Quantum many-body dynamics in heavy-ion fusion reactions around the Coulomb barrier

Kouichi Hagino
Kyoto University, Kyoto, Japan

OMEG Seminar 2022.3.24

from my slide on
Sep. 21, 2018

감사합니다

SOONGSIL UNIVERSITY 1897

KNU 강원대학교 KANGWON NATIONAL UNIVERSITY

한국항공대학교 KOREA AEROSPACE UNIVERSITY 1952

TOHOKU UNIVERSITY

Quantum many-body dynamics in heavy-ion fusion reactions around the Coulomb barrier

Kouichi Hagino

Kyoto University, Kyoto, Japan

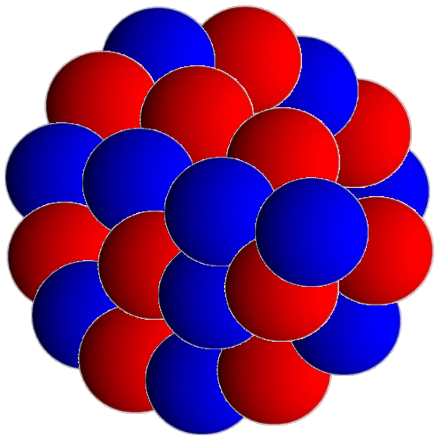
1. Nuclear Reactions: overview
2. Fusion of light nuclei and Feshbach resonances
3. Fusion of medium-heavy nuclei and quantum tunneling
4. Fusion for superheavy nuclei
5. Microscopic modelling of low-energy nuclear reactions
6. Fission
7. Summary

Introduction: low-energy nuclear physics

□ behaviors of atomic nuclei as a quantum many-body systems

← understanding based on strong interaction

- static properties: nuclear structure
  - ✓ ground state properties (mass, size, shape,….)
  - ✓ excitations
  - ✓ nuclear matter
  - ✓ decays



- dynamics: nuclear reactions

nucleus: a composite system

✓ various sort of reactions

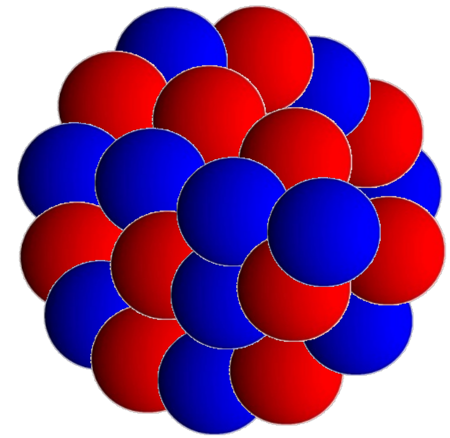
- elastic scattering
- inelastic scattering
- transfer rection
- breakup reactions
- fusion reactions

Introduction: low-energy nuclear physics

- behaviors of atomic nuclei as a quantum many-body systems

  ← understanding based on strong interaction

- static properties: nuclear structure
  - ✓ ground state properties
    (mass, size, shape,…..)
  - ✓ excitations
  - ✓ nuclear matter
  - ✓ decays

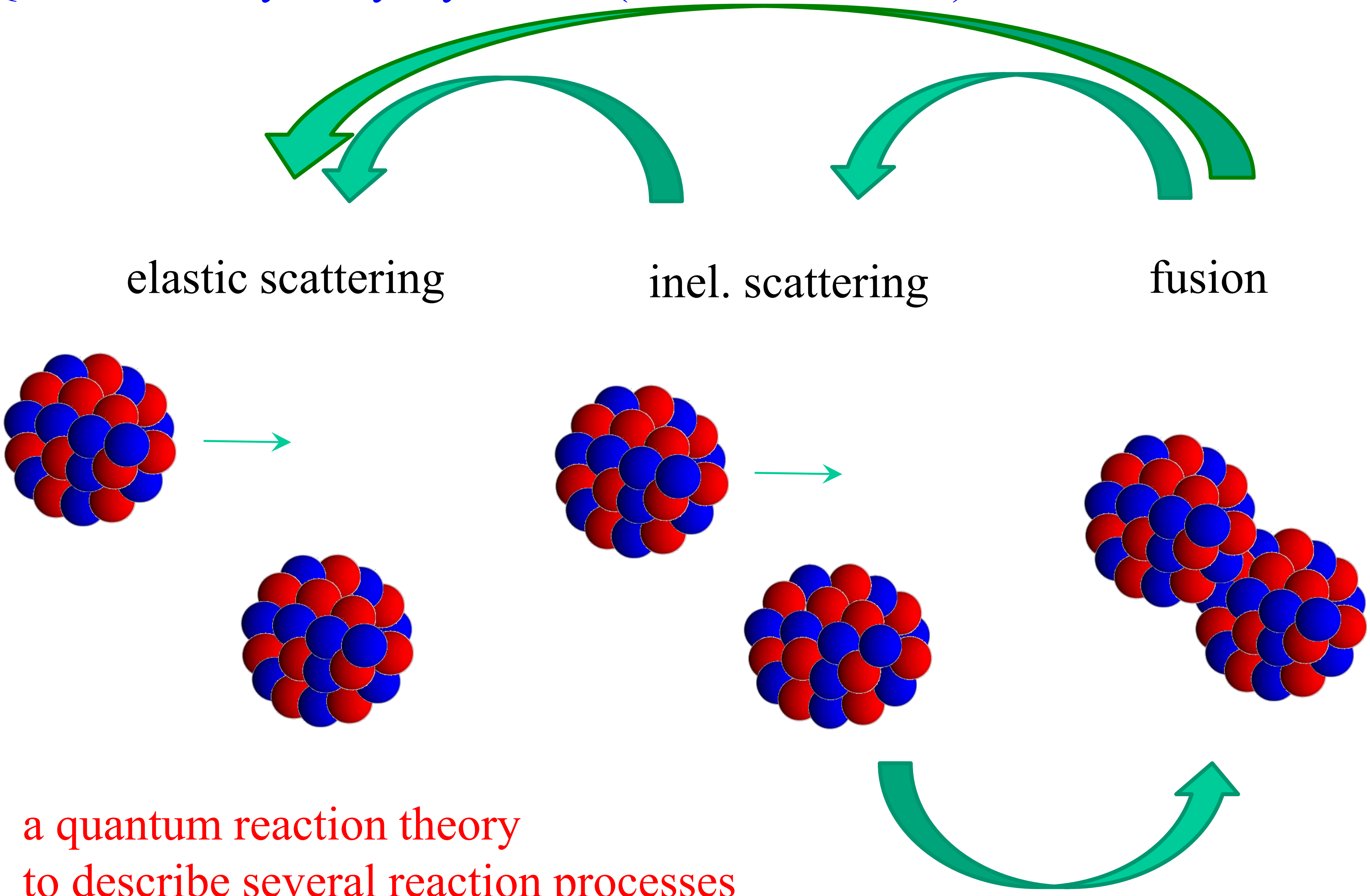


- dynamics: nuclear reactions

nucleus: a composite system
✓ various sort of reactions
✓ an interplay between nuclear structure and reaction

- elastic scattering
- inelastic scattering
- transfer rection
- breakup reactions
- fusion reactions

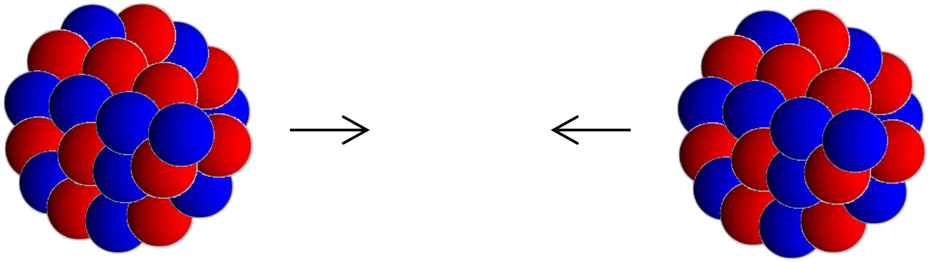
Quantum Many-body Dynamics (nuclear reactions)



a quantum reaction theory
to describe several reaction processes
simultaneously

Coupled-channels method: a quantal scattering theory with excitations

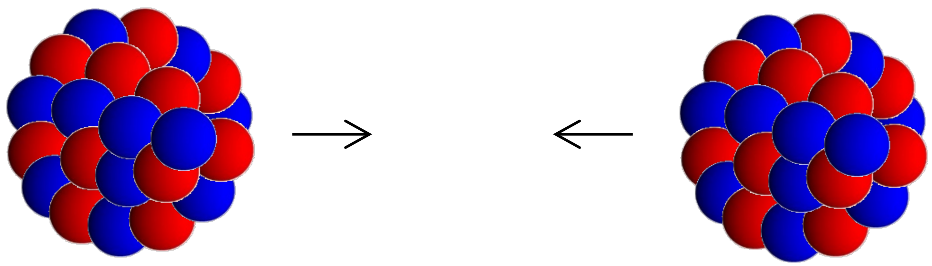
many-body problem



still very challenging

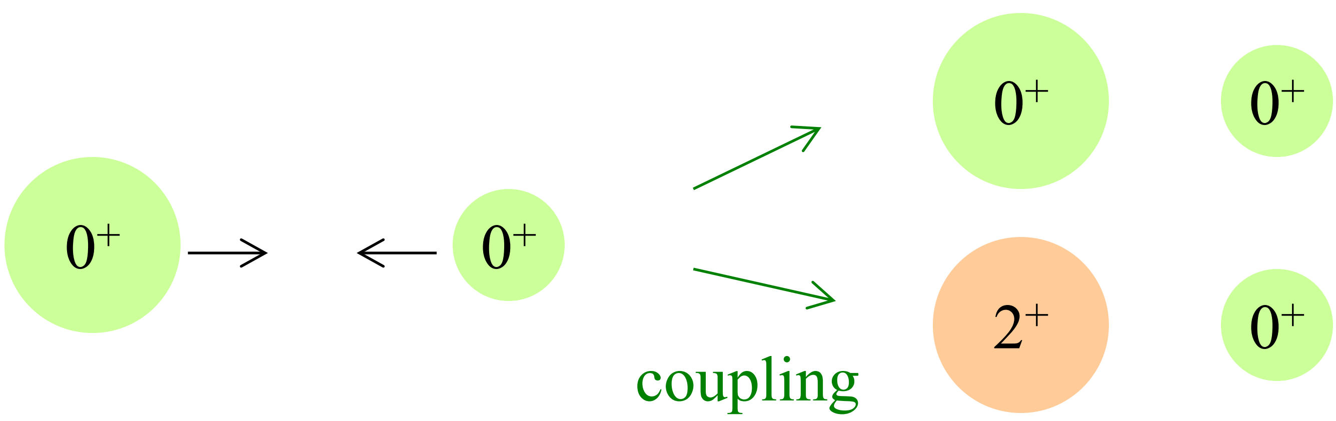
Coupled-channels method: a quantal scattering theory with excitations

many-body problem



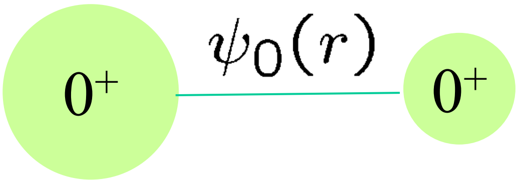
still very challenging

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



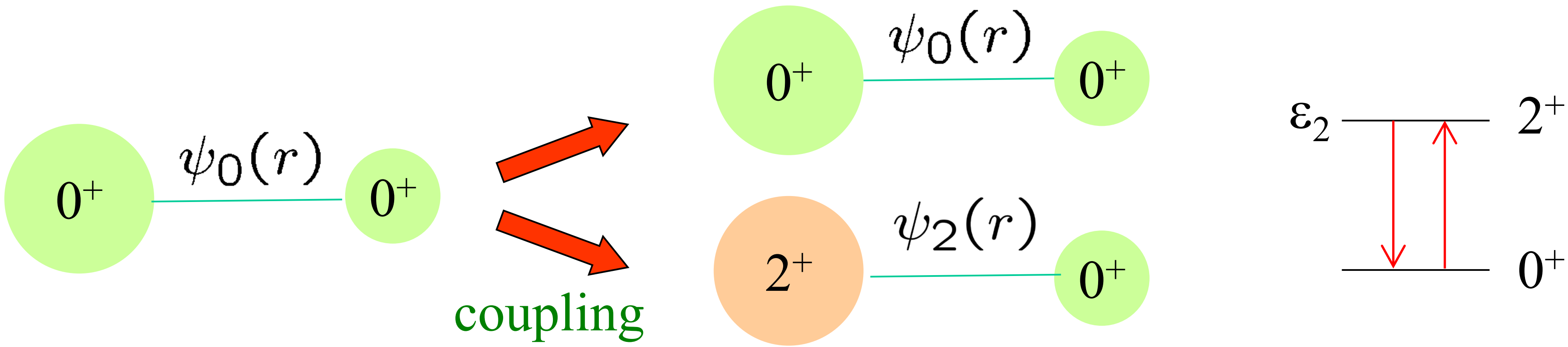
scattering theory with excitations

Coupled-channels method: a quantal scattering theory with excitations



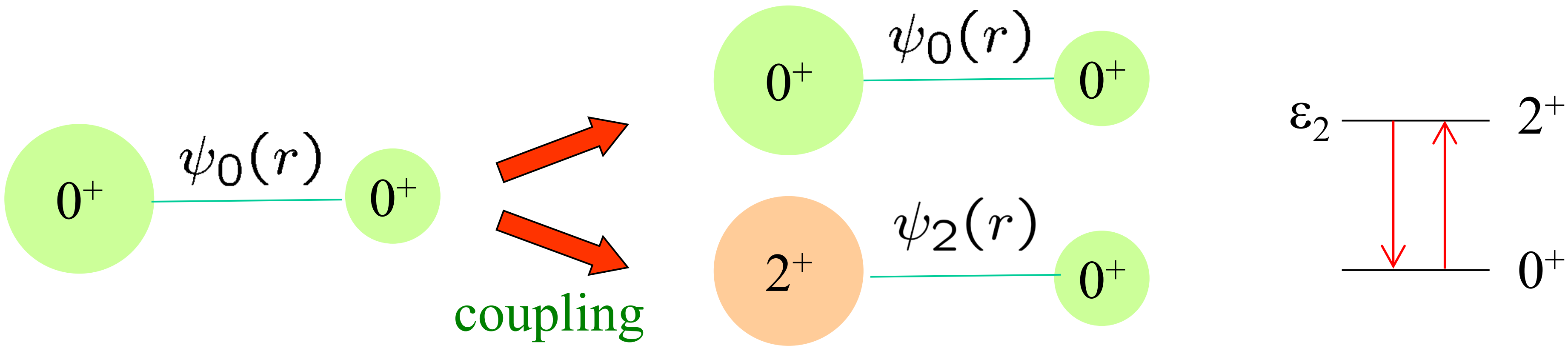
$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V_0(r) - E\right]\psi_0(\boldsymbol{r}) = 0$$

Coupled-channels method: a quantal scattering theory with excitations



$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V_0(r) - E\right]\psi_0(\boldsymbol{r}) = -F_{0\to 2}(r)\psi_2(\boldsymbol{r})$$

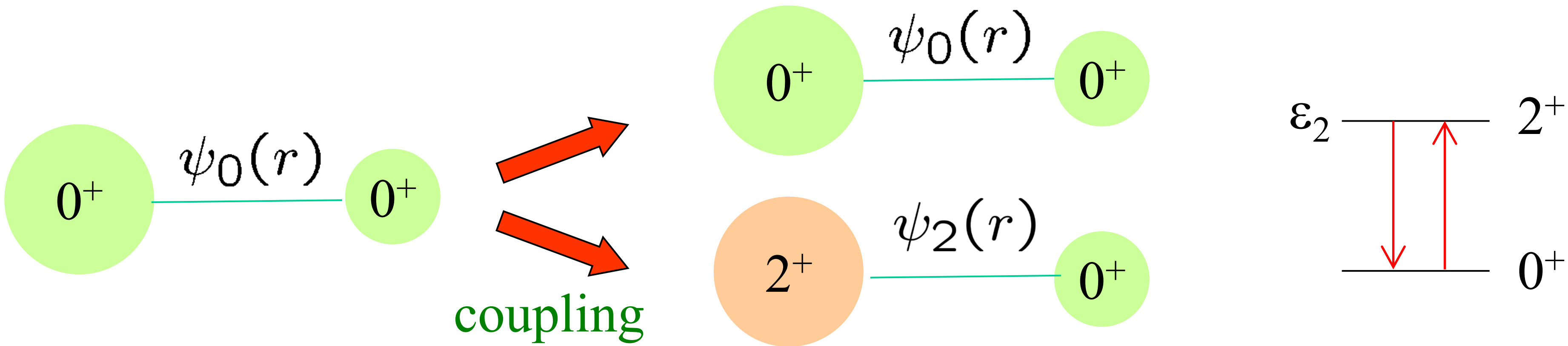
Coupled-channels method: a quantal scattering theory with excitations



$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V_0(r) - E\right]\psi_0(\boldsymbol{r}) = -F_{0\to 2}(r)\psi_2(\boldsymbol{r})$$

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V_2(r) - (E-\epsilon_2)\right]\psi_2(\boldsymbol{r}) = -F_{2\to 0}(r)\psi_0(\boldsymbol{r})$$

Coupled-channels method: a quantal scattering theory with excitations



$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V_0(r) - E\right]\psi_0(\boldsymbol{r}) = -F_{0\to 2}(r)\psi_2(\boldsymbol{r})$$

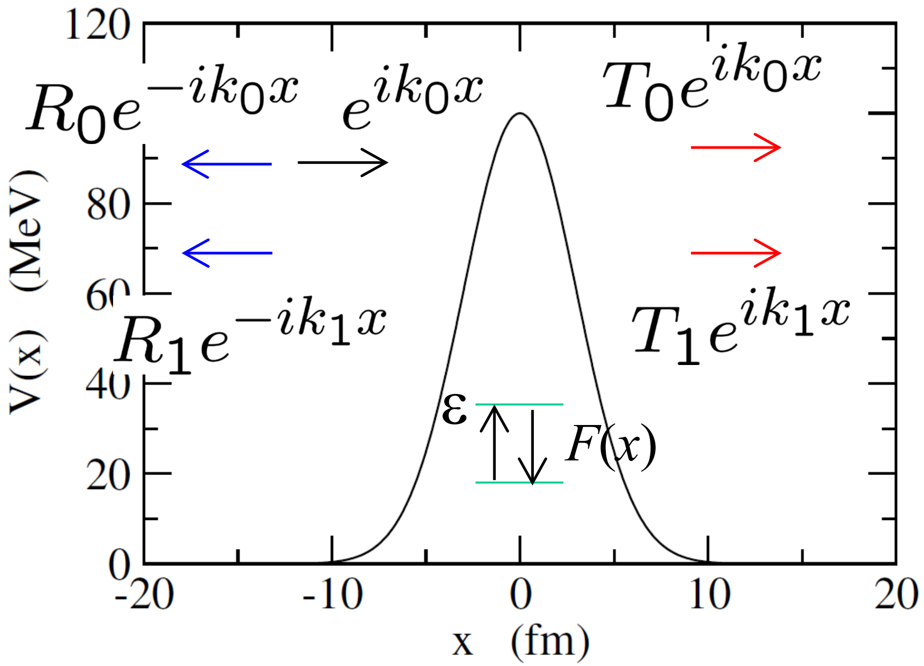
$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V_2(r) - (E-\epsilon_2)\right]\psi_2(\boldsymbol{r}) = -F_{2\to 0}(r)\psi_0(\boldsymbol{r})$$

- Fusion → an absorbing potential (an optical potential)
- excitations to unbound states → breakup reactions (neutron-rich nuclei)

a recent review: K. Hagino, K. Ogata, and A.M. Moro, PPNP in press.

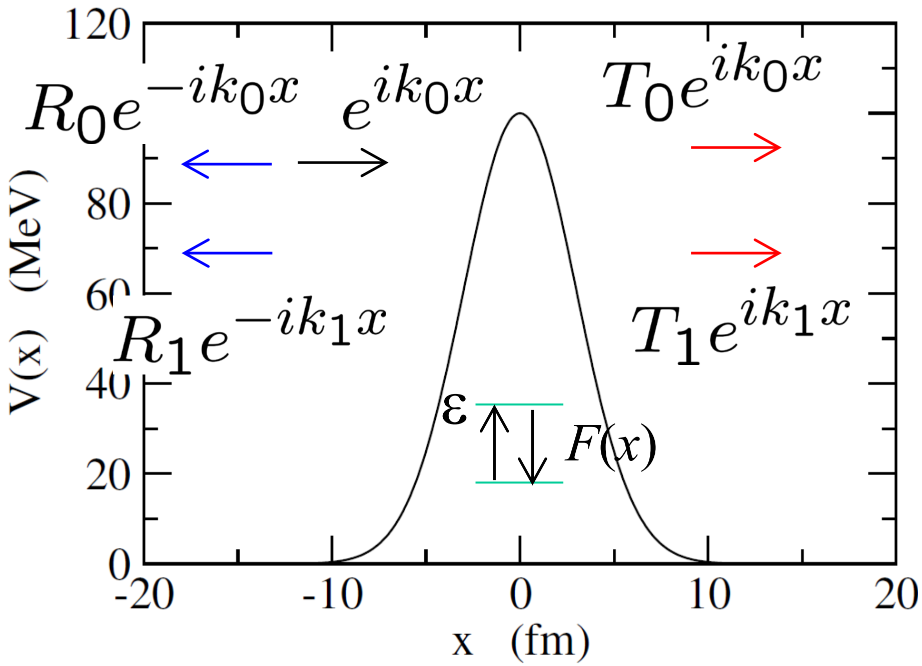
arXiv: 2201.09512

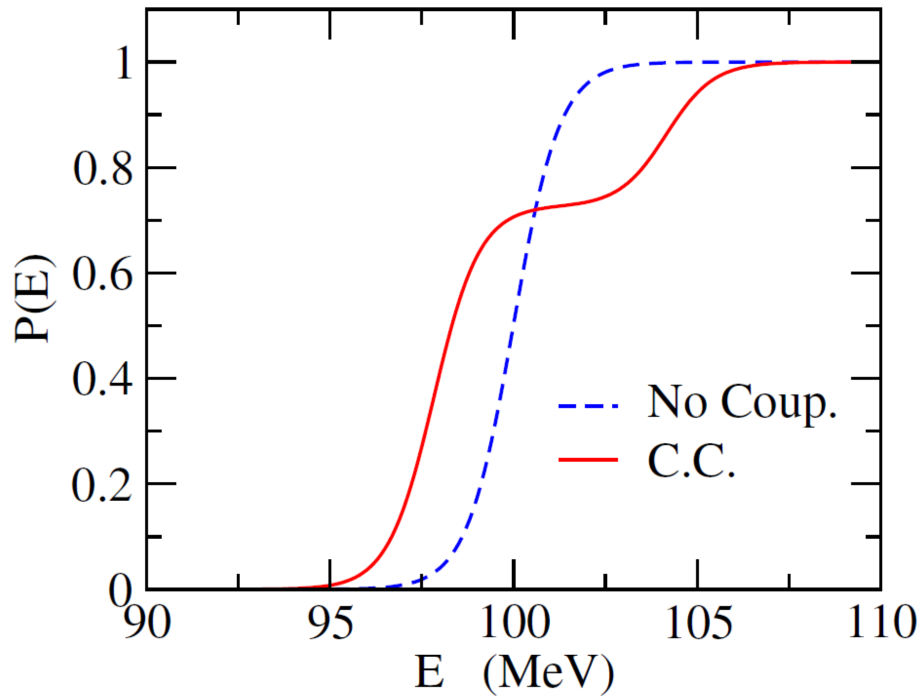
one-dimensional 2 level problem



$$P(E) = |T_0|^2 + \frac{k_1}{k_0}|T_1|^2$$

one-dimensional 2 level problem



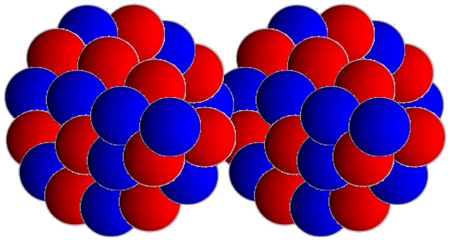


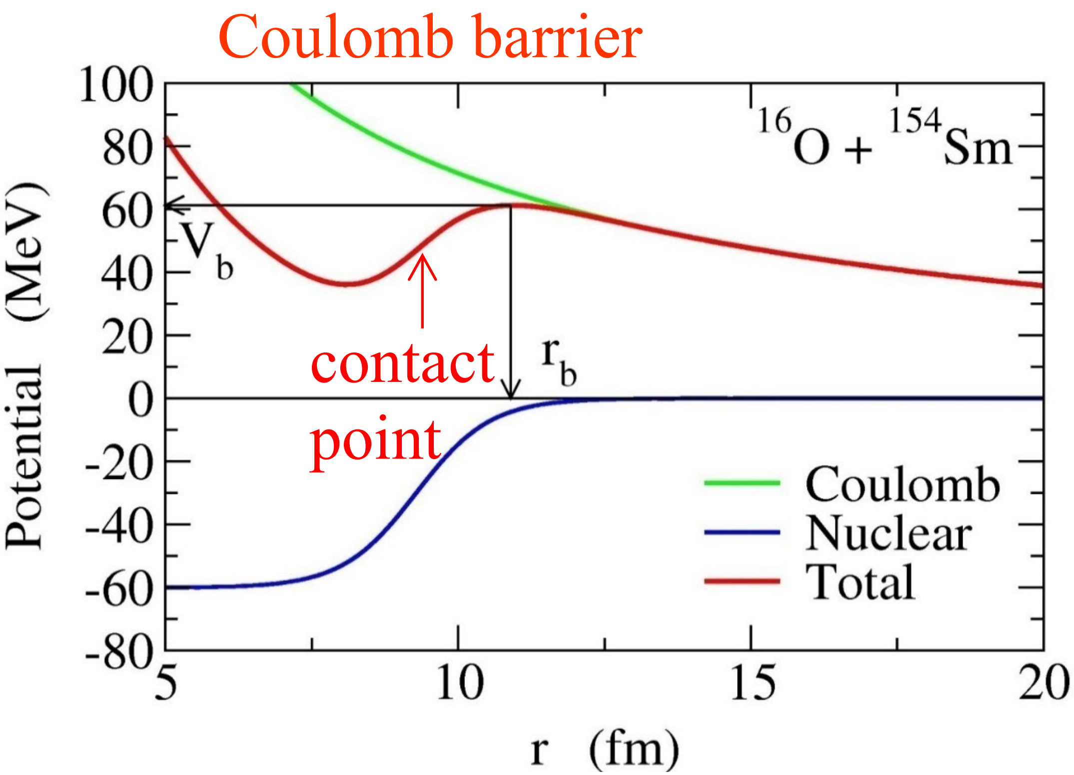
$$P(E) = |T_0|^2 + \frac{k_1}{k_0}|T_1|^2$$

$$V(x) = V_0\, e^{-x^2/2s^2}$$
$$F(x) = F_0\, e^{-x^2/2s^2}$$

V_0 = 100 MeV, F_0 = 3 MeV, s=3 fm,
ε = 2 MeV, m = 29 m_N

Fusion Reactions





- Nuclear interaction (attractive)
- Coulomb interaction (repulsive)

