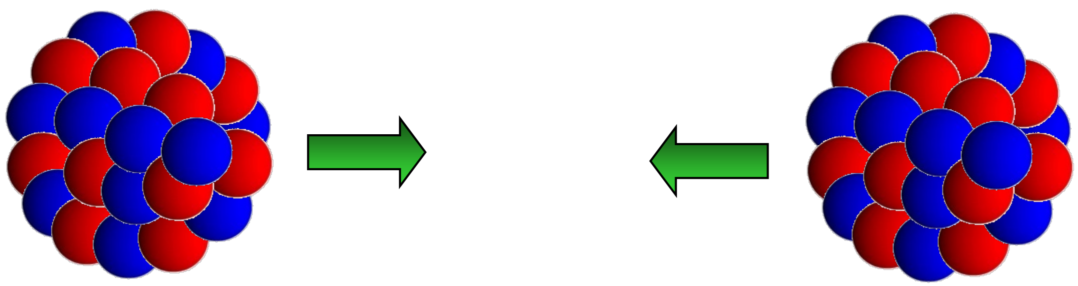
Perspectives on nuclear reaction theory and superheavy elements

Kouichi Hagino

Tohoku University, Sendai, Japan



1. Nuclear Reactions: overview
2. Heavy-ion fusion reactions
3. Fusion for superheavy elements
4. Summary

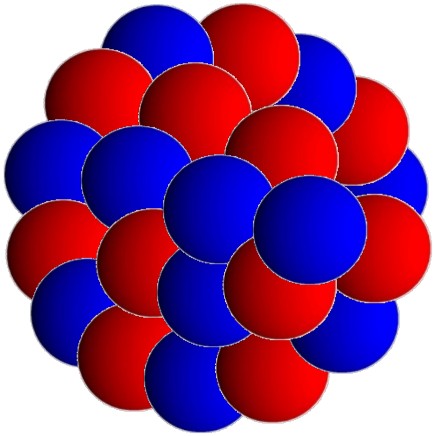
KEK, 2019.7.9

Introduction: low-energy nuclear physics

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

  ⟵ understanding based on strong interaction

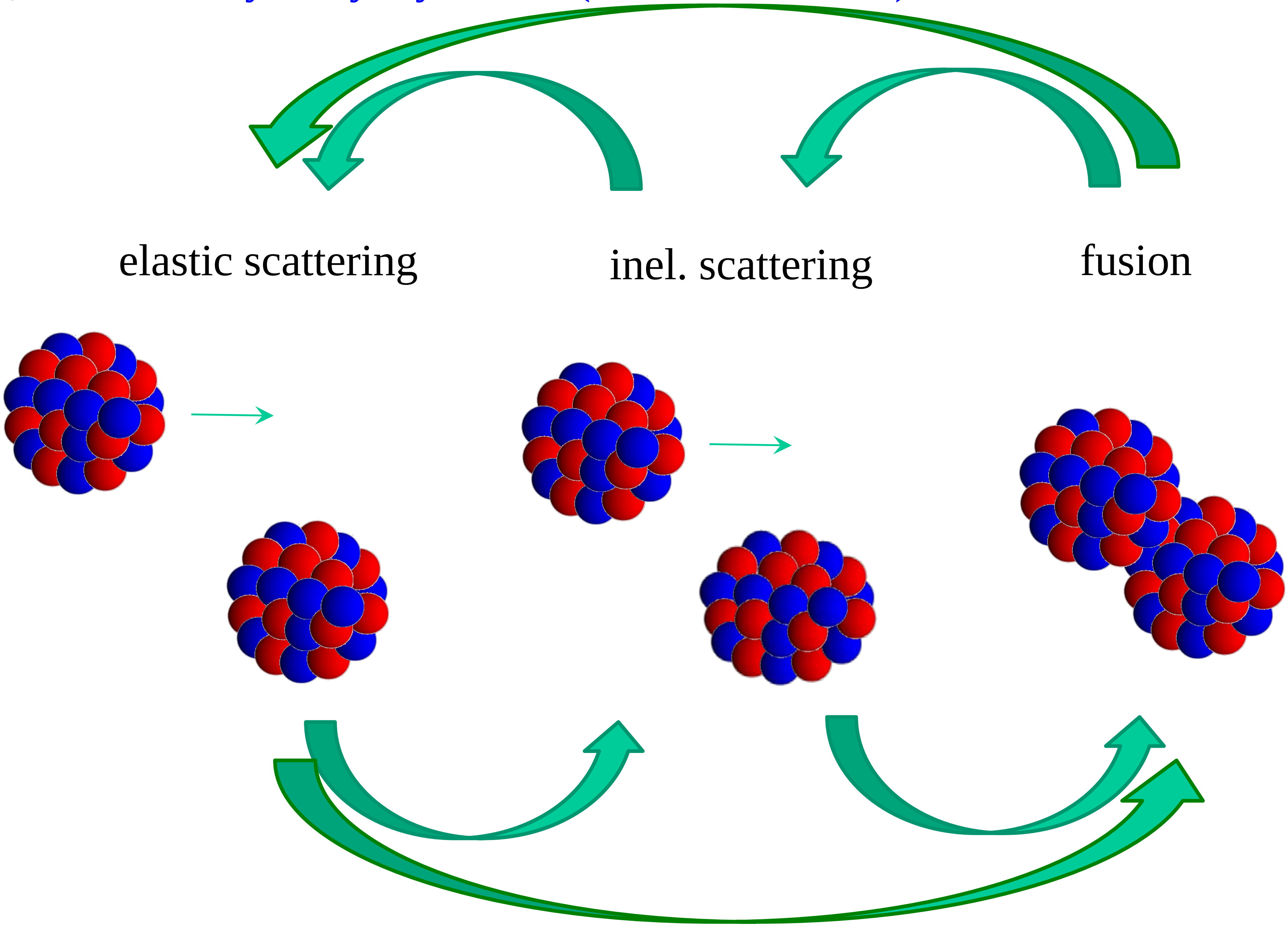
- static properties: nuclear structure
  - ✓ ground state properties
    (mass, size, shape,….)
  - ✓ excitations
  - ✓ nuclear matter



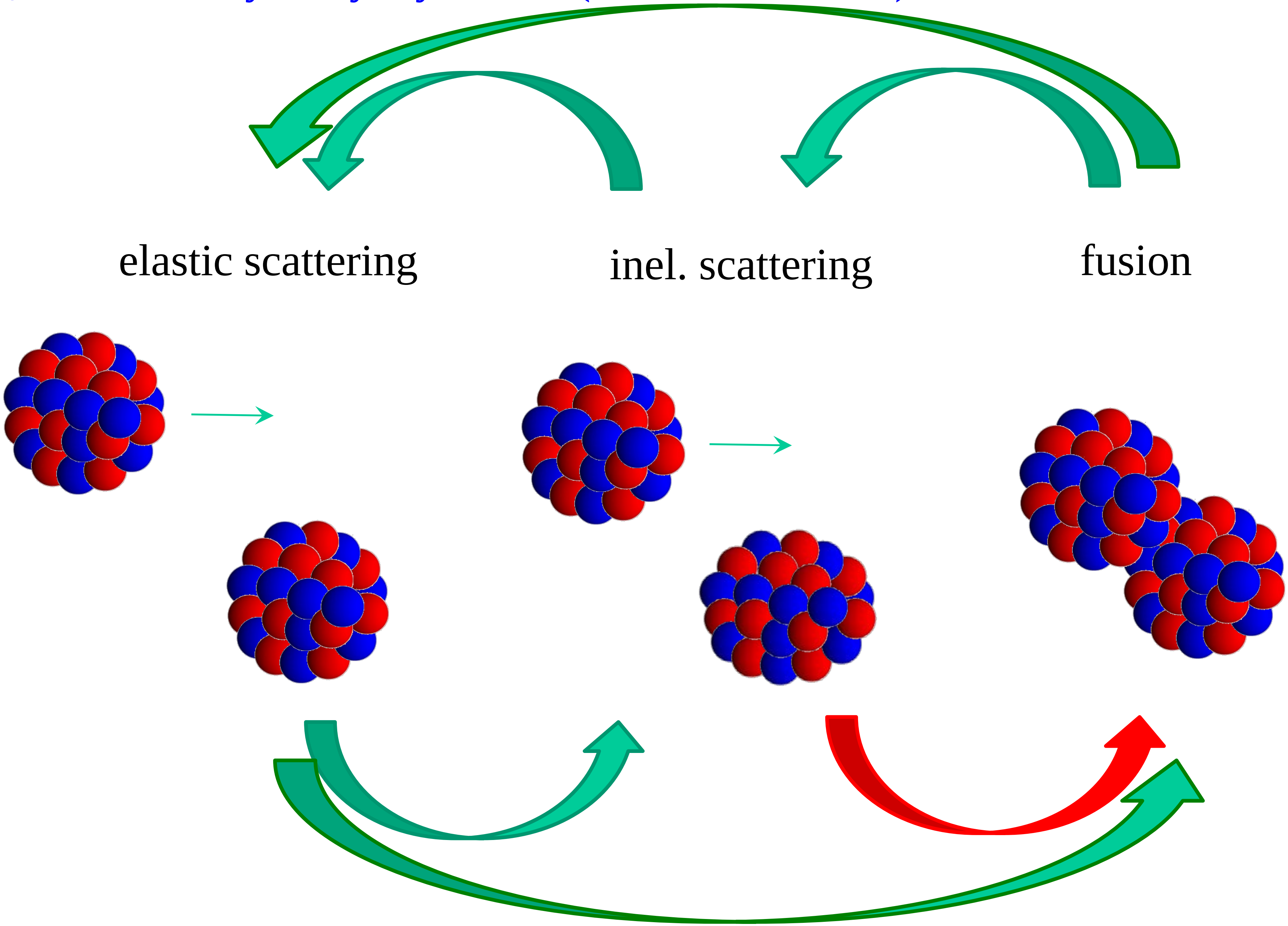
- dynamics: nuclear reactions

an interplay between these

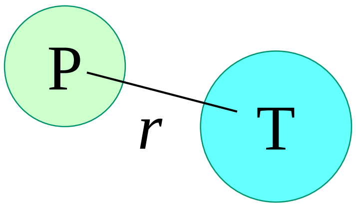
Quantum Many-body Dynamics (nuclear reactions)

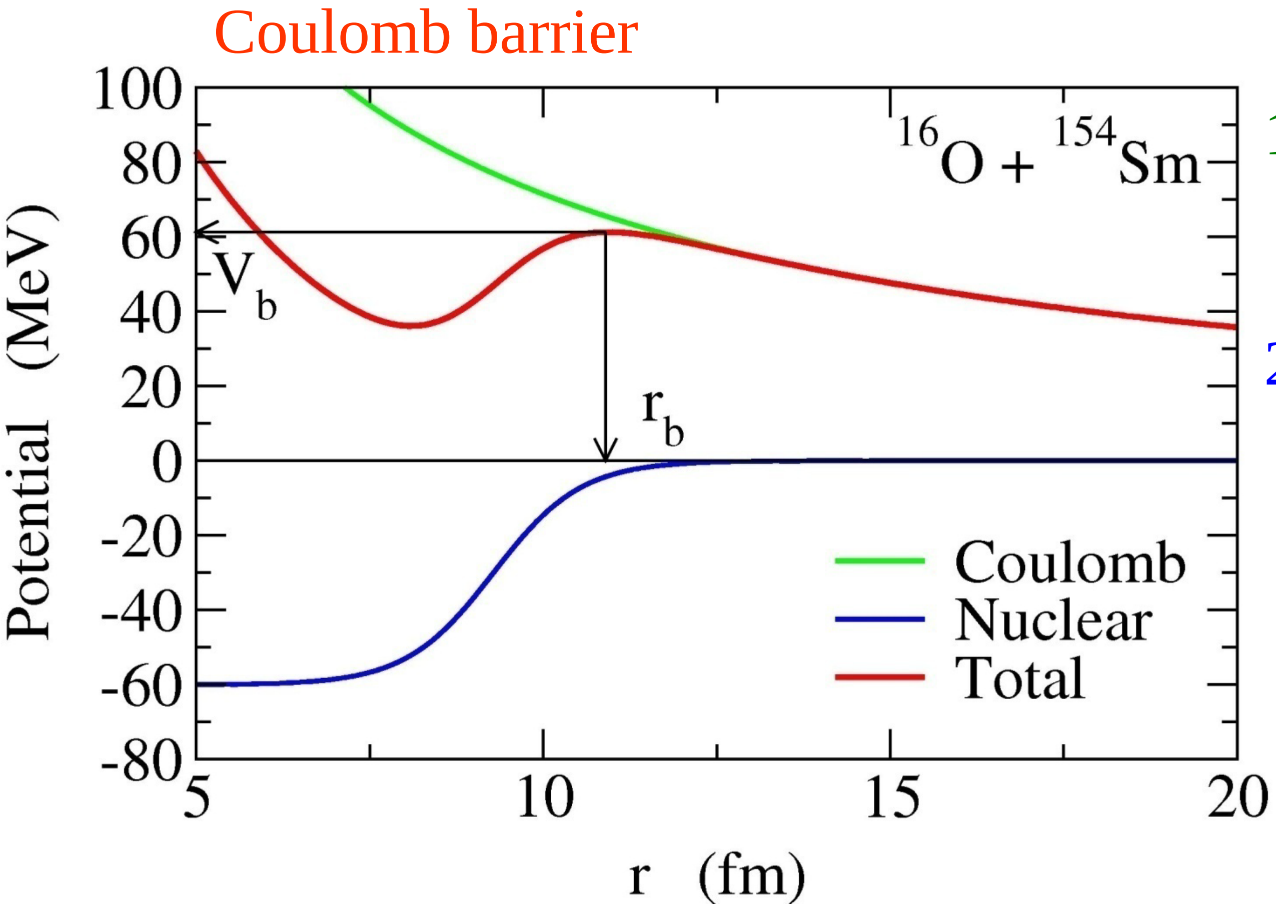


Quantum Many-body Dynamics (nuclear reactions)



Coulomb barrier





1. Coulomb interaction
long range
repulsion

2. Nuclear interaction
short range
attraction

Potential barrier
(Coulomb barrier)

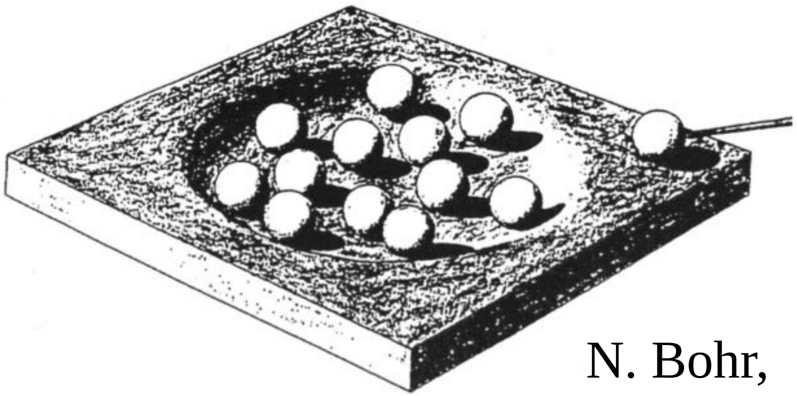
the barrier height → defines the energy scale of a system

Fusion reactions at energies around the Coulomb barrier

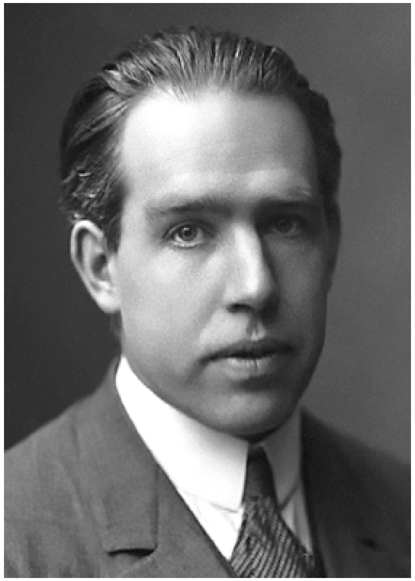
Fusion reactions: compound nucleus formation

Niels Bohr (1936)

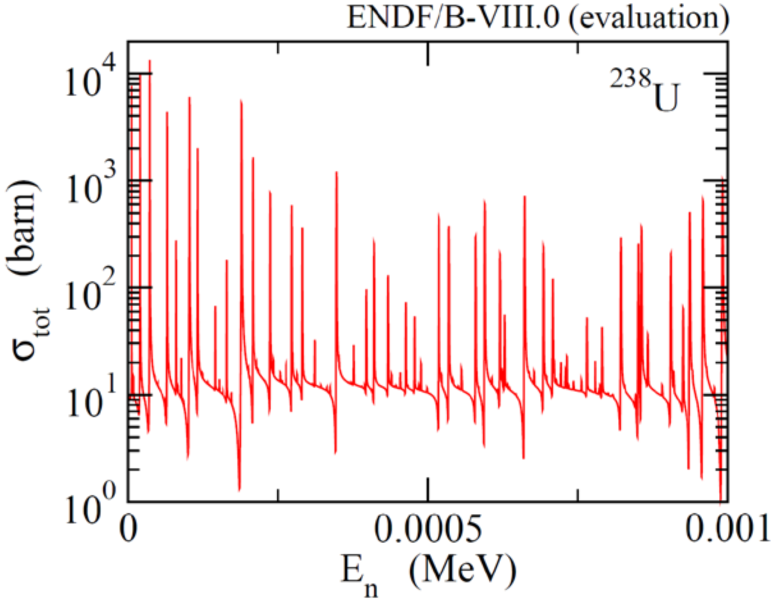
Neutron capture of nuclei → compound nucleus



