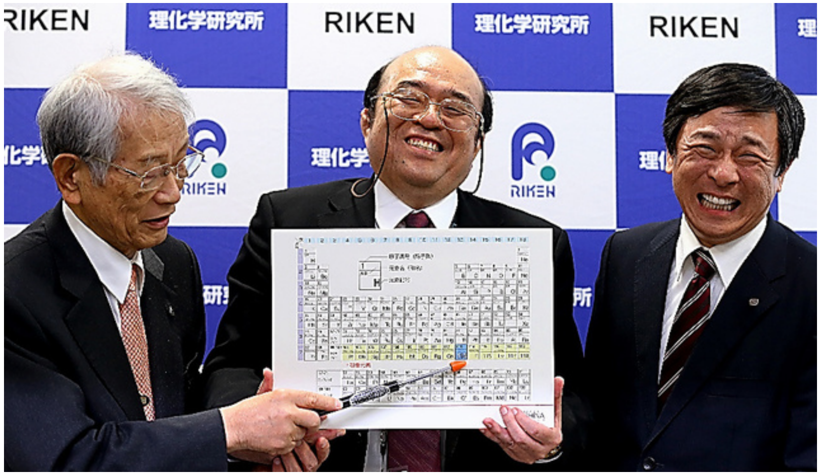
Heavy-ion fusion reactions: quantum tunneling with many degrees of freedom and superheavy elements

Kouichi Hagino
Tohoku University



Element 113
Nihonium (Nh)

Nov., 2016

Physics of SHE
→ very current topics

theory:
improvement of predictive power

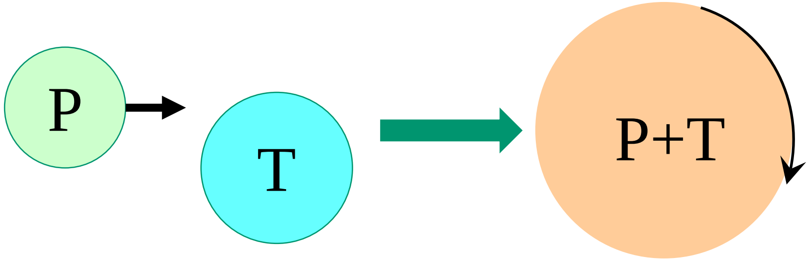
Heavy-ion fusion reactions: quantum tunneling with many degrees of freedom and superheavy elements

Kouichi Hagino
Tohoku University

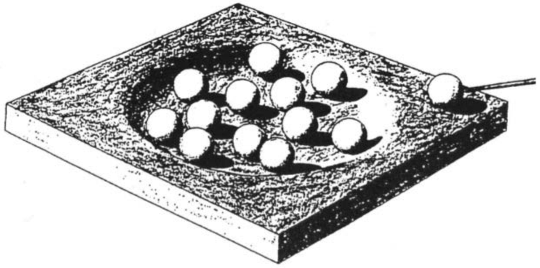
1. H.I. fusion reactions: why are they interesting?
2. Coupled-channels approach
3. Remaining challenges
4. Future perspectives: superheavy elements

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

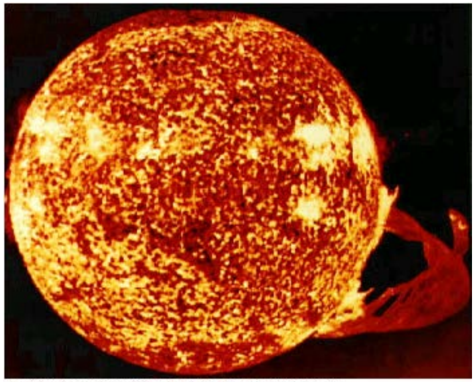
Fusion reactions: compound nucleus formation



compound
nucleus

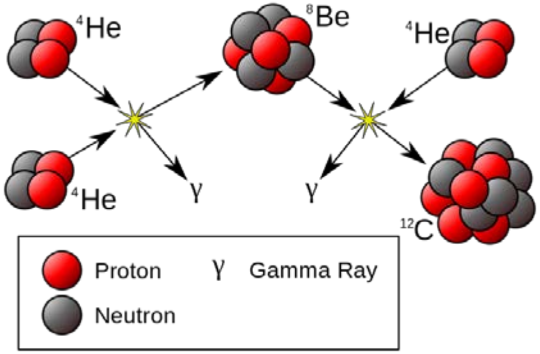


cf. Bohr ‘36

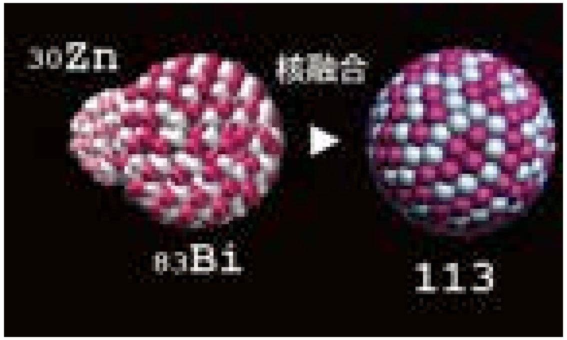


NASA, Skylab space station December 19, 1973, solar flare reaching 588 000 km off solar surface

energy production
in stars (Bethe ‘39)



nucleosynthesis

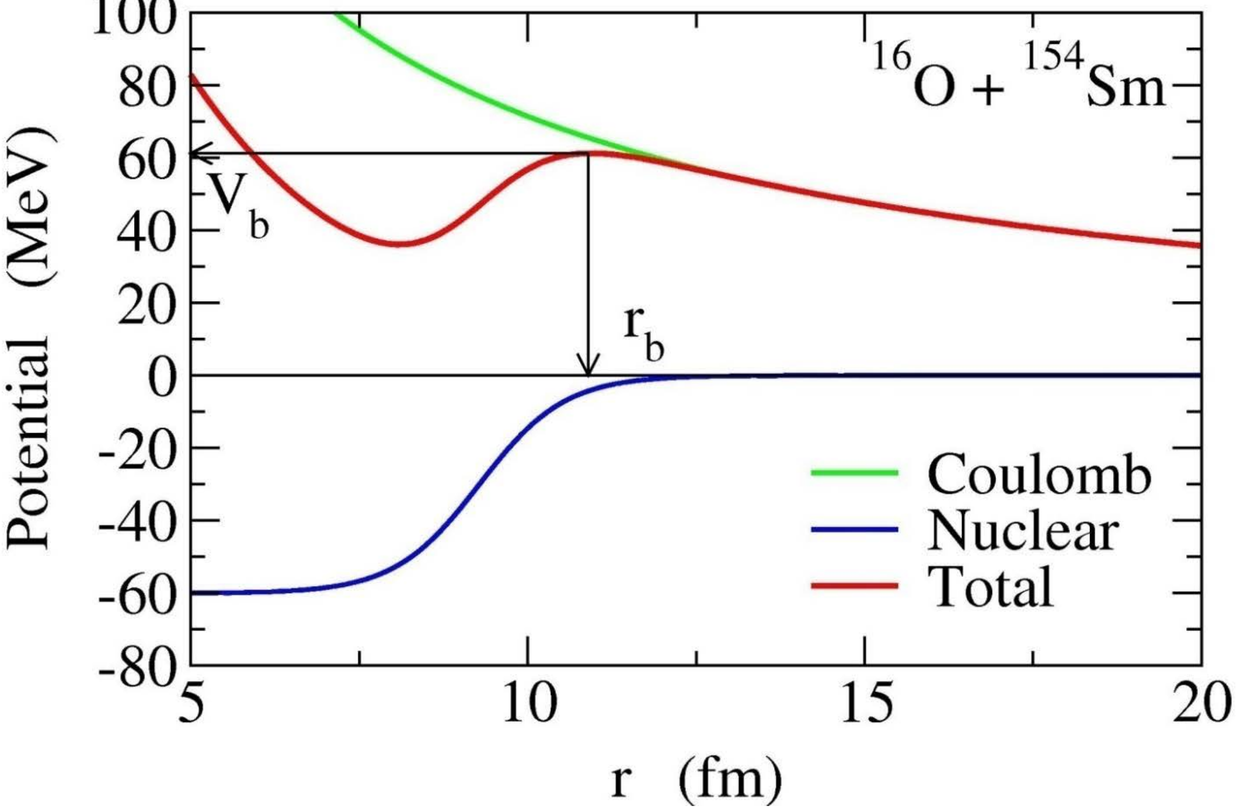


superheavy elements

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

⟵ microscopic understanding: an ultimate goal of nuclear physics

Inter-nucleus potential



Two interactions:

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

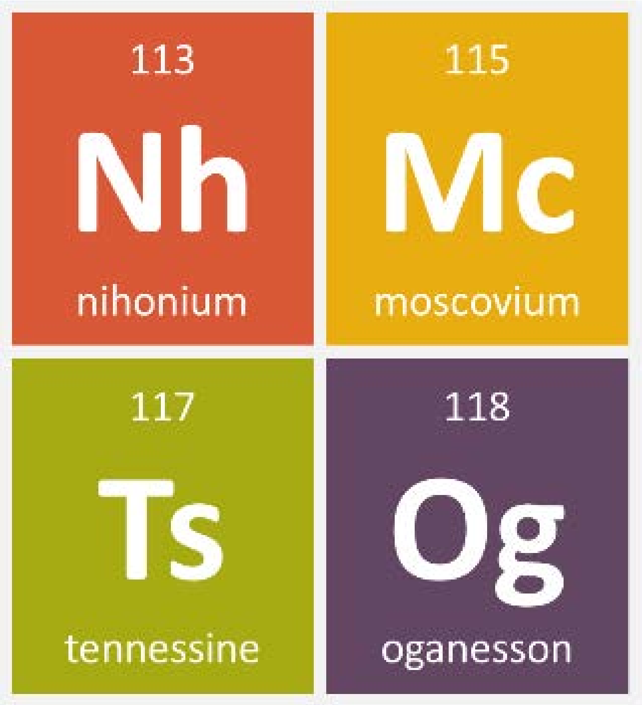
⬇

<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:

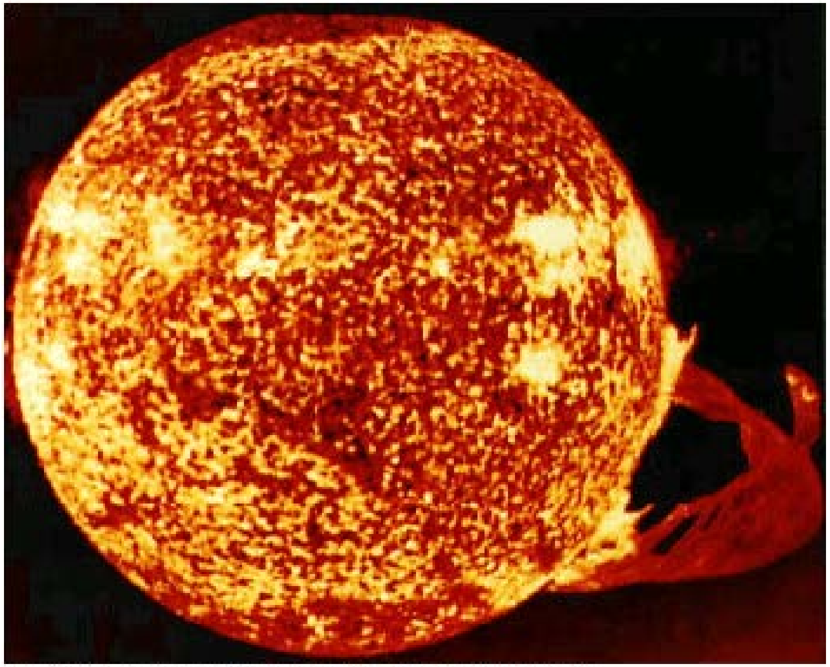


superheavy elements

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

$V_B \sim 260$ MeV

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



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

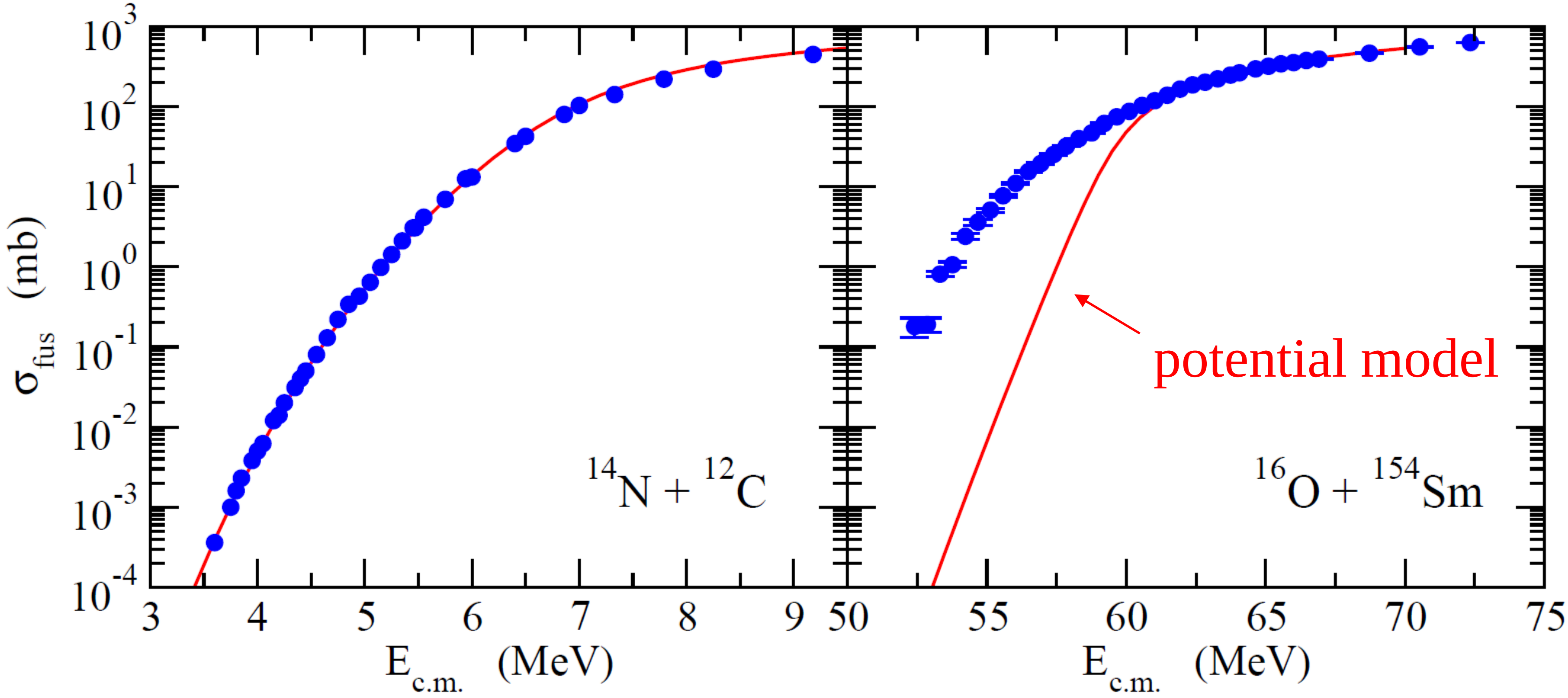
- many types of intrinsic degrees of freedom
  (several types of collective vibrations,
  deformation with several multipolarities, transfer)
- energy dependence of tunneling probability
  cf. alpha decay: fixed energy

