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

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Kyoto University （京都大学）, Kyoto, Japan

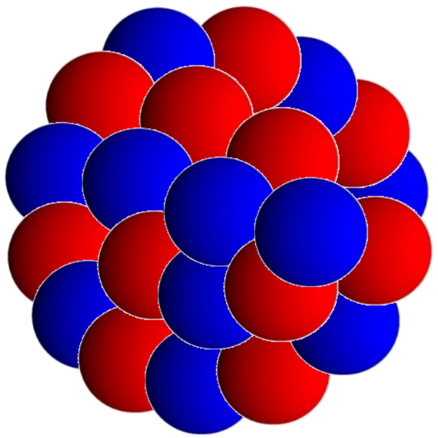
1. Nuclear Reactions: overview
2. Fusion of light nuclei and Feshbach resonances
3. Fusion of medium-heavy nuclei and quantum tunneling
4. Fusion for superheavy nuclei and open quantum systems
5. Microscopic modelling of low-energy nuclear reactions
6. Fission
7. Summary

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

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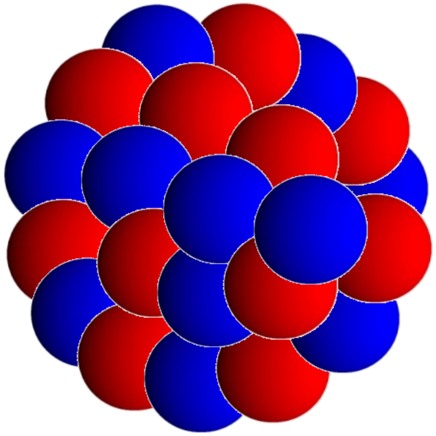
    - ✓ ground state properties
      (mass, size, shape,…..)
    - ✓ excitations
    - ✓ nuclear matter
    - ✓ decays

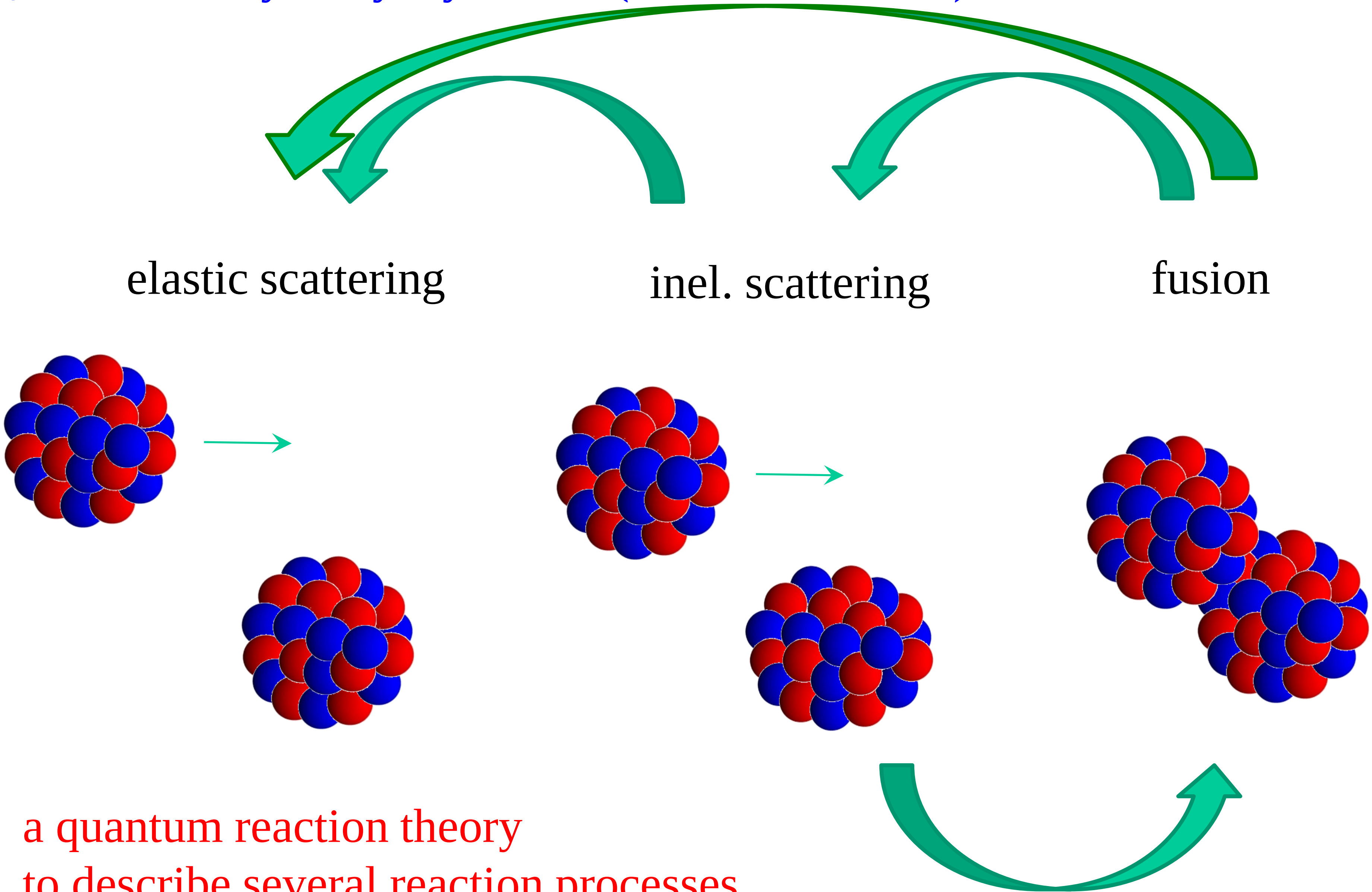


  - dynamics: nuclear reactions

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

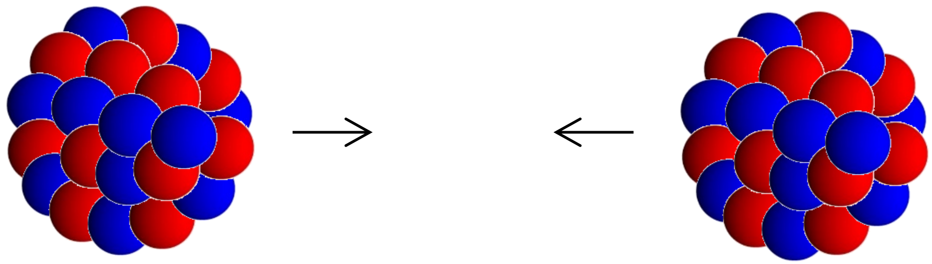
Quantum Many-body Dynamics (nuclear reactions)



a quantum reaction theory
to describe several reaction processes
simultaneously

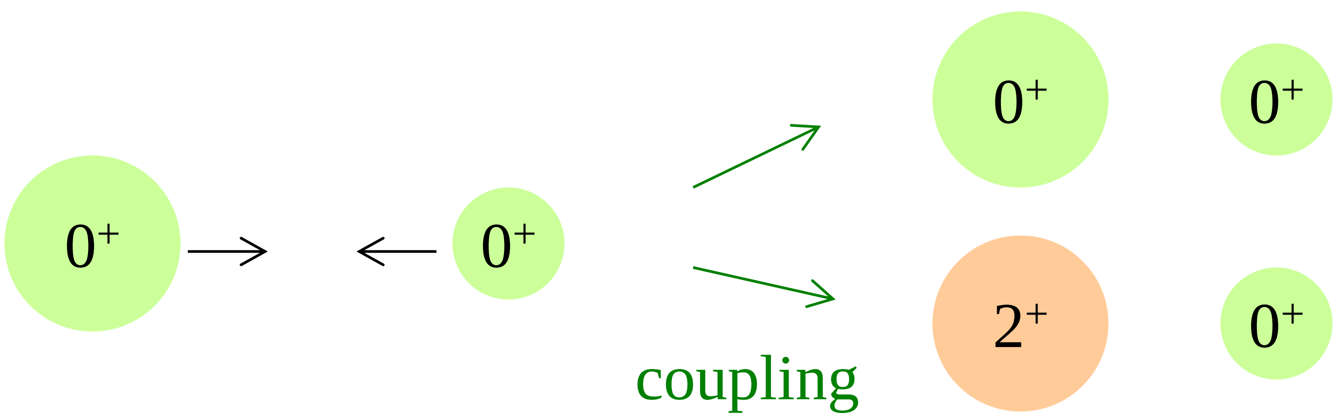
Coupled-channels method: a quantal scattering theory with excitations

many-body problem



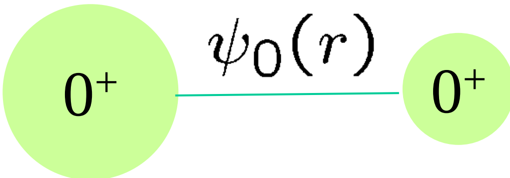
still very challenging

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



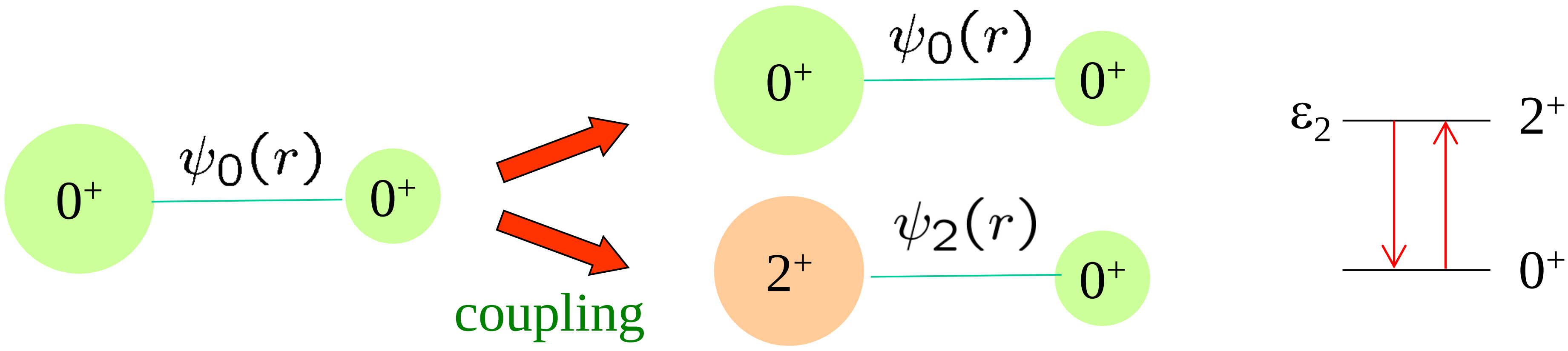
scattering theory with excitations

Coupled-channels method: a quantal scattering theory with excitations



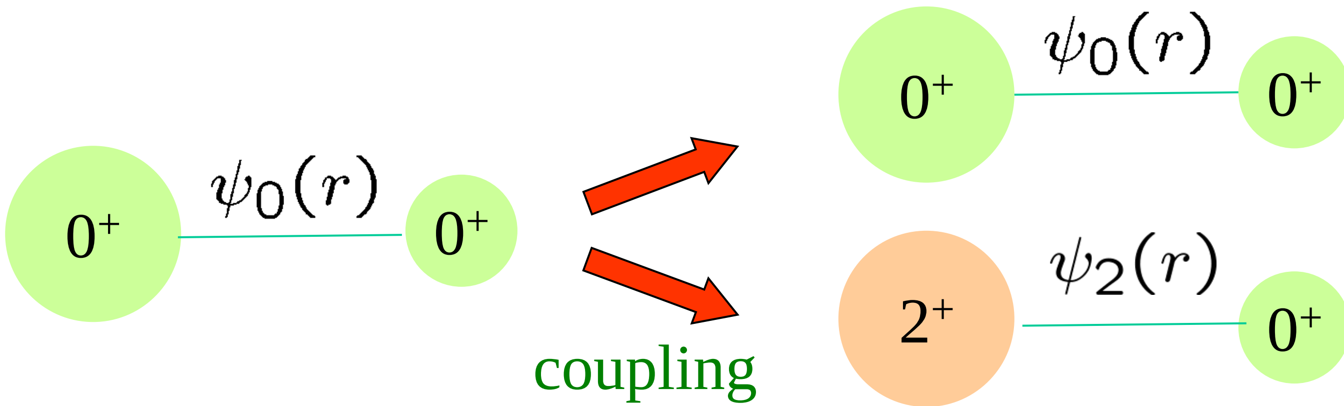
$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V_0(r) - E\right]\psi_0(\boldsymbol{r}) = 0$$

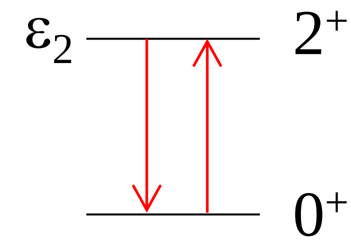
Coupled-channels method: a quantal scattering theory with excitations



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

Coupled-channels method: a quantal scattering theory with excitations





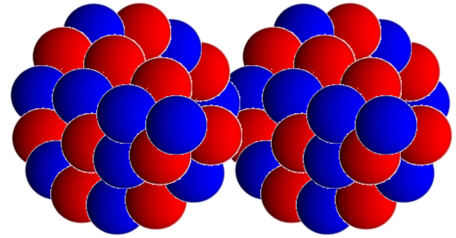
$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V_0(r) - E\right]\psi_0(\boldsymbol{r}) = -F_{0\to 2}(r)\psi_2(\boldsymbol{r})$$

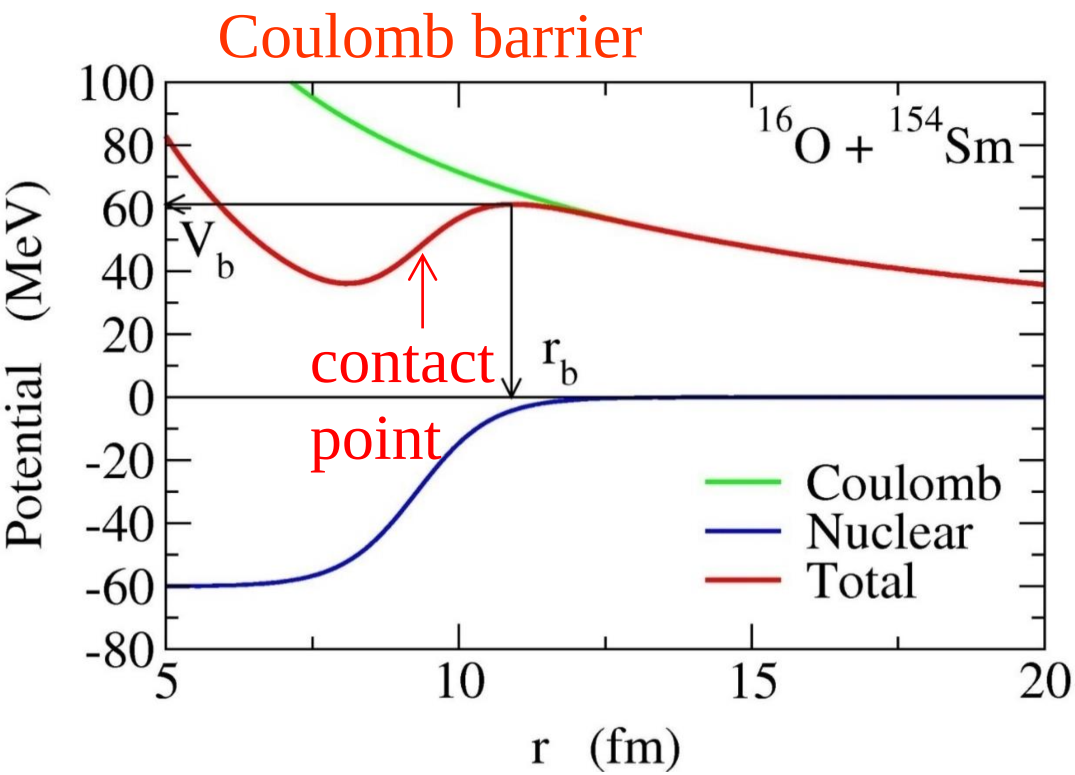
$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V_2(r) - (E - \epsilon_2)\right]\psi_2(\boldsymbol{r}) = -F_{2\to 0}(r)\psi_0(\boldsymbol{r})$$

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

a recent review: K. Hagino, K. Ogata, and A.M. Moro, PPNP in press.
arXiv: 2201.09512

Fusion Reactions





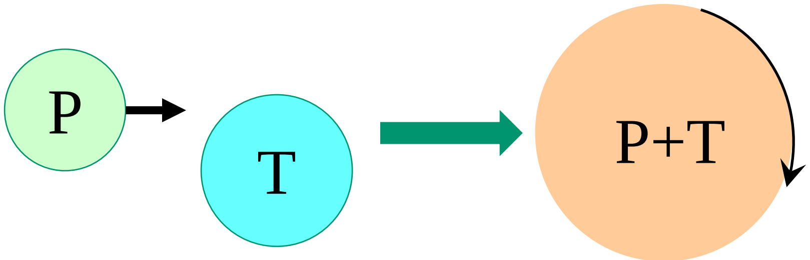
- Nuclear interaction (attractive)
- Coulomb interaction (repulsive)

potential barrier

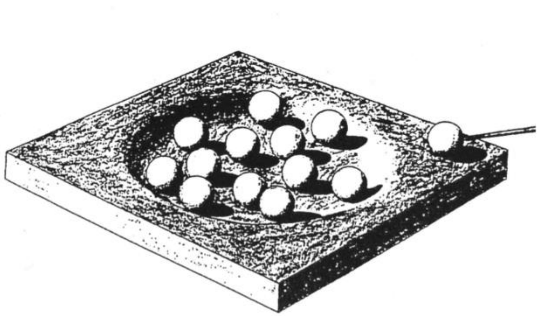
Fusion reactions → a many-body quantum tunneling

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

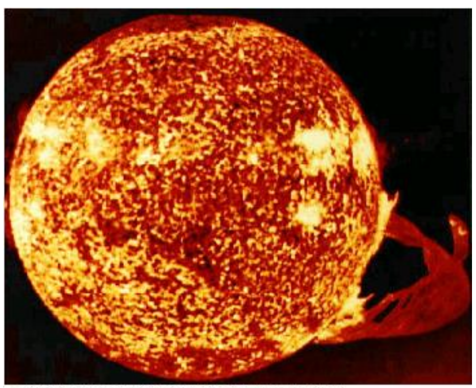
Fusion Reactions



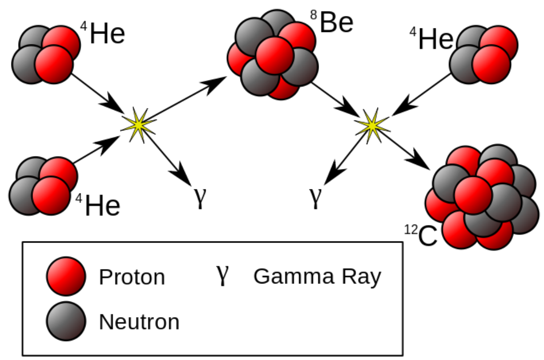
compound nucleus



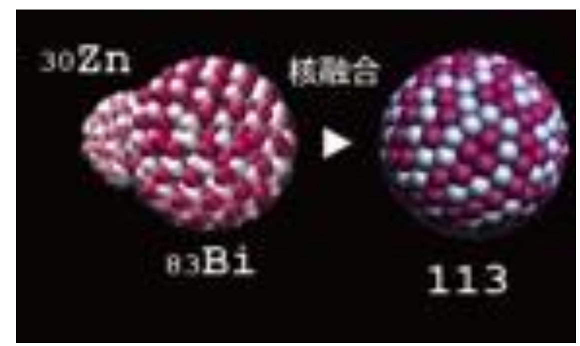
cf. Bohr '36



energy production in stars (Bethe '39)



nucleosynthesis

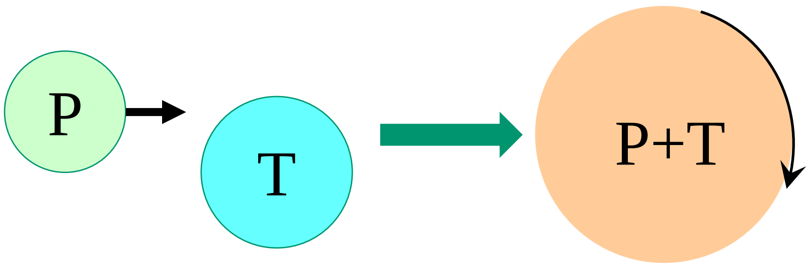


superheavy elements

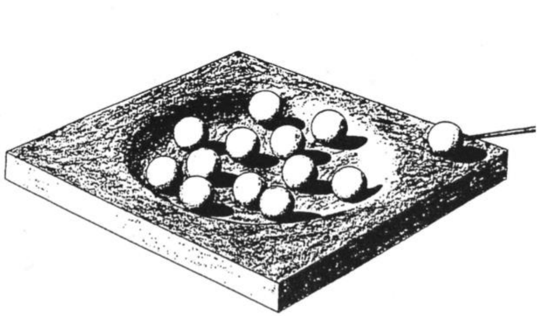
Fusion and fission: large amplitude motions of quantum many-body systems with strong interaction