N. Bohr,
Nature 137 ('36) 351



Wikipedia

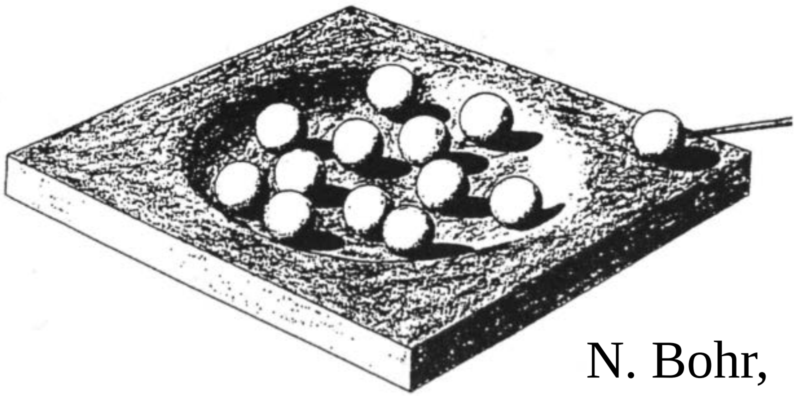


cf. Experiment of Enrico Fermi (1935)
many very narrow (=long life-time) resonances (width ~ eV)

Fusion reactions: compound nucleus formation

Niels Bohr (1936)

Neutron capture of nuclei → compound nucleus



N. Bohr,
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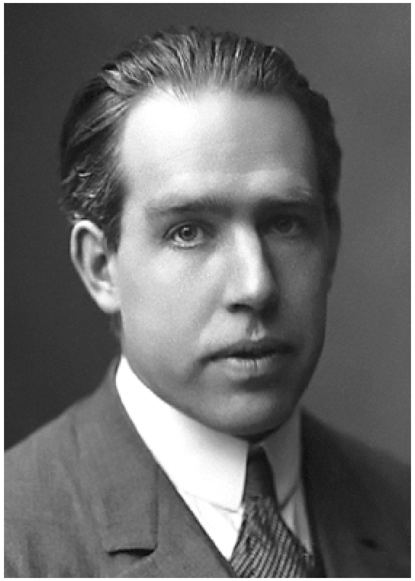
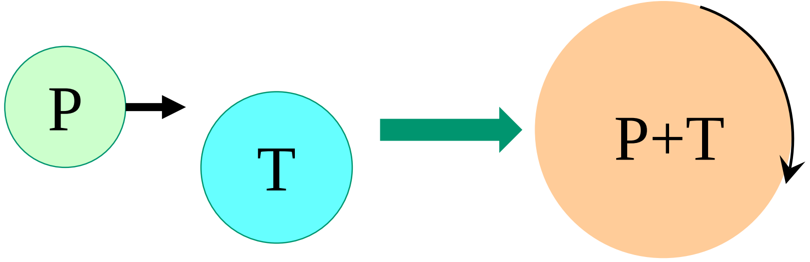


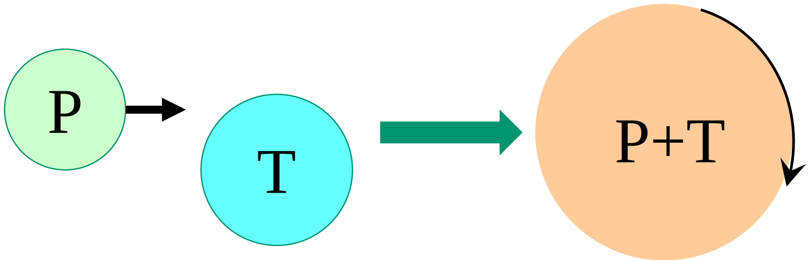
Wikipedia

forming a compound nucleus with heavy-ion reactions = H.I. fusion

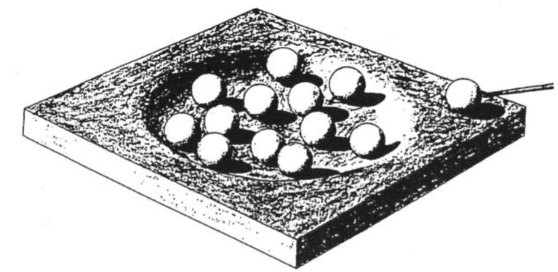


compound nucleus

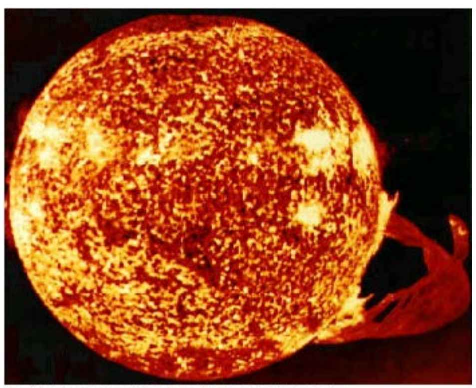
Fusion reactions: compound nucleus formation



compound
nucleus

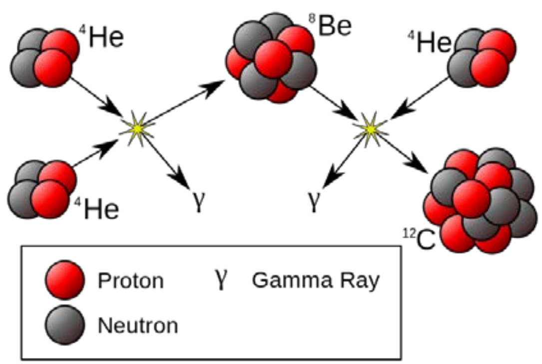


cf. Bohr '36

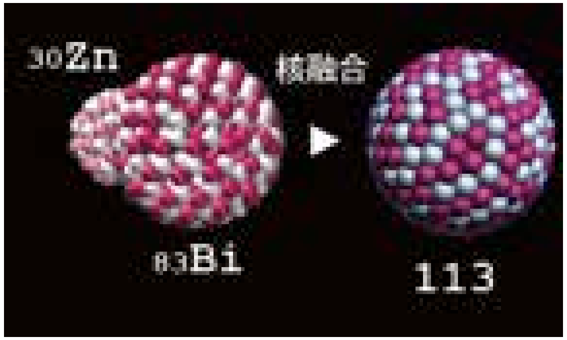


NASA, Skylab space station December 19, 1973, solar flare reaching 588 000 km off solar surface

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

Low-energy heavy-ion fusion reactions and quantum tunneling

✓Reaction dynamics

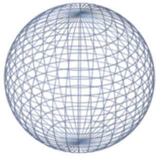
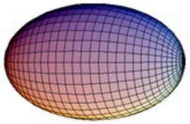
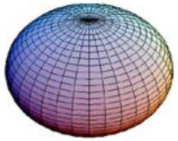
strong interplay between reaction and structure

cf. high E reactions: much simpler reaction mechanisms

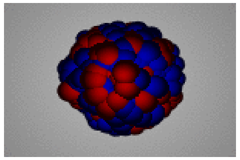
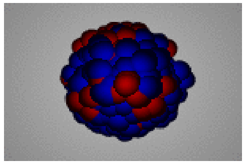
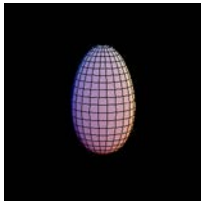
✓ Many-particle tunneling

cf. ▪rich intrinsic motions

- several nuclear shapes

- several surface vibrations

several modes
and adiabaticities

Low-energy heavy-ion fusion reactions and quantum tunneling

✓Reaction dynamics

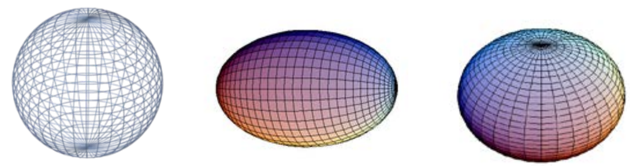
strong interplay between reaction and structure

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

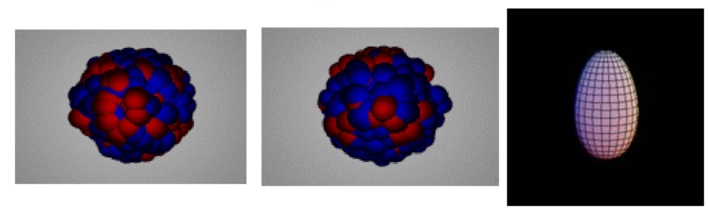
✓ Many-particle tunneling

cf. ▪rich intrinsic motions

- several nuclear shapes



- several surface vibrations



- several types of nucleon transfers

“environment” can be changed relatively freely

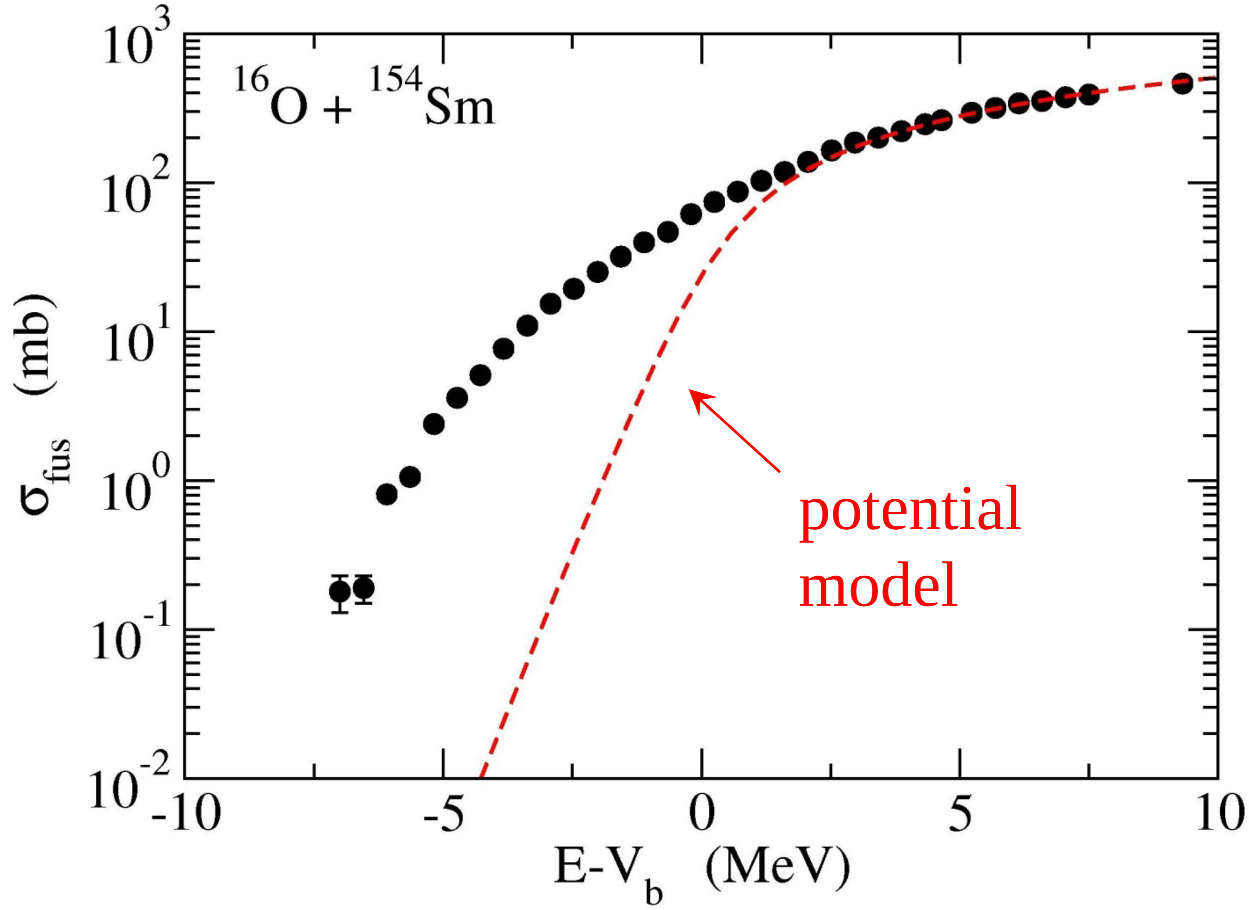
▪*E*: variable cf. α decays: fixed energy

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

Discovery of large sub-barrier enhancement of σ_{fus} (~80's)

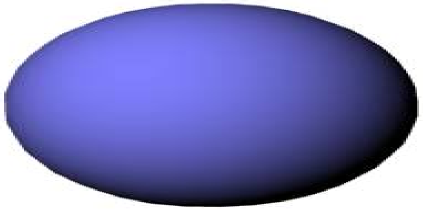
potential model: inert nuclei (no structure)

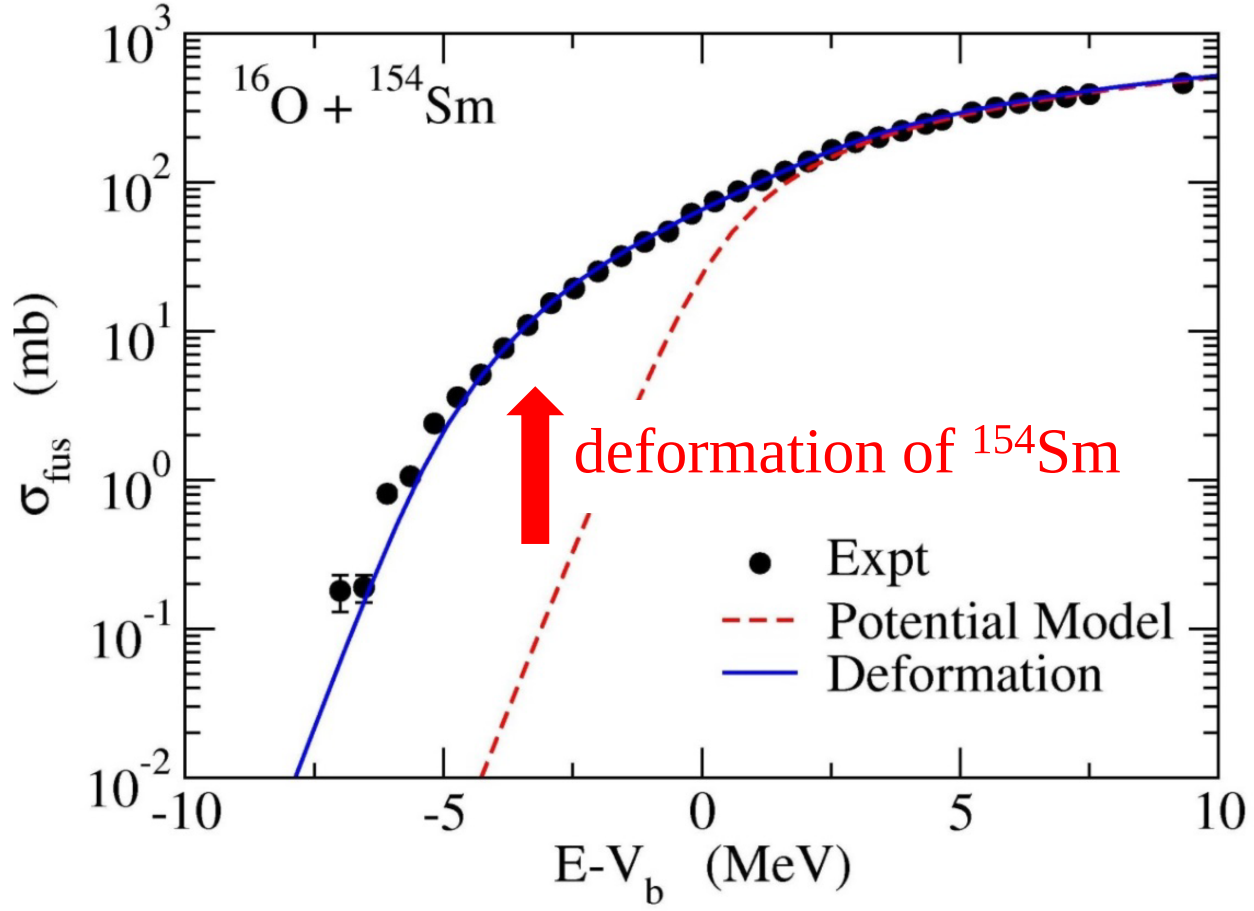
$$\sigma_{\rm fus} = \frac{\pi}{k^2}\sum_l (2l+1)(1-|S_l|^2)$$



Discovery of large sub-barrier enhancement of σ_{fus} (~80's)

^{154}Sm : a typical deformed nucleus

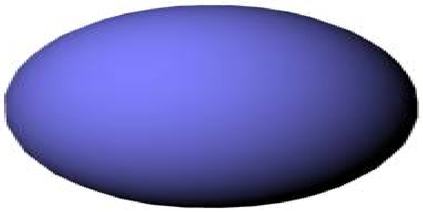


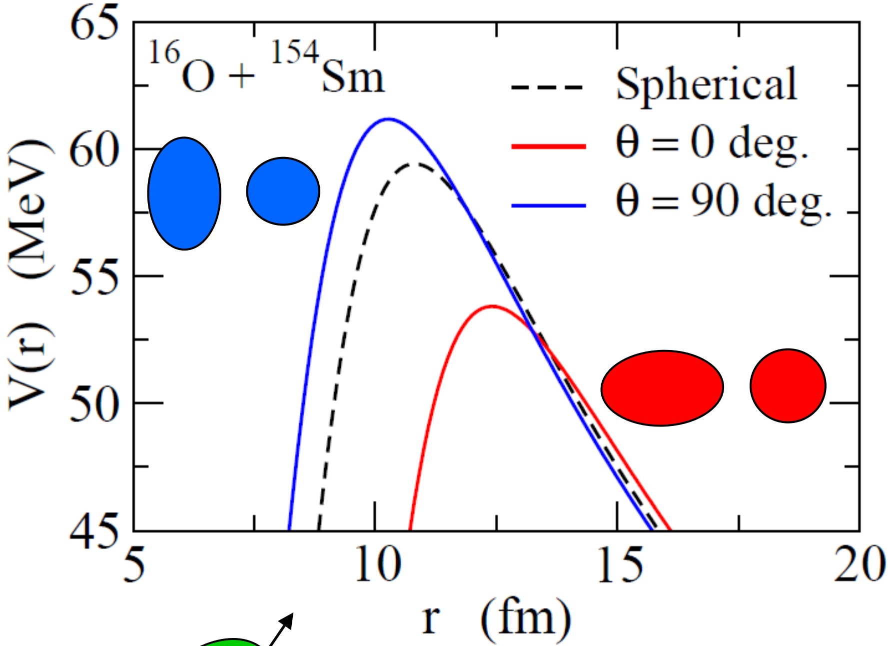


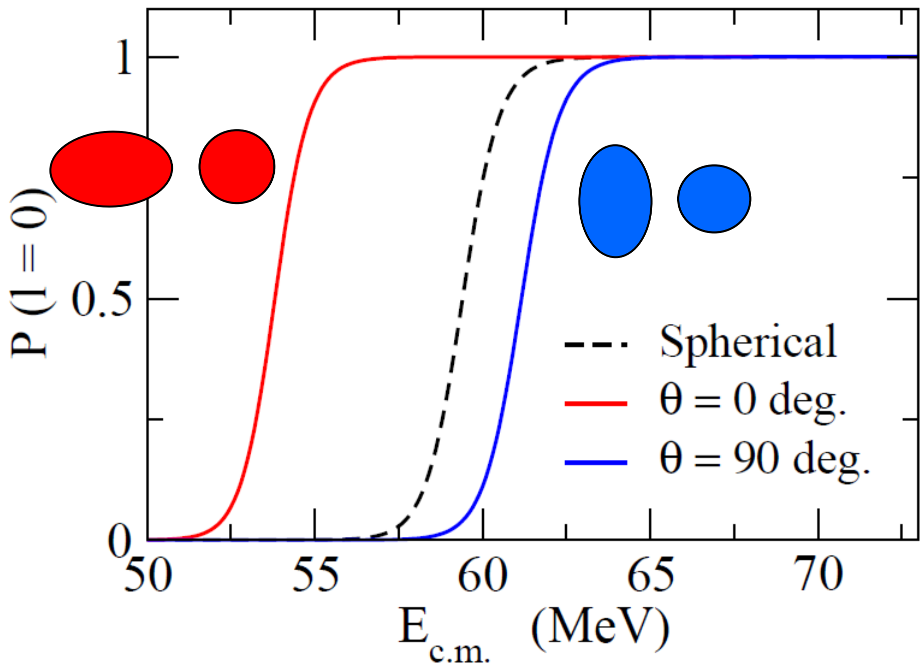
K. H. and N. Takigawa, Prog. Theo. Phys.128 ('12)1061.

