Perspectives on nuclear reaction theory and superheavy elements

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1. Nuclear Reactions: overview
2. Coupled-channels approach with a beyond-mean-field method
3. Time-dependent GCM for many-body tunneling
4. Fusion for superheavy elements and TDHF
5. Summary

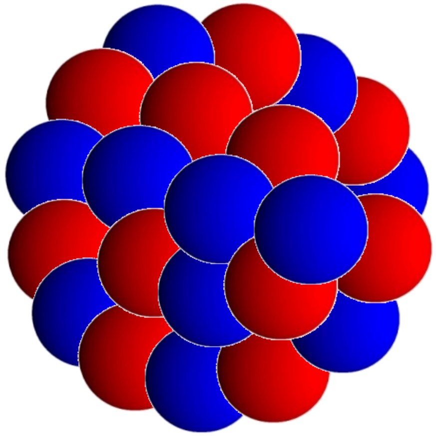
Workshop on new generation nuclear density functionals, 2019.11.18-22, Peking University

Introduction: low-energy nuclear physics

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

  ⟵ understanding based on strong interaction

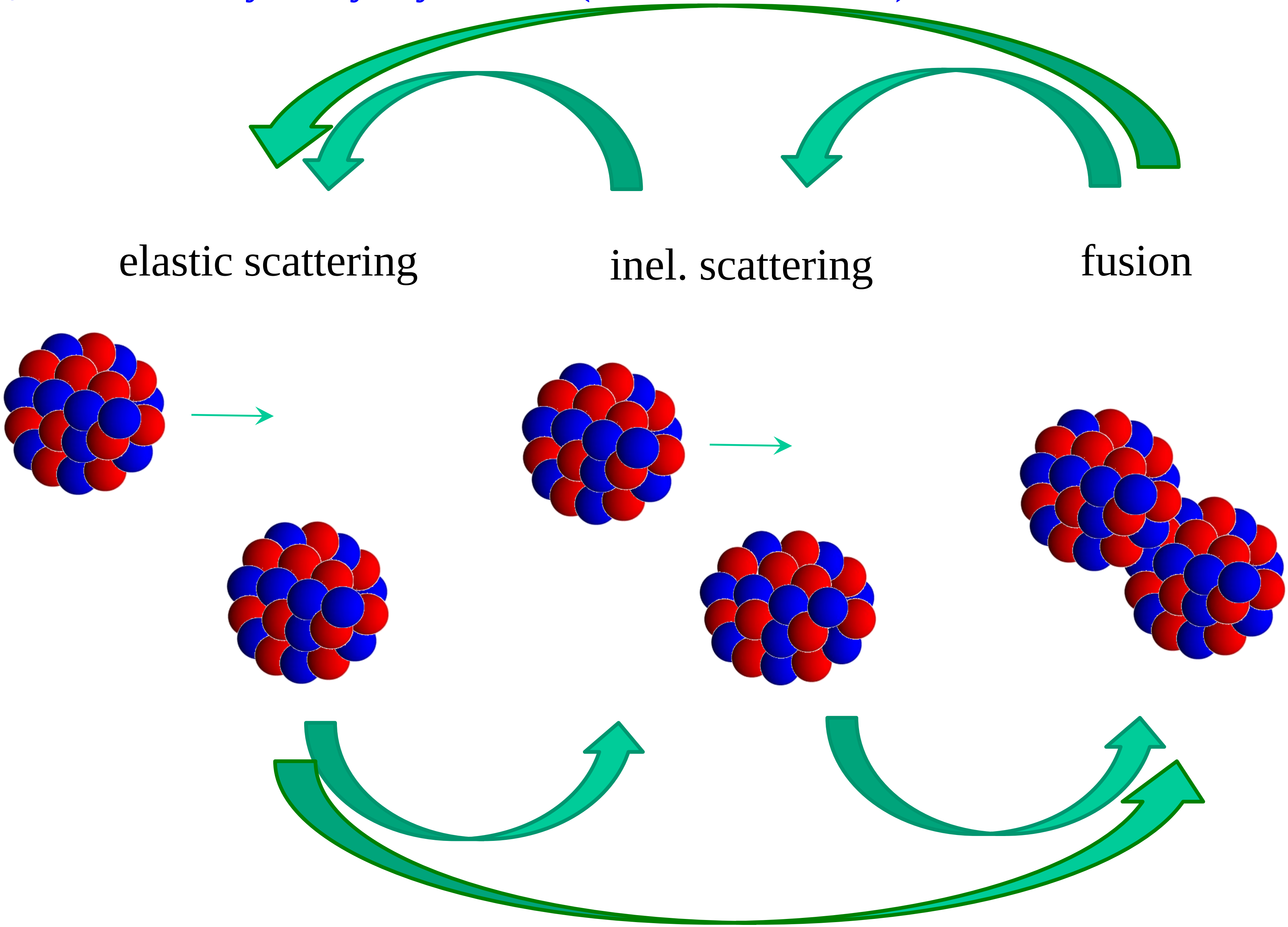
- static properties: nuclear structure
  - ✓ ground state properties (mass, size, shape,….)
  - ✓ excitations
  - ✓ nuclear matter
  - ✓ decays



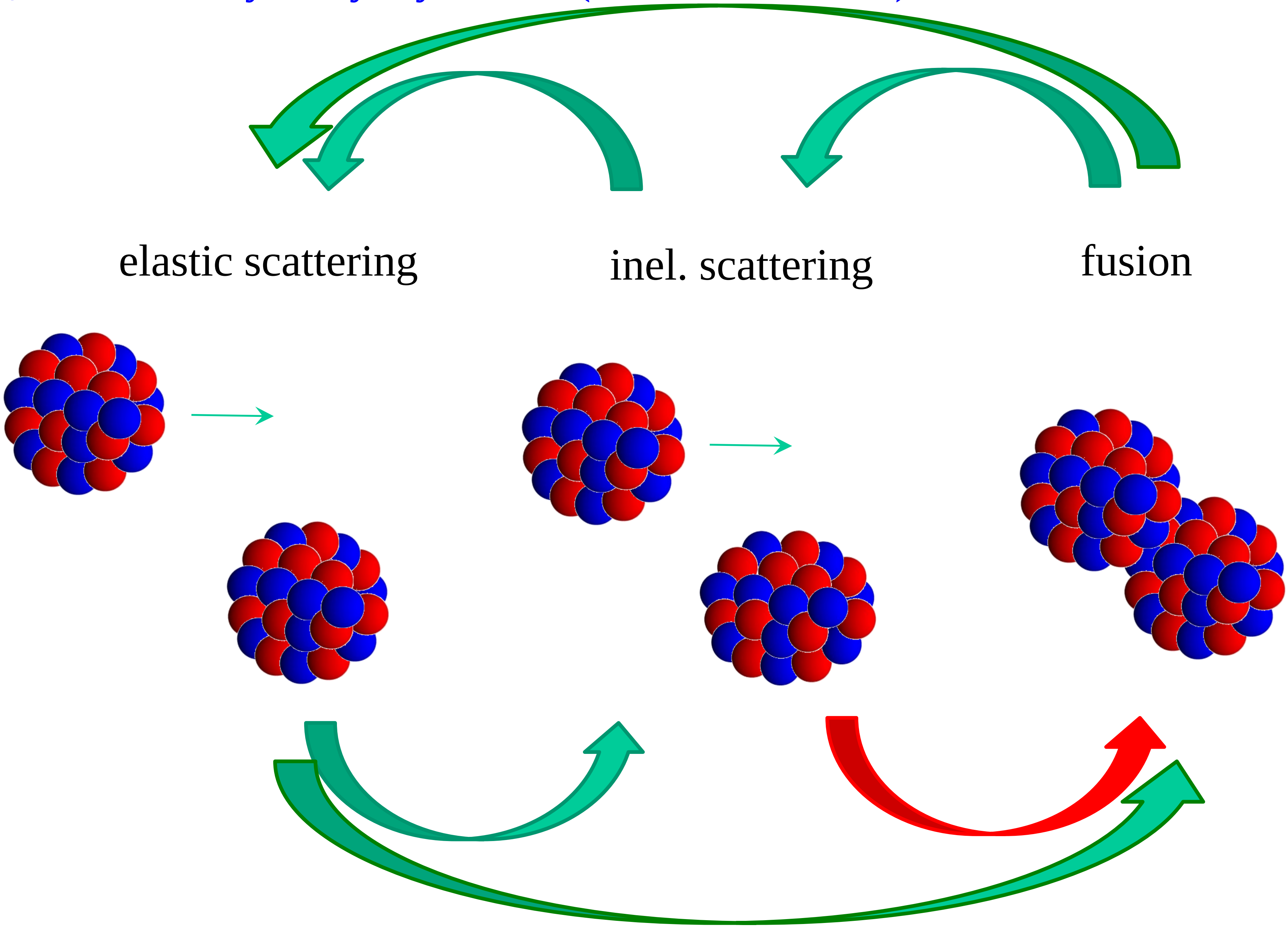
- dynamics: nuclear reactions

an interplay between nuclear structure and nuclear reaction

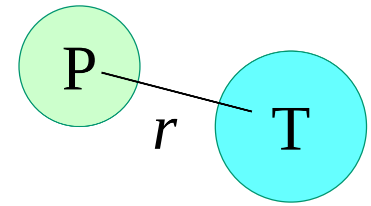
Quantum Many-body Dynamics (nuclear reactions)



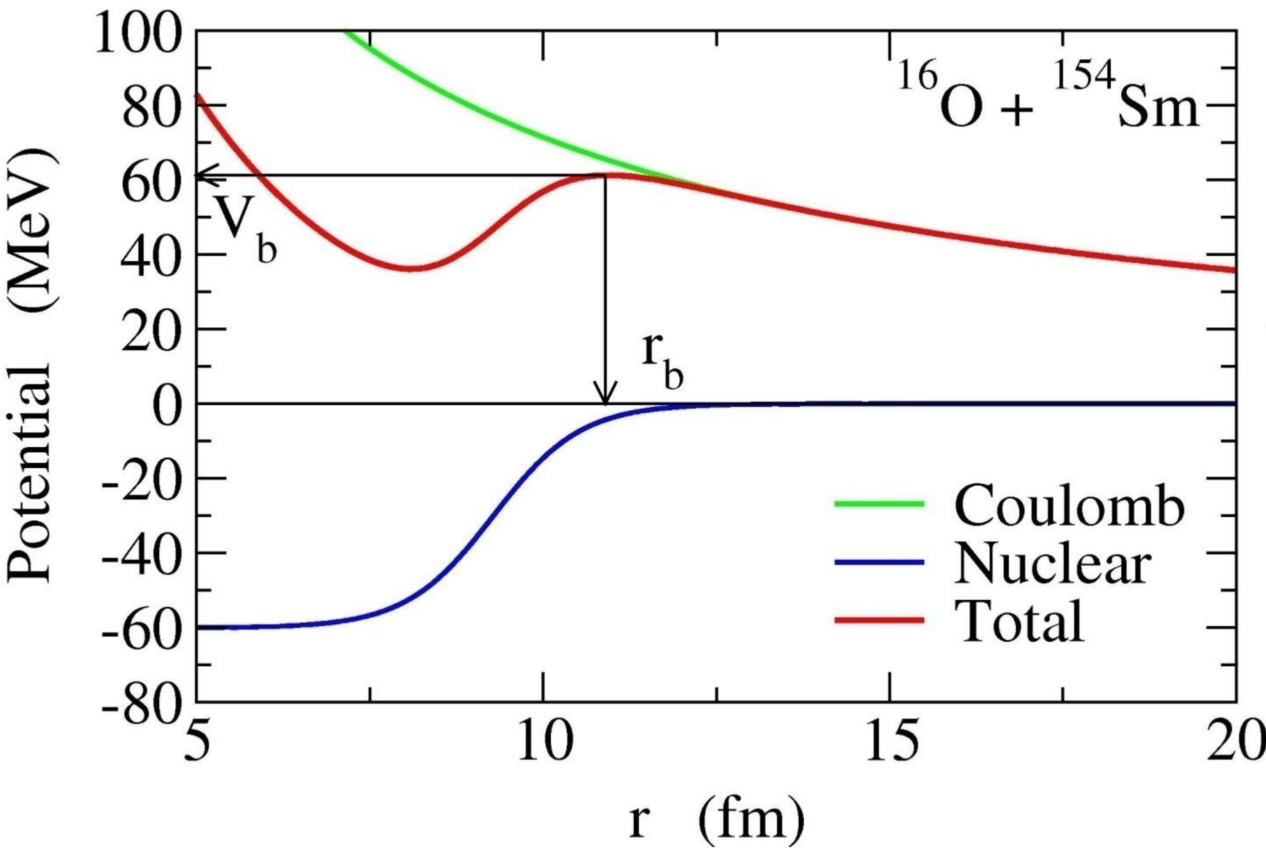
Quantum Many-body Dynamics (nuclear reactions)



Coulomb barrier



Coulomb barrier



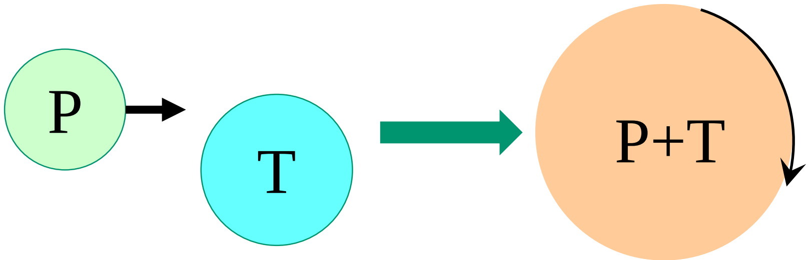
1. Coulomb interaction
   long range repulsion
2. Nuclear interaction
   short range attraction

Potential barrier (Coulomb barrier)

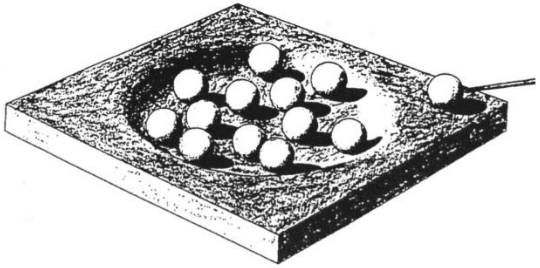
the barrier height → defines the energy scale of a system

Fusion reactions at energies around the Coulomb barrier

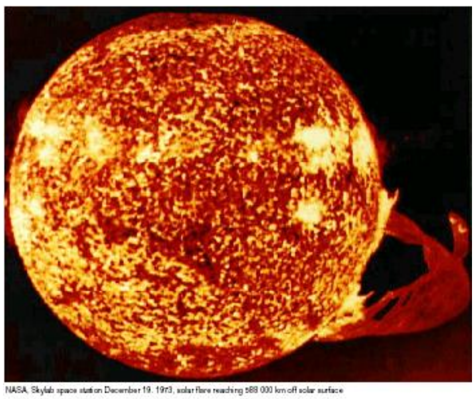
Fusion reactions: compound nucleus formation