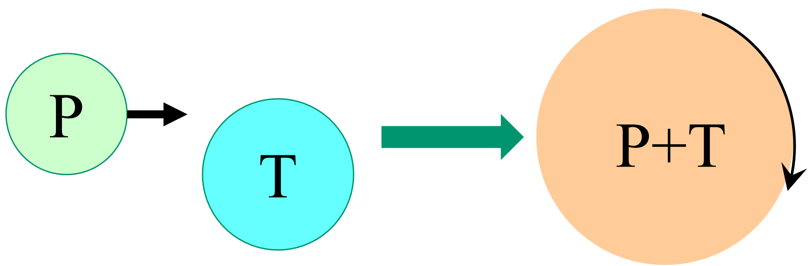
↓

potential barrier

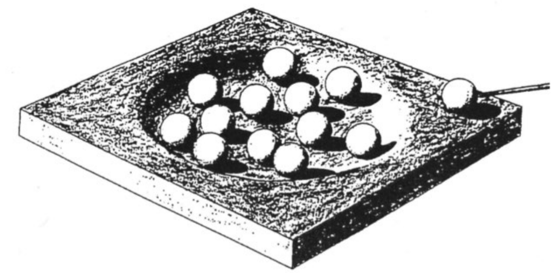
Fusion reactions → a many-body quantum tunneling

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

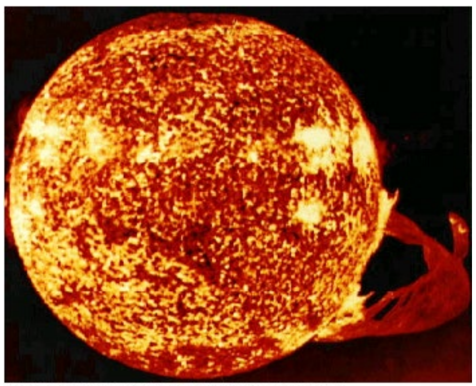
Fusion Reactions



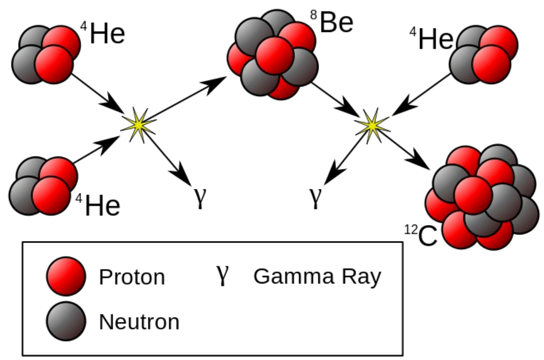
compound nucleus



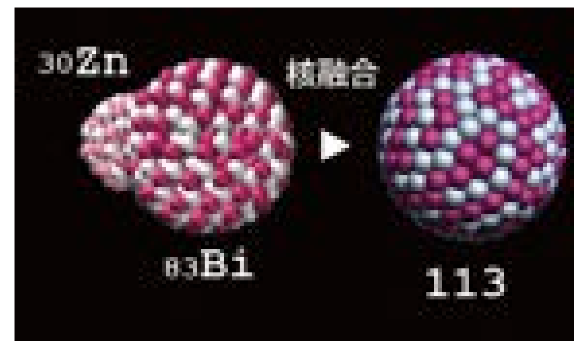
cf. Bohr '36



energy production in stars (Bethe '39)



nucleosynthesis

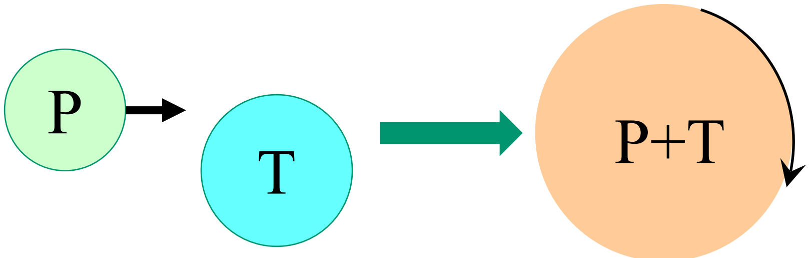


superheavy elements

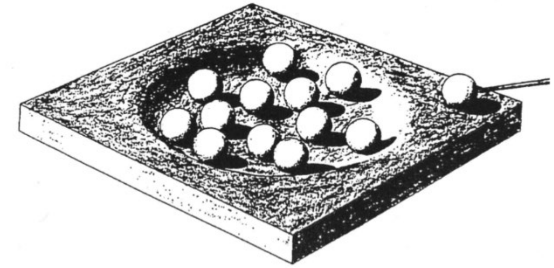
Fusion and fission: large amplitude motions of quantum many-body systems with strong interaction

⟵ microscopic understanding: an ultimate goal of nuclear physics

Fusion Reactions



compound nucleus

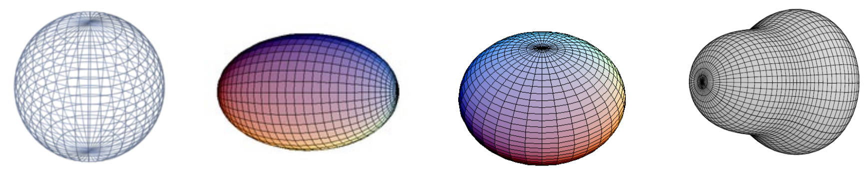


cf. Bohr '36

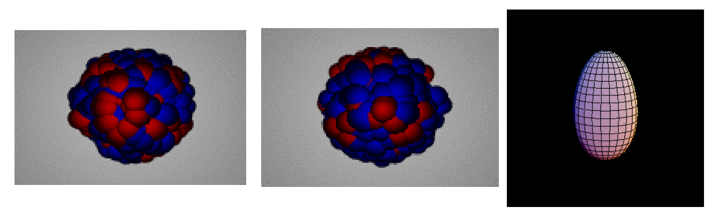
✓ Many-particle tunneling

▪ rich intrinsic motions

- several nuclear shapes

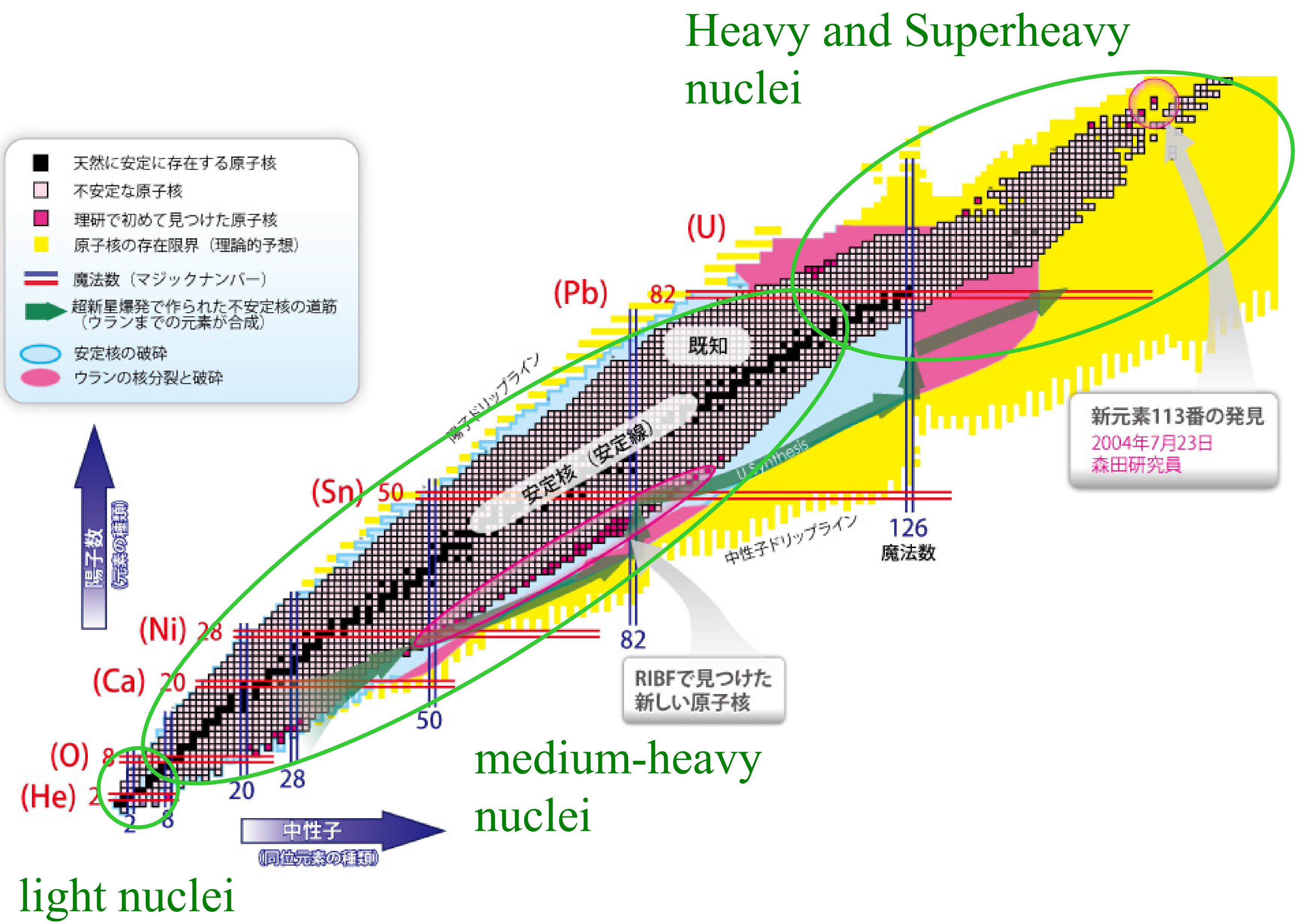


- several surface vibrations

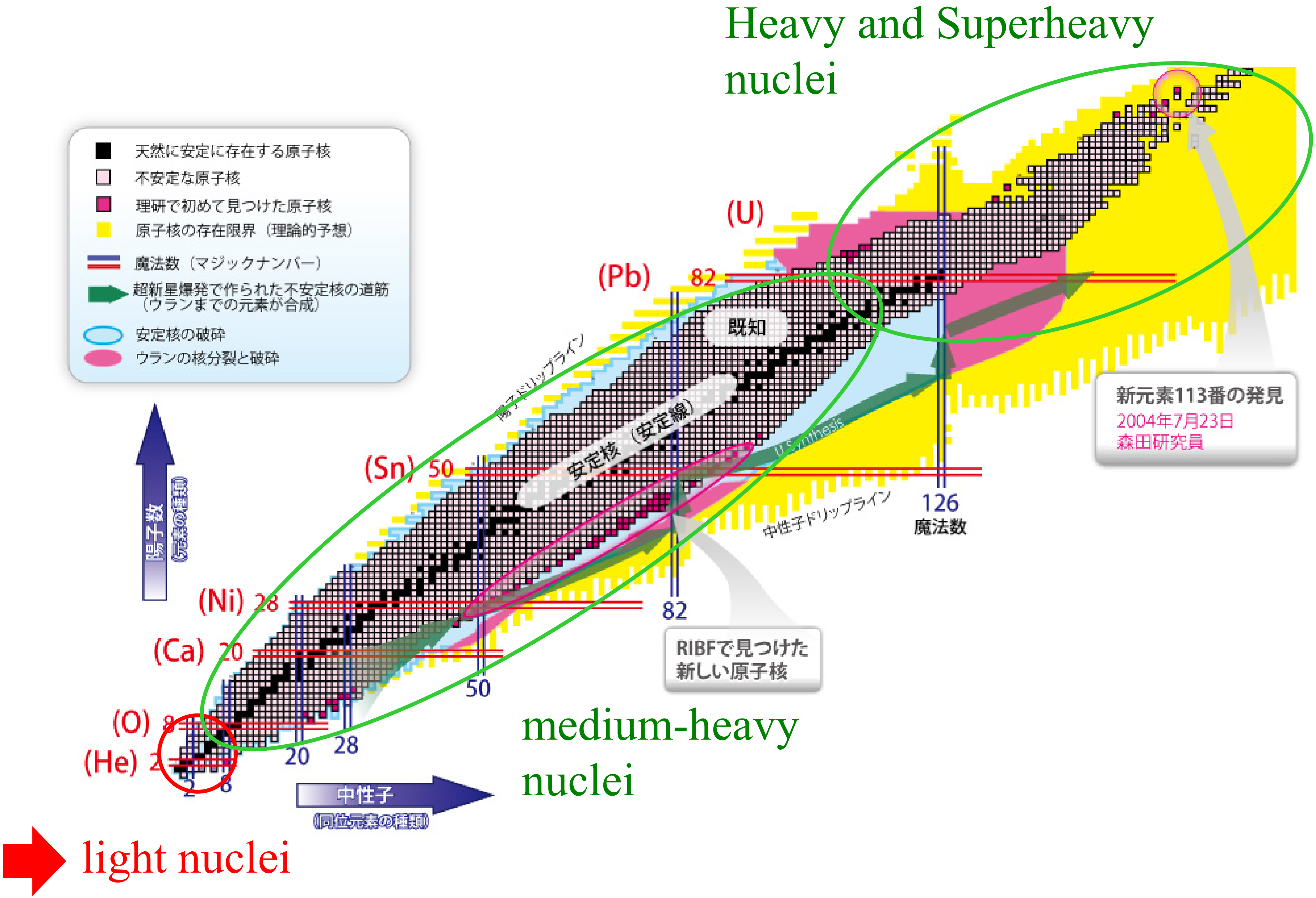


several modes
and adiabaticities

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



Nuclear Chart: RIKEN Nishina Center



Nuclear Chart: RIKEN Nishina Center

Fusion of light nuclei: nuclear astrophysics

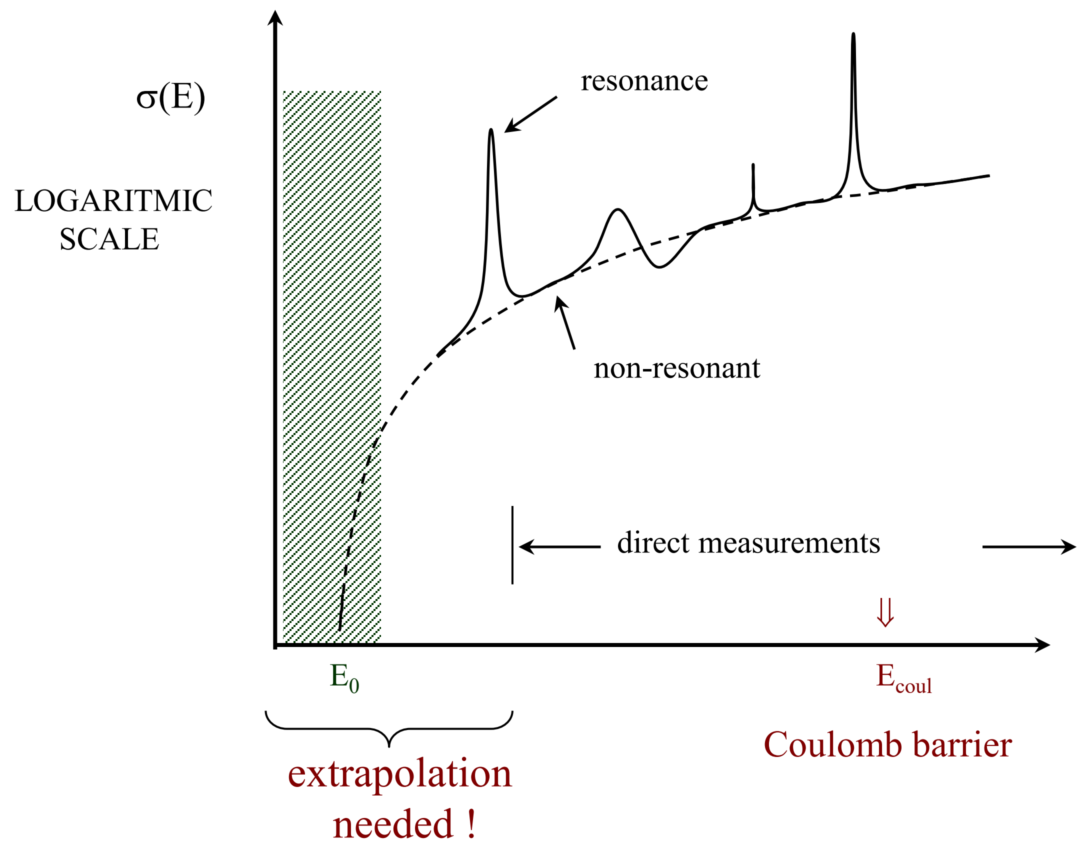
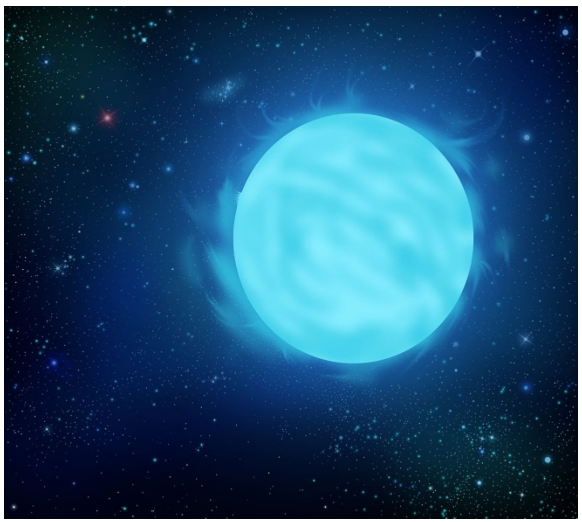


figure: M. Aliotta

Fusion of light nuclei: nuclear astrophysics

$^{12}C+^{12}C$ fusion : a key reaction in nuclear astrophysics

Carbon burning
in massive stars



$^{12}C+^{12}C \rightarrow \alpha + ^{20}Ne$

$^{12}C+^{12}C \rightarrow p + ^{23}Na$

also

- ✓ Type Ia supernovae
- ✓ X-ray superburst

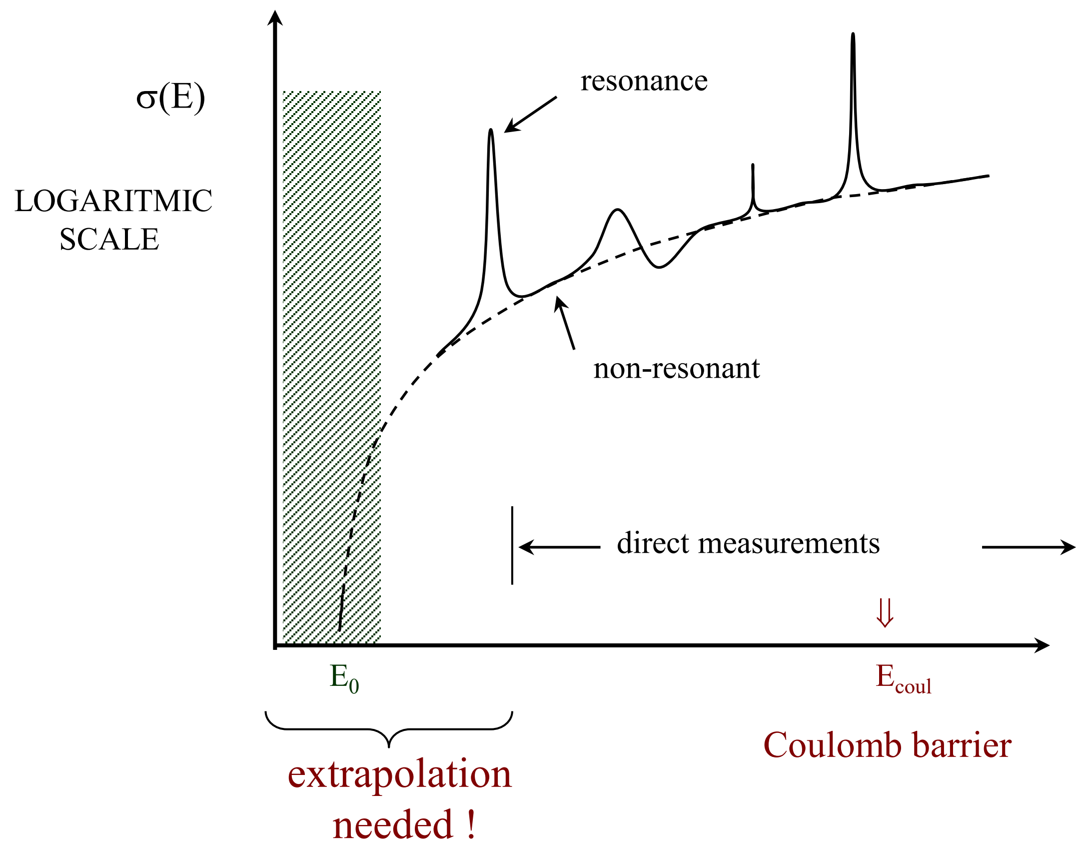
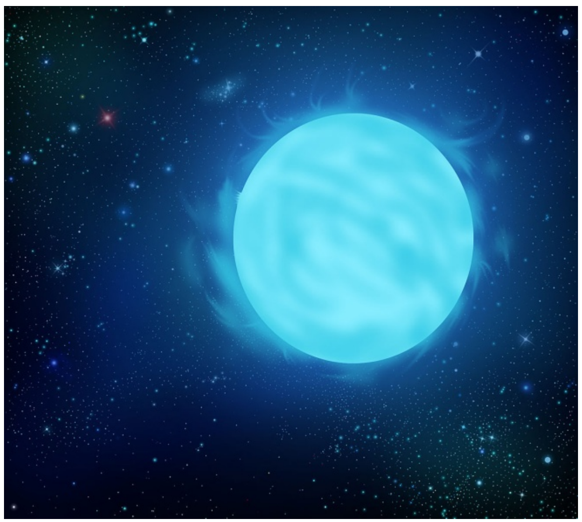