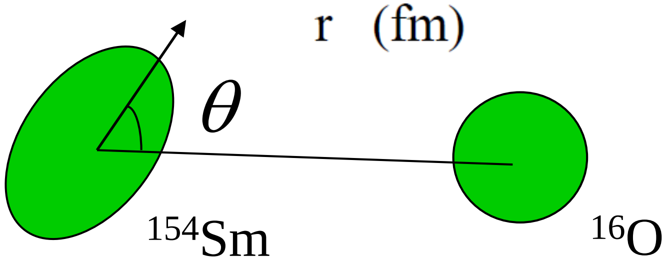
Effects of nuclear deformation

^{154}Sm : a typical deformed nucleus









Effects of nuclear deformation

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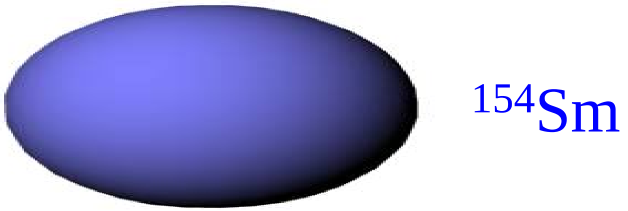
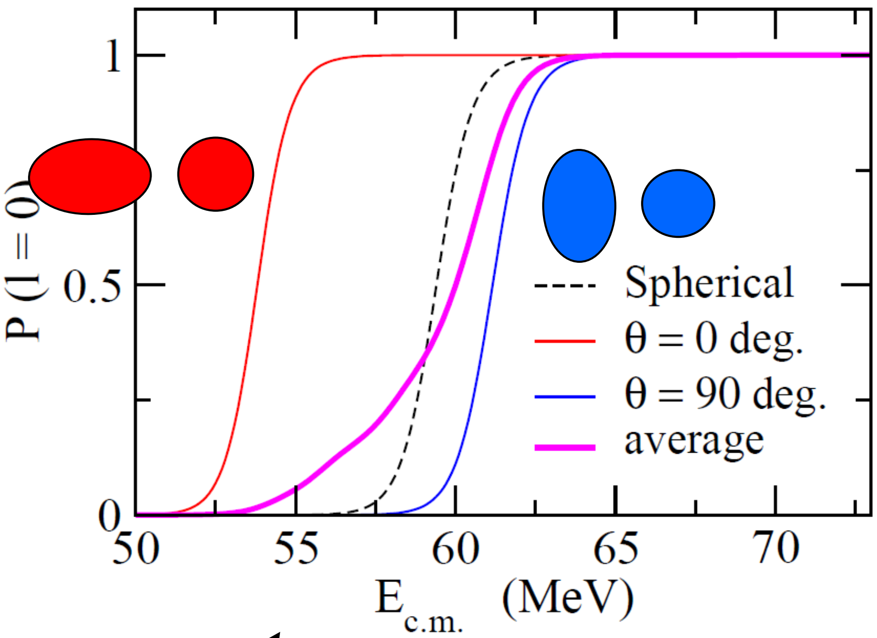
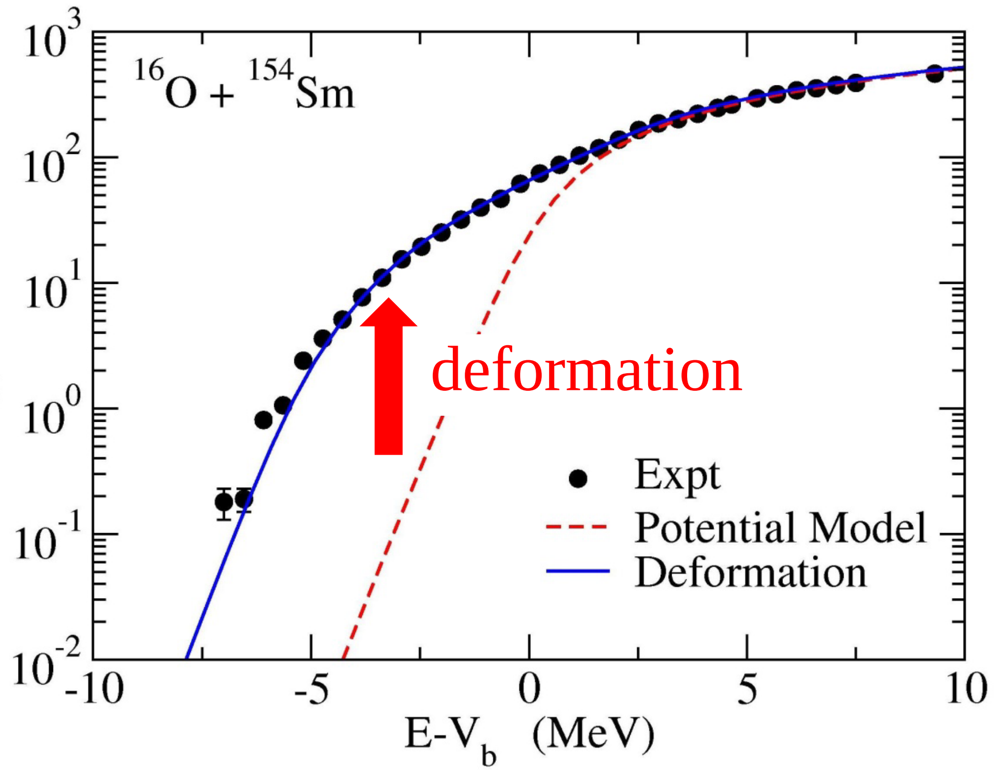
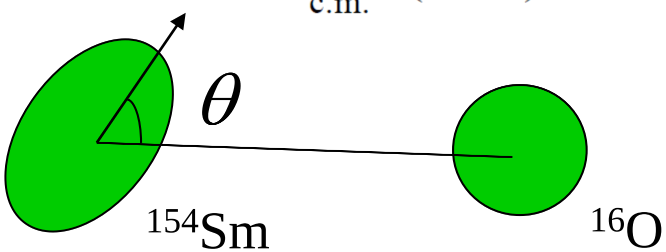


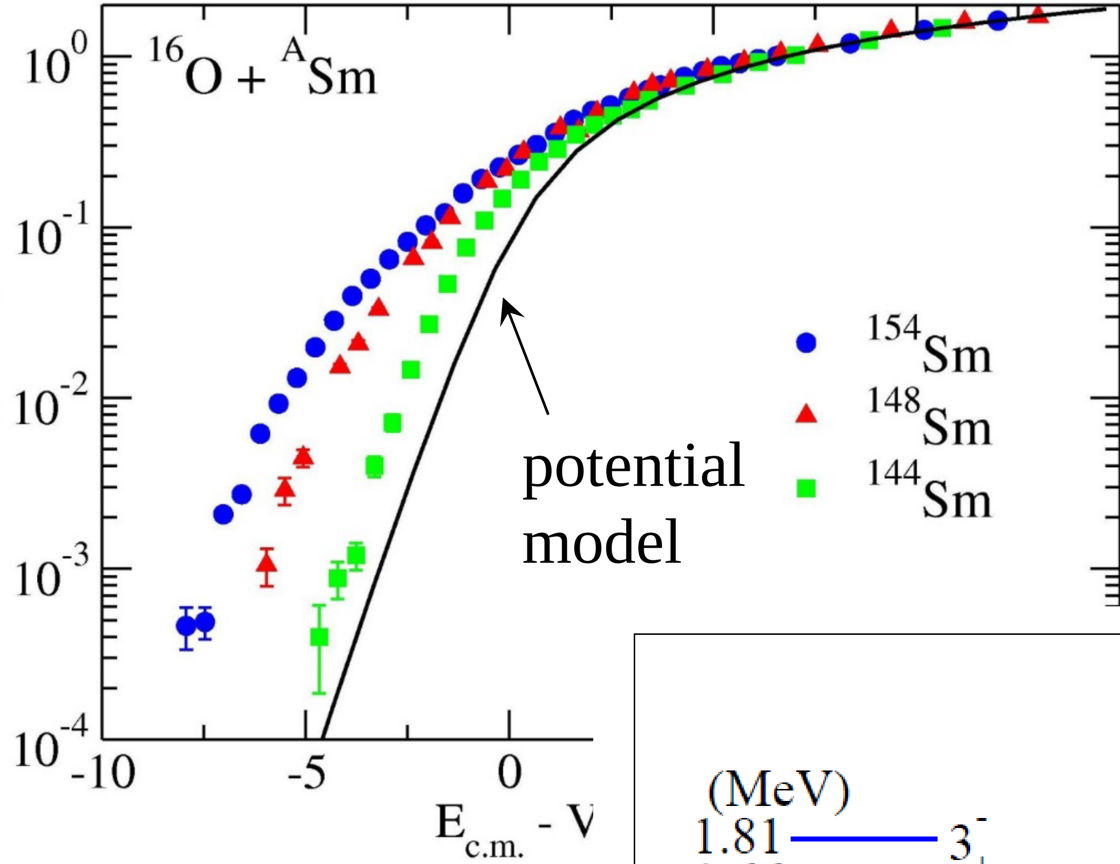




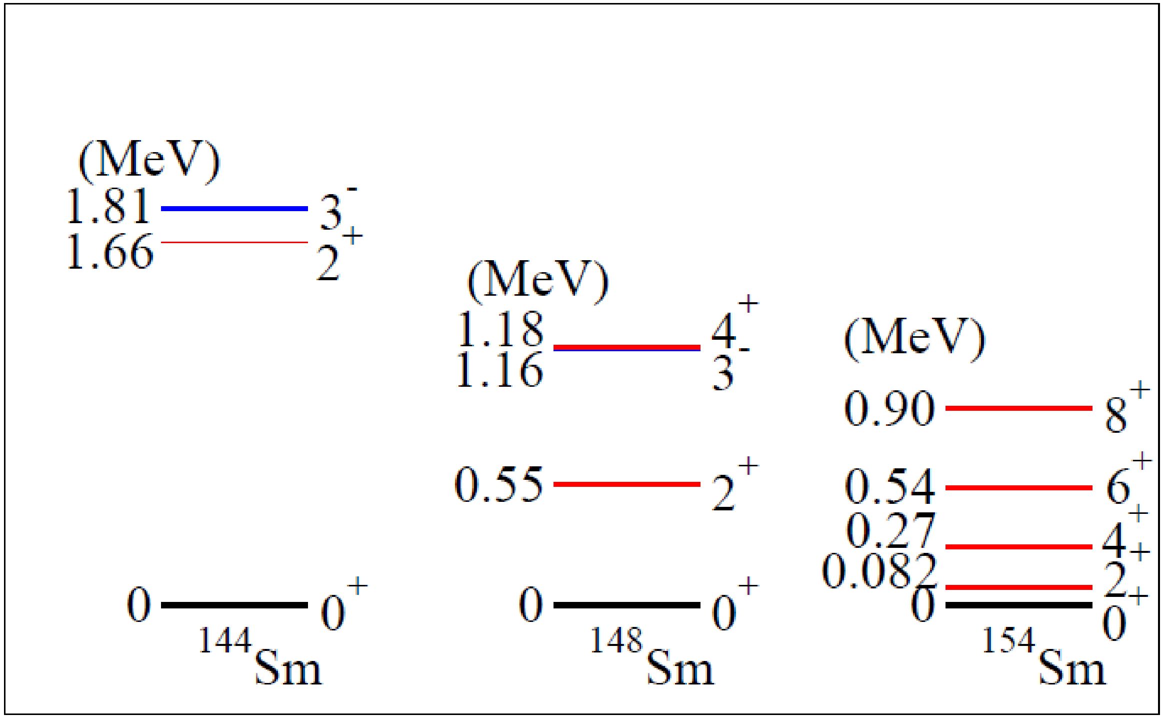


$$\sigma_{\mathrm{fus}}(E) = \int_0^1 d(\cos\theta)\,\sigma_{\mathrm{fus}}(E;\theta)$$

Fusion: strong interplay between nuclear structure and reaction



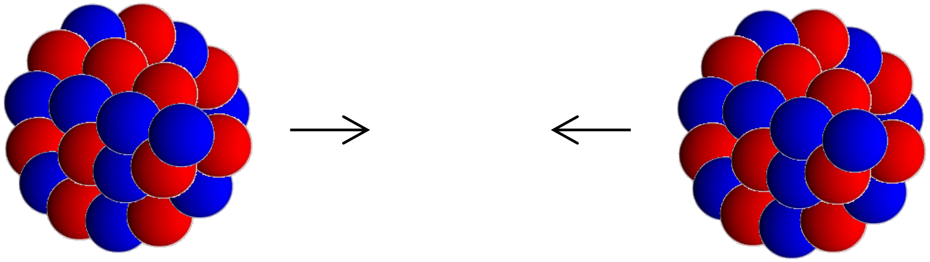
enhancement of fusion cross sections
: a general phenomenon



strong correlation with nuclear spectrum
→ coupling assisted tunneling

Coupled-channels method: a quantal scattering theory with excitations

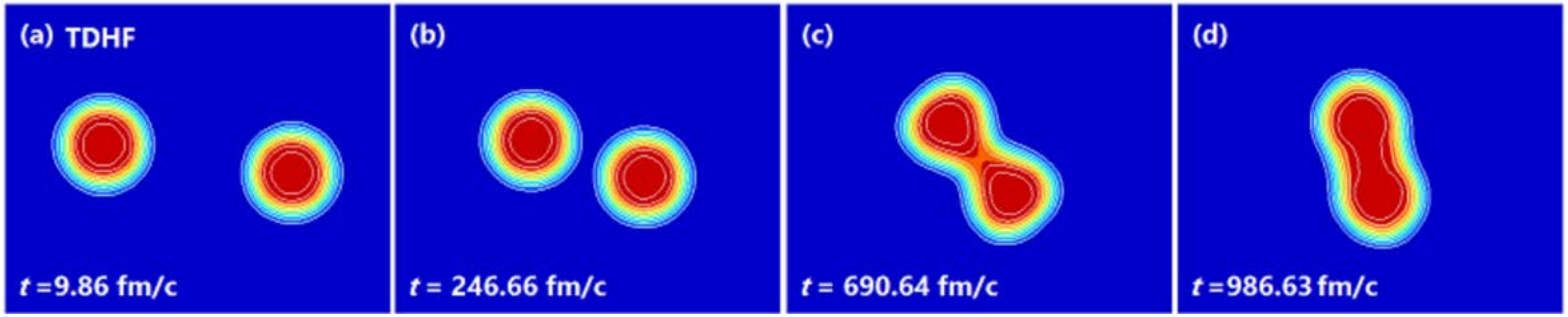
many-body problem



still very challenging

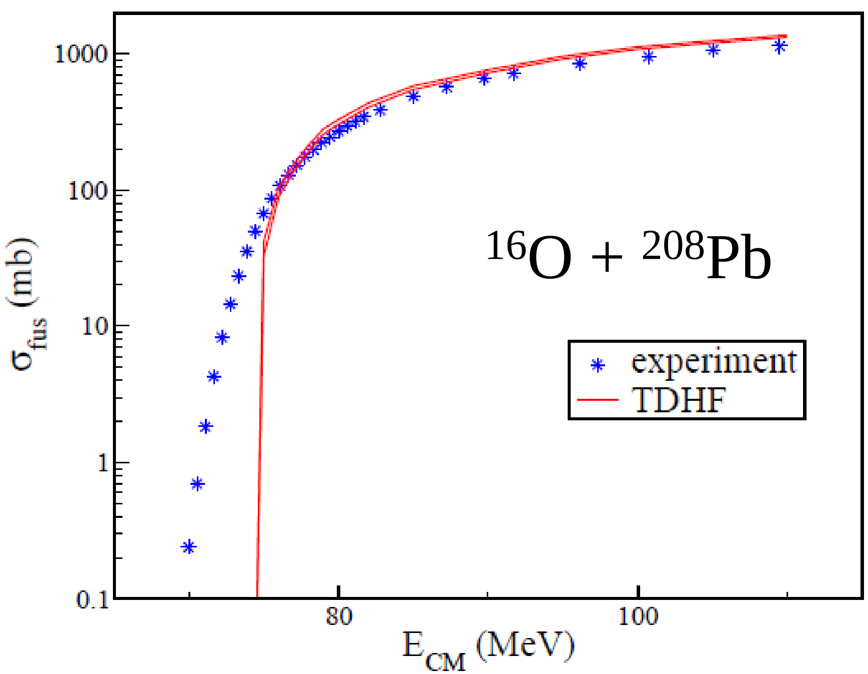
TDHF simulation

TDHF = Time Dependent Hartree-Fock
(a single Slater determinant)



