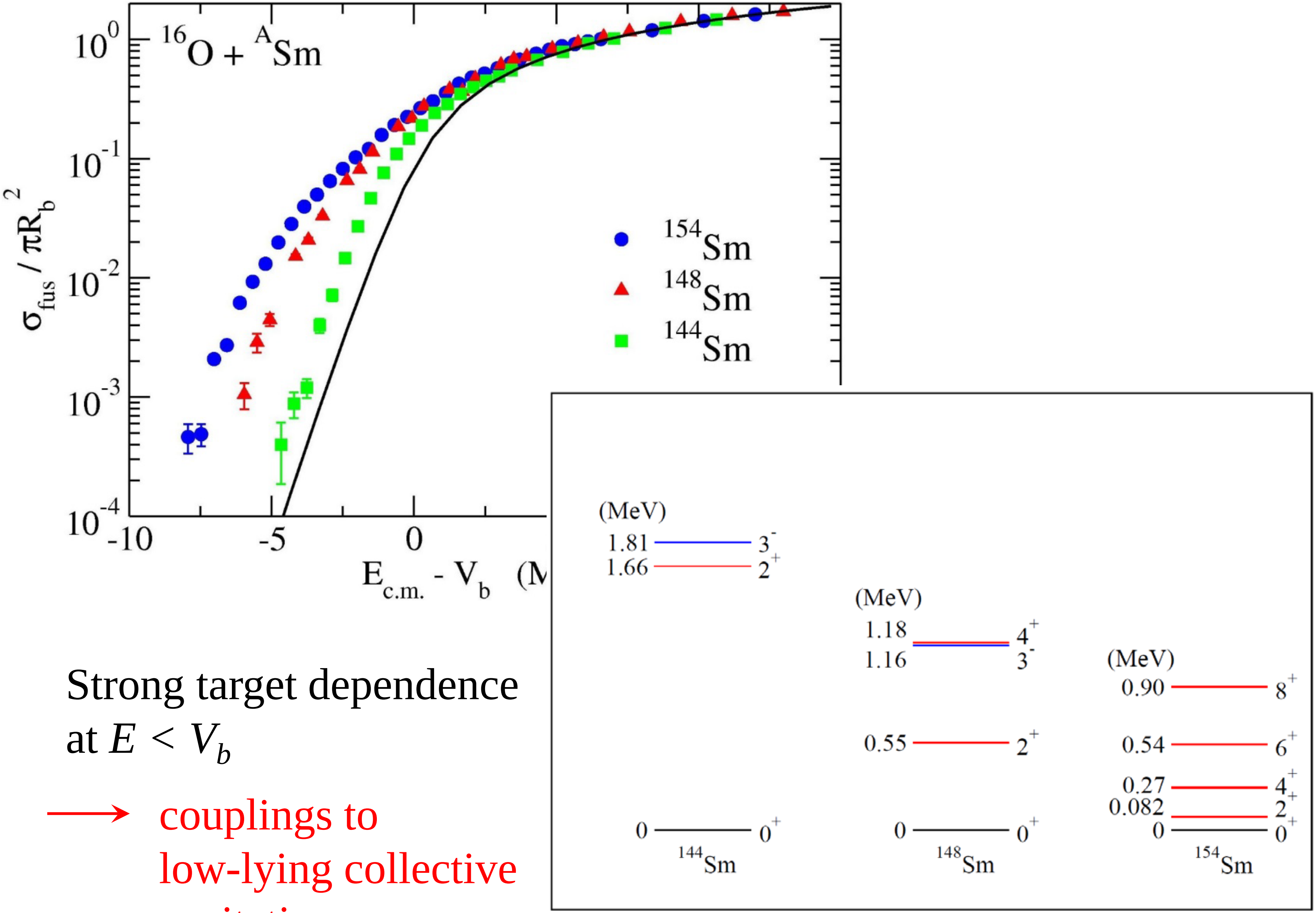
-5

0

5

10

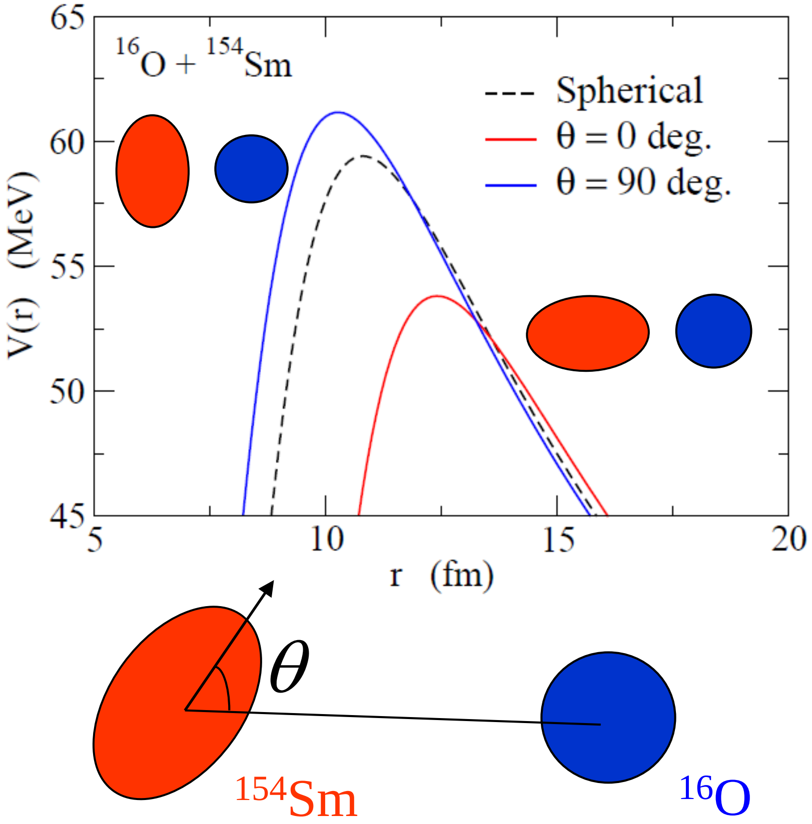
15



Strong target dependence at $E < V_b$

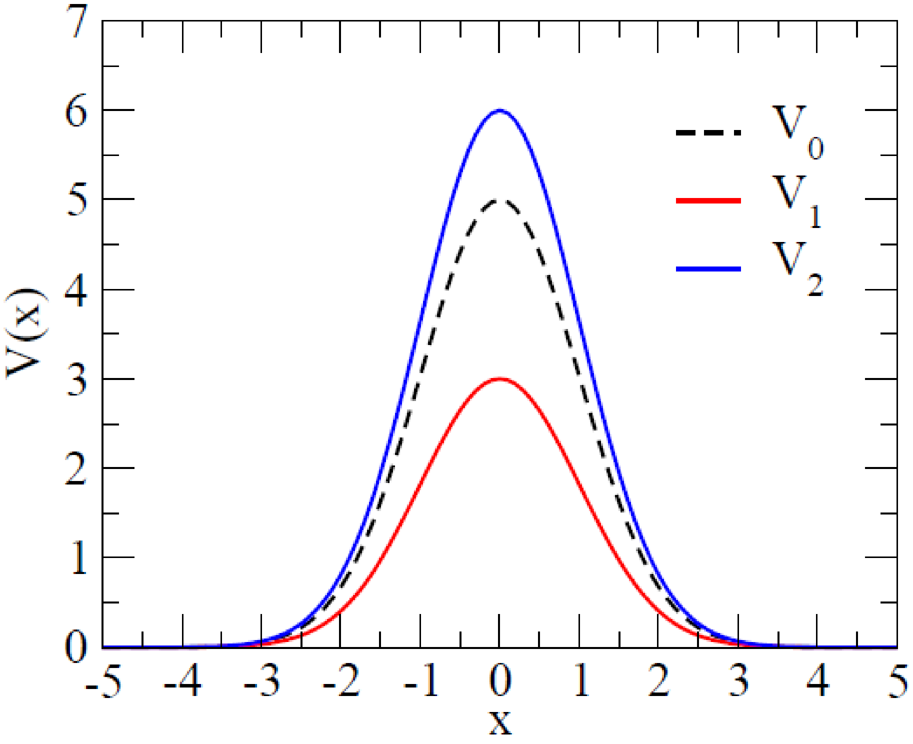
→ couplings to low-lying collective excitations

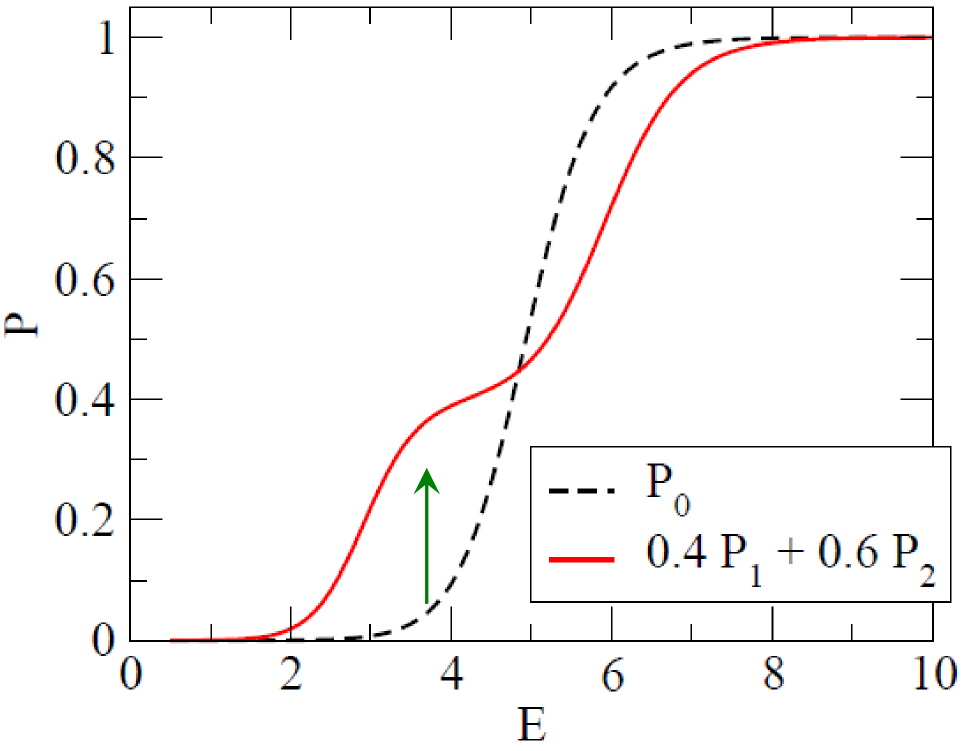
Enhancement of tunneling probability



Enhancement of tunneling probability
: a problem of two potential barriers

$$P(E) = P(E; V_0) \to w_1 P(E; V_1) + w_2 P(E; V_2)$$

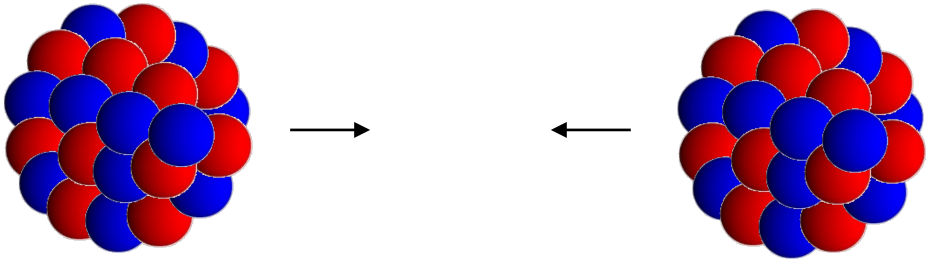




“barrier distribution” due to couplings to excited states in projectile/target nuclei