figure: M. Aliotta

Fusion of light nuclei: nuclear astrophysics

$^{12}C+^{12}C$ fusion : a key reaction in nuclear astrophysics

Carbon burning
in massive stars



$^{12}C+^{12}C \rightarrow \alpha + ^{20}Ne$

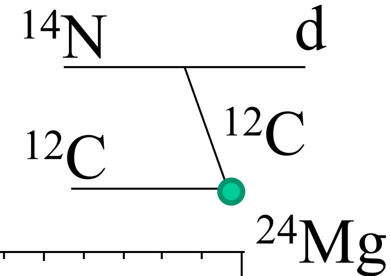
$^{12}C+^{12}C \rightarrow p + ^{23}Na$

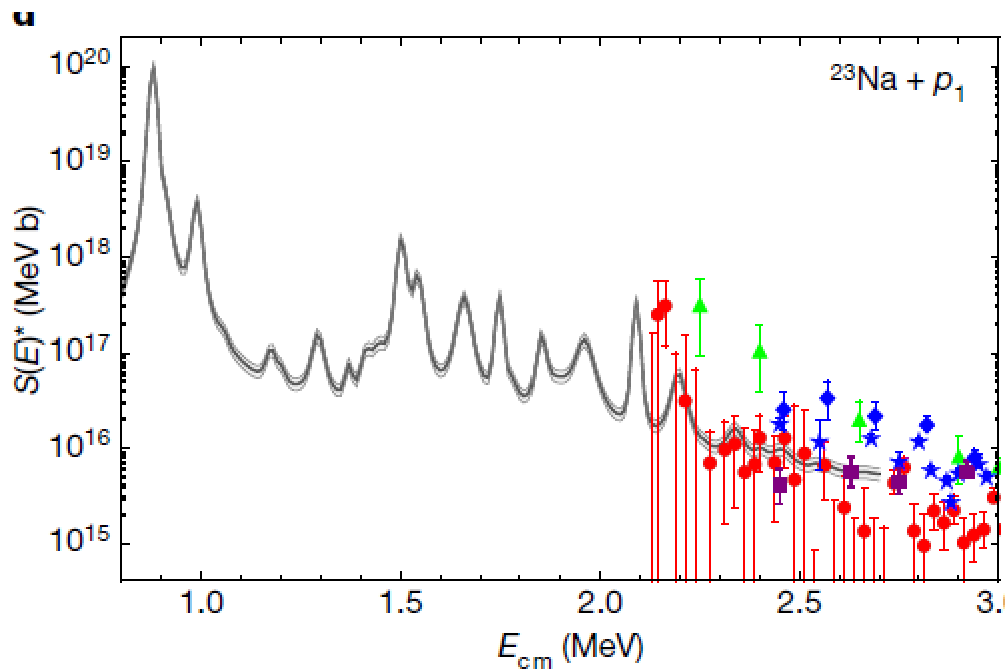
also

✓ Type Ia supernovae

✓ X-ray superburst

Trojan Horse Method



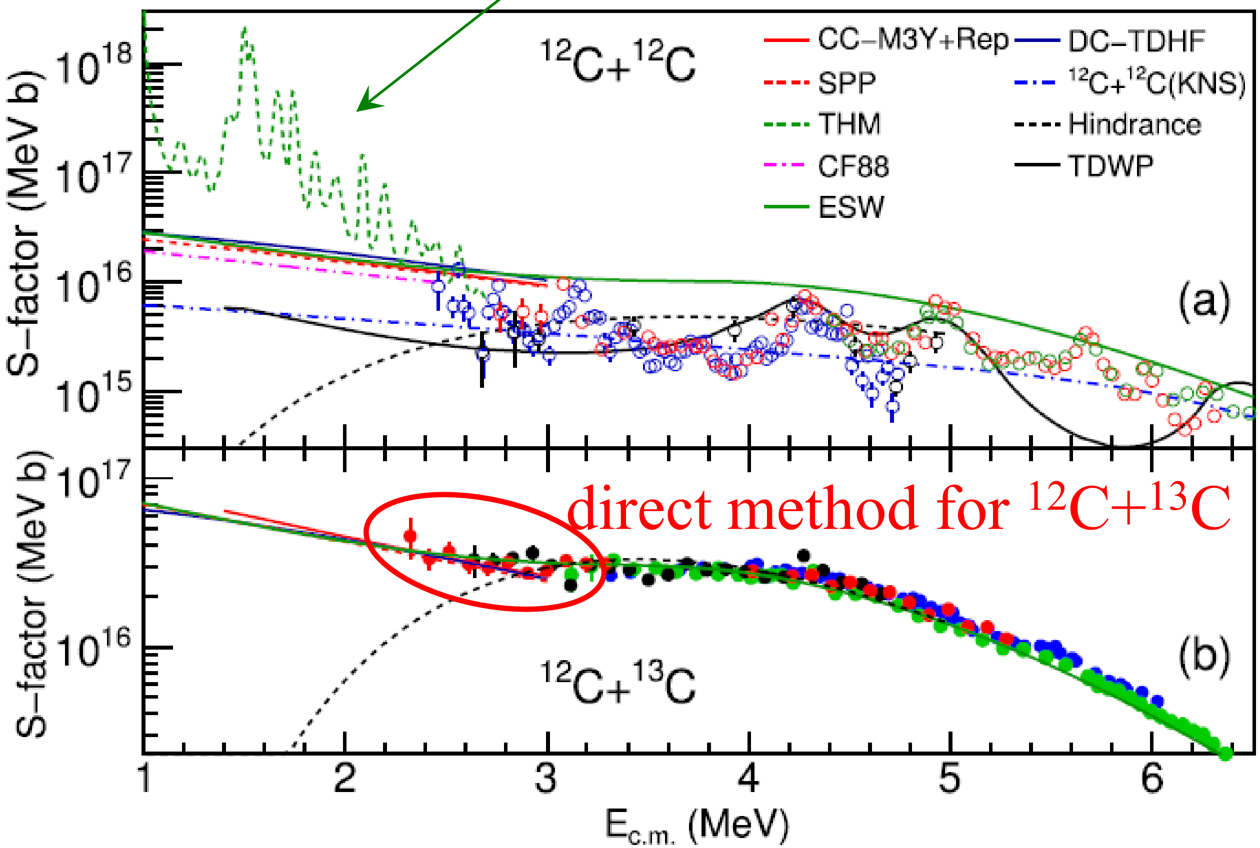


A. Tumino et al., Nature557 ('18) 687

~ 25 times larger than before
→ lots of debates

$^{12}C+^{12}C$ fusion reaction

Trojan Horse Method



The THM data are not supported.

PWIA→DWIA?

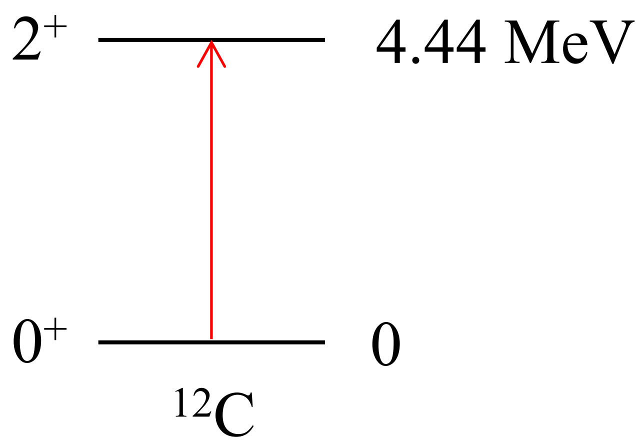
A.M. Mukhamedzhanov et al., PRC99 (‘19) 064618

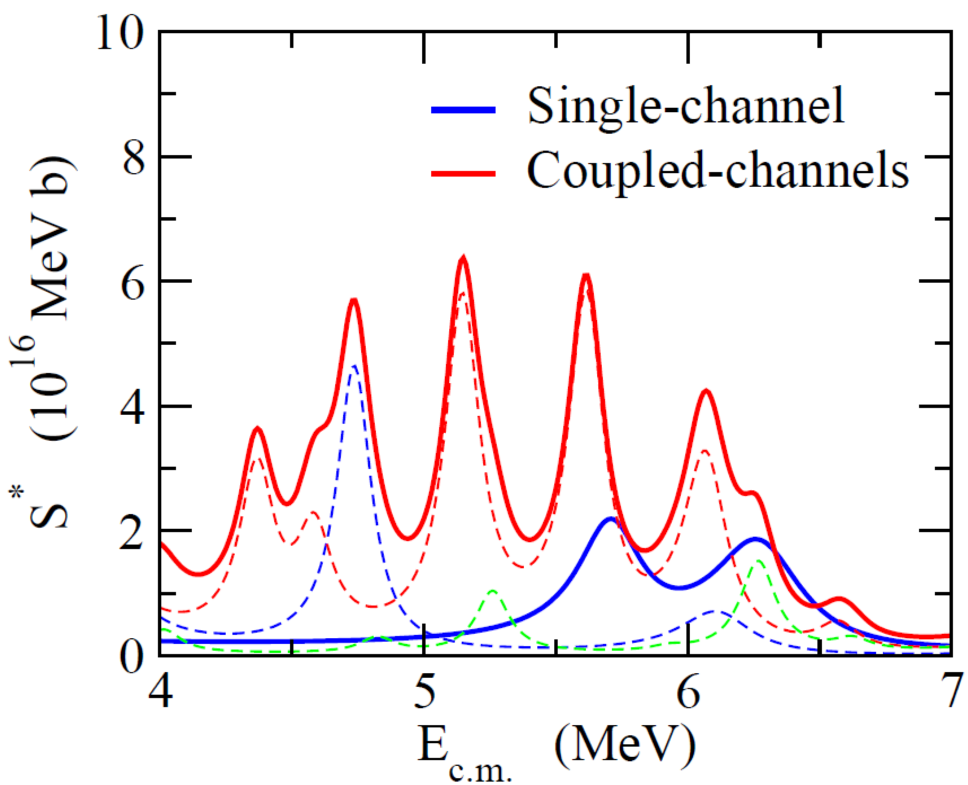
cf. recent direct measurement for $^{12}C+^{12}C$:

W.P. Tan et al., PRL124 (‘20) 192702

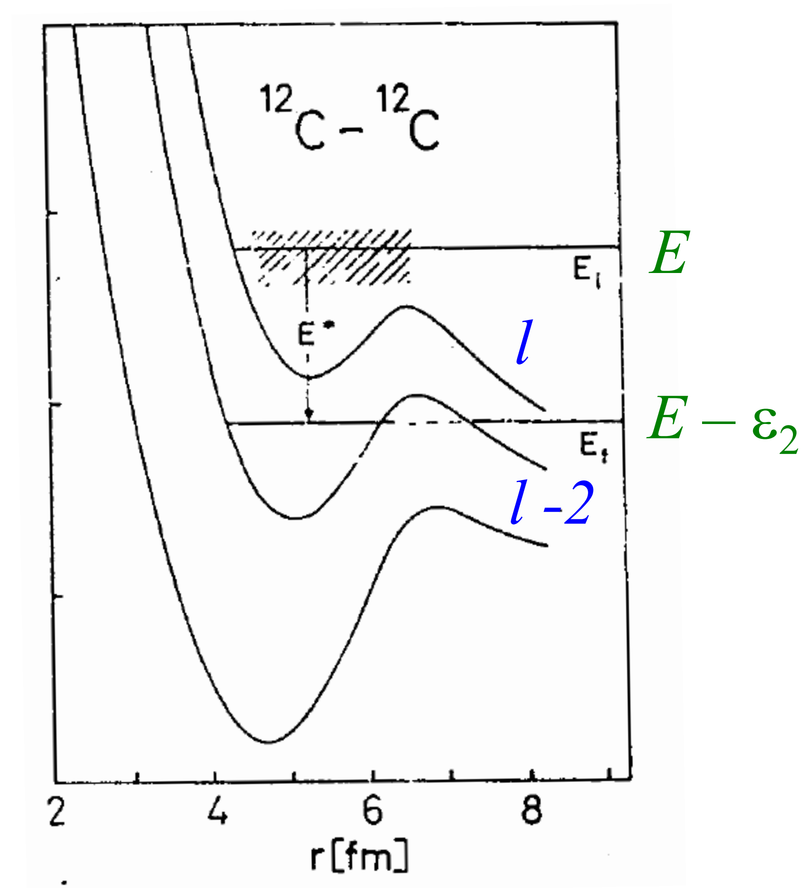
N.T. Zhang,…, K.H., S. Kubono, …., C.J. Lin,….
XiaoDong Tang (IMP) et al., Phys. Lett. B801 (2020) 135170

$^{12}C+^{12}C$ fusion: many resonance peaks





K.H., unpublished (2015)

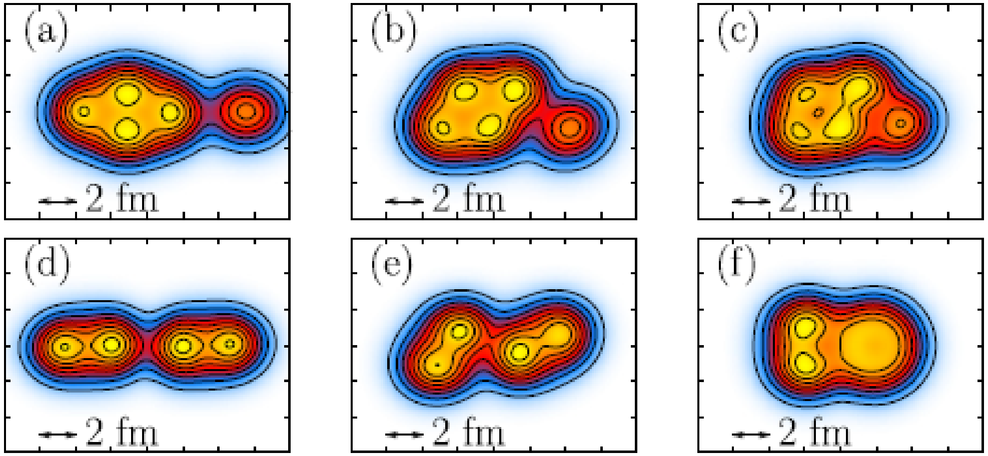


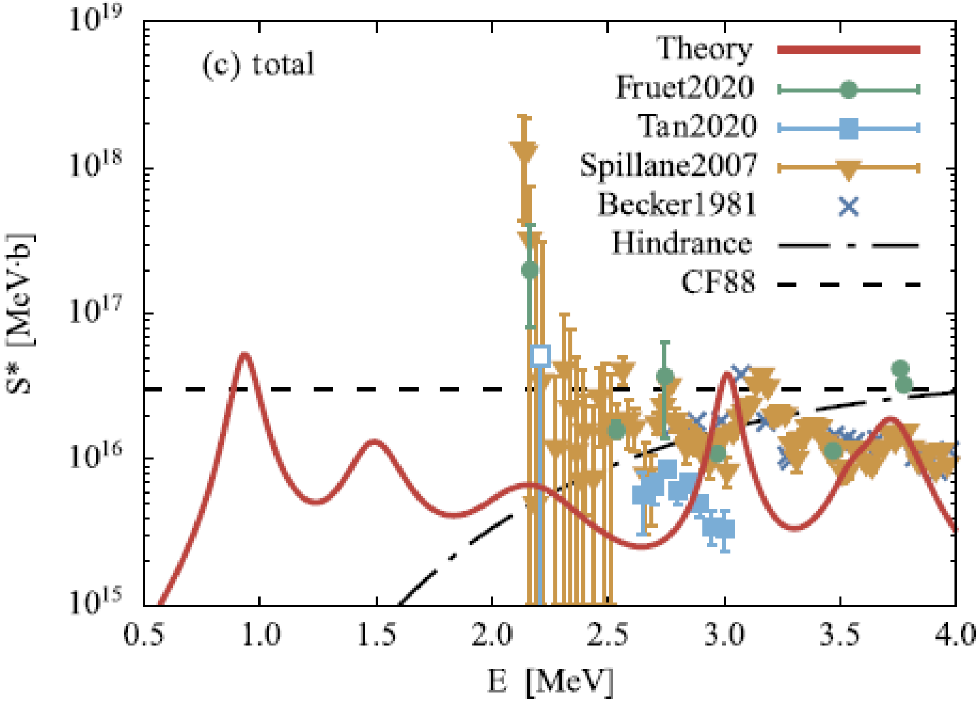
H.-J. Fink, W. Scheid, and W. Greiner, NPA188 ('72) 259

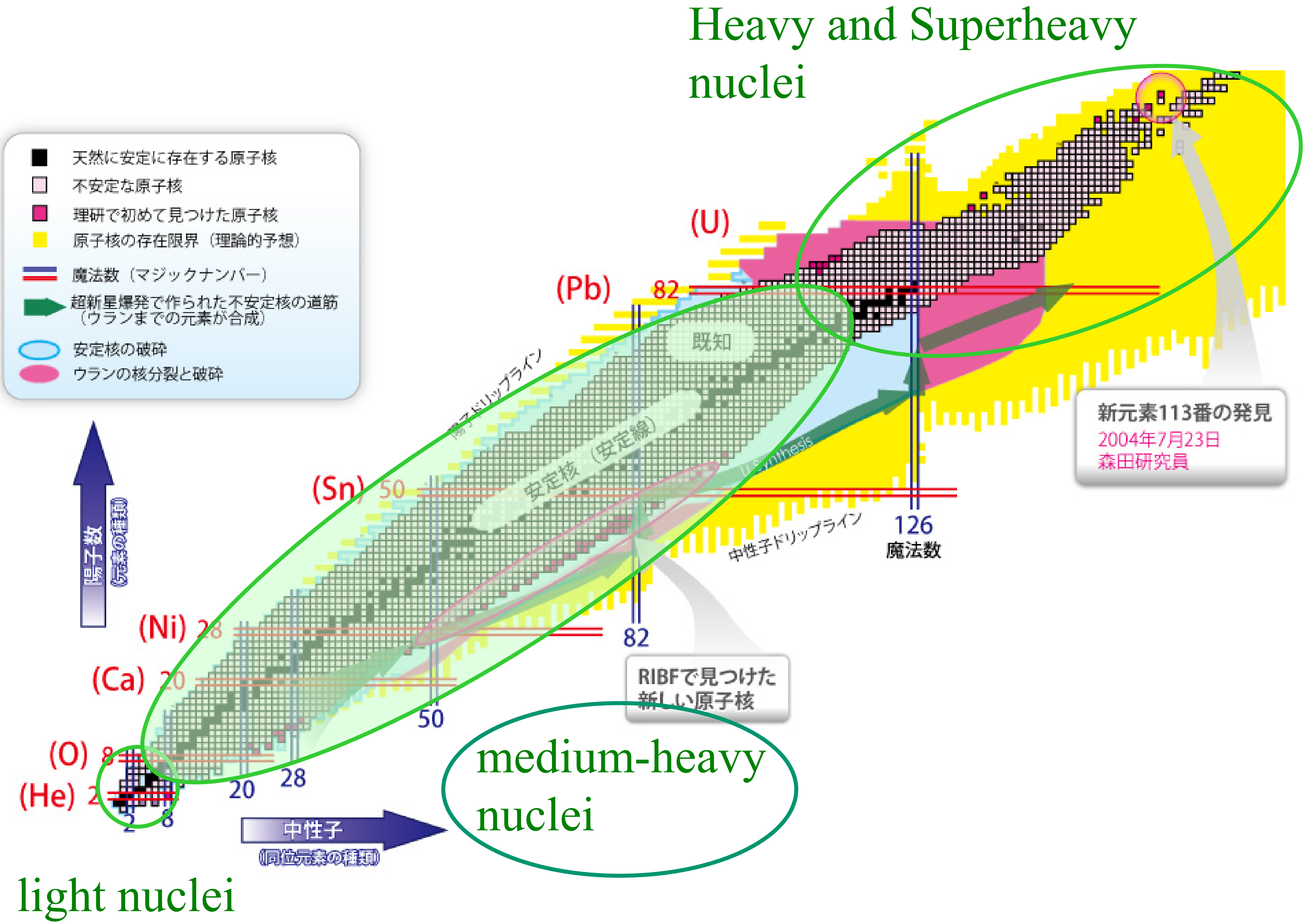
a kind of Feshbach resonance

A recent AMD calculation

Y. Taniguchi and M. Kimura, PLB823 ('21) 136790





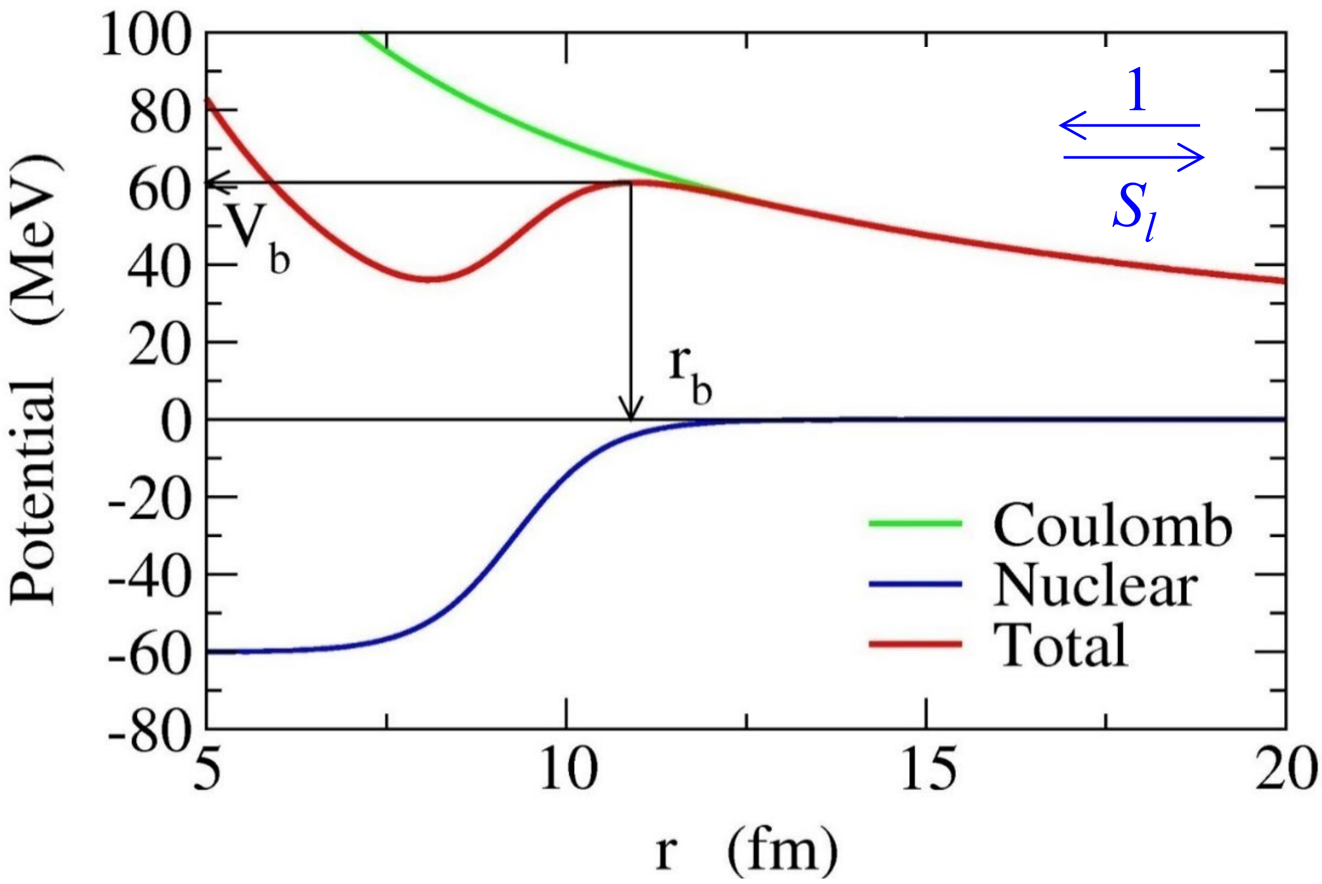


Nuclear Chart: RIKEN Nishina Center

Fusion reactions of medium-heavy nuclei

potential model: inert nuclei (no structure)

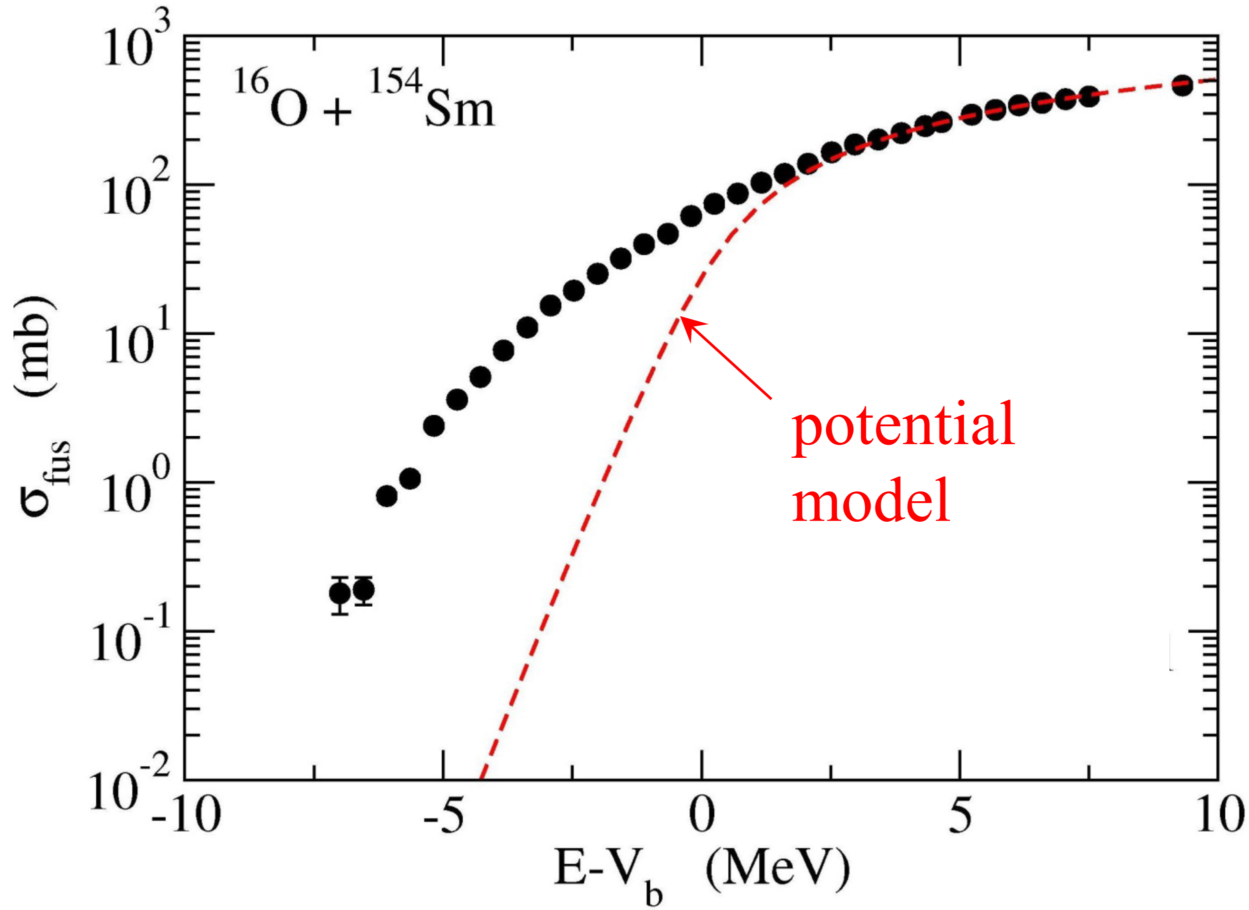
$$\sigma_{\text{fus}} = \frac{\pi}{k^2} \sum_l (2l+1)(1 - |S_l|^2)$$