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

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

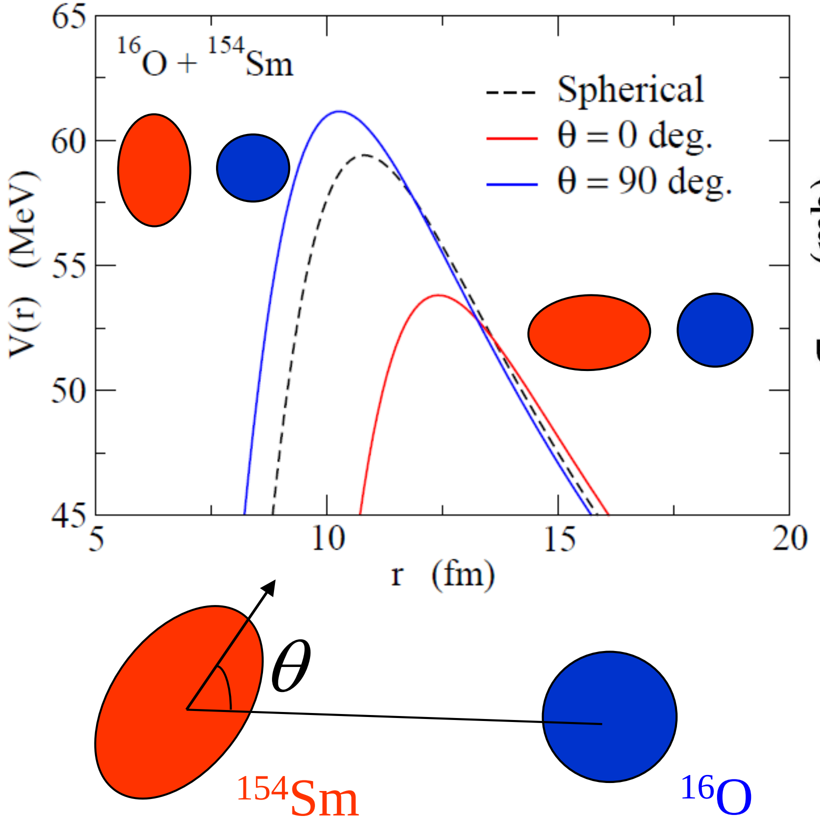


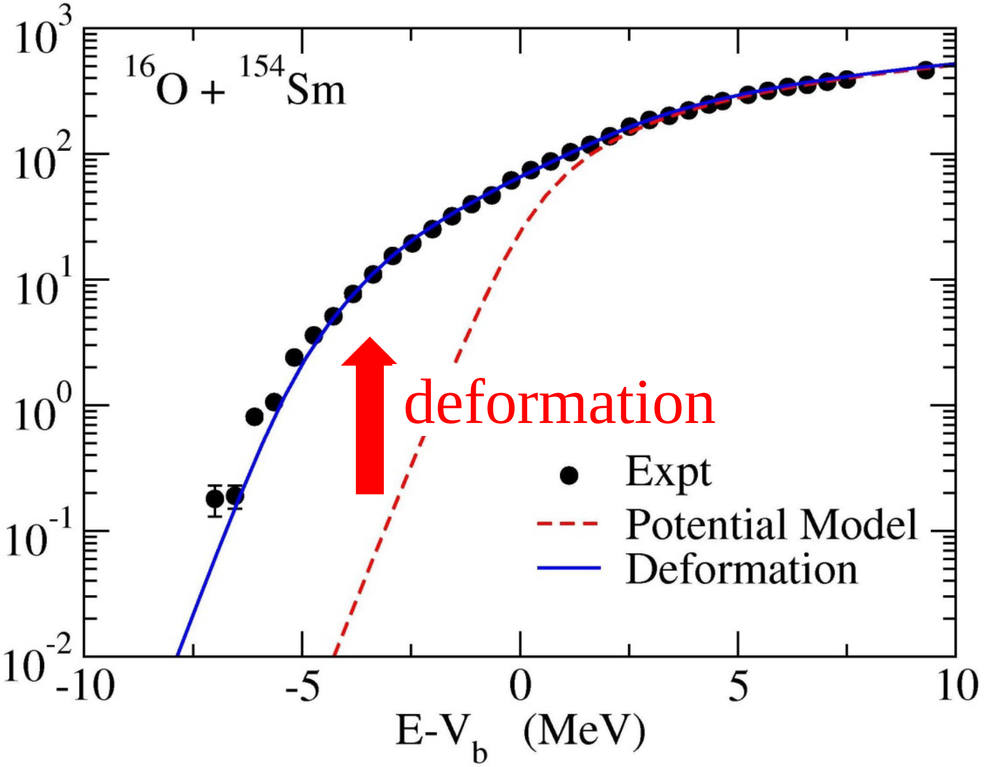
cf. seminal work:
R.G. Stokstad et al., PRL41('78) 465

Effects of nuclear deformation

^{154}Sm : a typical deformed nucleus

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

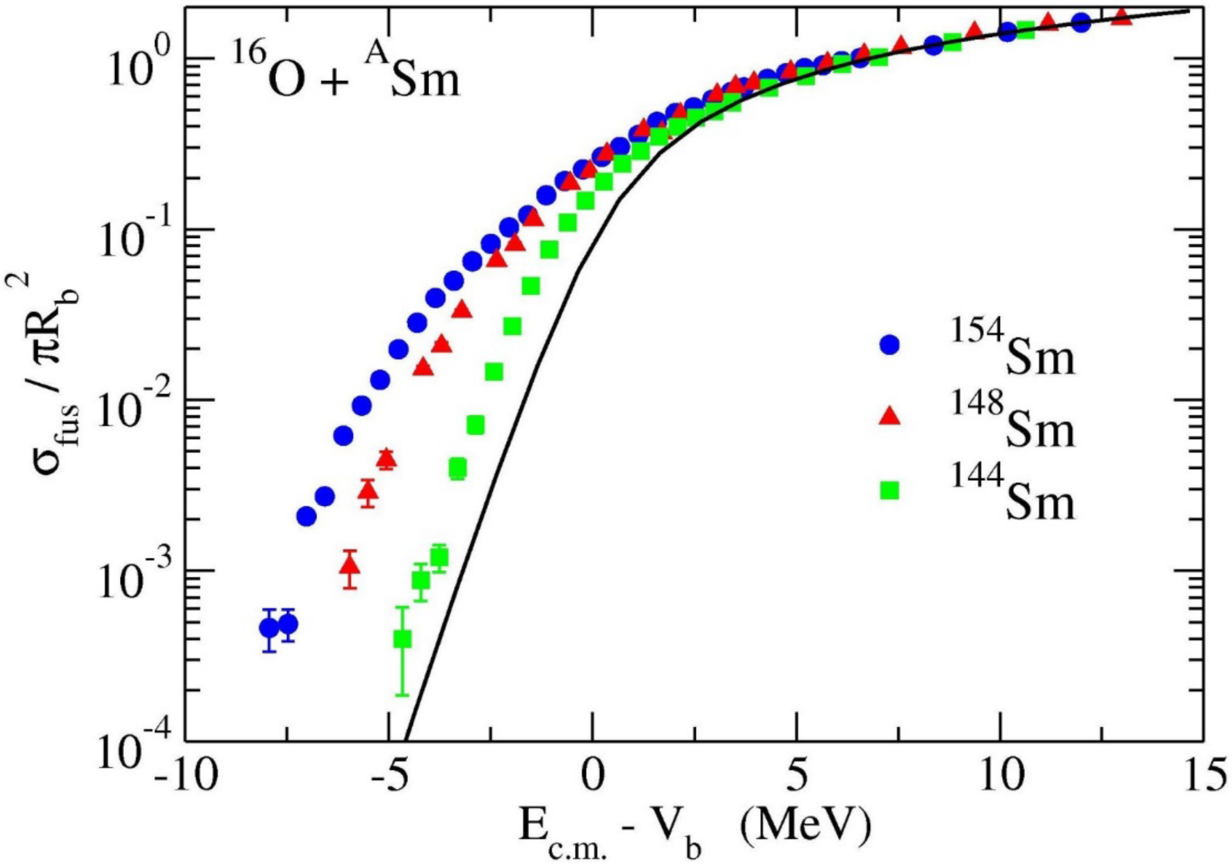




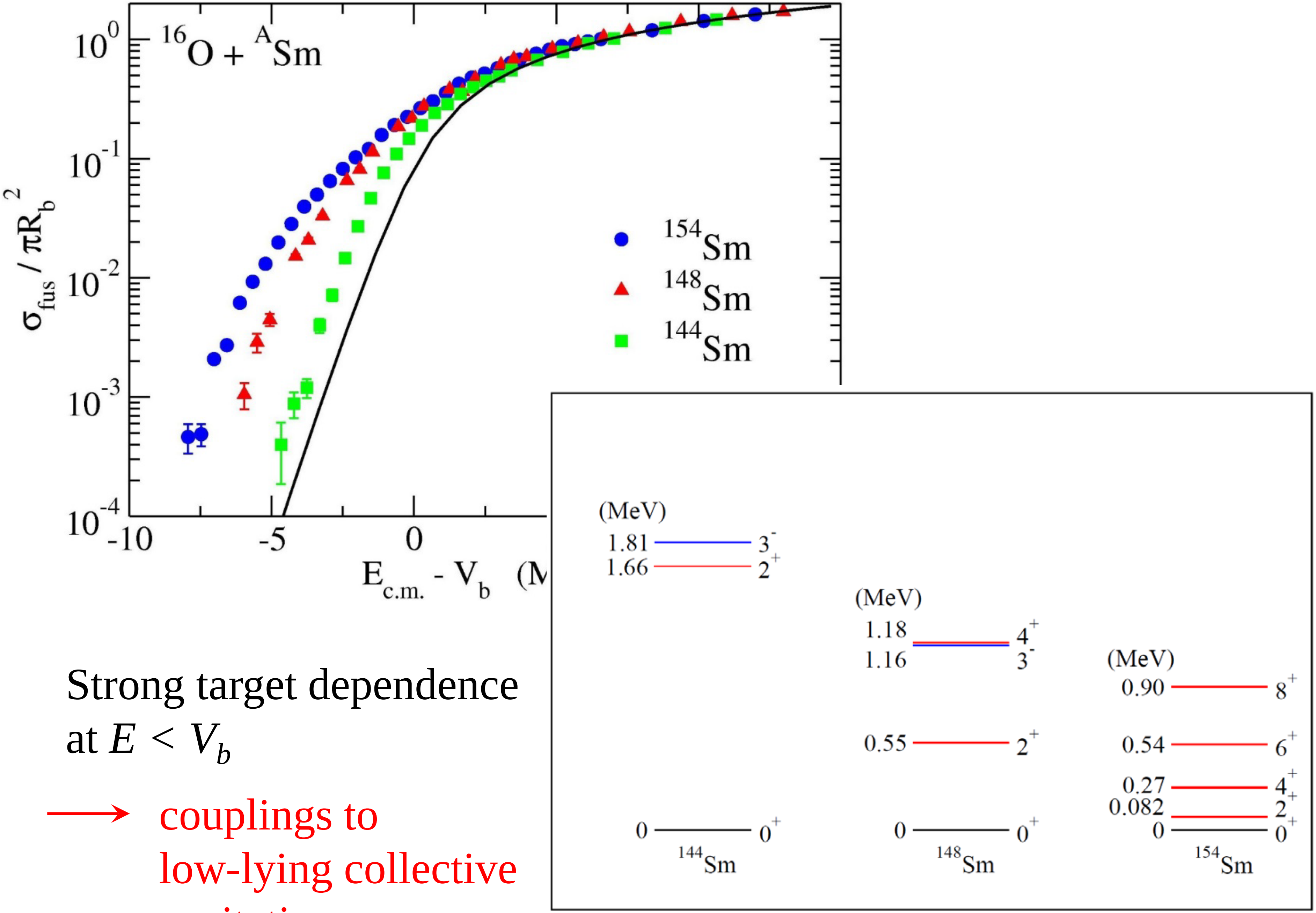
Fusion: strong interplay between nuclear structure and reaction

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

couplings to low-lying collective excitations → coupling assisted tunneling



$^{16}O + {}^{A}Sm$
$\sigma_{fus} / \pi R_b^2$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
-10
-5
0
5
10
15
$E_{c.m.} - V_b$ (MeV)
● ^{154}Sm
▲ ^{148}Sm
■ ^{144}Sm