⟵ microscopic understanding: an ultimate goal of nuclear physics

Fusion Reactions



compound
nucleus

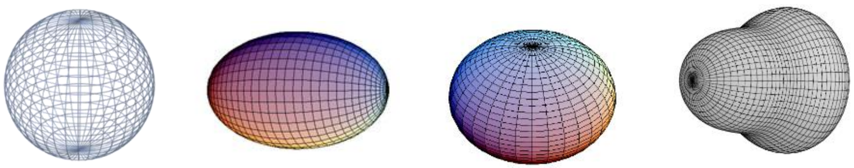


cf. Bohr '36

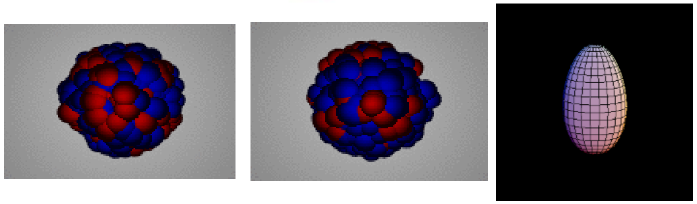
✓ Many-particle tunneling

▪rich intrinsic motions

- several nuclear shapes



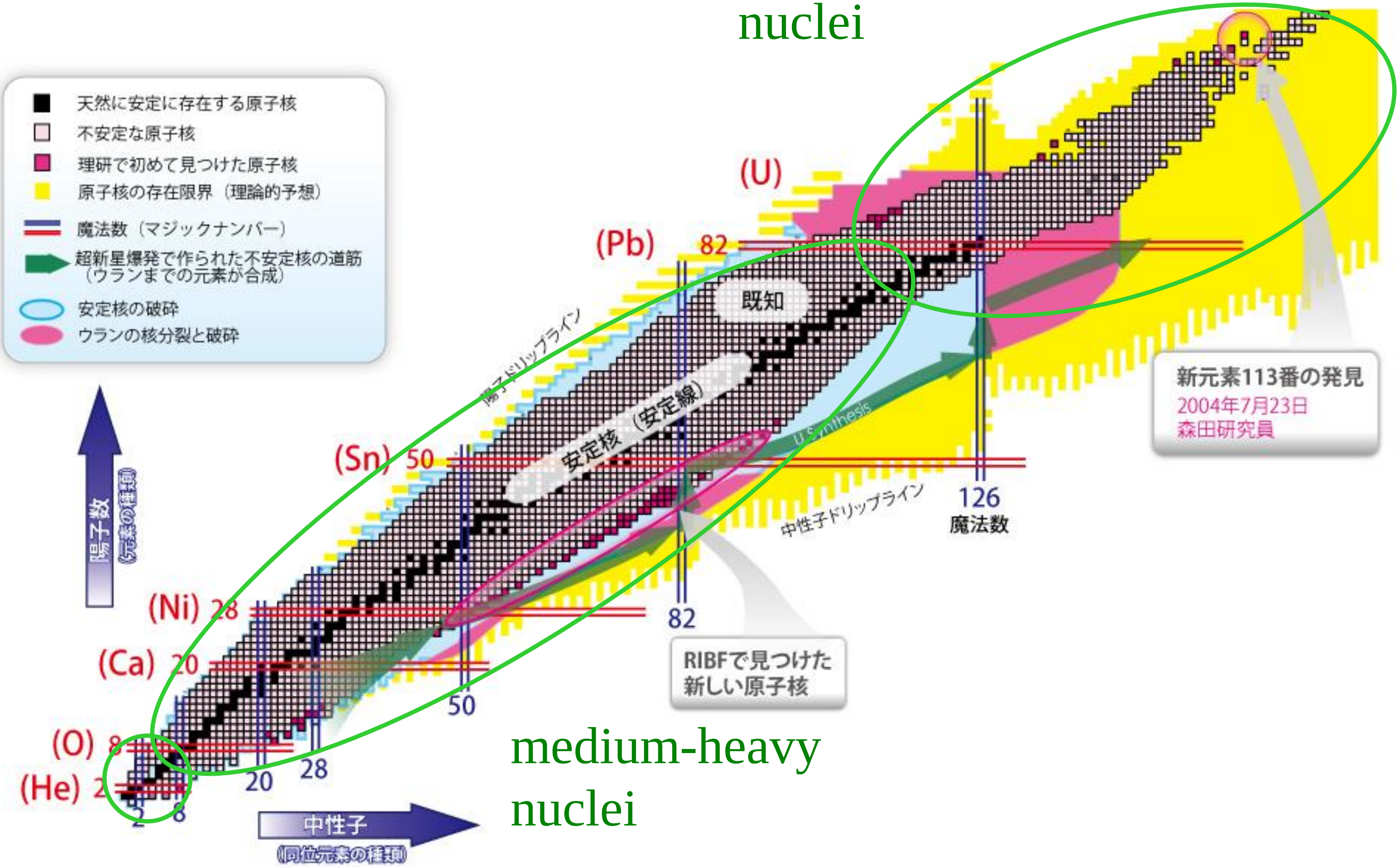
- several surface vibrations



several modes
and adiabaticities

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

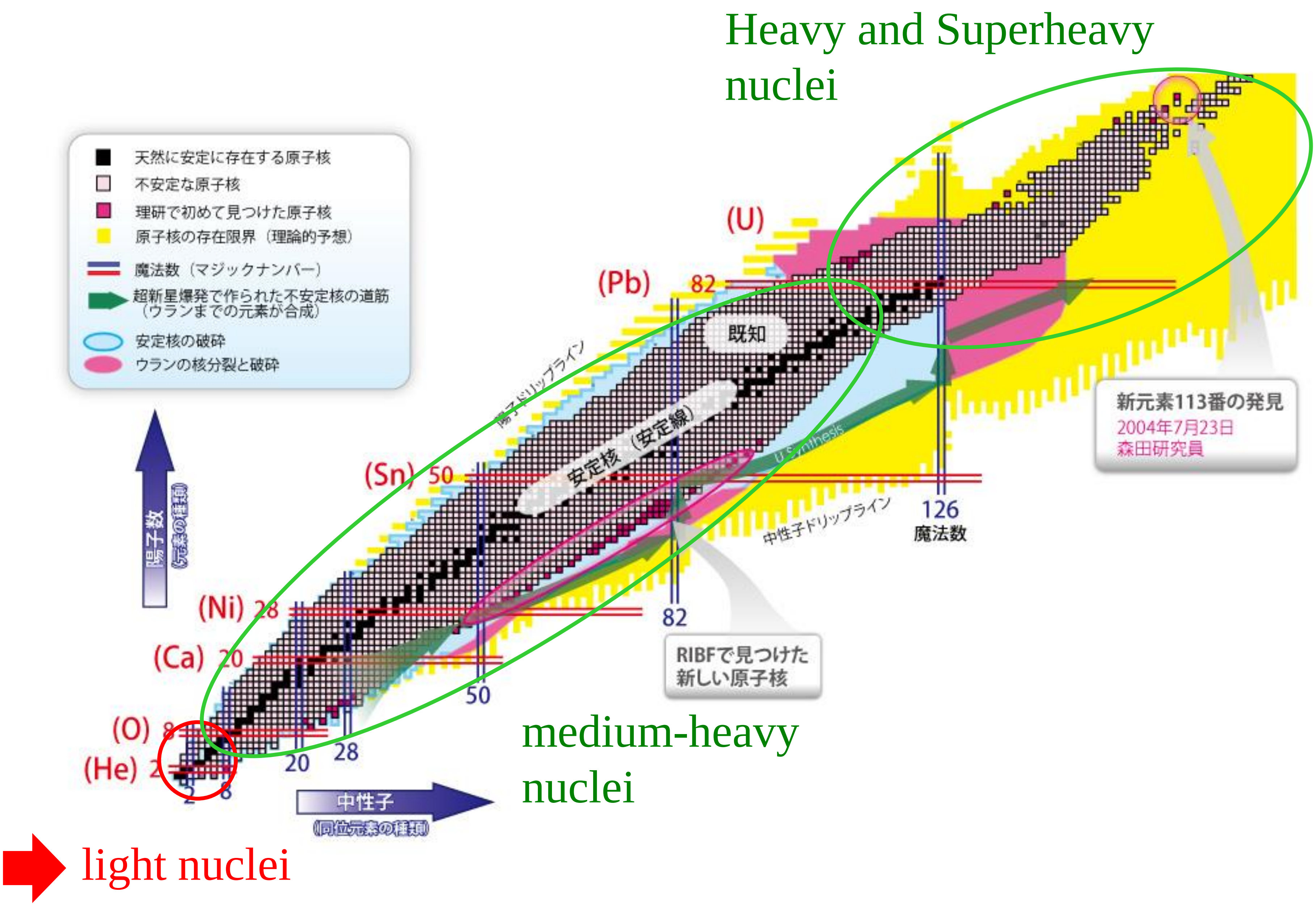
Heavy and Superheavy nuclei



medium-heavy nuclei

light nuclei

Nuclear Chart: RIKEN Nishina Center

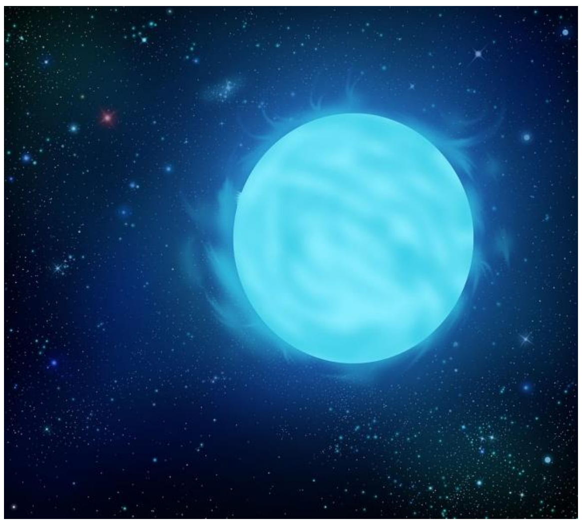


Nuclear Chart: RIKEN Nishina Center

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

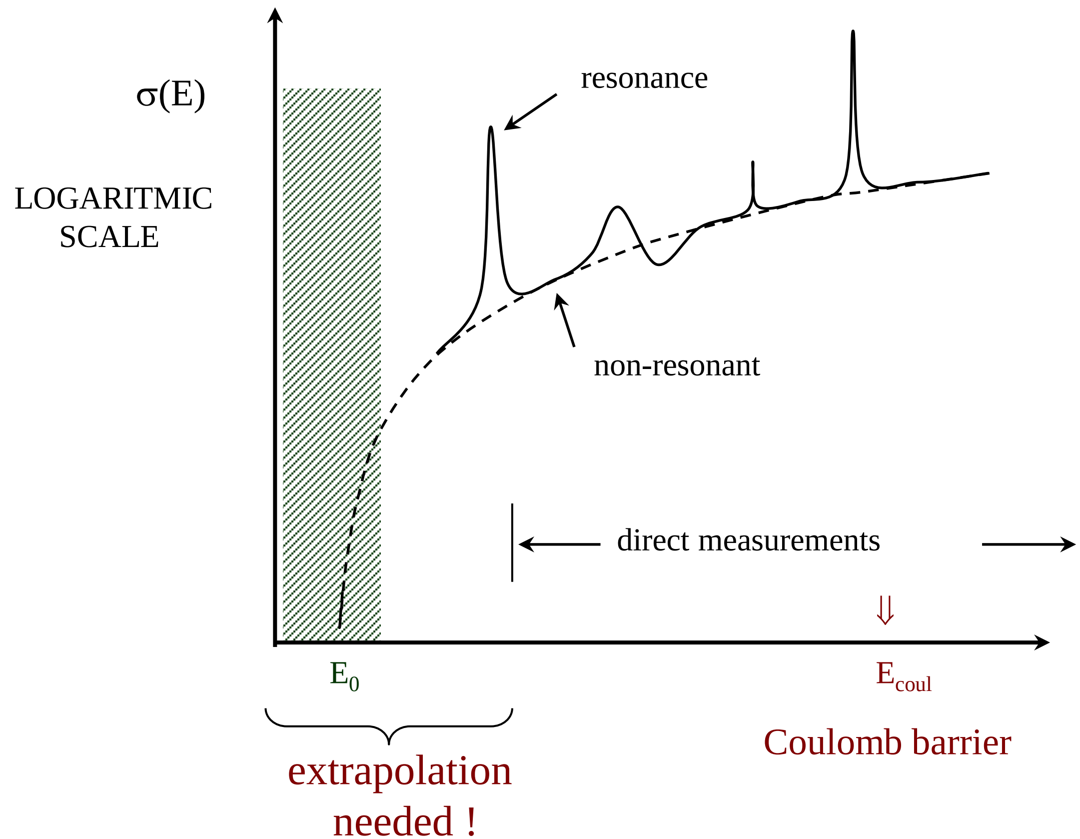


figure: M. Aliotta

Fusion of light nuclei: nuclear astrophysics

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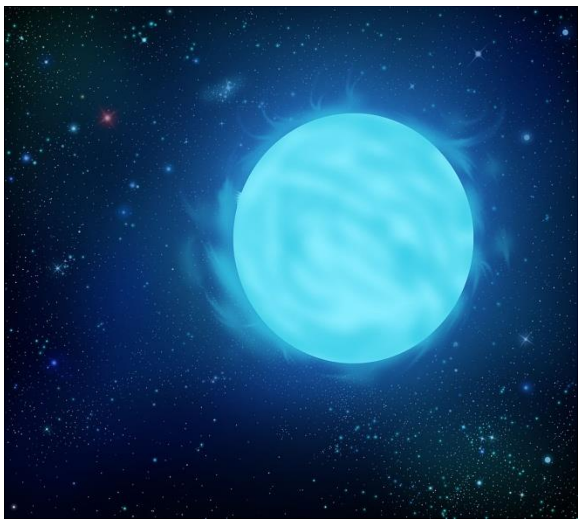

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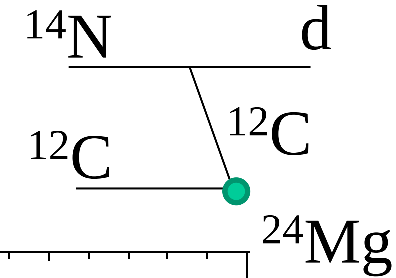
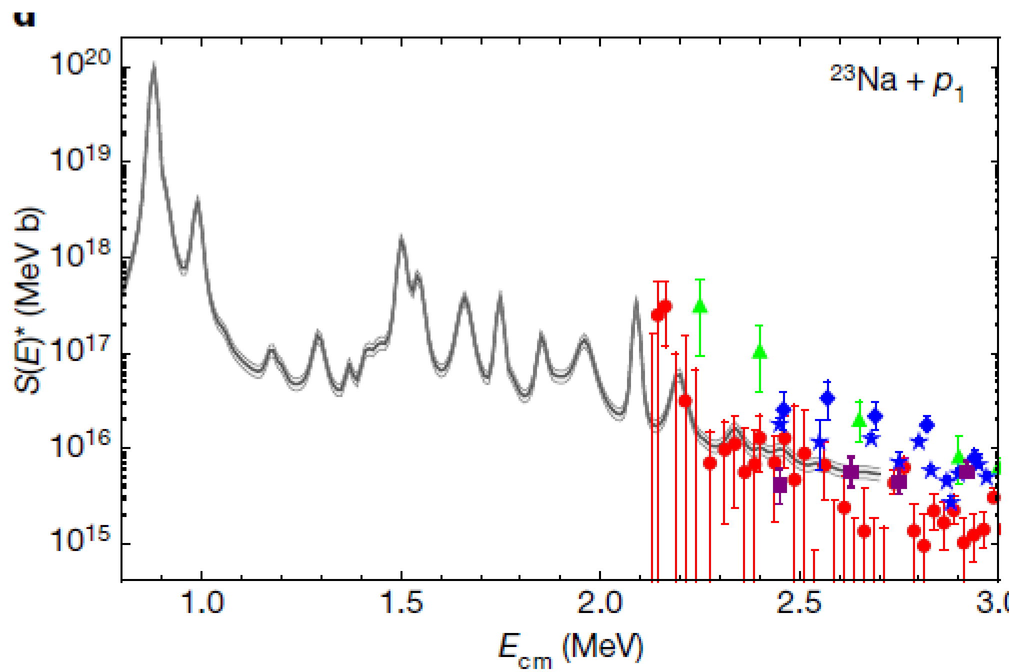
Trojan Horse Method



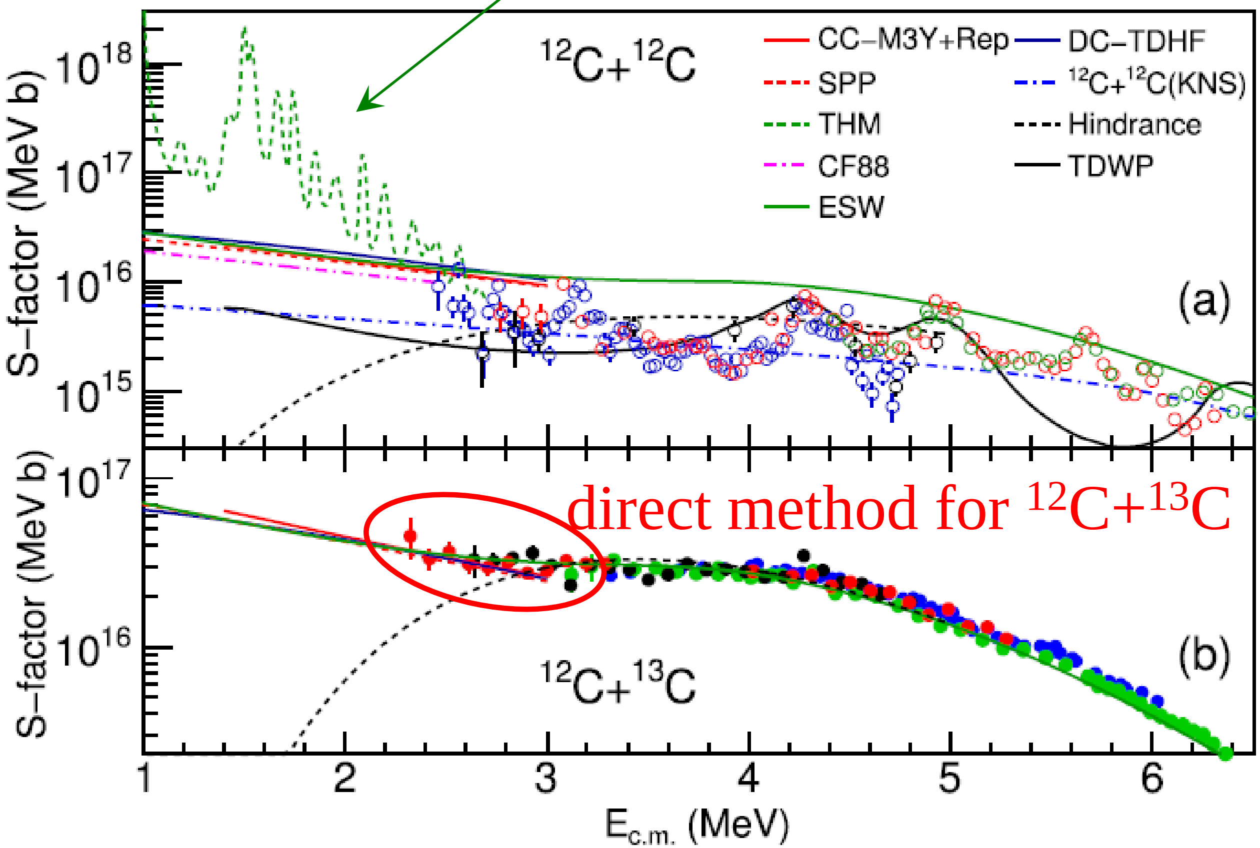


A. Tumino et al., Nature557 ('18) 687

~ 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?