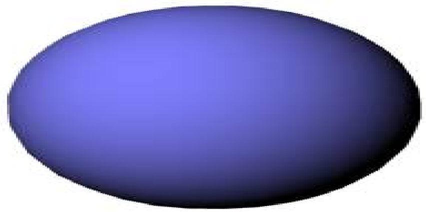
Fusion reactions of medium-heavy nuclei

potential model: inert nuclei (no structure)

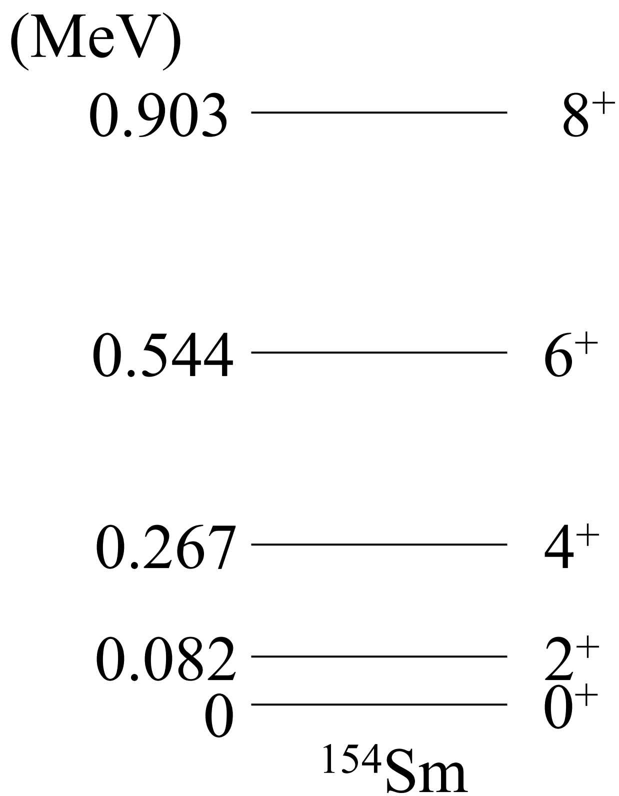
$$\sigma_{\mathrm{fus}} = \frac{\pi}{k^2}\sum_l (2l+1)(1-|S_l|^2)$$



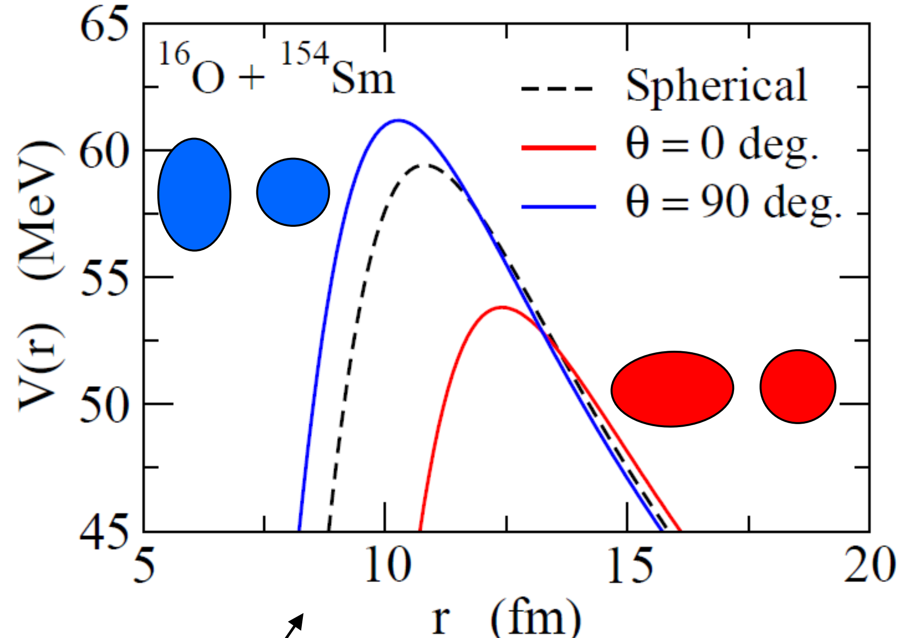
^{154}Sm : a typical deformed nucleus

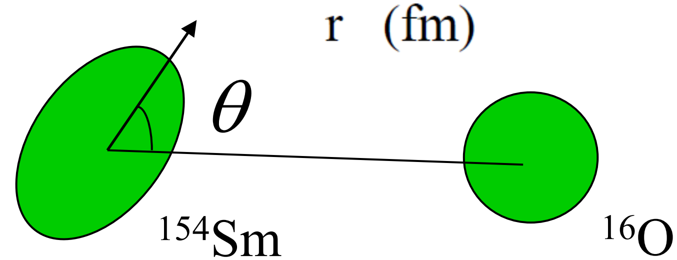


^{154}Sm

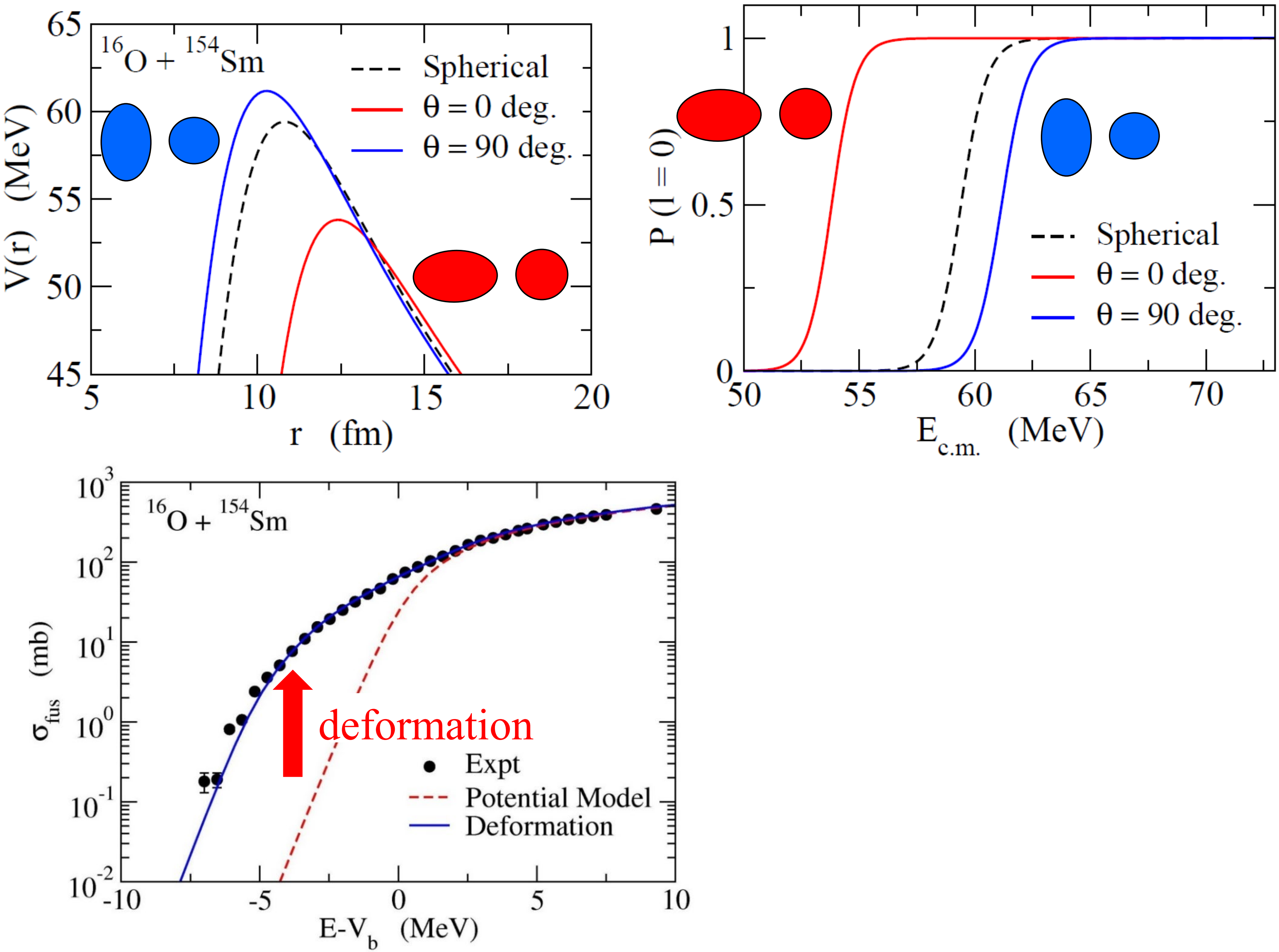


rotational spectrum

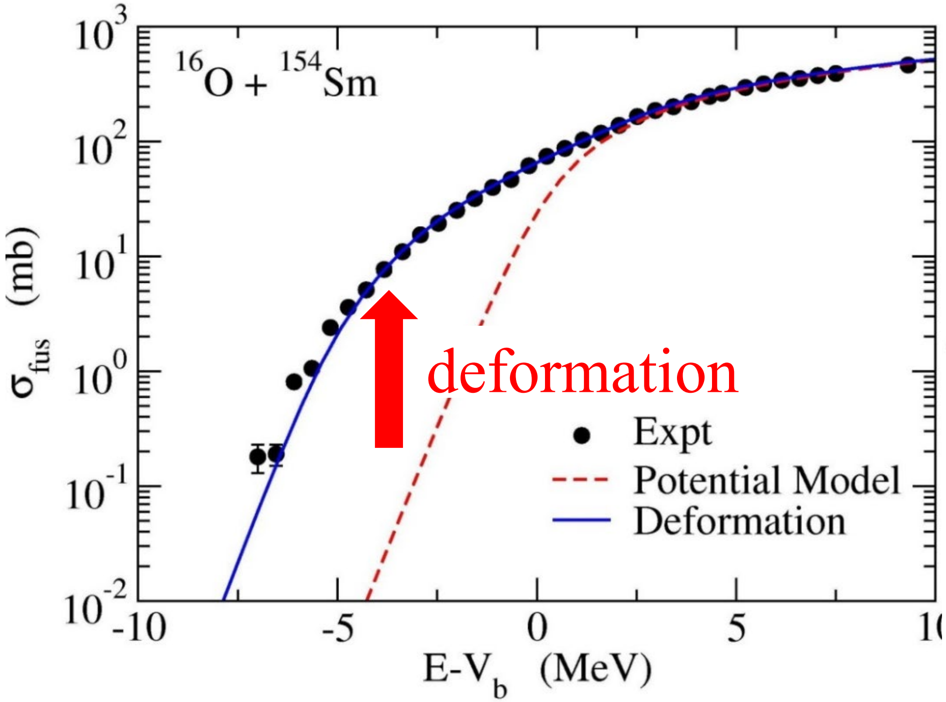




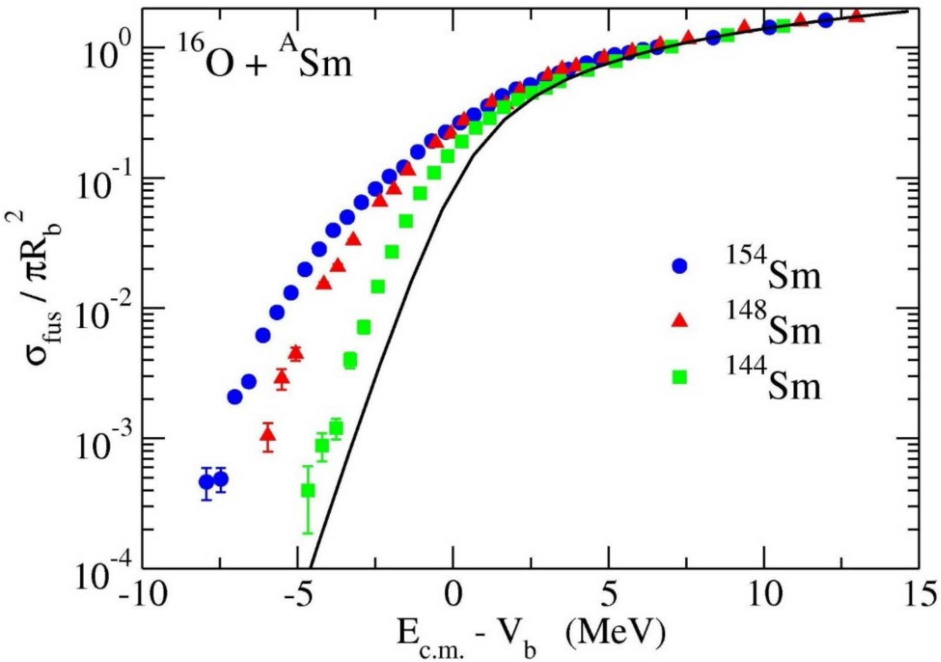
$$\sigma_{\mathrm{fus}}(E) = \int_0^1 d(\cos\theta)\,\sigma_{\mathrm{fus}}(E;\theta)$$



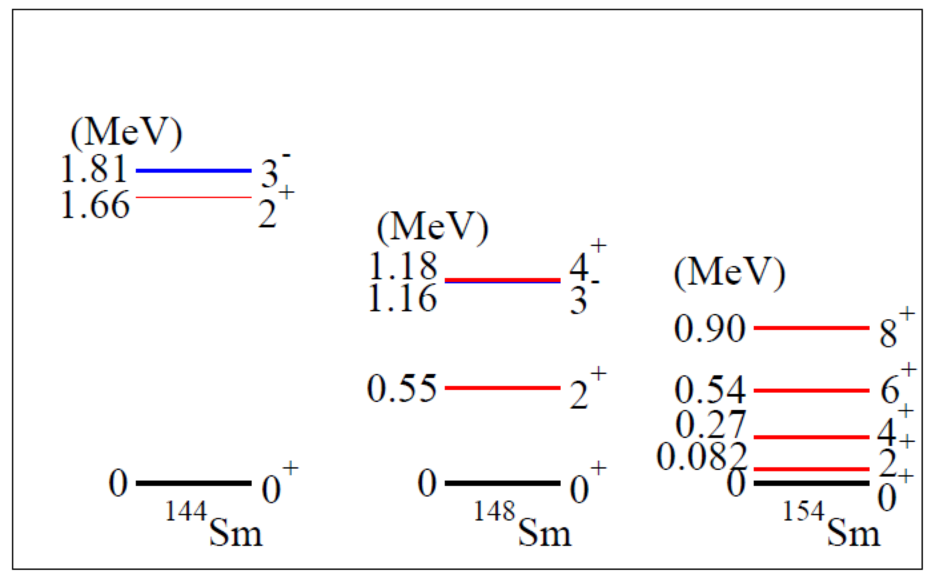
$^{16}O + ^{154}Sm$
Spherical
θ = 0 deg.
θ = 90 deg.
V(r) (MeV)
r (fm)
P (l = 0)
$E_{c.m.}$ (MeV)
$^{16}O + ^{154}Sm$
deformation
Expt
Potential Model
Deformation
σ_{fus} (mb)
$E-V_b$ (MeV)



similar enhancement
for non-deformed nuclei

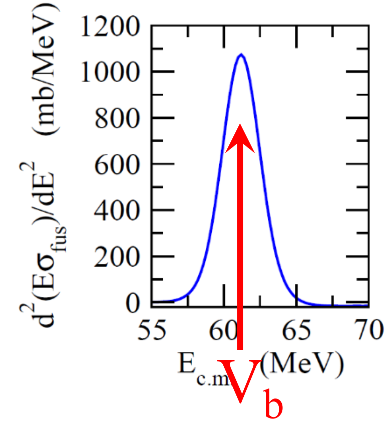


strong correlation
with nuclear spectrum
→ coupling assisted
tunneling phenomena

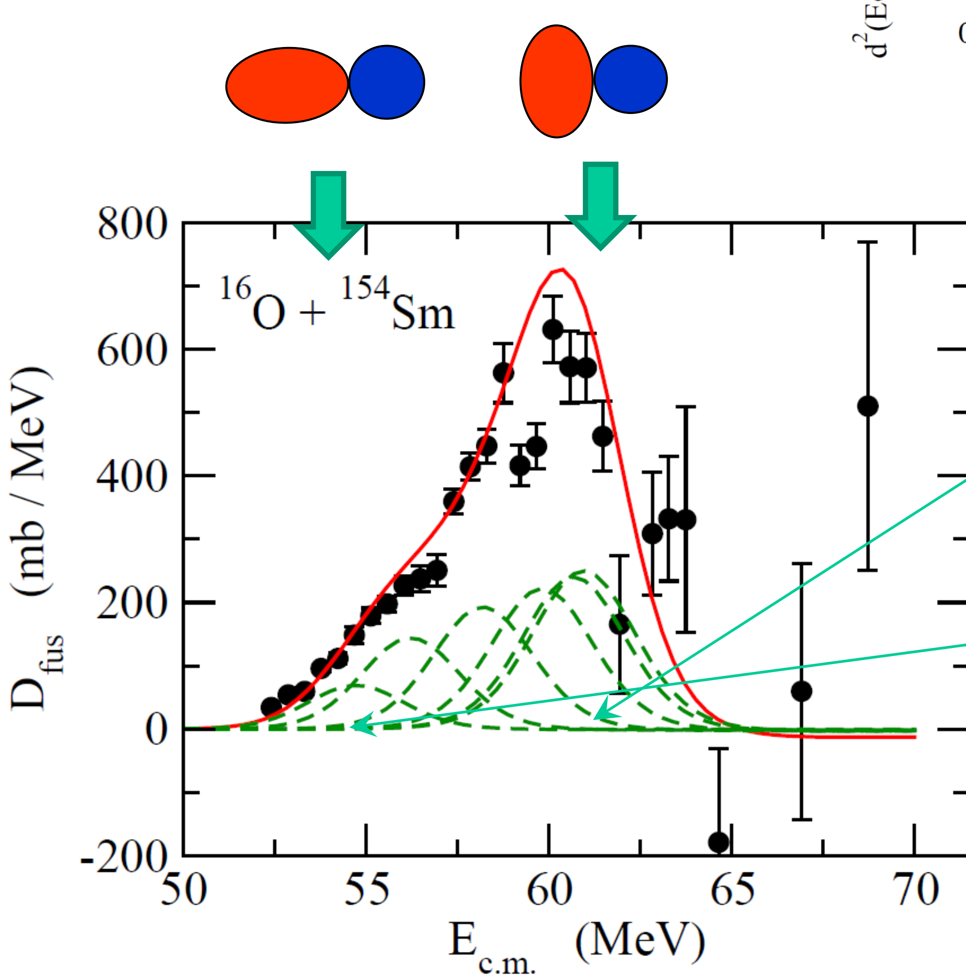


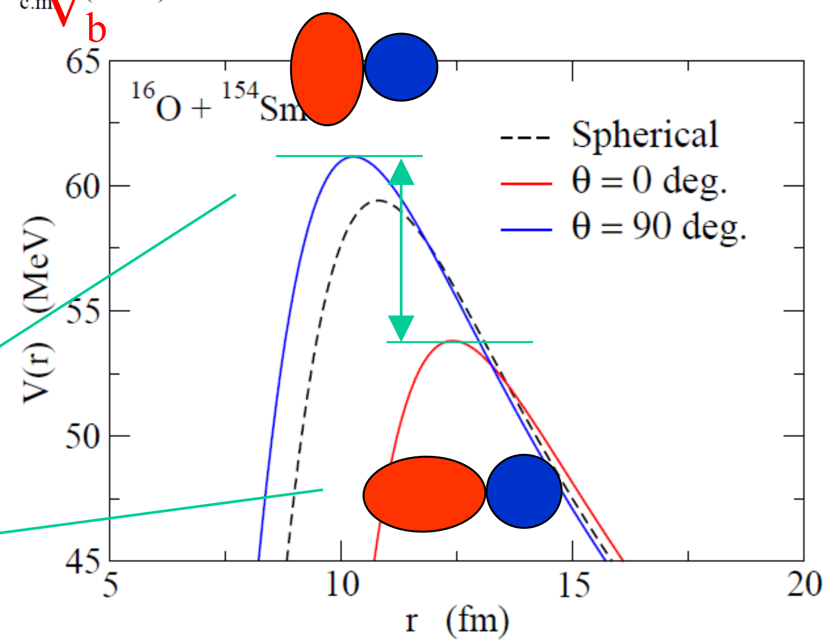
✓ Fusion barrier distribution (Rowley, Satchler, Stelson, PLB254('91))

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



single channel

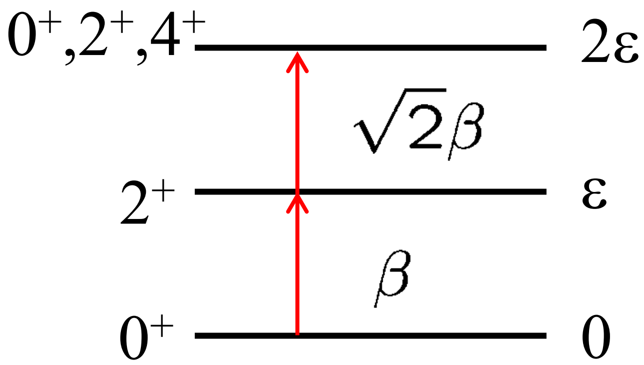




Semi-microscopic modelling of subbarrier fusion reactions

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

simple harmonic oscillator

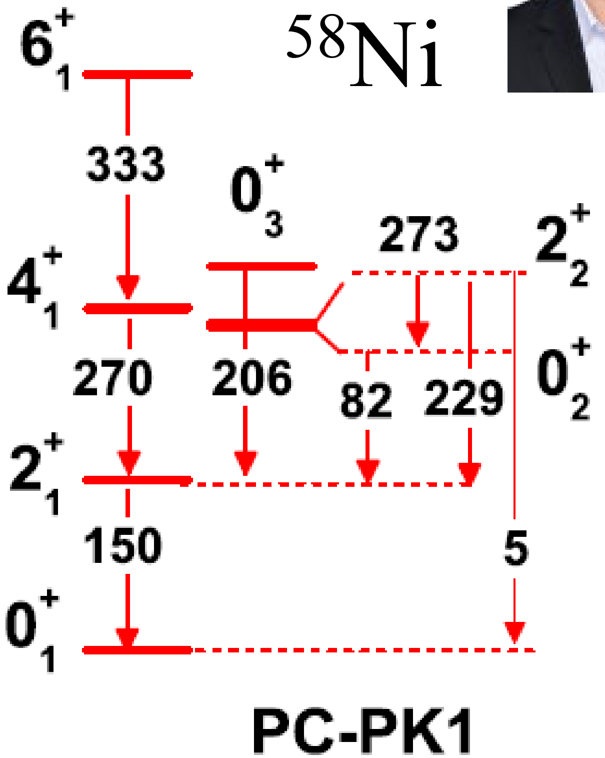


Semi-microscopic modelling of subbarrier fusion reactions

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

$$|JM\rangle = \int d\beta\, f_J(\beta)\hat{P}^J_{M0}|\Phi(\beta)\rangle$$

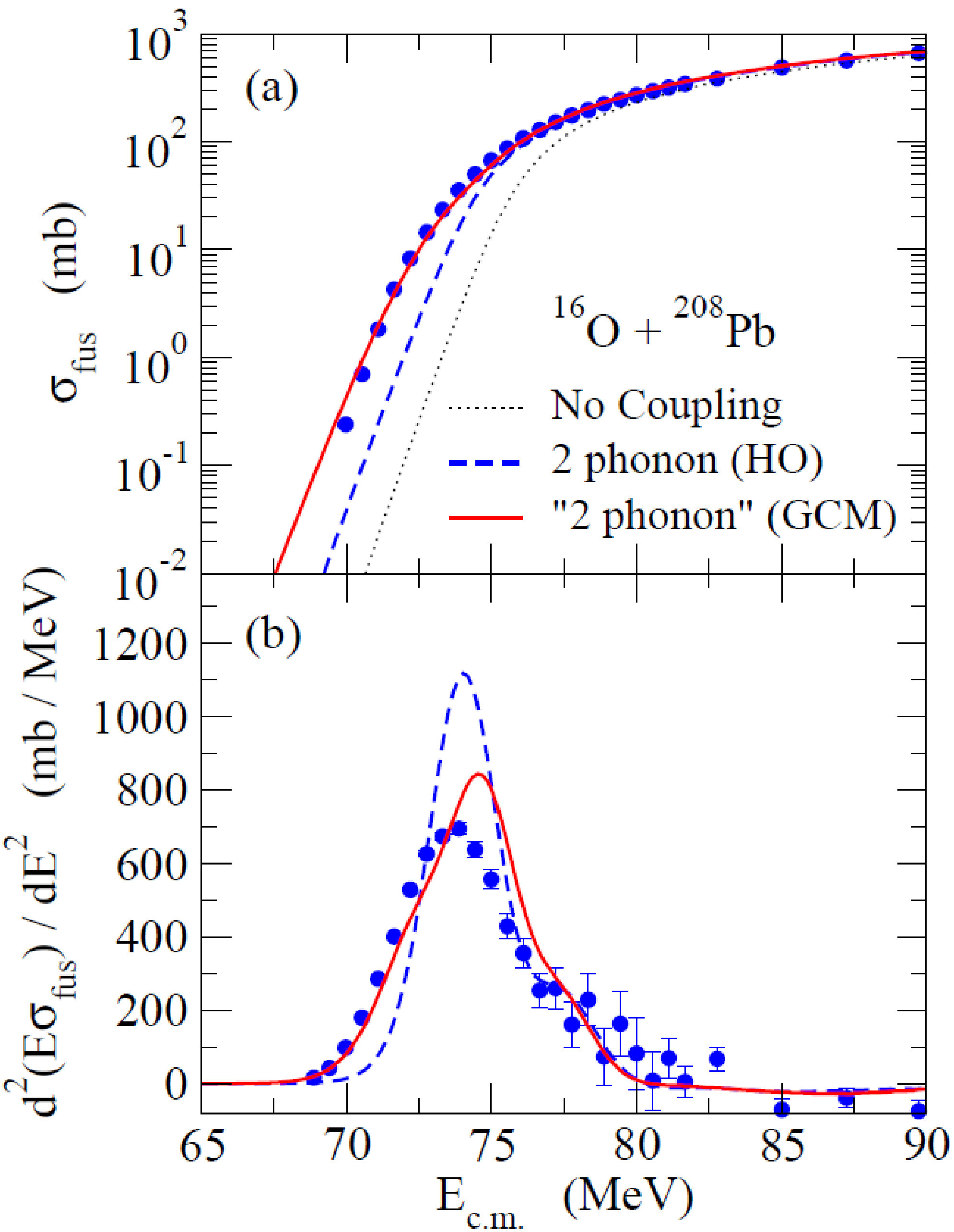
✓ MF + ang. mom. projection
+ particle number projection
+ generator coordinate method (GCM)