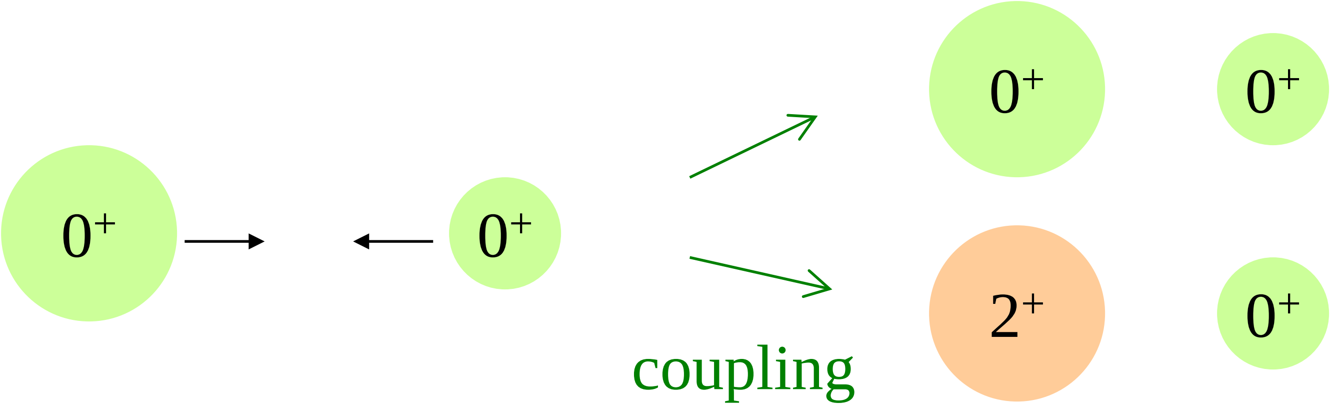
Coupled-channels method: a quantal scattering theory with excitations

many-body problem

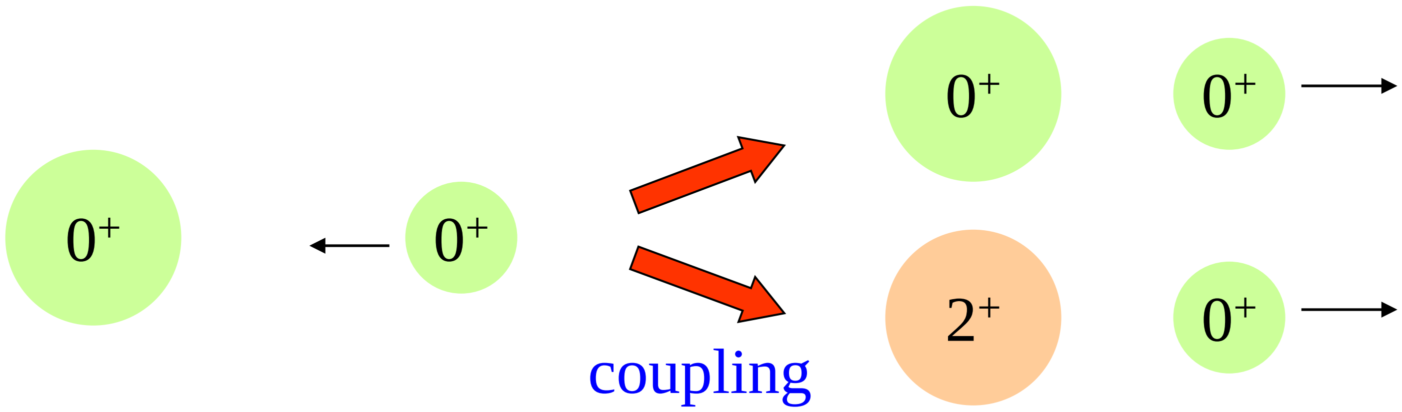


still very challenging

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



Coupled-channels method: a quantal scattering theory with excitations



coupling

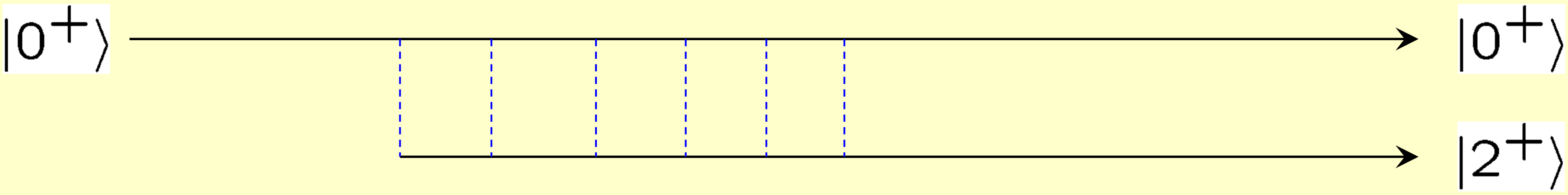
entrance channel

excited channel

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2+V_0(r)+\epsilon_k-E\right]\psi_k(\boldsymbol{r})+\sum_{k'}\langle\phi_k|V_{\rm coup}|\phi_{k'}\rangle\psi_{k'}(\boldsymbol{r})=0$$

excitation energy

excitation operator



full order treatment of excitation/de-excitation dynamics during reaction

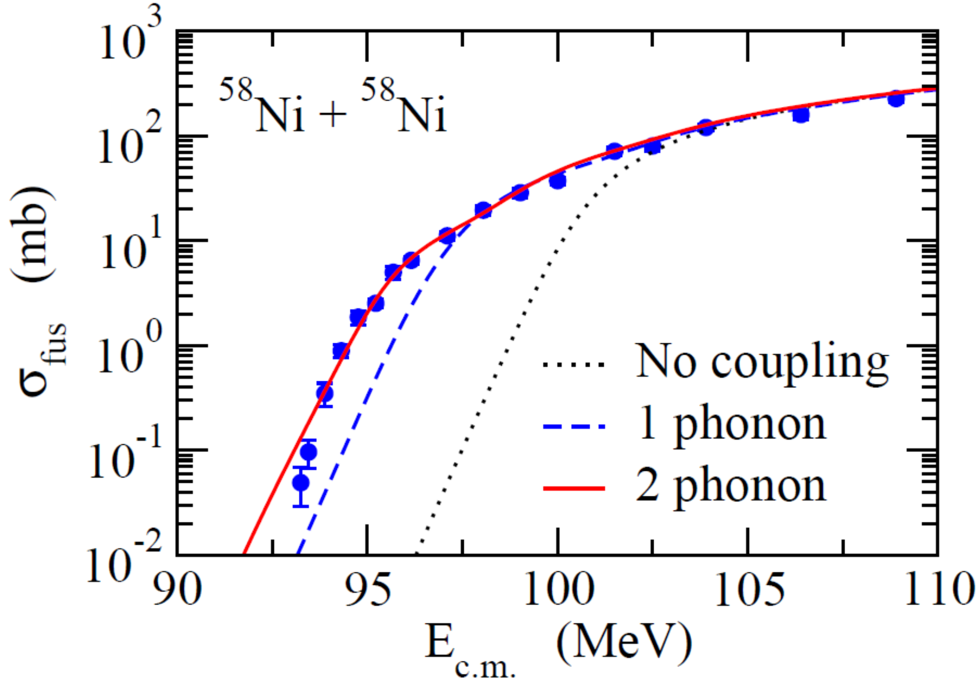
Inputs for C.C. calculations

i) Inter-nuclear potential

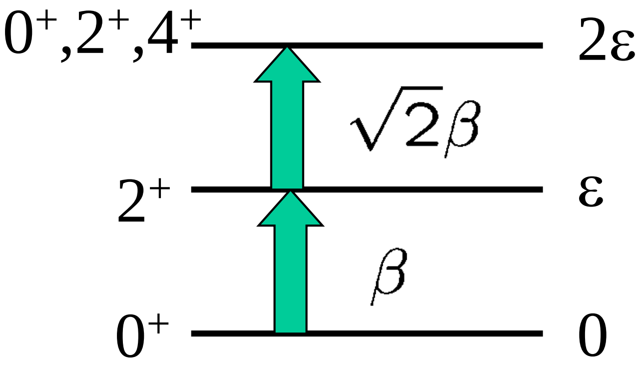
a fit to experimental data at above barrier energies

ii) Intrinsic degrees of freedom

in most of cases, (macroscopic) collective model
(rigid rotor / harmonic oscillator)