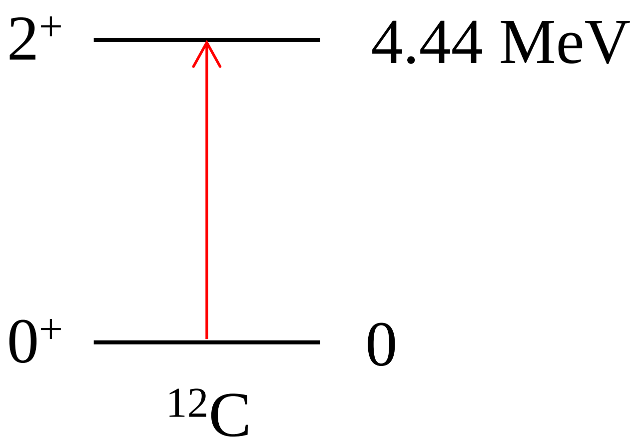
A.M. Mukhamedzhanov et al., PRC99 ('19) 064618

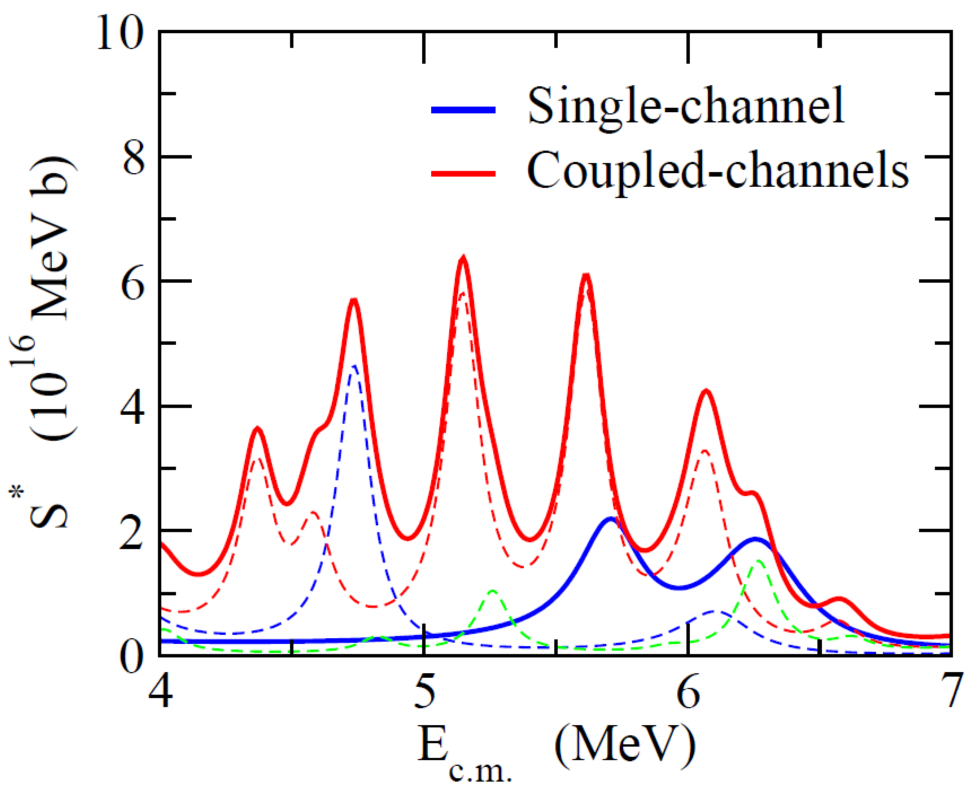
cf. recent direct measurement for $^{12}C+^{12}C$:

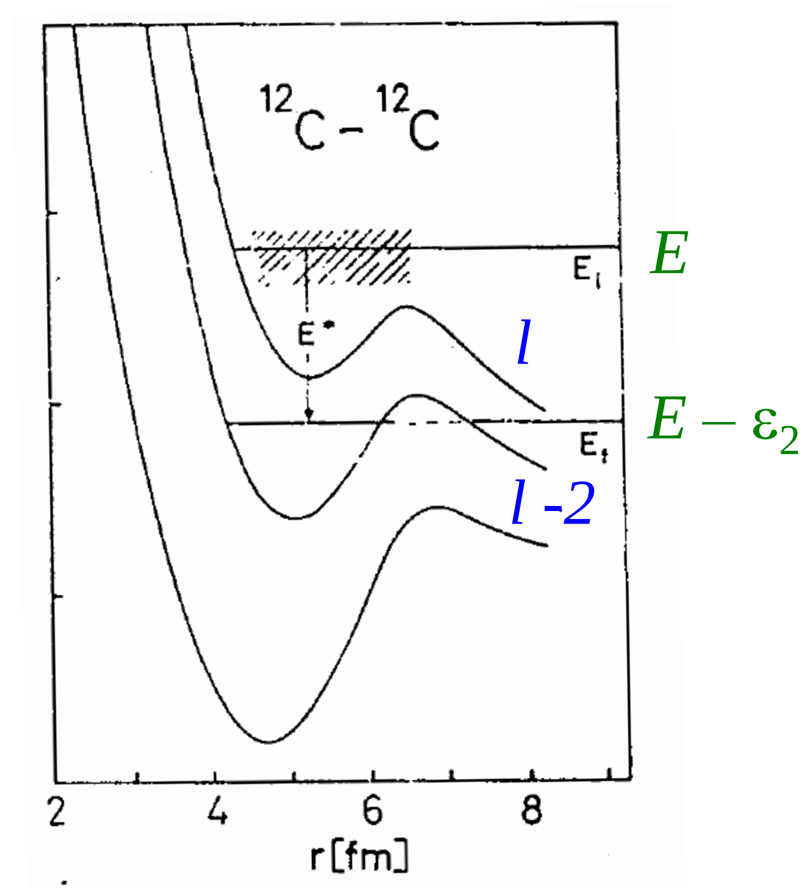
W.P. Tan et al., PRL124 ('20) 192702

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







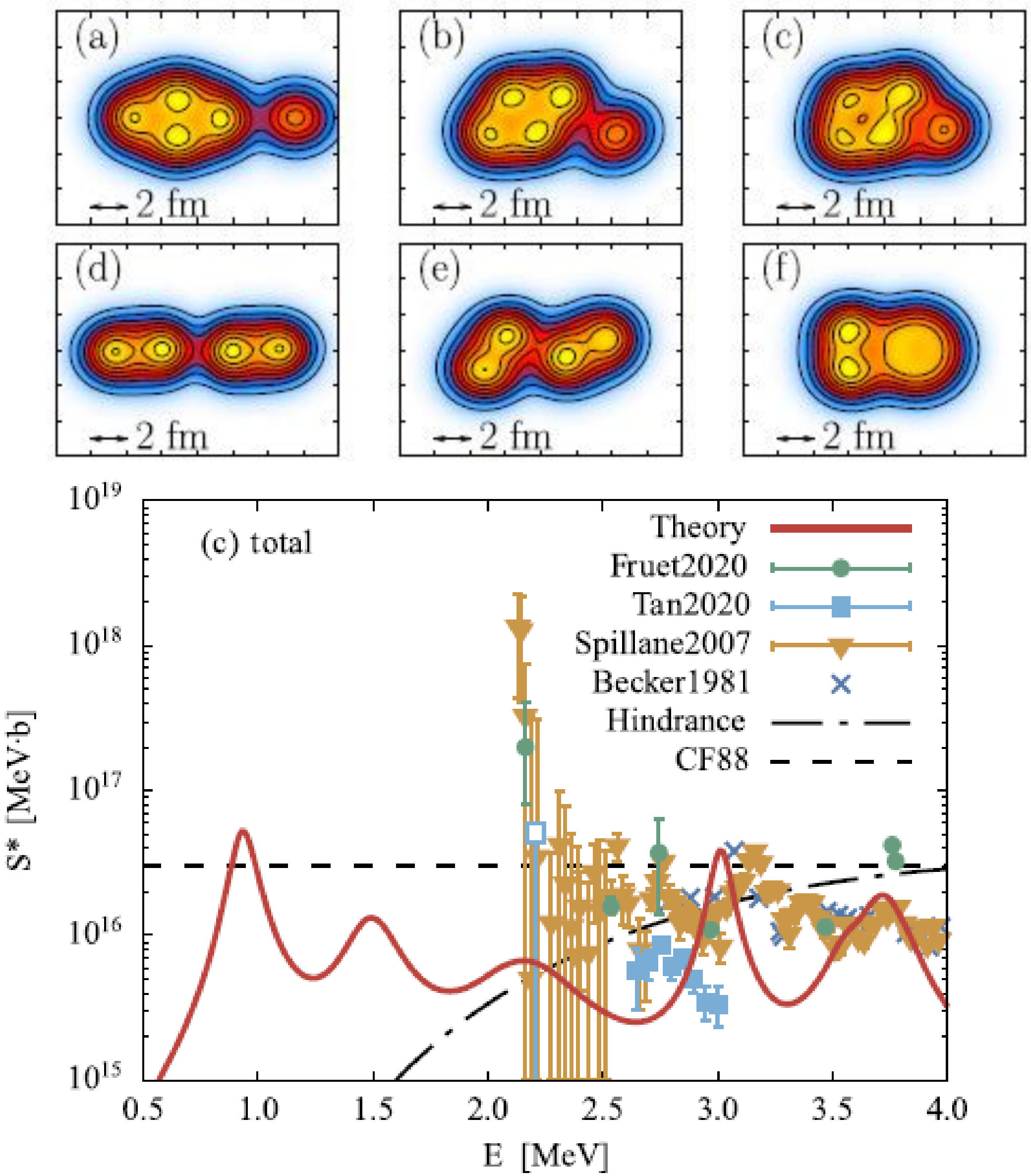
H.-J. Fink, W. Scheid, and W. Greiner, NPA188 (‘72) 259

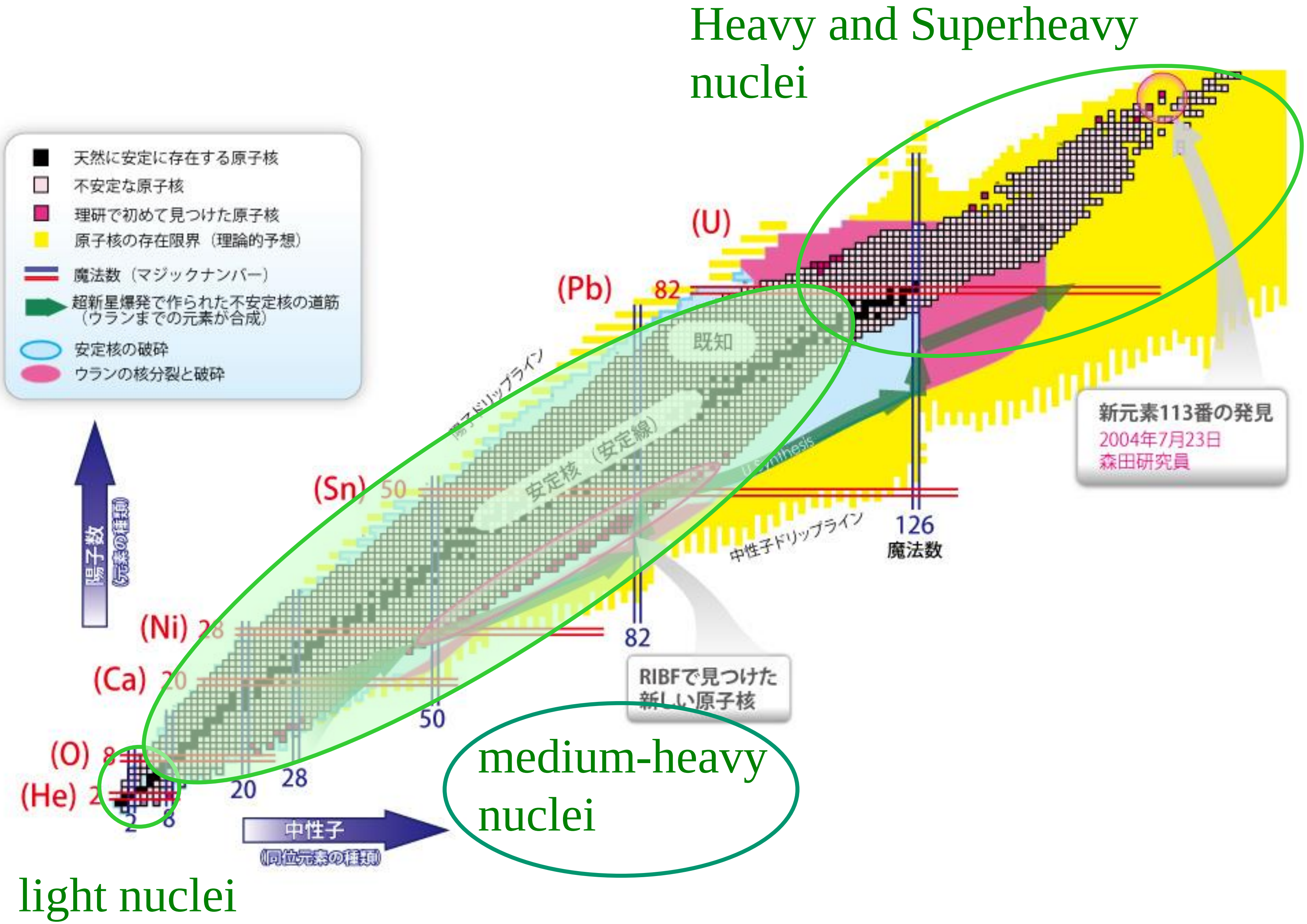
a kind of Feshbach resonance

K.H., unpublished (2015)

A recent AMD calculation

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



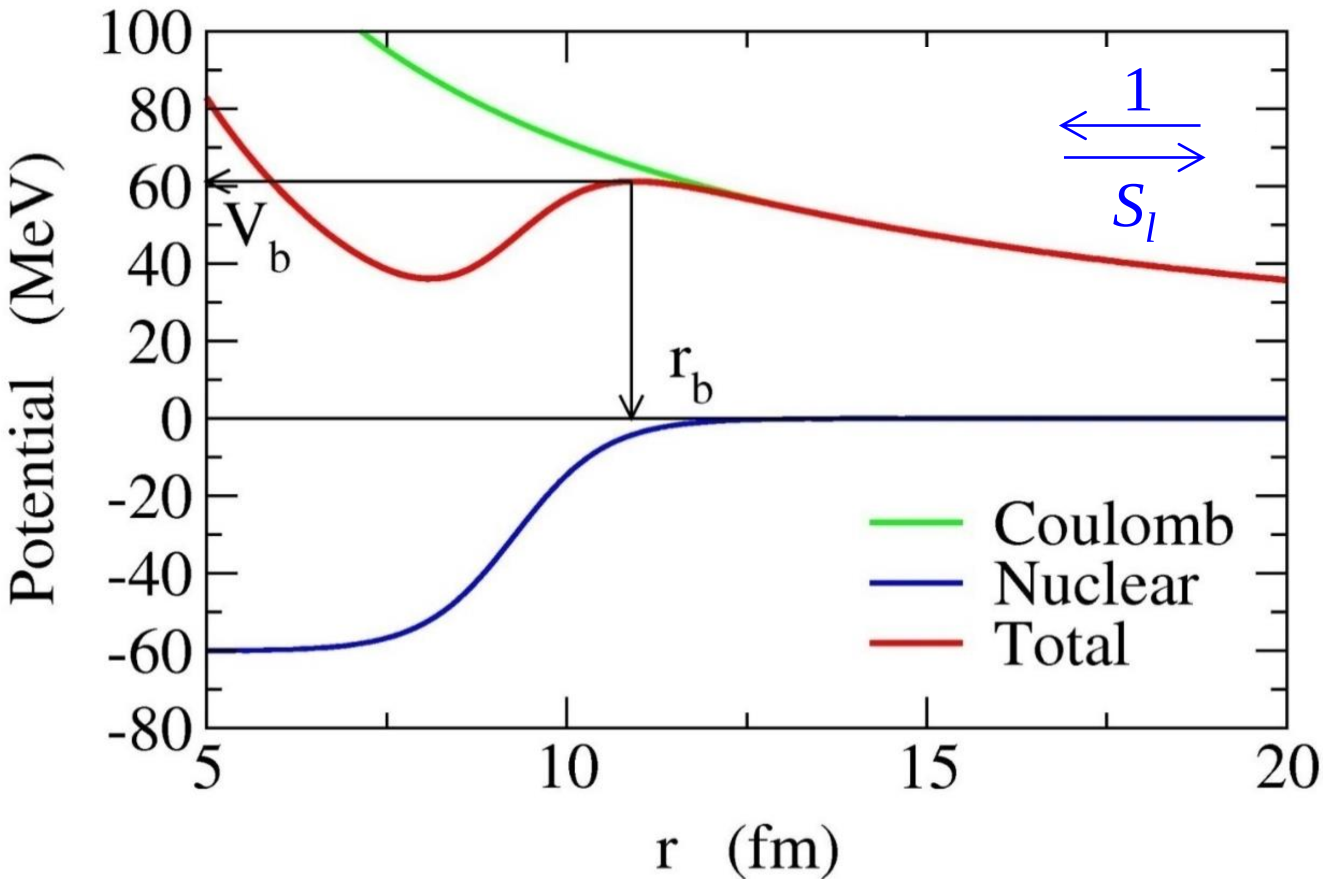


Nuclear Chart: RIKEN Nishina Center

Fusion reactions of medium-heavy nuclei

potential model: inert nuclei (no structure)