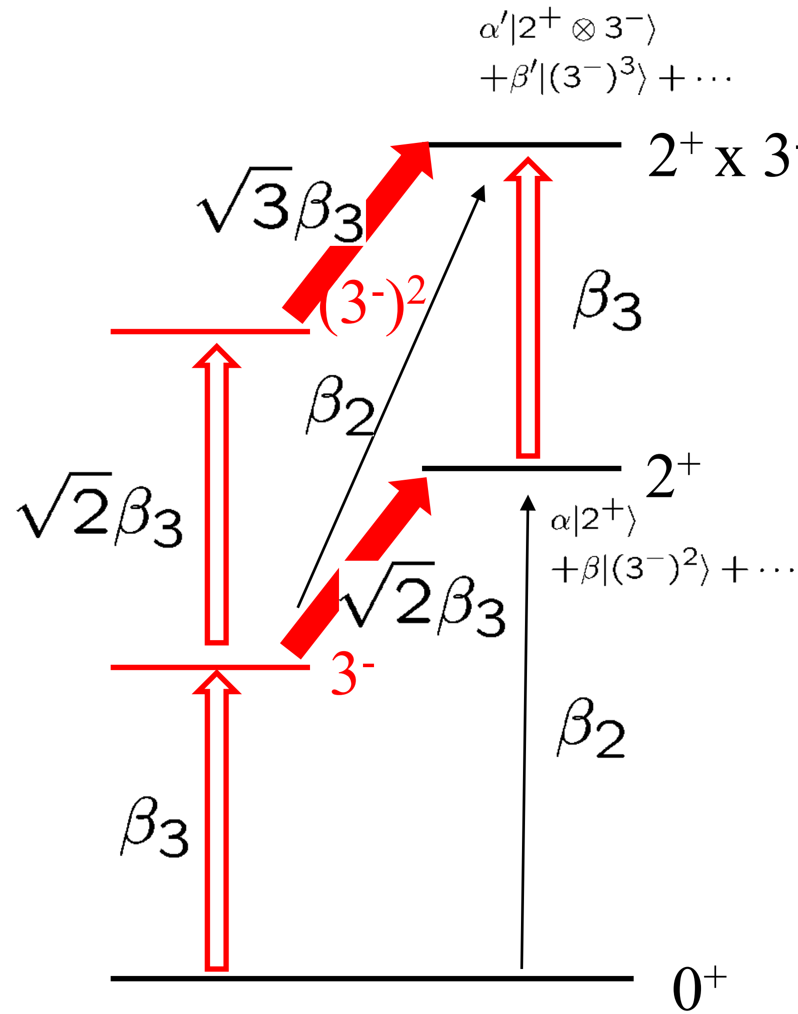


Beyond-mean-field method

anharmonicity of phonon spectra

→ C.C. calculations with
a phenomenological potential





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

From phenomenological approach to microscopic approach

Macroscopic (phenomenological)

C.C. with collective model

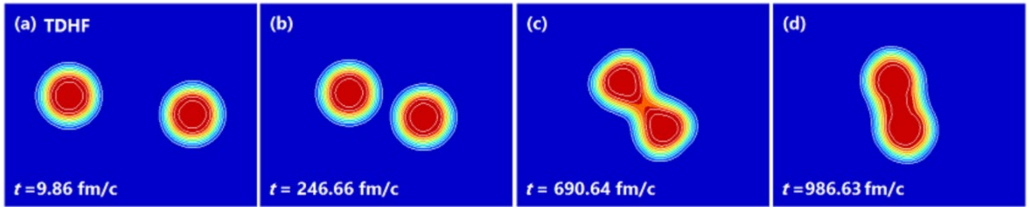
C.C. with inputs from microscopic nuclear structure calculations

C.C. with inputs based on TDHF

TDHF simulations

Microscopic

TDHF = Time Dependent Hartree-Fock



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

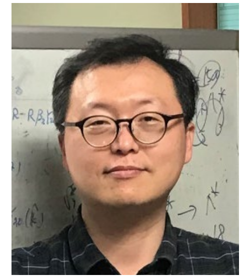
ab initio, but no tunneling

Fusion of neutron-rich nuclei

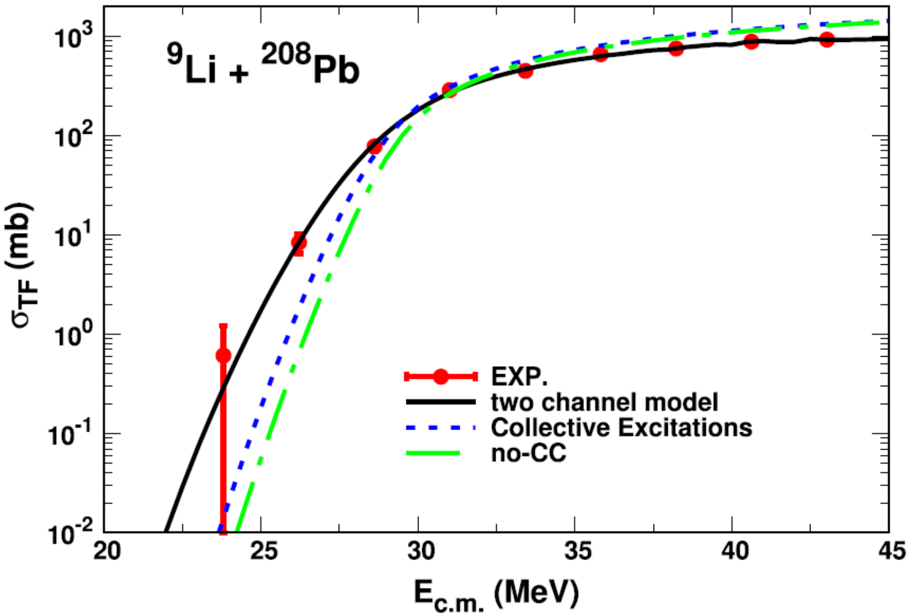
SOONGSIL UNIVERSITY 1897

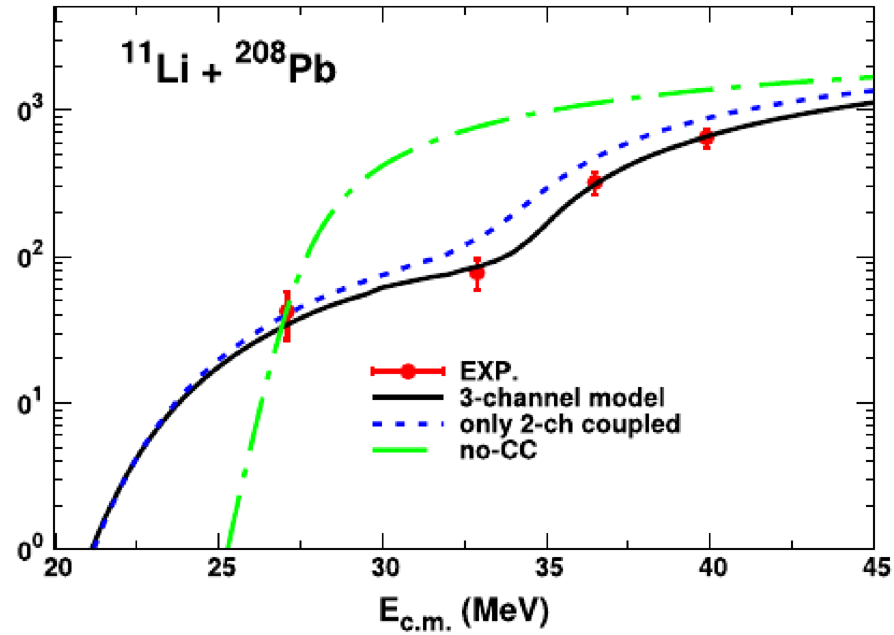
KOREA AEROSPACE UNIVERSITY 1952

KNU 강원대학교 KANGWON NATIONAL UNIVERSITY



K.-S. Choi, M.-K. Cheoun, W.Y. So, K.H., and K.S. Kim, Phys. Lett. B780 ('18) 455



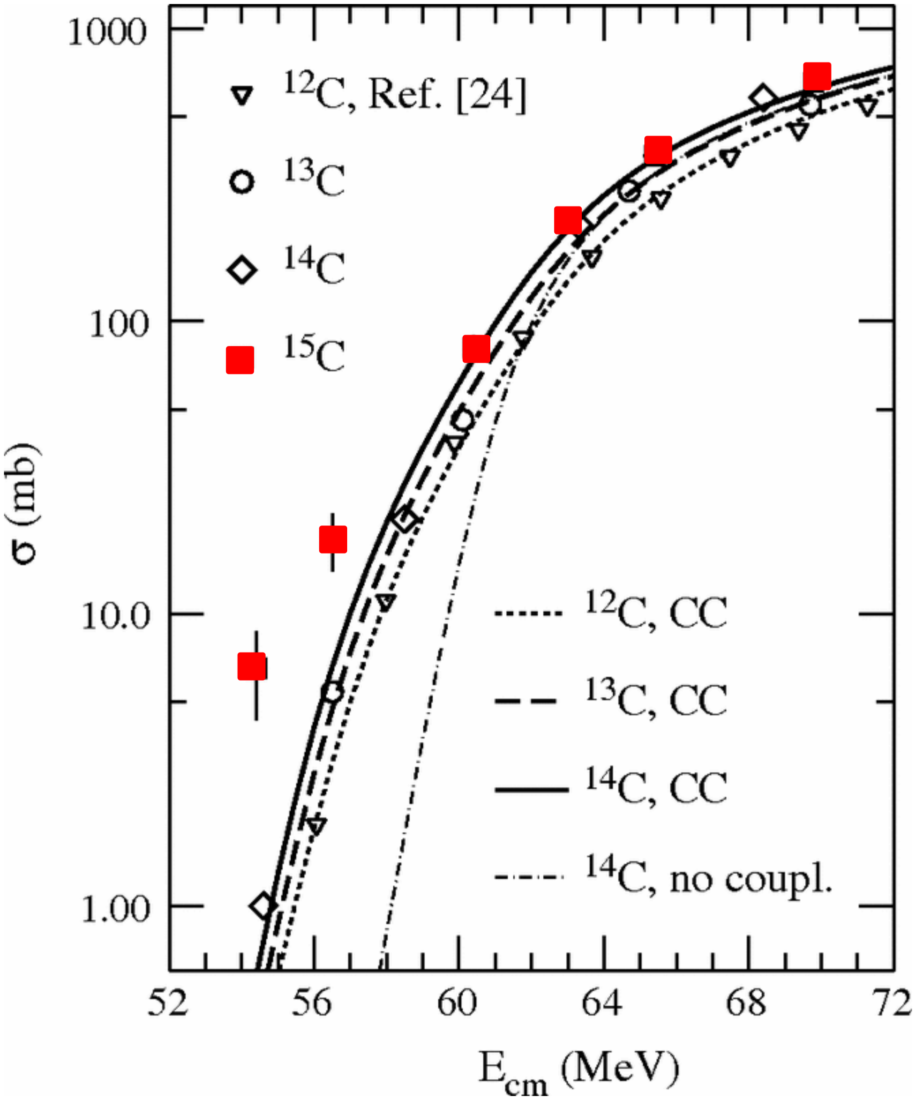


simultaneous explanation for ^{9}Li+^{208}Pb and ^{11}Li+^{208}Pb with:

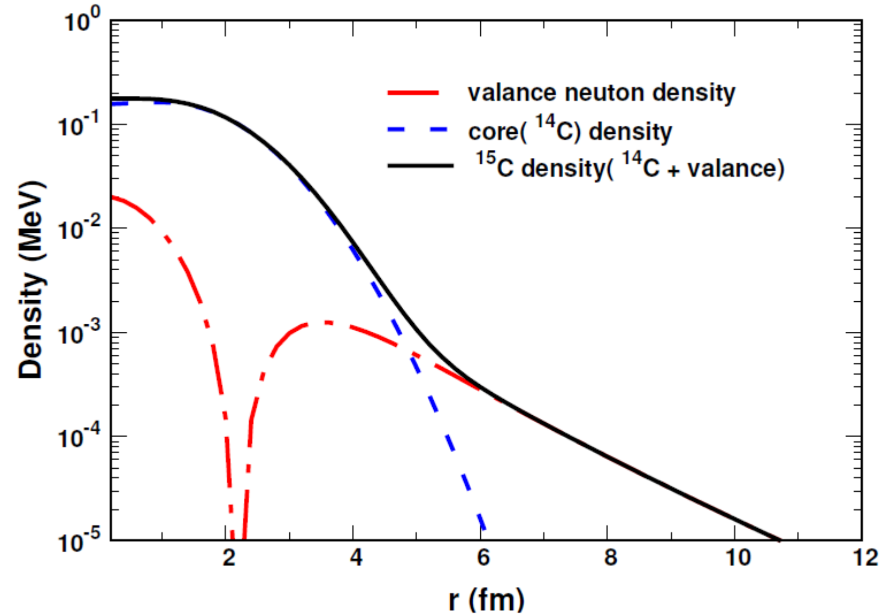
^{11}Li+^{208}Pb ⟵⟶ ^{9}Li+^{210}Pb ⟵⟶ ^{7}Li+^{212}Pb transfer couplings