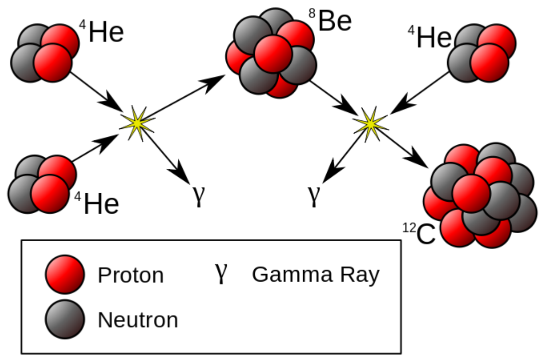
compound nucleus



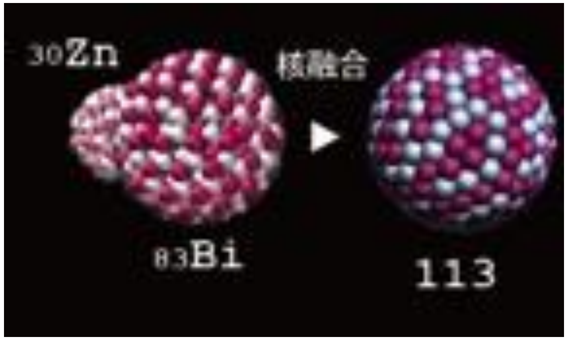
cf. Bohr '36



energy production in stars (Bethe '39)



nucleosynthesis



superheavy elements

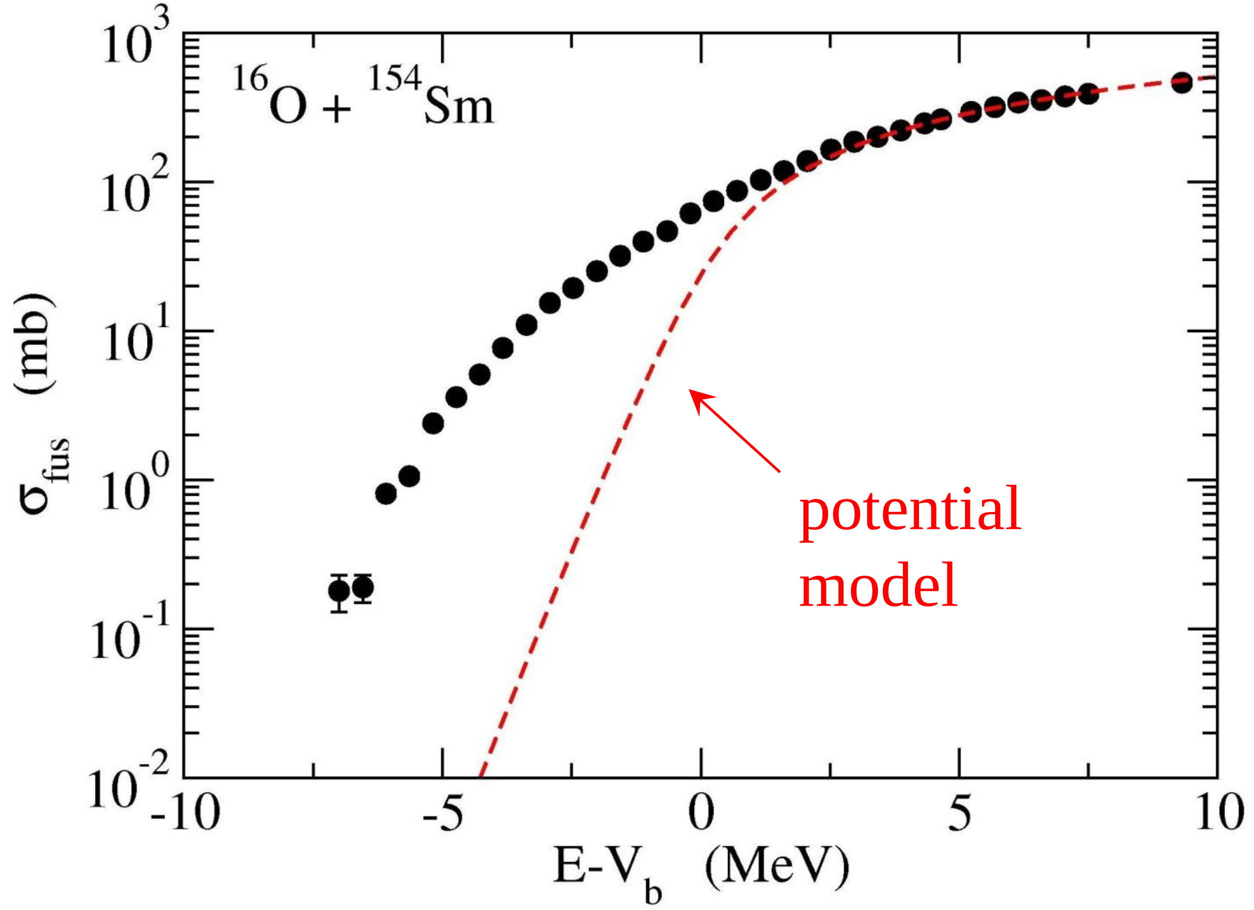
Fusion and fission: large amplitude motions of quantum many-body systems with strong interaction

⟵ microscopic understanding: an ultimate goal of nuclear physics

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

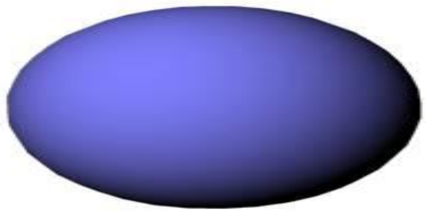
potential model: inert nuclei (no structure)

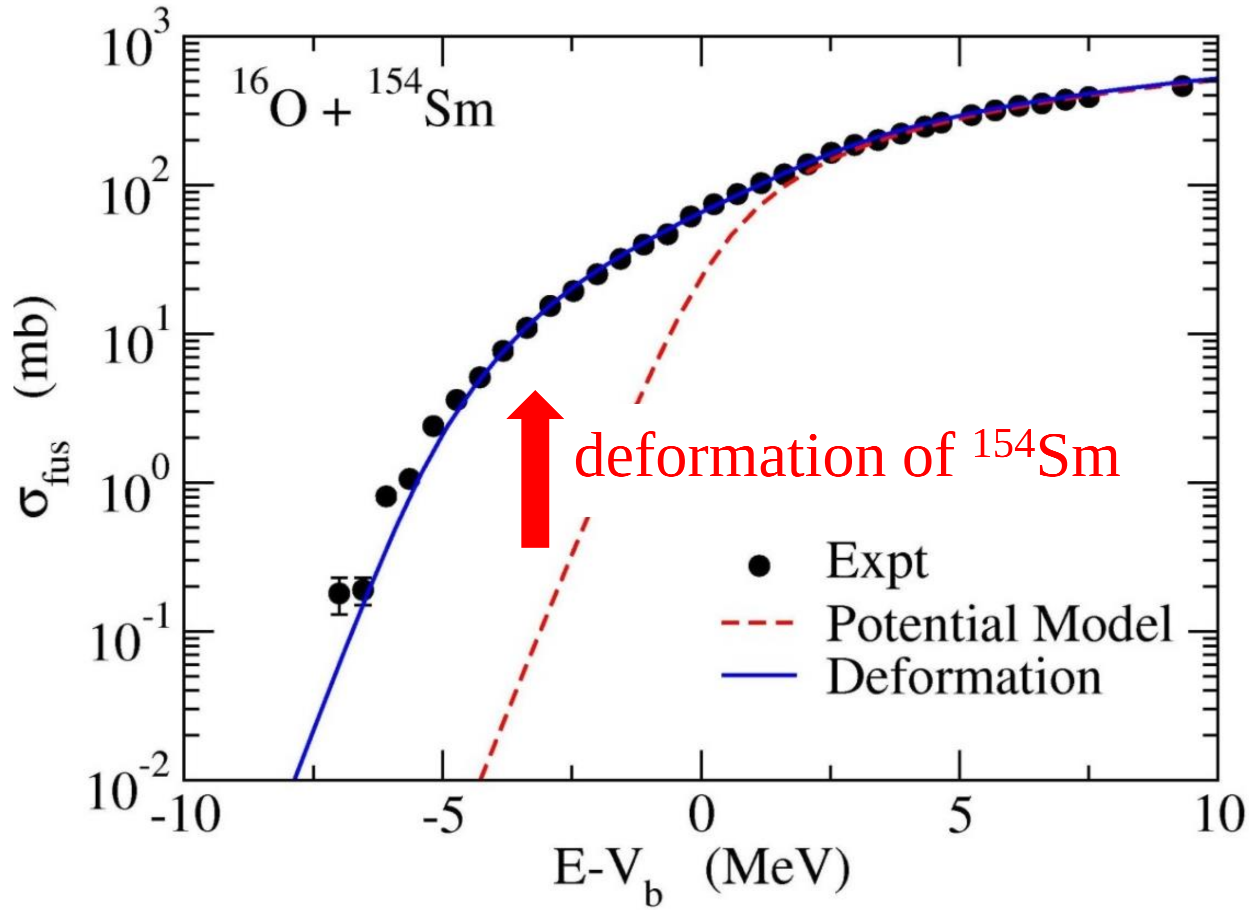
$$\sigma_{\rm fus} = \frac{\pi}{k^2}\sum_l (2l+1)(1-|S_l|^2)$$



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

^{154}Sm : a typical deformed nucleus

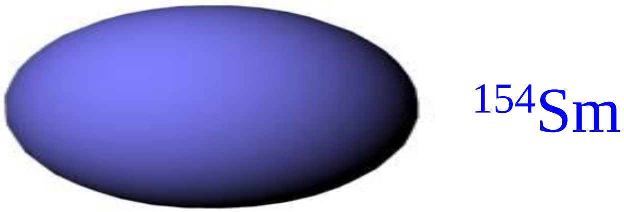


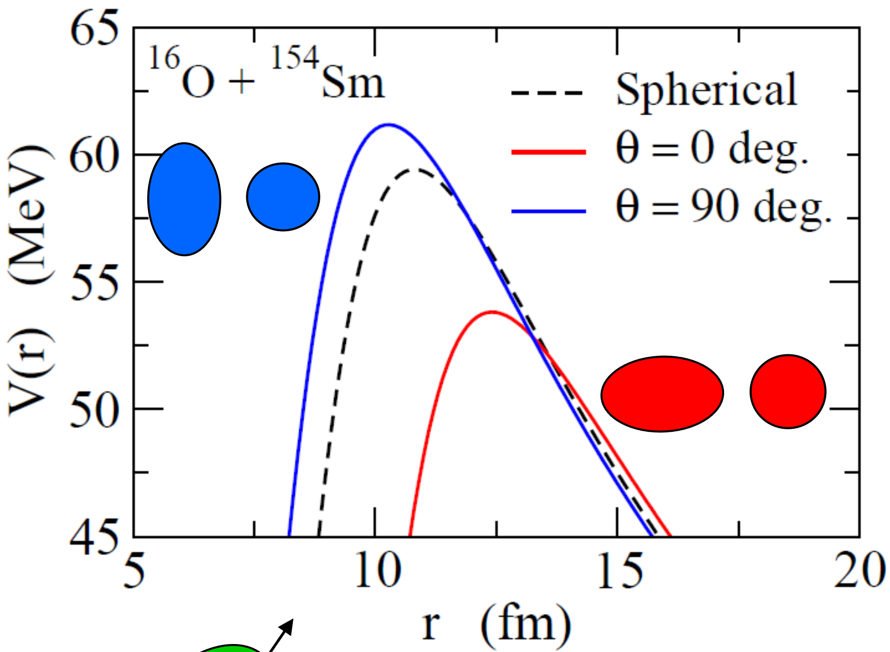


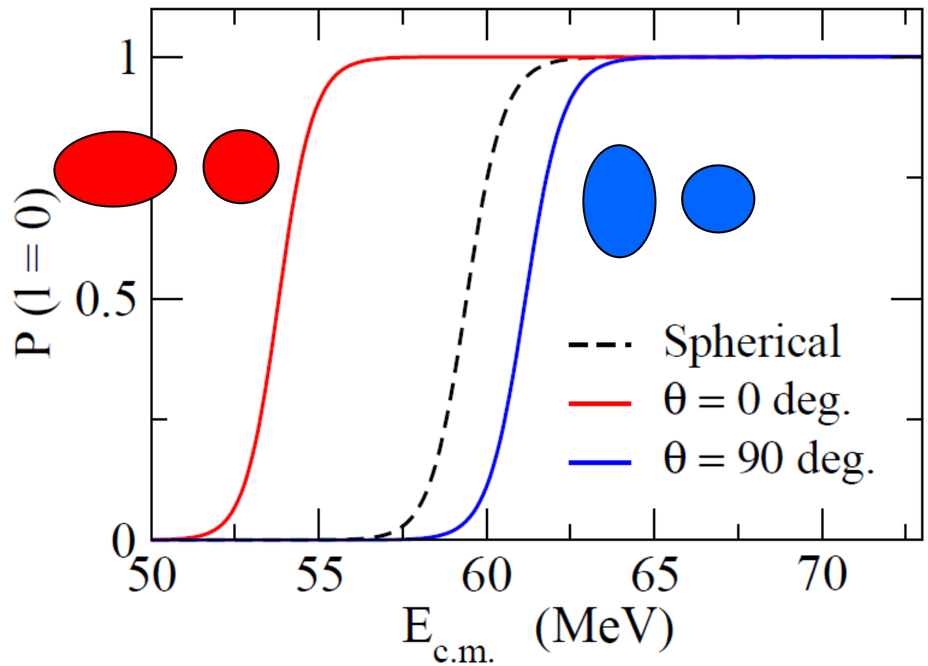
K. H. and N. Takigawa, Prog. Theo. Phys.128 ('12)1061.