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



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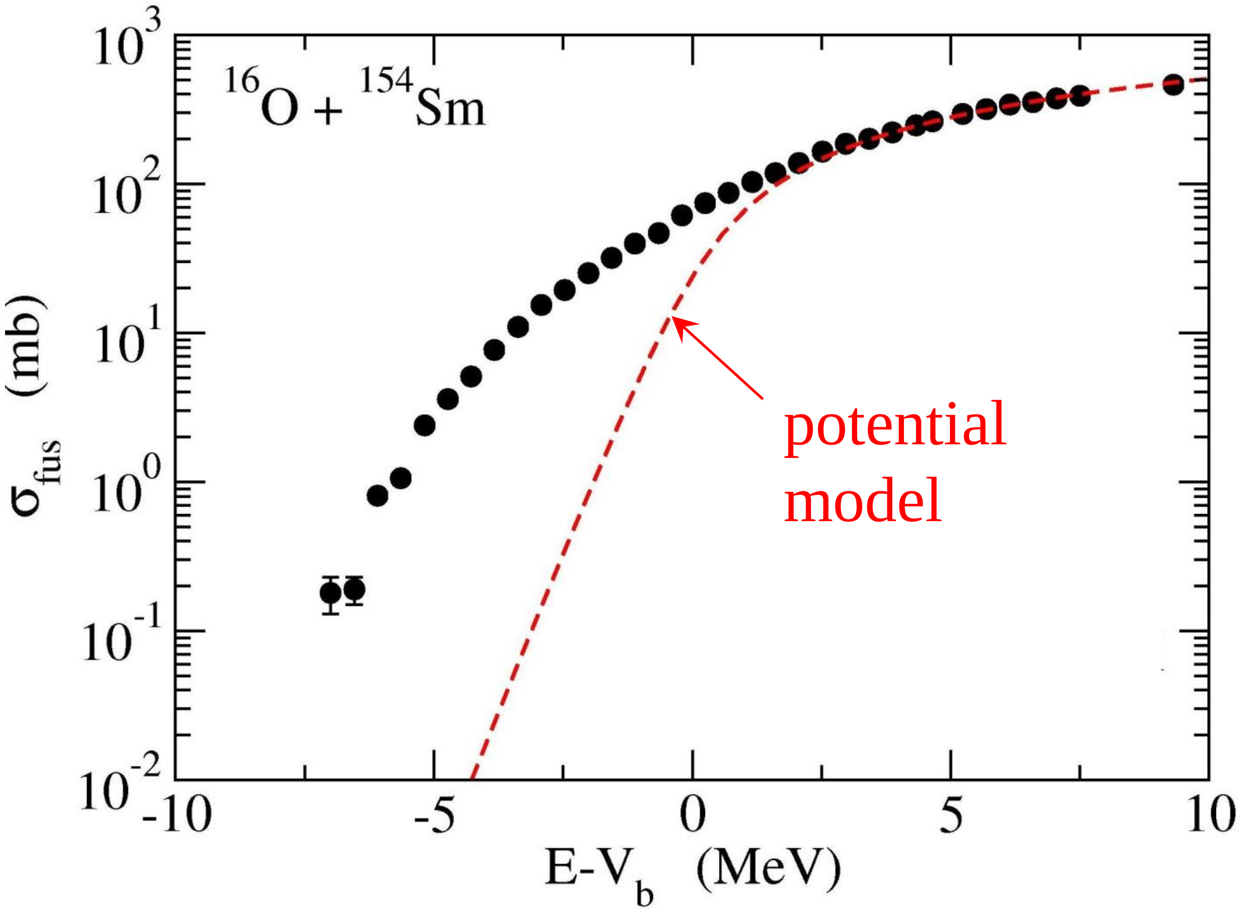
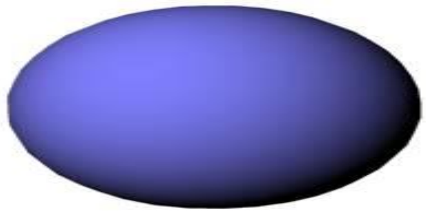
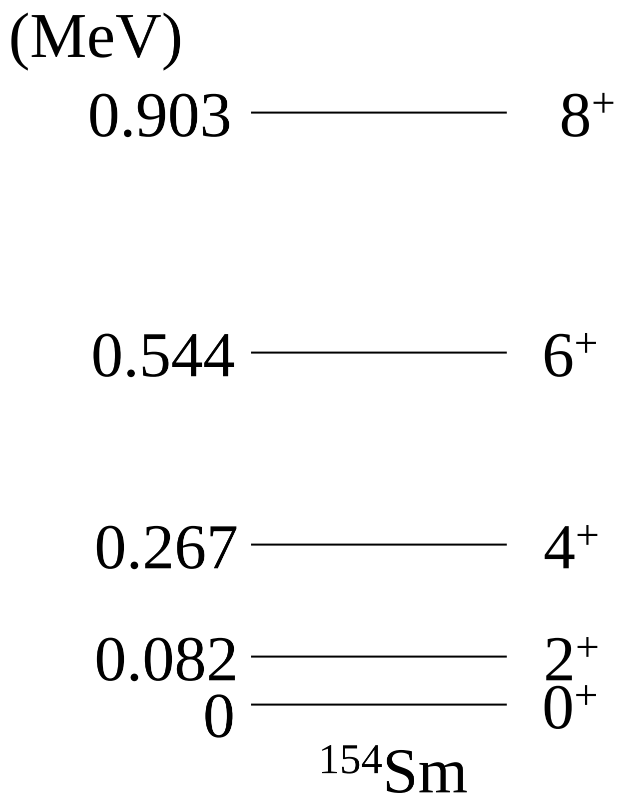
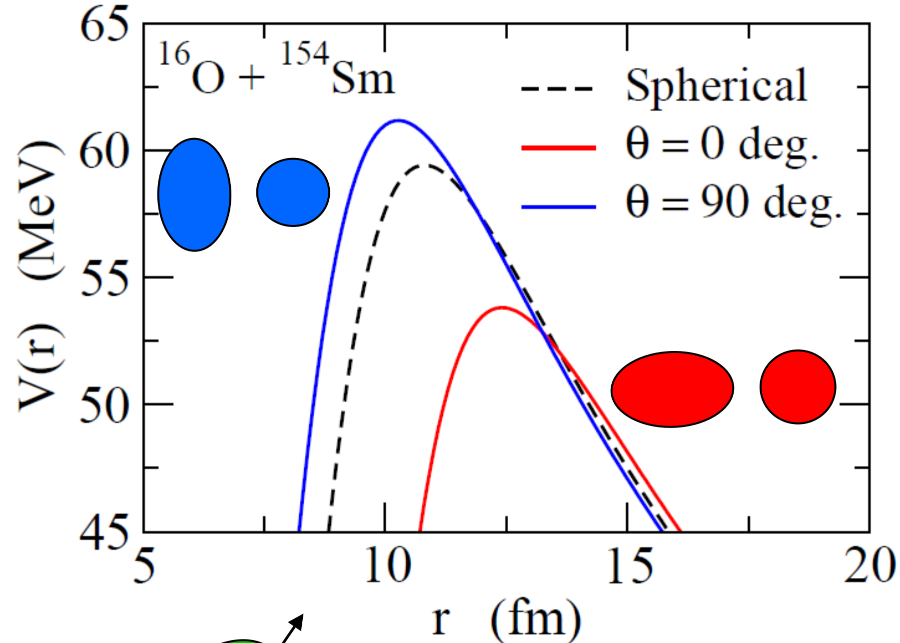


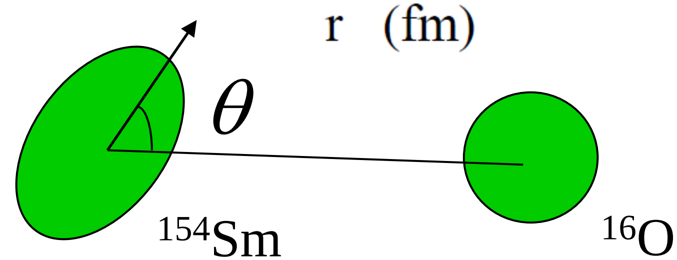
^{154}Sm : a typical deformed nucleus



^{154}Sm

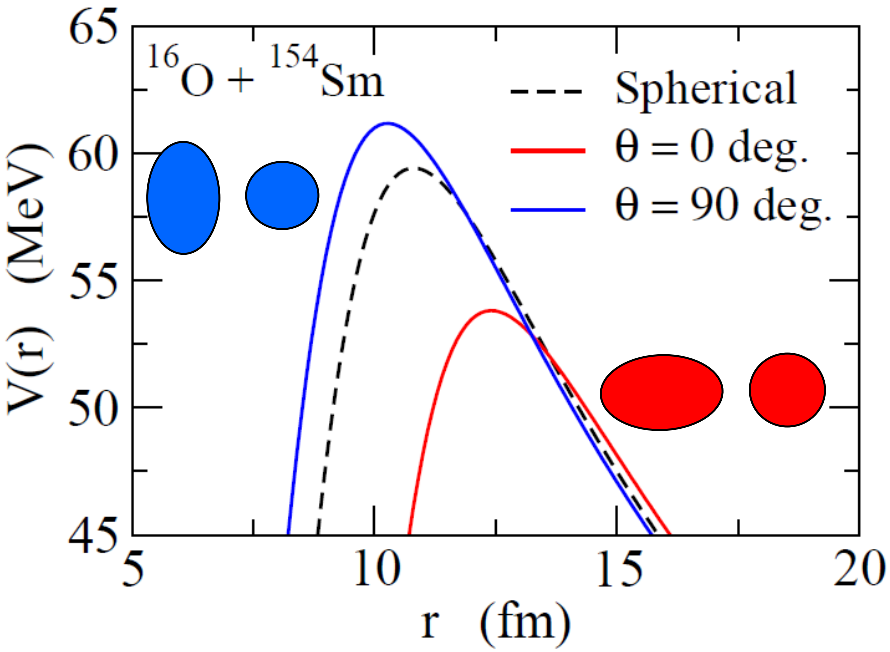




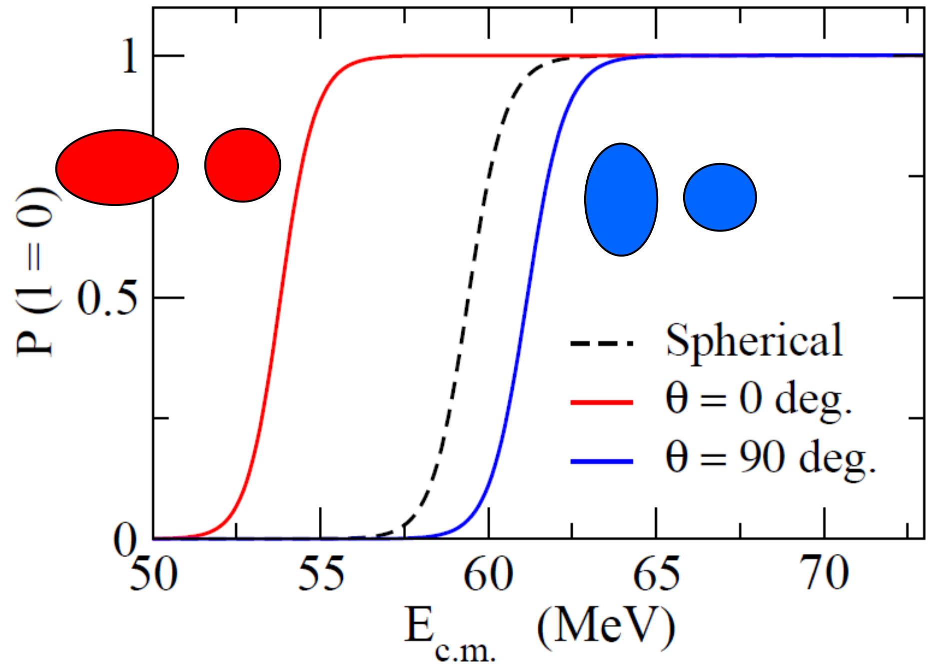


$$\sigma_{\mathsf{fus}}(E) = \int_0^1 d(\cos\theta)\sigma_{\mathsf{fus}}(E;\theta)$$

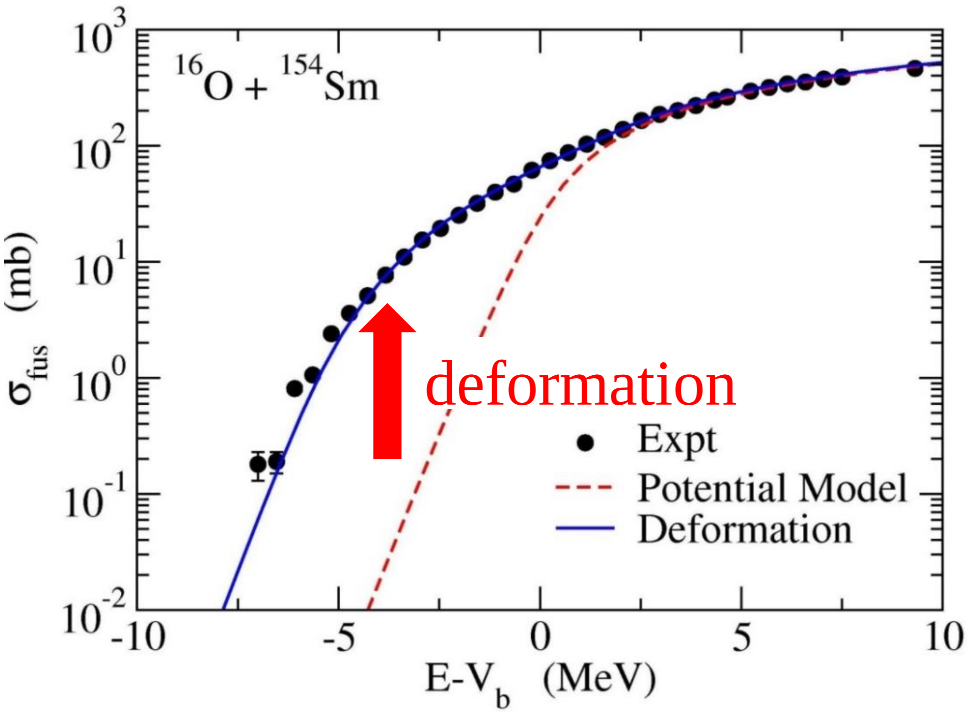
rotational spectrum



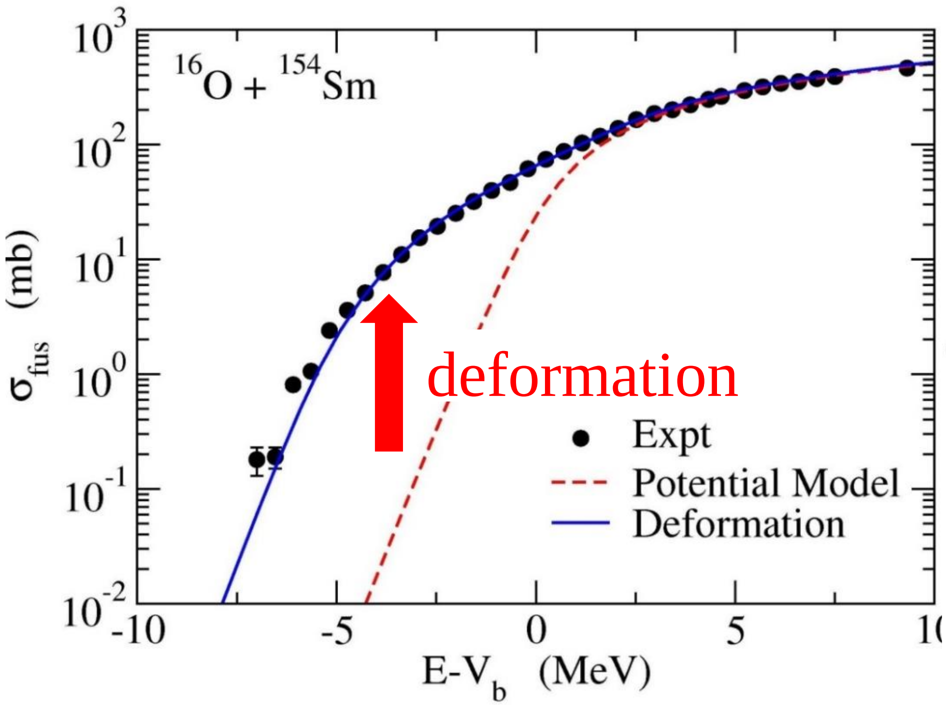
^{16}O + ^{154}Sm
Spherical
θ = 0 deg.
θ = 90 deg.
V(r) (MeV)
r (fm)
65
60
55
50
45
5
10
15
20



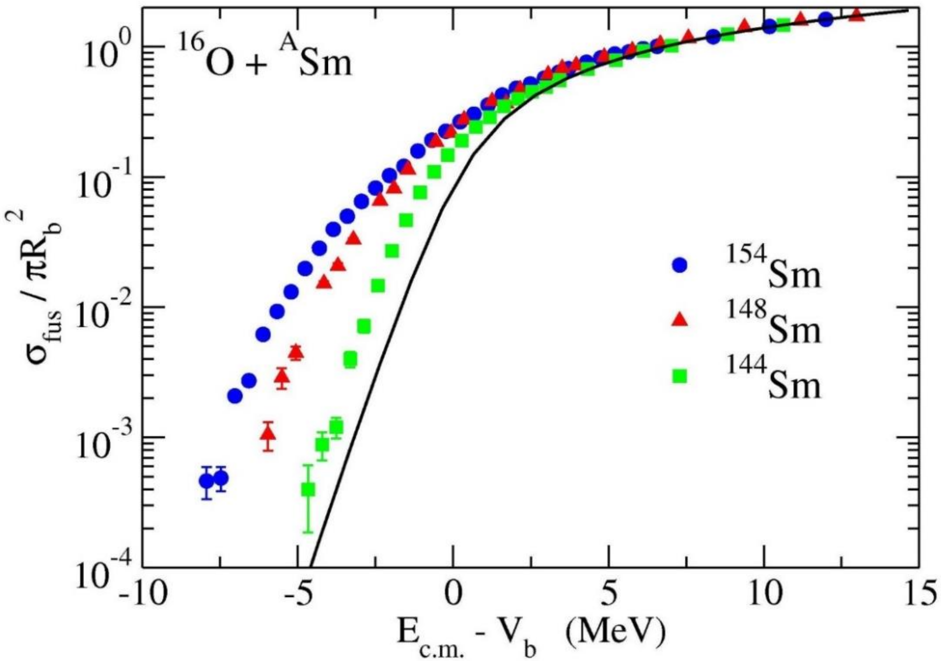
P (l = 0)
$E_{c.m.}$ (MeV)
Spherical
θ = 0 deg.
θ = 90 deg.
1
0.5
0
50
55
60
65
70



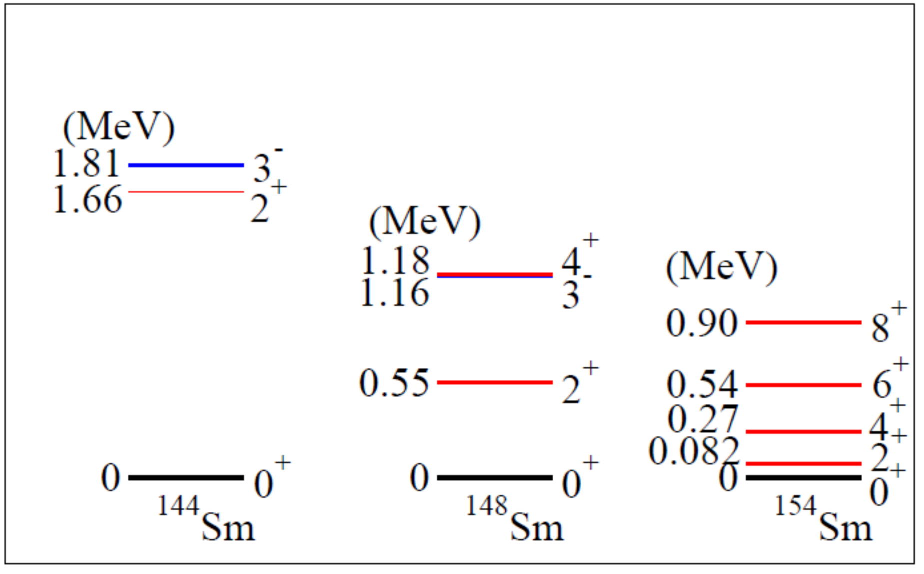
^{16}O + ^{154}Sm
deformation
Expt
Potential Model
Deformation
σ_{fus} (mb)
$E-V_b$ (MeV)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
-10
-5
0
5
10



similar enhancement
for non-deformed nuclei



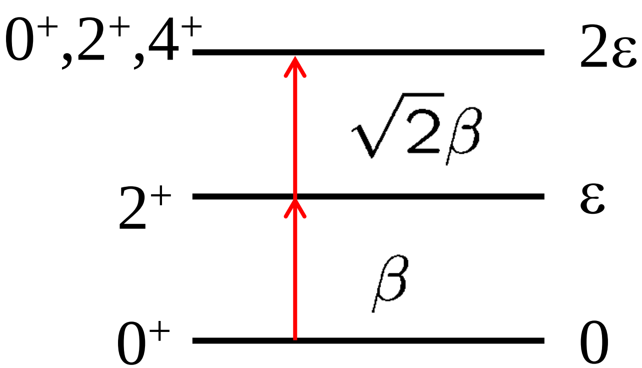
strong correlation
with nuclear spectrum
→ coupling assisted
tunneling phenomena



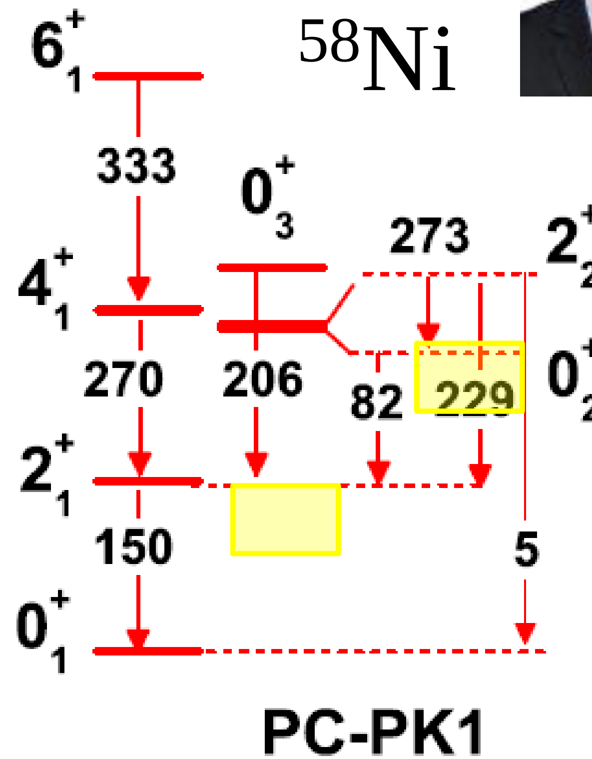
Semi-microscopic modelling of subbarrier fusion reactions