simple harmonic oscillator

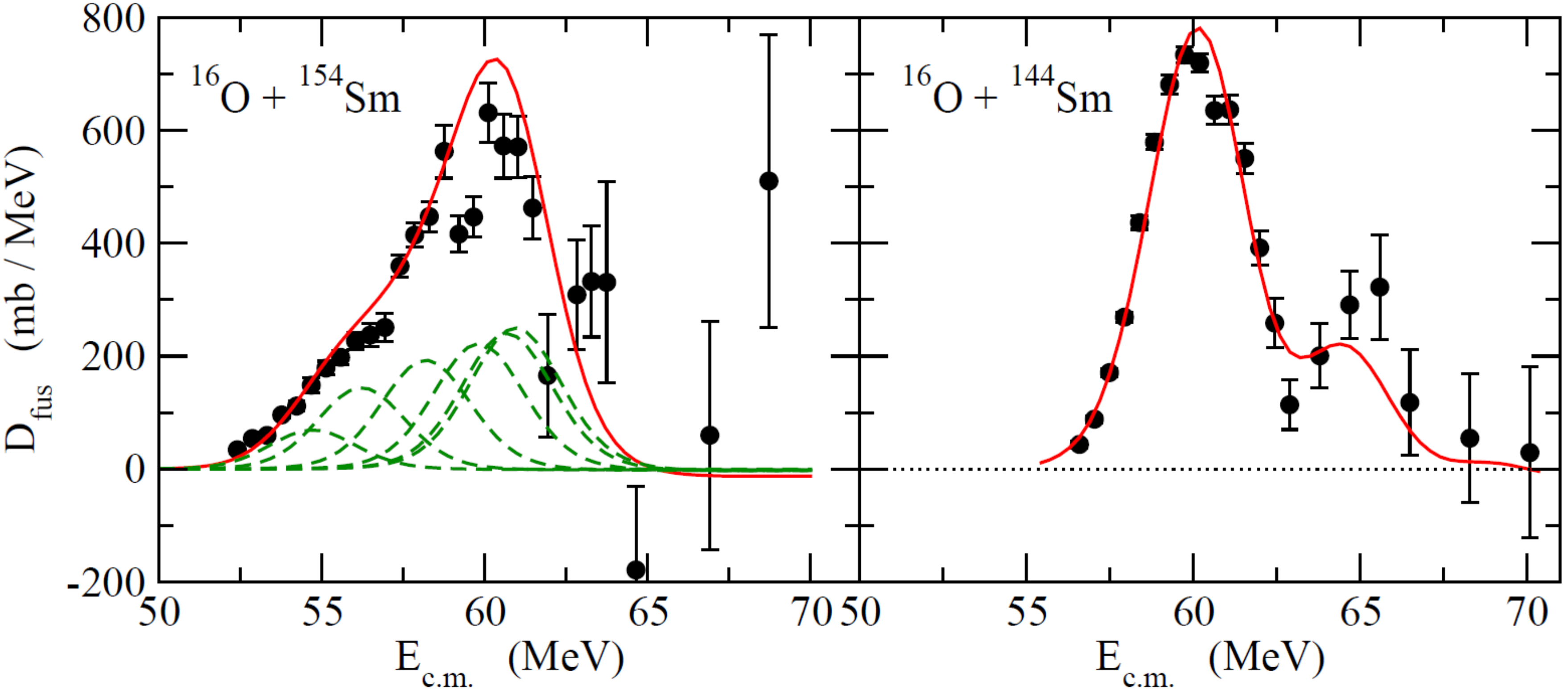


C.C. approach: a standard tool for sub-barrier fusion reactions

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

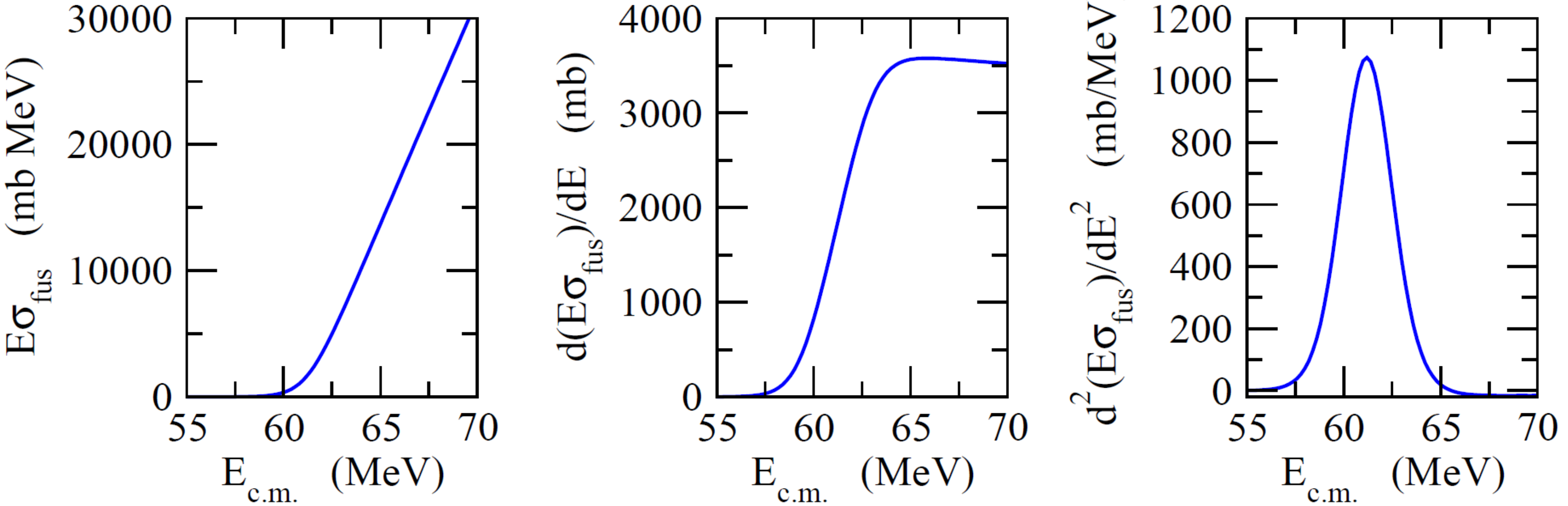
✓ Fusion barrier distribution (Rowley, Satchler, Stelson, PLB254(‘91))

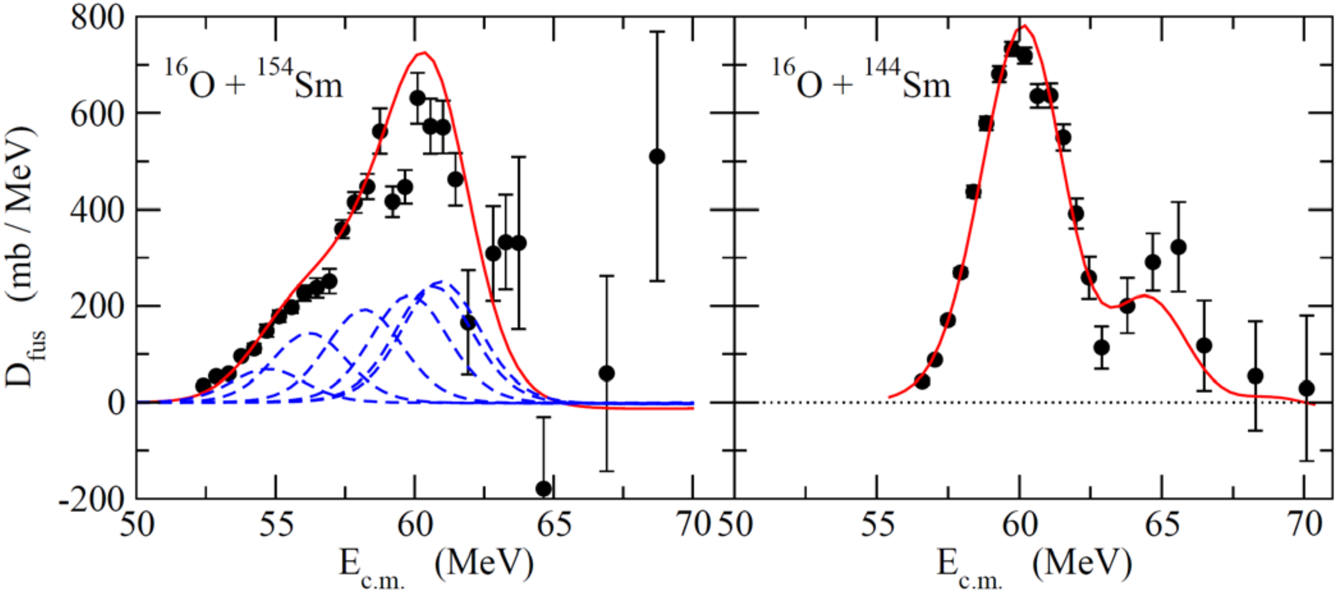
$$D_{\text{fus}}(E) = \frac{d^2(E\sigma_{\text{fus}})}{dE^2}$$



K.H., N. Takigawa, PTP128 (‘12) 1061

$\sim \pi R_b^2\, P_{l=0}(E)$ $\sim \pi R_b^2 \cdot dP_{l=0}/dE$

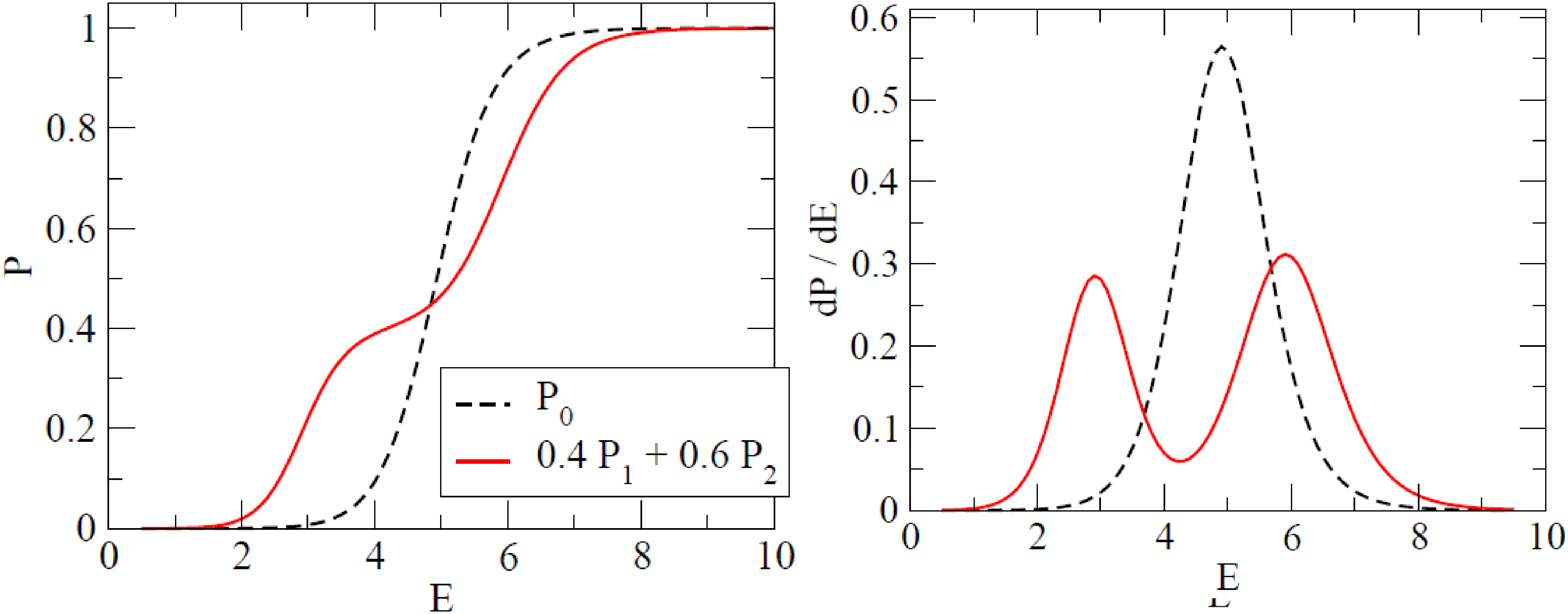




K.H. and N. Takigawa, PTP128 ('12) 1061

barrier distribution: a problem of two potential barriers

$$P(E) = P(E;V_0) \rightarrow w_1 P(E;V_1) + w_2 P(E;V_2)$$

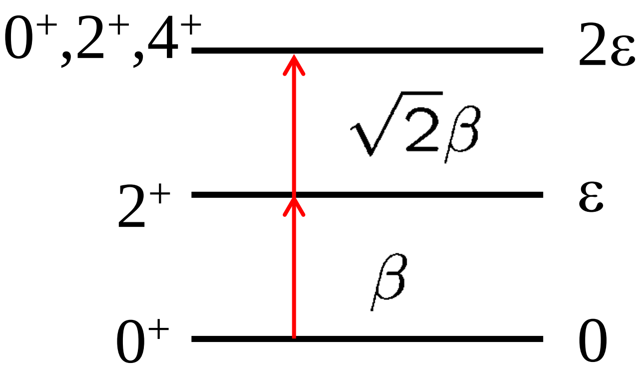


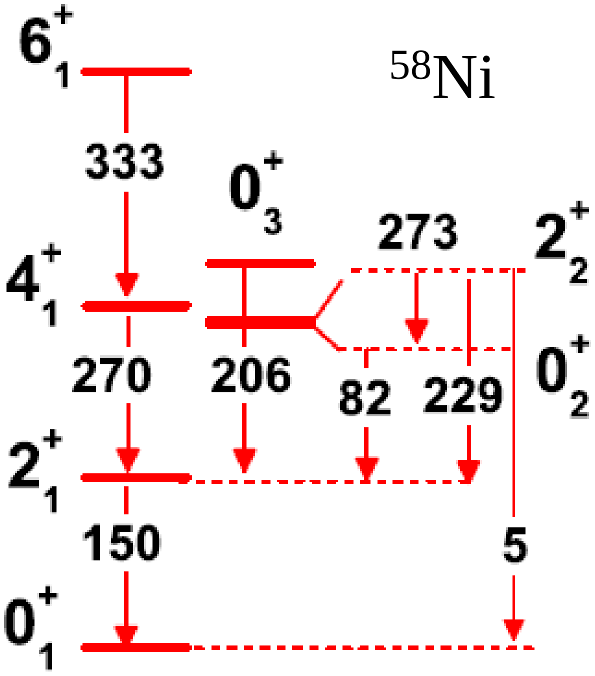
Further development: semi-microscopic modelling