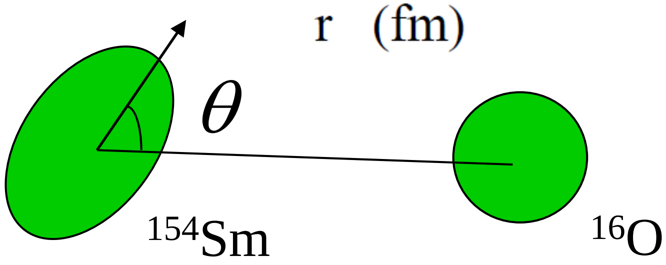
Effects of nuclear deformation

^{154}Sm : a typical deformed nucleus



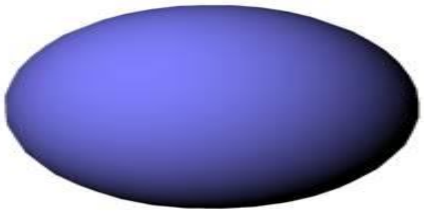




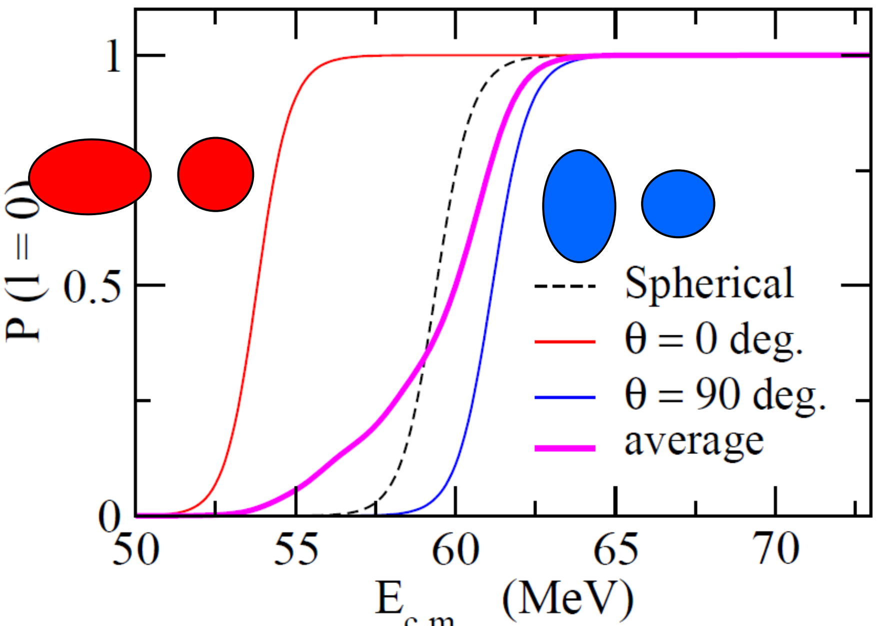


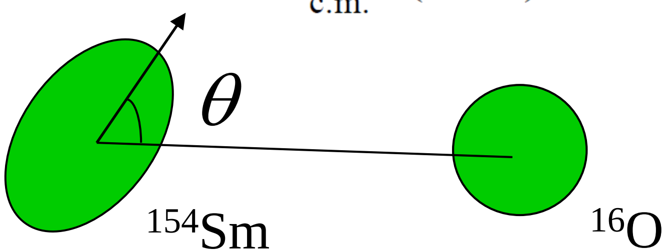
Effects of nuclear deformation

^{154}Sm : a typical deformed nucleus

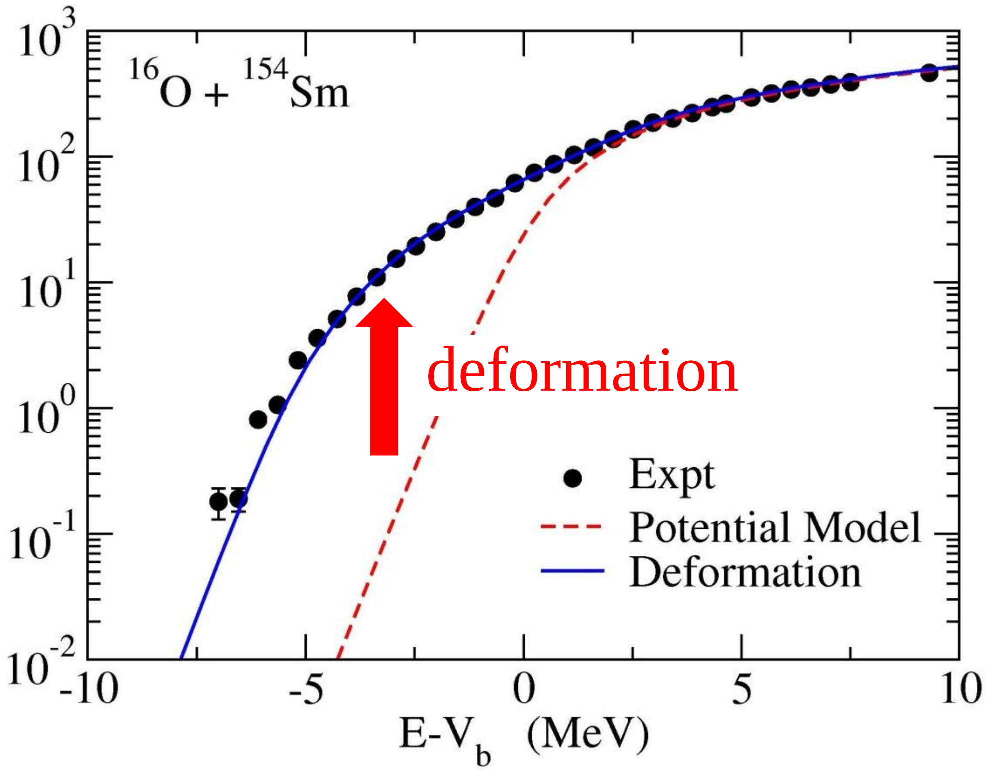


^{154}Sm

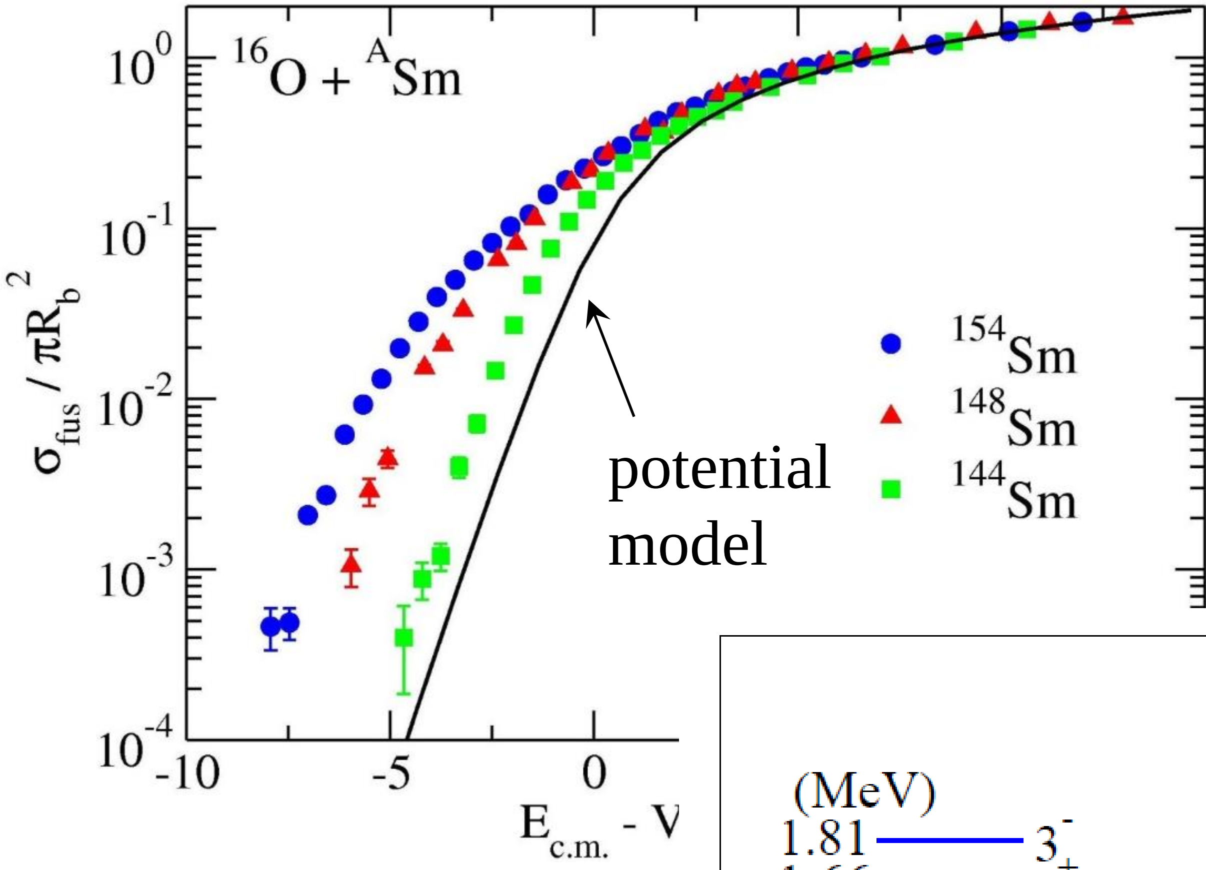




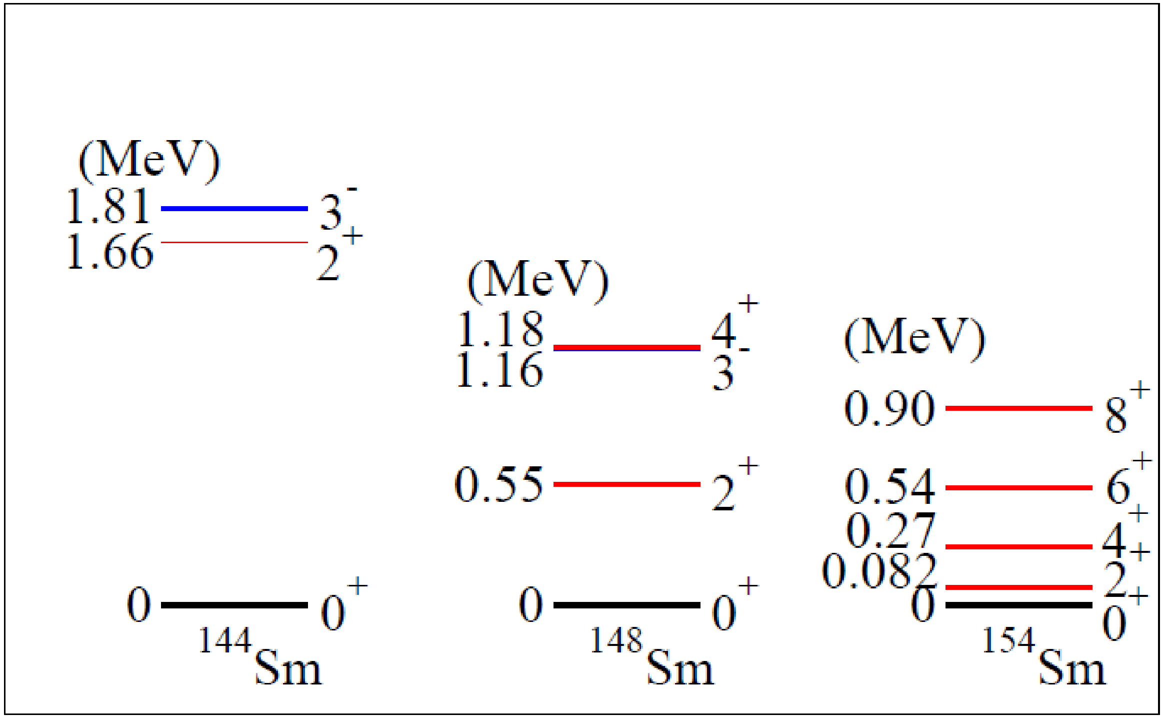
$$\sigma_{\rm fus}(E) = \int_0^1 d(\cos\theta)\sigma_{\rm fus}(E;\theta)$$



Fusion: strong interplay between nuclear structure and reaction



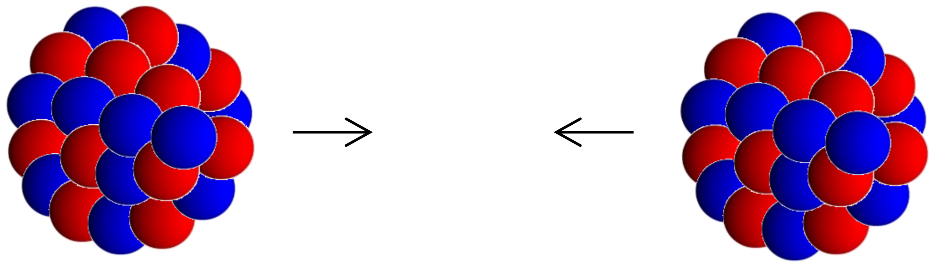
enhancement of fusion cross sections
: a general phenomenon



strong correlation with nuclear spectrum
→ coupling assisted tunneling

Coupled-channels method: a quantal scattering theory with excitations

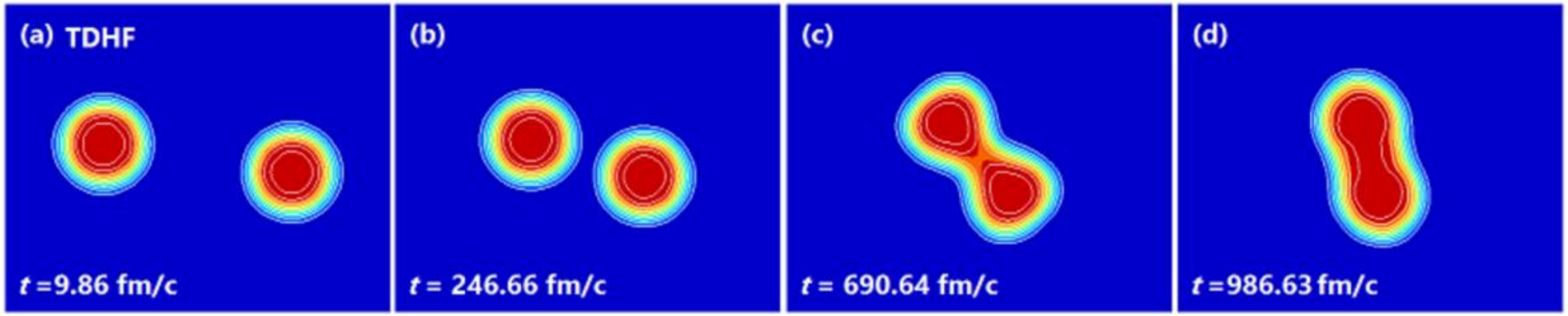
many-body problem



still very challenging

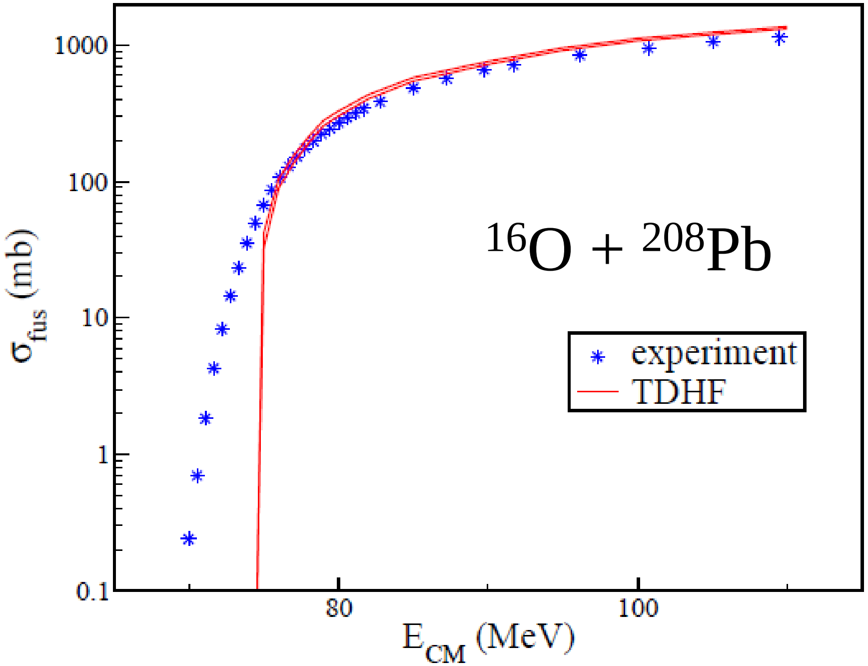
TDHF simulation

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



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

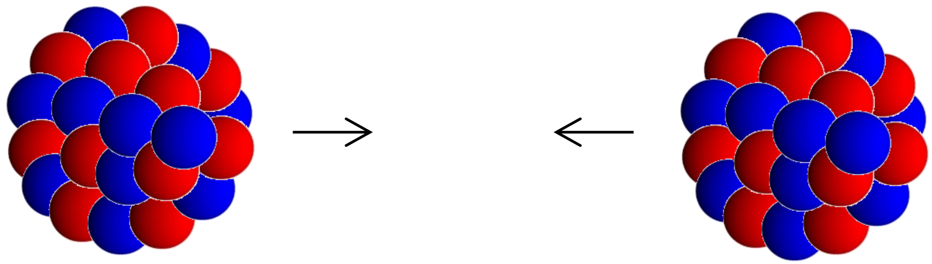
ab-initio, but no tunneling



C. Simenel,
EPJA48 (’12) 152

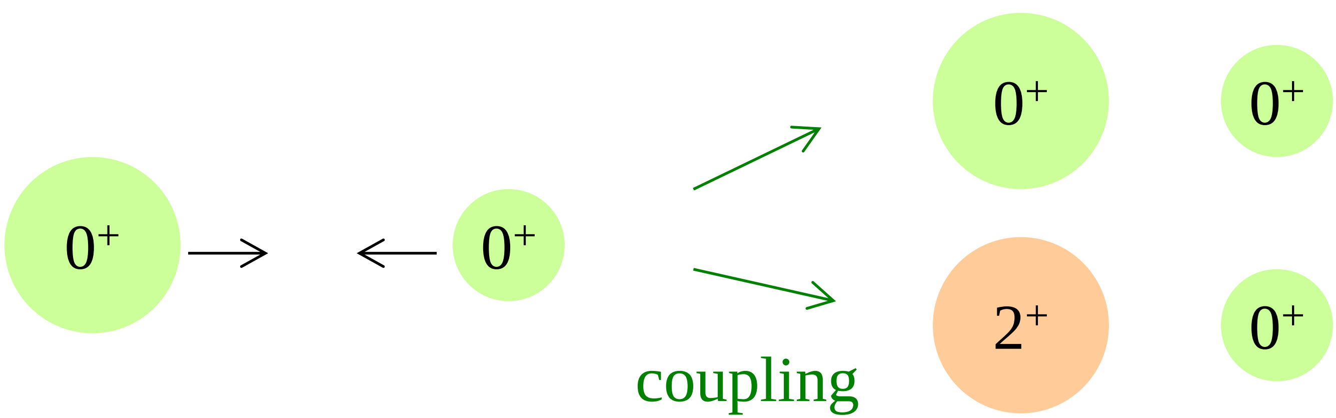
Coupled-channels method: a quantal scattering theory with excitations

many-body problem



still very challenging

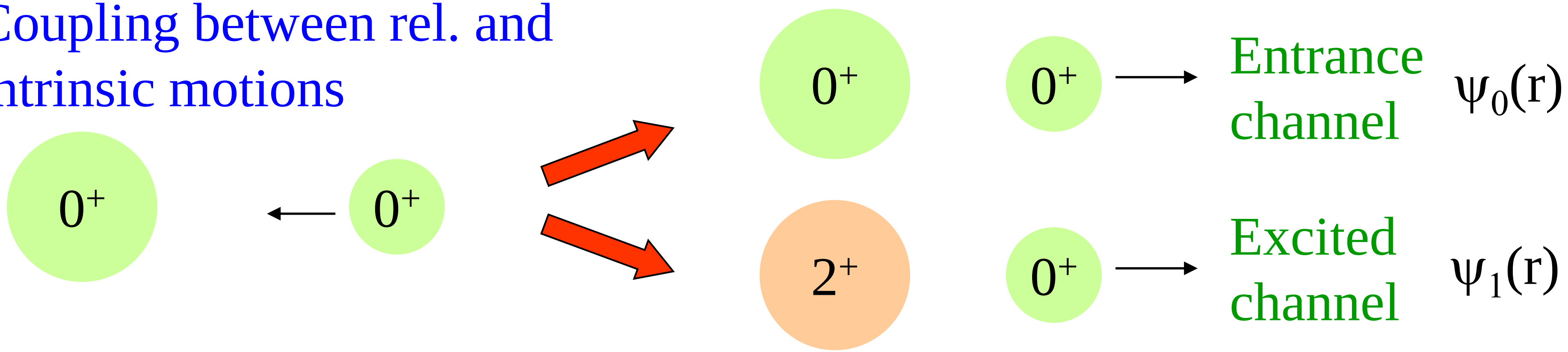
two-body problem, but with excitations
(coupled-channels approach)