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

simple harmonic oscillator



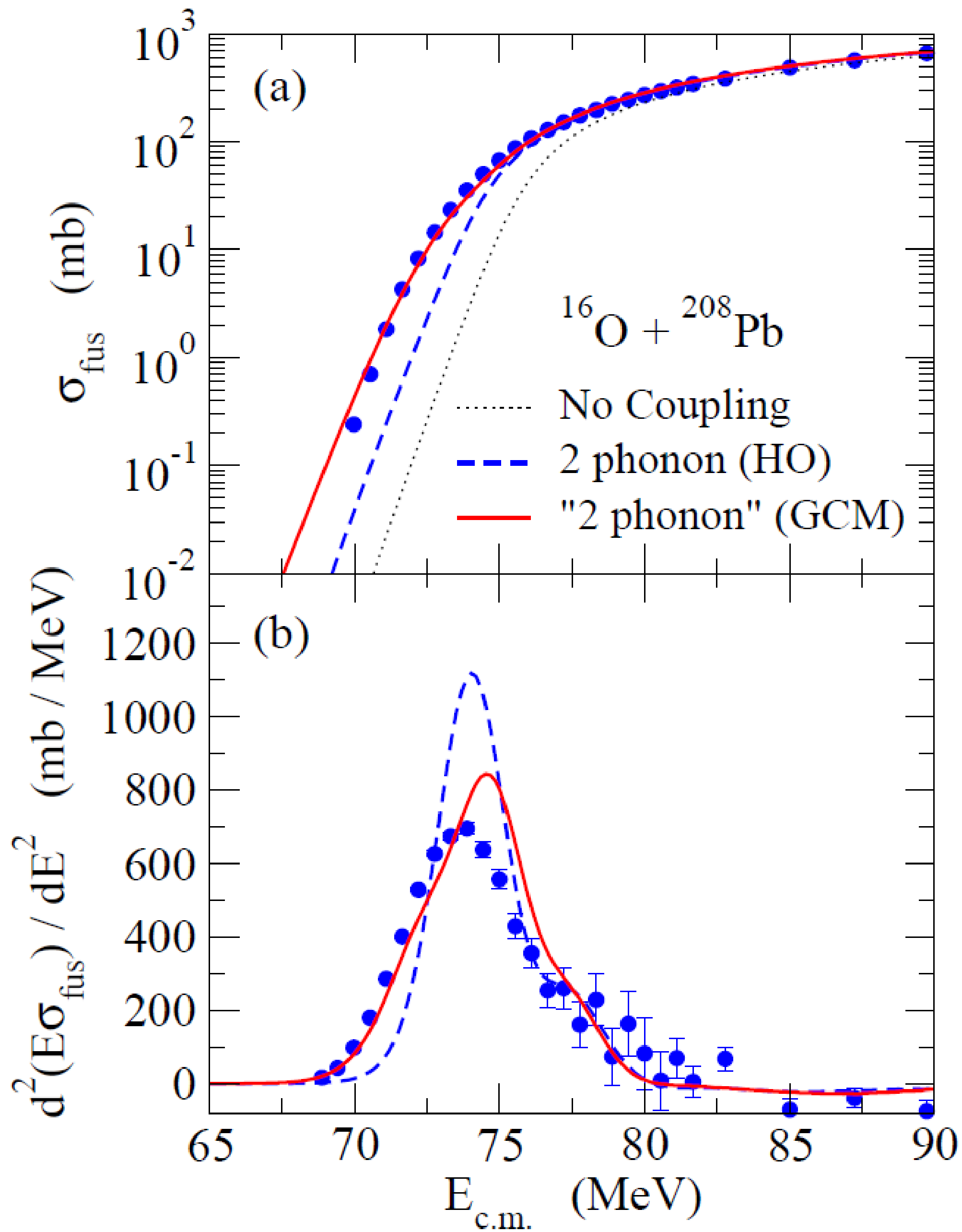
^{58}Ni

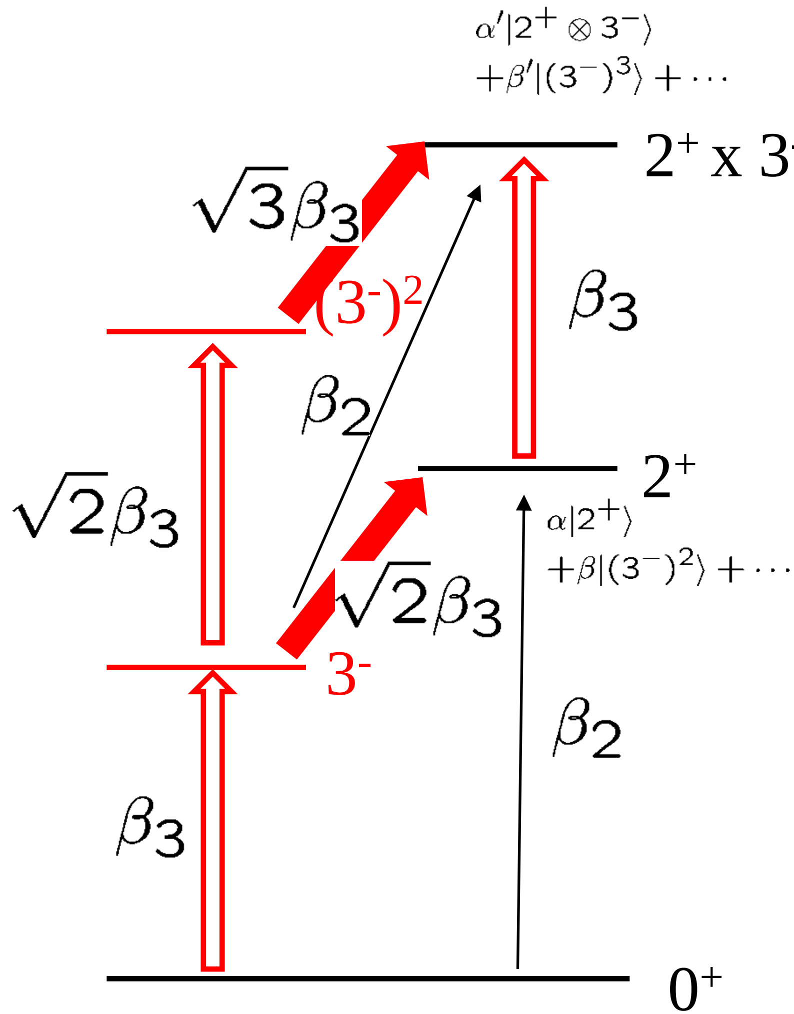


Beyond-mean-field method

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

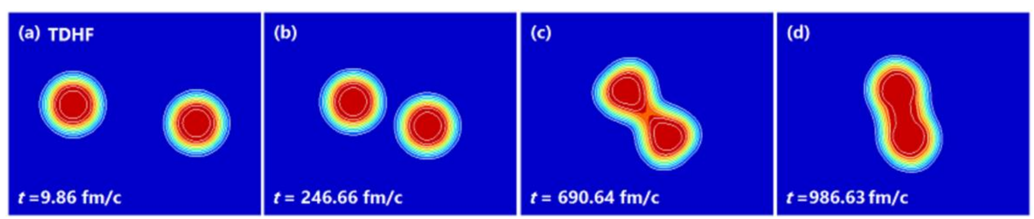
C.C. with inputs from microscopic nuclear structure calculations

C.C. with inputs based on TDHF

TDHF simulations

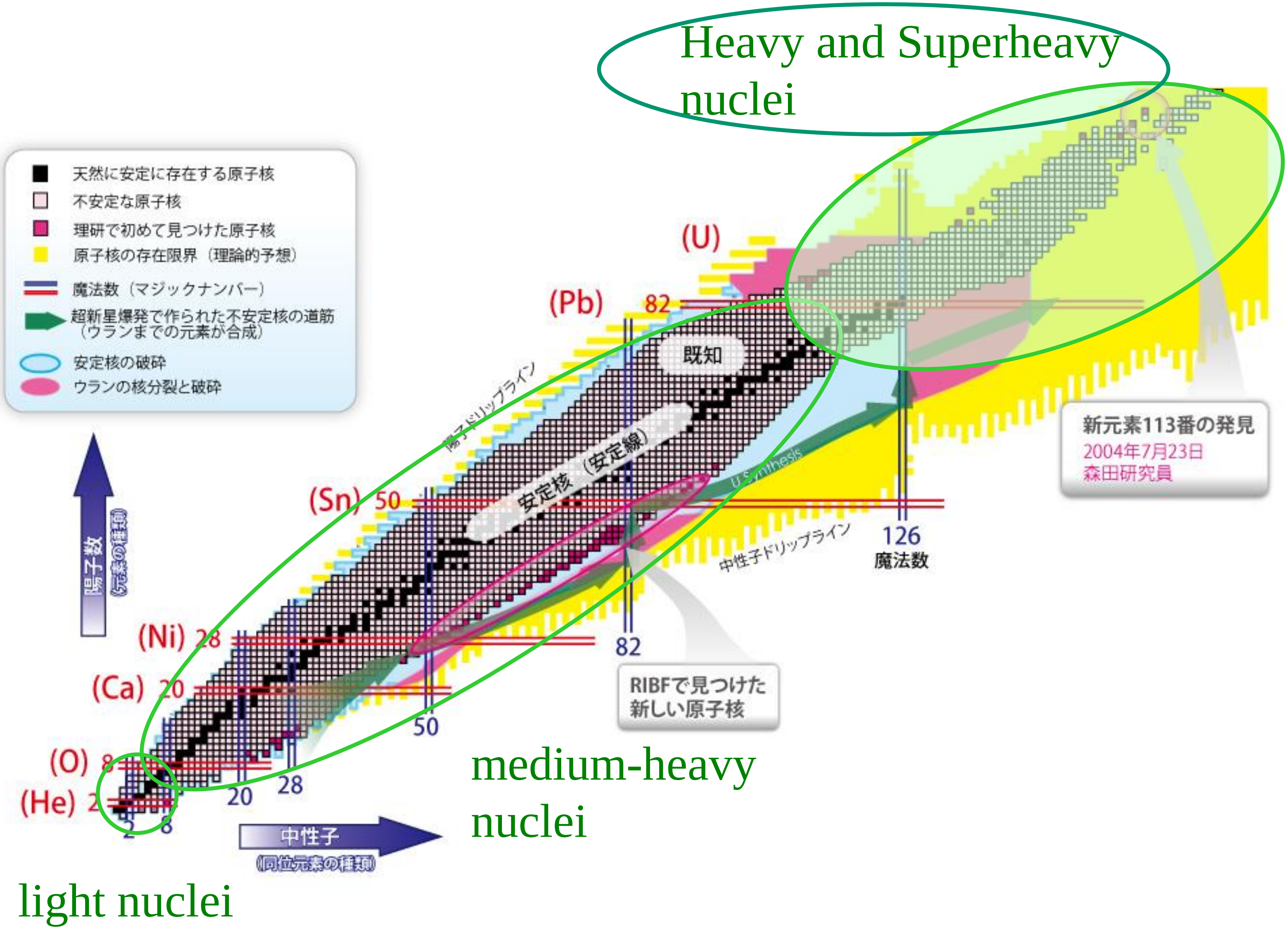
Microscopic

TDHF = Time Dependent Hartree-Fock



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

ab initio, but no tunneling

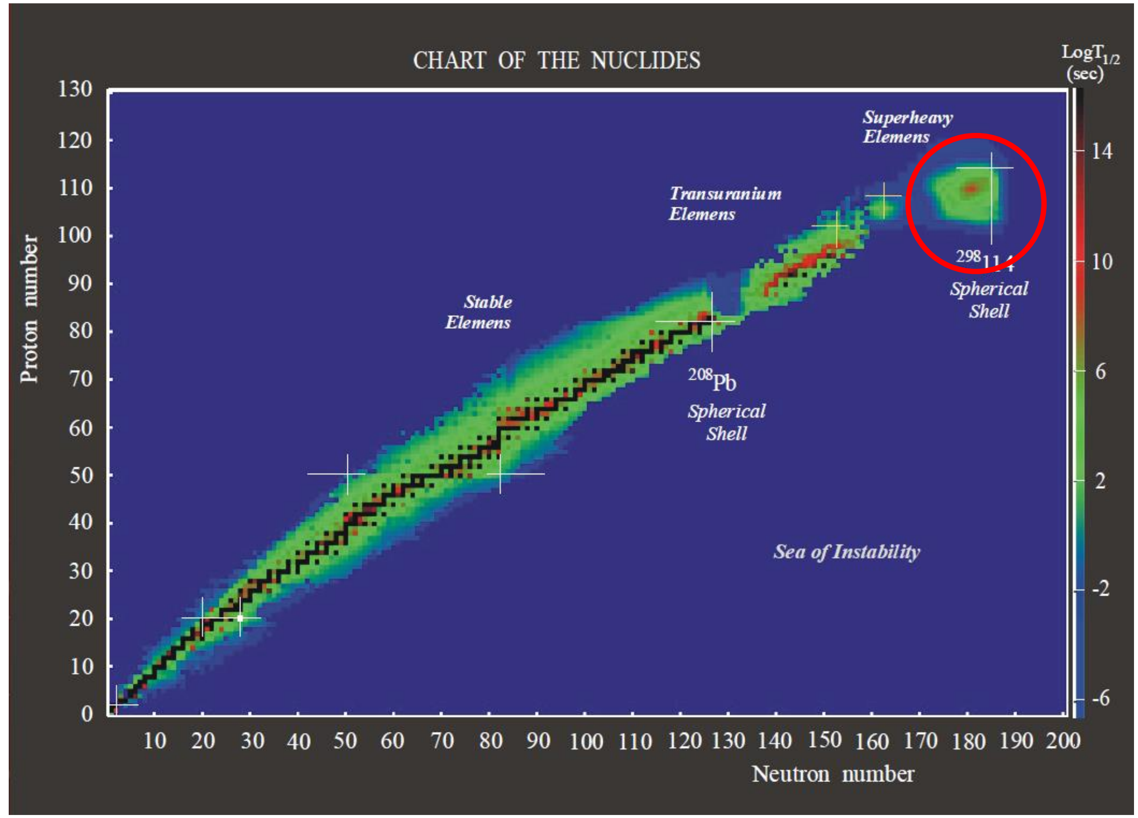


Nuclear Chart: RIKEN Nishina Center

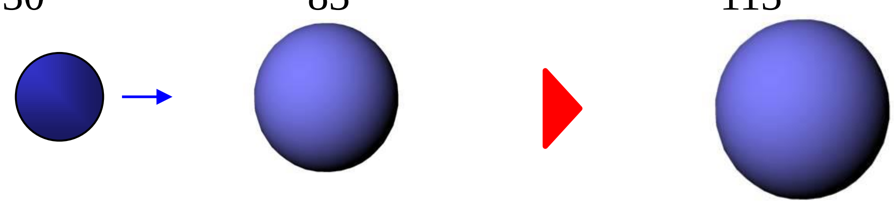
Superheavy elements

November, 2016

the island of stability（安定的島）

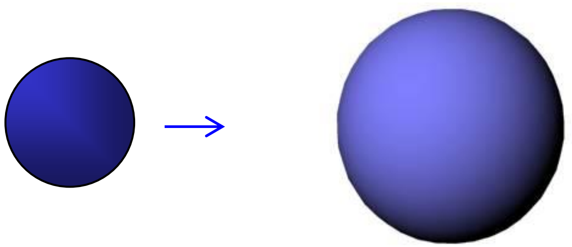


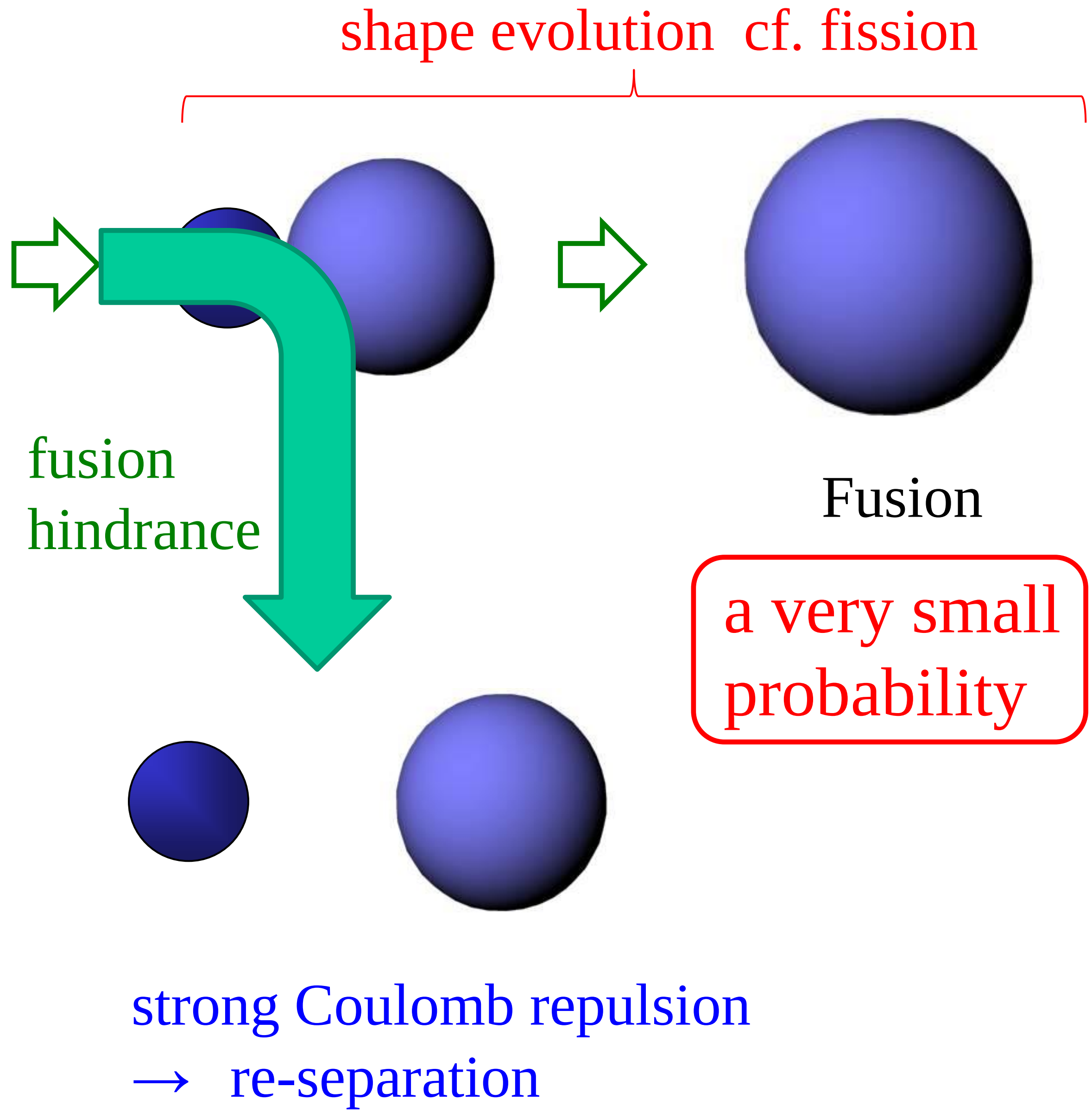
$^{70}_{30}$Zn $\quad$ $^{209}_{83}$Bi $\quad$ $^{279}_{113}$Nh*



Heavy-ion fusion reaction

Fusion of heavy nuclei and superheavy elements

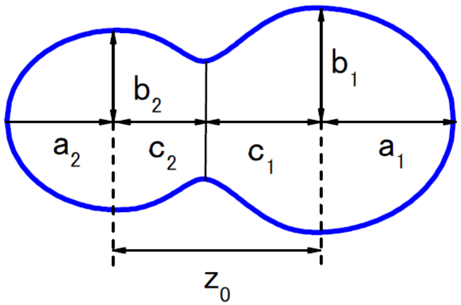


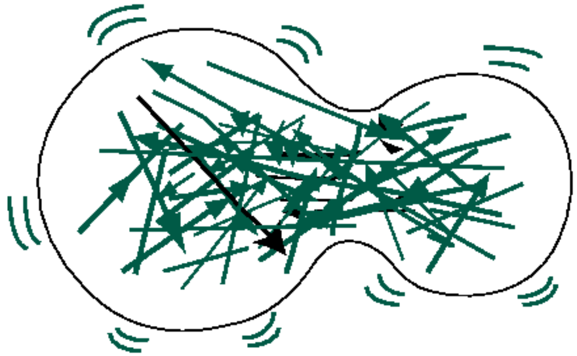


cf. Nihonium (RIKEN)