K.H. and J.M. Yao, PRC91(‘15) 064606

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

simple harmonic
oscillator

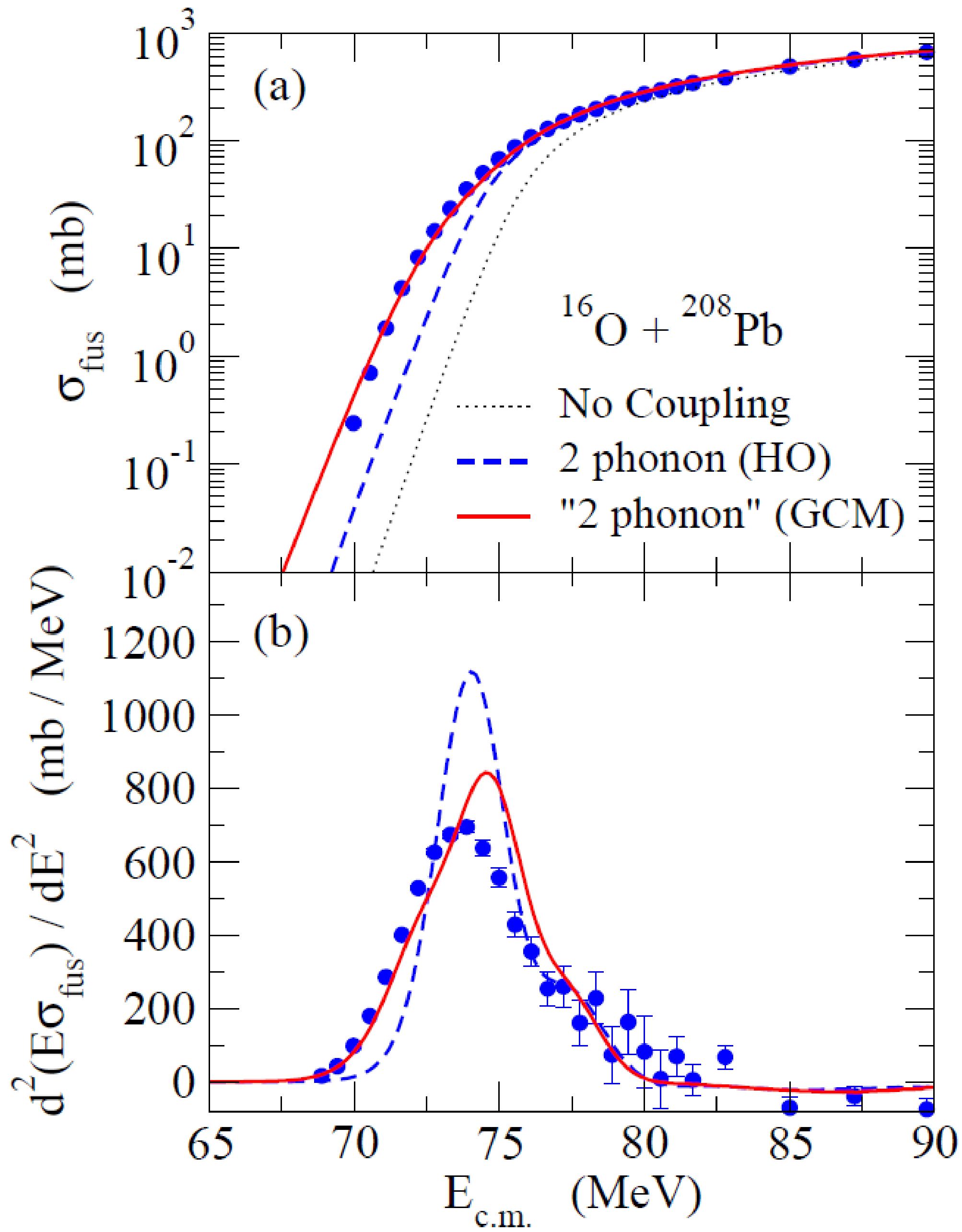


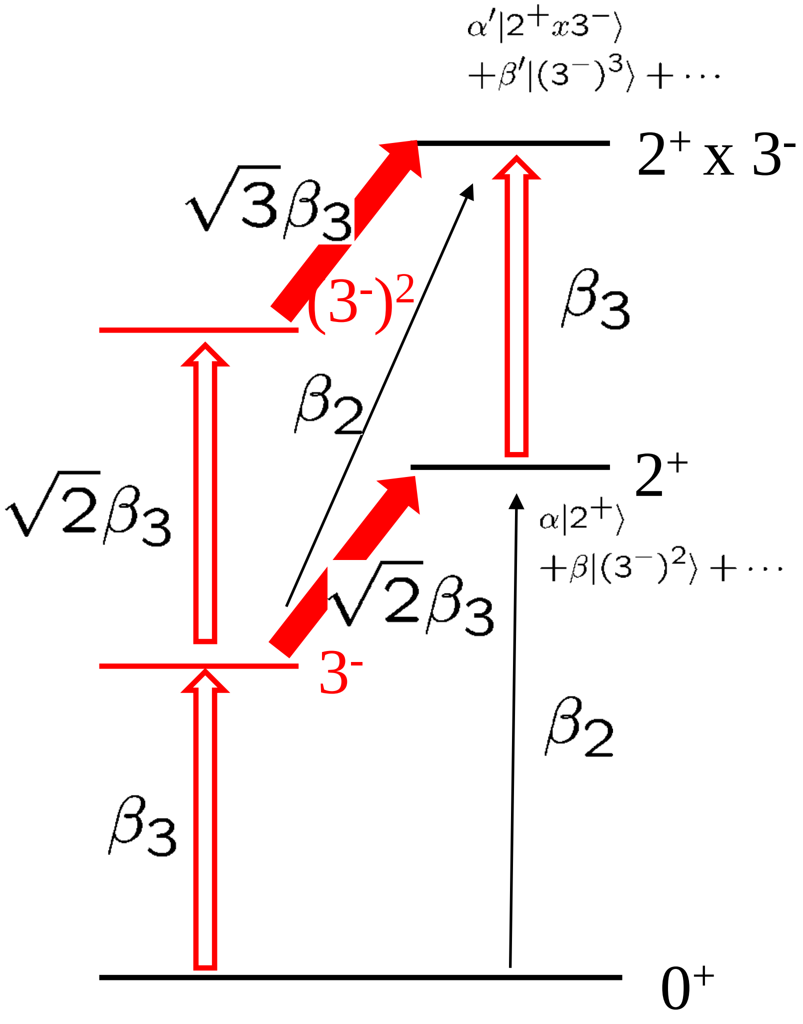


relativistic MF + GCM

anharmonicity of phonon spectra

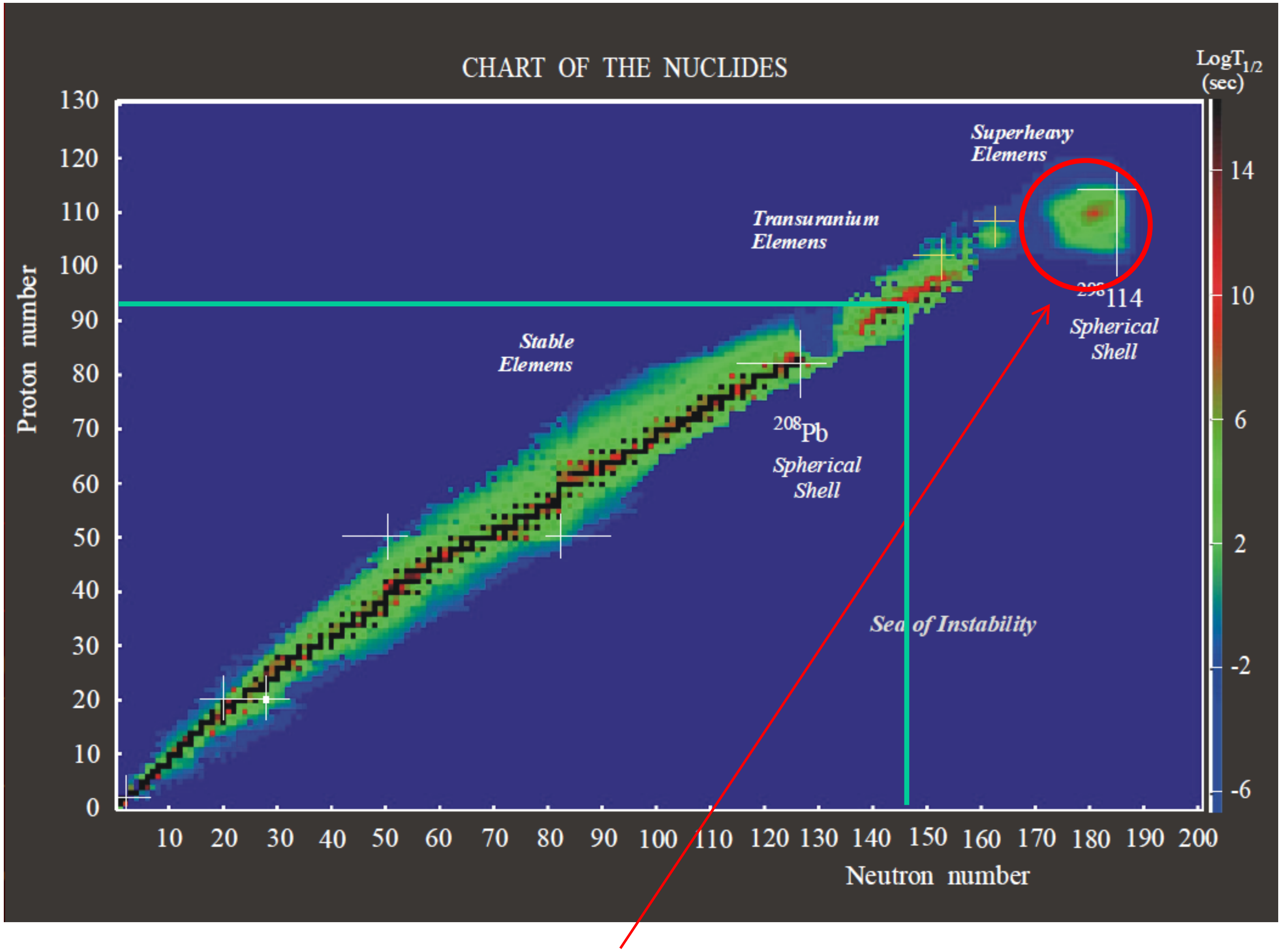
CCFULL with RMF+GCM





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

Future perspectives: Superheavy elements

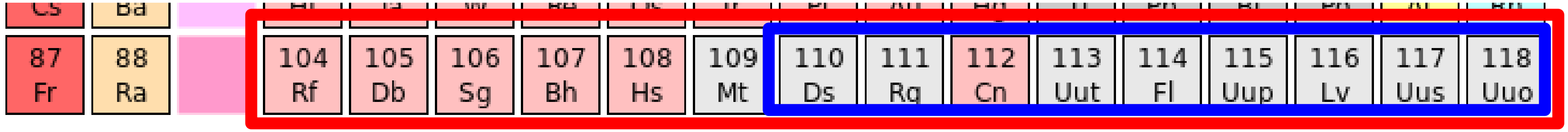


Yuri Oganessian

island of stability around Z=114, N=184

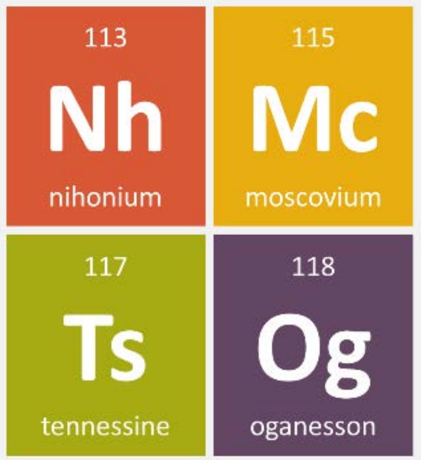
W.D. Myers and W.J. Swiatecki (1966), A. Sobiczewski et al. (1966)

who is she?



7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus