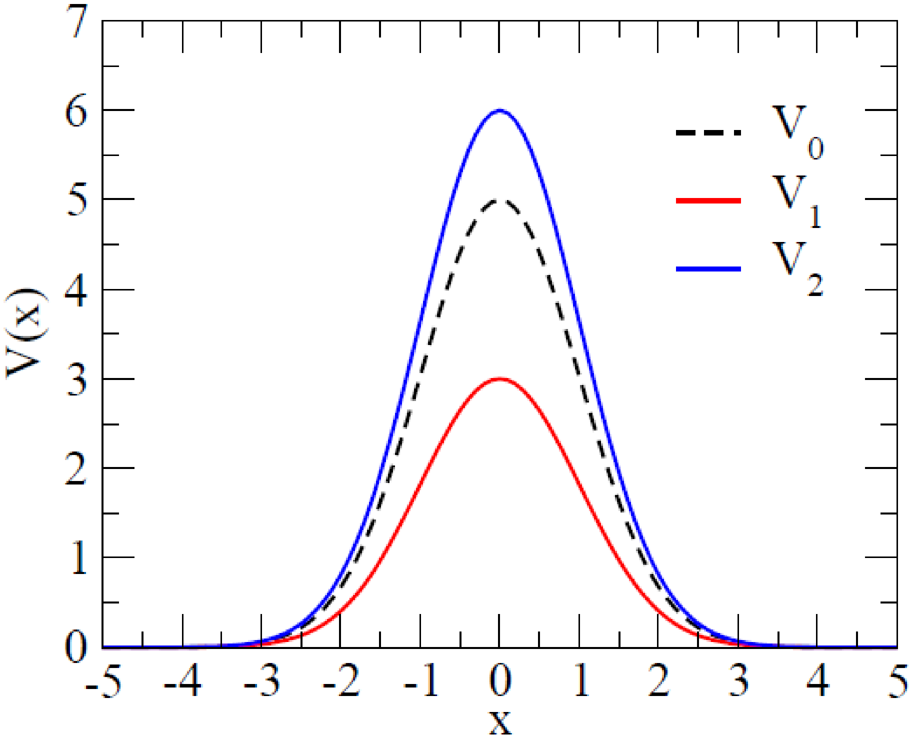


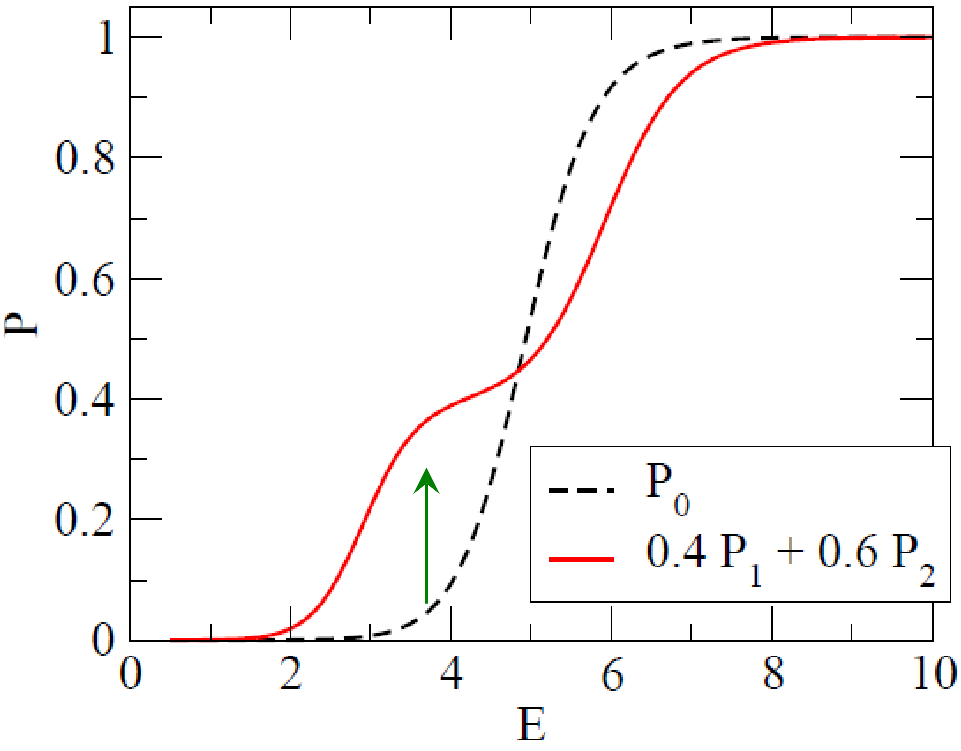
Strong target dependence
at $E < V_b$

→ couplings to
low-lying collective
excitations

Enhancement of tunneling probability
: a problem of two potential barriers

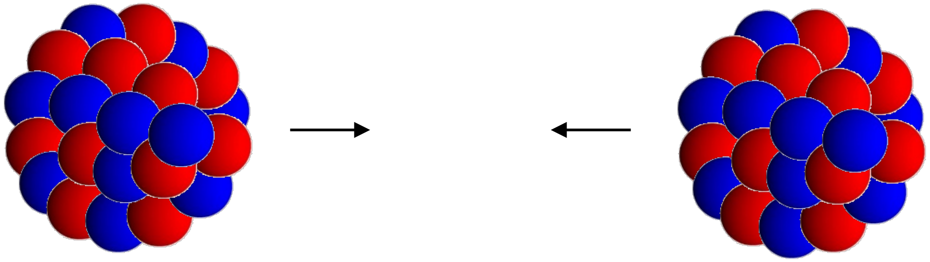
$$P(E) = P(E; V_0) \to w_1 P(E; V_1) + w_2 P(E; V_2)$$





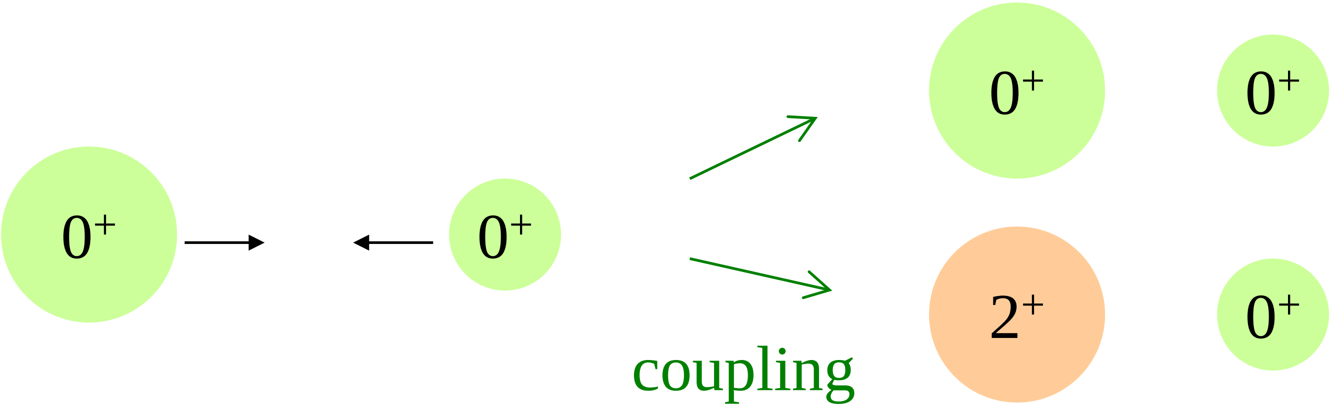
Coupled-channels method: a quantal scattering theory with excitations

many-body problem

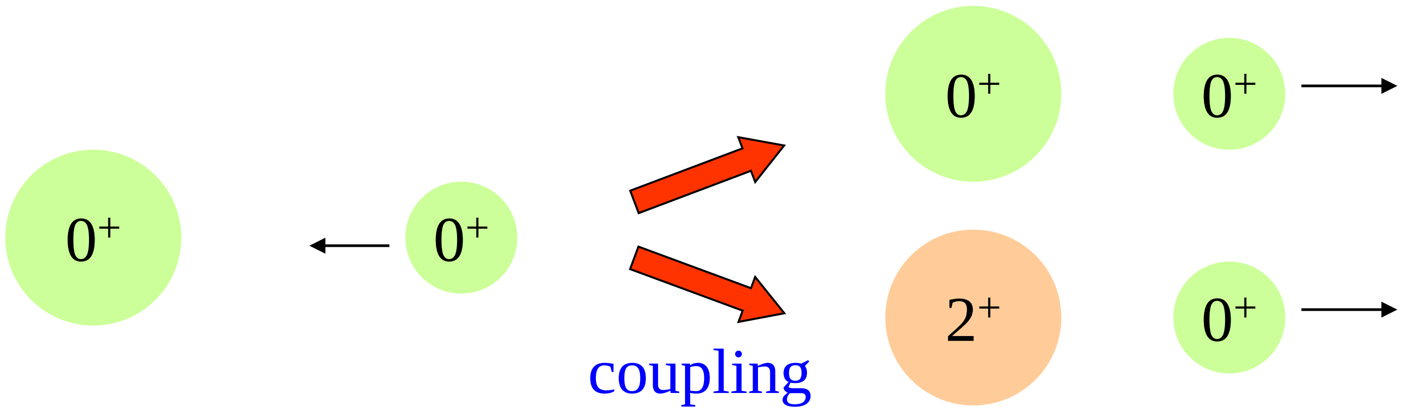


still very challenging

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



Coupled-channels method: a quantal scattering theory with excitations



coupling

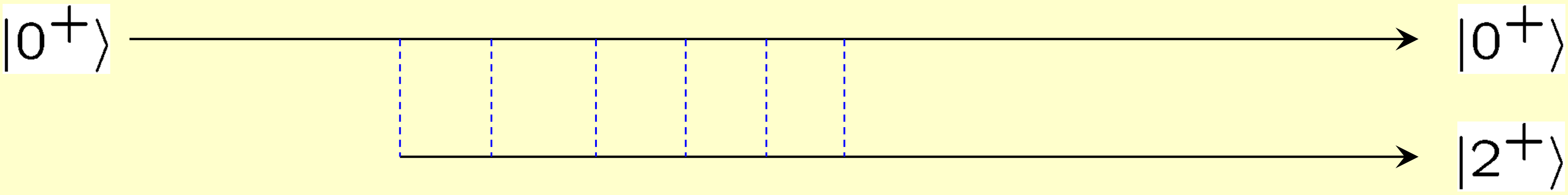
entrance channel

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

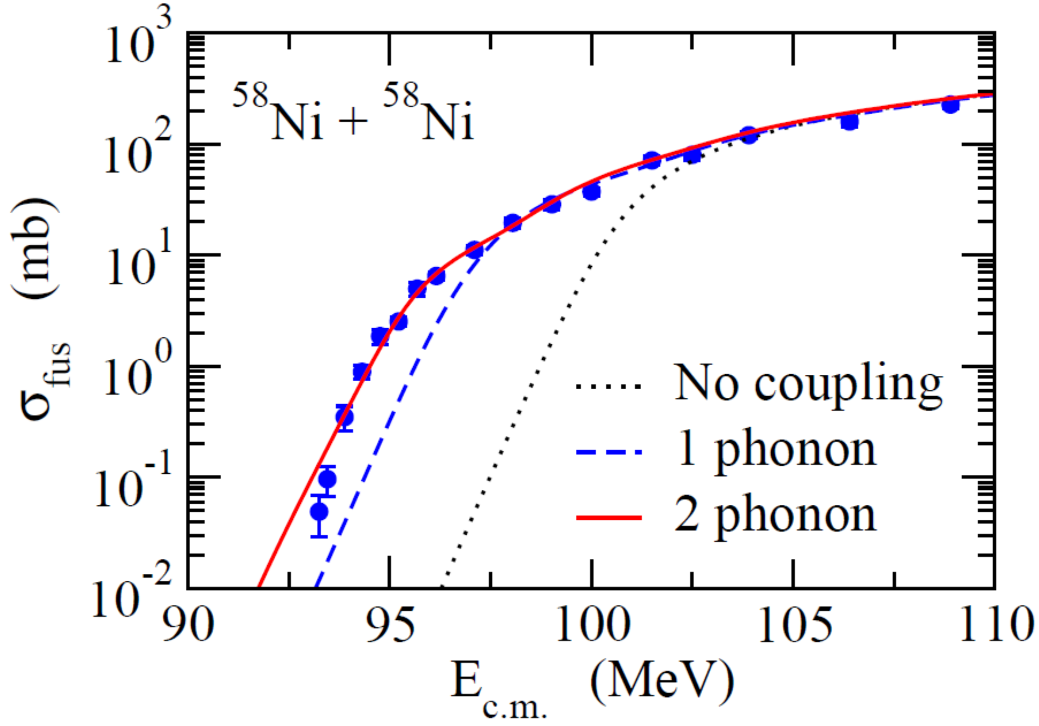
Inputs for C.C. calculations

i) Inter-nuclear potential

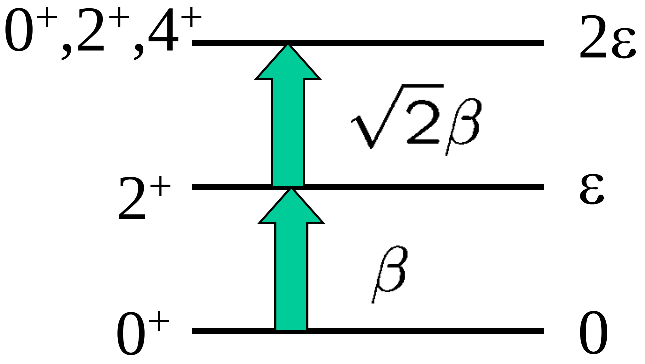
a fit to experimental data at above barrier energies

ii) Intrinsic degrees of freedom

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

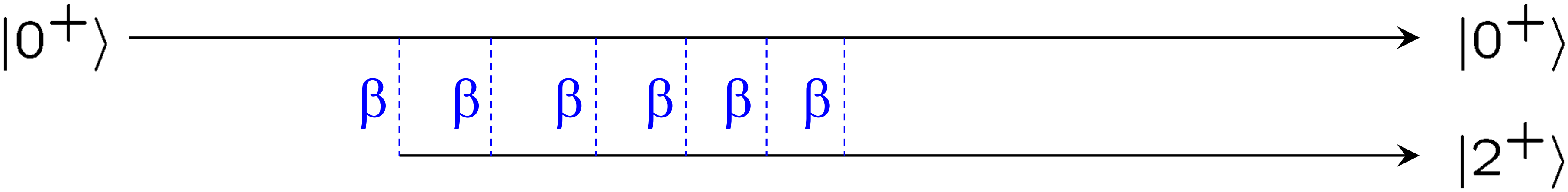


simple harmonic oscillator



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

cf. CC*FULL* (K.H., N. Rowley, A.T. Kruppa, CPC123 ('99) 143)



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

but only 1st order in Hamiltonian → inconsistency

$$V_{\rm coup}(r) \sim -R\beta\,\frac{dV_N(r)}{dr}$$

→ improve to include all orders also in Hamiltonian

$$\langle\phi_n|V(r-x)|\phi_m\rangle \sim V(r)\,\delta_{n,m} - \frac{dV(r)}{dr}\,\langle\phi_n|x|\phi_m\rangle$$

$$\Longrightarrow\quad \boxed{\langle\phi_n|V(r-x)|\phi_m\rangle = \int dx\,\phi_n^*(x)\phi_m(x)\,V(r-x)}$$

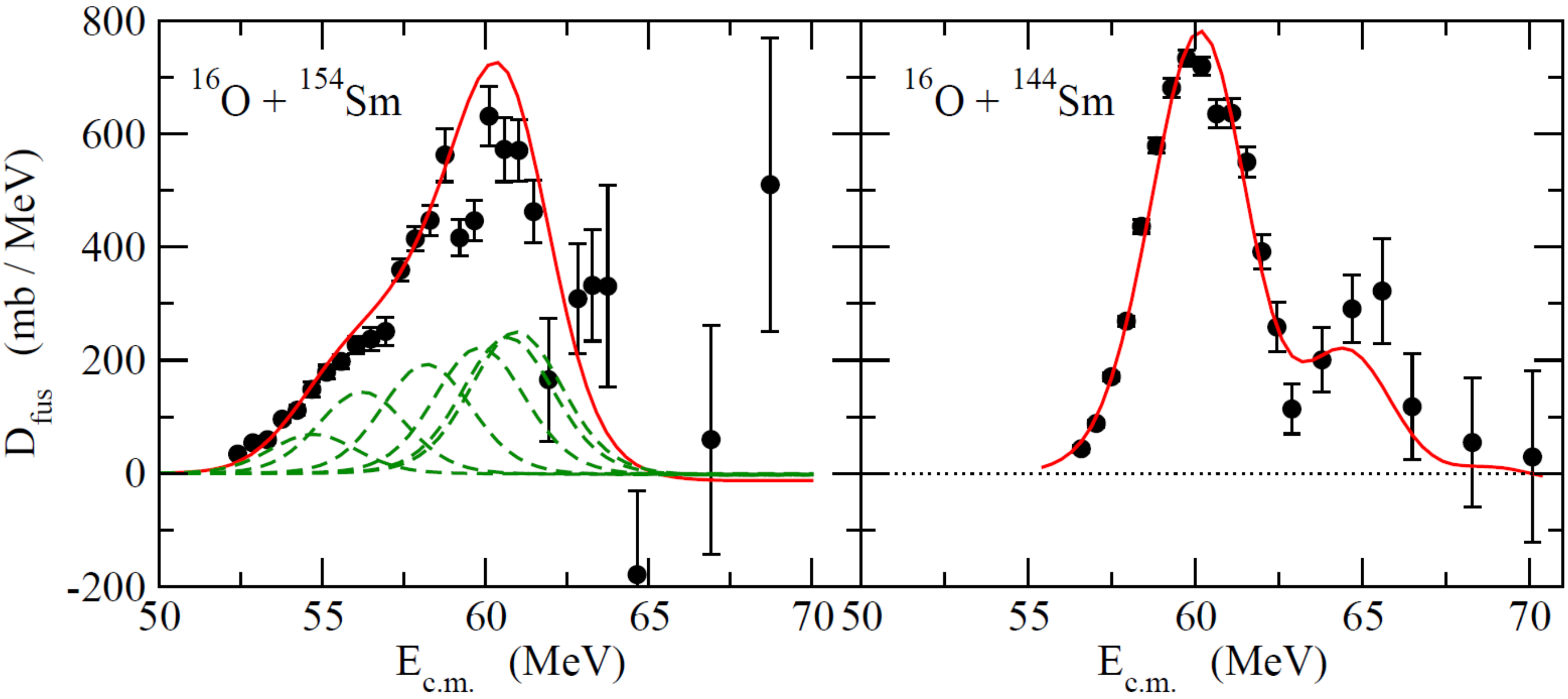
C.C. approach: a standard tool for sub-barrier fusion reactions