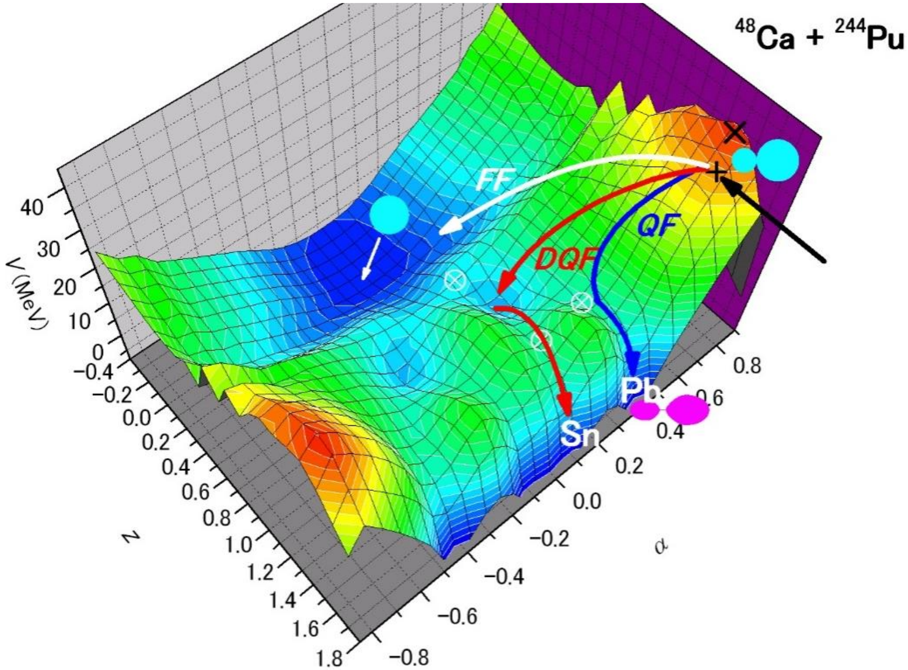
$^{70}\mathrm{Zn} + {}^{209}\mathrm{Bi} \rightarrow {}^{278}\mathrm{Nh} + n$

Nuclear shape evolution





nucleus = many-body system of nucleons



⇩

nuclear intrinsic d.o.f.
: internal environment

→physics of open quantum systems

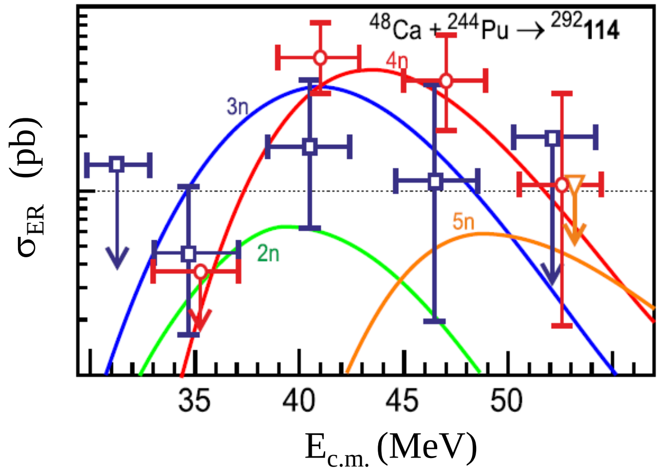
Y. Aritomo, K. Hagino, K. Nishio, and S. Chiba, PRC85 (2012) 044614

cf. Classical Langevin equation

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

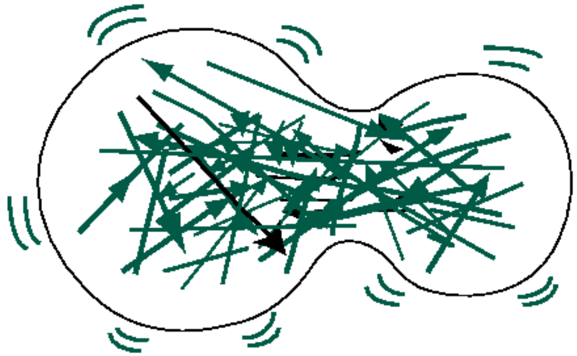
Nuclear shape evolution

- successful as a phenomenological approach



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

- a more microscopic approach?
- quantum effects?



nucleus = many-body system of nucleons

⇩

nuclear intrinsic d.o.f.
: internal environment

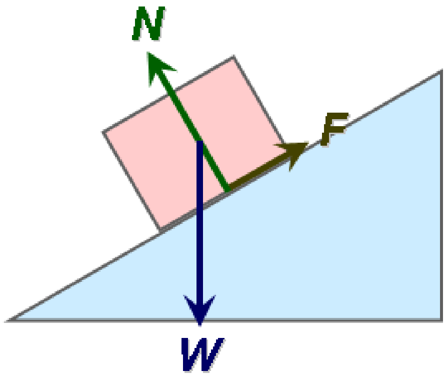
→physics of open quantum systems

cf. Classical Langevin equation

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

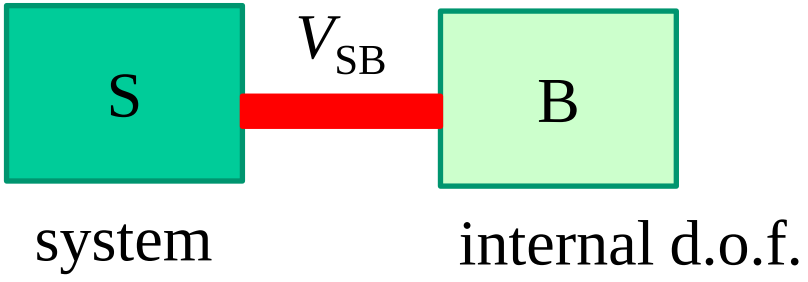
Fusion from a viewpoint of open quantum systems

classical mechanics



heat generation when a rigid body stops

quantum mechanics



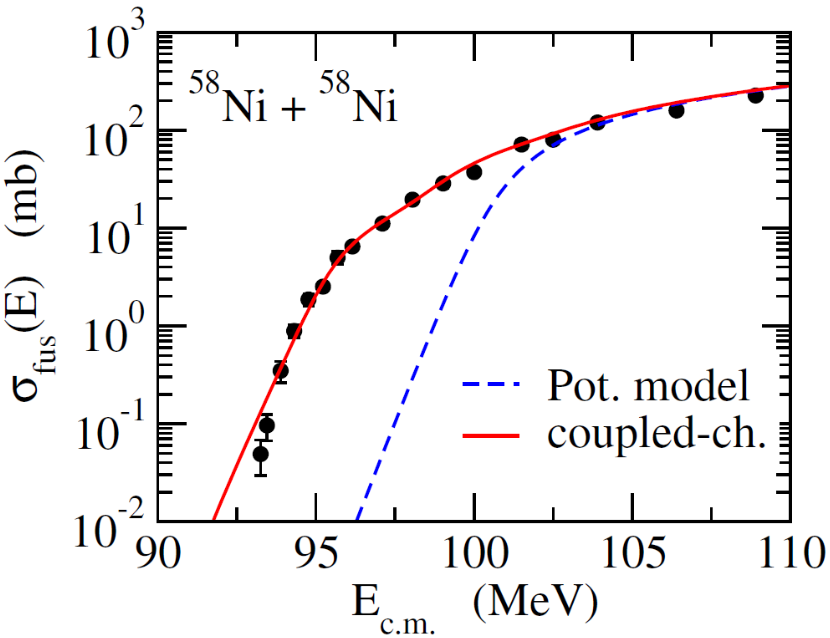
Caldeira-Leggett model

$$H_S = \frac{p^2}{2m} + V(q)$$

$$H_{\rm int} = \sum_i \frac{p_i^2}{2m_i} + \frac{1}{2} m_i \omega_i^2 x_i^2$$

a collection of H.O.

Fusion from a viewpoint of open quantum systems

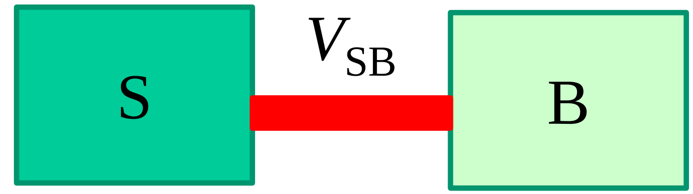


cf. a vib. coupling in subbarrier fusion

2.90 MeV	———	$0^+, 2^+, 4^+$
1.45 MeV	———	2^+
	———	0^+

^{58}Ni

quantum mechanics



system internal d.o.f.

Caldeira-Leggett model

$$H_S = \frac{p^2}{2m} + V(q)$$

$$H_{\rm int} = \sum_i \frac{p_i^2}{2m_i} + \frac{1}{2} m_i \omega_i^2 x_i^2$$

a collection of H.O.

$\rightarrow$ C.C. calculations

Fusion from a viewpoint of open quantum systems

Caldeira-Leggett model

$$H_S = \frac{p^2}{2m} + V(q)$$
$$H_{\rm int} = \sum_{i=1}^{\infty} (a_i^\dagger a_i + 1/2)\hbar\omega_i$$

how to deal with a huge number of phonon modes?

→ an efficient truncation scheme

$$\boxed{b_k^\dagger = \sum_{i=1}^{\infty} C_{ki}\, a_i^\dagger \qquad (k = 1, \cdots K)}$$

$$e^{-i\omega t} \sim \sum_{k=0}^{K} \eta_k(\omega) J_k(t)$$

$$\rightarrow b_k^\dagger = \sum_i \left[\frac{d_i}{\hbar}\eta_k(\omega_i)\right] a_i^\dagger$$

cf. a "two-phonon" state

2.90 MeV	═══	$0^+, 2^+, 4^+$
1.45 MeV	───	2^+
	───	0^+

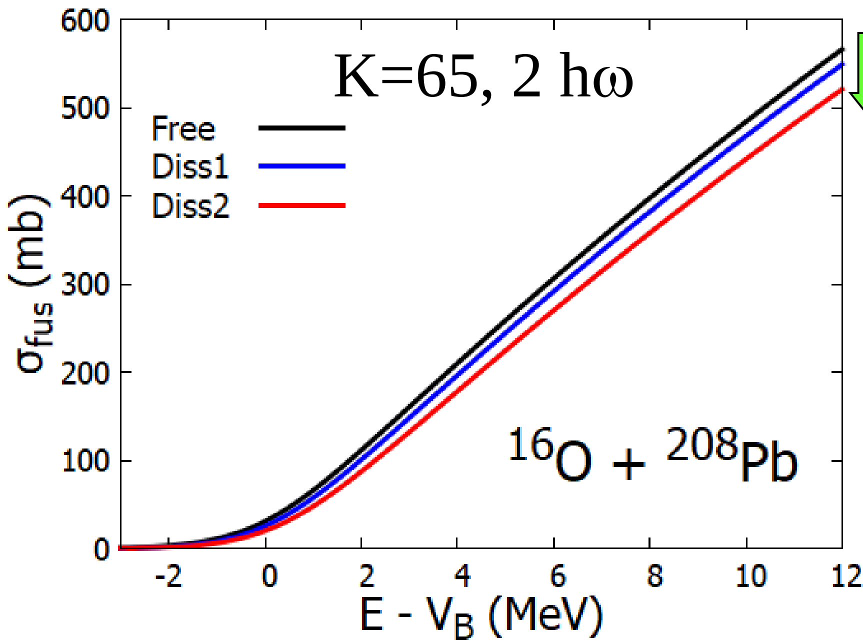
^{58}Ni

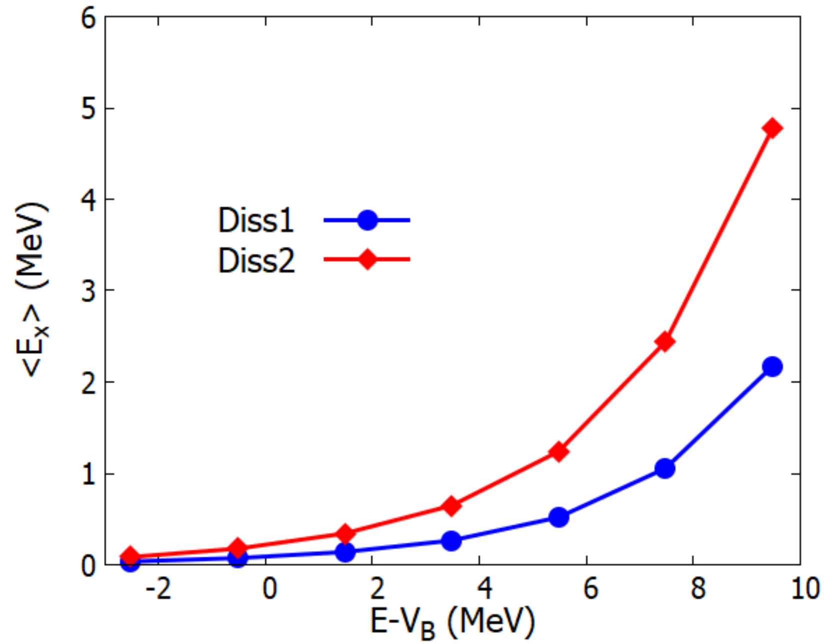
$$|2ph\rangle = \sum_I \langle 2020|I0\rangle |\phi_I\rangle$$

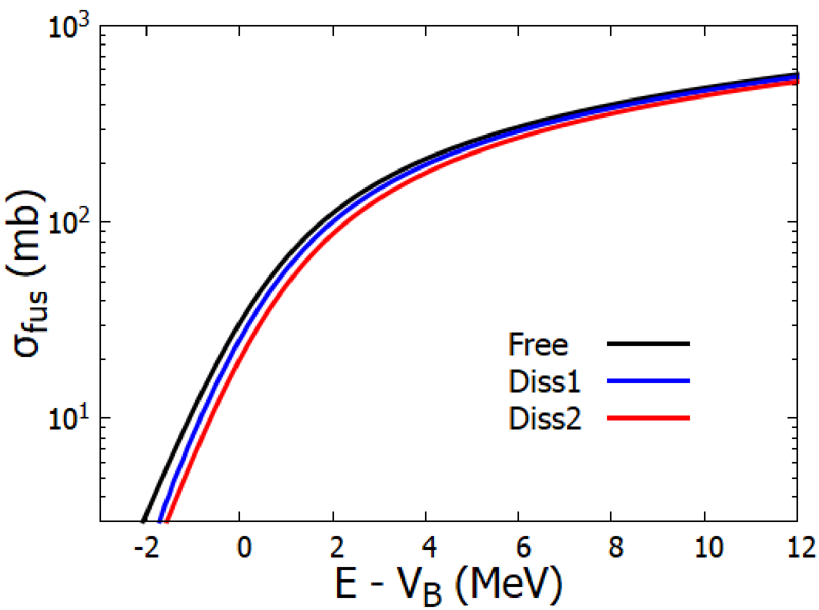
M. Tokieda and K. Hagino,
Ann. of Phys. 412 (2020) 168005
Front. in Phys. 8 (2020) 8.

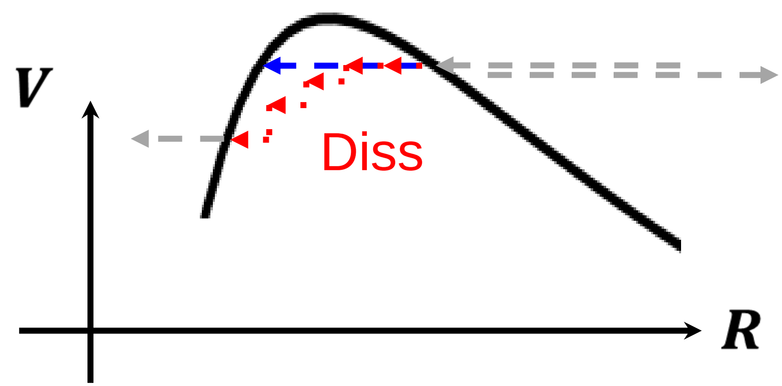
fusion cross sections

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





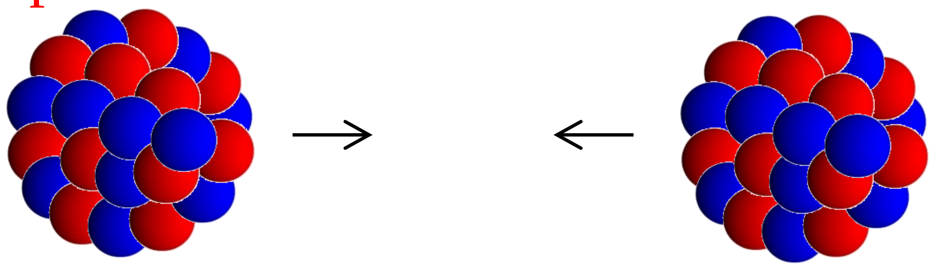




M. Tokieda, Ph.D. thesis (2021), Tohoku University

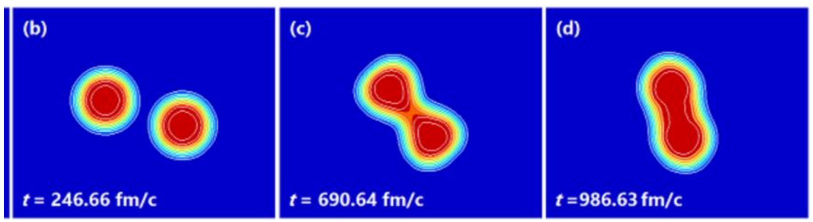
Towards a microscopic nuclear reaction theory

many-body problems



still very challenging

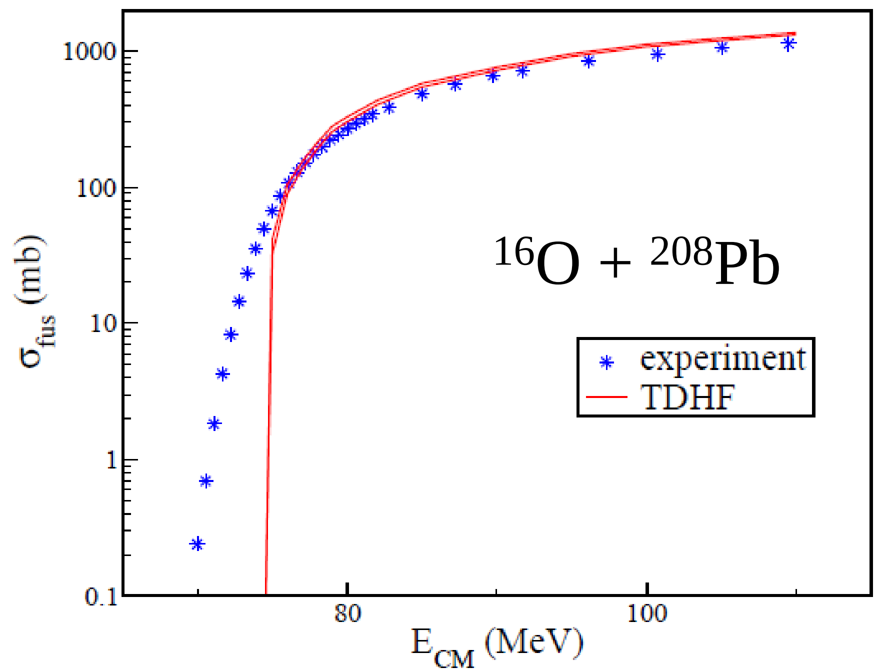
Time-dependent mean-field theory (TDHF/TDDFT)



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

(semi) classical → no tunneling

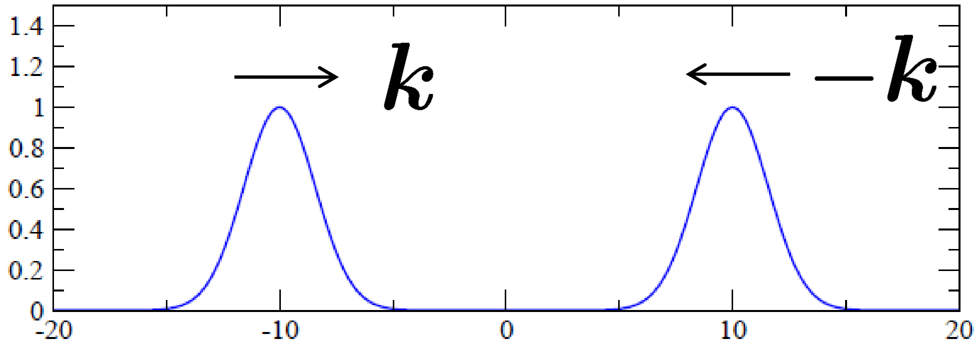
a microscopic understanding of
many-body tunneling?