Z=110	Darmstadtium (Ds)	1994 Germany
Z=111	Roentgenium (Rg)	1994 Germany
Z=112	Copernicium (Cn)	1996 Germany
Z=113	**Nihonium (Nh)**	2003 Russia / 2004 Japan
Z=114	Flerovium (Fl)	1999 Russia
Z=115	**Moscovium (Mc)**	2003 Russia
Z=116	Livermoriun (Lv)	2000 Russia
Z=117	**Tennessine (Ts)**	2010 Russia
Z=118	**Oganesson (Og)**	2002 Russia



Z=113: Nihonium (Nh)

Ni ppon

日本

Ni hon

Ancient Chinese: “Jippon”
→ Japan (Giappone)

⟶ Nihonium

cf.

日本

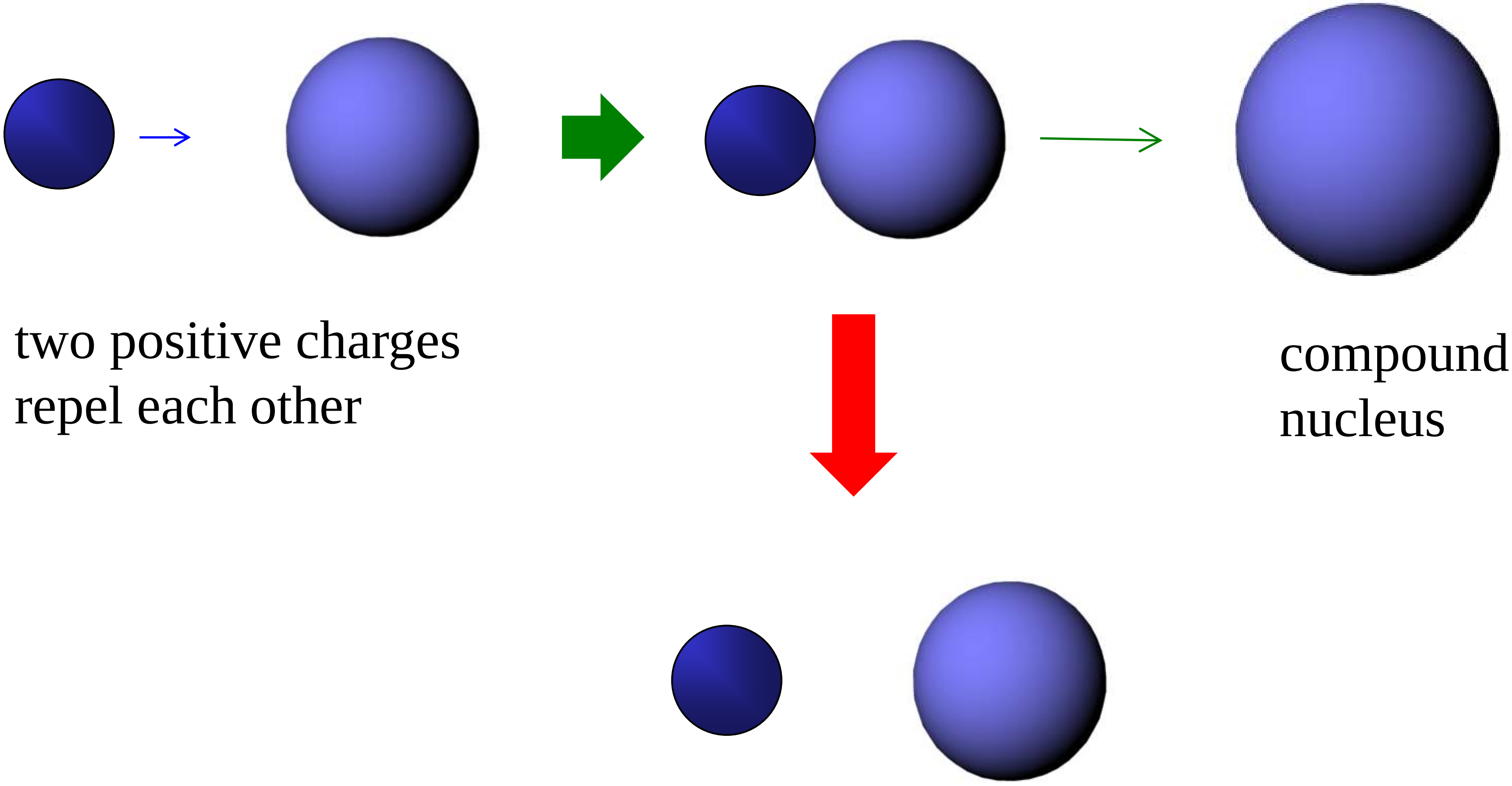
sole origine

How to synthesize SHE?

Nuclear fusion reactions

e.g.,

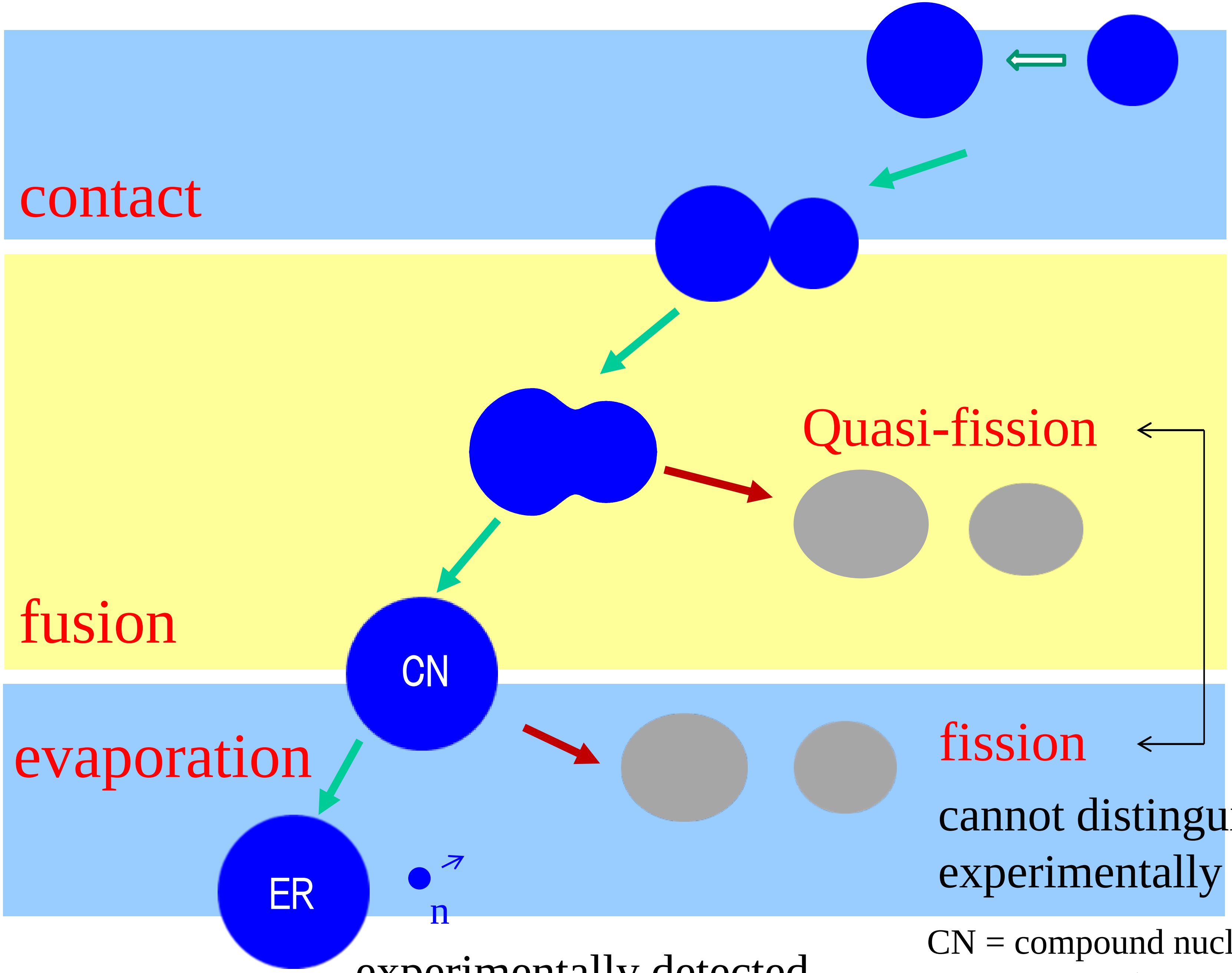
$^{70}\mathrm{Zn} + {}^{209}\mathrm{Bi} \longrightarrow {}^{279}113$