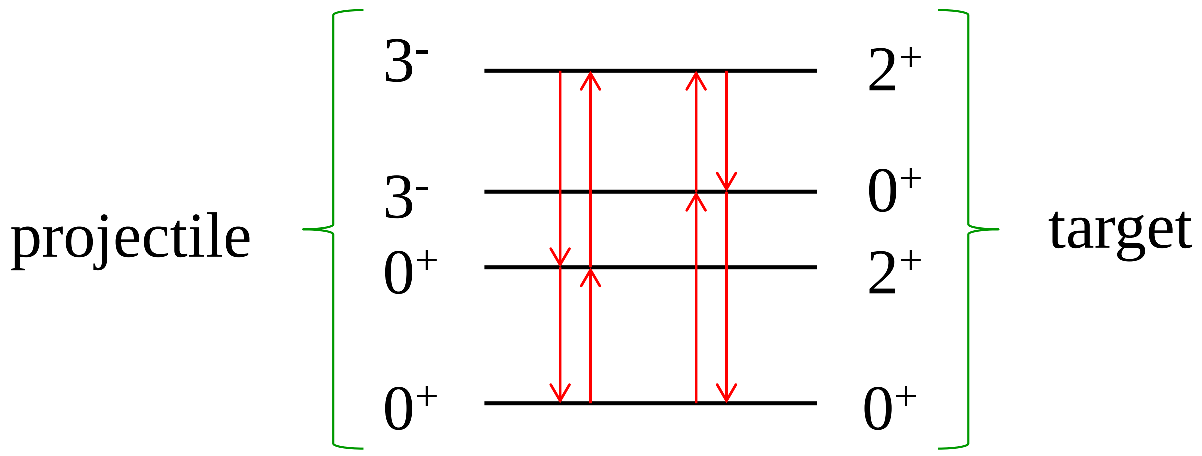


scattering theory with excitations

Coupled-channels method: a quantal scattering theory with excitations

Coupling between rel. and intrinsic motions





$$\Psi(\boldsymbol{r},\xi)=\sum_k \psi_k(\boldsymbol{r})\phi_k(\xi)$$

coupled Schroedinger equations for $\psi_k(r)$

Inputs for C.C. calculations

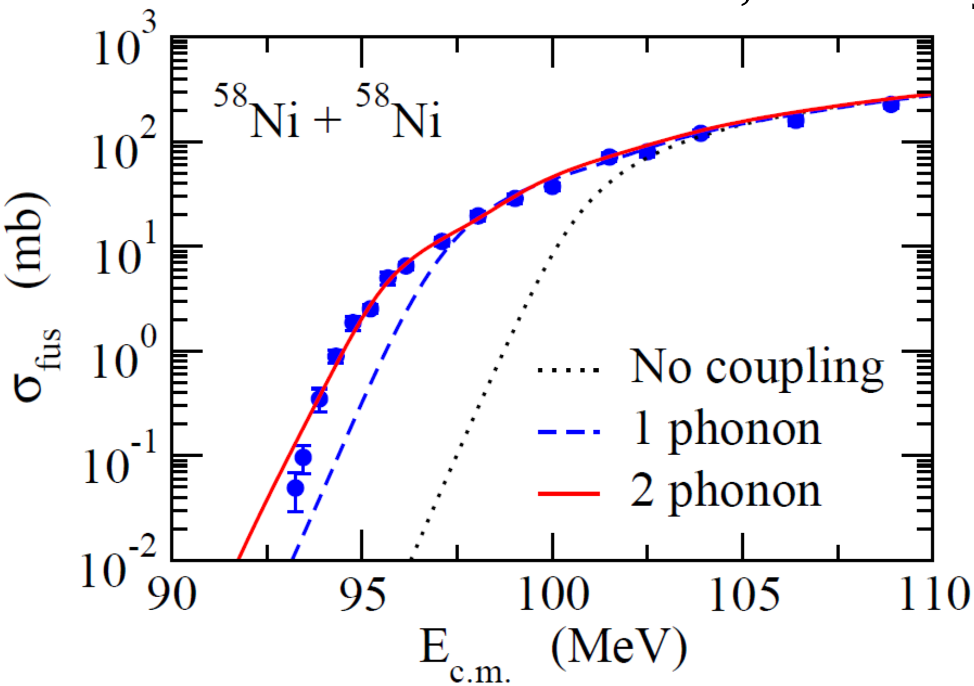
i) Inter-nuclear potential

✓ a fit to experimental data at above barrier energies

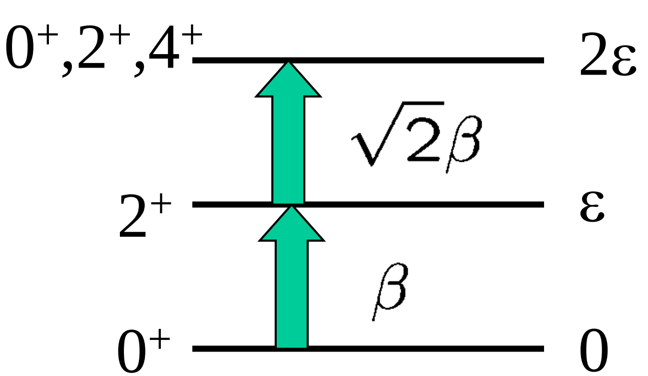
ii) Intrinsic degrees of freedom

✓ types of collective motions (rotation / vibration) a/o transfer
✓ coupling strengths and excitation energies
✓ how many states

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



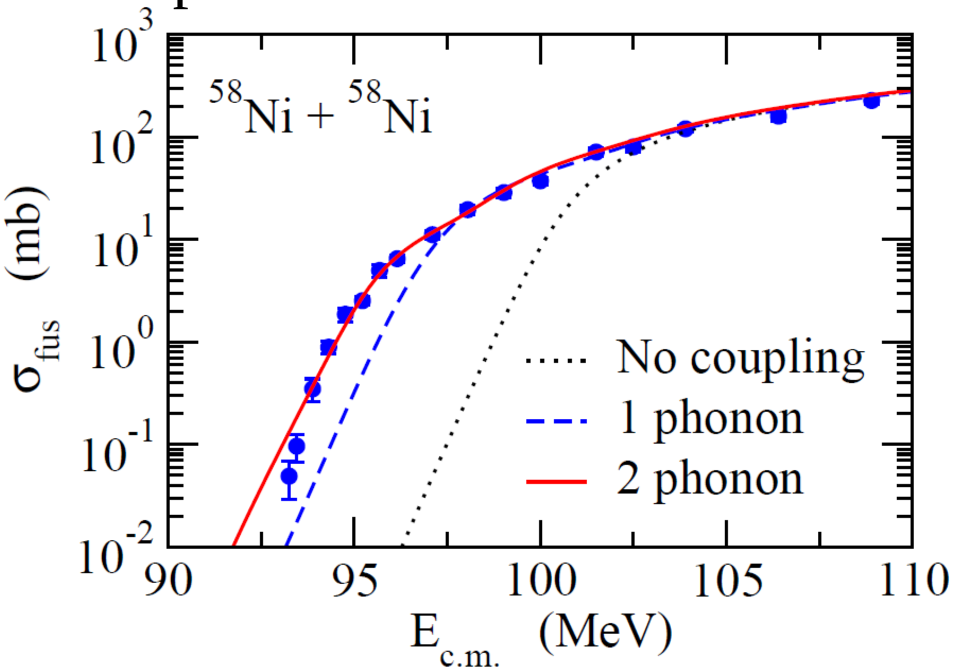
simple harmonic oscillator

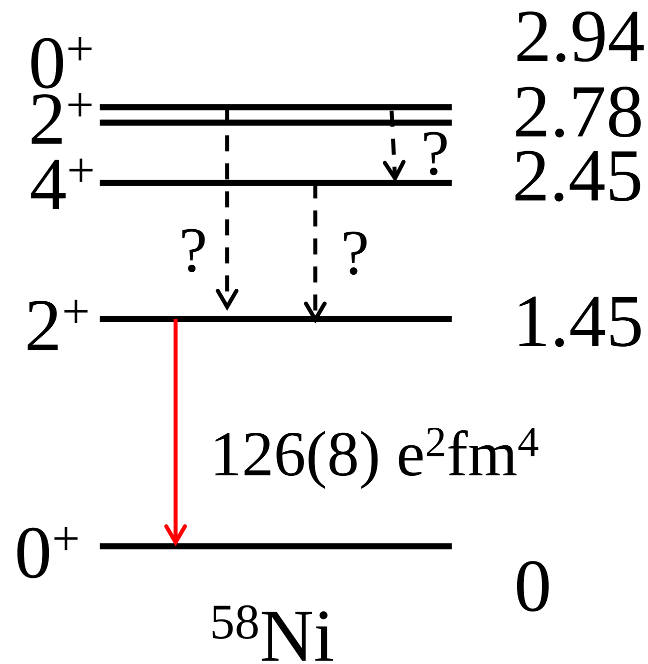


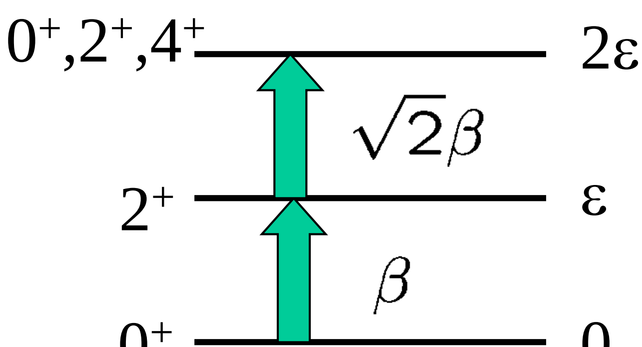
Semi-microscopic modeling of sub-barrier fusion

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

multi-phonon excitations







$Q(2_1^+) = -10 +/- 6\ e\text{fm}^2$

Simple harmonic oscillator
→ justifiable?

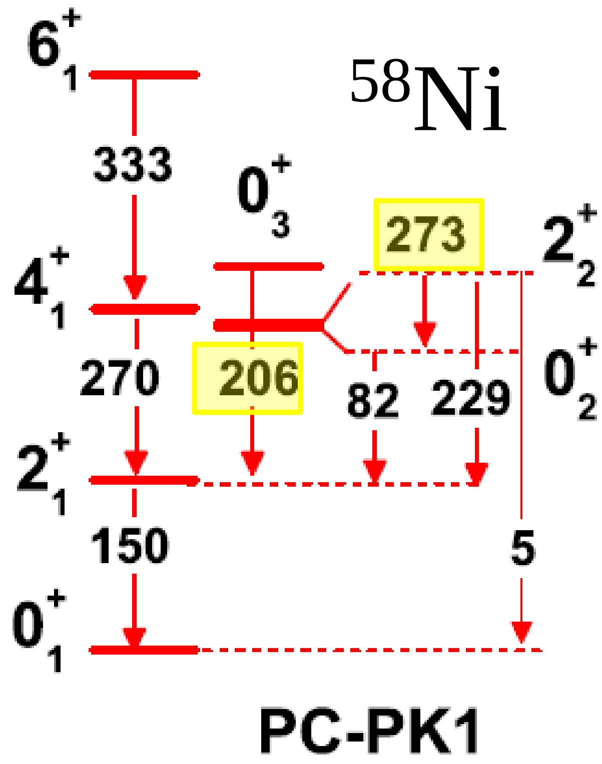
Anharmonic vibrations

- Boson expansion
- Quasi-particle phonon model
- Shell model
- Interacting boson model
- Beyond-mean-field method

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

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

M. Bender, P.H. Heenen, P.-G. Reinhard, Rev. Mod. Phys. 75 ('03) 121
J.M. Yao et al., PRC89 ('14) 054306

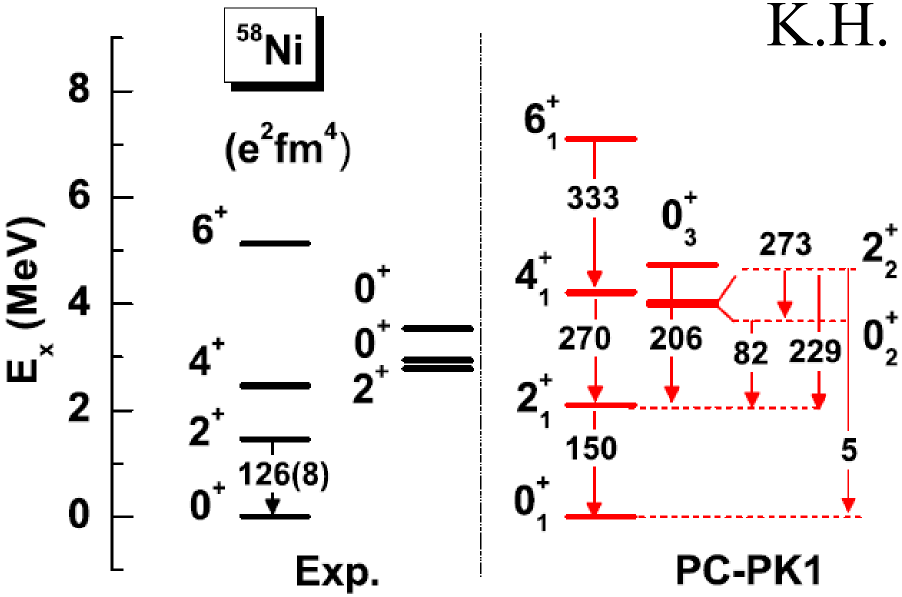


cf. Harmonic limit:
$B(E2: I_{2ph}^+ \to 2_1^+) = 2 \times B(E2: 2_1^+ \to 0_1^+)$

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

Semi-microscopic coupled-channels model for sub-barrier fusion

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



microscopic
multi-pole operator

✓ $$V_{\rm coup} \sim -R_T \frac{dV_N}{dr} \alpha_\lambda \cdot Y_\lambda(\hat{\boldsymbol{r}}) \rightarrow -R_T \frac{dV_N}{dr} Q_\lambda \cdot Y_\lambda(\hat{\boldsymbol{r}})$$

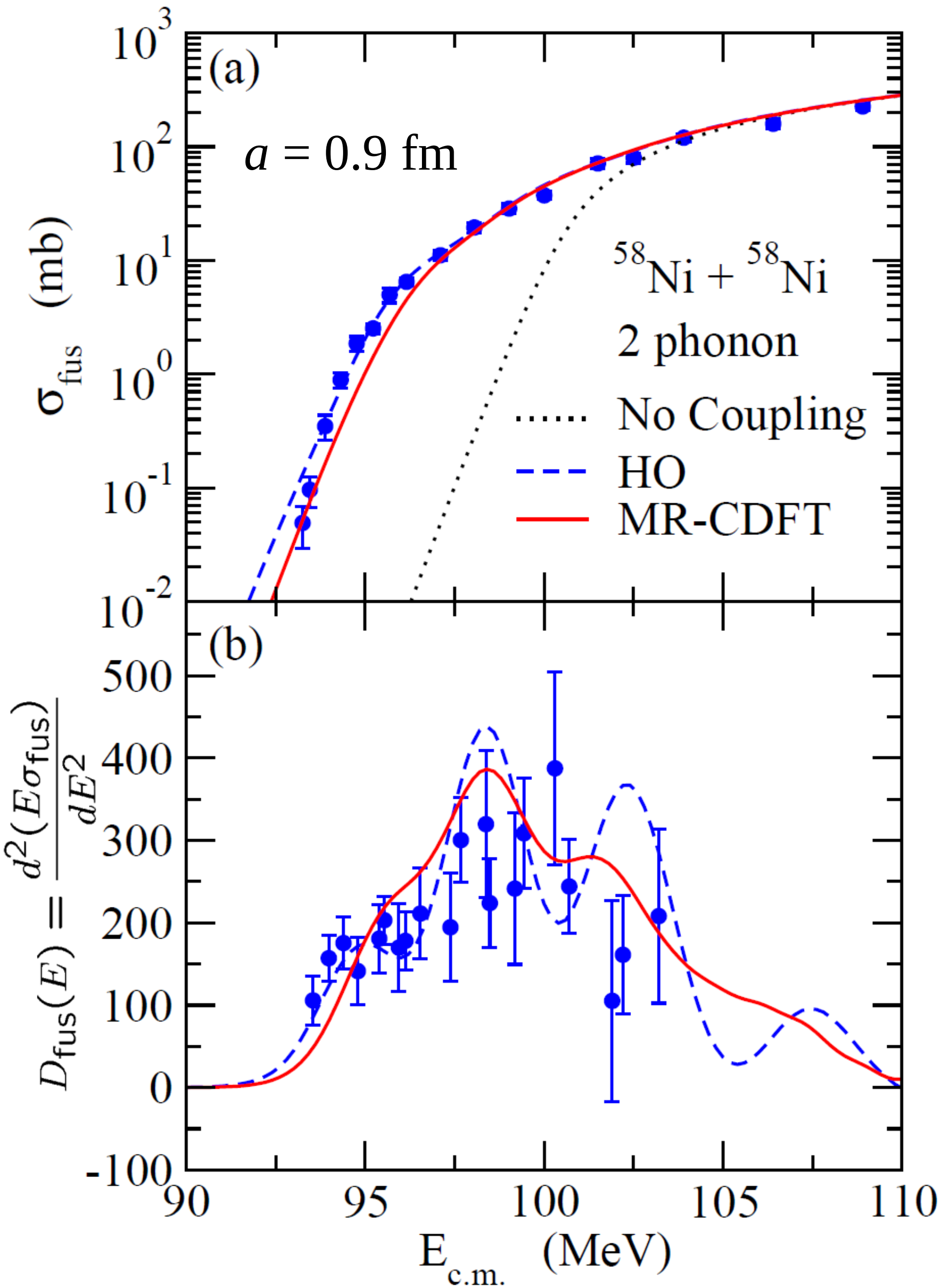
✓ *M*(E2) from MR-DFT calculation ← among higher members of phonon states