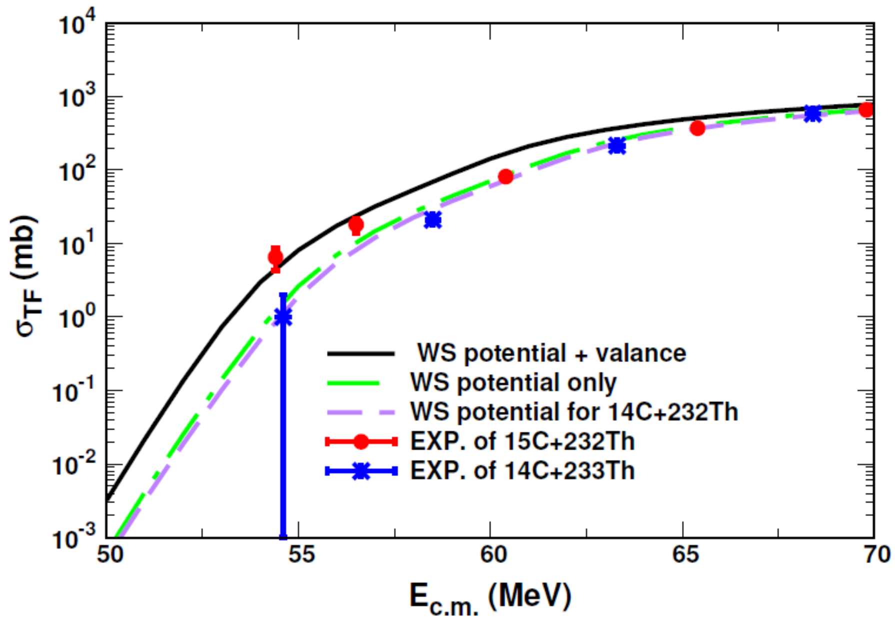
Fusion of neutron-rich nuclei

$^{12,13,14,15}C + ^{232}Th$

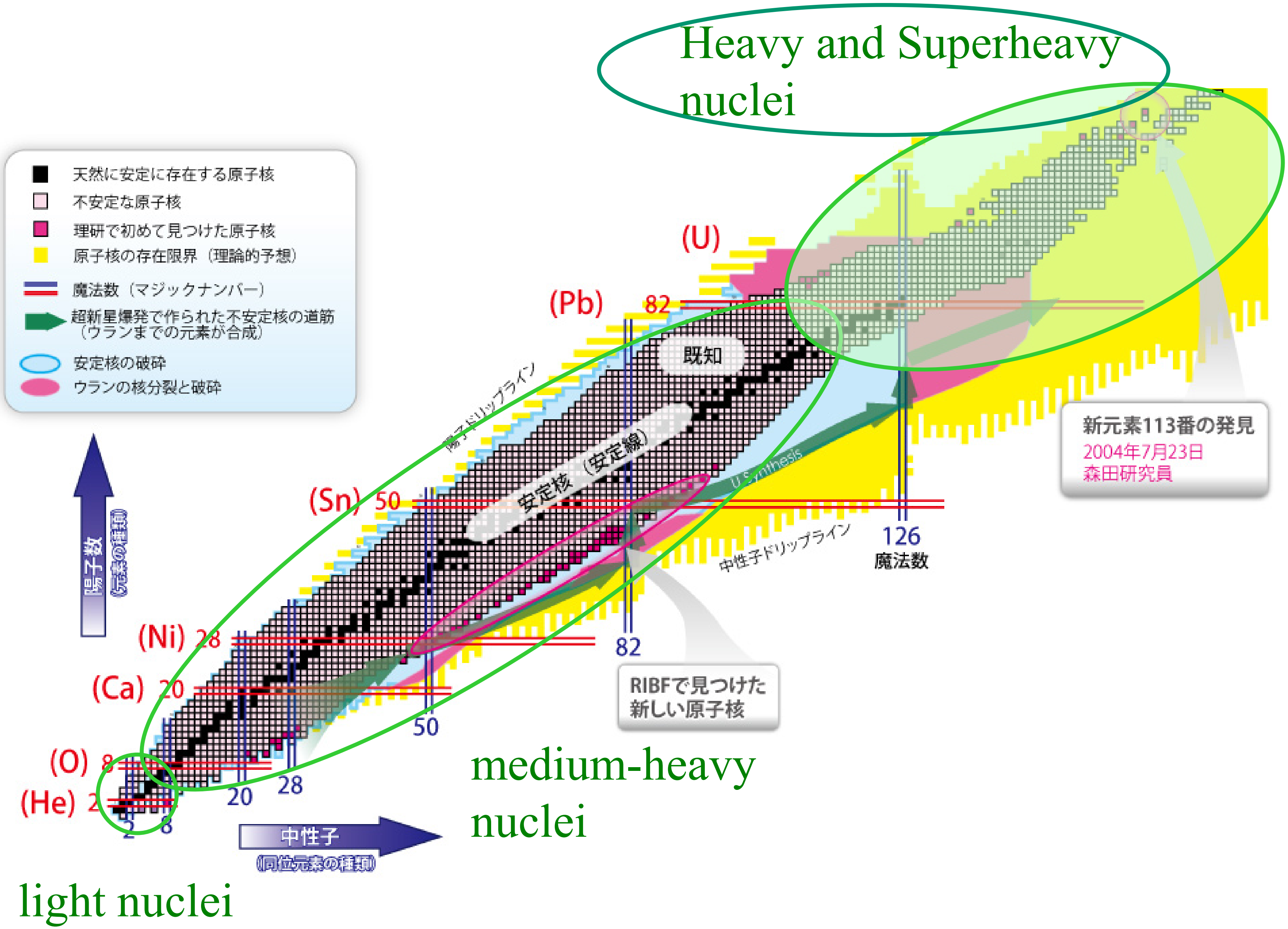


M. Alcorta et al., PRL106('11)





K.-S. Choi,…,K.H. et al., in preparation

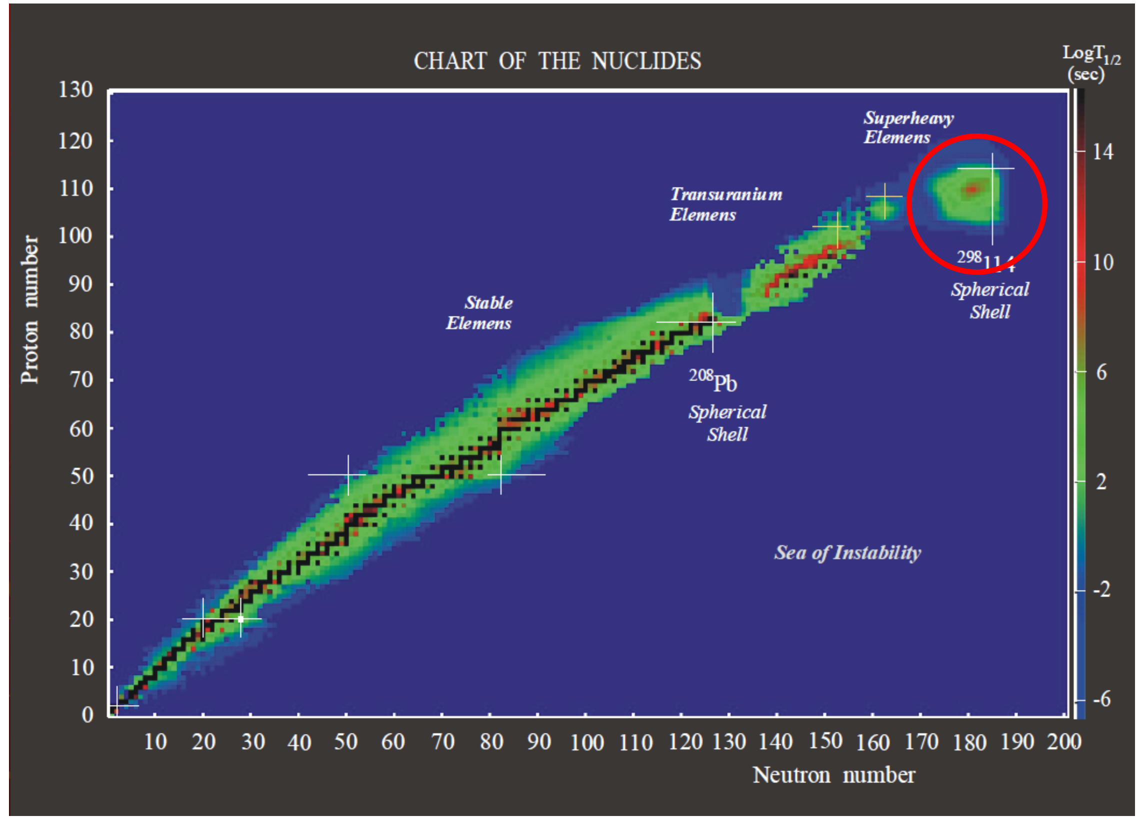


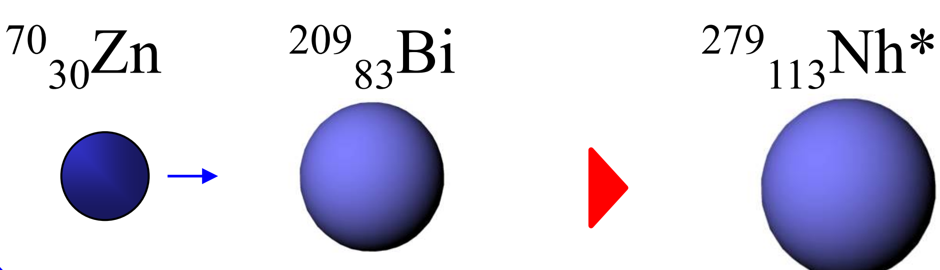
Nuclear Chart: RIKEN Nishina Center

Superheavy elements

the island of stability（安定的島）

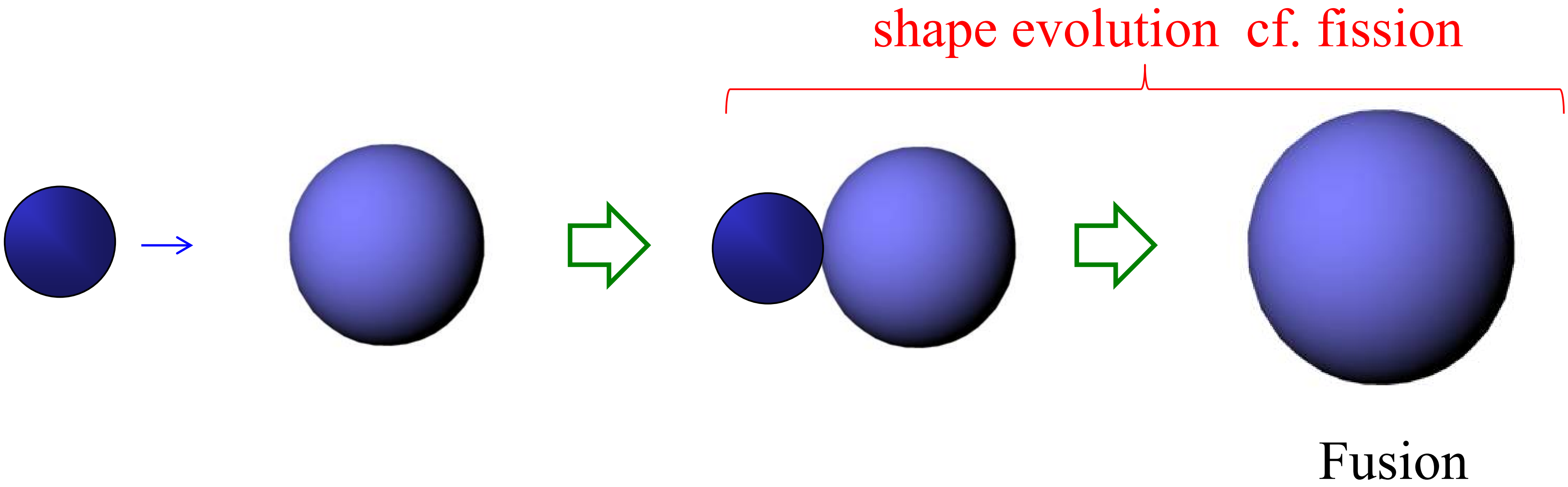
November, 2016





Heavy-ion fusion reaction

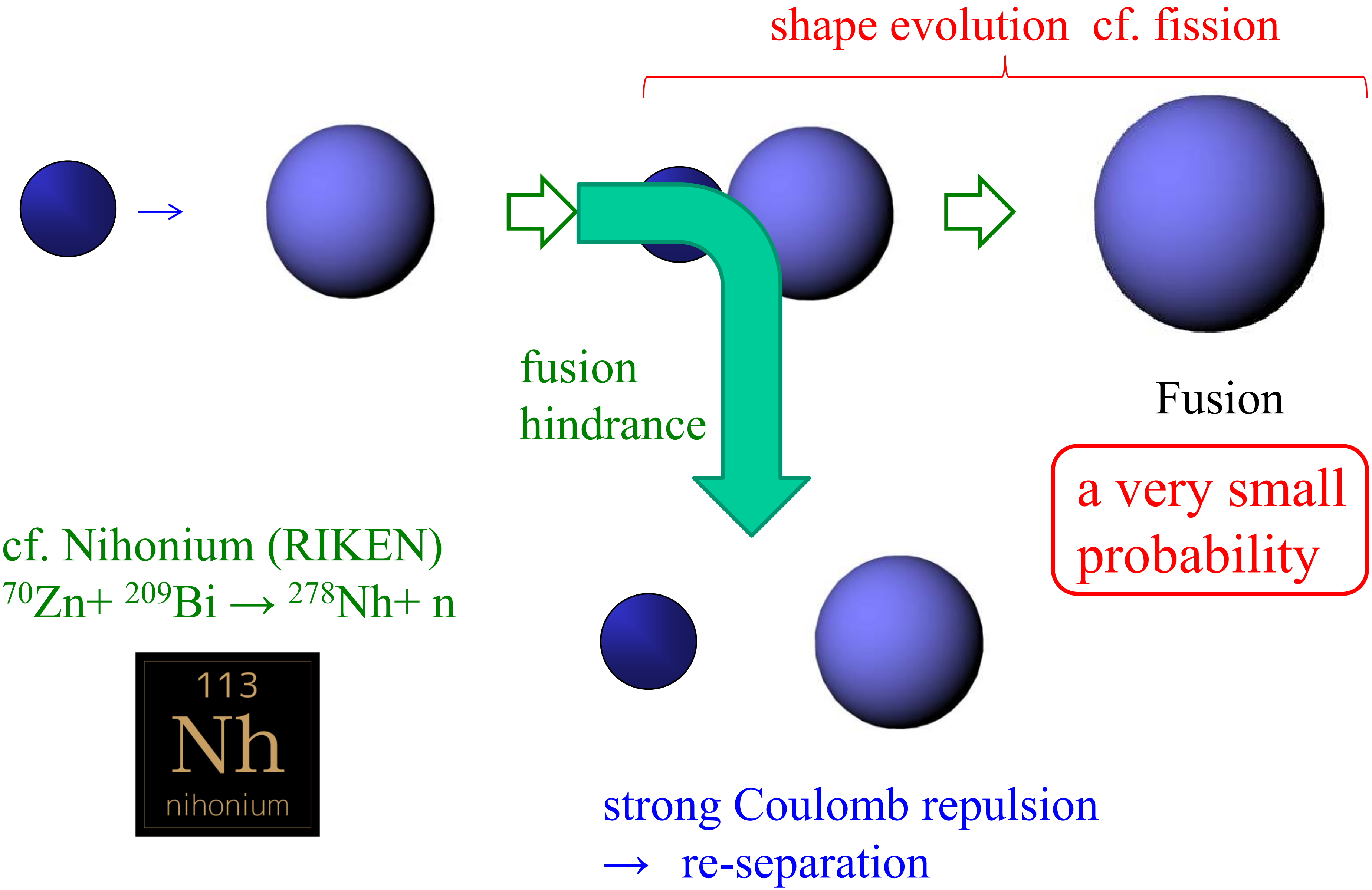
Fusion of heavy nuclei and superheavy elements



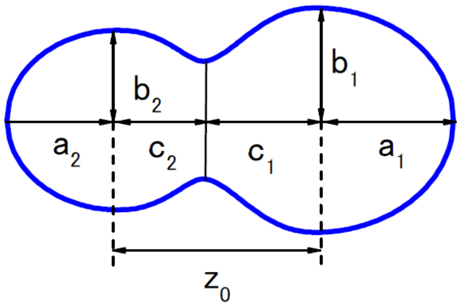
cf. Nihonium (RIKEN)

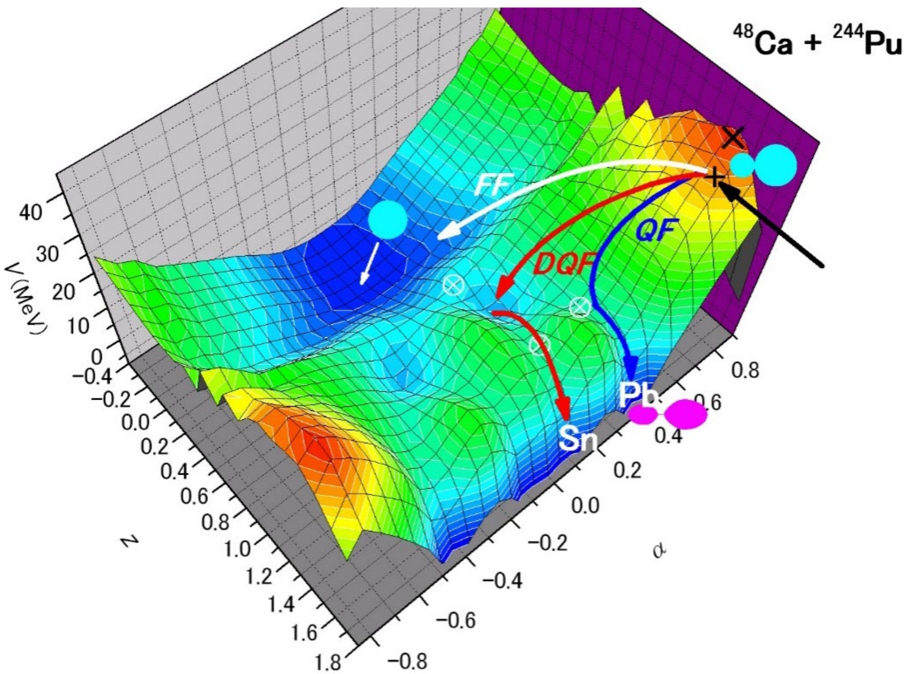
$^{70}\mathrm{Zn} + {}^{209}\mathrm{Bi} \longrightarrow {}^{278}\mathrm{Nh} + n$

Fusion of heavy nuclei and superheavy elements

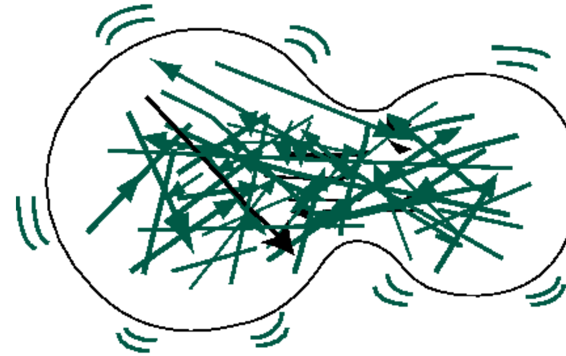


Nuclear shape evolution





Y. Aritomo, K. Hagino, K. Nishio, and S. Chiba, PRC85 (2012) 044614



nucleus = many-body system of nucleons

⇩

nuclear intrinsic d.o.f.

: internal environment

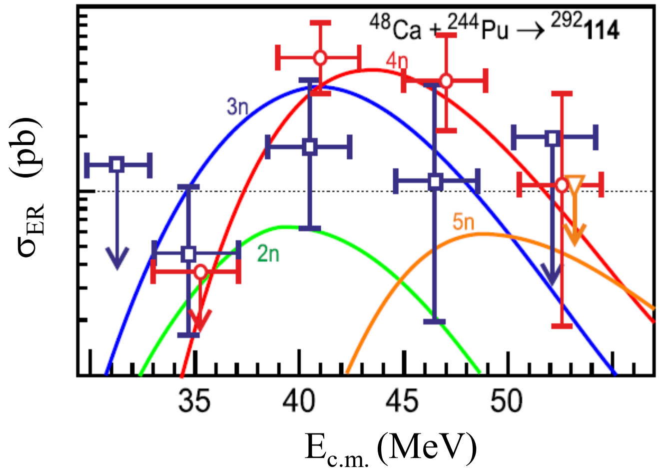
→physics of open quantum systems

cf. Classical Langevin equation

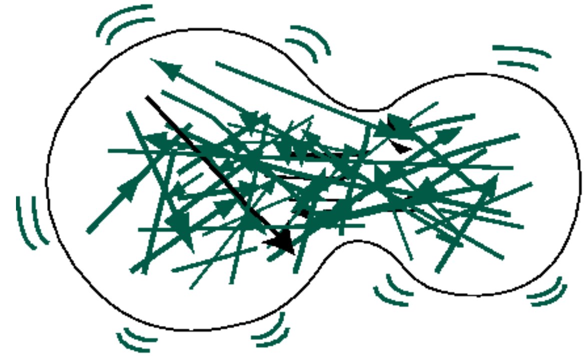
$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$

Nuclear shape evolution

- successful as a phenomenological approach



V.I. Zagrebaev and W. Greiner (2015)



nucleus = many-body system of nucleons

⇩

nuclear intrinsic d.o.f.
: internal environment

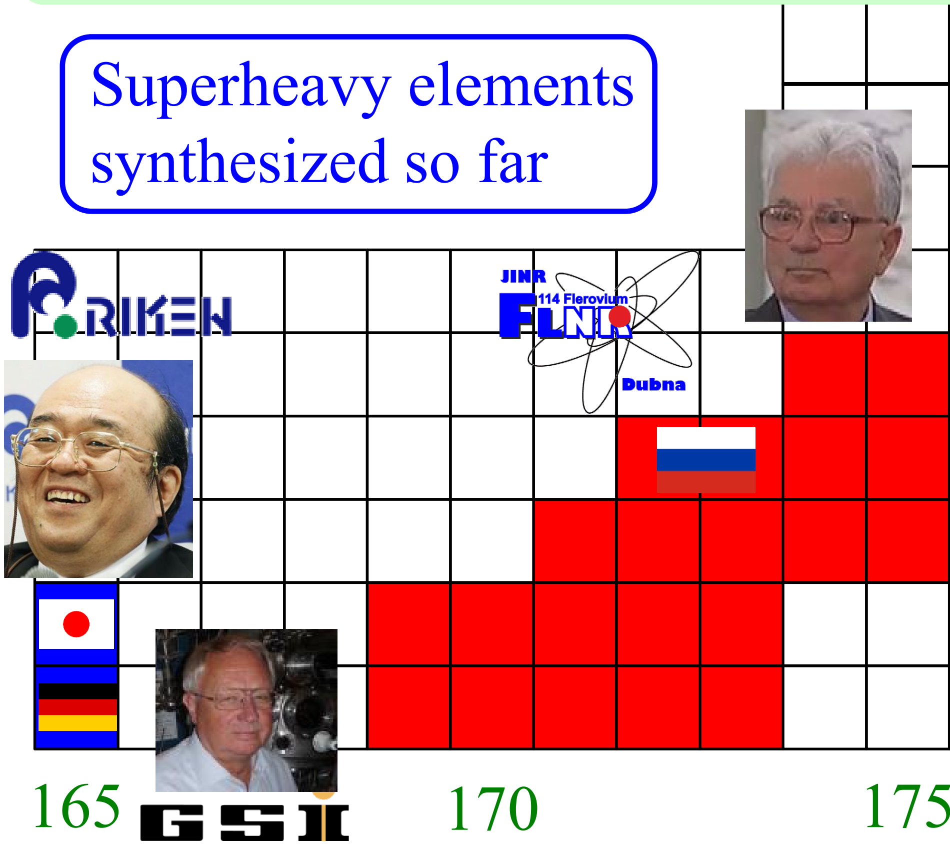
→physics of open quantum systems

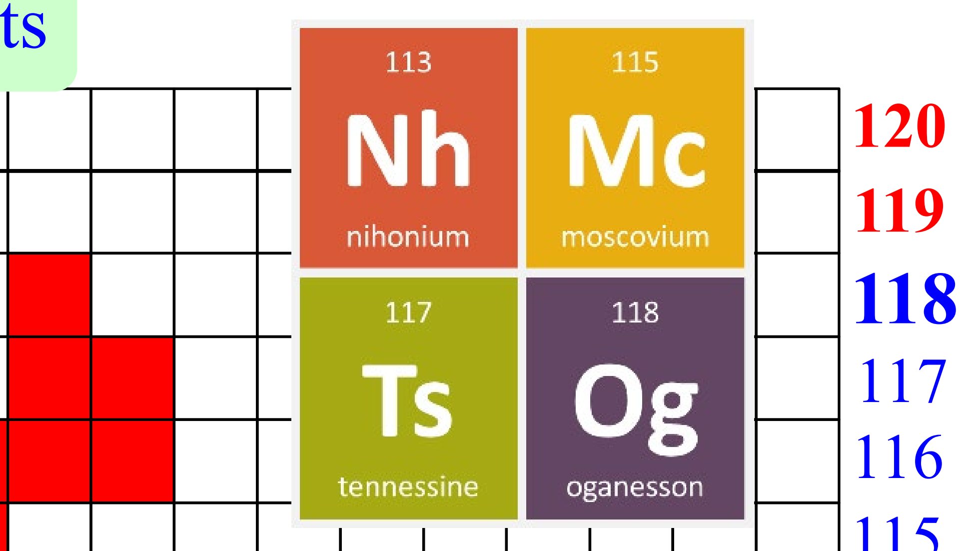
cf. Classical Langevin equation

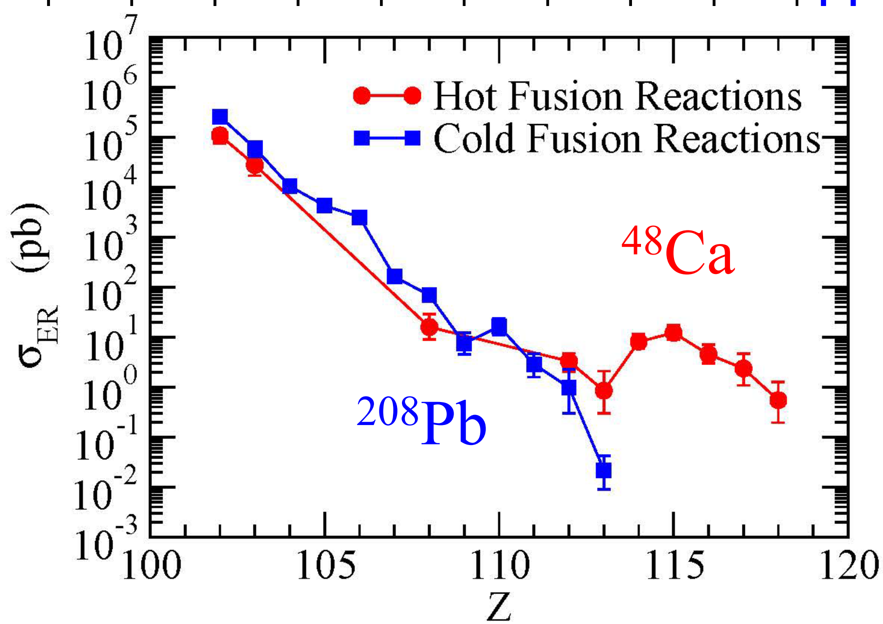
$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$

Fusion for superheavy elements

Superheavy elements synthesized so far







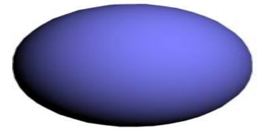
RIKEN (2018-)

$^{51}V + ^{248}Cm \rightarrow 119$

- ✓ optimum bombarding energy?
- ✓ ^{51}V rather than ^{48}Ca?

optimum bombarding energy

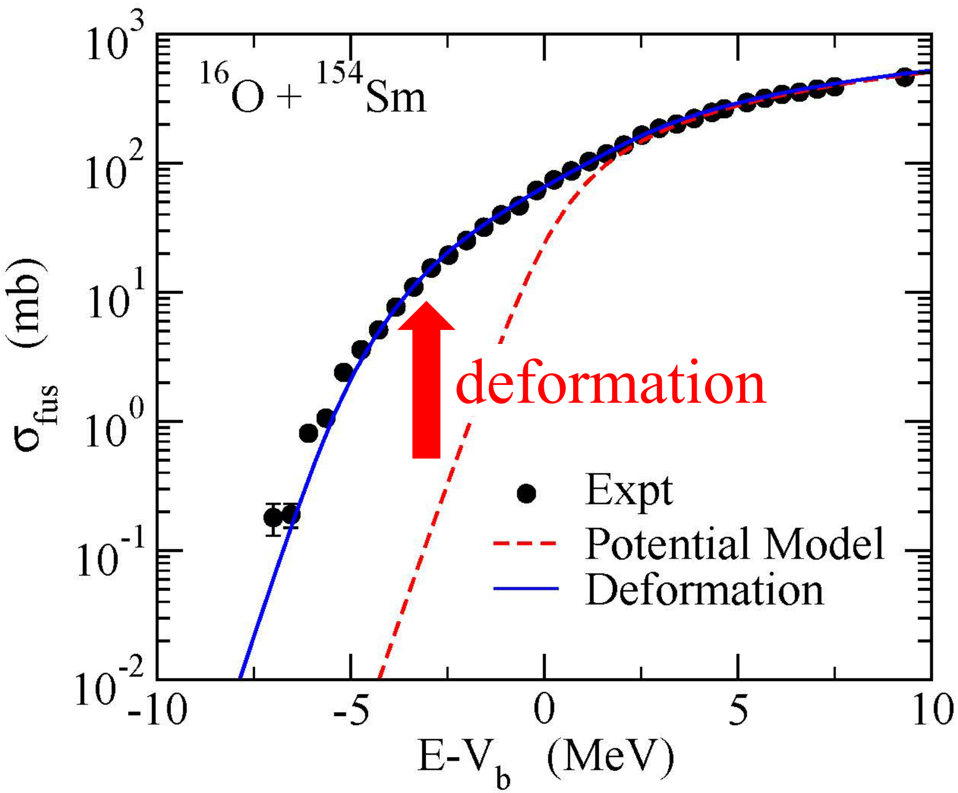
hot fusion: ^{48}Ca + deformed target

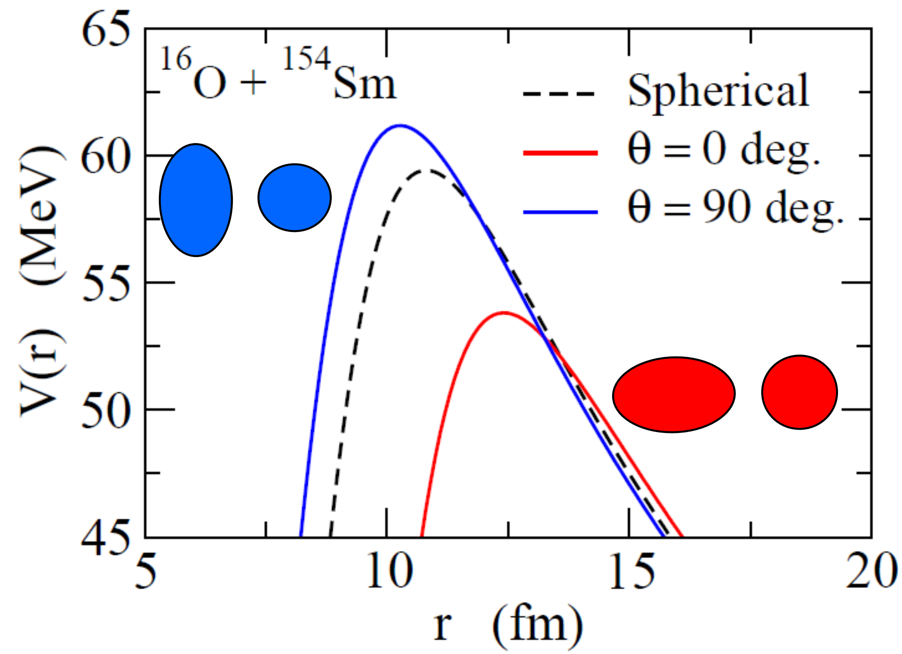


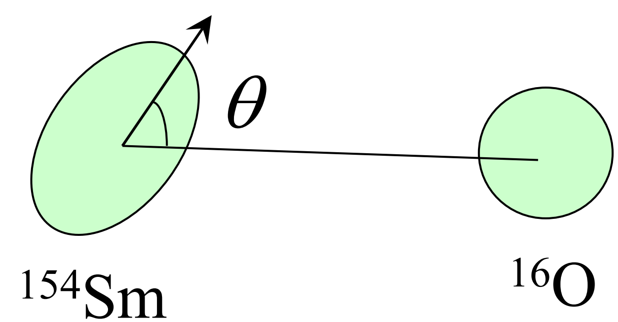
the role of deformation in heavy-ion reactions?

Nuclear deformation → a large sub-barrier enhancement of fusion (capture) cross sections

$^{16}O+^{154}Sm$

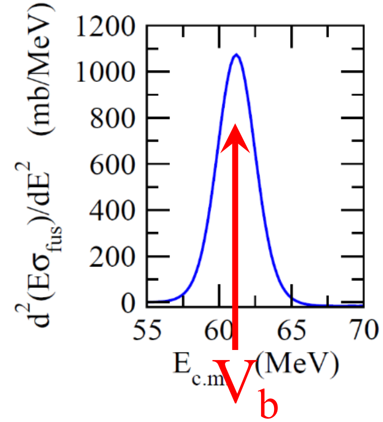




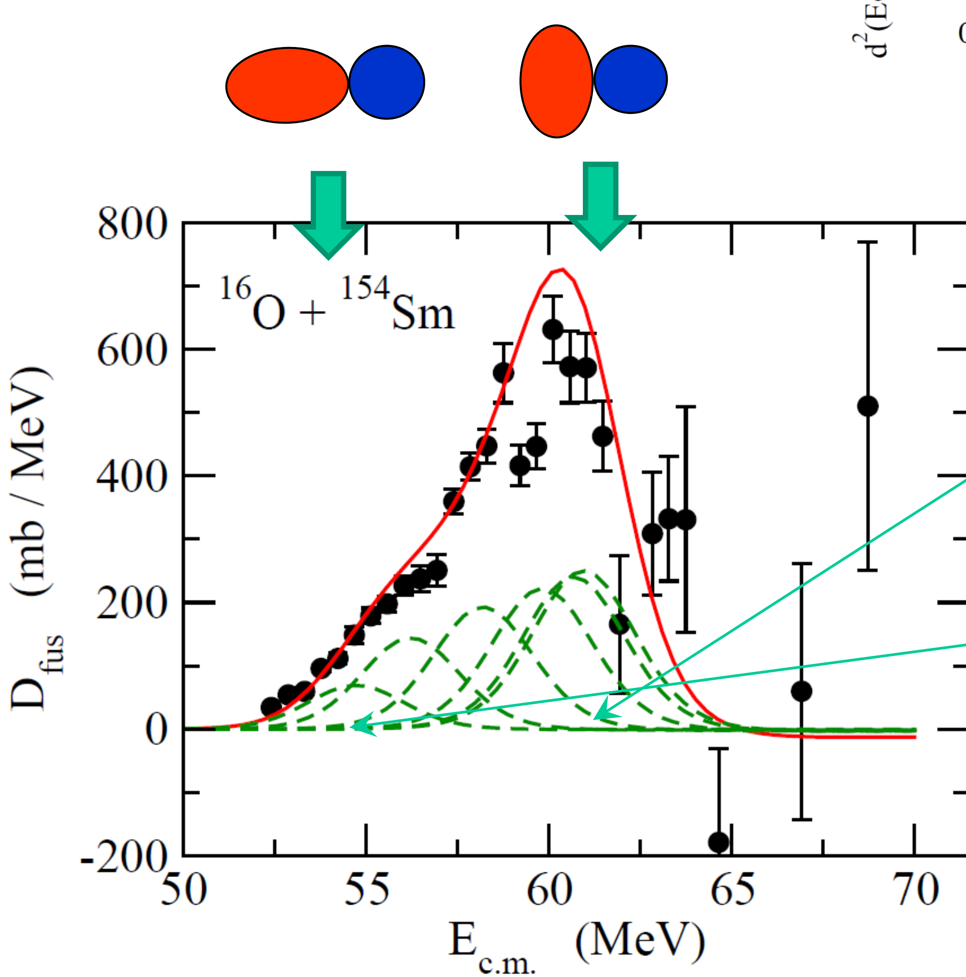


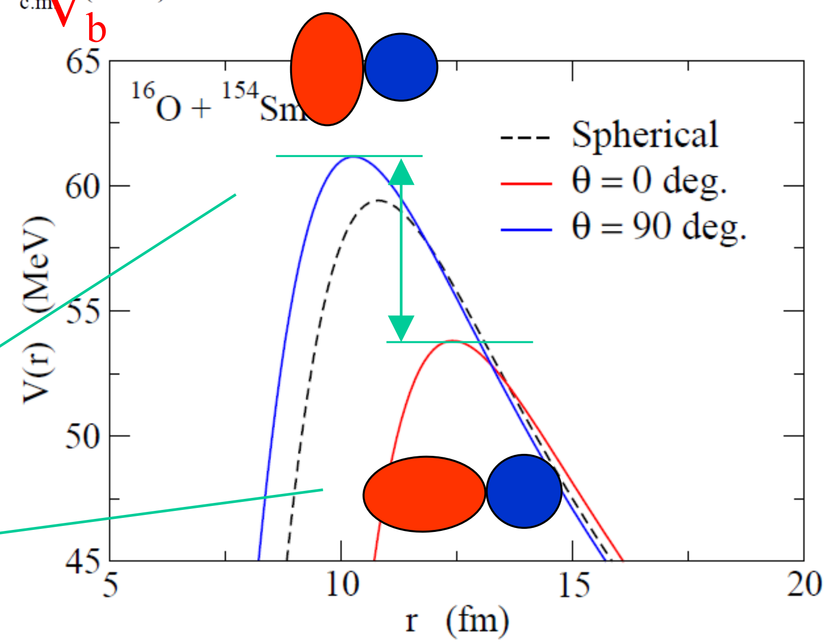
✓ Fusion barrier distribution (Rowley, Satchler, Stelson, PLB254('91))