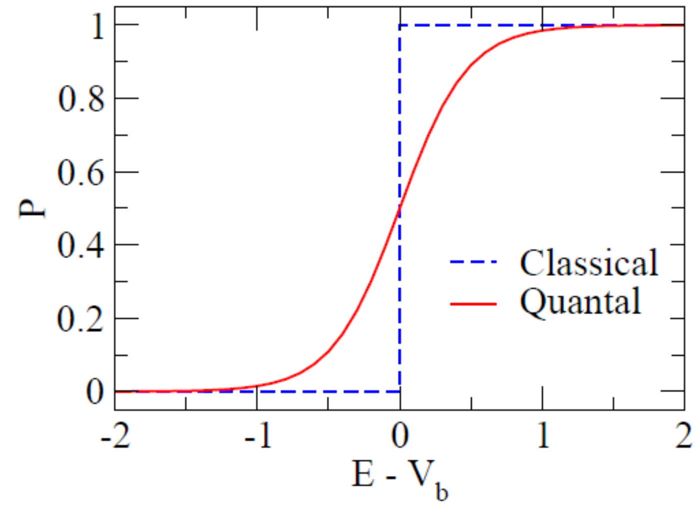


C. Simenel, EPJA48 ('12) 152

TDHF

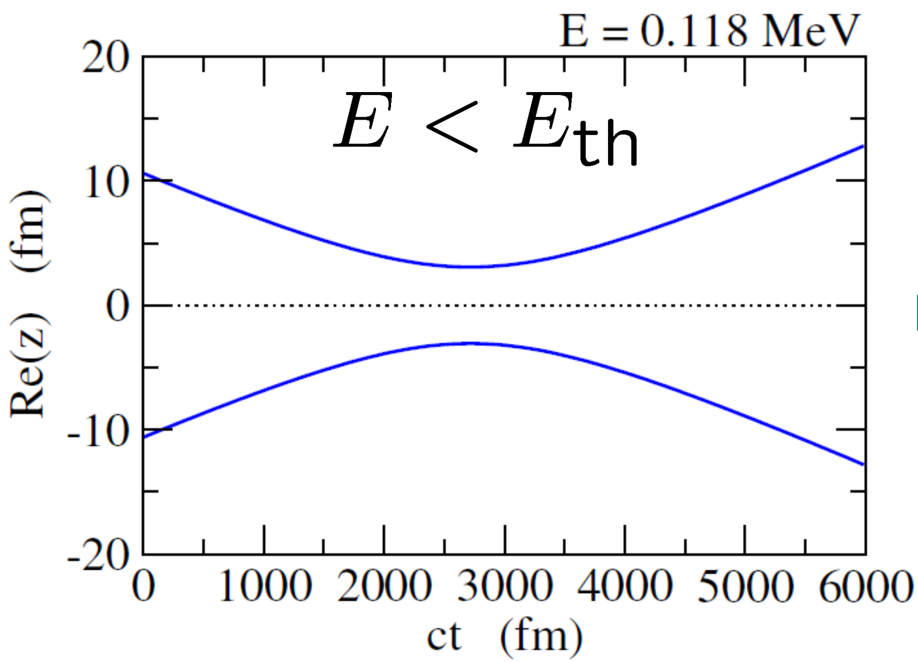
$$\Psi(t) = \Phi_{\mathrm{SD}}(t)$$

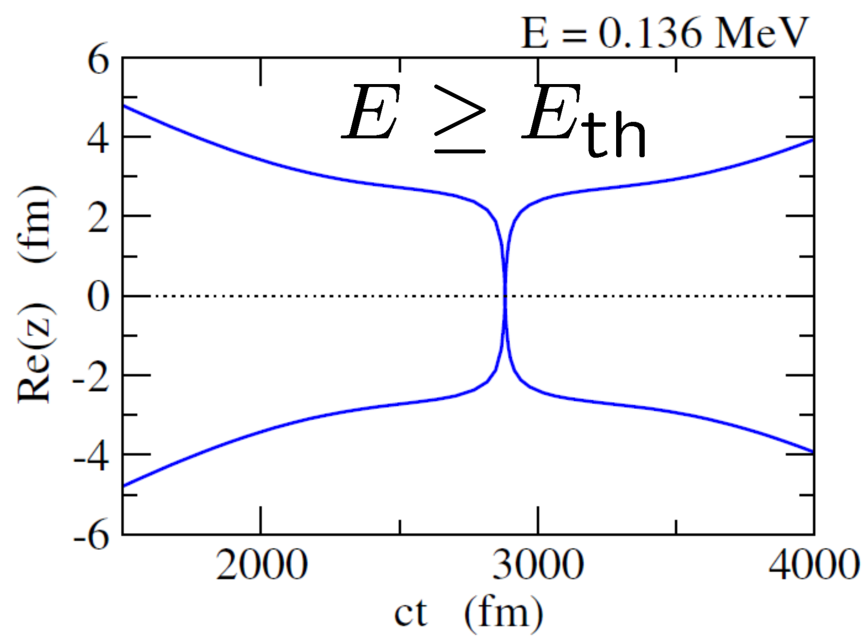




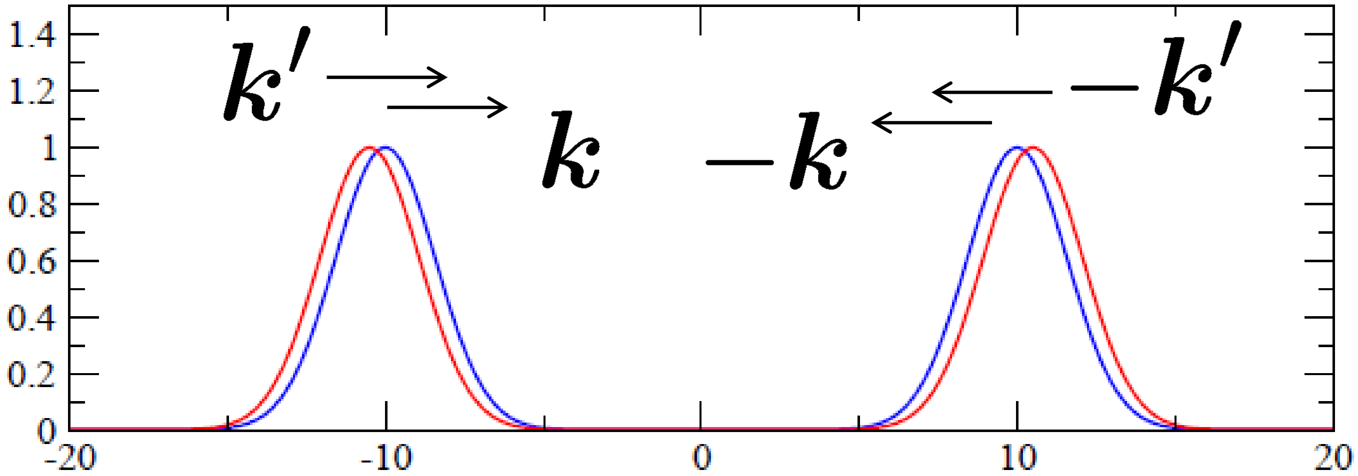
a single Slater determinat for a many-body wave function

α+α in 1D





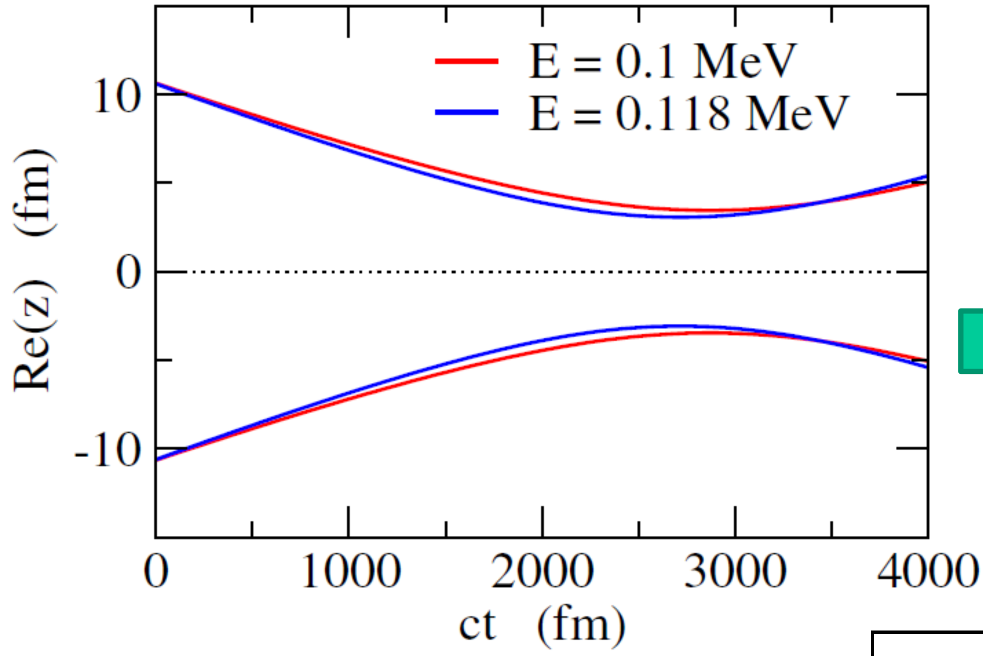
a linear superposition of many Slater determinants



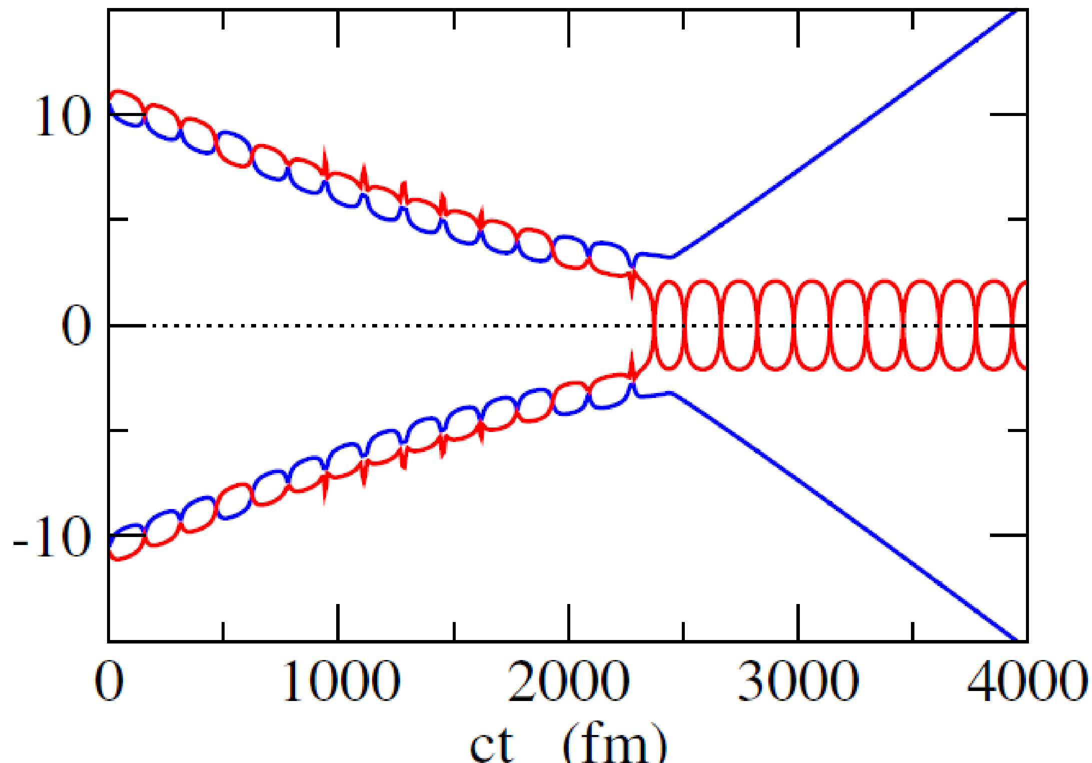
$$\Psi(t) = \sum_k \underline{f_k(t)}\,\underline{\Phi_{\mathsf{SD},k}(t)}$$

time-dependent variational principle

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

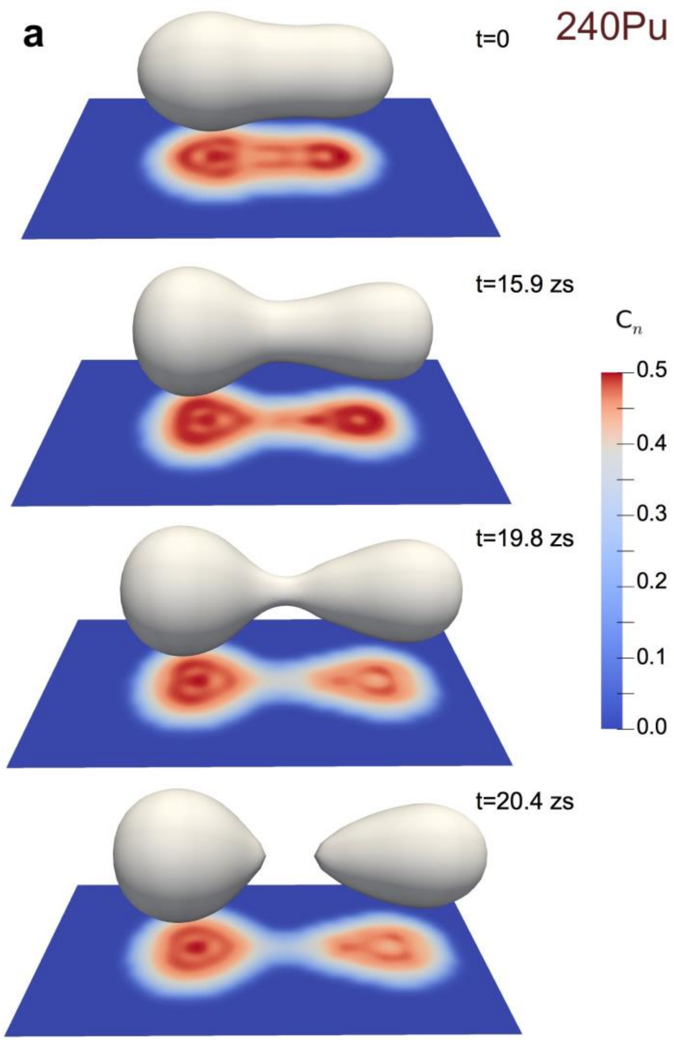


TDGCM
(a superposition of 2 SD)



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

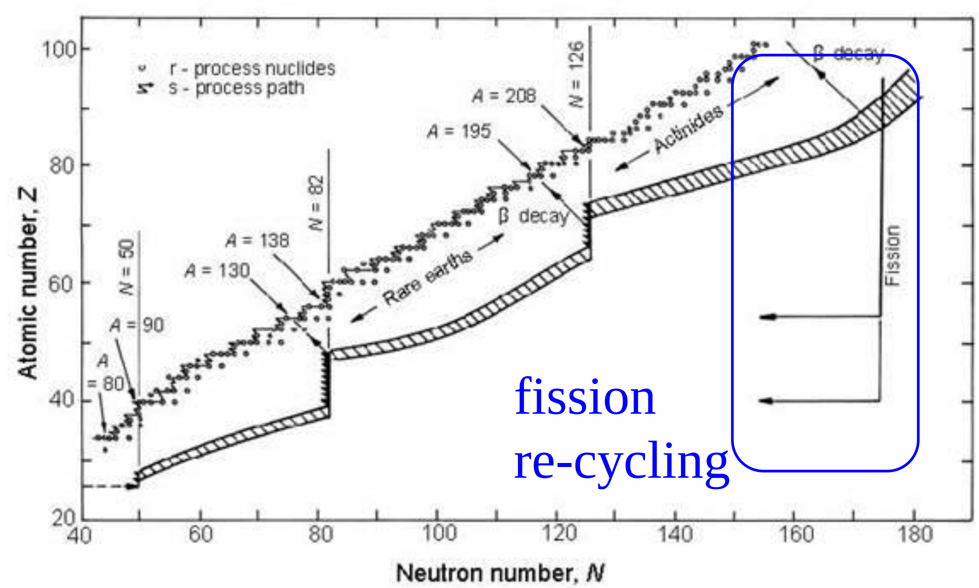
Nuclear Fission



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

➢ important role in:

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



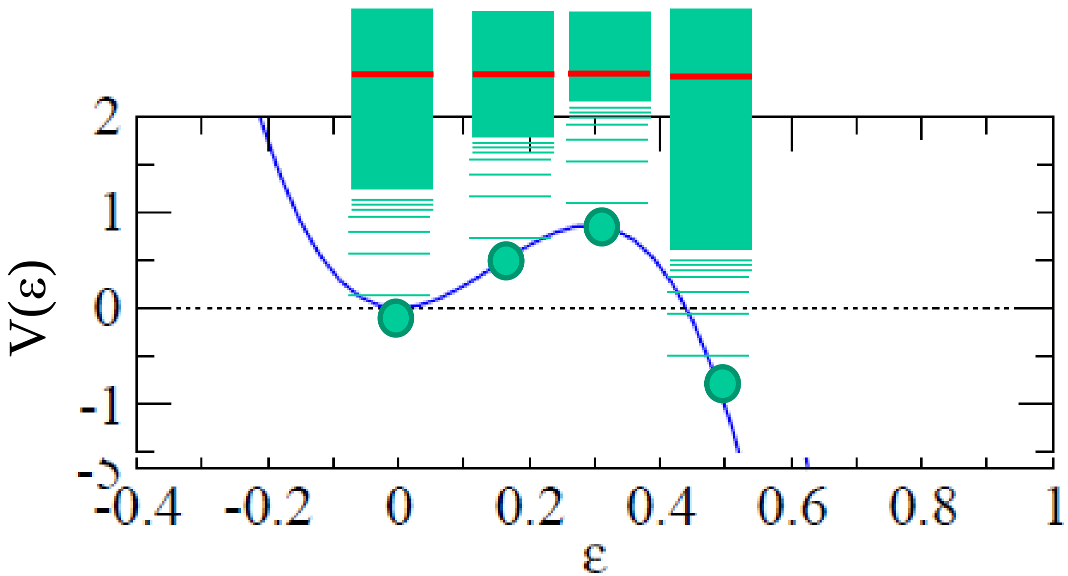
very complicated dynamics:

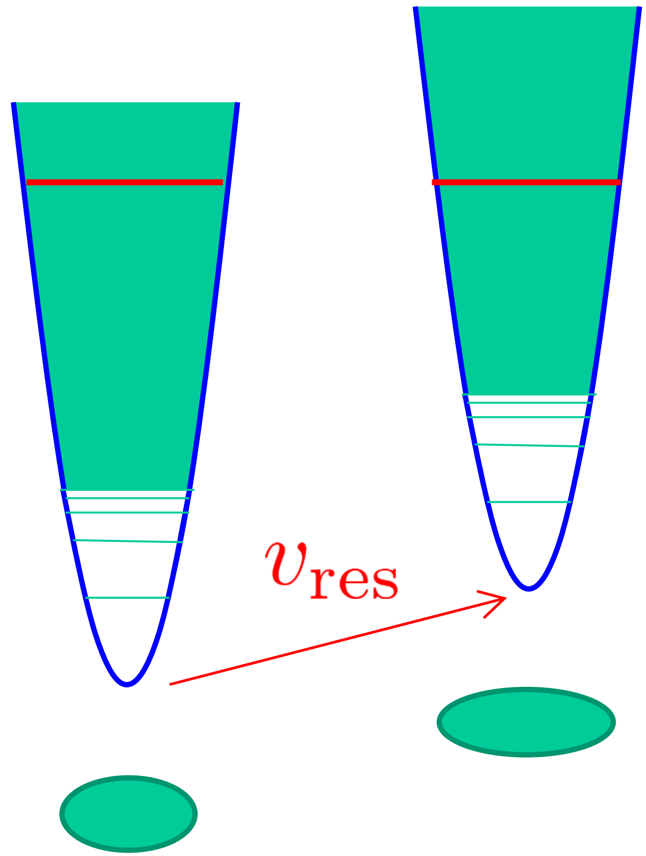
a microscopic understanding

→ far from complete

CI approach: a novel way to understand fission

K.H. and G.F. Bertsch





c.f. Generator Coordinate Method (GCM)