two positive charges
repel each other

compound
nucleus

re-separation



contact

fusion

Quasi-fission

CN

evaporation

fission

cannot distinguish experimentally

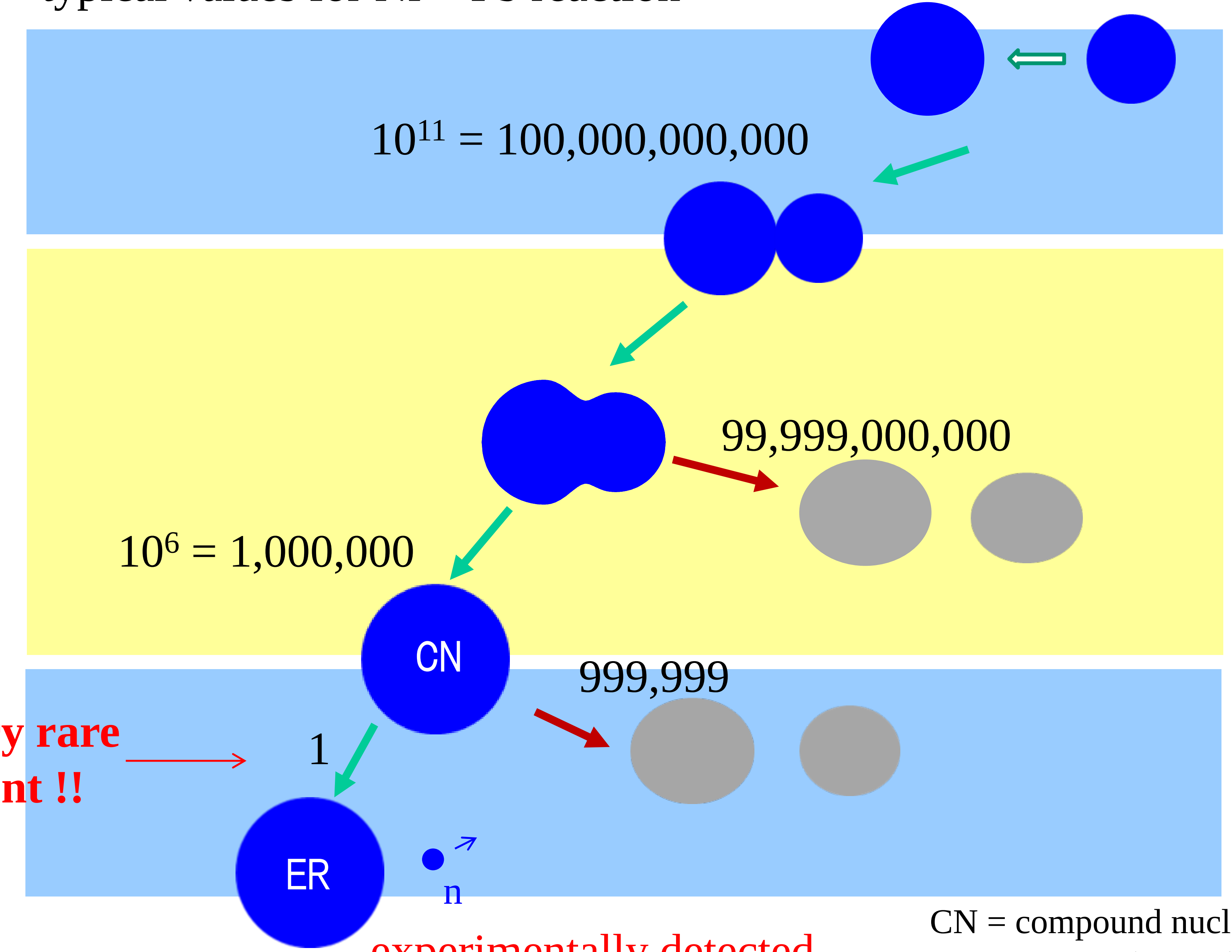
ER

n

experimentally detected

CN = compound nucleus
ER = evaporation residue

typical values for Ni + Pb reaction



10^{11} = 100,000,000,000

99,999,000,000

10^{6} = 1,000,000

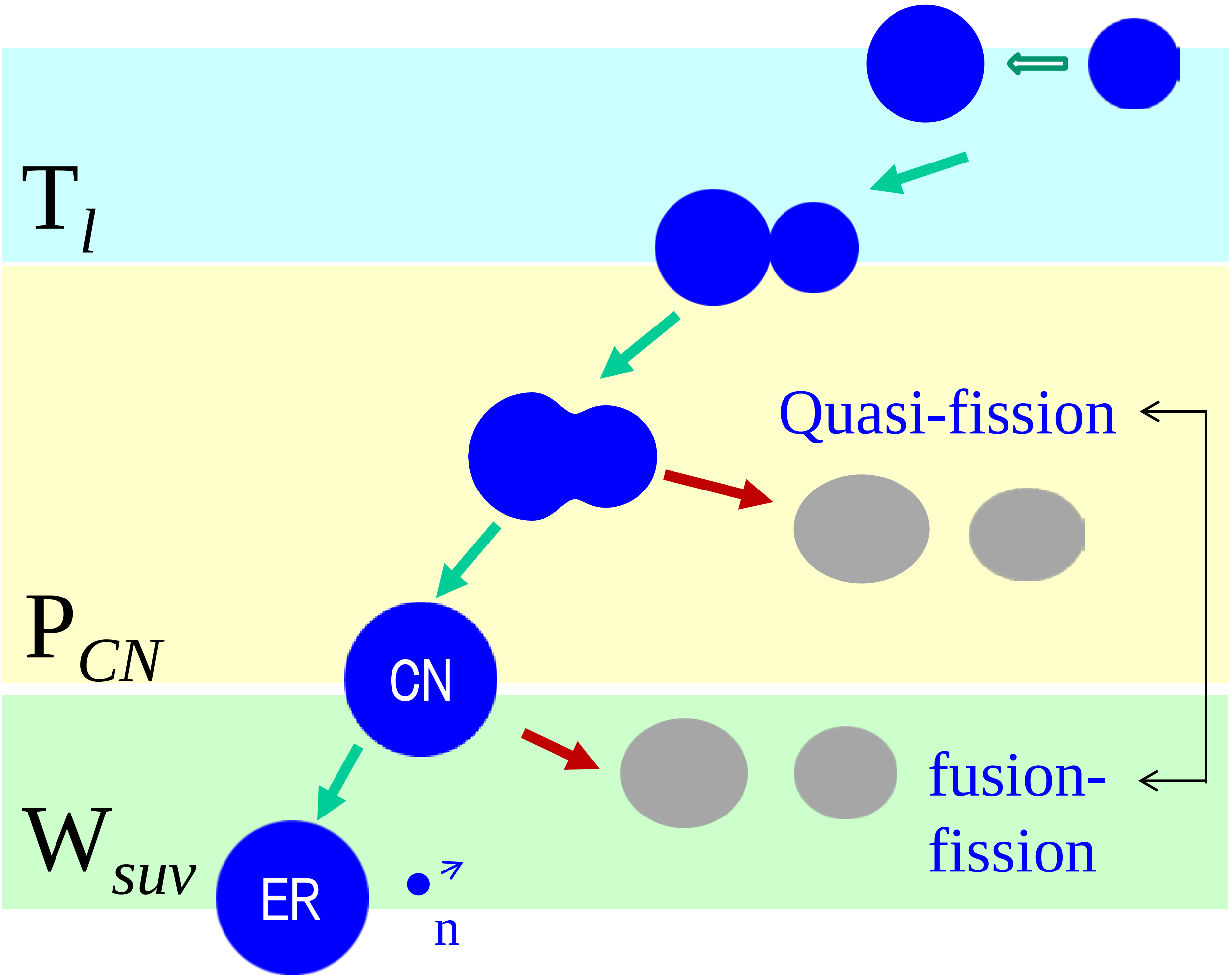
999,999

very rare event !! →

1

experimentally detected

CN = compound nucleus
ER = evaporation residue



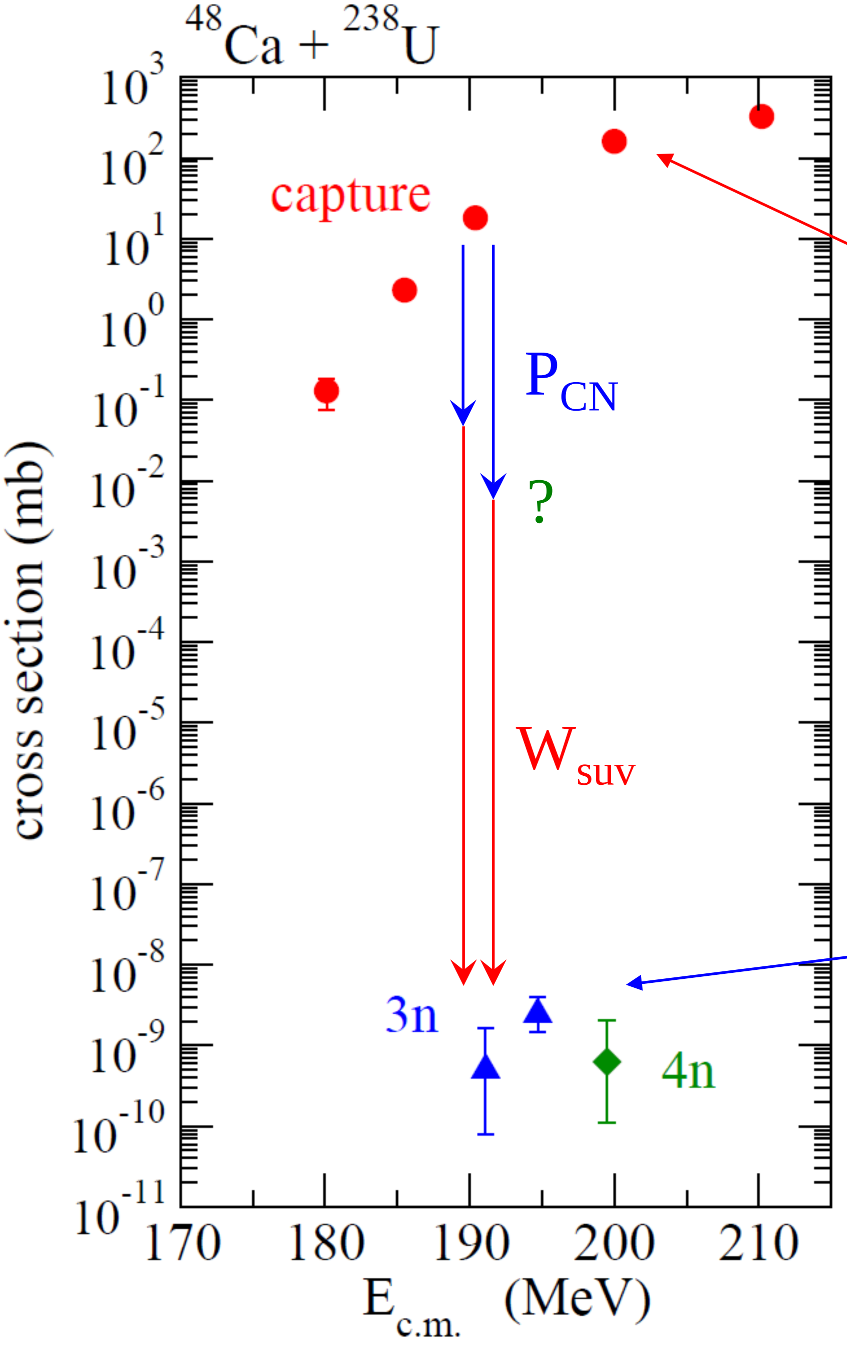
Coupled-channels

Langevin approach

statistical model

CN = compound nucleus
ER = evaporation residue

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



no experimental data for P_{CN}

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

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

not available