✓ scale to the empirical B(E2; $2_1^+ \rightarrow 0_1^+$)

✓ still use a phenomenological potential

✓ use the experimental values for E_x

* axial symmetry (no 3^+ state)



^{58}Ni+^{58}Ni

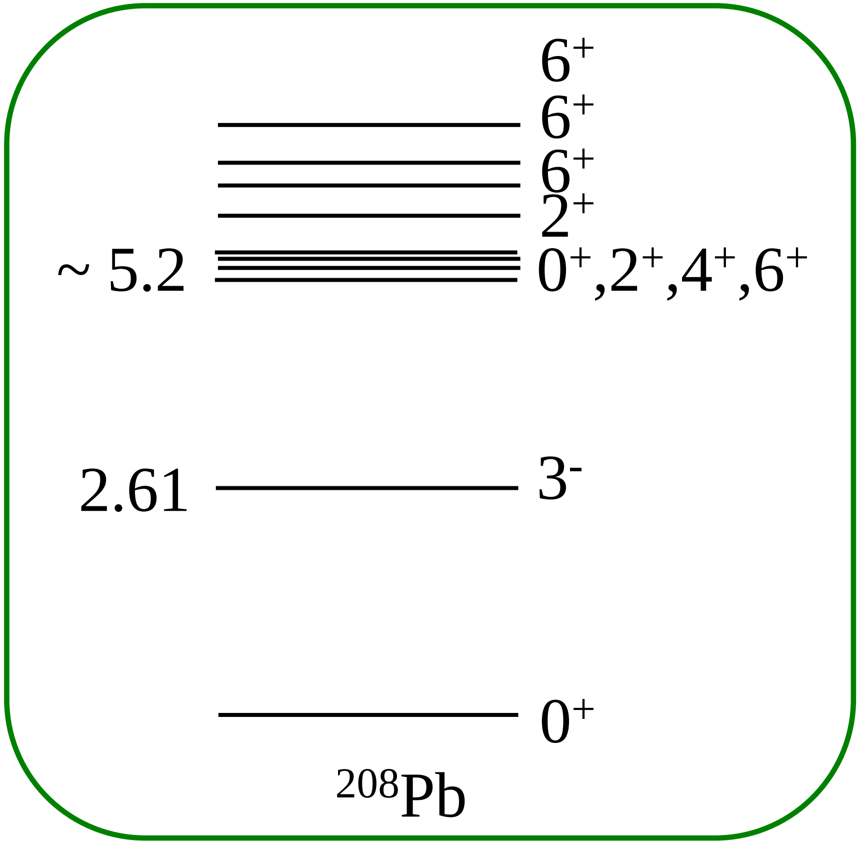
anharmonicity of 2^+ phonon
→ only a minor improvement

Next, more non-trivial case with 2^+ - 3^- coupling:
anharmonicity of oct. vib. in ^{208}Pb

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

Application to $^{16}O + ^{208}Pb$ fusion reaction

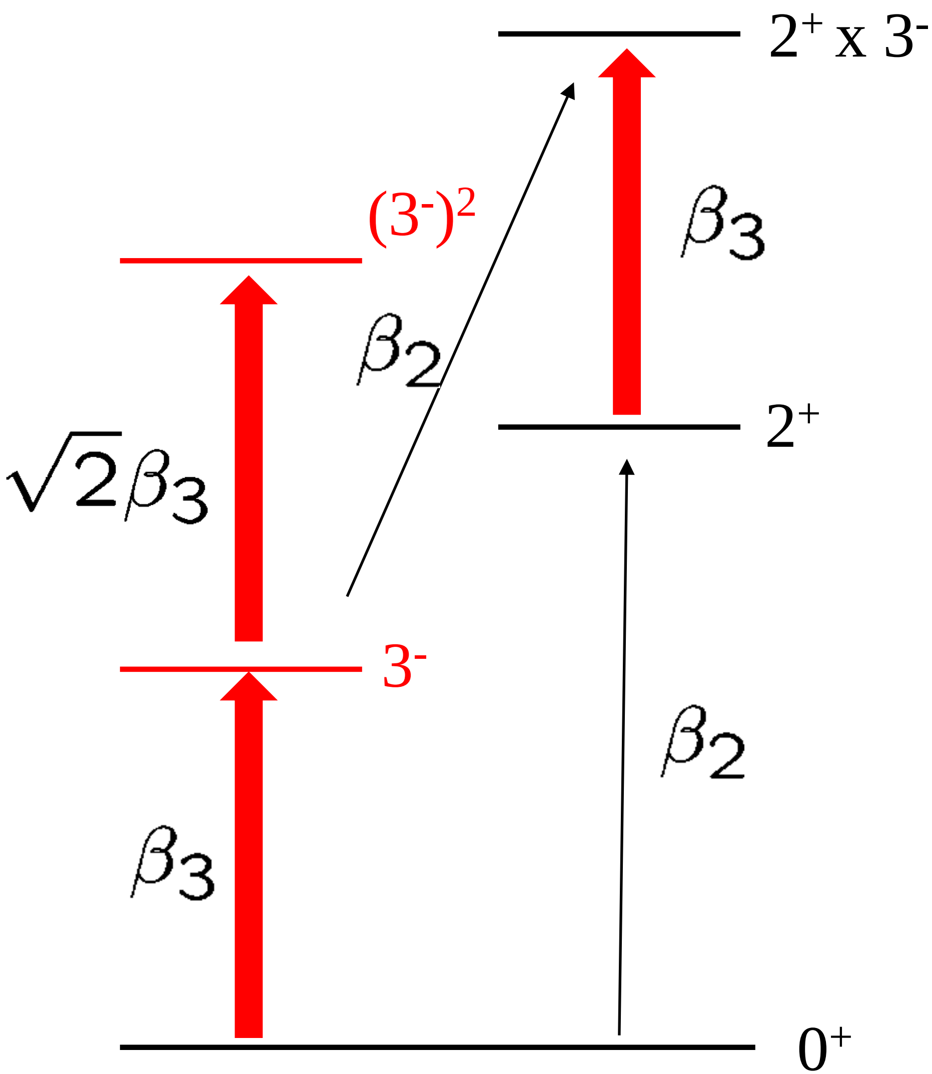
double-octupole phonon states in ^{208}Pb

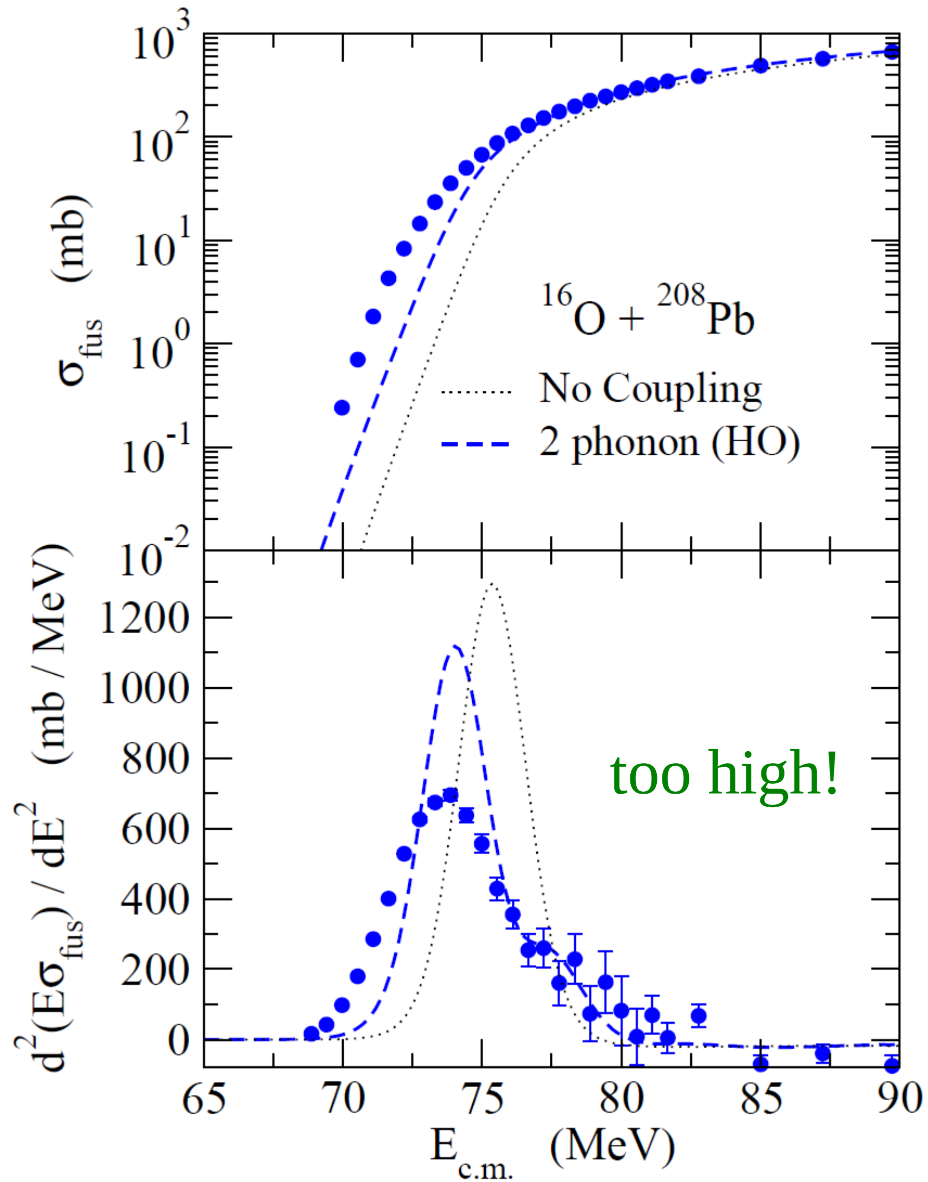


M. Yeh, M. Kadi, P.E. Garrett et al., PRC57 (‘98) R2085
K. Vetter, A.O. Macchiavelli et al., PRC58 (‘98) R2631
V. Yu. Pnomarev and P. von Neumann-Cosel, PRL82 (‘99) 501
B.A. Brown, PRL85 (‘00) 5300

large fragmentations, especially 6^+ state

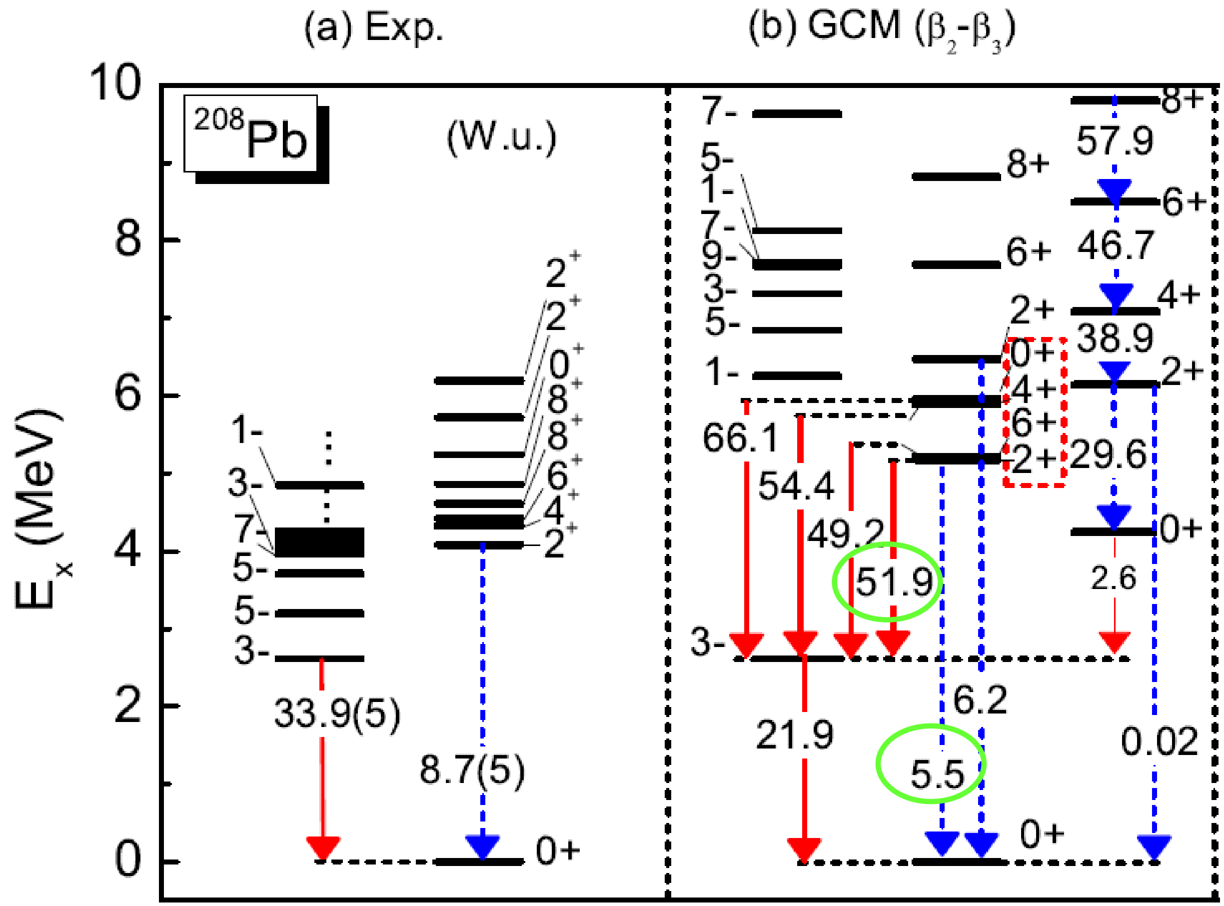
Application to $^{16}O + ^{208}Pb$ fusion reaction





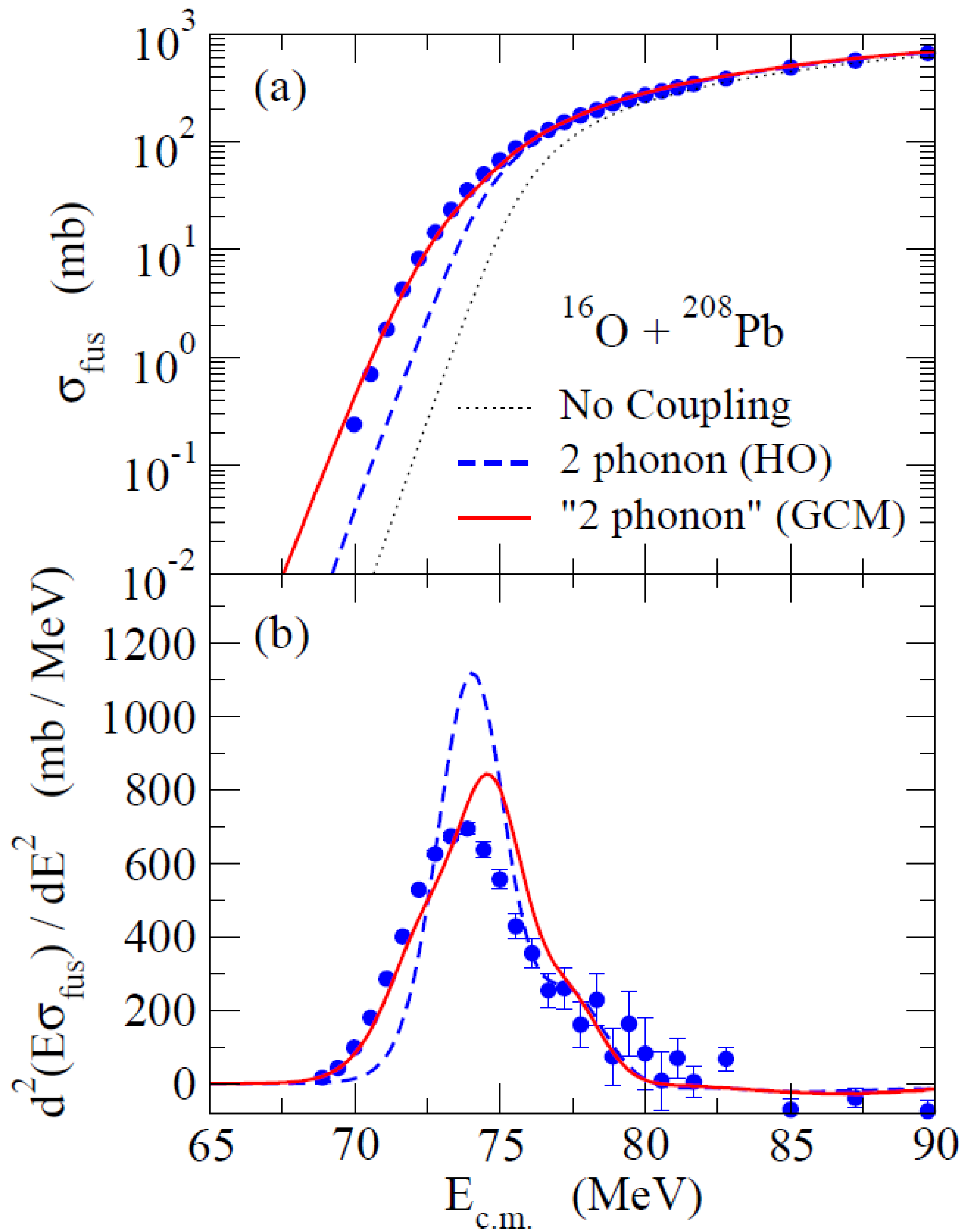
cf. C.R. Morton et al., PRC60('99) 044608 expt. data