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

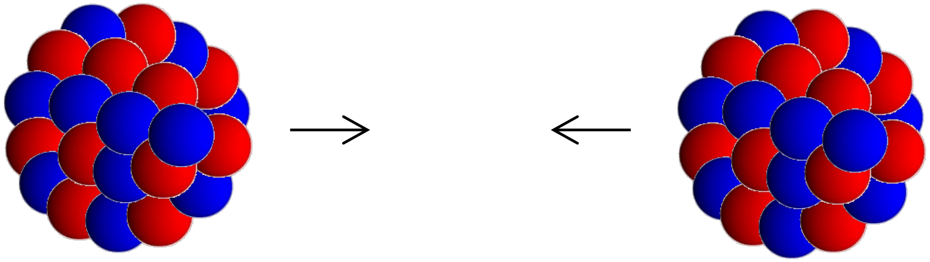
ab-initio, but no tunneling



C. Simenel,
EPJA48 (’12) 152

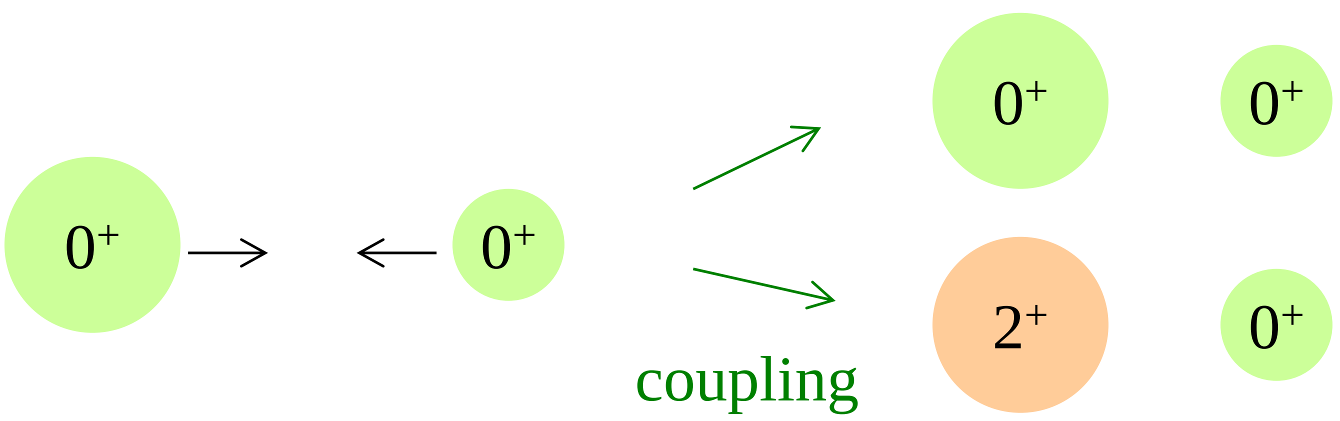
Coupled-channels method: a quantal scattering theory with excitations

many-body problem



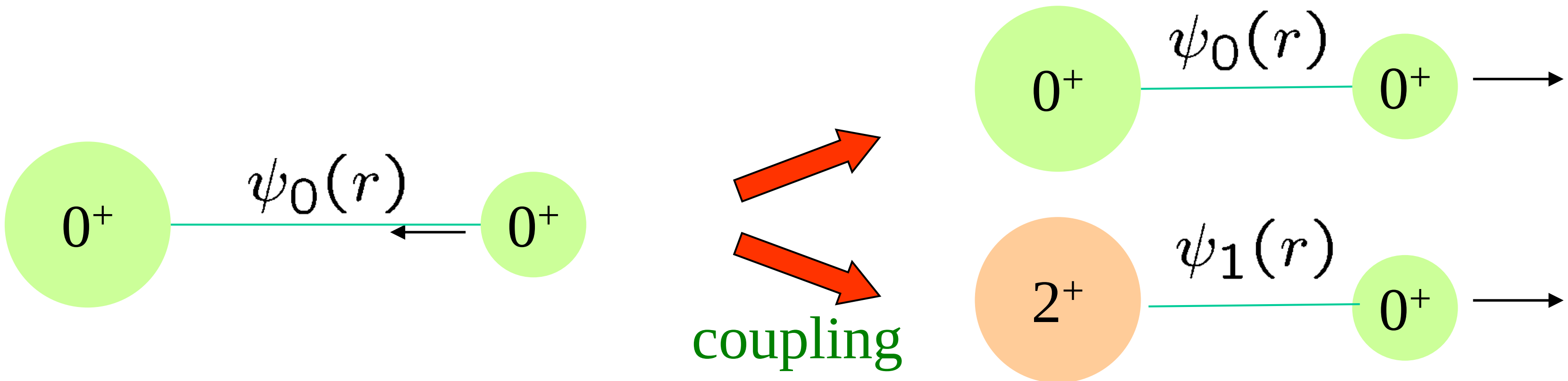
still very challenging

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

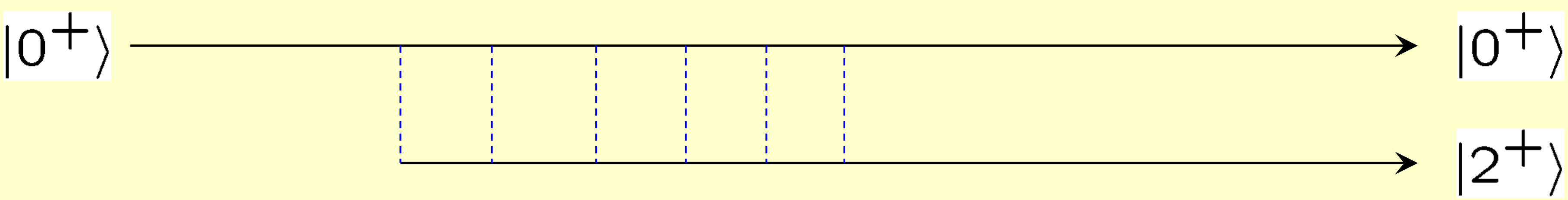


scattering theory with excitations

Coupled-channels method: a quantal scattering theory with excitations



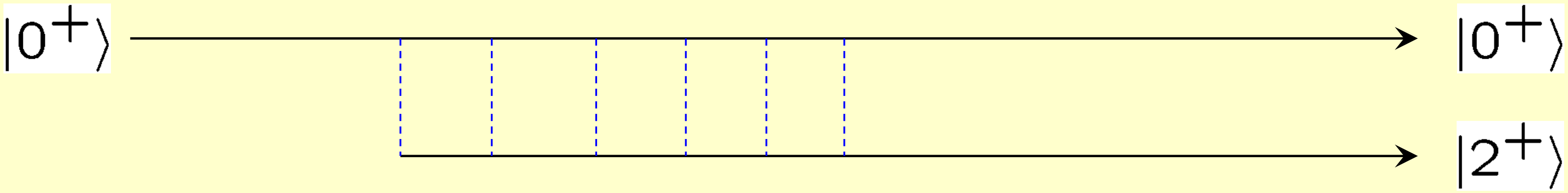
$$\left[-\frac{\hbar^2}{2\mu}\nabla^2+\overleftrightarrow{V}(r)-\overleftrightarrow{E}\right]\vec{\psi}(r)=0$$



dynamics of excitations/de-excitations during reaction

- ✓ Non-perturbative (full order)
- ✓ Non-adiabatic (excitation energy)

Coupled-channels method : a quantal scattering theory with excitations



dynamics of excitations/de-excitations during reaction

- ✓ Non-perturbative (full order)
- ✓ Non-adiabatic (excitation energy)

in the past, the linear coupling approximation in a Hamiltonian :

$$H = -\frac{\hbar^2}{2\mu}\nabla^2 + V_0(r) + \beta f(r)\hat{O}$$

full order treatment

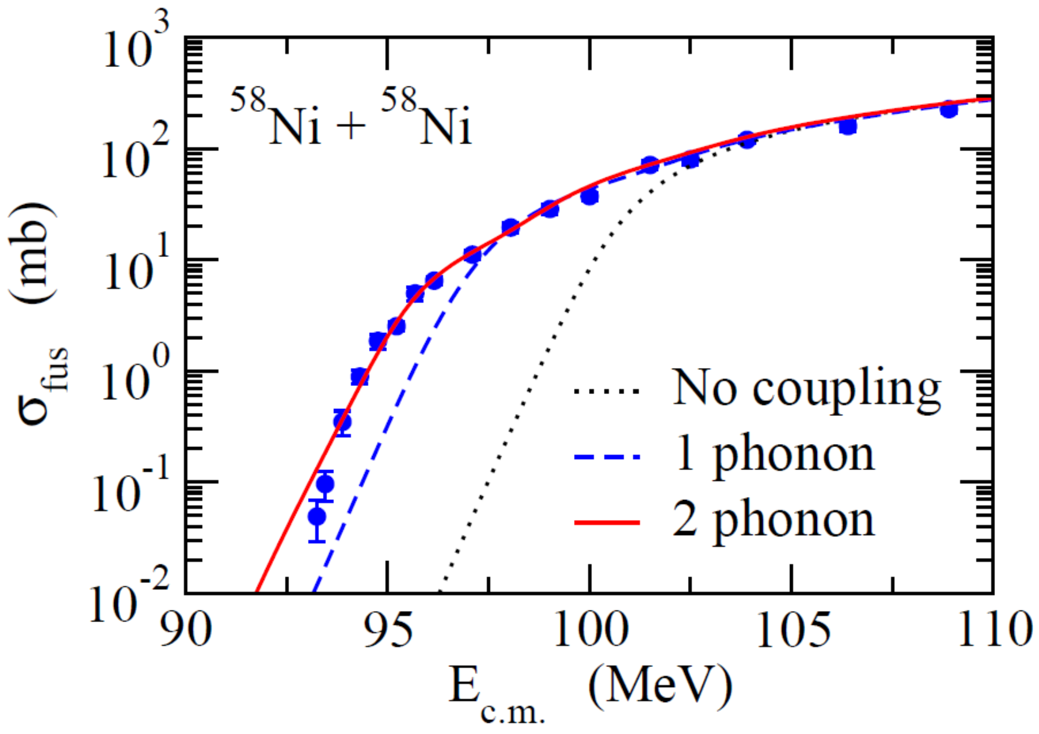
$$V(r, \beta\hat{O})$$

K.H., N. Rowley, and A.T. Kruppa,
Comp. Phys. Comm. 123('99) 143.

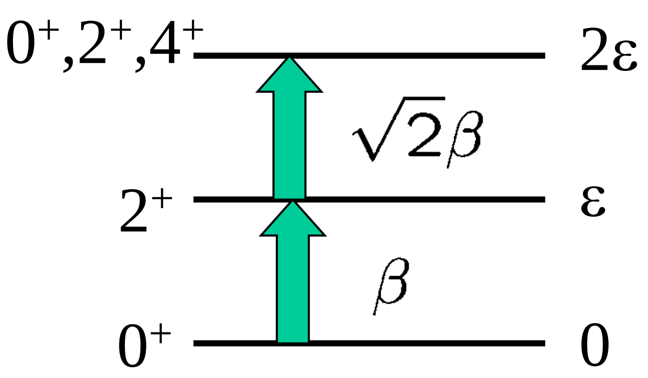
a standard method

modellings of coupled-channels calculations

- K.H., N. Rowley, A.T. Kruppa, CPC123 (‘99) 143
- M. Zamrun, K.H., S. Mitsuoka, H. Ikezoe, PRC77 (’08) 034604
- T. Ichikawa, K.H., A. Iwamoto, PRL103 (‘09) 202701
- S. Yusa, K.H., and N. Rowley, PRC88 (‘13) 044620
- J.M. Yao and K.H., PRC94 (‘16) 11303(R)   etc.



harmonic oscillations

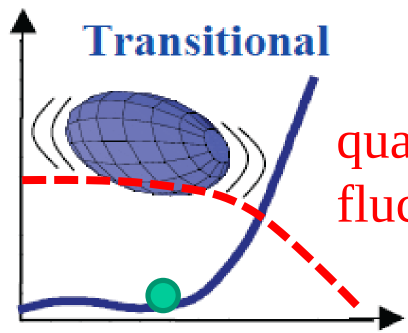


review：K. Hagino and N. Takigawa, Prog. Theo. Phys.128 (‘12)1061.

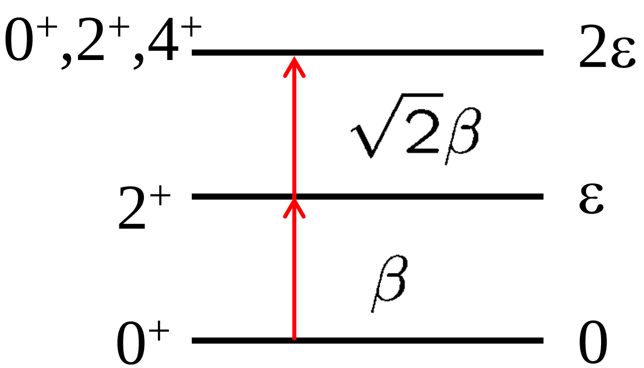
Further development: semi-microscopic modelling

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

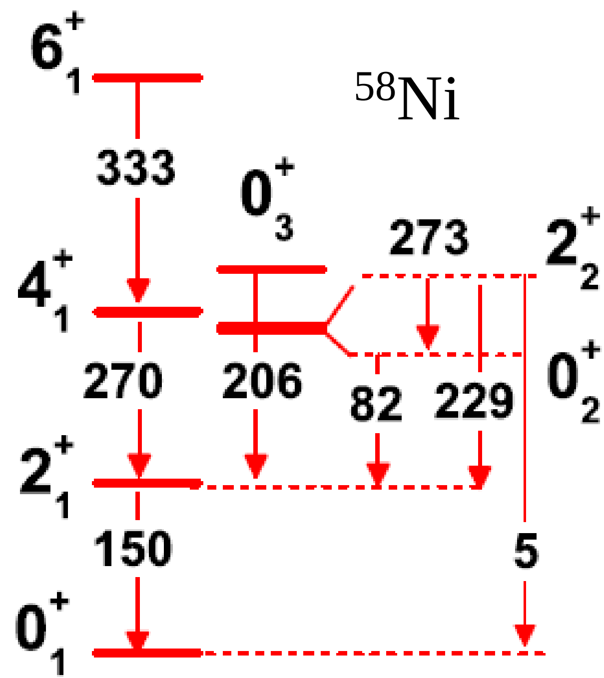
Coupled-channels
+ microscopic nuclear structure calculations
(GCM, Shell Model, IBM…..)



simple harmonic oscillator

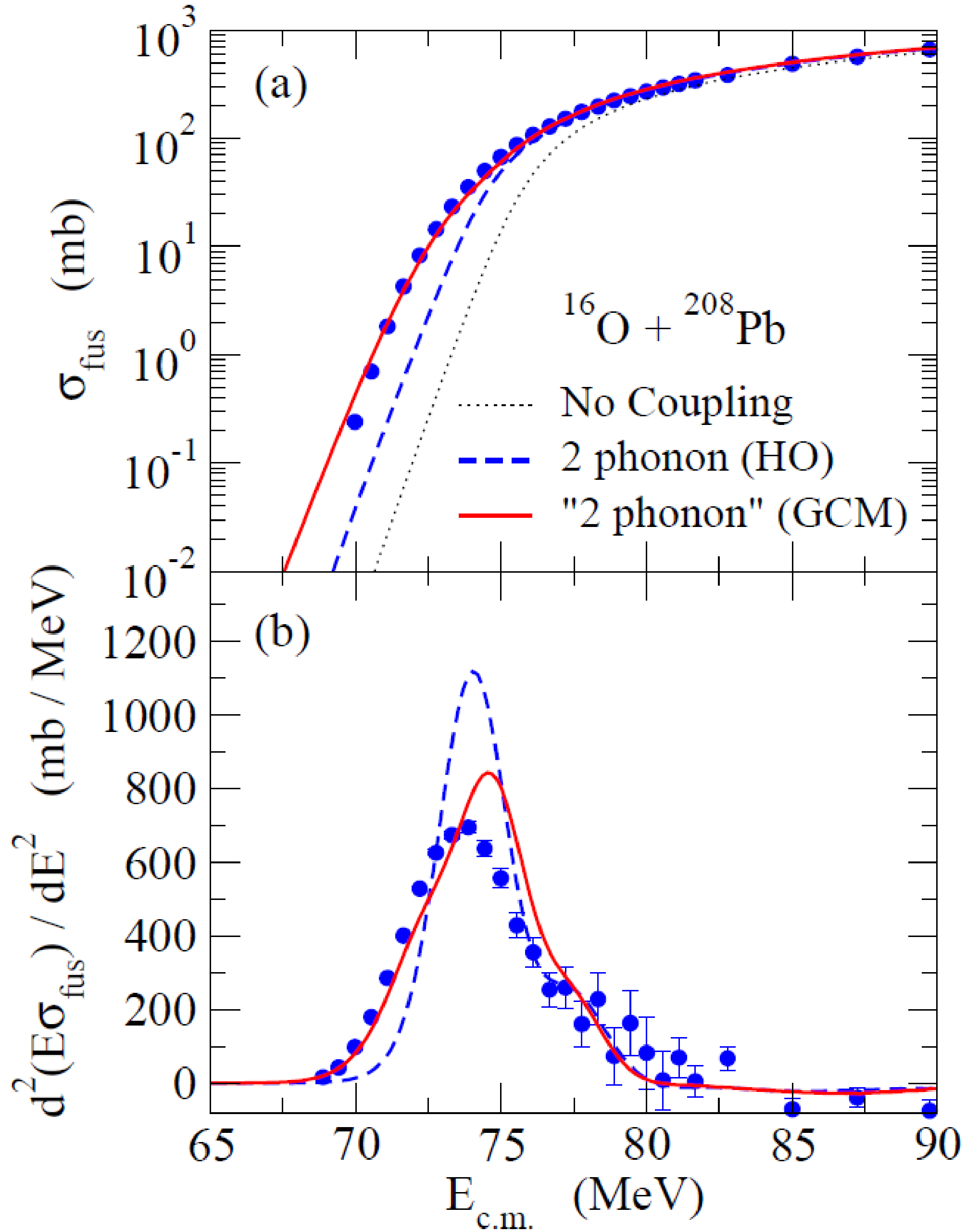


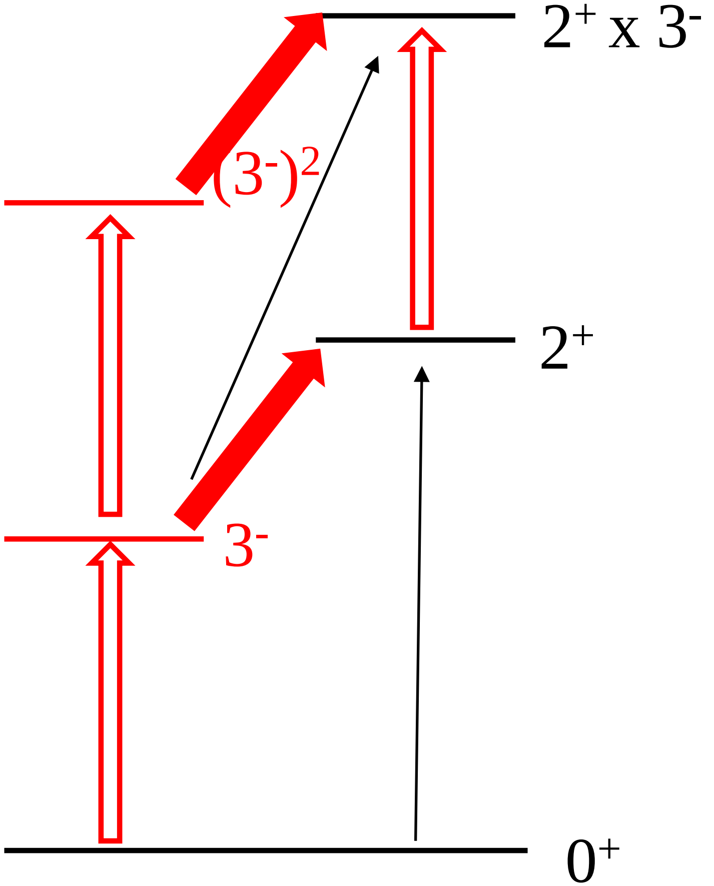
anharmonicity in phonon spectra



relativistic MF + GCM

Relativistic Mean-Field + Quantum fluctuation + coupled-channels





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

From phenomenological approach to microscopic approach

Macroscopic (phenomenological)