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

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

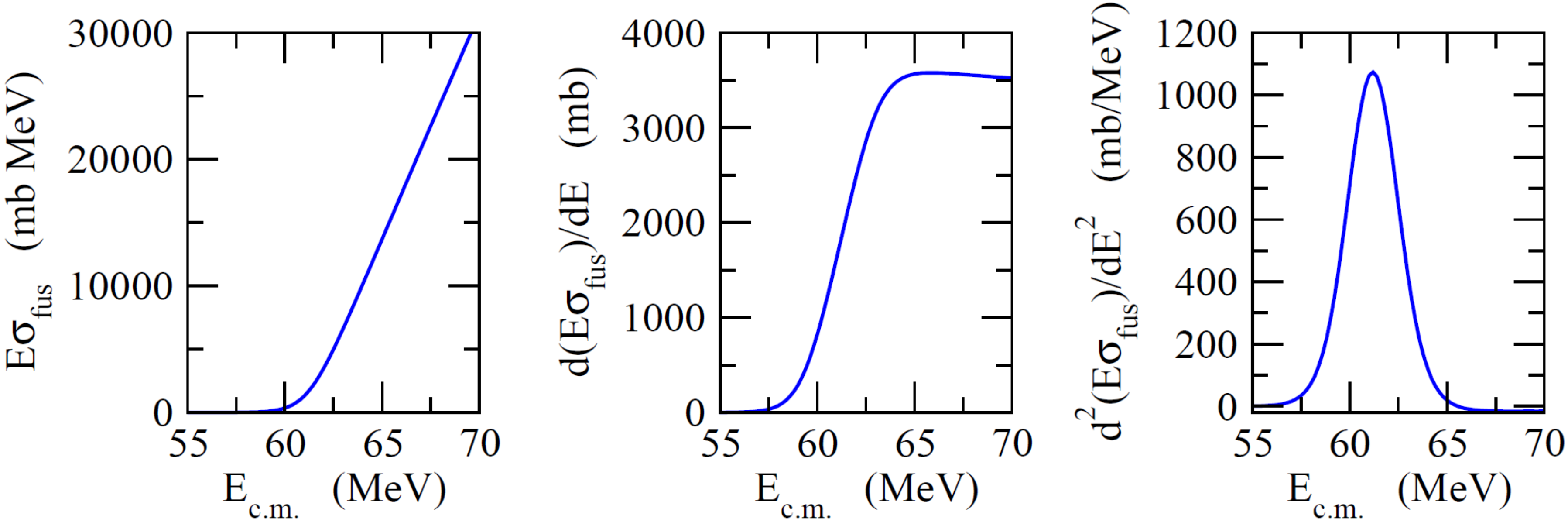
$$D_{\text{fus}}(E) = \frac{d^2(E\sigma_{\text{fus}})}{dE^2}$$

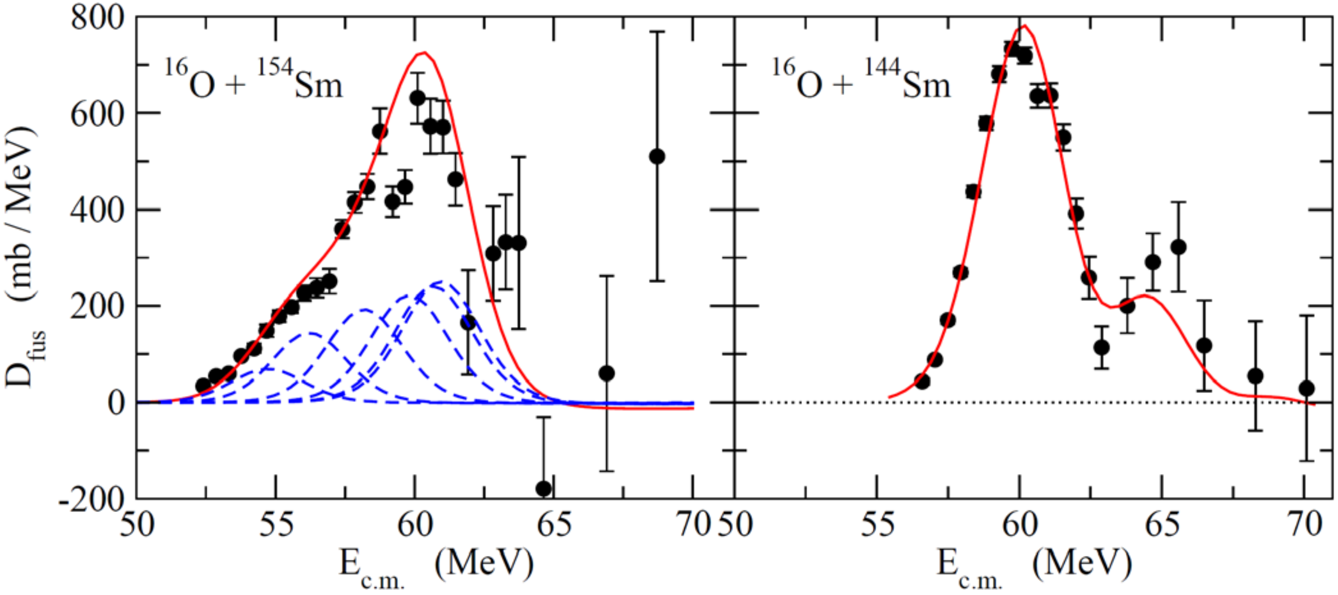
—— c.c. calculations



K.H., N. Takigawa, PTP128 (‘12) 1061

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

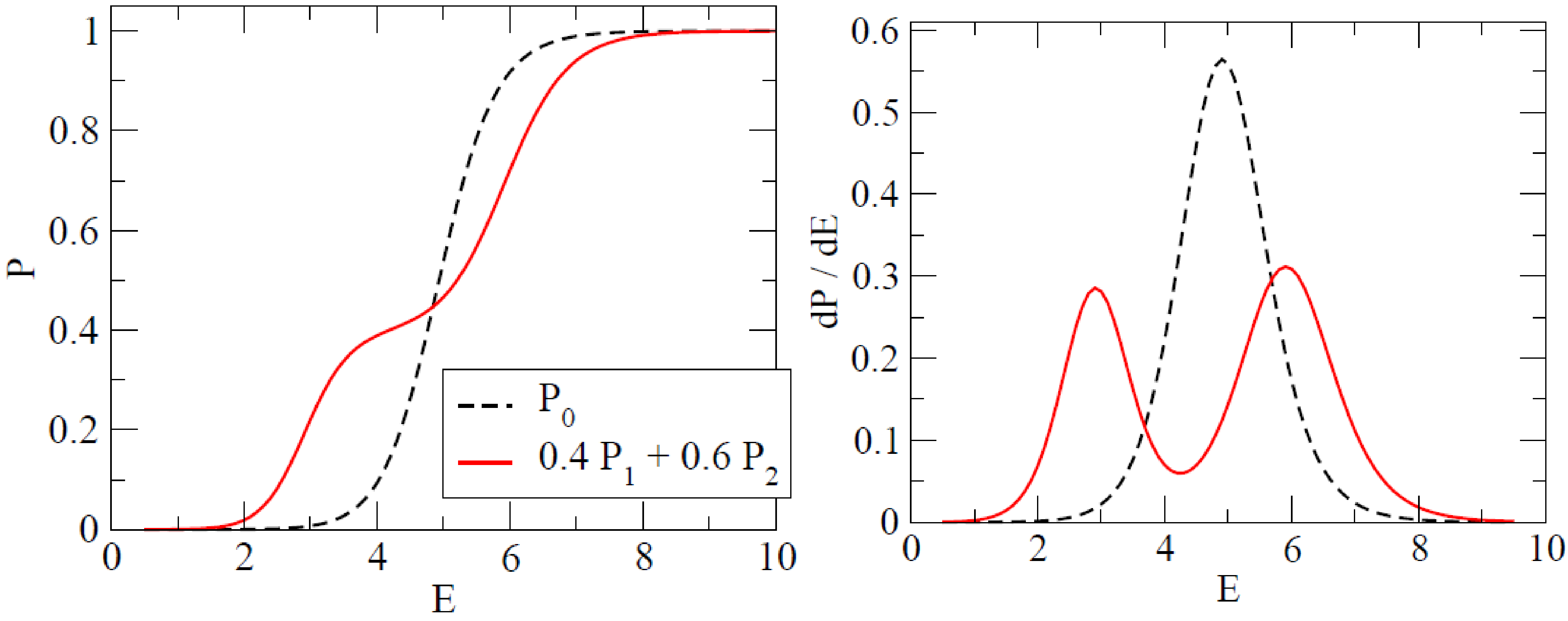




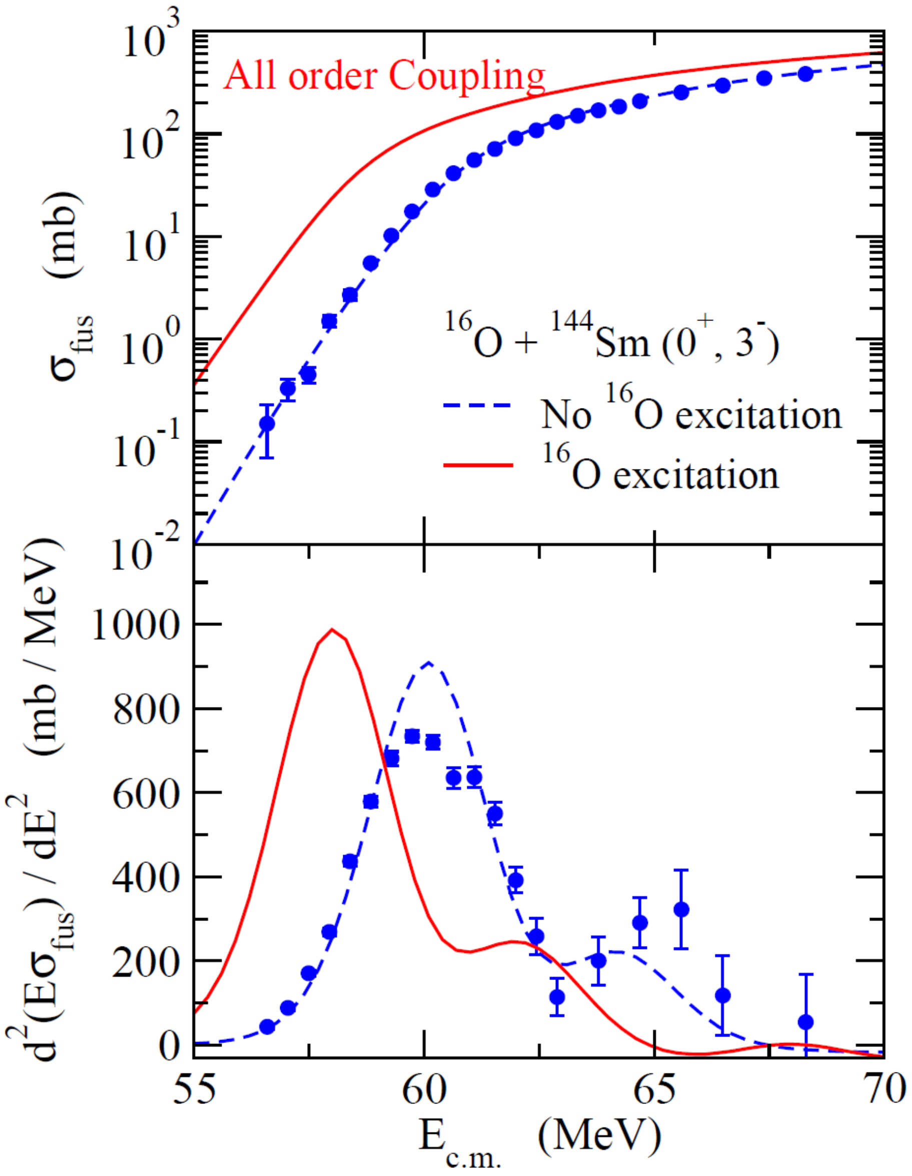
K.H. and N. Takigawa, PTP128 ('12) 1061

barrier distribution: a problem of two potential barriers

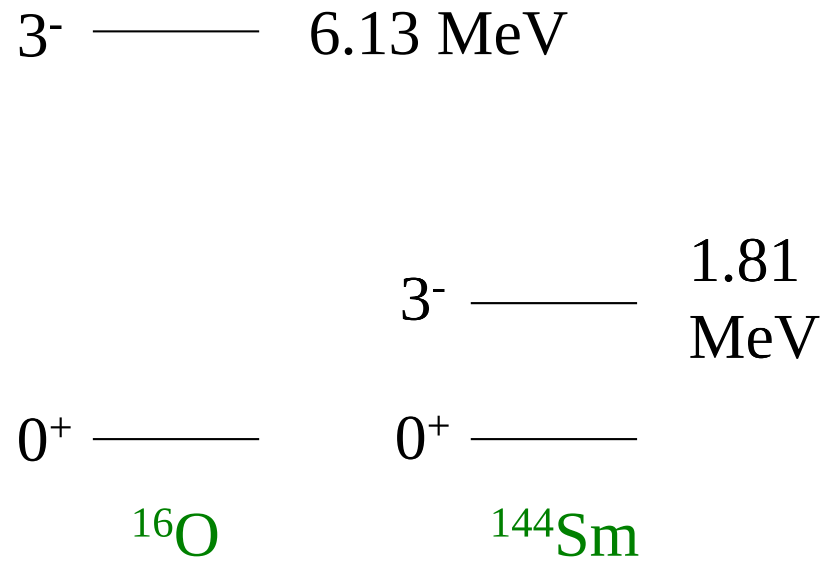
$$P(E) = P(E;V_0) \to w_1 P(E;V_1) + w_2 P(E;V_2)$$