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



single channel

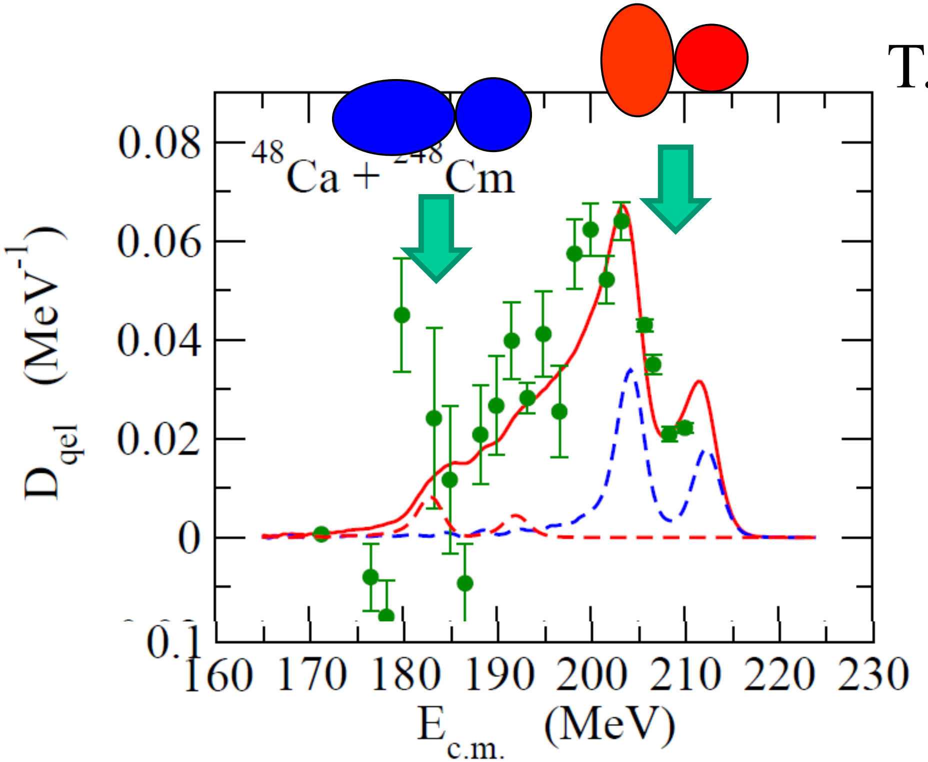




can be used to identify the side/tip collisions

Application to hot fusion reactions

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

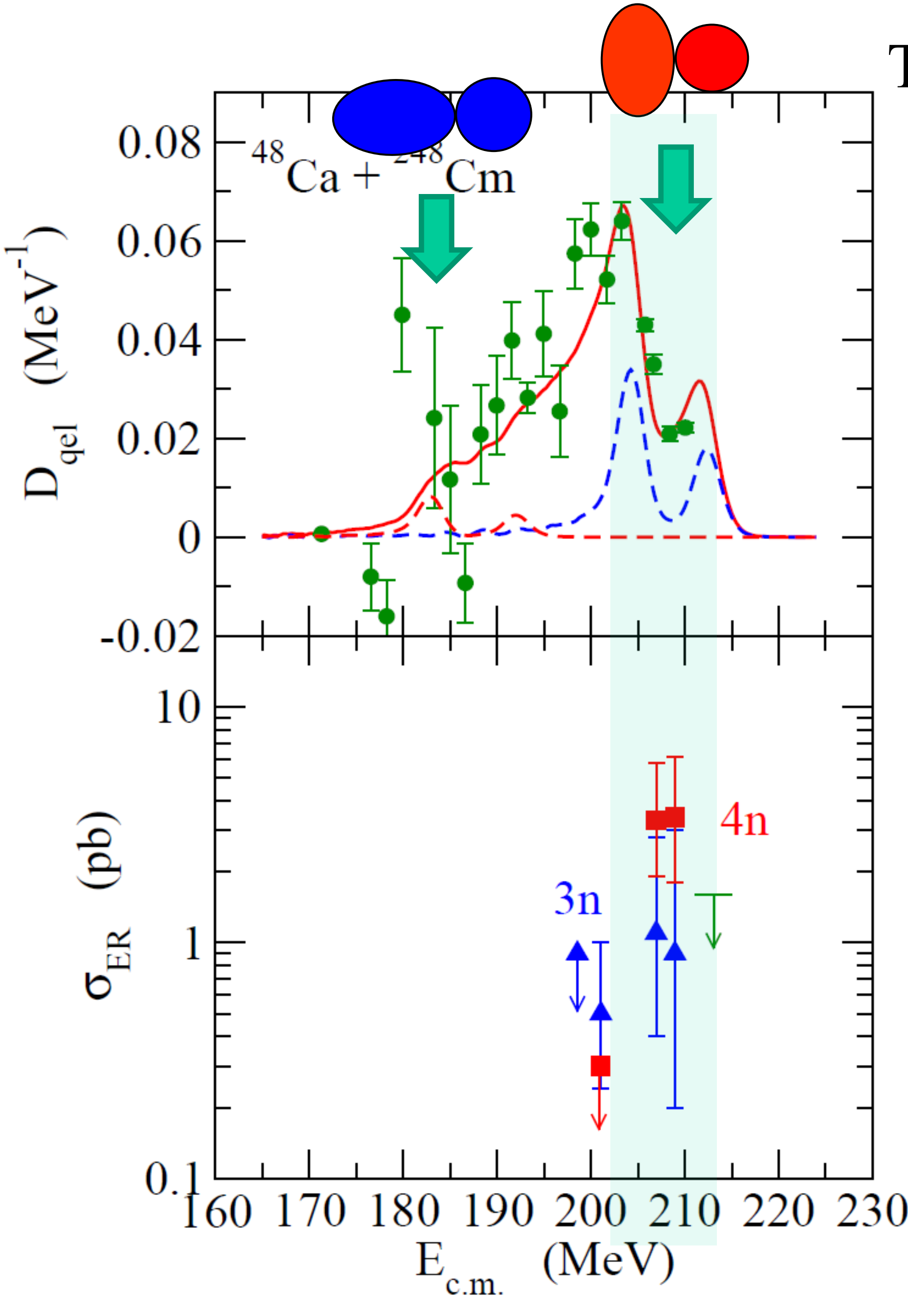


T. Tanaka,..., K.H., et al., JPSJ 87 ('18) 014201 PRL124 ('20) 052502

capture barrier distribution

Application to hot fusion reactions

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

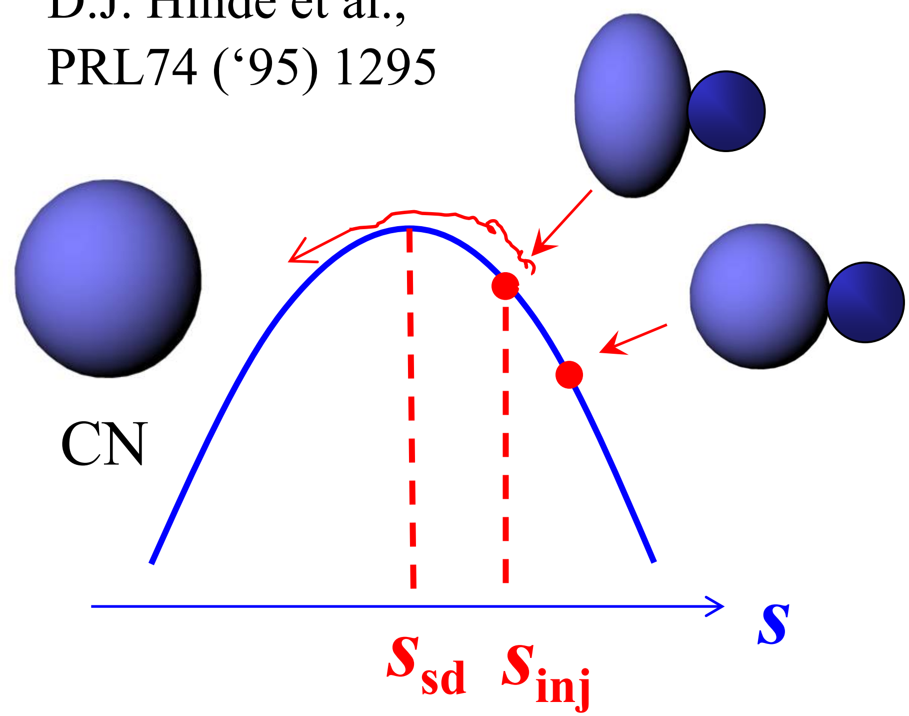


T. Tanaka,..., K.H., et al.,
JPSJ 87 ('18) 014201
PRL124 ('20) 052502

capture barrier distribution

cf. notion of compactness:

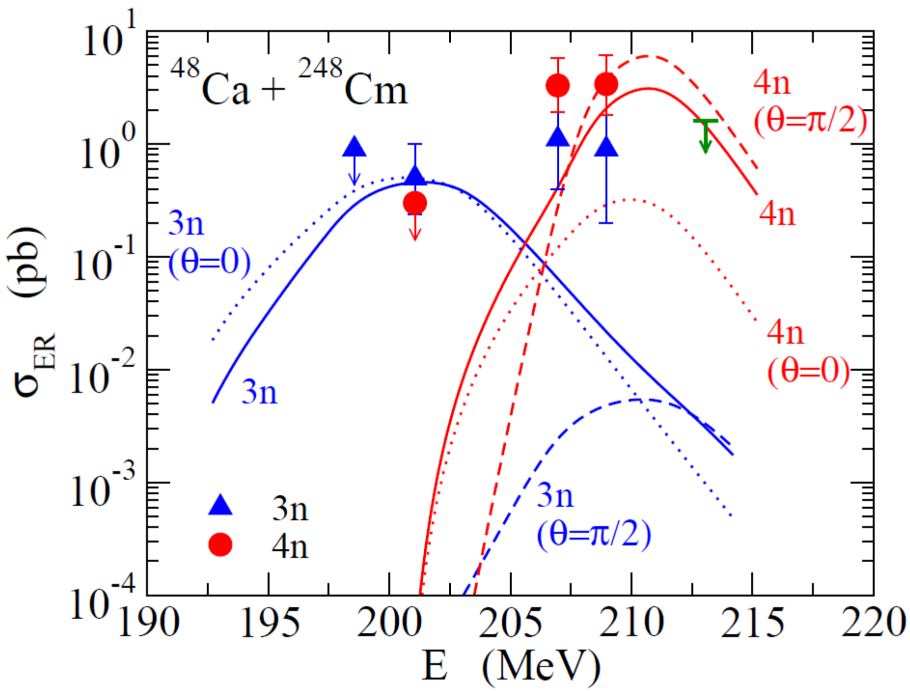
D.J. Hinde et al.,
PRL74 ('95) 1295



Application to hot fusion reactions

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

T. Tanaka,..., K.H., et al.,
JPSJ 87 ('18) 014201
PRL124 ('20) 052502

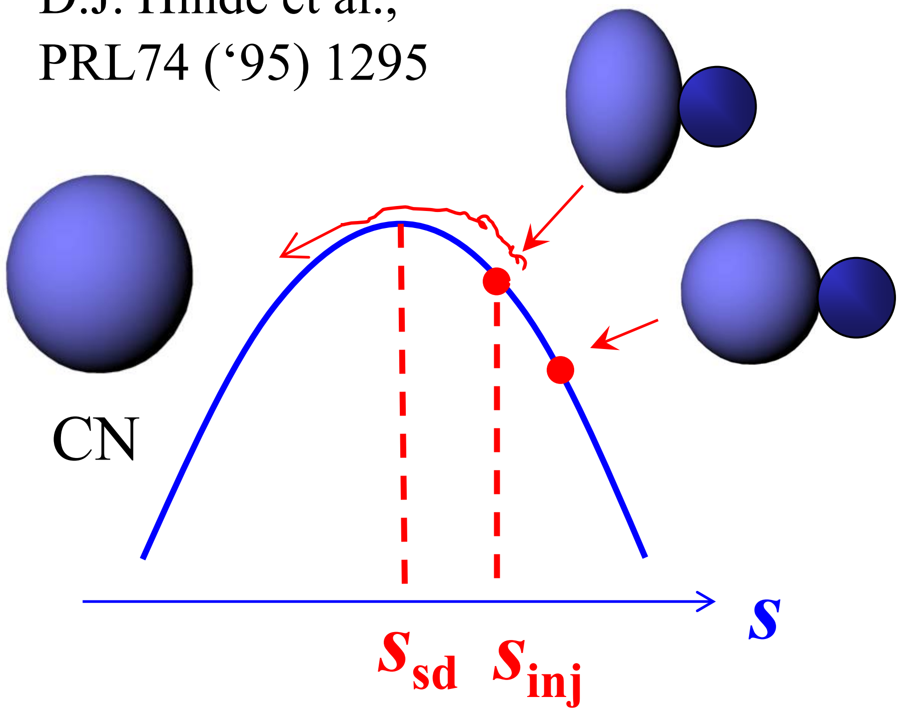


K. Hagino, PRC98 ('18) 014607

capture barrier distribution

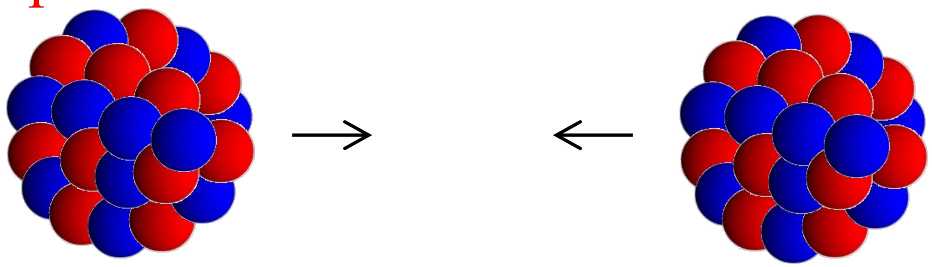
cf. notion of compactness:

D.J. Hinde et al.,
PRL74 ('95) 1295



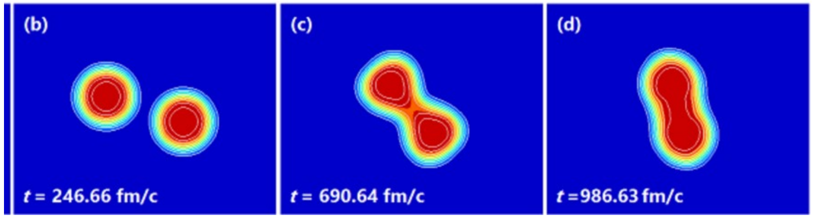
Towards a microscopic nuclear reaction theory

many-body problems



still very challenging

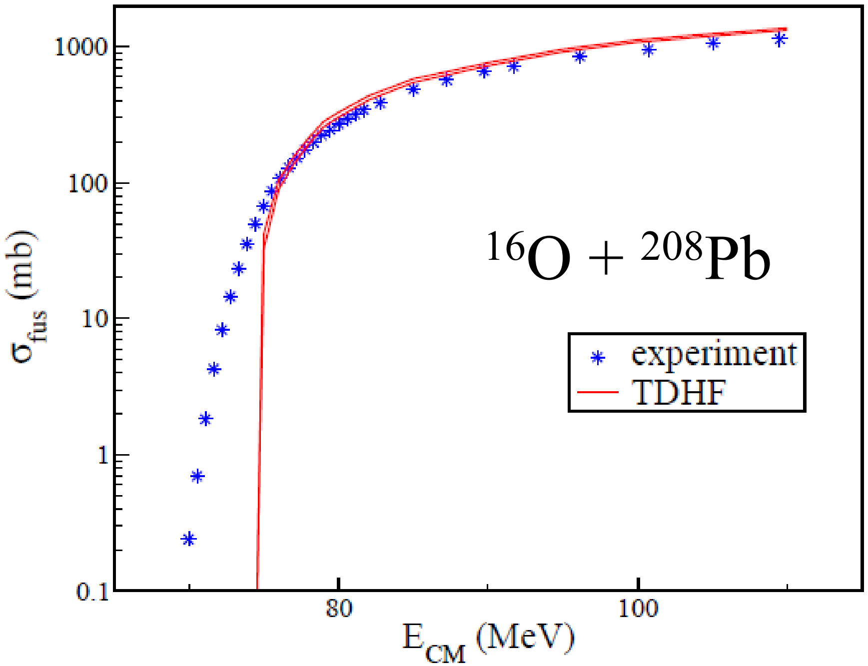
Time-dependent mean-field theory (TDHF/TDDFT)



S. Ebata, T. Nakatsukasa,
JPC Conf. Proc. 6 ('15) 020056

(semi) classical → no tunneling

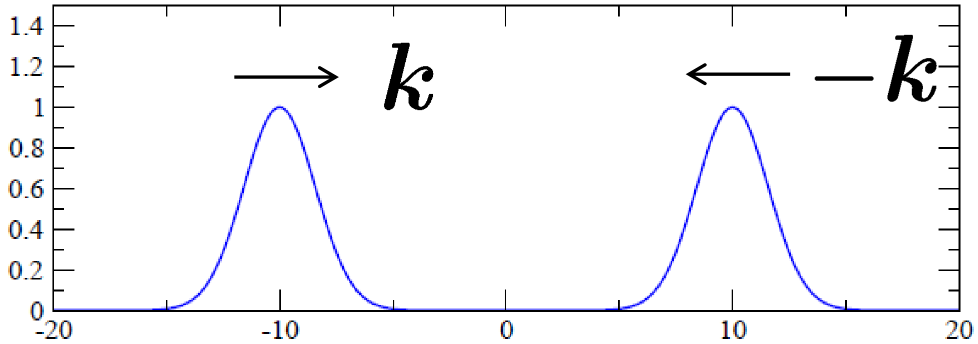
a microscopic understanding of many-body tunneling?

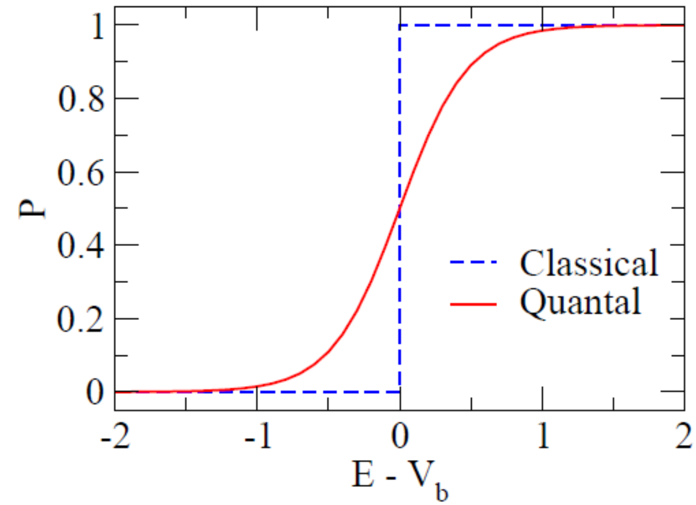


C. Simenel, EPJA48 ('12) 152

[TDHF]

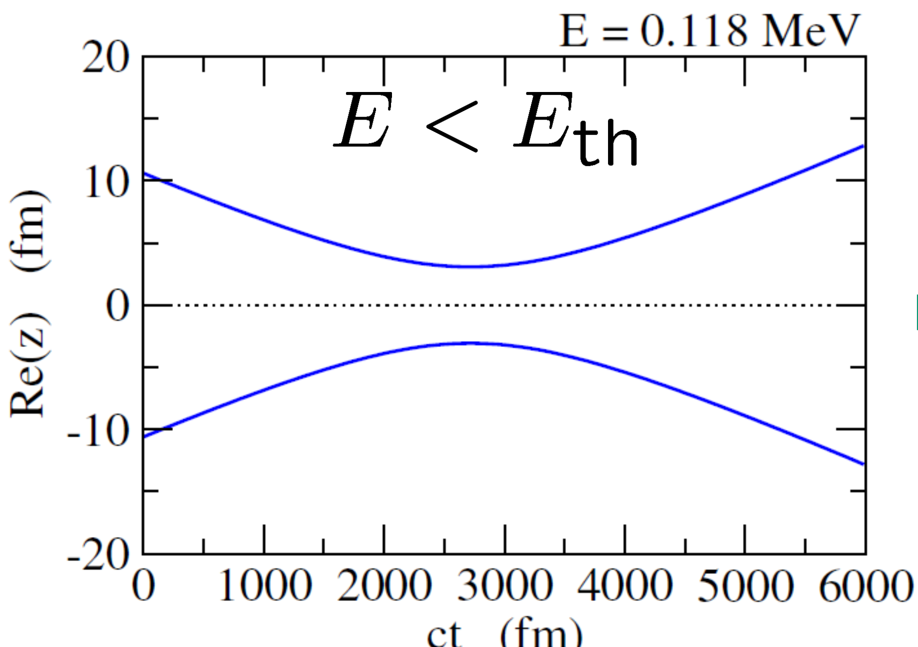
$$\Psi(t) = \Phi_{SD}(t)$$

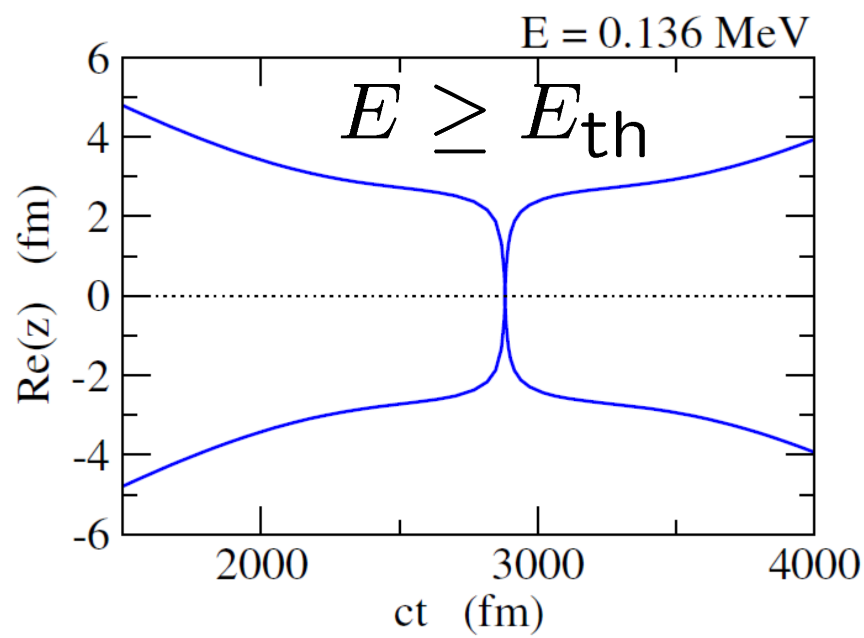




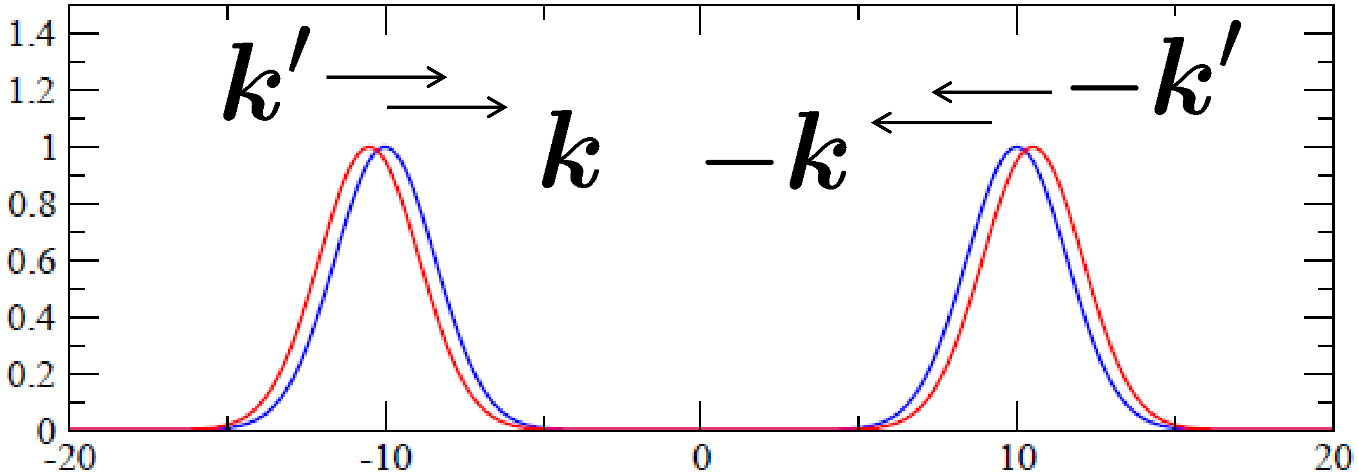
a single Slater determinat for a many-body wave function