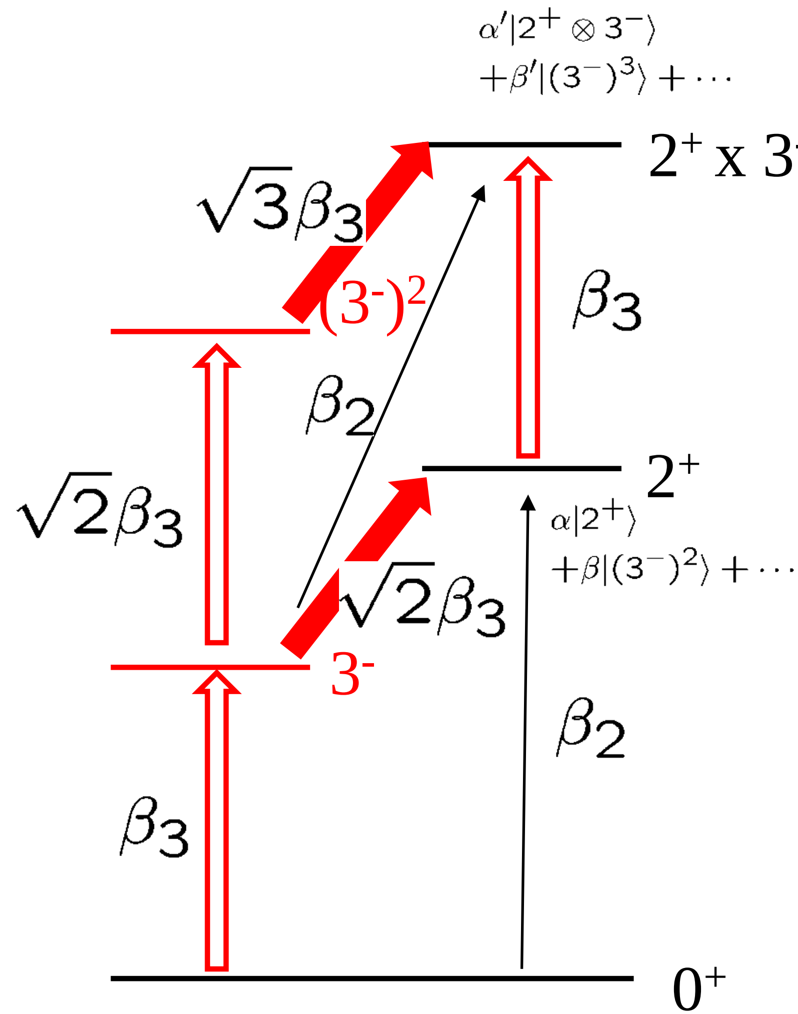
fluctuation both in β_3 and β_2



2_1^+ state: strong coupling both to g.s. and 3_1^-

$$\longrightarrow \quad |2_1^+\rangle = \alpha|2^+\rangle_{HO} + \beta|[3^- \otimes 3^-]^{(I=2)}\rangle_{HO} + \cdots$$





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

From phenomenological approach to microscopic approach

Macroscopic (phenomenological)

C.C. with collective model

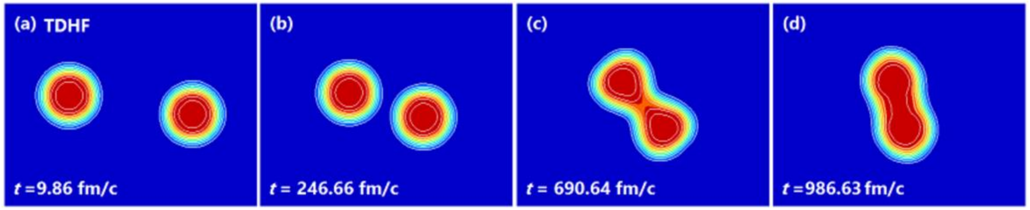
C.C. with inputs from microscopic nuclear structure calculations

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

Time-dependent GCM for many-body tunneling

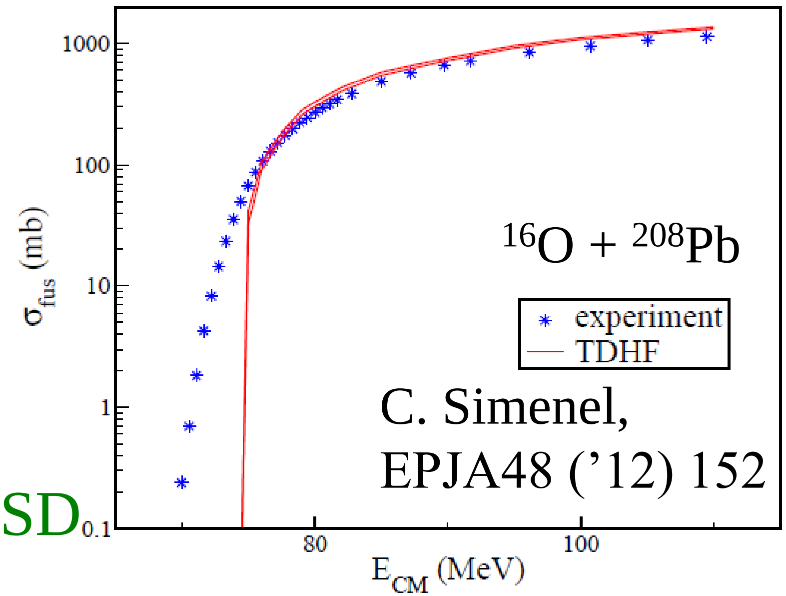
N. Hasegawa, K.H., and Y. Tanimura, in preparation

TDHF simulations

ab initio, but no tunneling

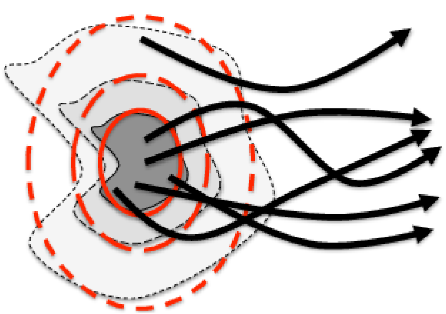
need to go Beyond the mean-field app.

✓ Time-dependent GCM



a single Slater determinant (SD) to multi-SD

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

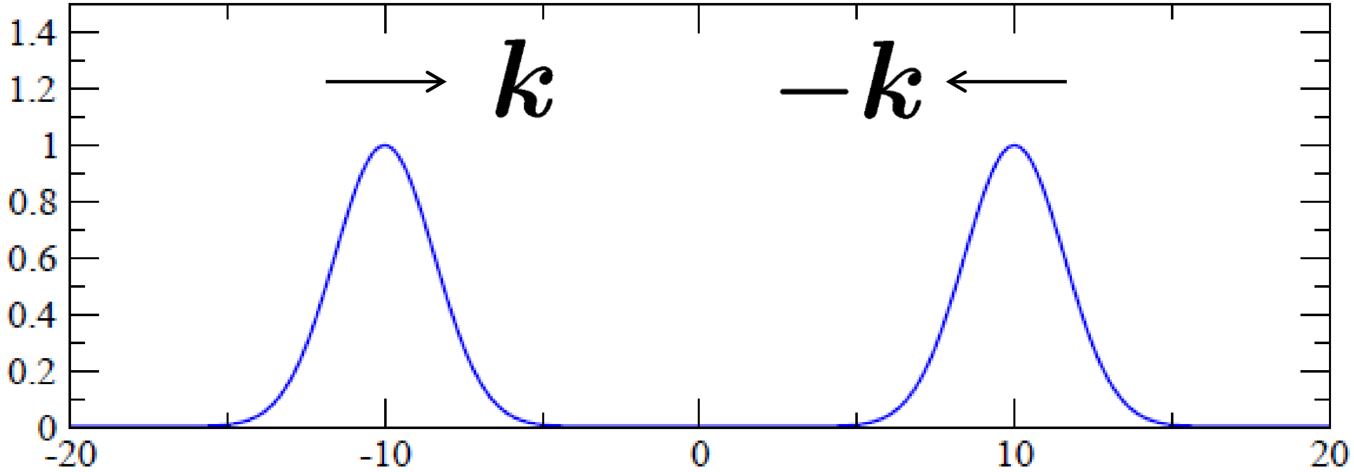


dynamics with a superposition of many "TDHF trajectories (Slater determinants)"