C.C. with collective model

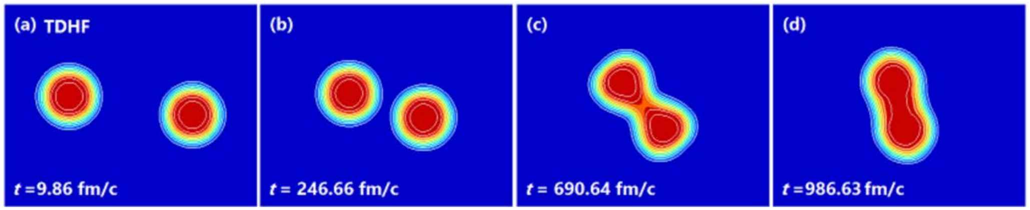
C.C. with inputs from microscopic nuclear structure calculations

C.C. with inputs based on TDHF

TDHF simulations

Microscopic

TDHF = Time Dependent Hartree-Fock



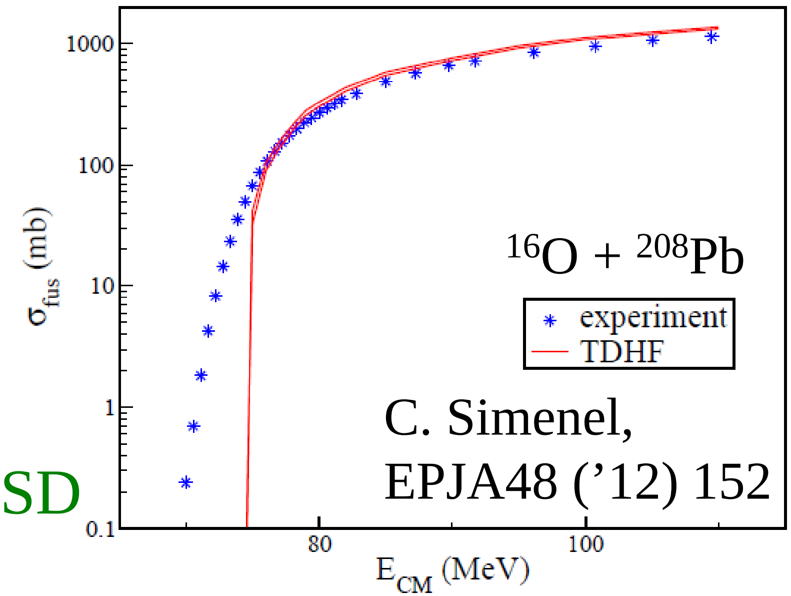
S. Ebata, T. Nakatsukasa, JPC Conf. Proc. 6 ('15)

ab initio, but no tunneling

From phenomenological approach to microscopic approach

TDHF simulations

ab initio, but no tunneling

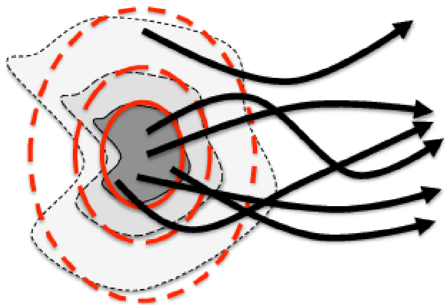


- "Beyond mean-field" approximations

✓ Time-dependent GCM?

a single Slater determinant (SD) to multi-SD

$$|\Psi(t)\rangle = \int dq\, f(q,t)|\Phi_q(t)\rangle$$

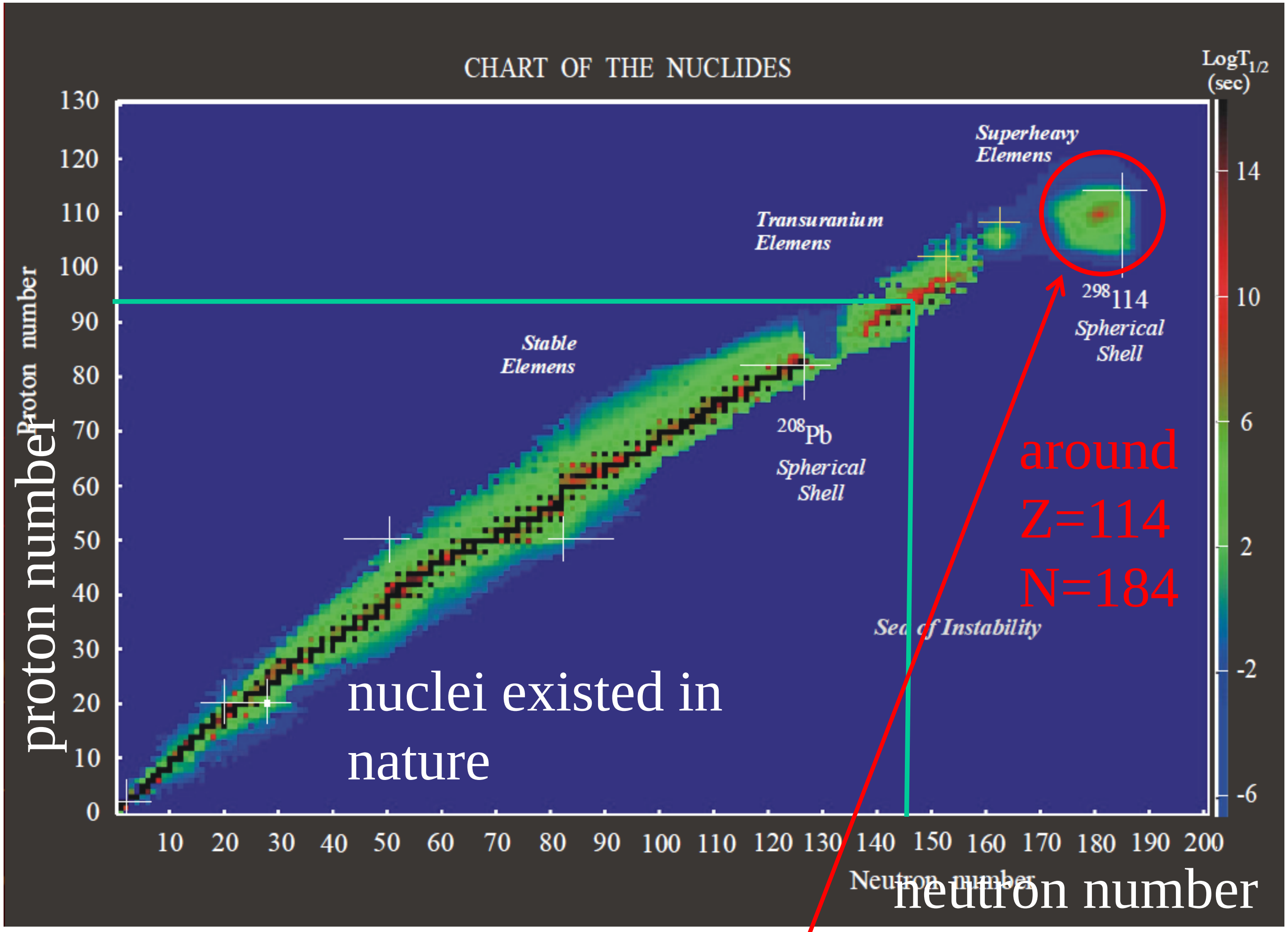


dynamics with a superposition of many "TDHF trajectories (Slater determinants)"

cf. Stochastic mean-field method
B. Yilmaz et al.,
PRC90 ('14) 054617

an open problem
K.H., N. Hasegawa, and Y. Tanimura,
a work in progress

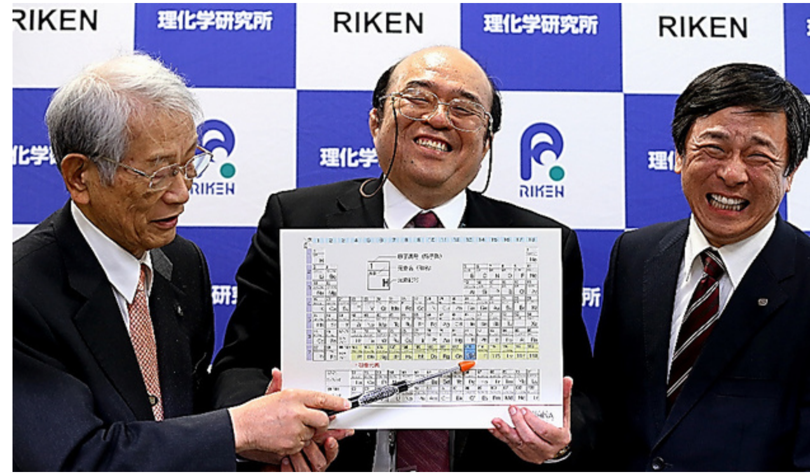
Future perspectives: fusion for superheavy elements



Yuri Oganessian

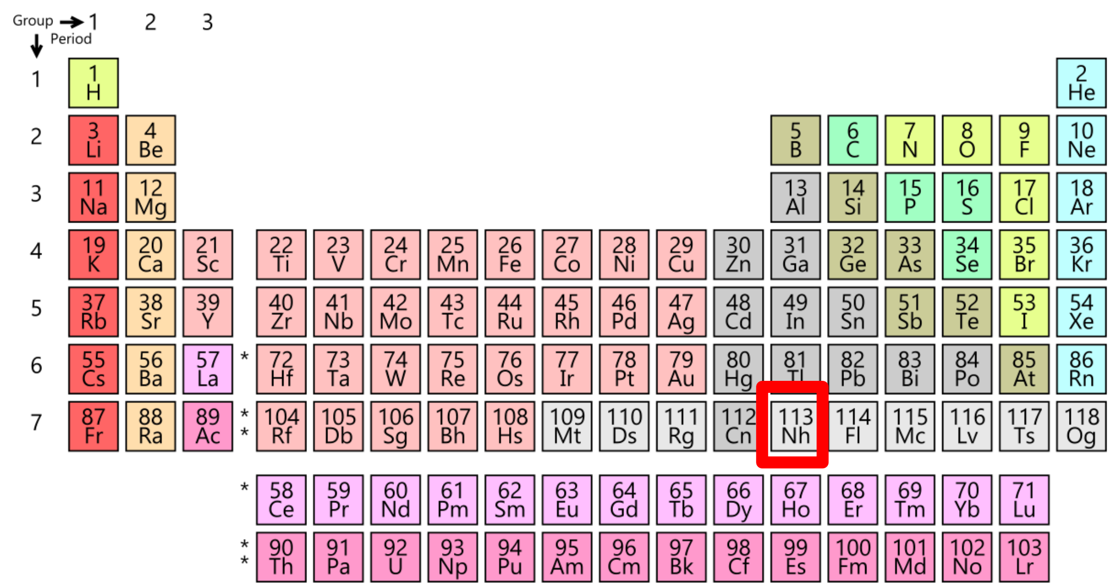
a prediction of island of stability
(Swiatecki et al., 1966)

Fusion reactions for SHE



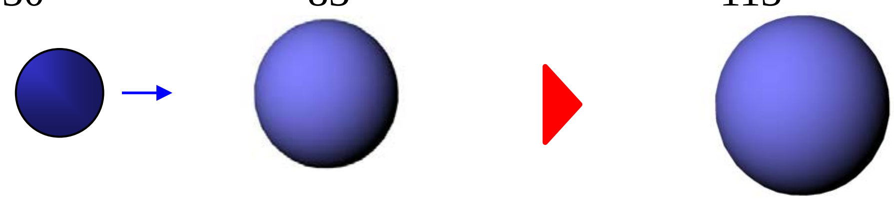
the element 113: Nh

November, 2016



Wikipedia

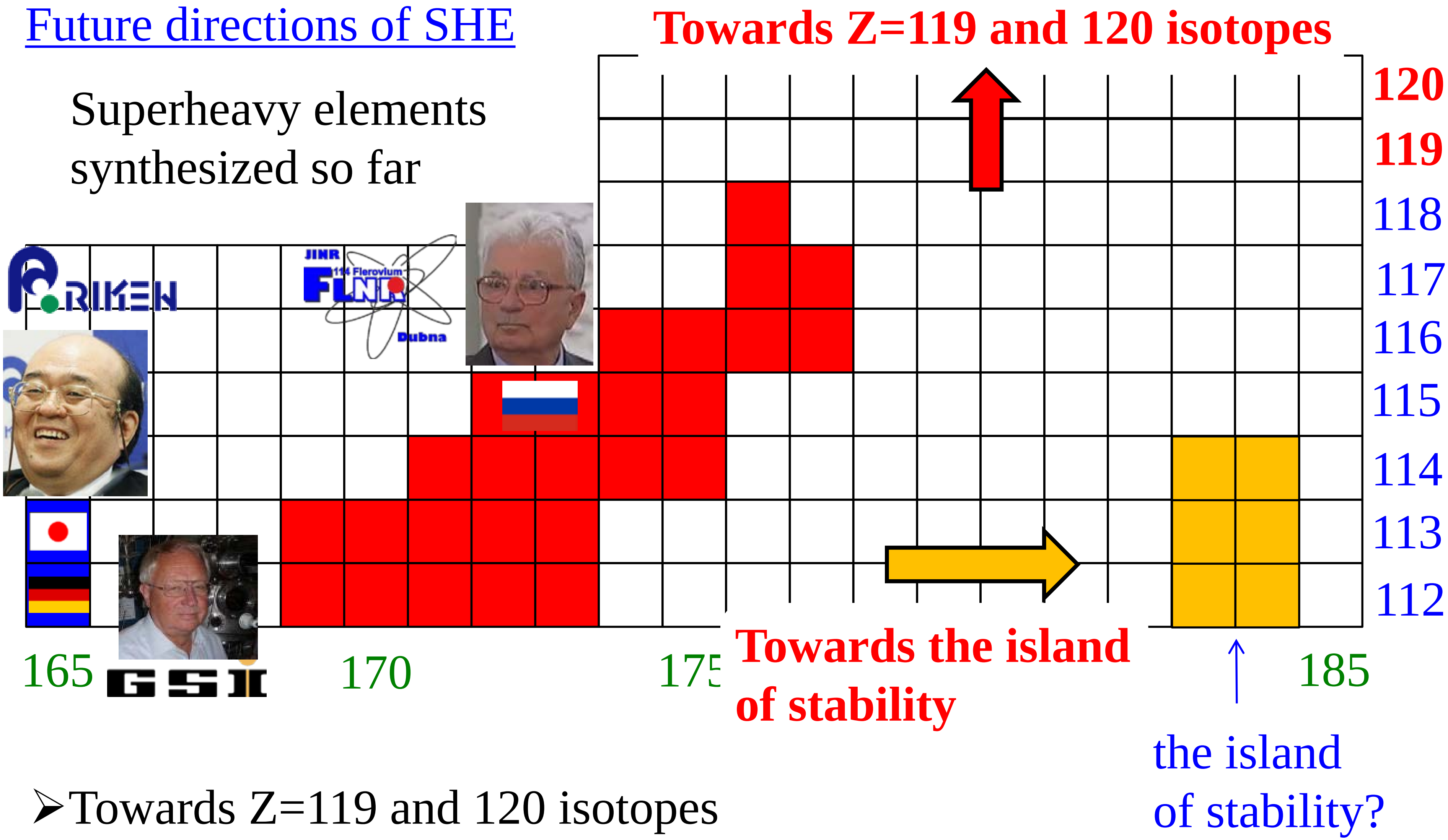
$^{70}_{30}Zn$ $^{209}_{83}Bi$ $^{279}_{113}Nh^*$