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

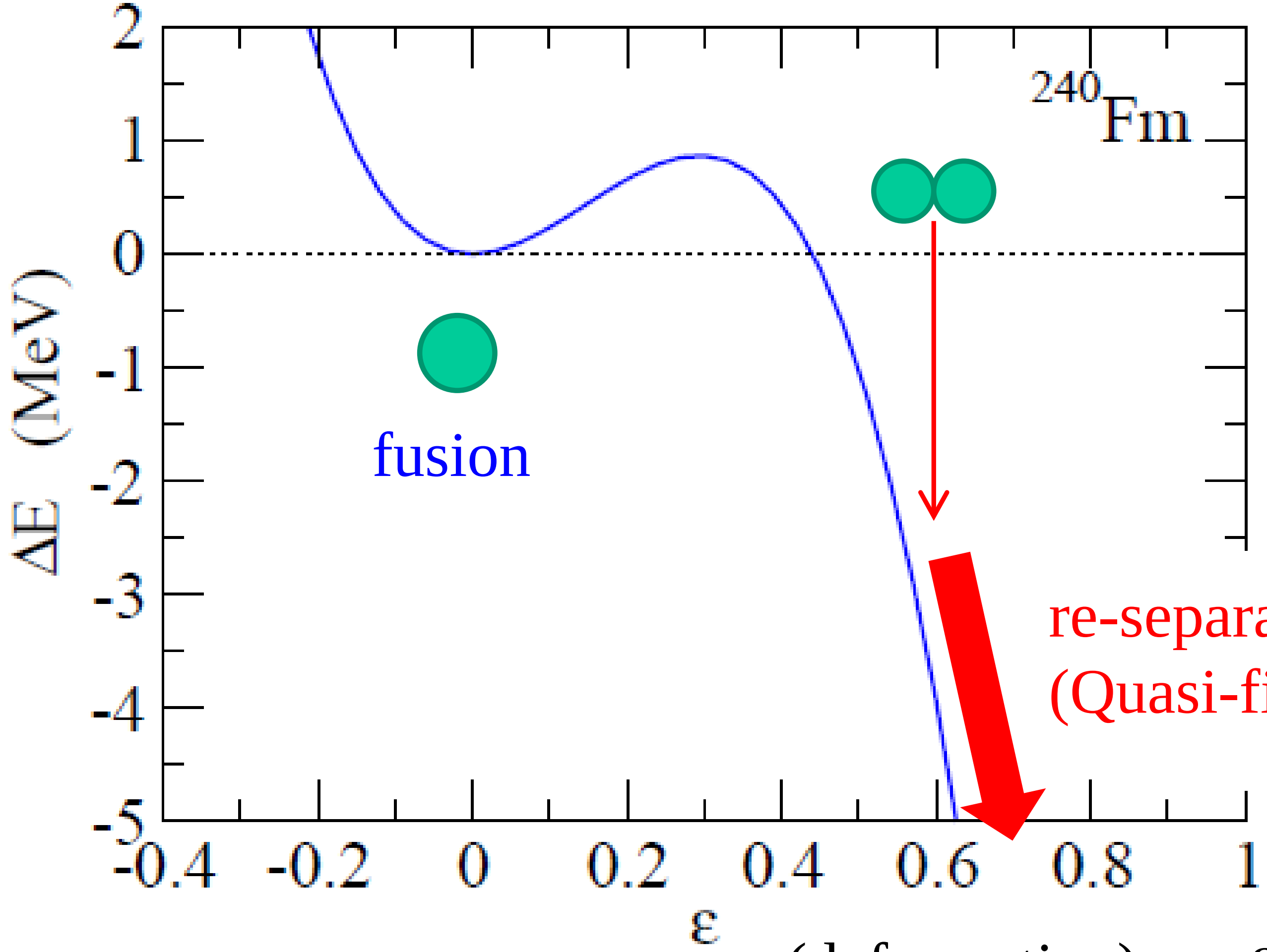
large uncertainties

Formation phase: Langevin approach

Fission barrier (Liquid Drop Model)

touching point:
outside the fission barrier

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



fusion

re-separation
(Quasi-fission)

(deformation)

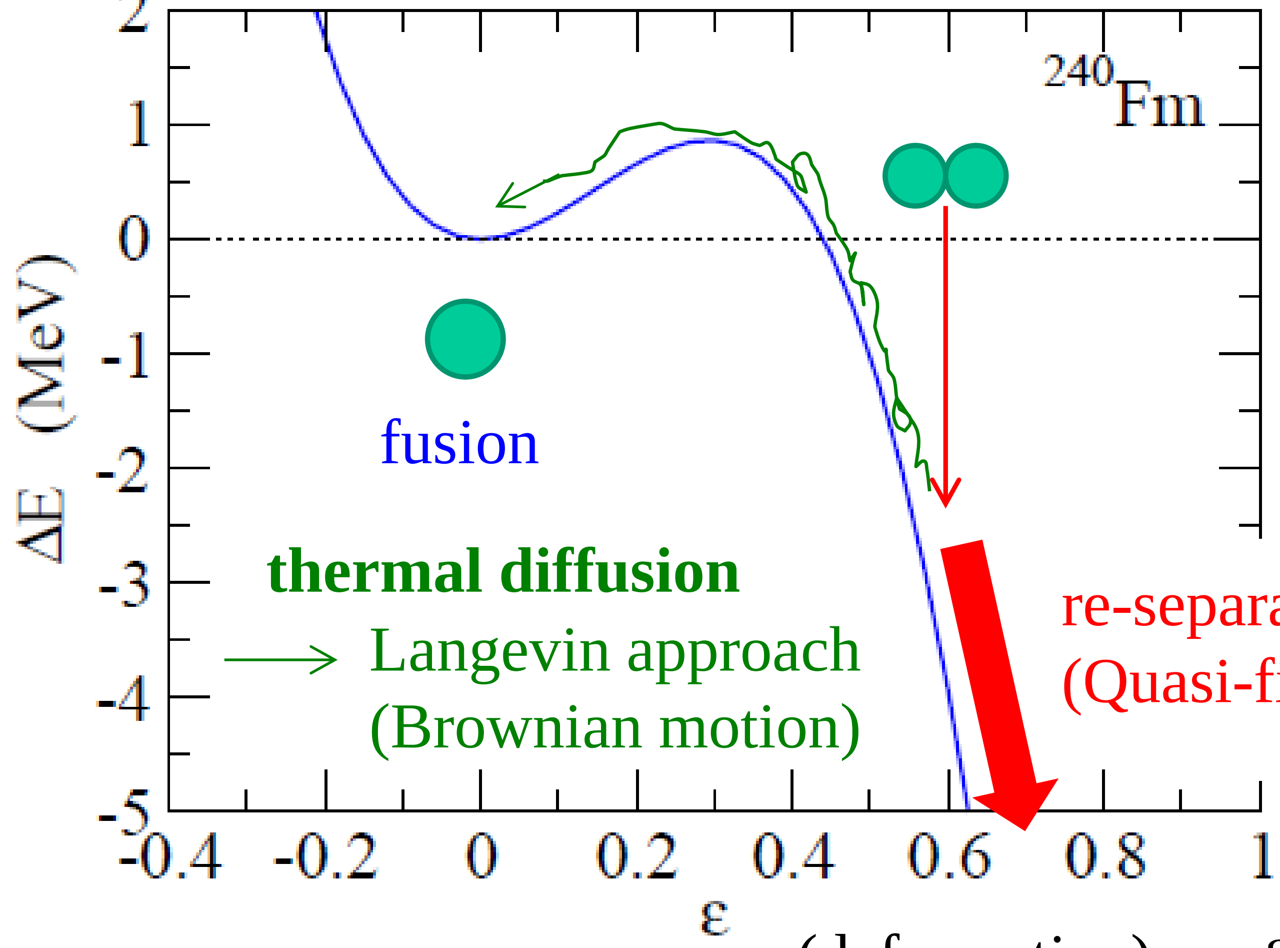
$\varepsilon_{\mathrm{touch}} \sim 0.587$

Formation phase: Langevin approach

Fission barrier (Liquid Drop Model)

touching point:
outside the fission barrier

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



fusion

thermal diffusion

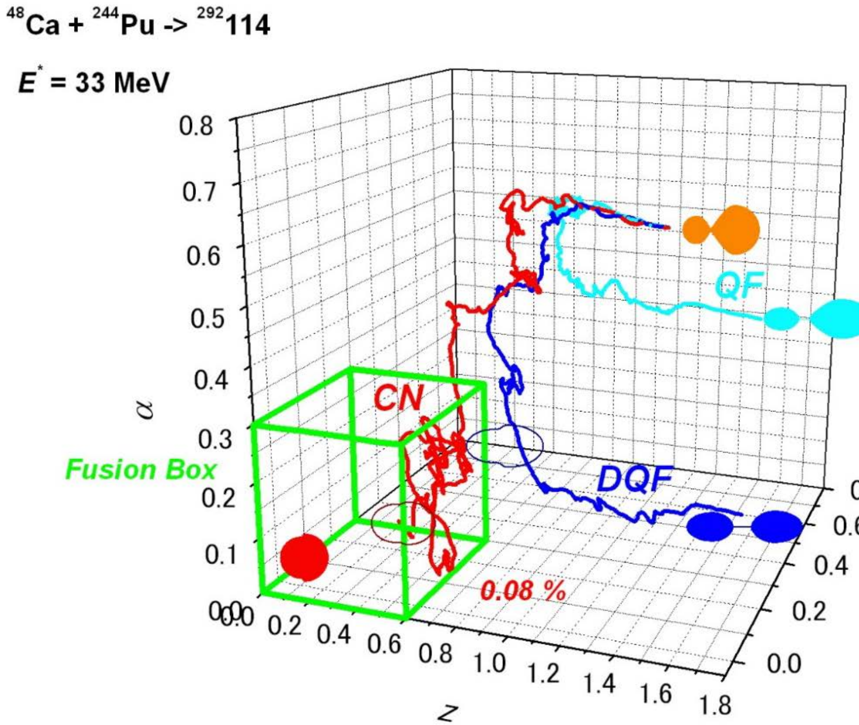
→ Langevin approach
(Brownian motion)

re-separation
(Quasi-fission)

(deformation)

$\varepsilon_{touch} \sim 0.587$

Langevin approach

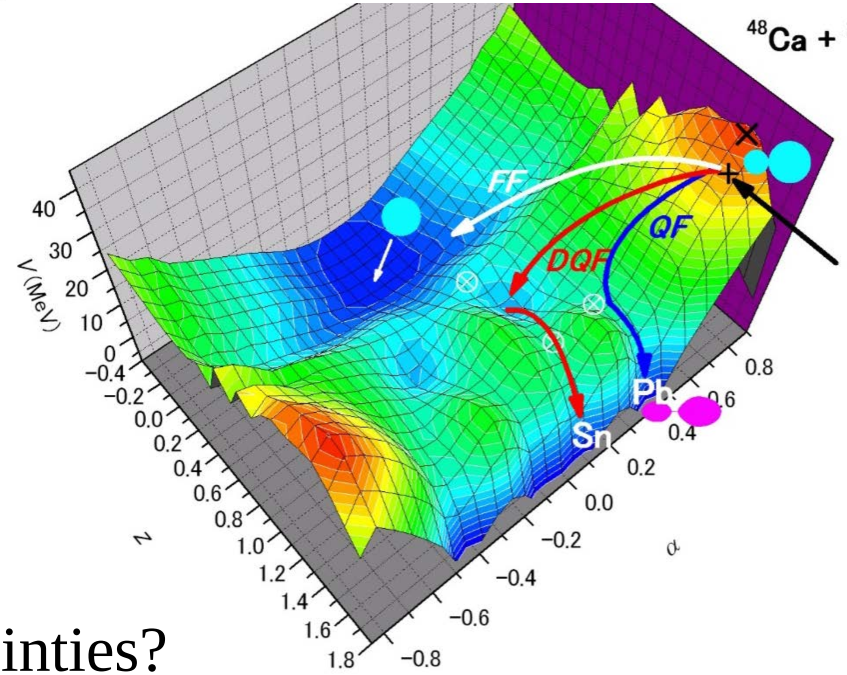


multi-dimensional extension of:

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

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

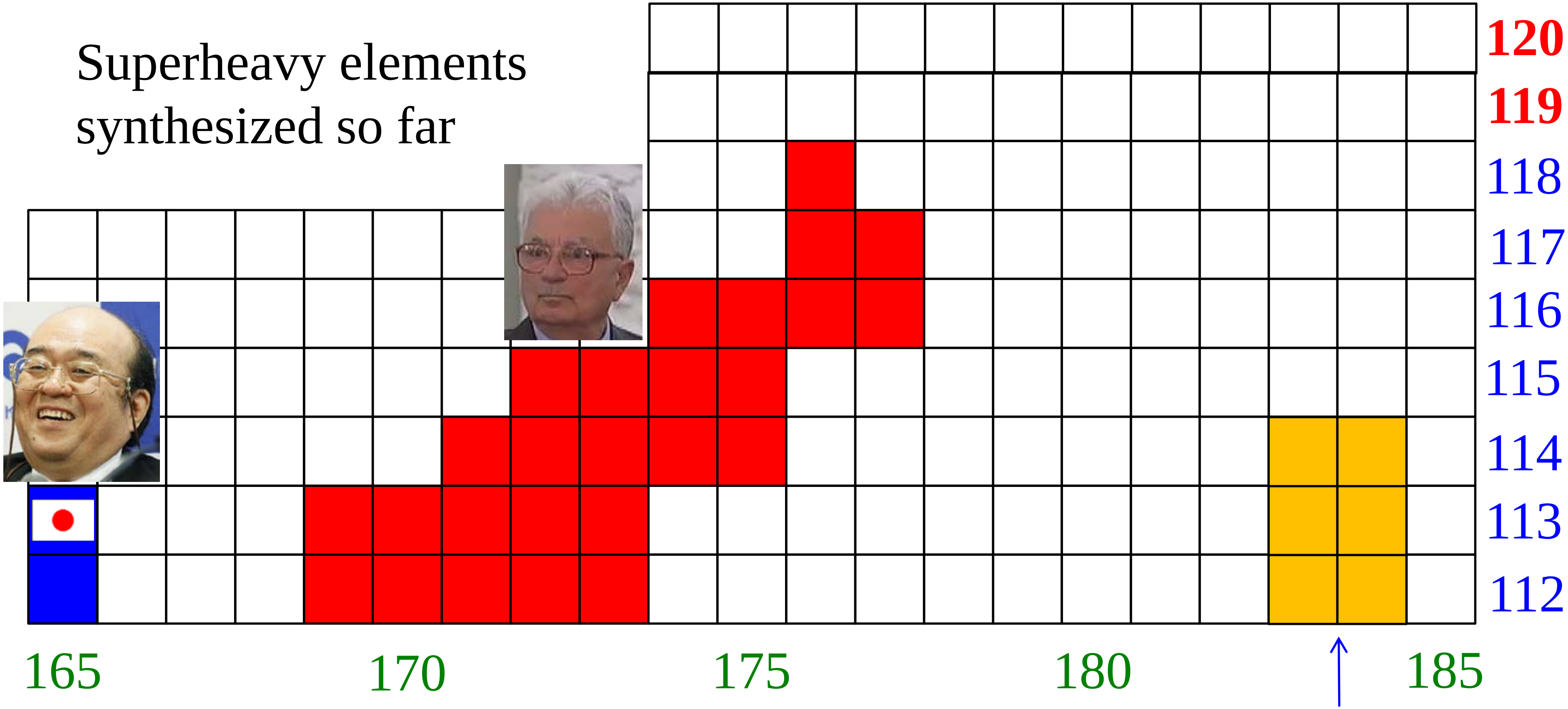
q:
- internuclear separation (*z*)
- deformation (δ)
- mass asymmetry (α) of the two fragments



a challenge: how to reduce
theoretical uncertainties?

Future directions

Superheavy elements
synthesized so far



the island of stability?

- ➢Towards Z=119 and 120 nuclei

  reaction dynamics? reliable prediction of fusion cross sections?

- ➢Towards the island of stability

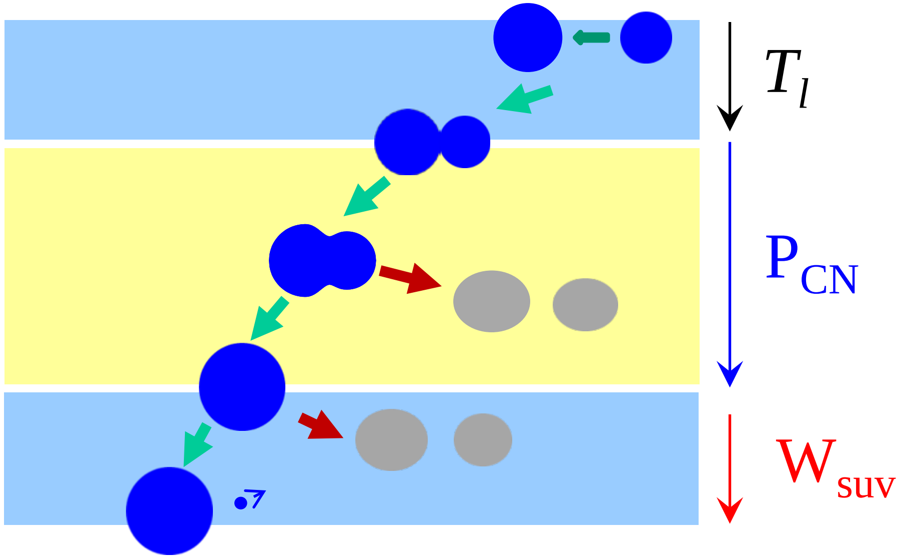
  neutron-rich beams: indispensable

Future directions -1

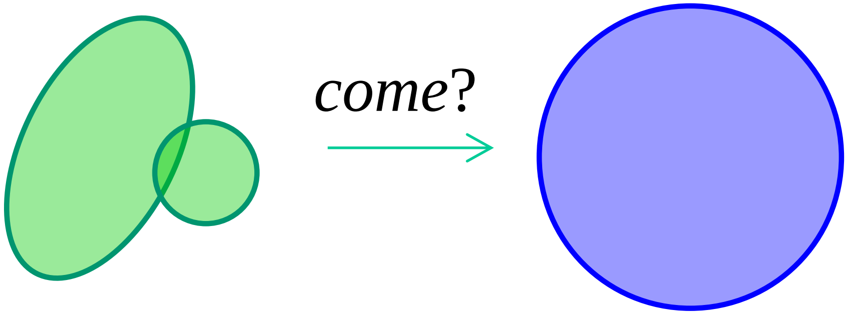
- Towards Z=119 and 120 nuclei

^{48}Ca projectile (hot fusion) → $^{50}_{22}$Ti, $^{51}_{23}$V, $^{54}_{24}$Cr projectile
+ deformed target nucleus

needs a proper understanding of deformation effects on SHE synthesis reactions



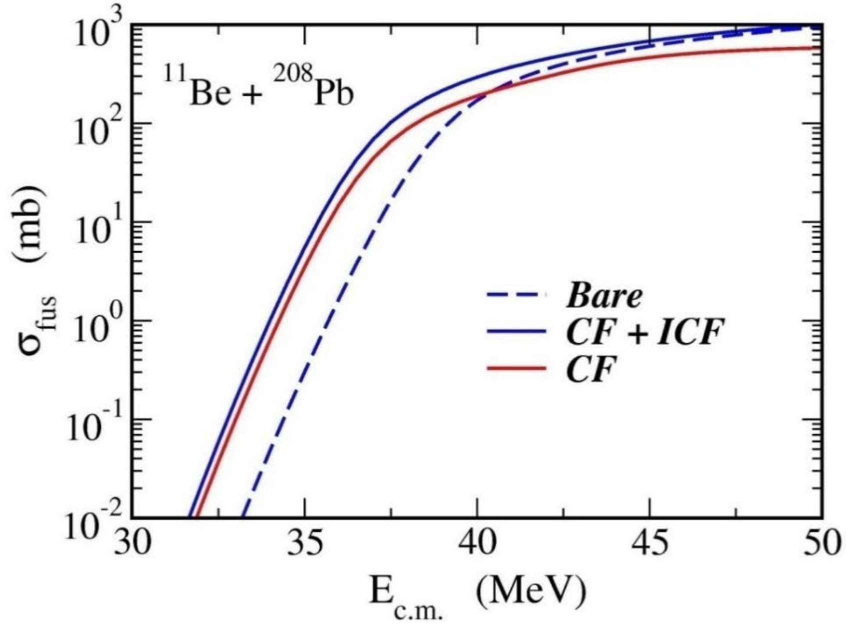
deformation effects on P_{CN} ?



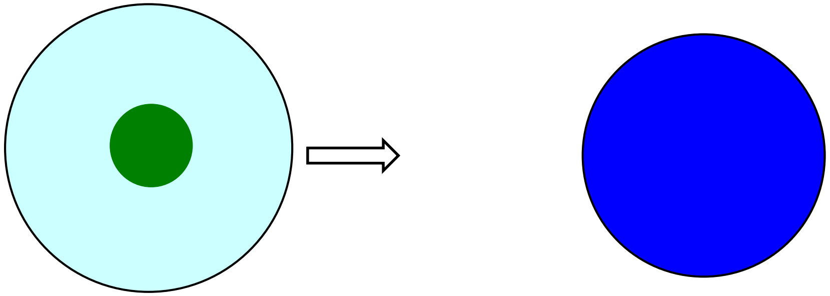
Future directions - 2

- ➢Towards the island of stability

  neutron-rich beams: indispensable



K. Hagino, A. Vitturi, C.H. Dasso,
and S.M. Lenzi, Phys. Rev. C61 ('00) 037602



simultaneous treatment
of breakup and transfer

→ an important future problem

Summary

Heavy-ion fusion reactions around the Coulomb barrier

- ✓Strong interplay between nuclear structure and reaction
- ✓Quantum tunneling with various intrinsic degrees of freedom
- ✓coupled-channels approach

Remaining challenges

- ✓ microscopic understanding of heavy-ion fusion reactions

Future perspectives: superheavy elements

- ✓ how to reduce theoretical uncertainties?
- ✓ Towards heavier SHE (Z = 119, 120)
- ✓ Towards the island of stability

investigations of physics of SHE with neutron-rich nuclei as a keyword