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

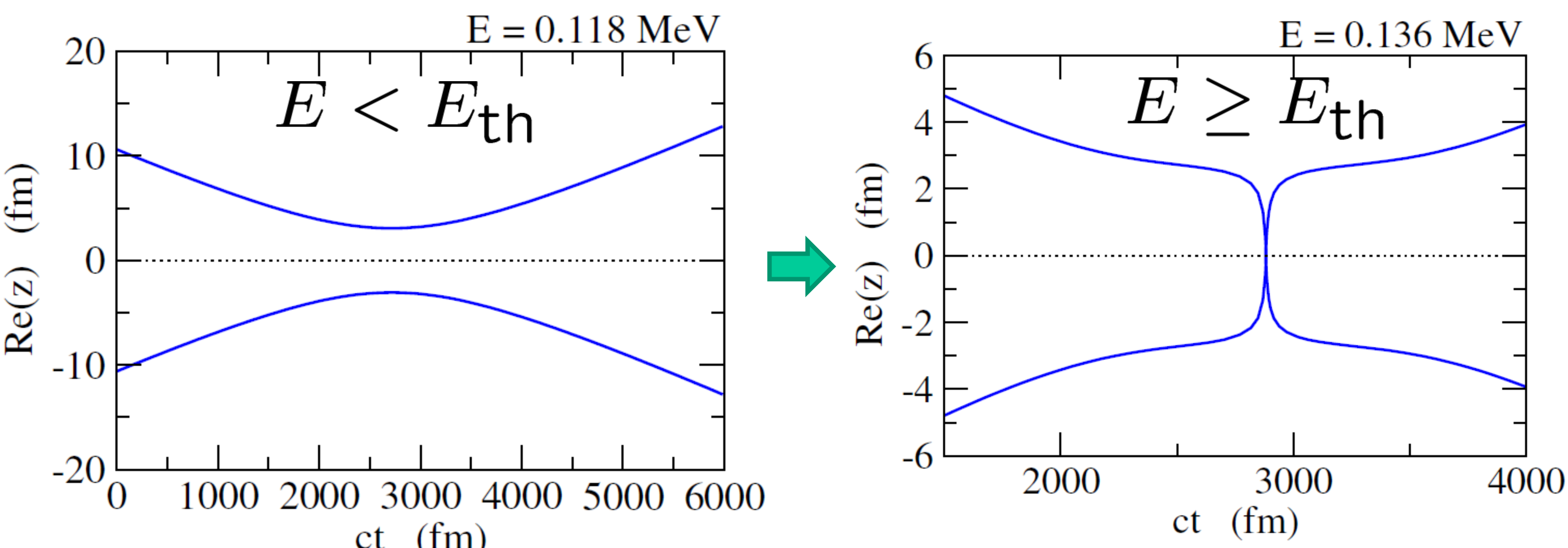
TDHF

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

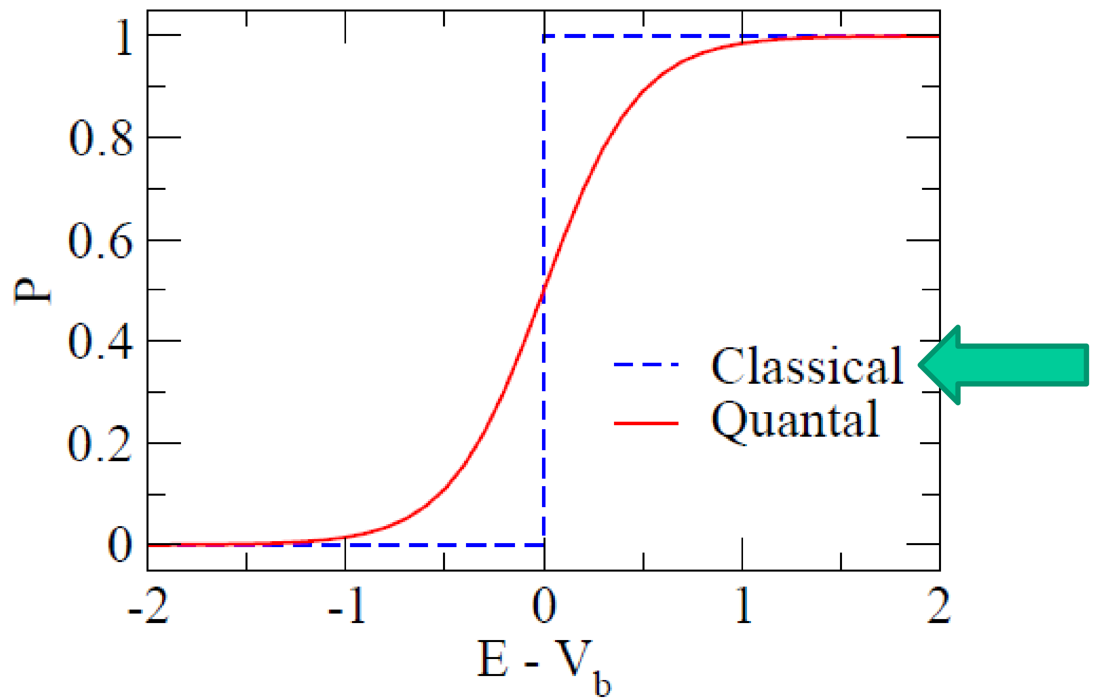


$$e^{ikx}\varphi_i(x + x_0) \qquad e^{-ikx}\varphi_i(x - x_0)$$

α+α in 1D

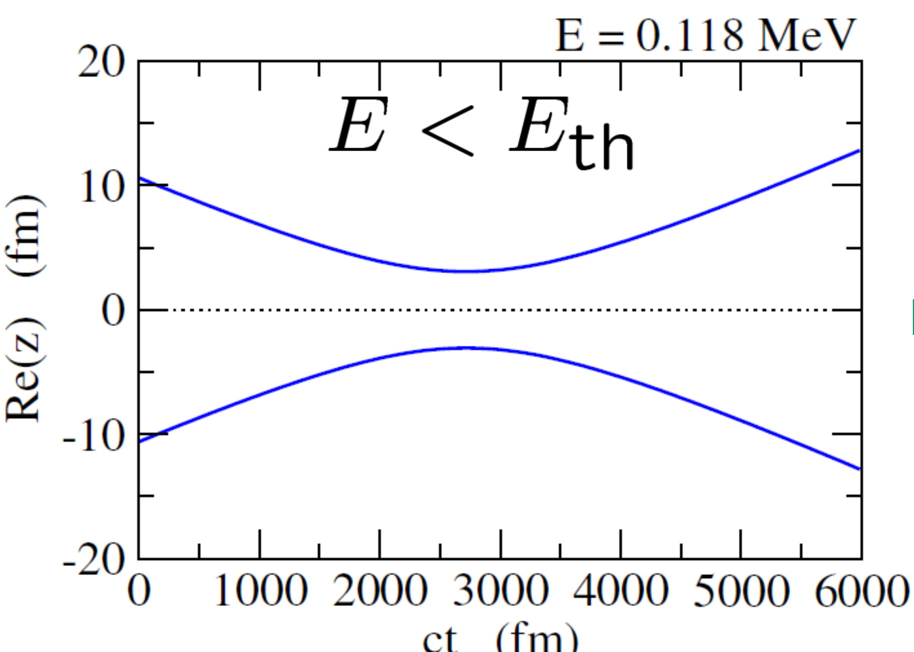


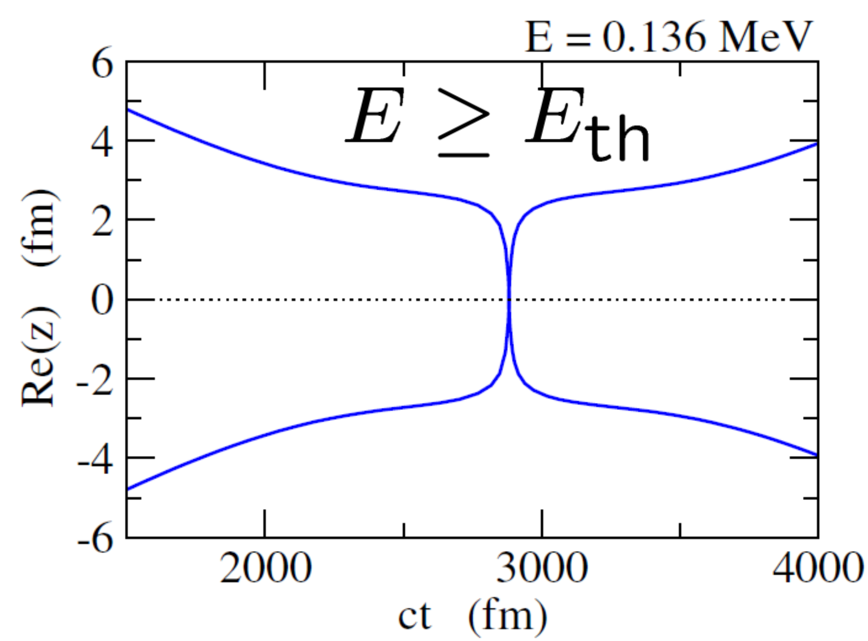
TDHF



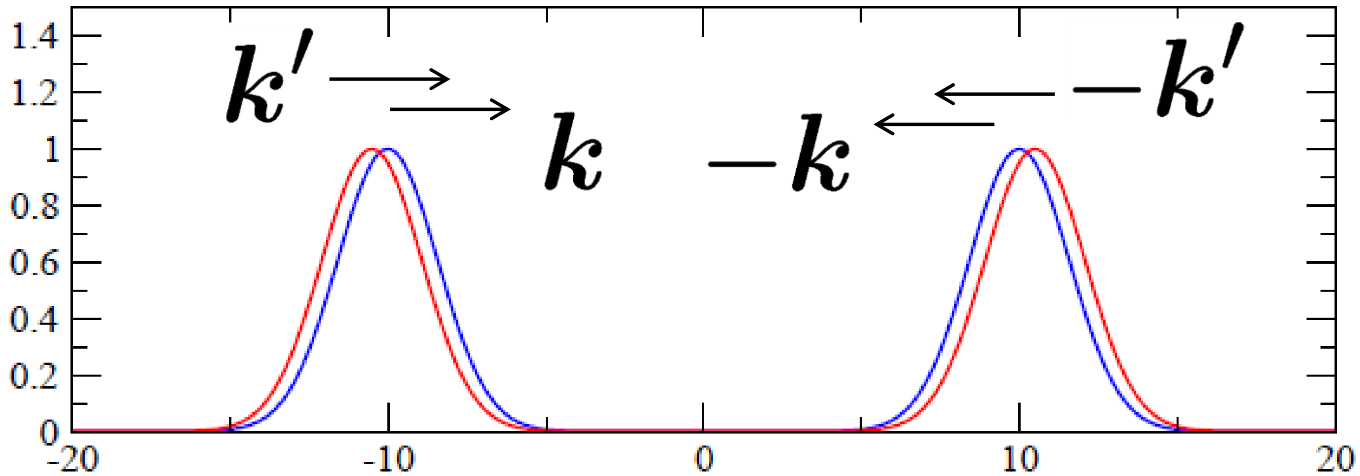
TDHF

α+α in 1D





TDGCM

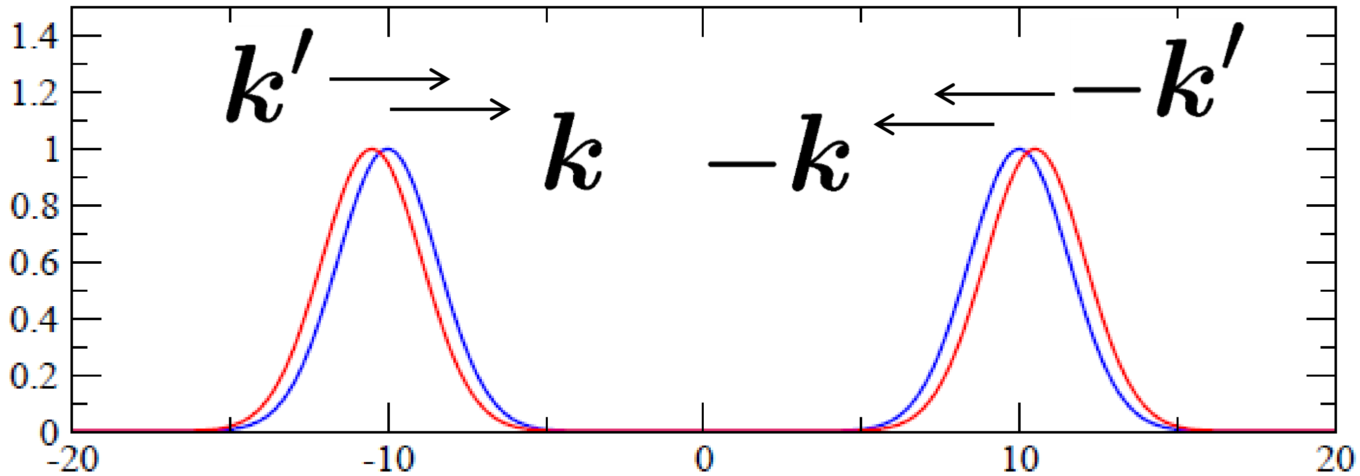


$$\Psi(t) = \sum_k f_k(t) \Phi_{\mathrm{SD},k}(t)$$

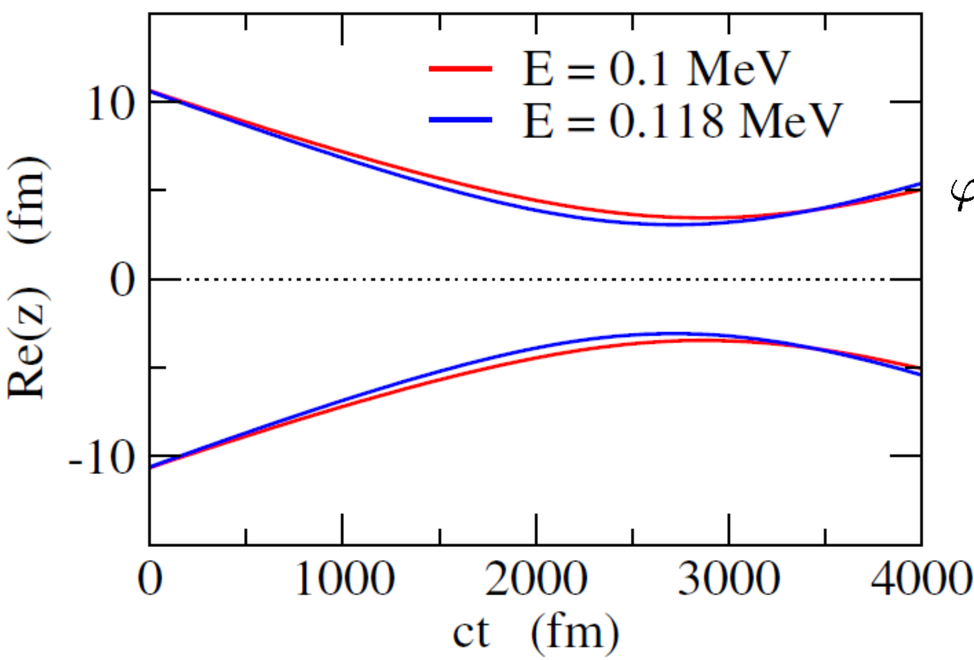
time-dep. variational principle

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

TDGCM



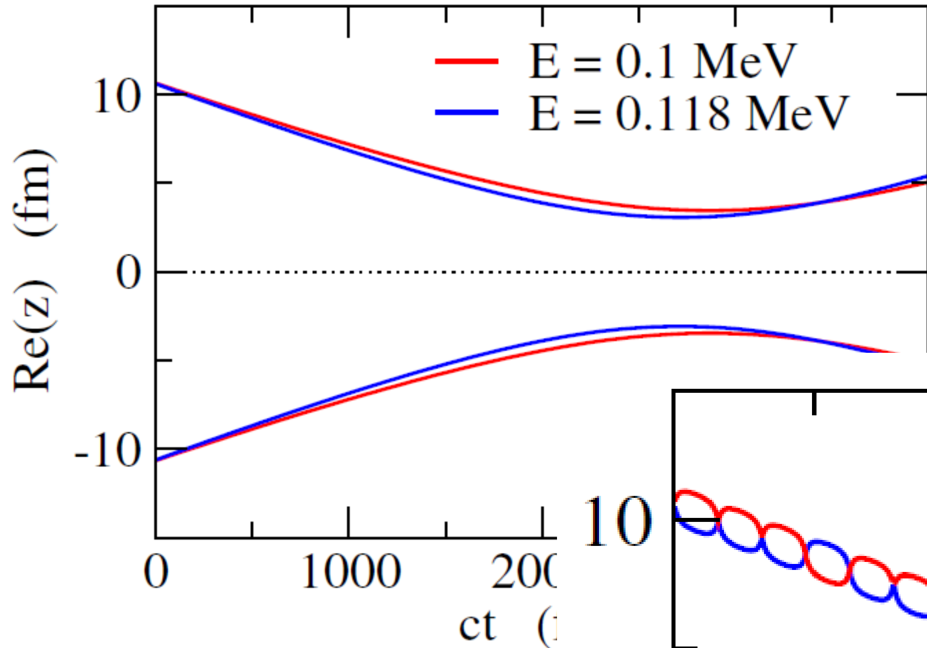
α+α in 1D



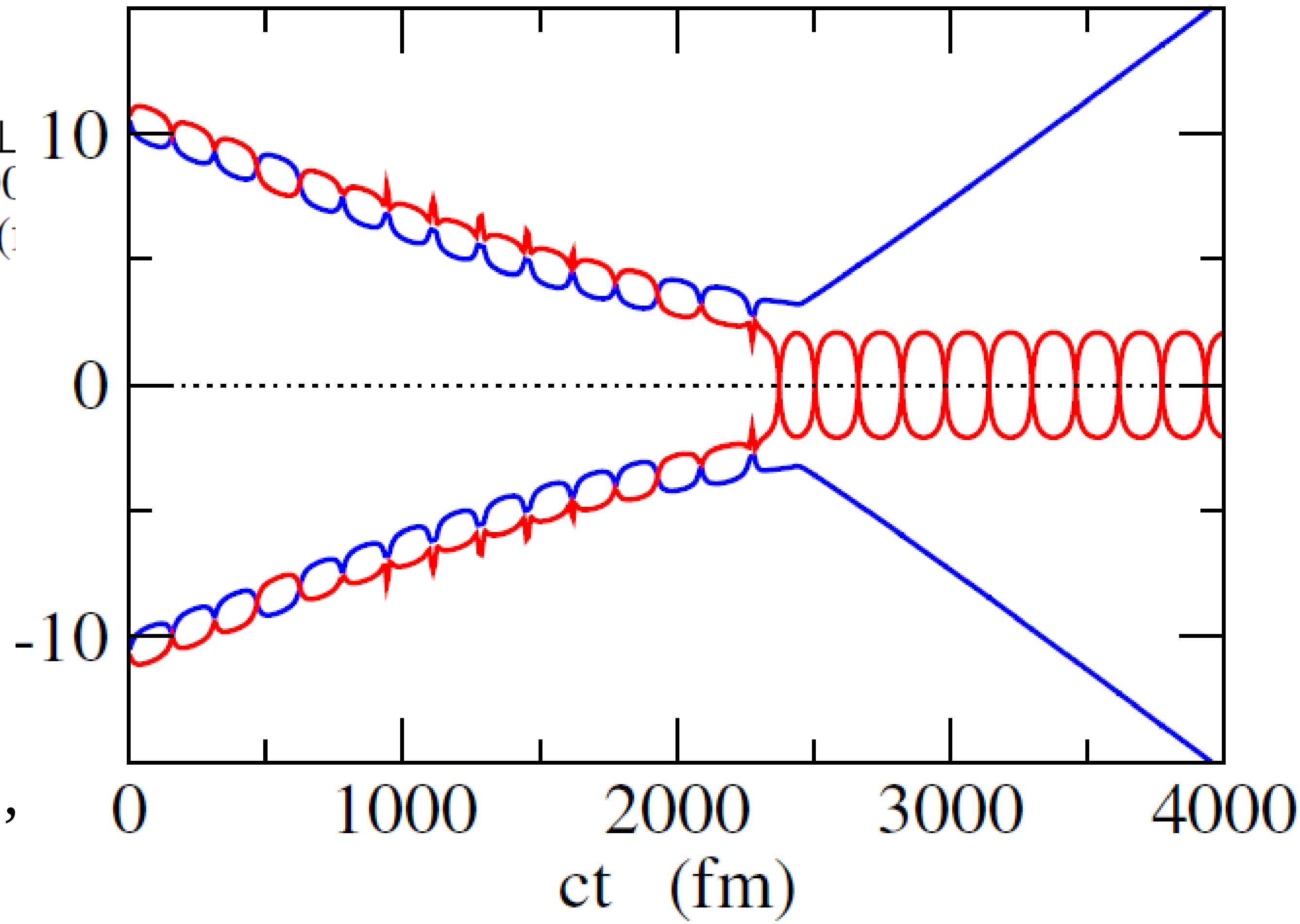
a simplification:

$$\varphi_i^{(k)}(x,t) \sim \exp\left[-\nu\left(x - \frac{Z_i^{(k)}(t)}{\sqrt{\nu}}\right)^2\right]$$

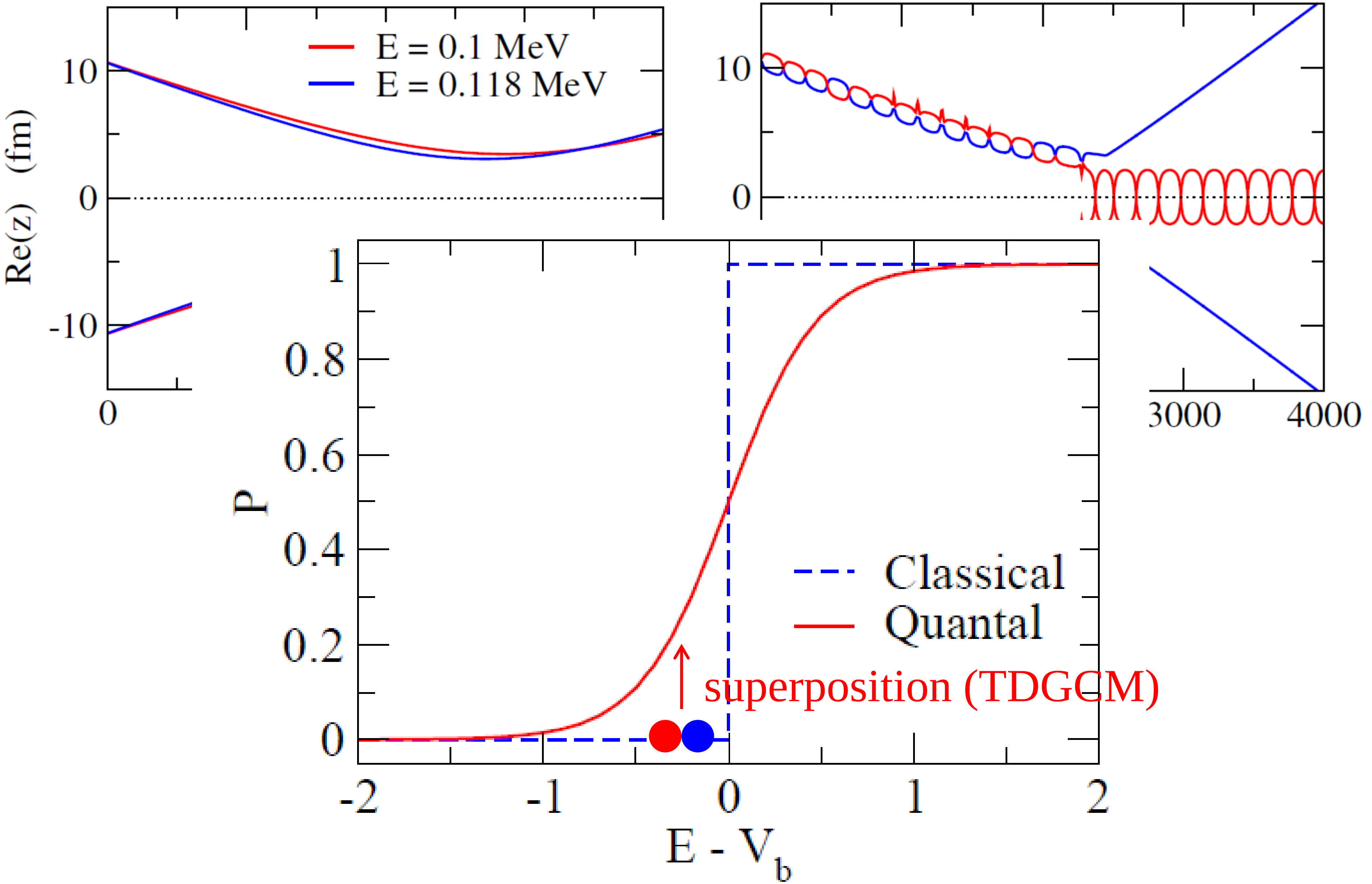
$$\Phi_{\mathrm{SD},k}(t) = \mathcal{A}\left[\{\varphi_i^{(k)}(x,t)\}\right]$$