Adiabatic potential renormalization

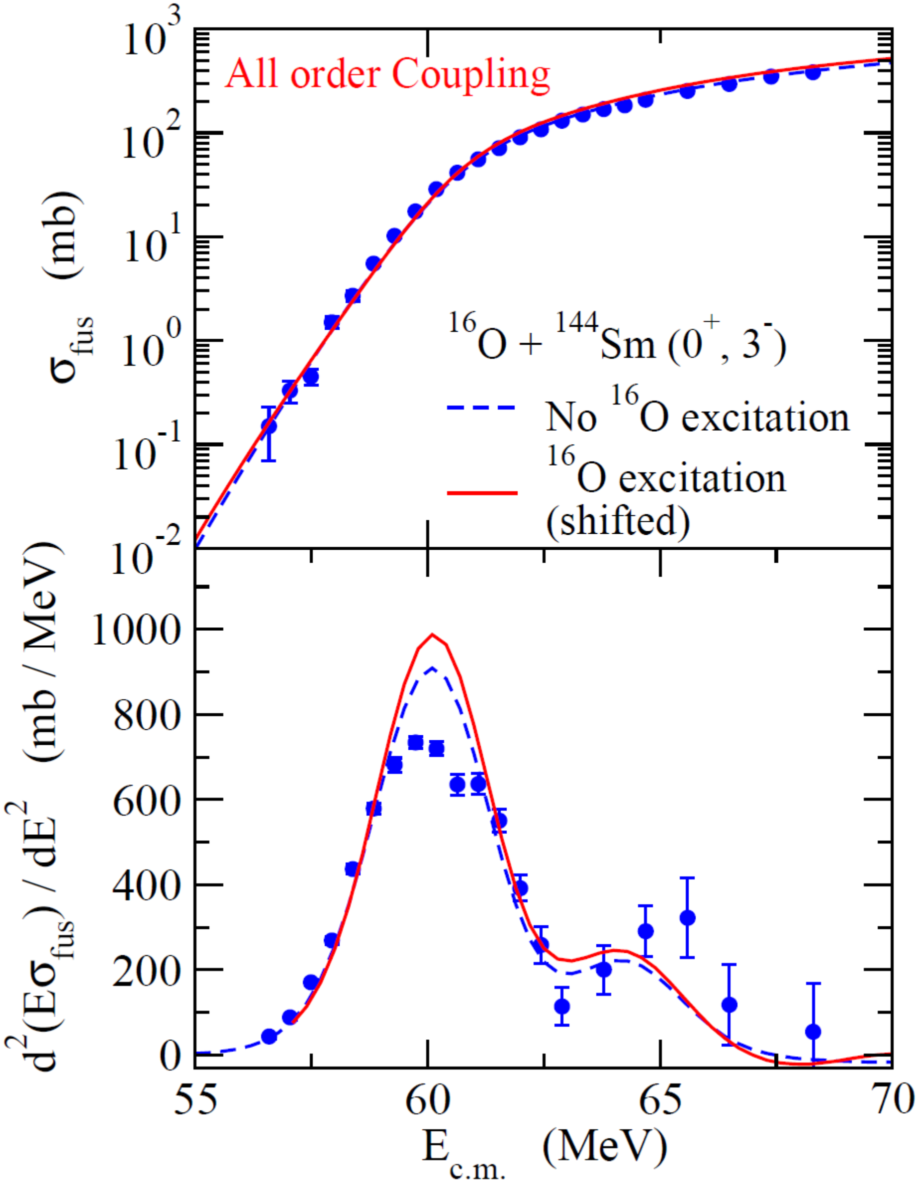


^{16}O + ^{144}Sm



K. Hagino, N. Takigawa, M. Dasgupta, D.J. Hinde, and J.R. Leigh, PRL79 (‘97) 2014

Adiabatic potential renormalization



- ✓ couplings to high-lying states
  : no change in *E*-dependence of
  fusion cross sections
- ✓ simply changes the static potential
  (adiabatic potential renormalization)

⬇

coupled-channels calculations:
sufficient only with low-lying
excitations

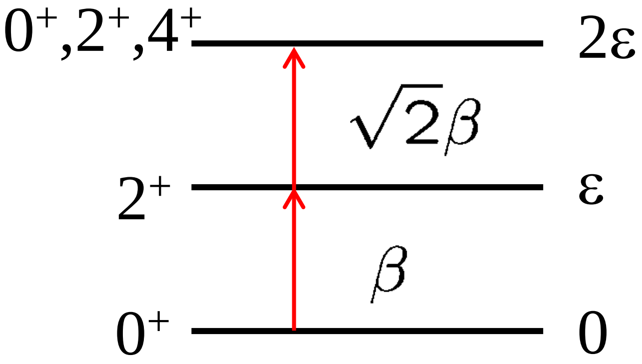
K. Hagino, N. Takigawa, M. Dasgupta, D.J. Hinde, and J.R. Leigh, PRL79 (‘97) 2014

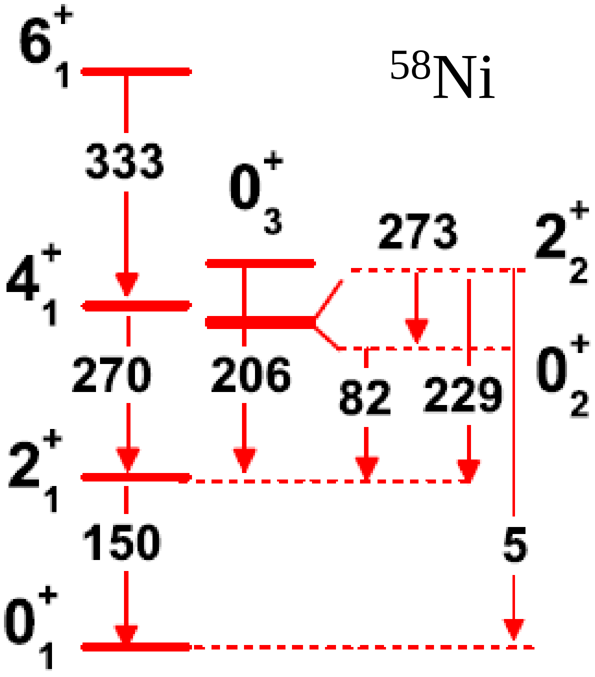
Further developments : C.C. with several nuclear structure models

K.H. and J.M. Yao, PRC91('15) 064606

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

simple harmonic
oscillator

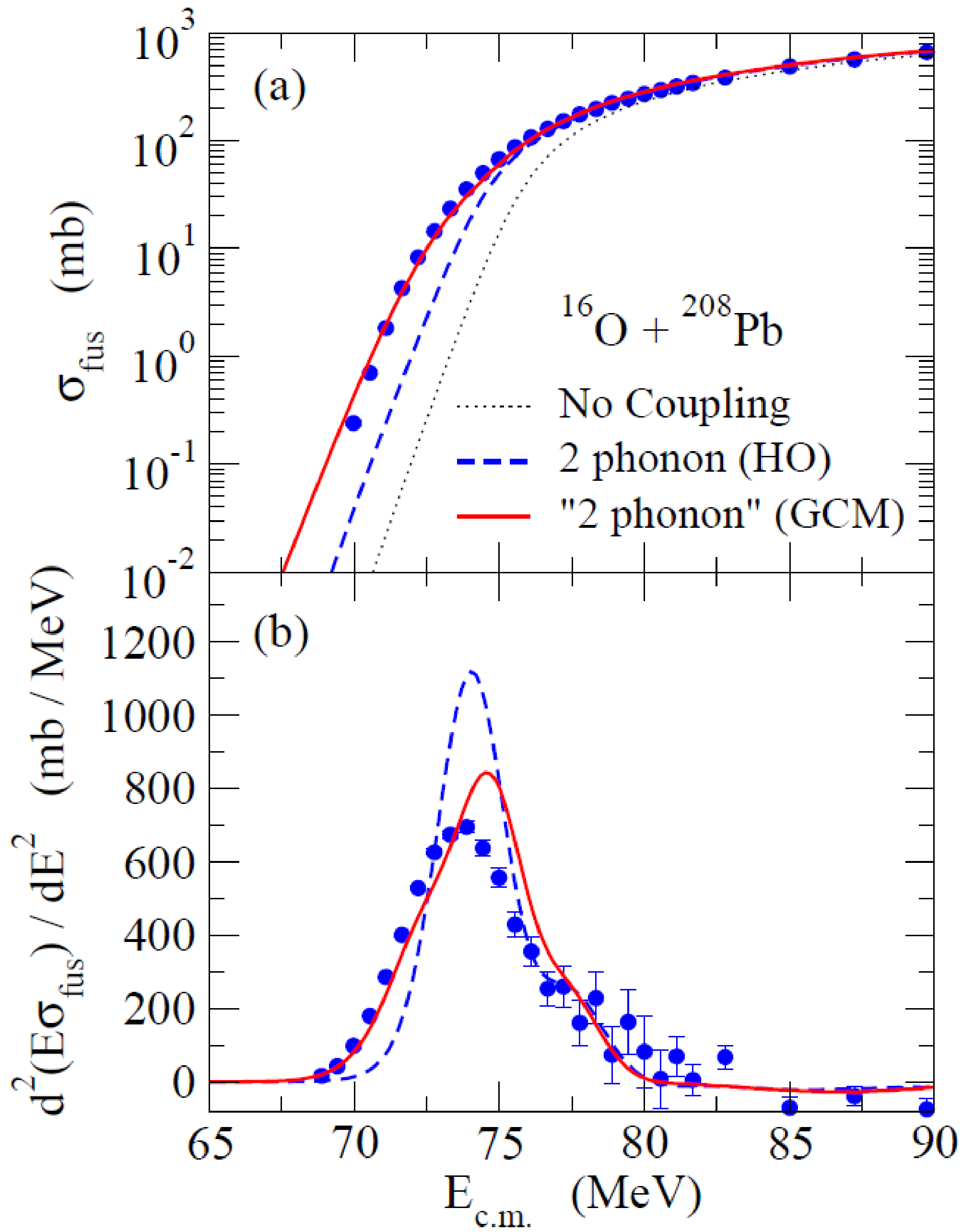


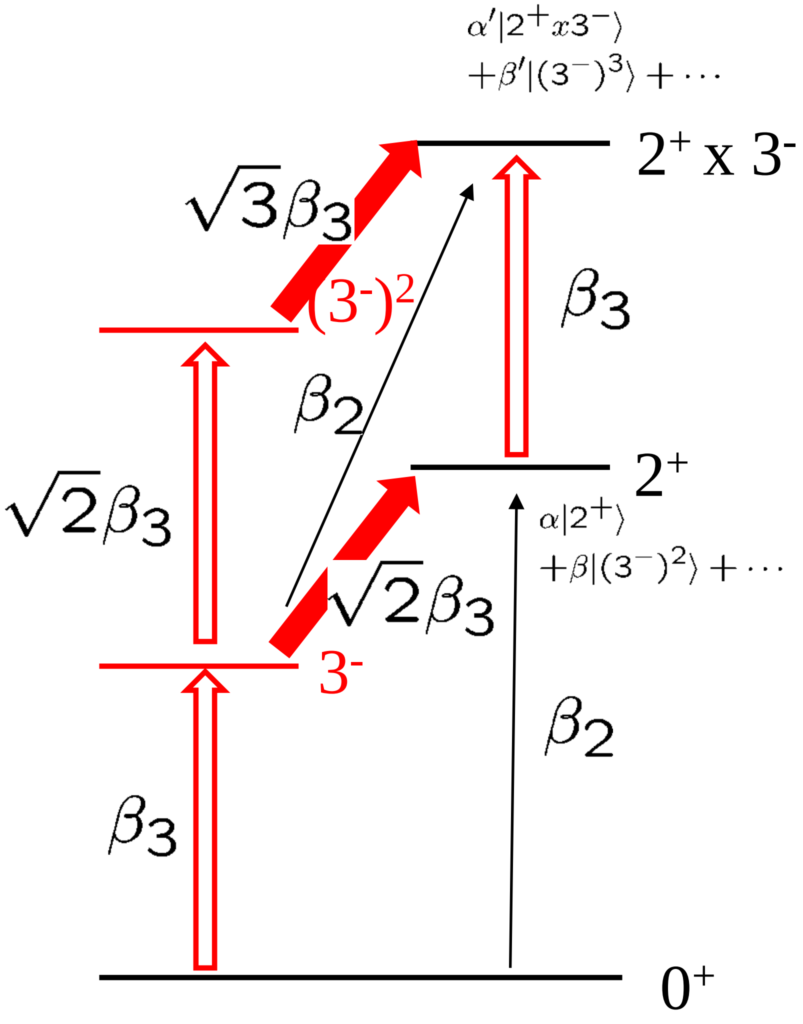


relativistic MF + GCM

anharmonicity of phonon spectra

CCFULL with RMF+GCM

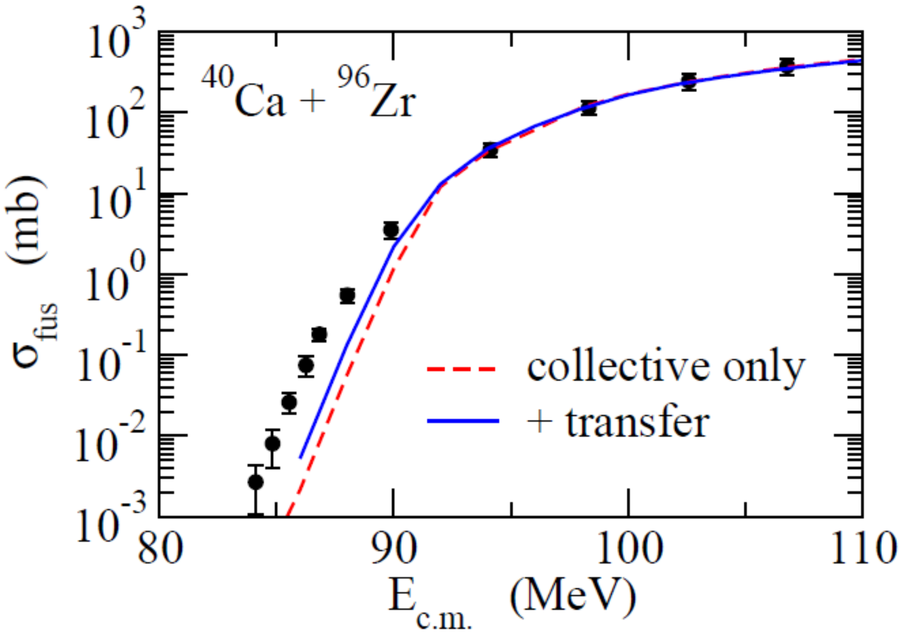




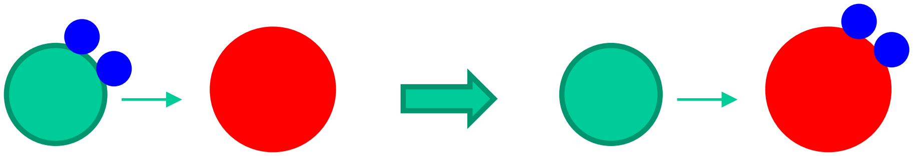
J.M. Yao and K.H.,
PRC94 (‘16) 11303(R)

Remaining challenges

1. Interplay between fusion and (multi-) nucleon transfer processes



G. Scamps and K. Hagino,
PRC92 ('16) 054616



fusion with multi-nucleon transfer
: needs a further development

◆ explain simultaneously
fusion and transfer cross sections?

◆ reaction dynamics of pair transfer?