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

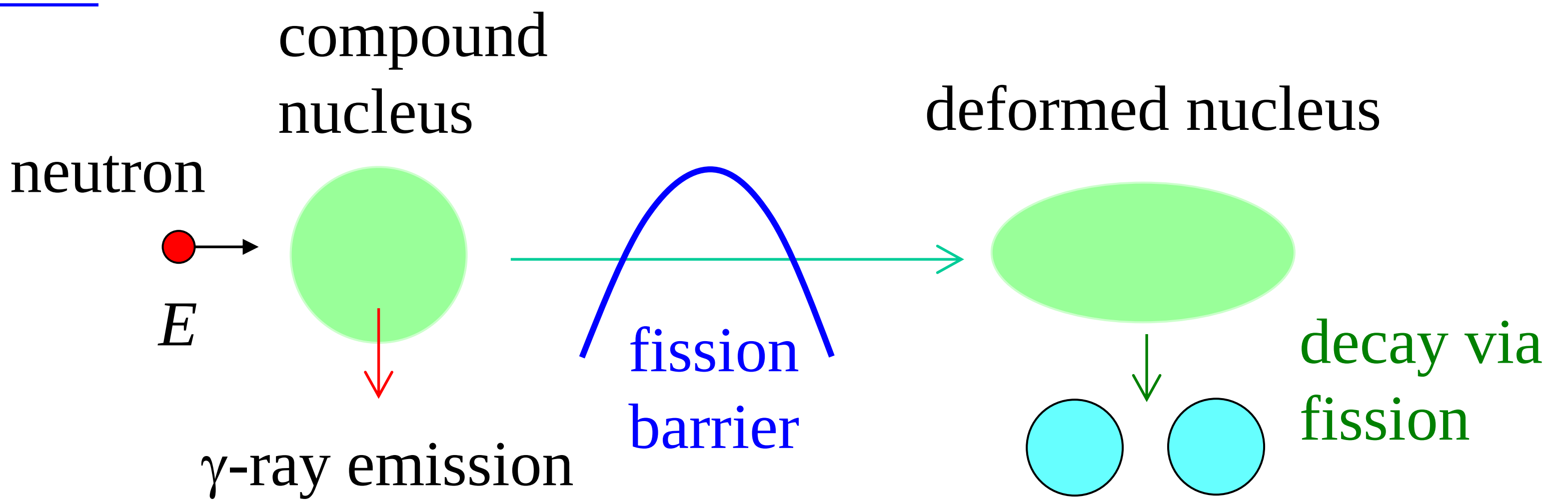
hopping due to the residual interaction

→ CI approach

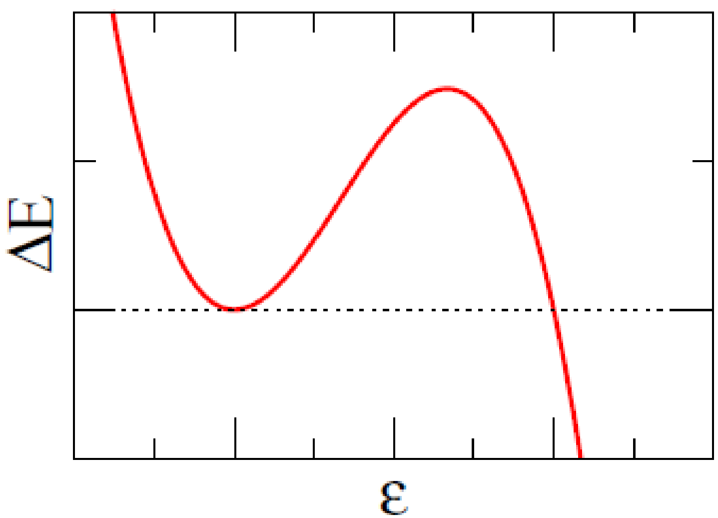
$$|\Psi\rangle = \int dQ \sum_i f_i(Q)|\Phi_Q(i)\rangle$$

→ shape evolution

nuclear fission



the transition state theory



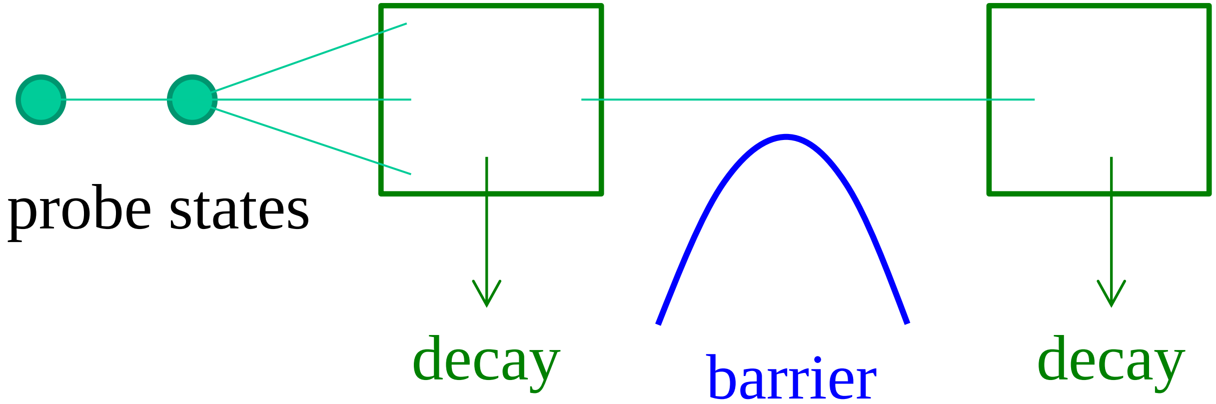
$$\Gamma_f = \frac{1}{2\pi\rho_{\rm gs}(E^*)}\sum_c T_c$$

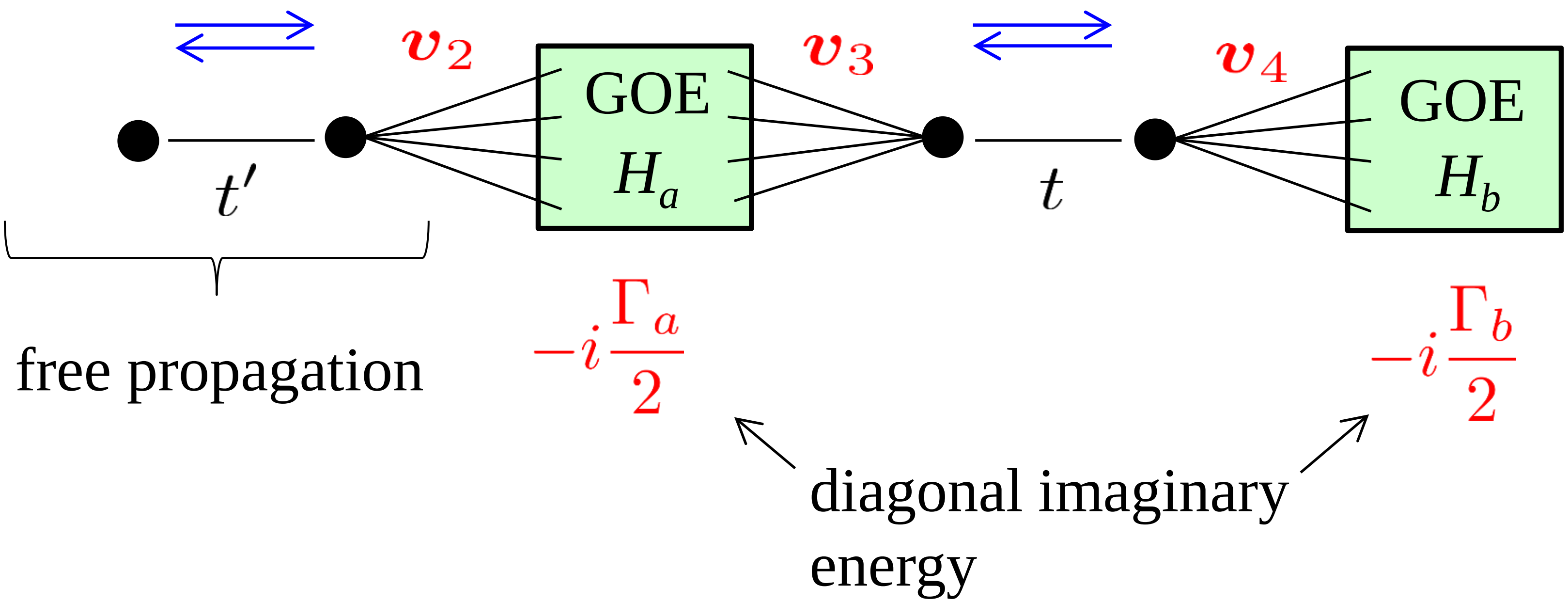
✓ decay dynamics: the saddle only

✓ the insenstitivity property

Can one derive the properties of the transition state theorybased on a *microscopic* many-body Hamiltonian?

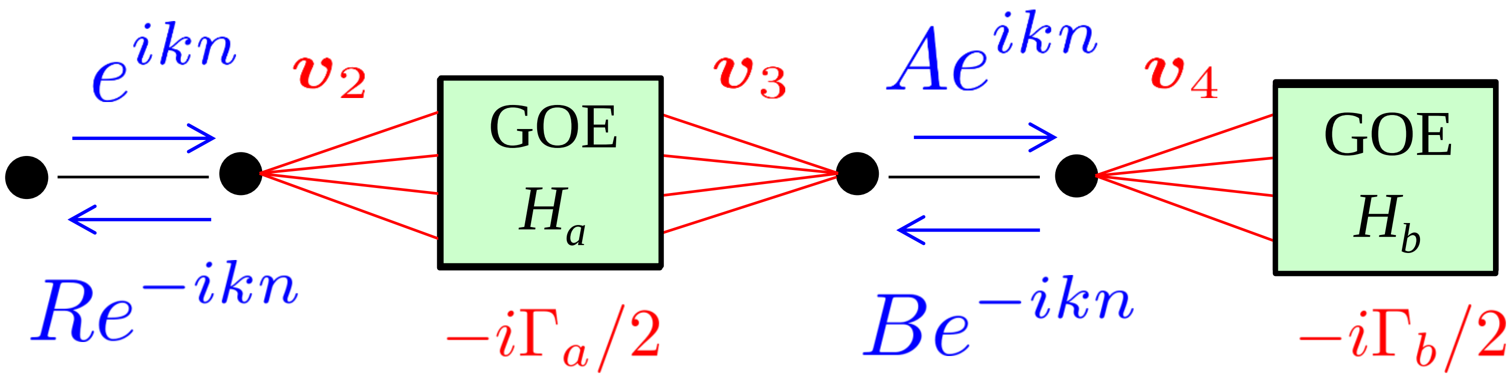
2 GOE Model





v_k (k = 2,3, 4): random interactions

G.F. Bertsch and K. Hagino, J. Phys. Soc. Jpn. 90, 11405 (2021)

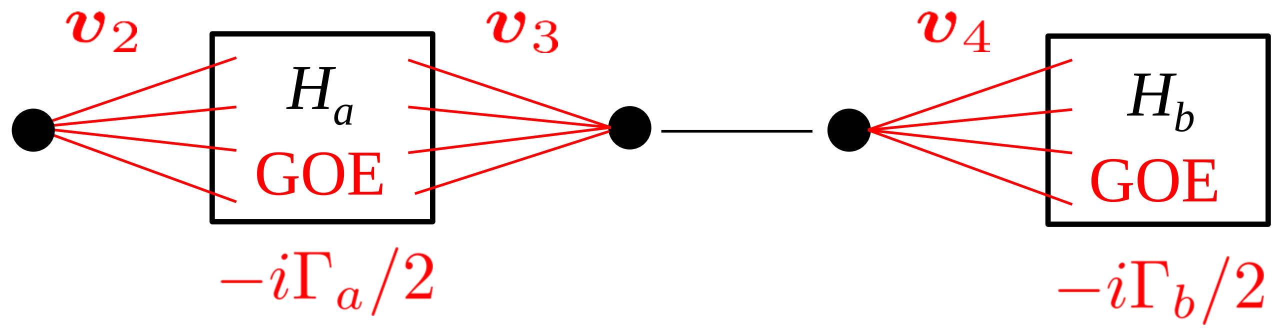


$$T(E) = T_a(E) + T_b(E) = 1 - |R(E)|^2$$

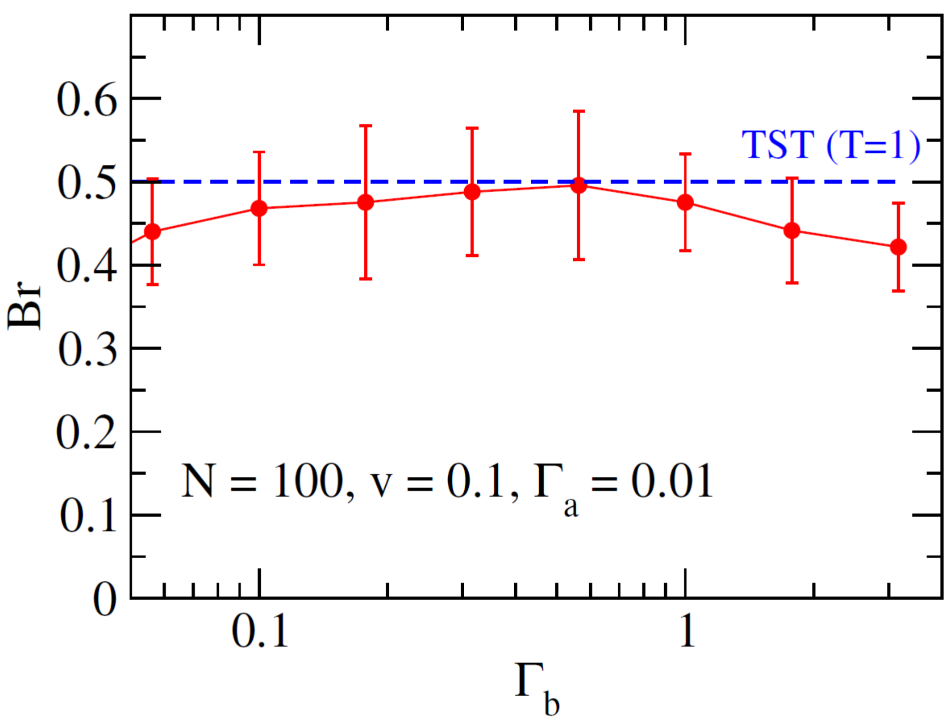
$$\begin{aligned} T_a(E) &= 1 - |R(E)|^2 - |A(E)|^2 + |B(E)|^2 \\ T_b(E) &= |A(E)|^2 - |B(E)|^2 \end{aligned}$$

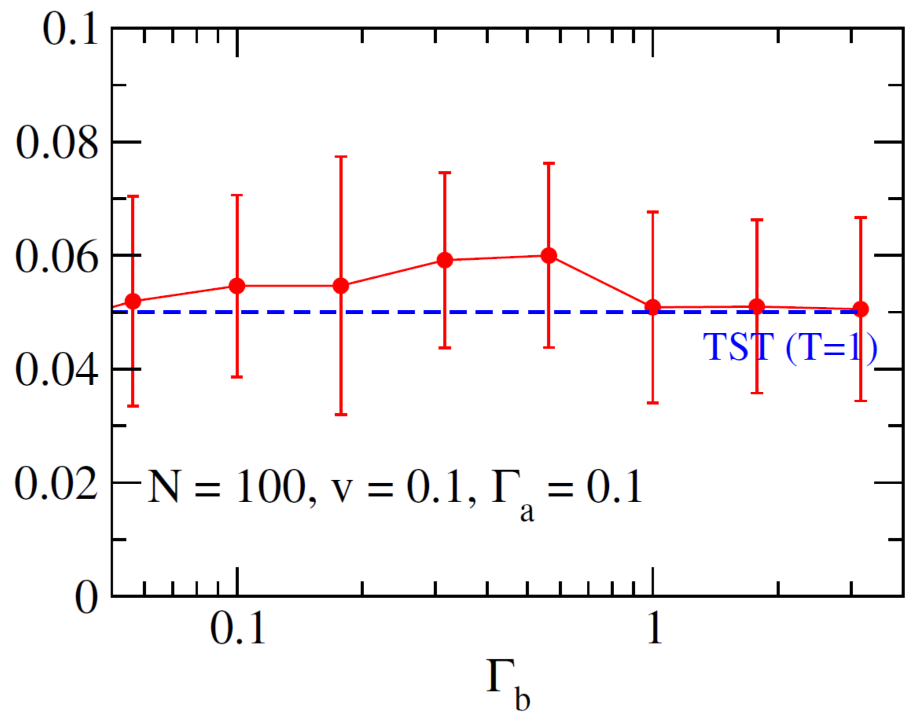
branching ratio: $\boxed{Br = \frac{\int dE\, T_b(E)}{\int dE\, T_a(E)}}$

branching ratios



the average and the variance with 20 ensembles





Branching ratios: **insensitive** to Γ_b $\leftarrow$ the main assumption of the TST

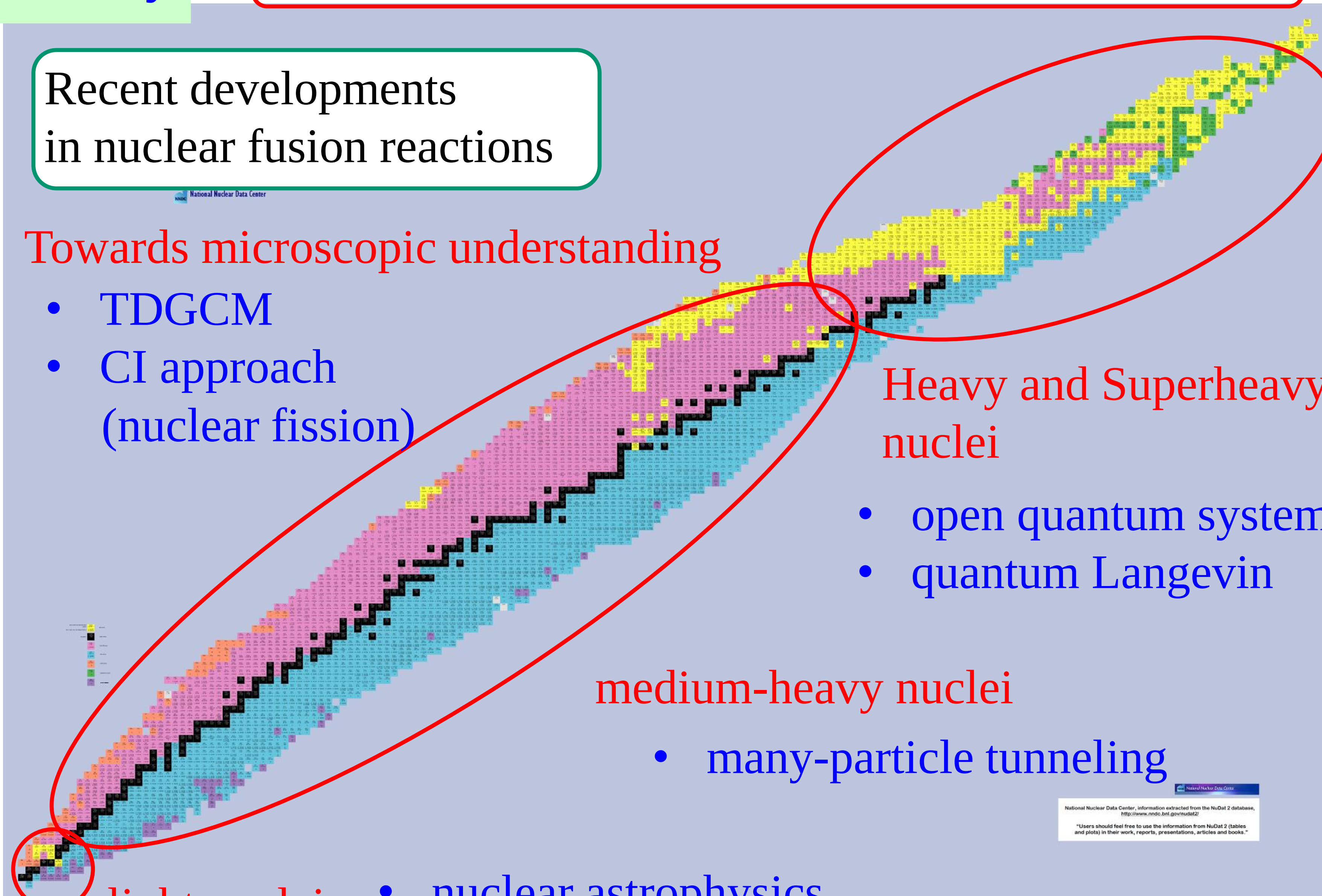
the first realization of TST with a many-body Hamiltonian

G.F. Bertsch and K.H., J. Phys. Soc. Jpn. 90, 11405 (2021)

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