Heavy-ion fusion reaction

Future directions of SHE

Superheavy elements synthesized so far



➢Towards Z=119 and 120 isotopes

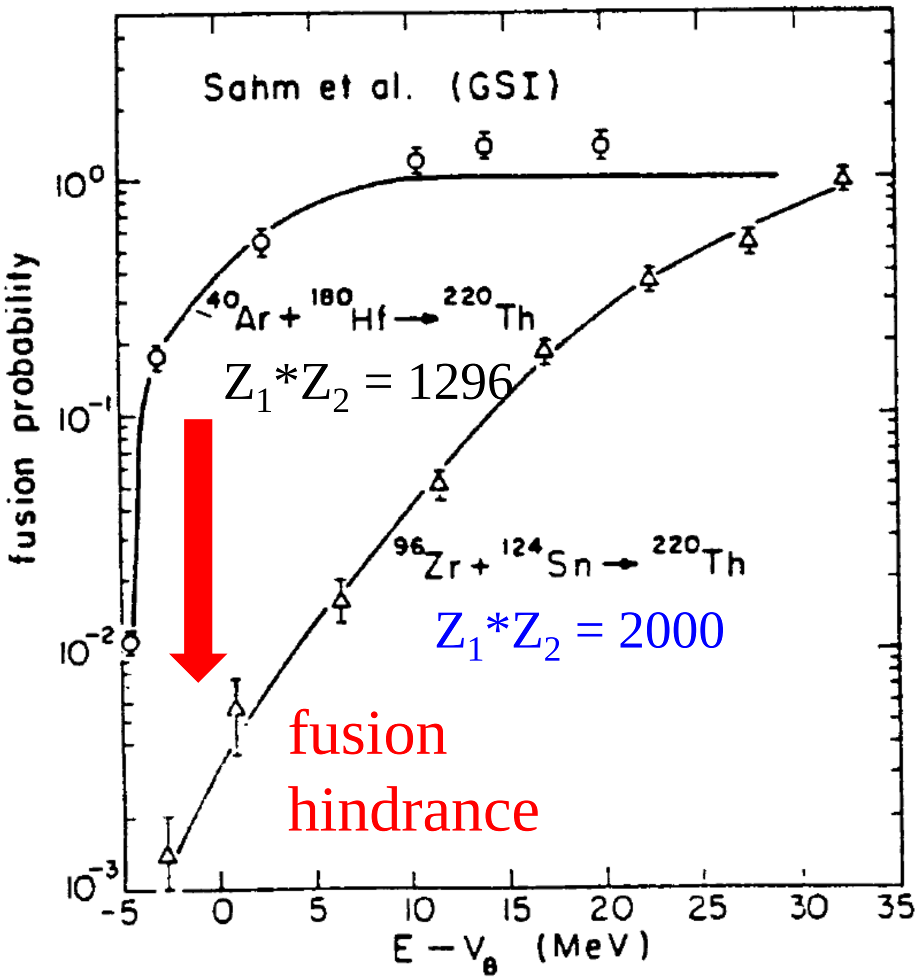
Hot fusion reactions with ^{48}Ca, $^{50}_{22}$Ti, $^{51}_{23}$V, $^{54}_{24}$Cr etc.

➢Towards the island of stability

neutron-rich beams: indispensable → reaction dynamics?

Fusion reactions in the SHE region ($Z_P*Z_T > 1600\sim1800$)

fusion hindrance



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

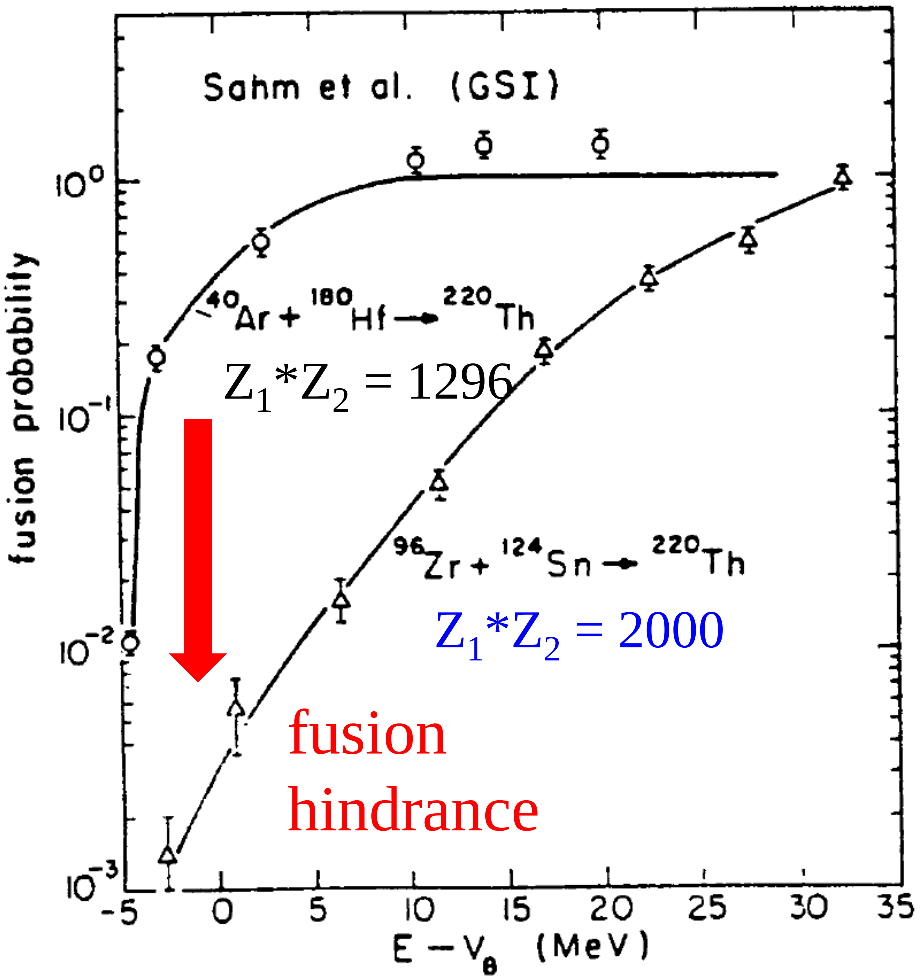
superheavy nuclei

syntheses with heavy-ion fusion reactions

theoretical issues: understanding the reaction dynamics

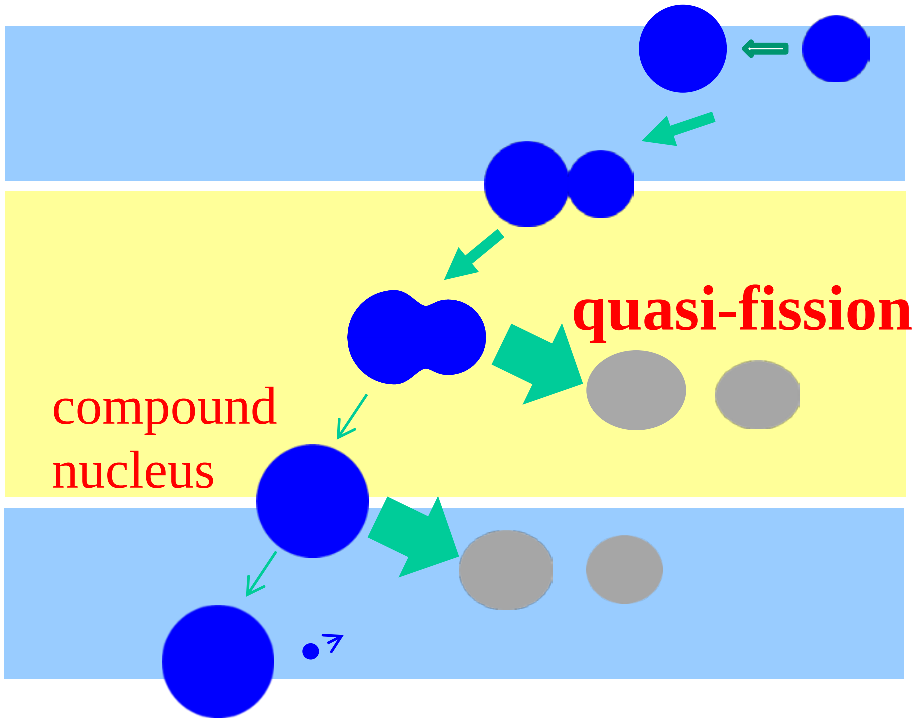
Fusion reactions in the SHE region (Z_P*Z_T > 1600~1800)

fusion hindrance



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

modern interpretation of hindrance



strong Coulomb repulsion
→re-separation before the compound nucleus

Fusion reactions in the SHE region (Z_P*Z_T > 1600~1800)

SHE formation: a very rare event

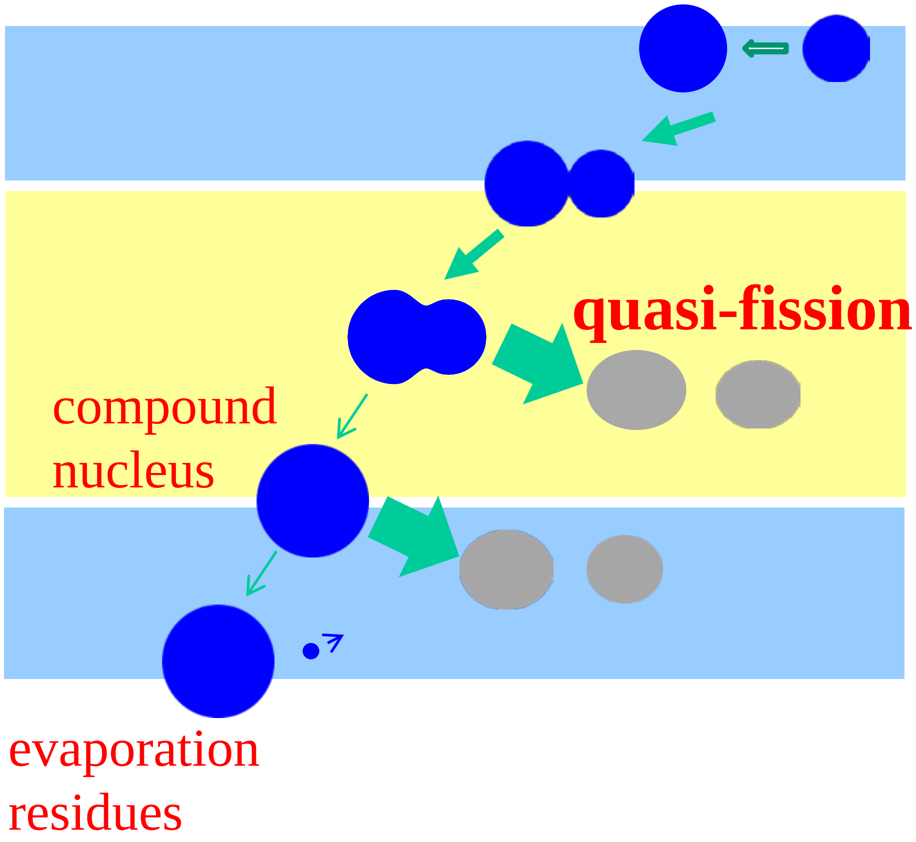
→ large theoretical uncertainties

✓No data for P_{CN}
✓Data: only for P_{ER}

CN＝compound nucleus
ER = evaporation residues

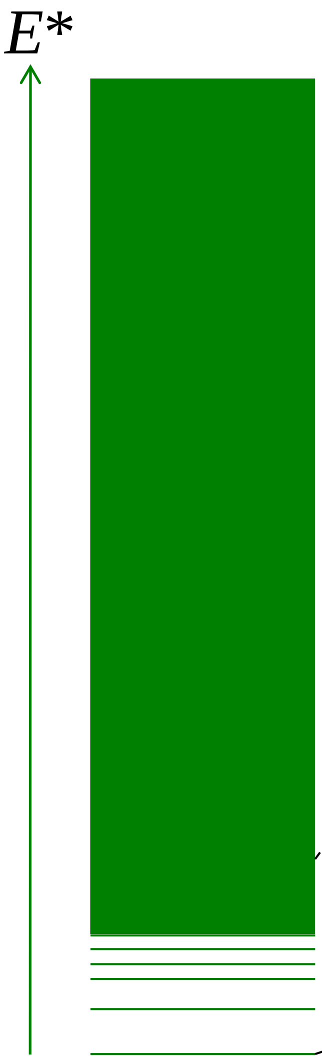
theoretical challenge:
to reduce theoretical uncertaintities
and make a reliable prediction

modern interpretation of hindrance

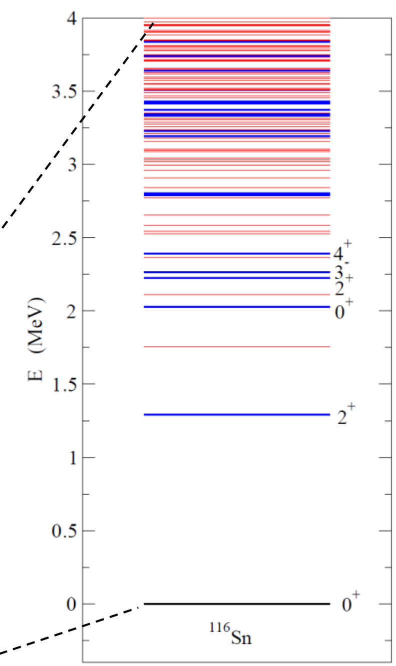


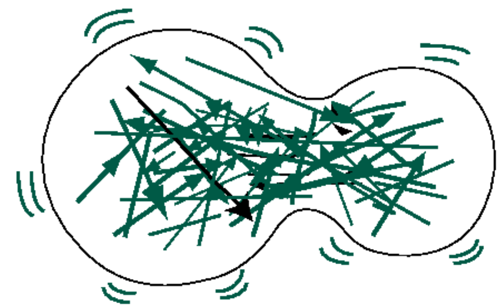
strong Coulomb repulsion
→re-separation before the compound nucleus

Nuclear friction and heavy-ion fusion reactions



$$\rho(E) \sim e^{2\sqrt{aE^*}}$$





These states:
are excited in a complicated way.

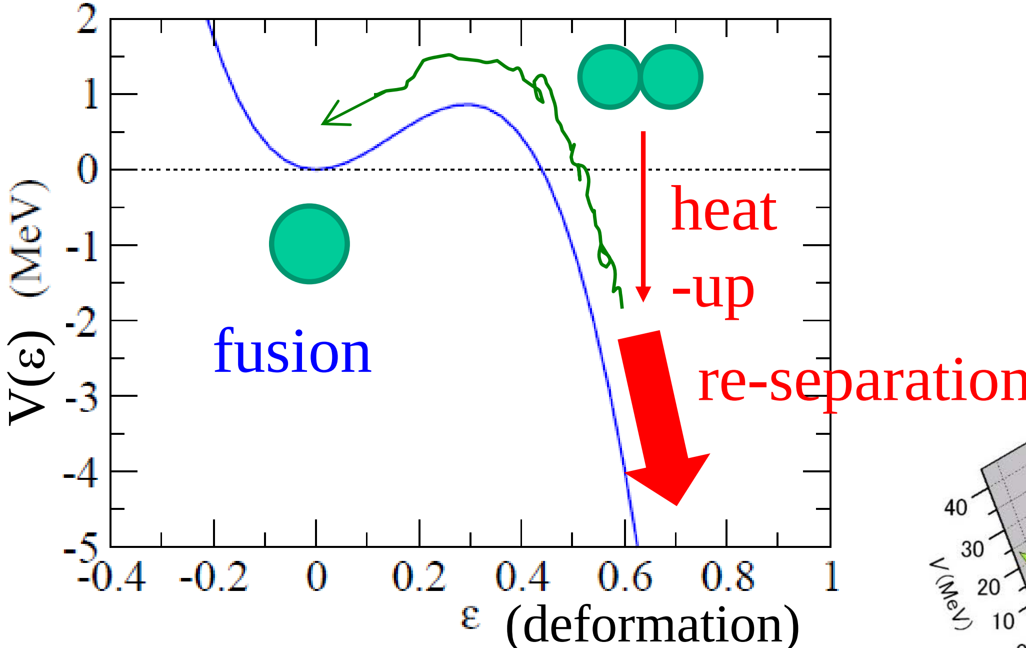
⇩

nuclear intrinsic d.o.f.
: act as environment

"*intrinsic* environment"
→ friction

nuclear spectrum

Langevin approach



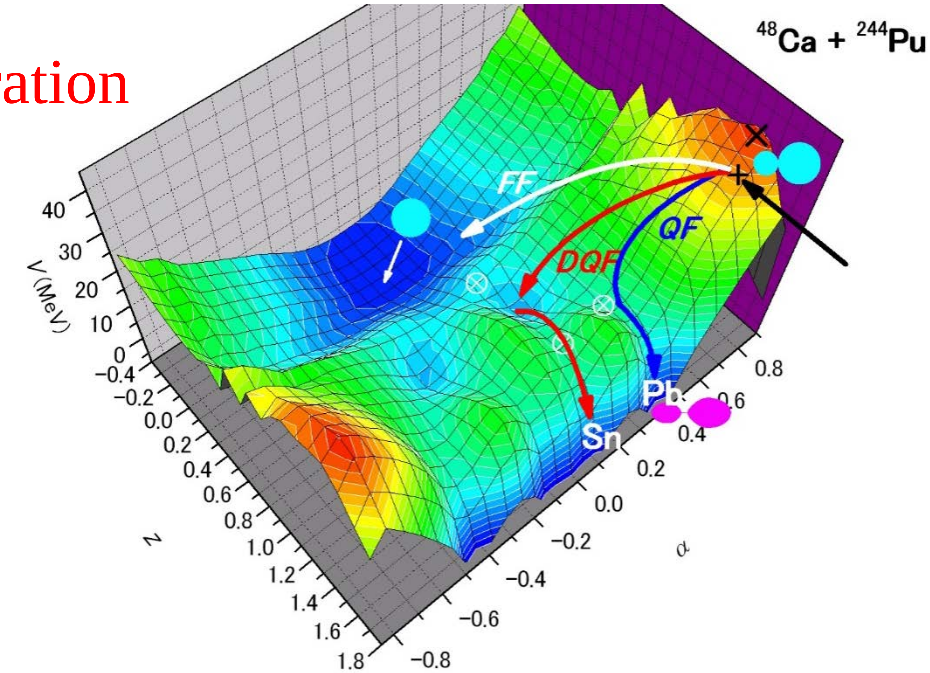
thermal diffusion

⟶ Langevin approach
(Brownian motion)