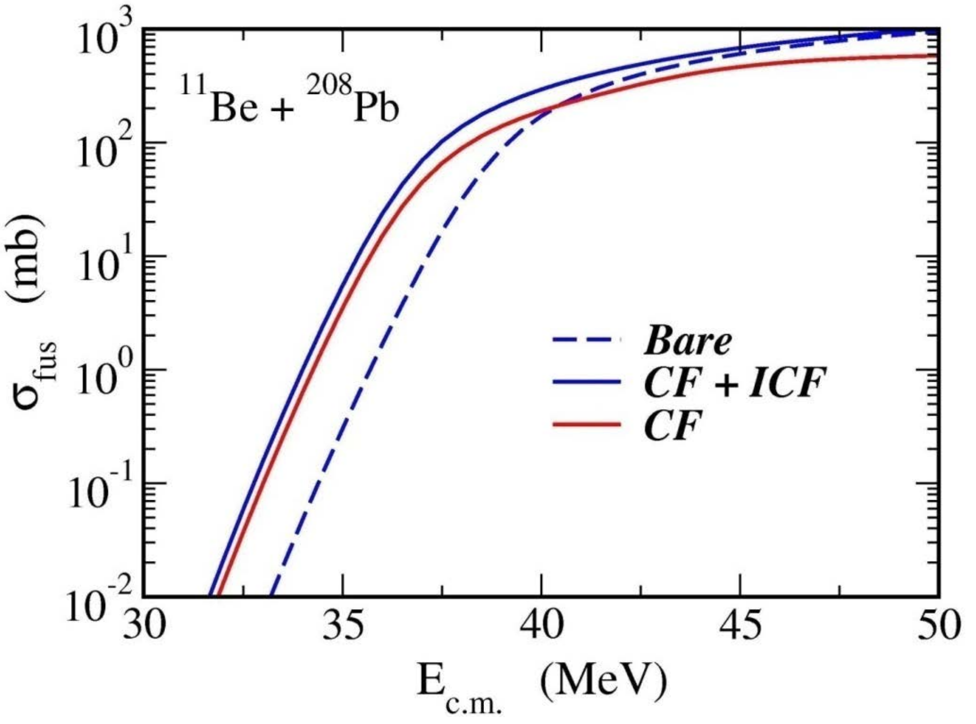
cf. pairing in neutron-rich nuclei

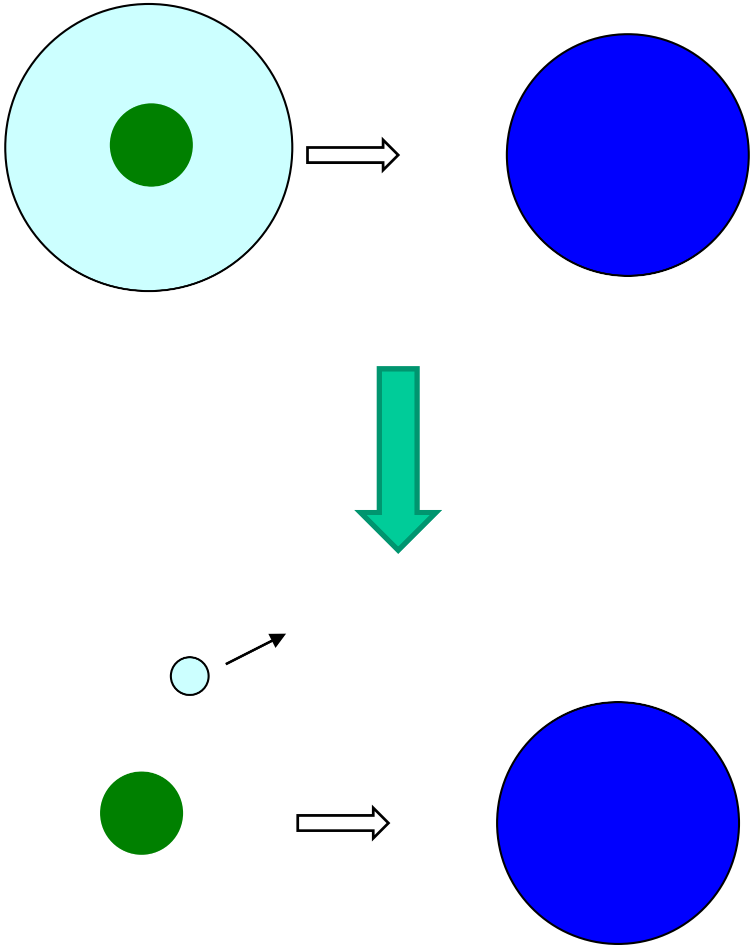
K. Hagino and H. Sagawa,
PRC72 ('05) 044321

Remaining challenges

2. Fusion of halo nuclei

calculations with breakup channels





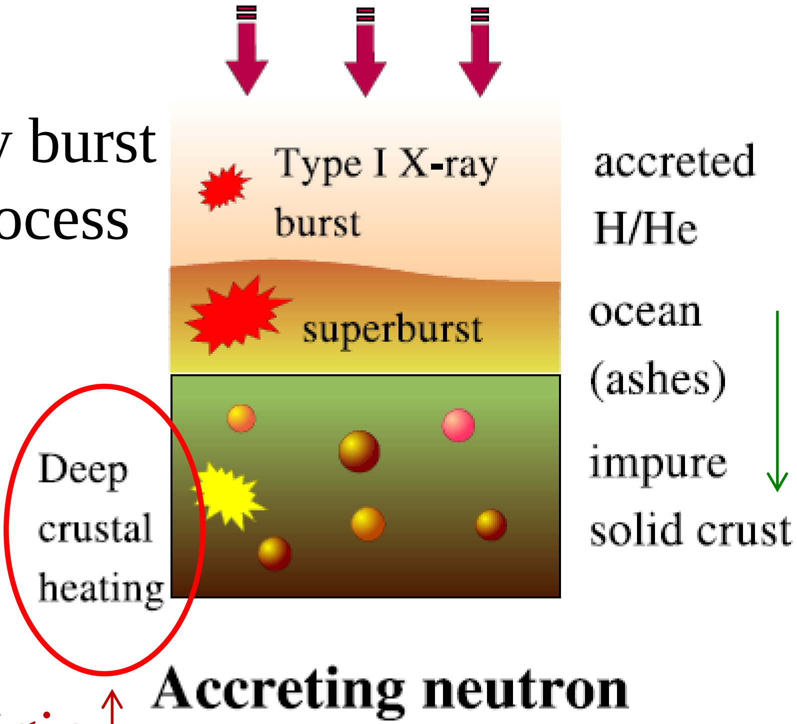
K. Hagino, A. Vitturi, C.H. Dasso,
and S.M. Lenzi, Phys. Rev. C61 ('00) 037602

→ needs an extension with breakup and particle transfer at the same time

also, what is the role of n/p unbalance in CN formation? (Shimoura-san)

fusion of neutron-rich nuclei in accreting（質量降着）neutron stars

X-ray burst
rp-process



origin ↑

fusion of neutron-rich nuclei
when Z becomes small enough

$^{24}O + {}^{24}O$, $^{28}Ne + {}^{28}Ne$ etc.

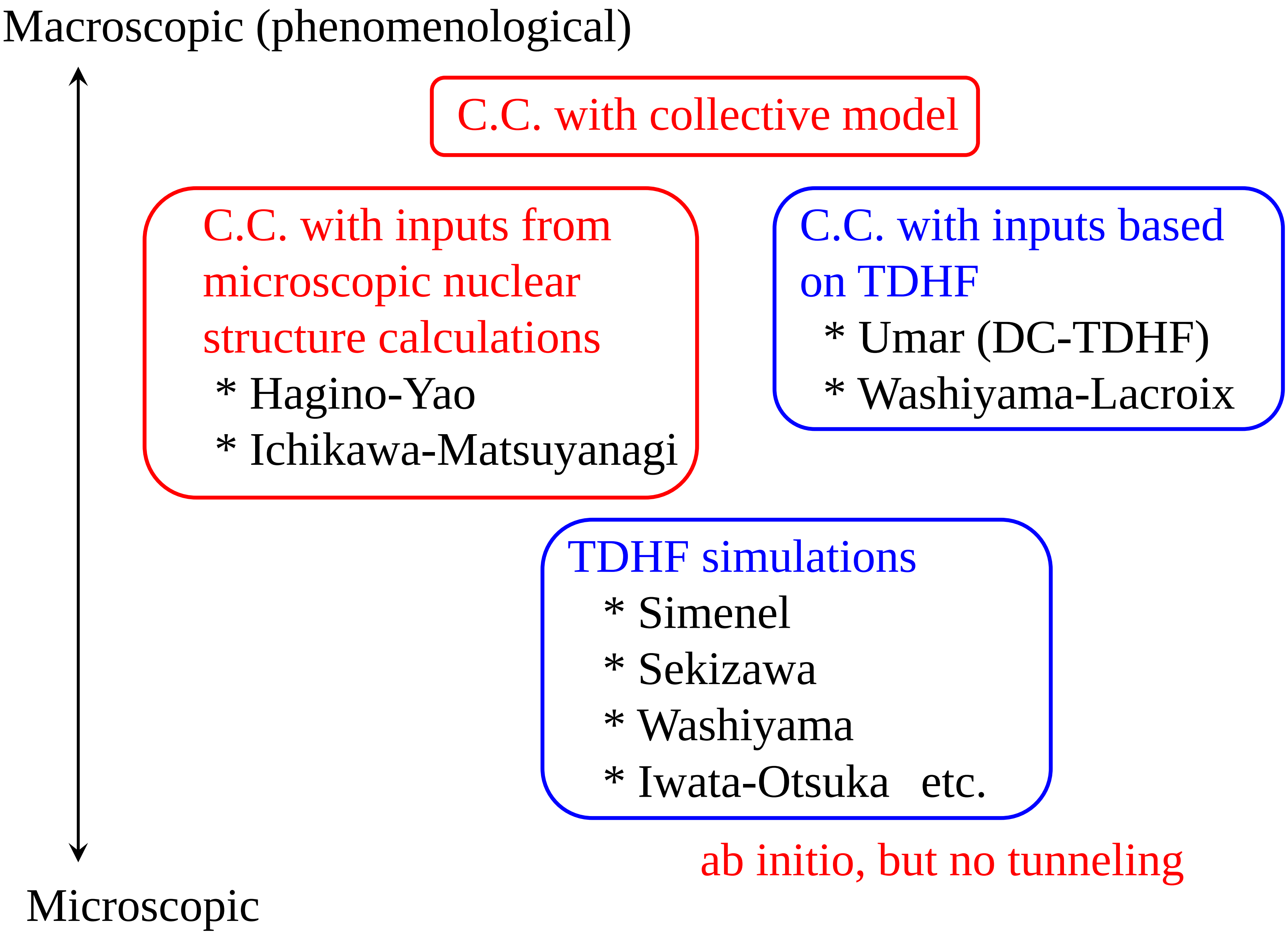
electron capture

$(A,Z) + e^- \rightarrow (A,Z-1) + \nu_e$

towards neutron-rich nuclei

N. Chamel and P. Haensel,
Living Rev. Relativity, 11 (‘08) 10.

From phenomenological approach to microscopic approach



Macroscopic (phenomenological)

C.C. with collective model

C.C. with inputs from microscopic nuclear structure calculations

- * Hagino-Yao
- * Ichikawa-Matsuyanagi

C.C. with inputs based on TDHF

- * Umar (DC-TDHF)
- * Washiyama-Lacroix

TDHF simulations

- * Simenel
- * Sekizawa
- * Washiyama
- * Iwata-Otsuka etc.

ab initio, but no tunneling

Microscopic

From phenomenological approach to microscopic approach

Macroscopic (phenomenological)

C.C. with collective model

C.C. with inputs from microscopic nuclear structure calculations

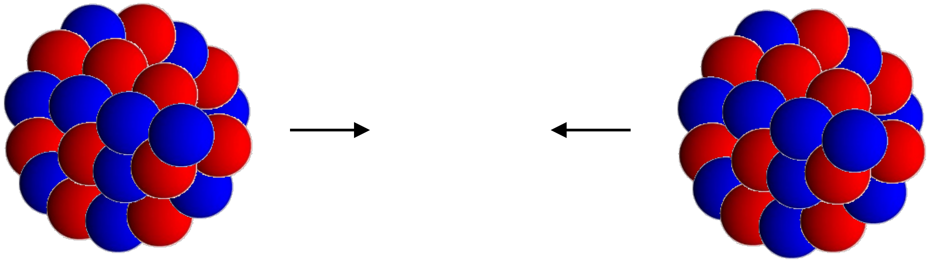
C.C. with inputs based on TDHF

TDHF simulations

Microscopic

ab initio, but no tunneling

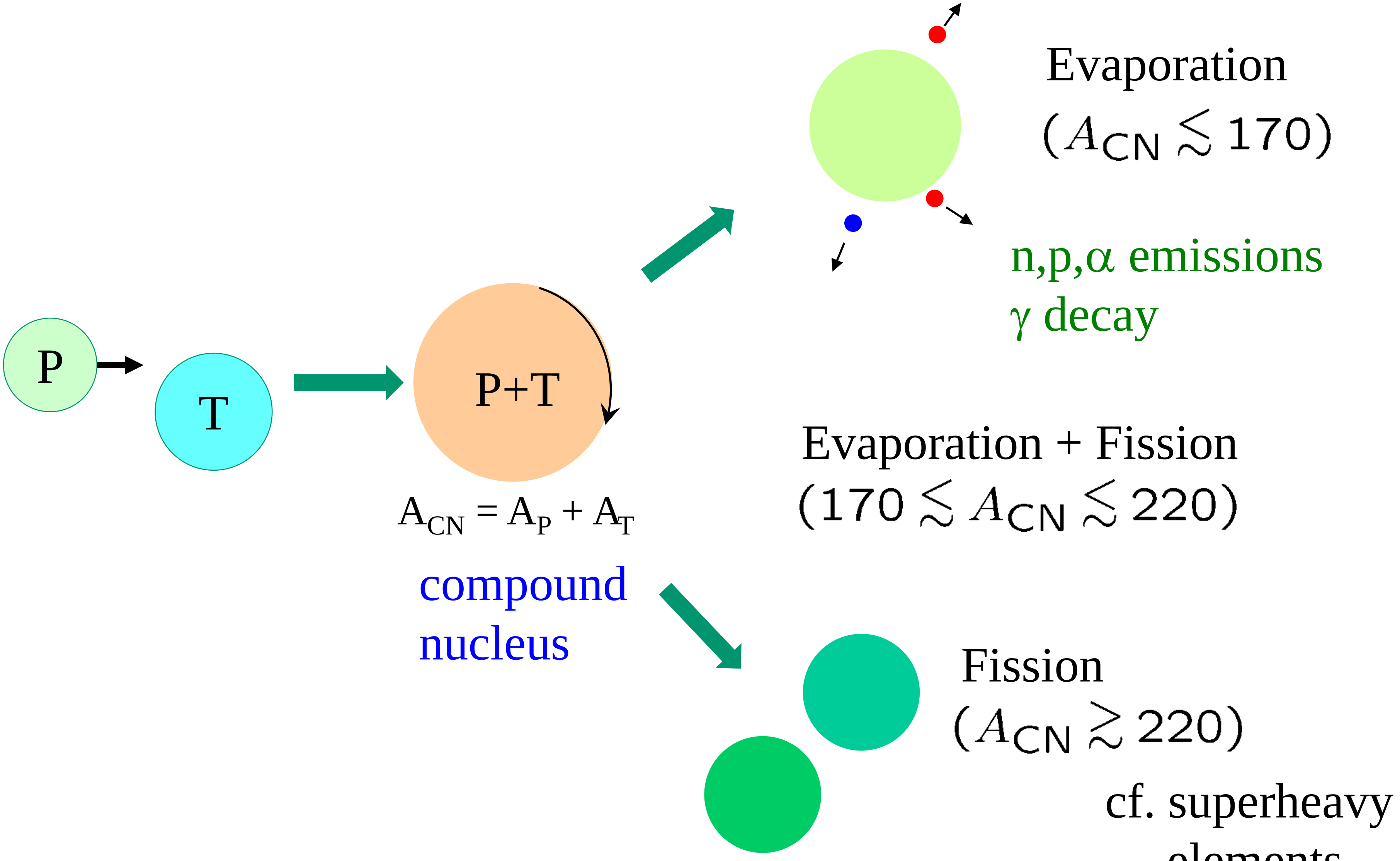
full microscopic description:



still very challenging

Future perspectives: Superheavy elements

$$P_{\mathrm{fus}}(E,l) \;=\; P_{\mathrm{form}}(E,l)$$



$A_{CN} = A_P + A_T$

compound nucleus

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

n,p,α emissions
γ decay

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

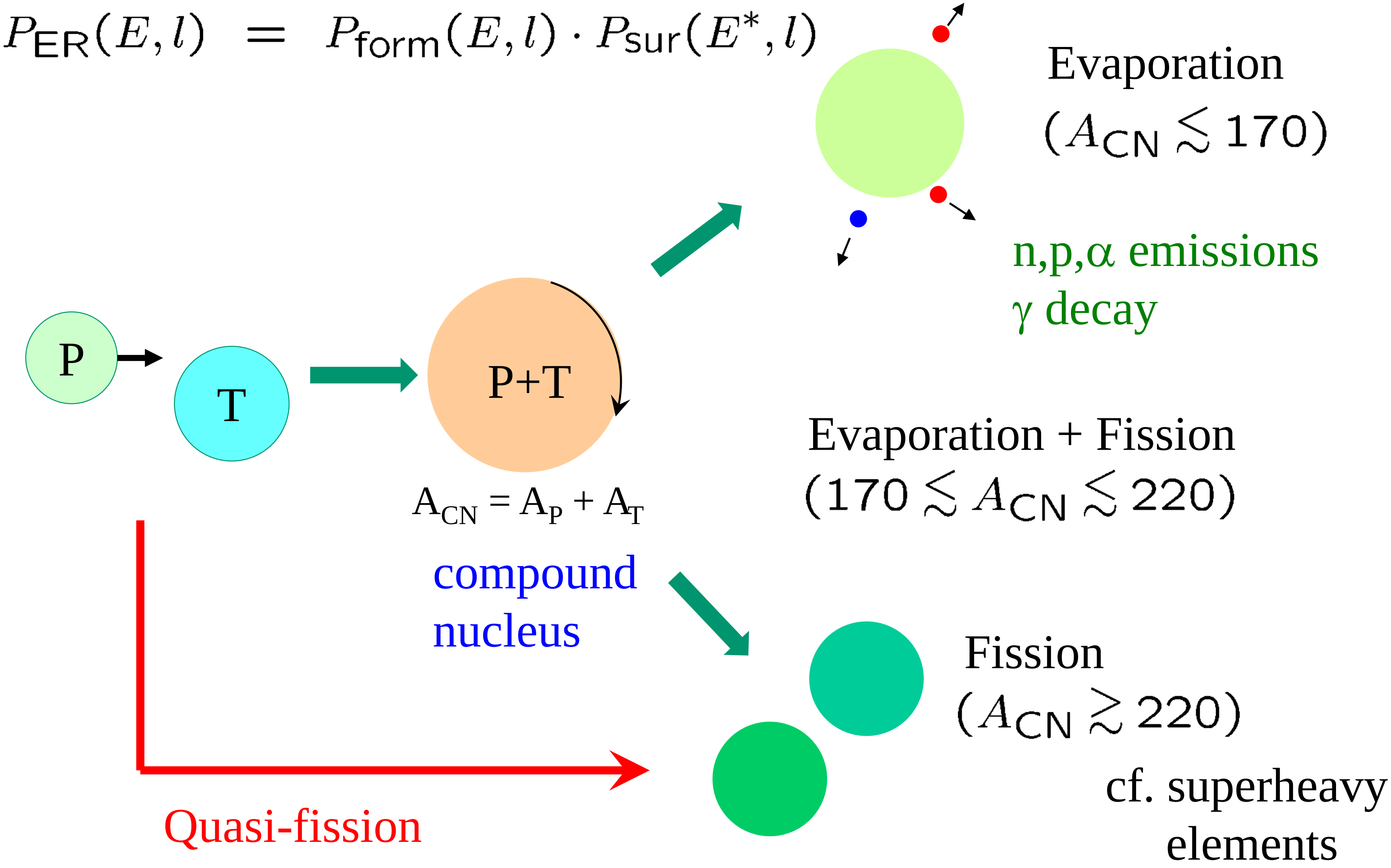
Fission
$(A_{\mathrm{CN}} \gtrsim 220)$

cf. superheavy elements

Future perspectives: Superheavy elements

$$P_{\mathrm{fus}}(E,l) = P_{\mathrm{form}}(E,l)$$

$$P_{\mathrm{ER}}(E,l) = P_{\mathrm{form}}(E,l) \cdot P_{\mathrm{sur}}(E^*,l)$$



P

T

P+T

$A_{CN} = A_P + A_T$

compound nucleus

Evaporation

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

n,p,α emissions

γ decay

Evaporation + Fission

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

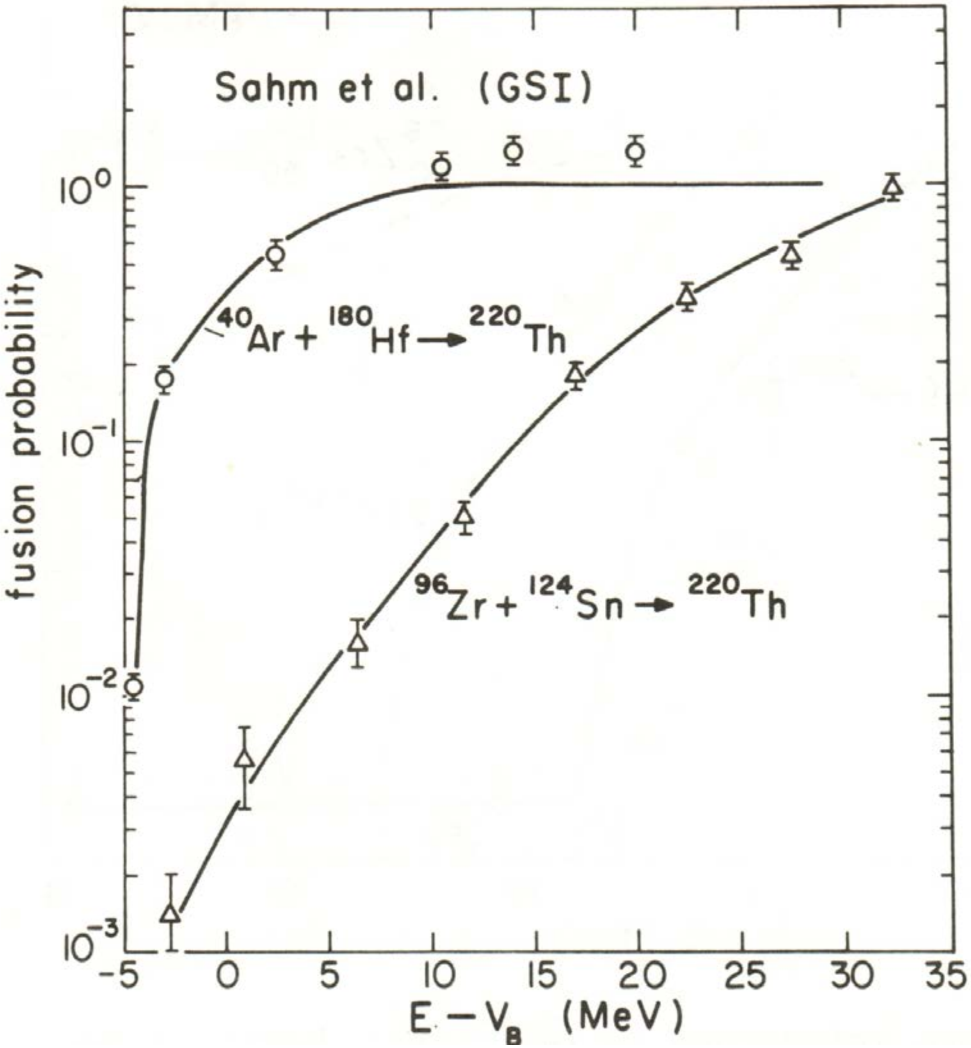
Fission

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

cf. superheavy elements

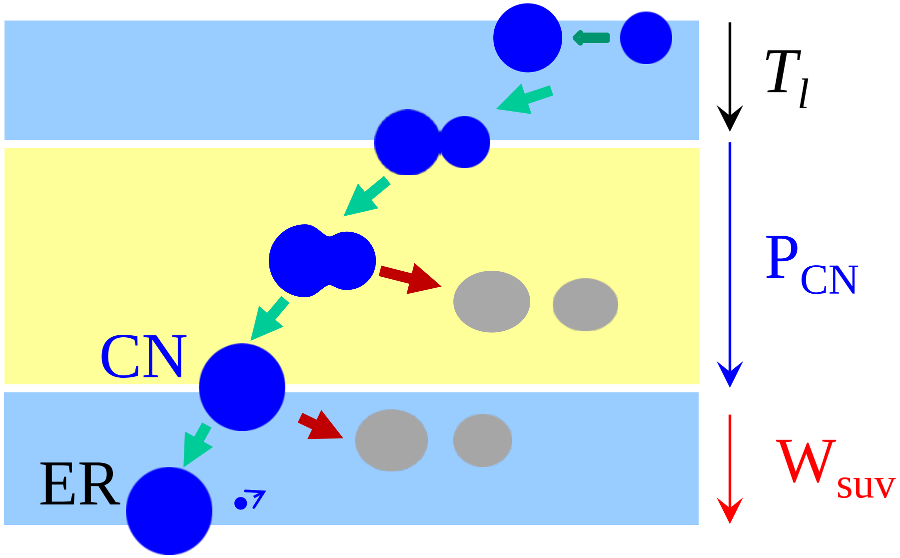
Quasi-fission

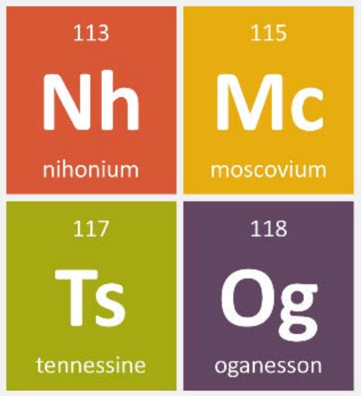
fusion hindrance



C.C. Sahm et al.,
Z. Phys. A319 (‘84) 113

Future perspectives: Superheavy elements

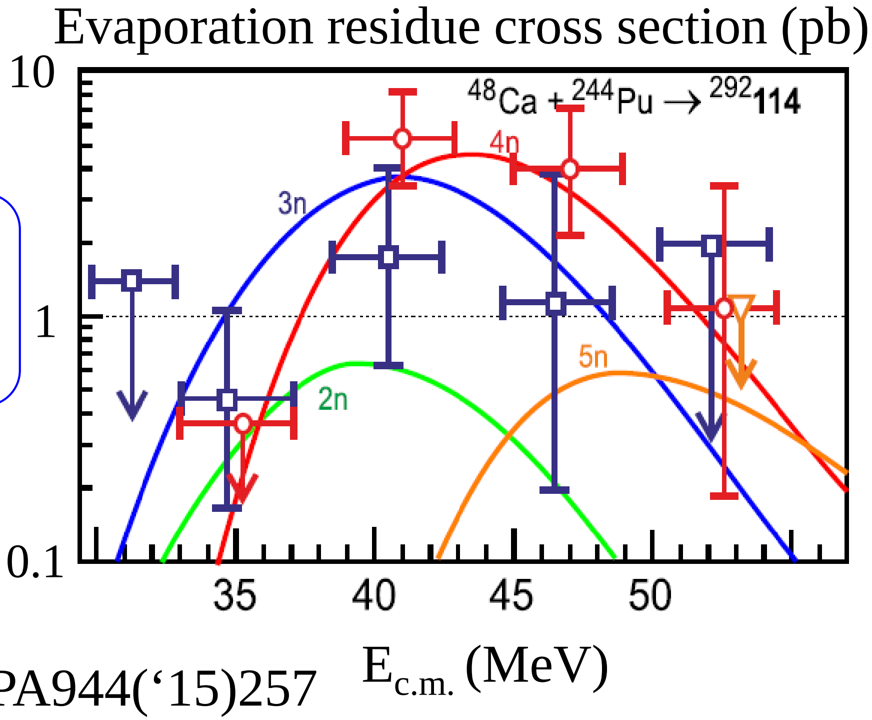




CN = compound nucleus
ER = evaporation residue

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

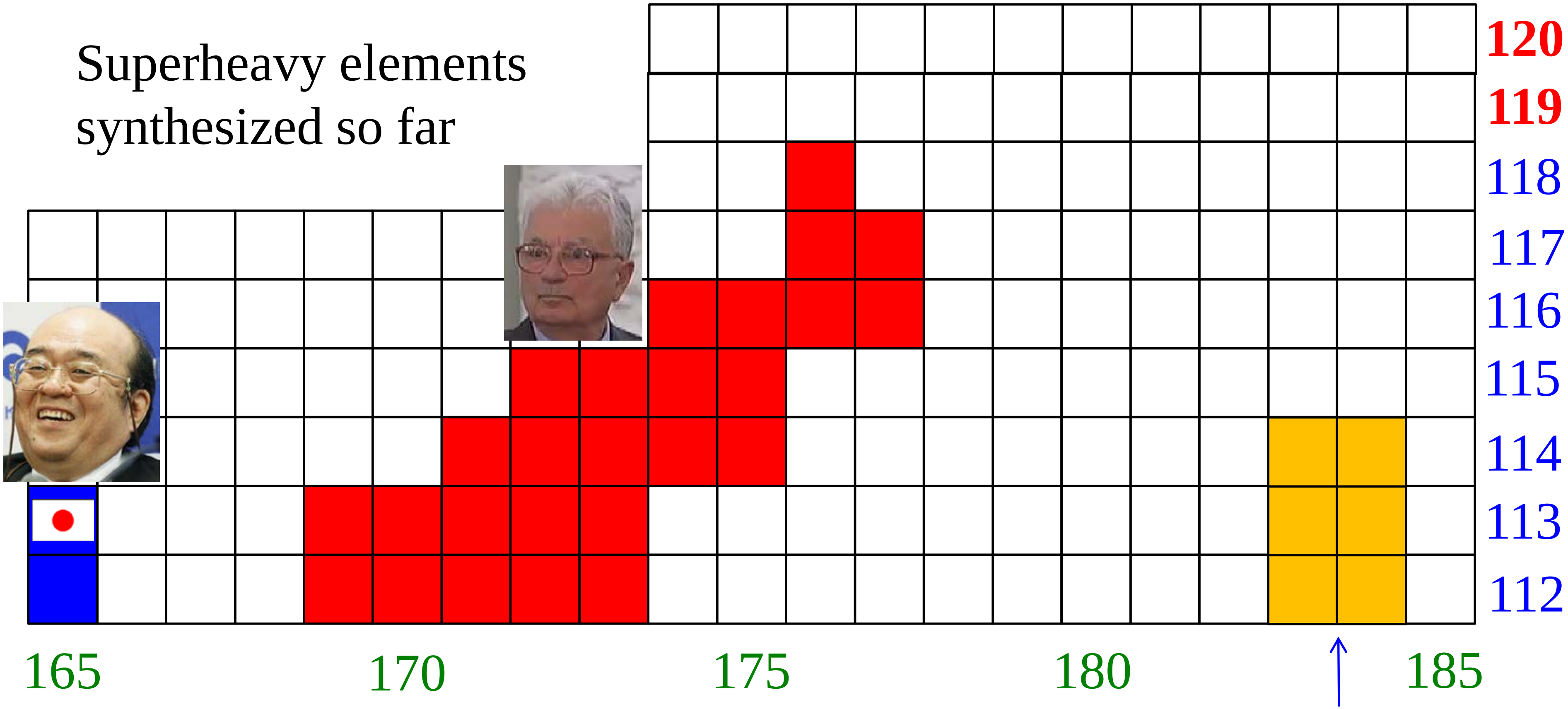
cf. no experimental data for P_{CN}
→ large uncertainty