α+α in 1D





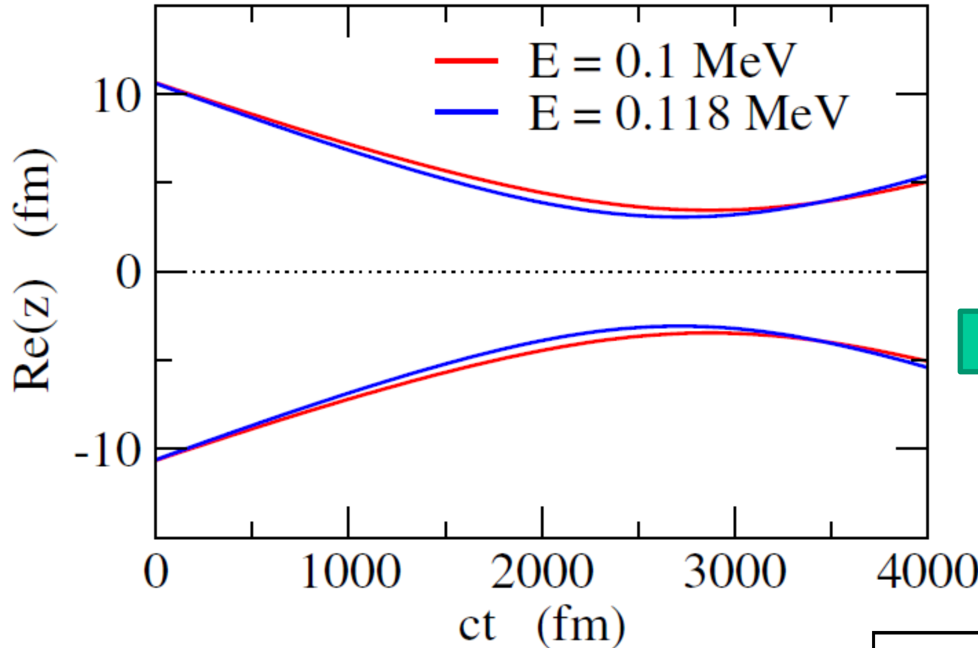
a linear superposition of many Slater determinants



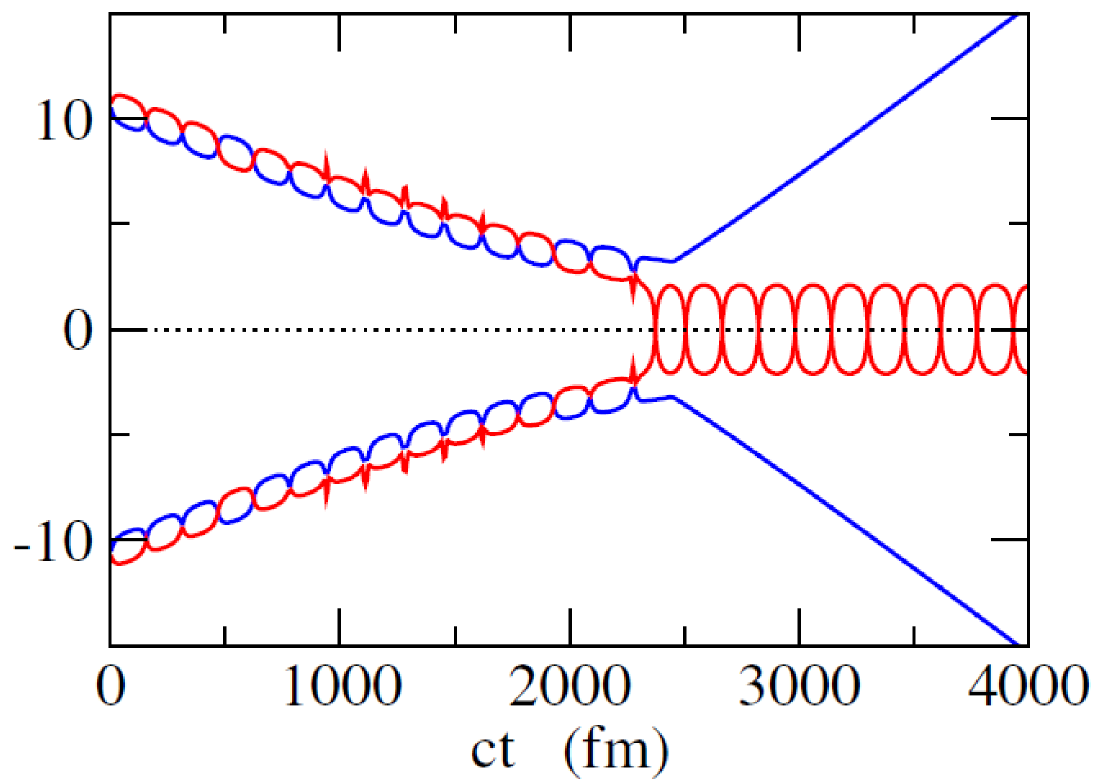
$$\Psi(t) = \sum_k f_k(t)\Phi_{\mathsf{SD},k}(t)$$

time-dependent variational principle

$$\delta \int dt \frac{\langle \Psi(t)|i\hbar\partial_t - H|\Psi(t)\rangle}{\langle \Psi(t)|\Psi(t)\rangle} = 0$$

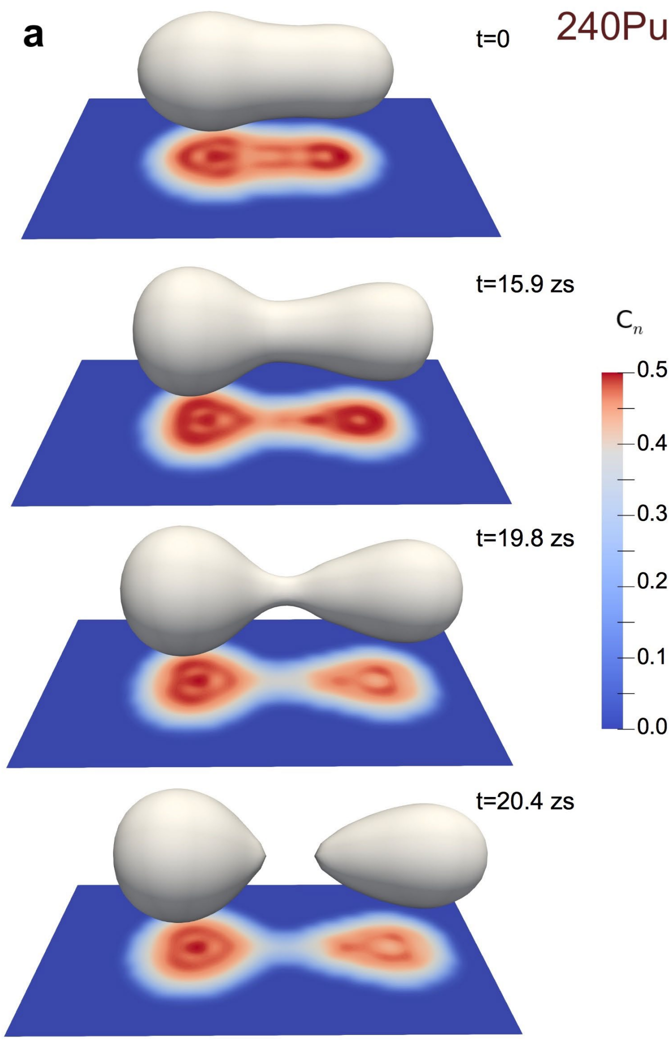


TDGCM
(a superposition of 2 SD)



N. Hasegawa, K.H.,
and Y. Tanimura,
PLB808, 135693 (2020)

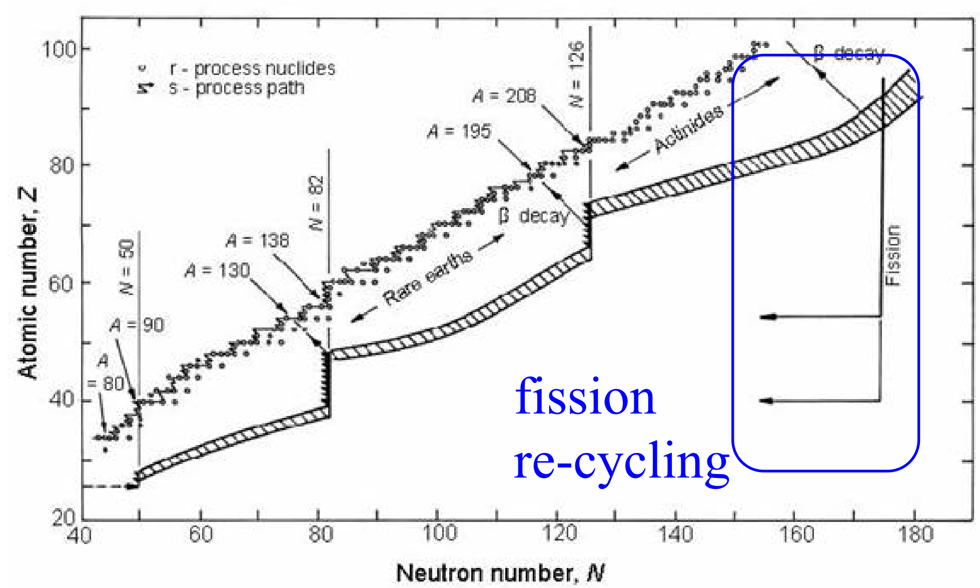
Nuclear Fission



G. Scamps and C. Simenel, Nature 564 (2018) 382

➢ important role in:

- energy production
- superheavy elements
- r-process nucleosynthesis
- production of neutron-rich nuclei



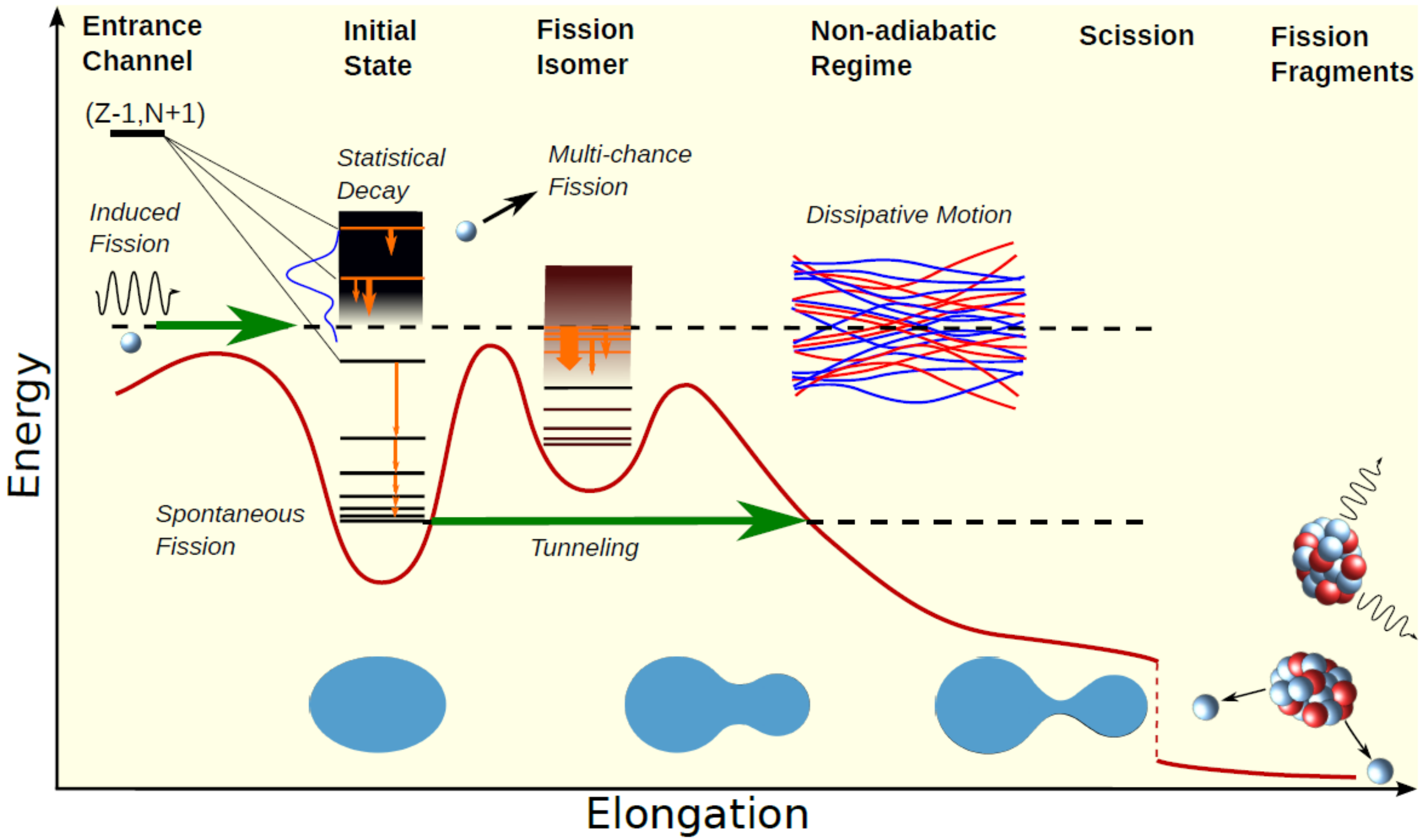
very complicated dynamics:

a microscopic understanding

→ far from complete

very complicated dynamics:

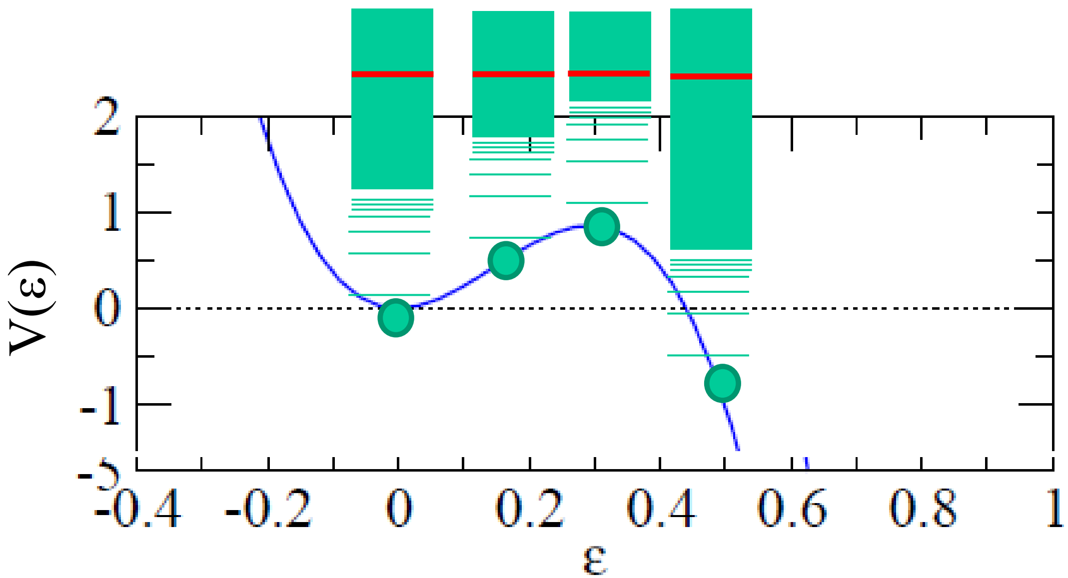
a microscopic understanding → far from complete

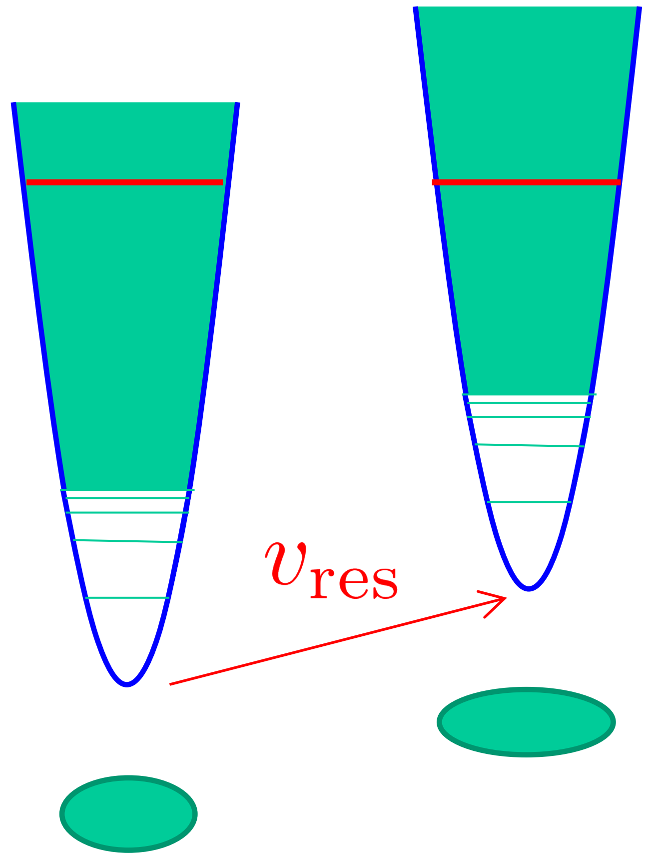


M. Bender et al., J. of Phys. G47, 113002 (2020)

CI approach: a novel way to understand fission

K.H. and G.F. Bertsch





c.f. Generator Coordinate Method (GCM)

$$|\Psi\rangle = \int dQ\, f(Q)|\Phi_Q\rangle$$

→ CI approach

$$|\Psi\rangle = \int dQ \sum_i f_i(Q)|\Phi_Q(i)\rangle$$

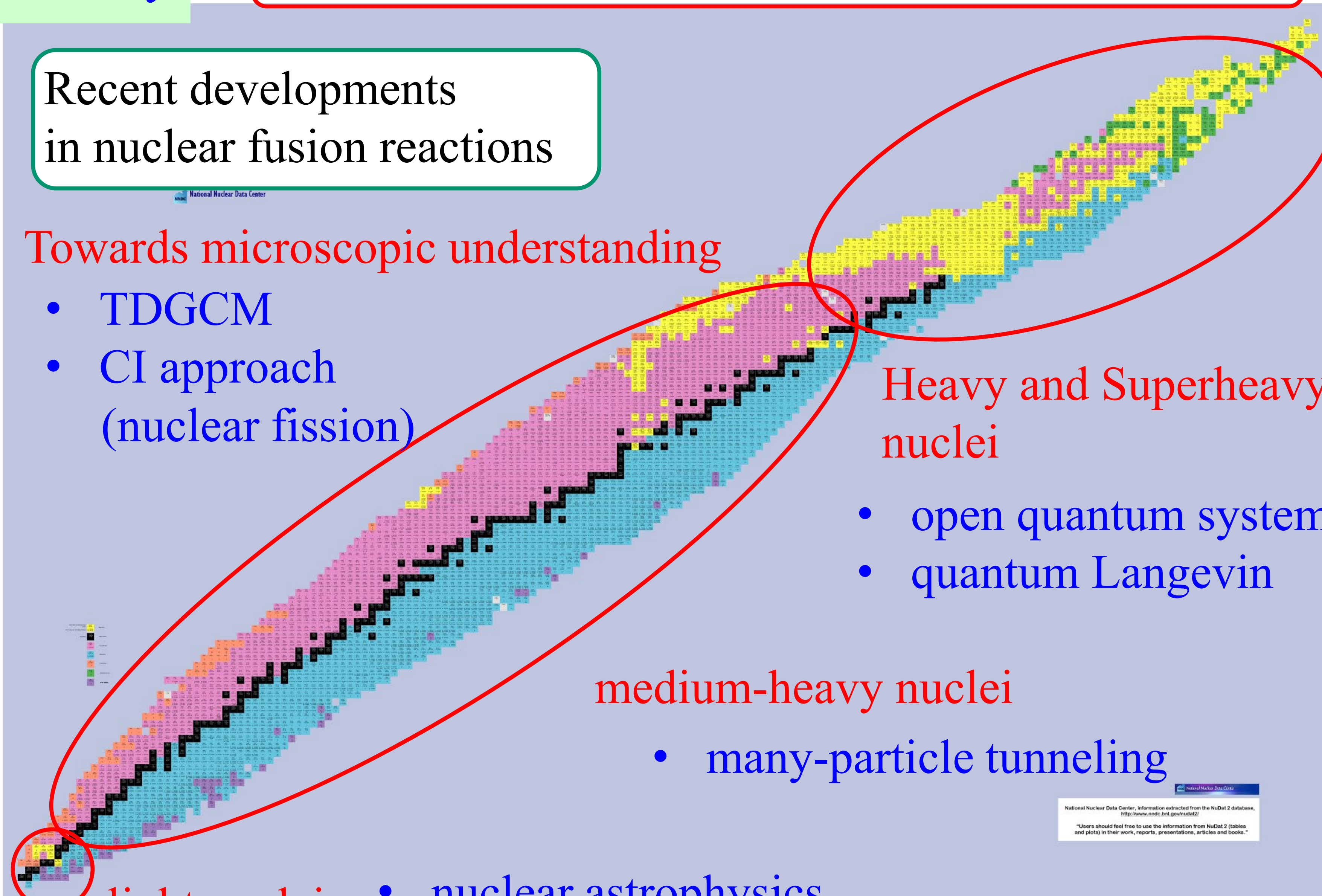
hopping due to the residual interaction

→ shape evolution

Summary

Nuclear Reactions: a variety of many-body dynamics

Recent developments
in nuclear fusion reactions



Towards microscopic understanding

- TDGCM
- CI approach
  (nuclear fission)

Heavy and Superheavy nuclei

- open quantum systems
- quantum Langevin

medium-heavy nuclei

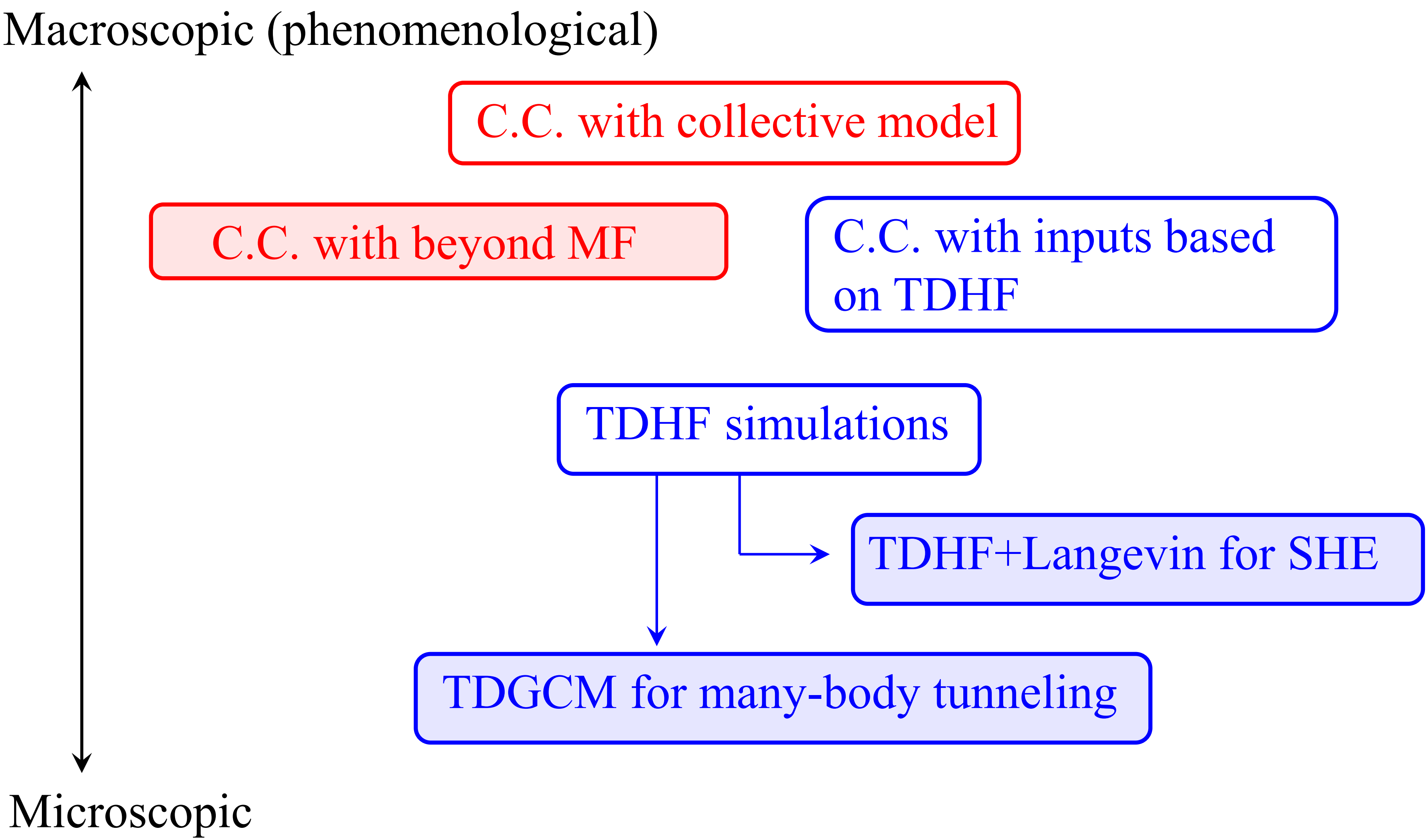
- many-particle tunneling

light nuclei

- nuclear astrophysics
- resonances

Summary

From phenomenological to microscopic nuclear reaction theories



A folding potential does not work for subbarrier fusion reactions