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

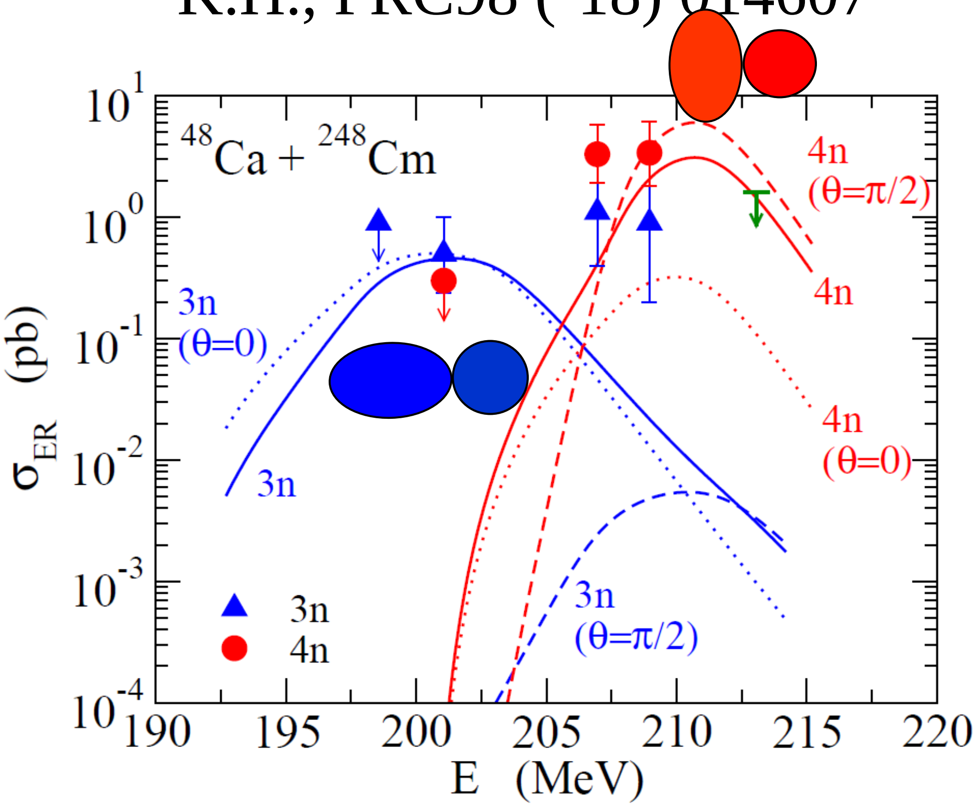
Multi-dimensional space

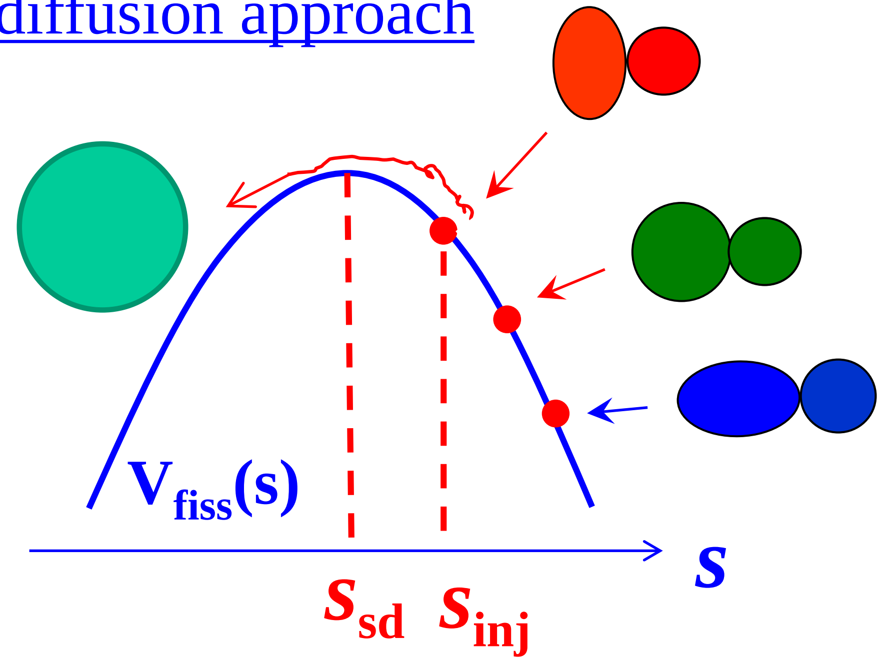
- internuclear separation
- deformation
- mass asymmetry
  of the two fragments



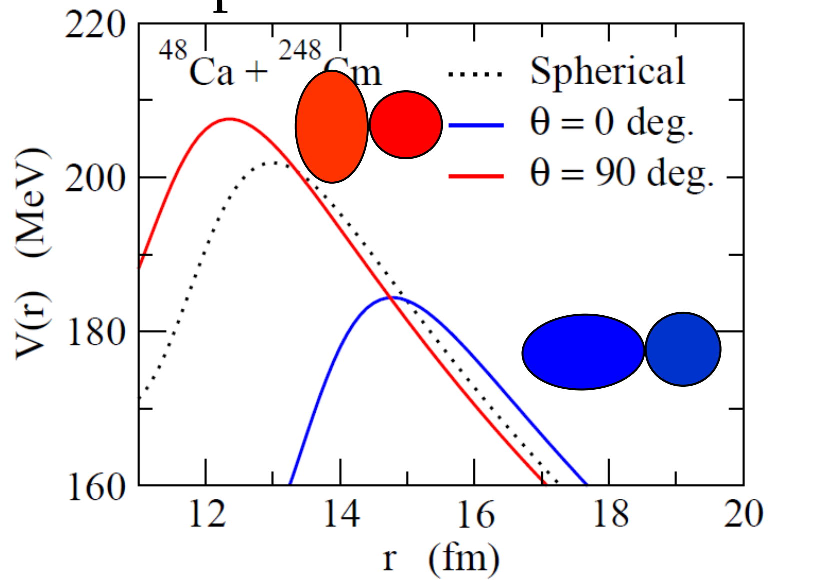
Analysis with an extended fusion-by-diffusion approach

K.H., PRC98 (‘18) 014607





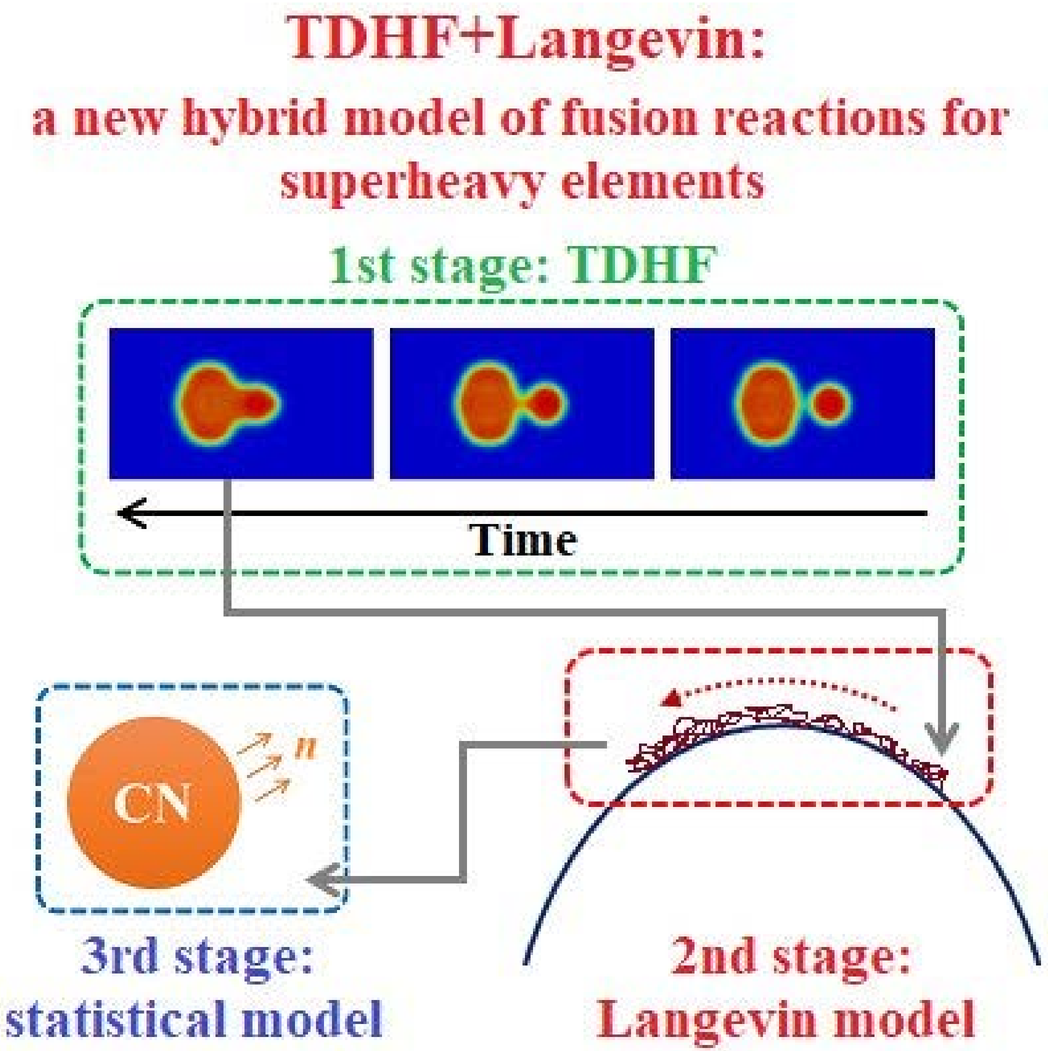
capture barrier:



New hybrid model: TDHF + Langevin approach

K. Sekizawa and K.H., PRC99 (2019) 051602(R)

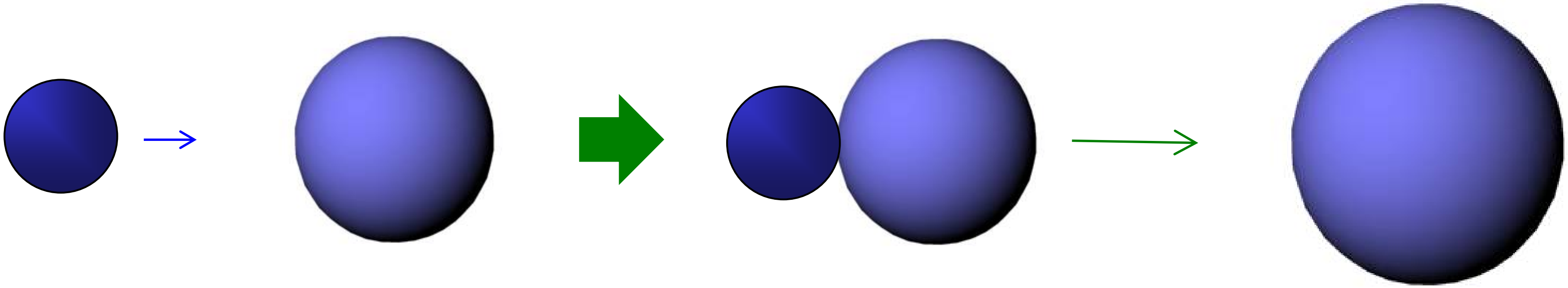
SUGGESTION

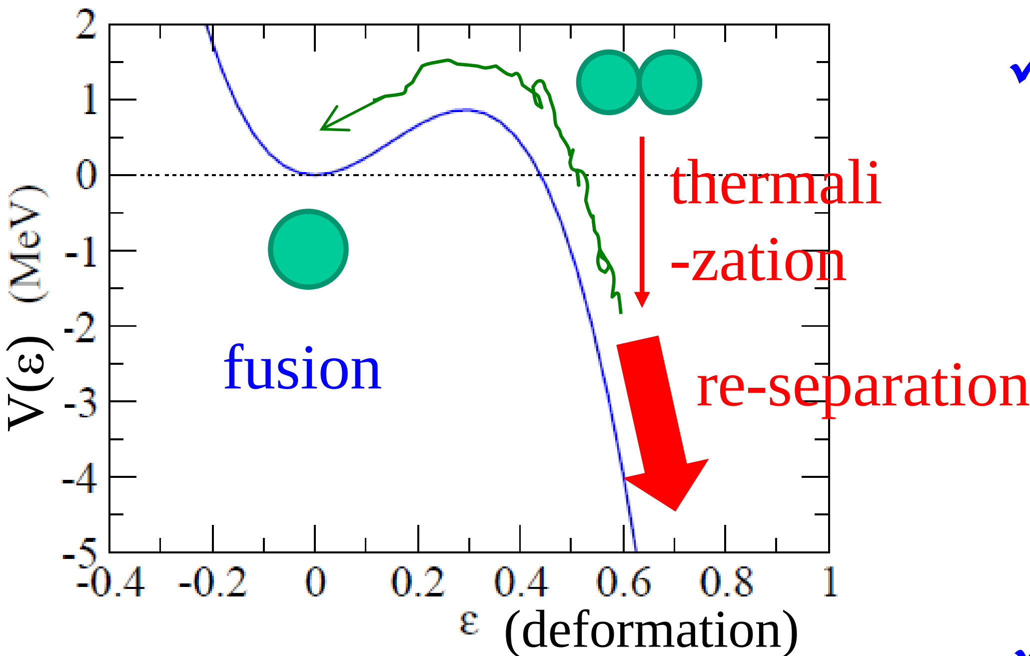


System	CN	R_{min} (fm)	P_{fus} ($\times 10^{13}$)
^{48}Ca+^{254}Fm	^{302}120	12.93	302
^{54}Cr+^{248}Cm	^{302}120	13.09	2.47
^{51}V+^{249}Bk	^{300}120	12.94	0.461
^{48}Ca+^{257}Fm	^{305}120	12.94	1.82

a special role of ^{48}Ca?

issues from the theoretical physics point of view





thermal diffusion

→ Langevin approach

✓ how to thermalize?

Quantum friction theory

c.f. tunneling with quantum friction

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

✓ non-Markov effect?

✓ quantum correction for diffusion over the barrier?

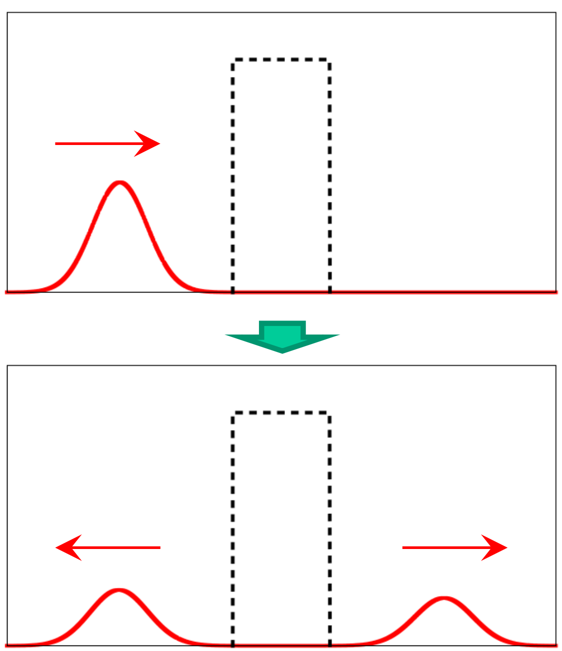
Quantum friction classical eq. of motion $\dot{p} = -V'(x) - \gamma p$

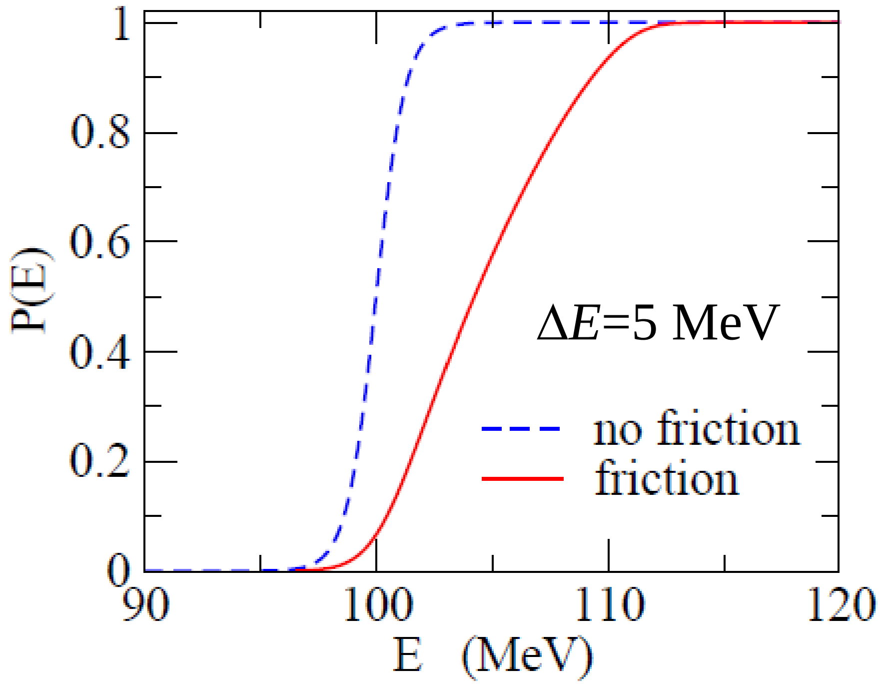
a quantization: Kanai model E. Kanai, PTP 3 (1948) 440

$$H = \frac{p^2}{2m} + V(x) \to \frac{\pi^2}{2m} e^{-\gamma t} + e^{\gamma t} V(x) \qquad (\pi = e^{\gamma t} p)$$

$$\Rightarrow \quad \frac{d}{dt}\langle p \rangle = -\langle V'(x) \rangle - \gamma \langle p \rangle$$

time-dep. wave packet approach

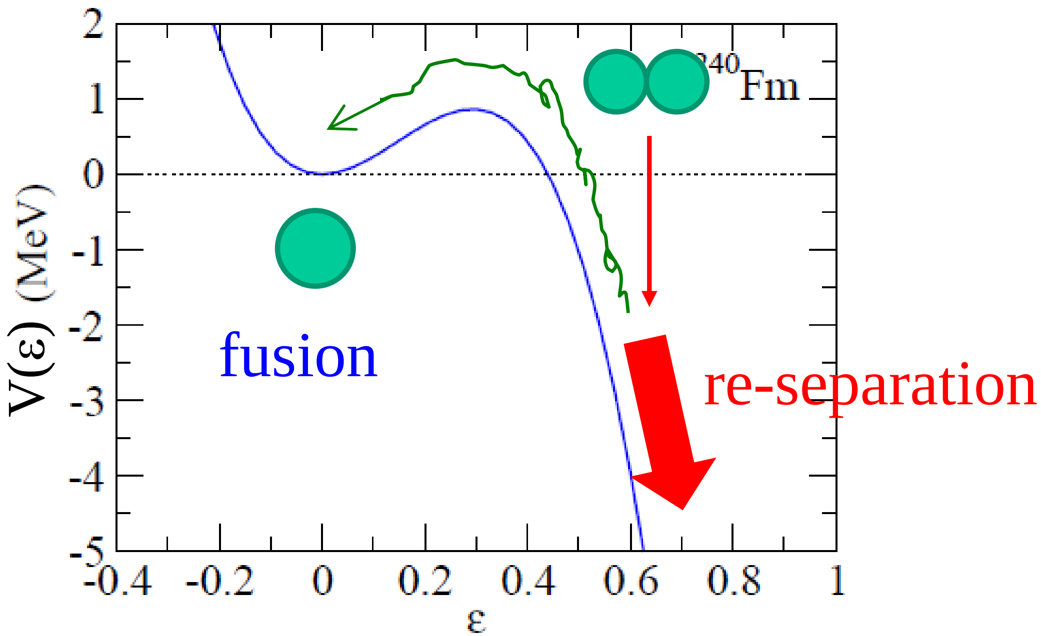




M. Tokieda and K.H., PRC95 ('17) 054604

Fusion reactions and non-equilibrium statistical mechanics
:Langevin dynamics under a temperature gradient