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

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

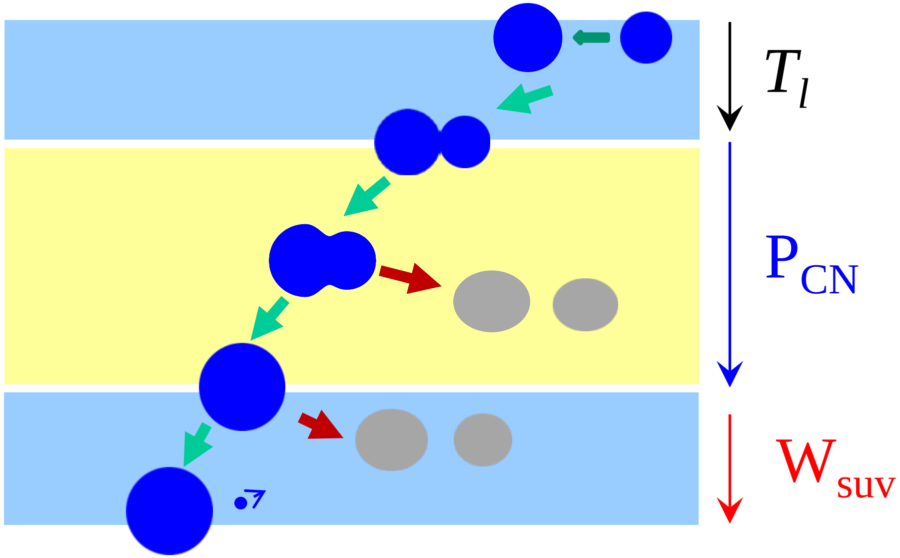
  neutron-rich beams: indispensable

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



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

✓ First step:

σ_{cap} : relatively easy to measure
→ but, one needs T_l
how?

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

✓ Second step:

deformation effects on P_{CN}

Extraction of T_l from H.I. quasi-elastic (QEL) scattering
(easier measurement than σ_{cap})

fit expt. data with multiple potential barriers:

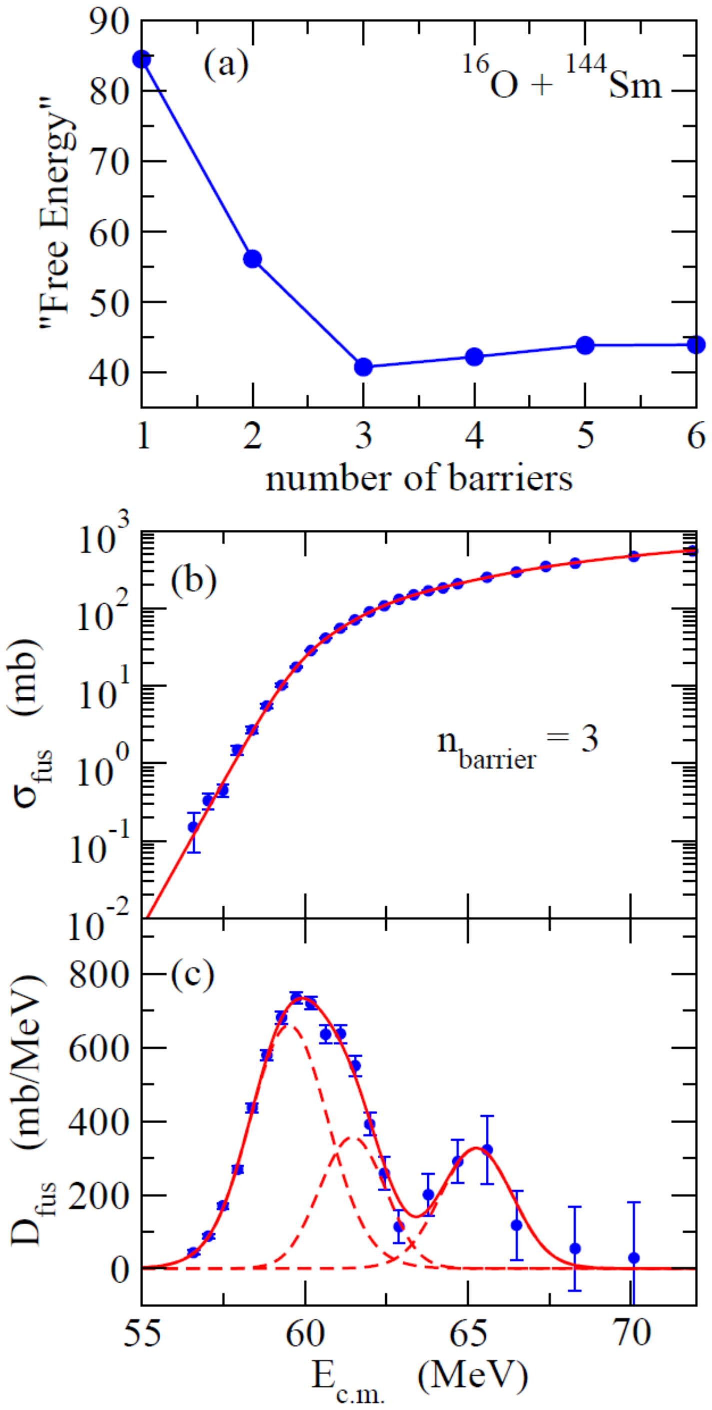
$$\sigma_{\rm exp}(E) = \sum_{k=1}^{N} w_k \sigma_0(E; V_k(r))$$

Bayesian spectrum deconvolution
→ to determine N

$$T_l = \sum_{k=1}^{N} w_k T_l(E; V_k(r))$$

* no need to know the details of the couplings

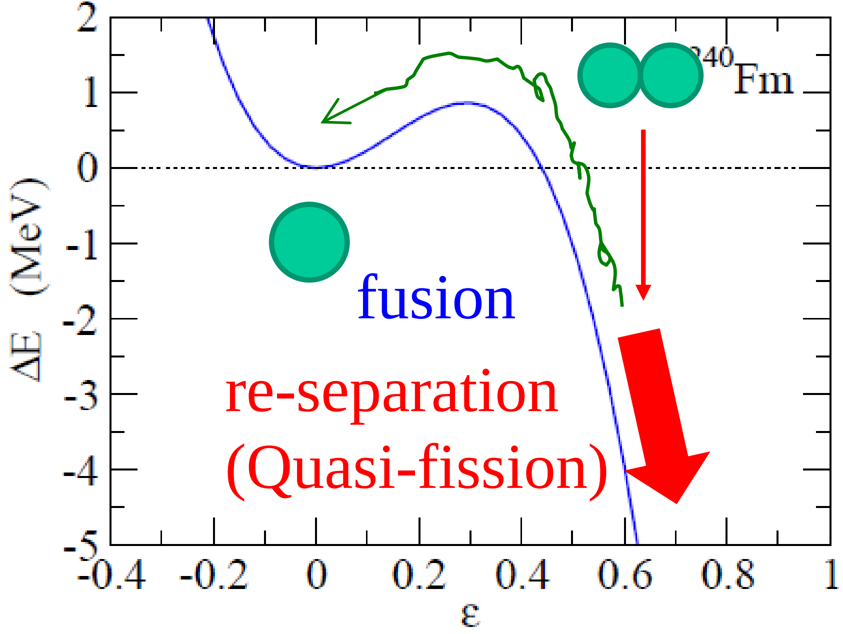
K.H., PRC93 ('16) 061601(R)

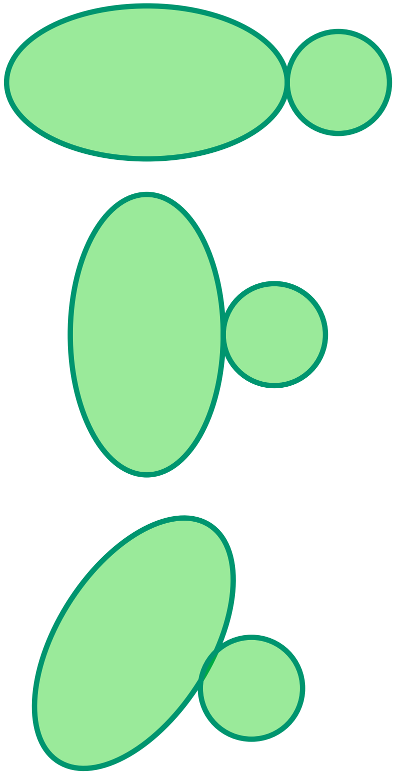


Fusion reactions of deformed nuclei

Thermal activation

→ Langevin equation
(Brownian motion)





distant contact point
→ re-separation

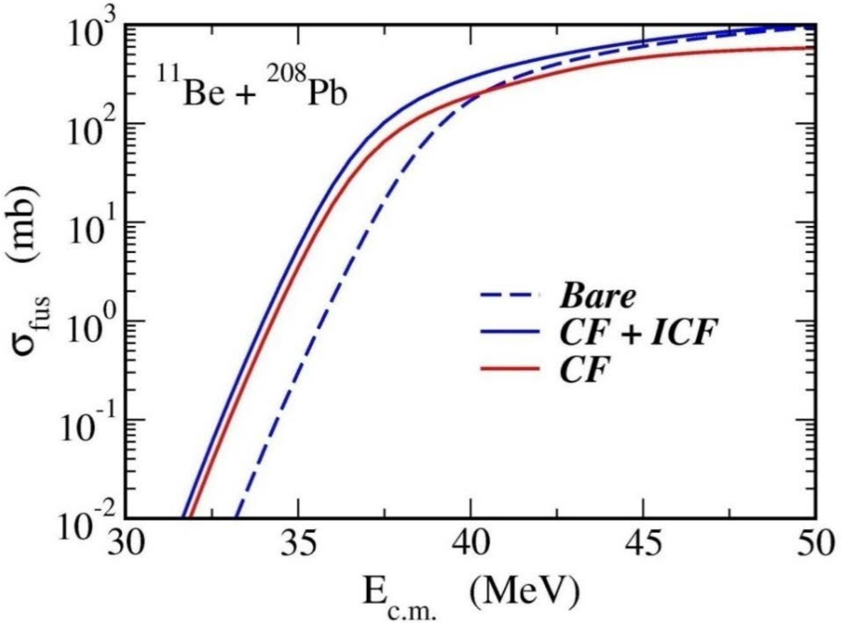
close contact point
→ advantage for
fusion

?

- ➢ how to evolve towards a compound nucleus?
  (what are intermediate shapes?)
- ➢ deformation: quantum effects
  how deformation reduces during the heat-up process?

Future directions - 2

- Towards the island of stability
  neutron-rich beams
  : indispensable

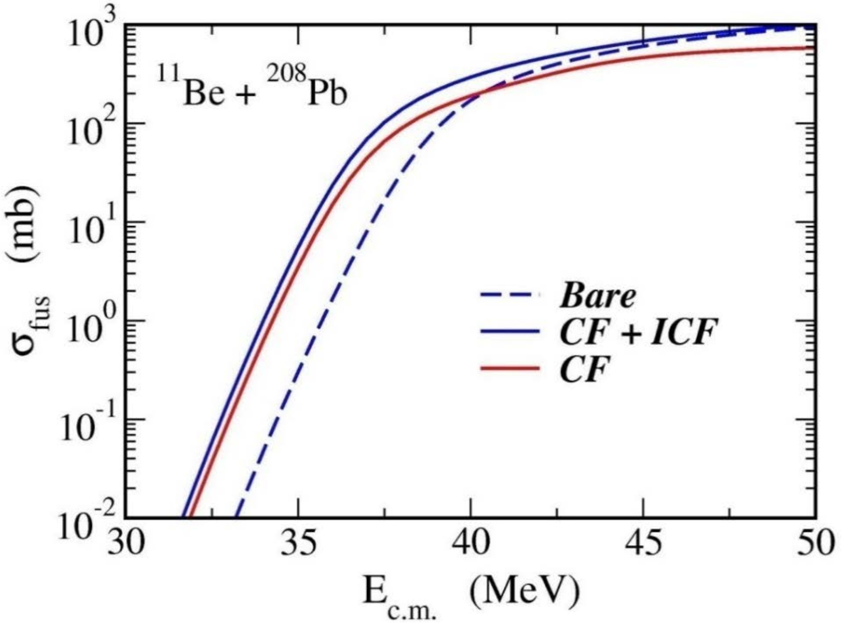


K. Hagino, A. Vitturi, C.H. Dasso,
and S.M. Lenzi, Phys. Rev. C61 ('00) 037602

Understanding of reaction dynamics
(breakup, particle transfer, fusion)

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

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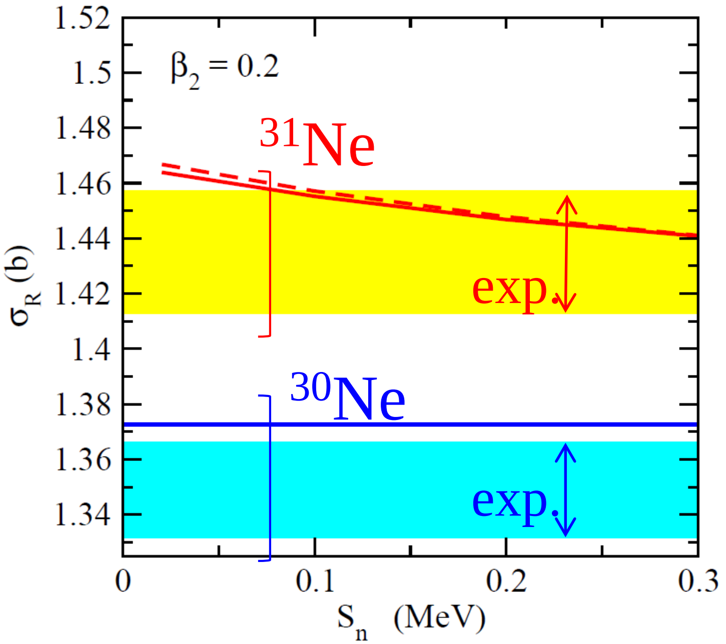
structure of neutron-rich nuclei
: equally important



Y. Urata, K. Hagino, and H. Sagawa,
PRC86('12) 044613

Understanding of reaction dynamics

中性子過剰核を軸にした超重核の物理の探究の可能性

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

- ✓fusion of halo nuclei (influence of breakup and particle transfer)
- ✓Microscopic understanding of low-E fusion reactions?
- ✓ how to understand many-particle tunneling phenomena?
- ✓ microscopic understanding of large amplitude motions

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

FUSION20

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