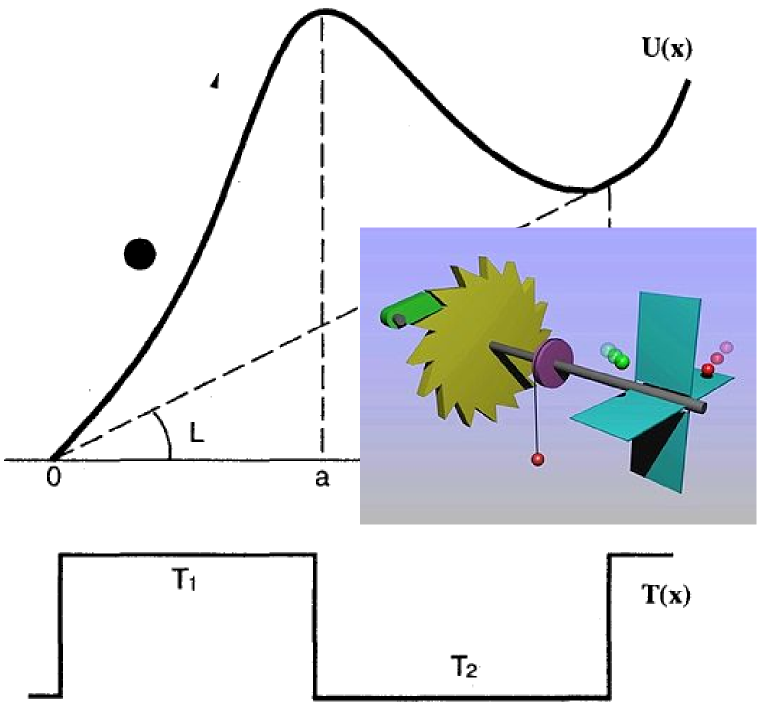
- Superheavy elements



$$E_{\rm int} = E^* - E_{\rm kin} - V(\epsilon) = aT^2$$

← coordinate dependent temperature

- a math model for molecular motors

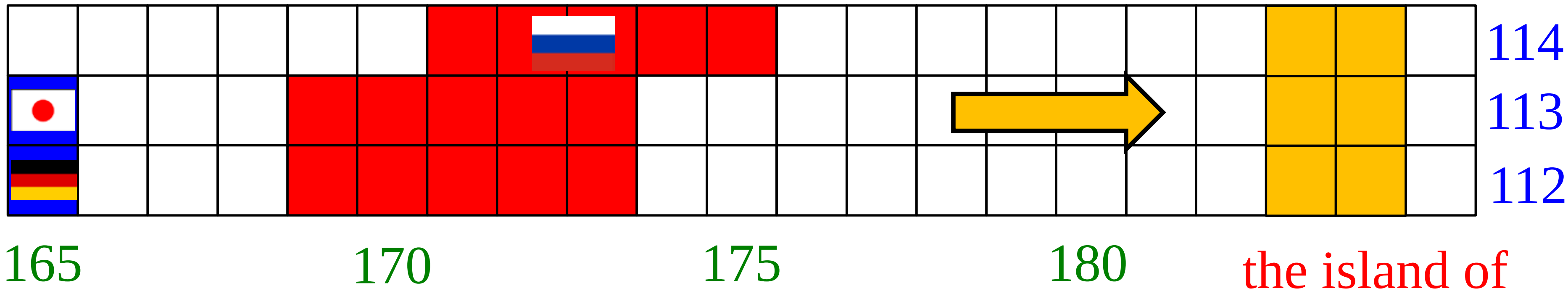


松尾美希、物性研究 73 (‘99) 557

temperature gradient
→ one-way dynamics

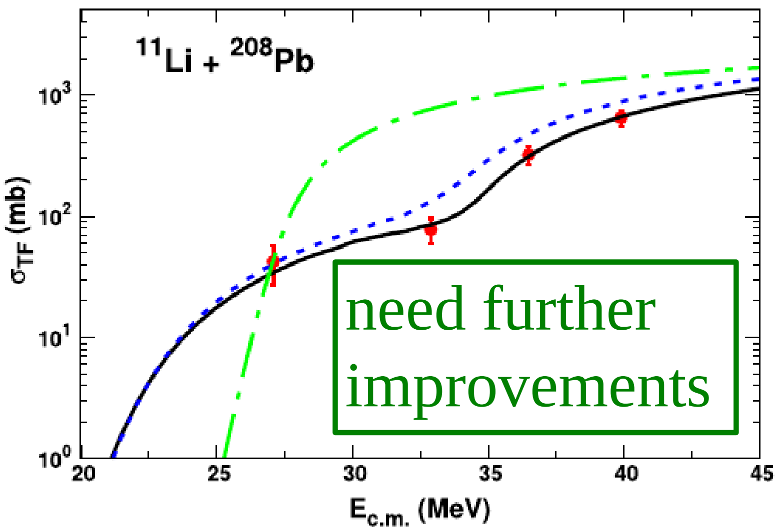
SHE formation reactions as a general problem of non-eq. stat. mechanics?

Fusion of unstable nuclei

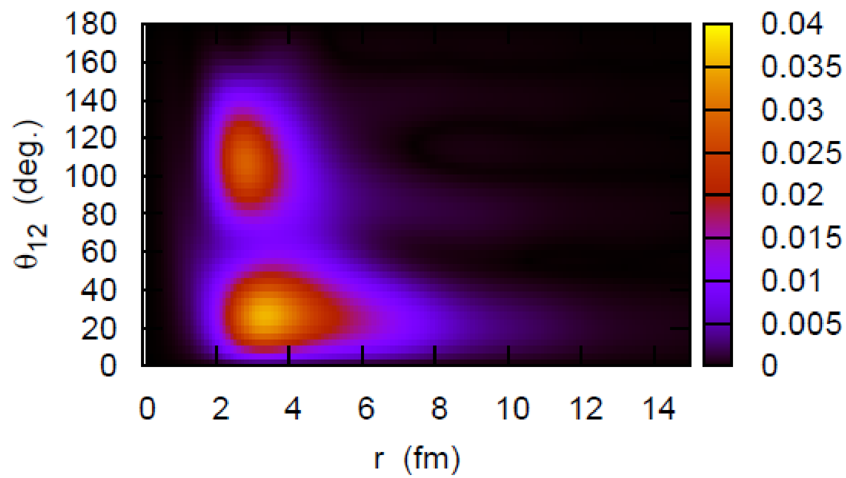


the island of stability

neutron-rich beams: indispensable→reaction dynamics?

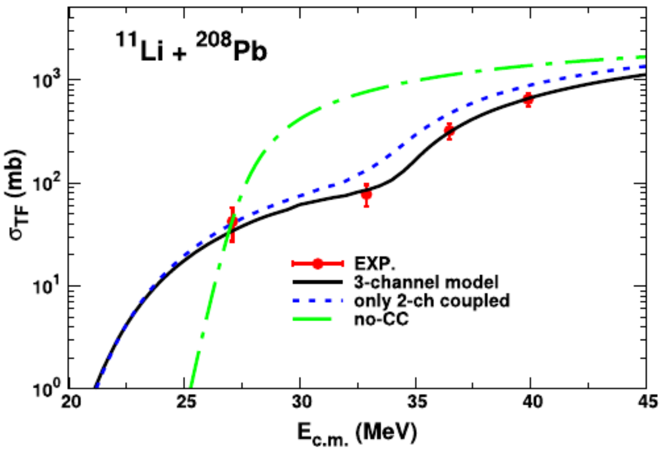


K.-S. Choi, K. Hagino et al., Phys. Lett. B780 ('18) 455

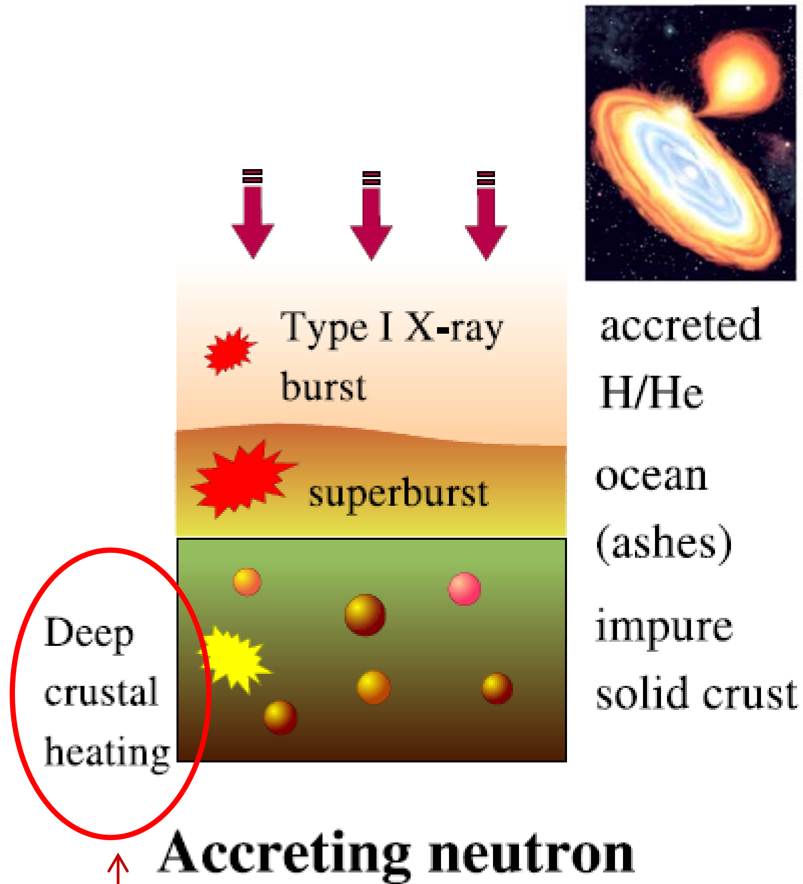


K.H. and H. Sagawa, PRC72('05)044321

good understandings of the structure of neutron-rich nuclei is also important reactions of neutron-rich nuclei



- ✓ fusion
- ✓ transfer

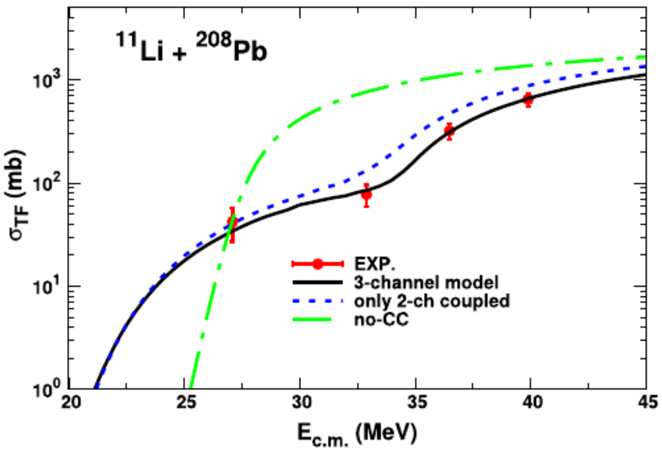


- ➢ development of microscopic nuclear reaction theory
- ➢ nuclear ractions in neutron stars

fusion of neutron-rich nuclei

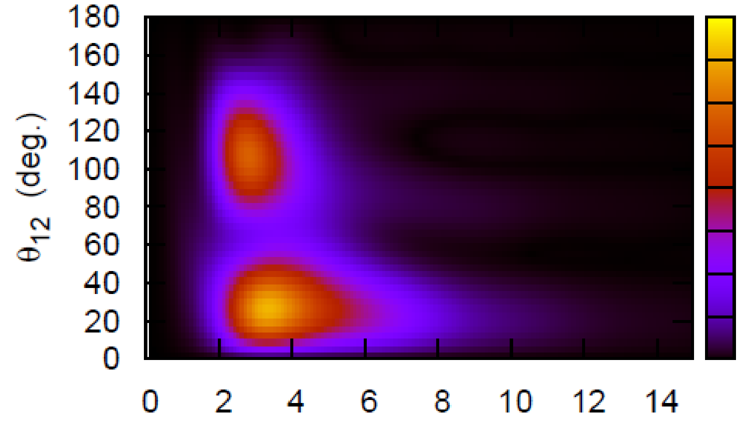
$^{24}O + ^{24}O$, $^{28}Ne + ^{28}Ne$ etc.

reactions of neutron-rich nuclei



- ✓ fusion
- ✓ transfer

structure of neutron-rich nuclei



- ✓ nucleon correlations
- ✓ collective motions
- ✓ fission

- ➢ development of microscopic nuclear reaction theory
- ➢ nuclear ractions in neutron stars

from few-body to many-body

Physics of SHE with n-rich nuclei as important ingredient

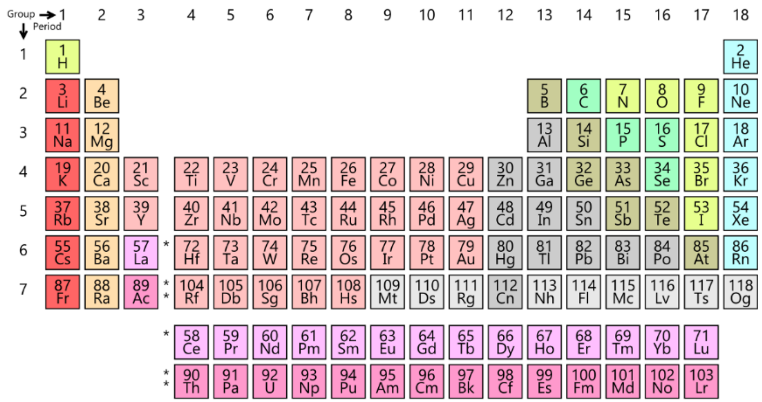
Summary

SHE: quantum many-body systems with a strong Coulomb field

physics

reaction dynamics
- ✓ quantum friction
- ✓ neutron-rich nuclei

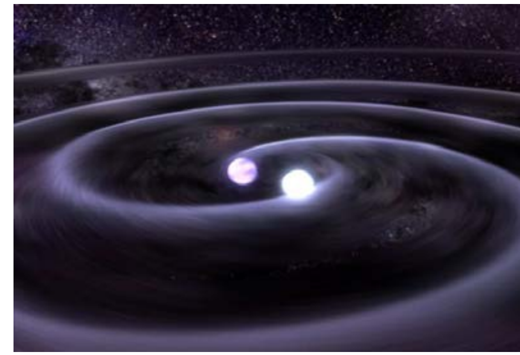
chemistry

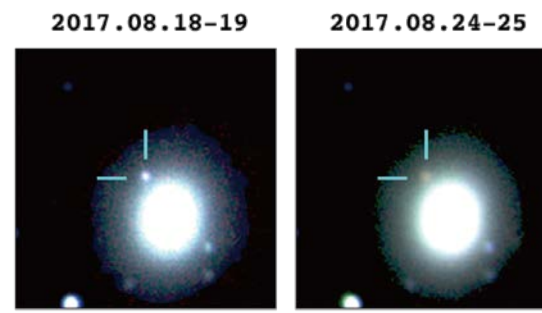


2019 IYPT

International Year
of the Periodic Table
of Chemical Elements

astronomy





- ✓ origin of elements
- ✓ r-process
- ✓ kilonova

interdisciplinary SHE science

$$H = -\frac{\hbar^2}{2\mu}\nabla^2 + V_0(r) + \beta f(r)\hat{O}$$

full order treatment

$$V(r, \beta\hat{O})$$

$$\hat{O}|\phi_k\rangle = \lambda_k|\phi_k\rangle$$ ← diagonalize $\langle n|\hat{O}|m\rangle$

$$\Rightarrow \langle n|V(r,\beta\hat{O})|m\rangle = \sum_k \langle n|\phi_k\rangle\langle\phi_k|m\rangle\, V(r,\beta\lambda_k)$$

K.H., N. Rowley, and A.T. Kruppa,
Comp. Phys. Comm. 123('99) 143.