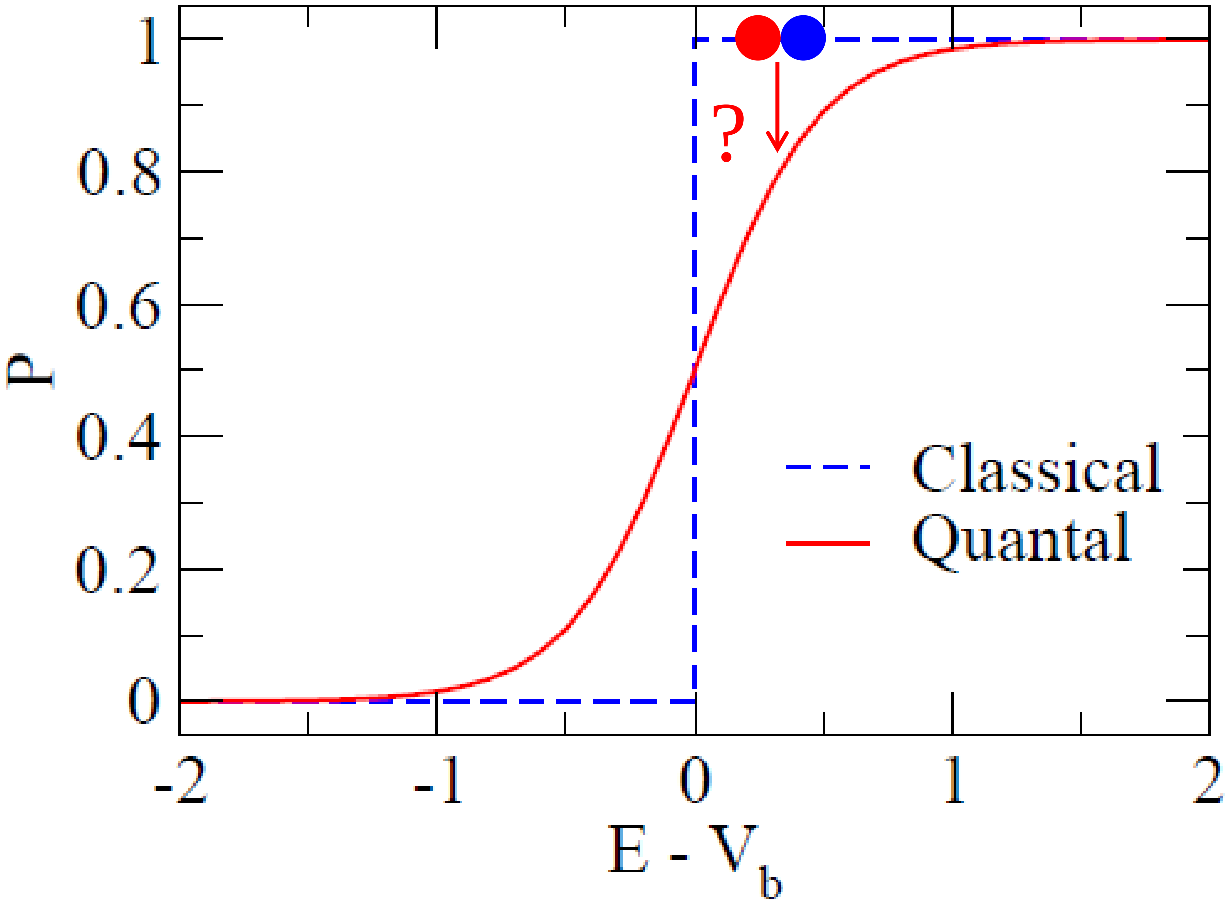
TDGCM
(a superposition
of two SD)



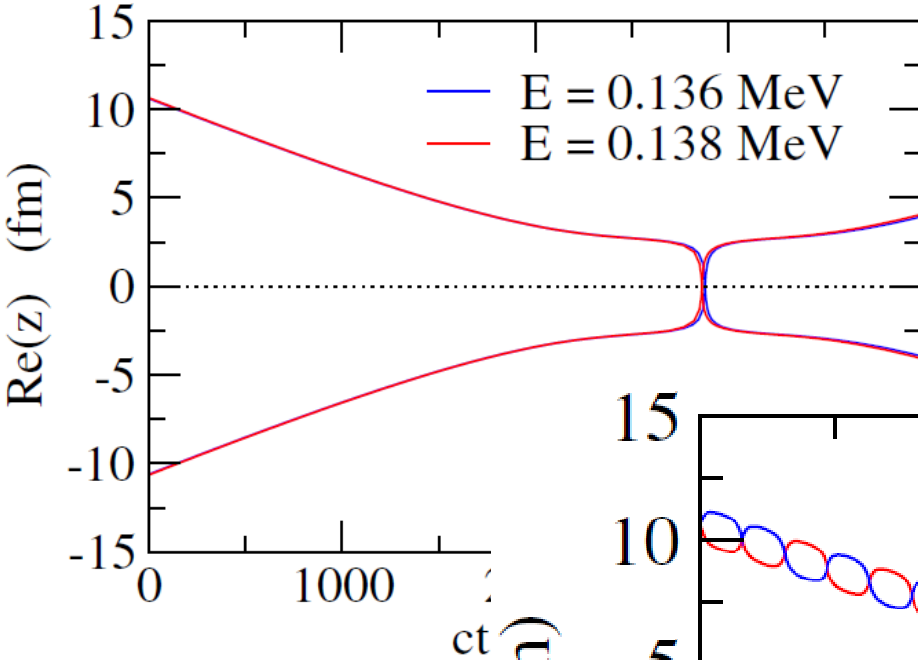
N. Hasegawa, K.H.,
and Y. Tanimura,
in preparation



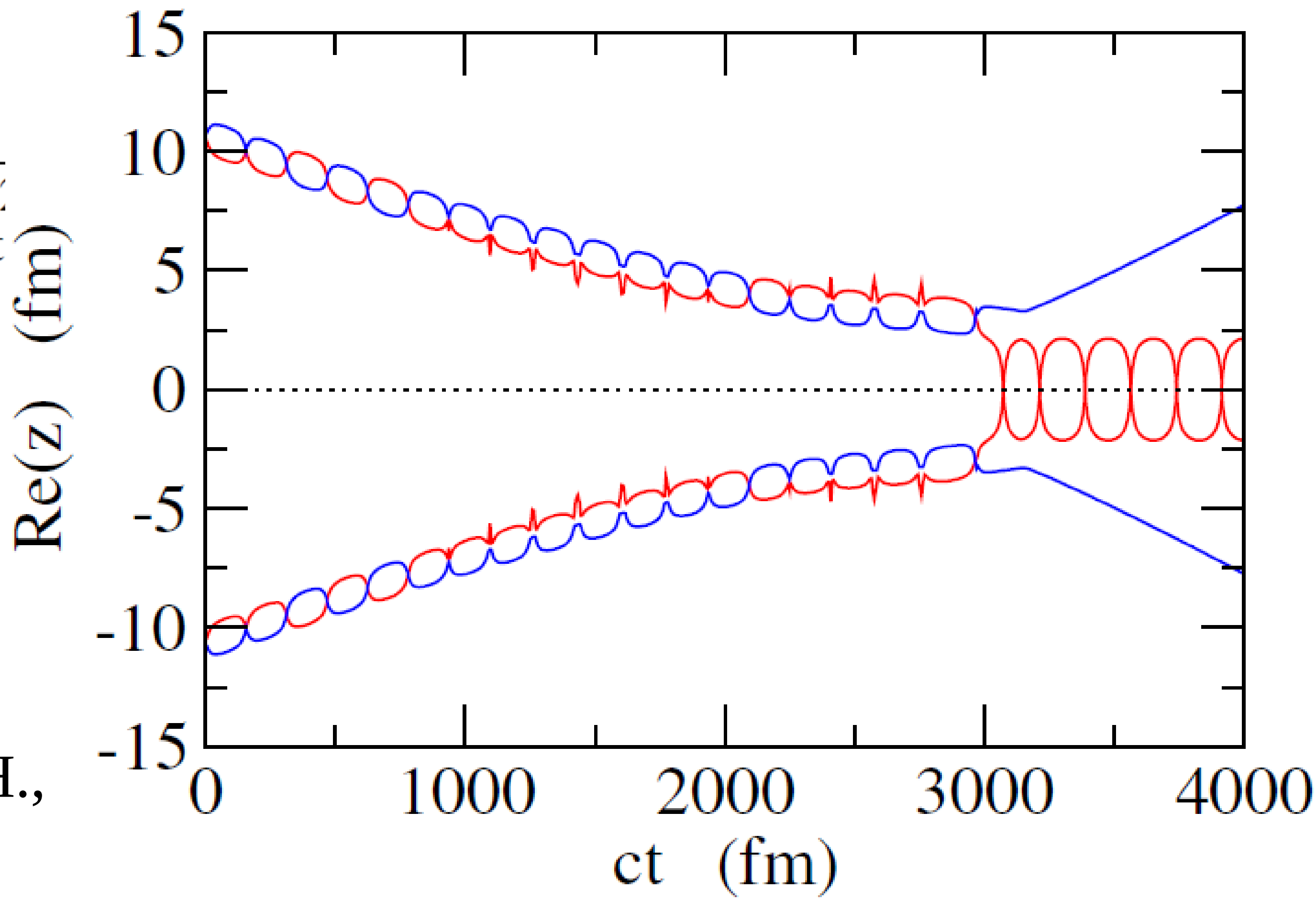
N. Hasegawa, K.H., and Y. Tanimura, in preparation



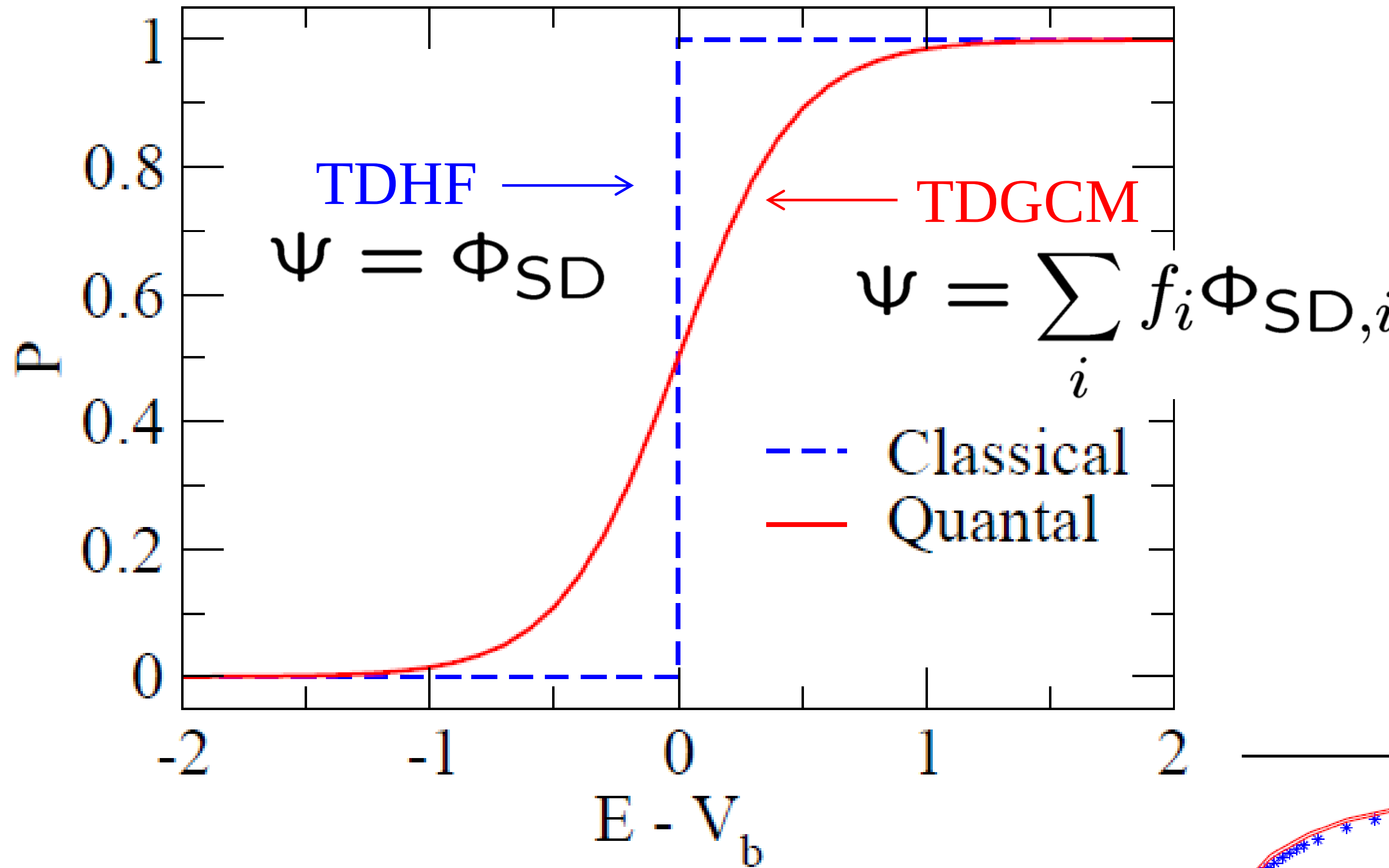
1
0.8
0.6
0.4
0.2
0
P
?
Classical
Quantal
-2
-1
0
1
2
E - V_b



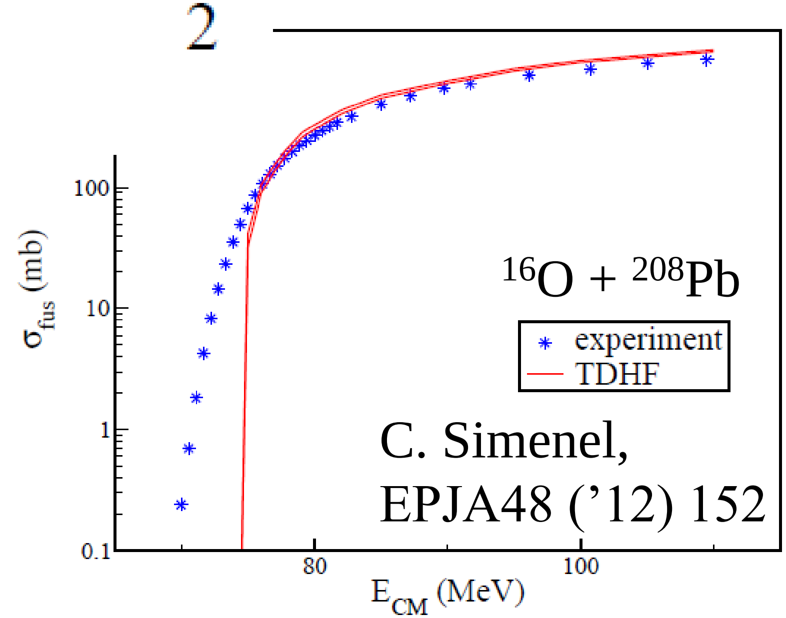
TDGCM
(a superposition of two SD)



N. Hasegawa, K.H., and Y. Tanimura, in preparation

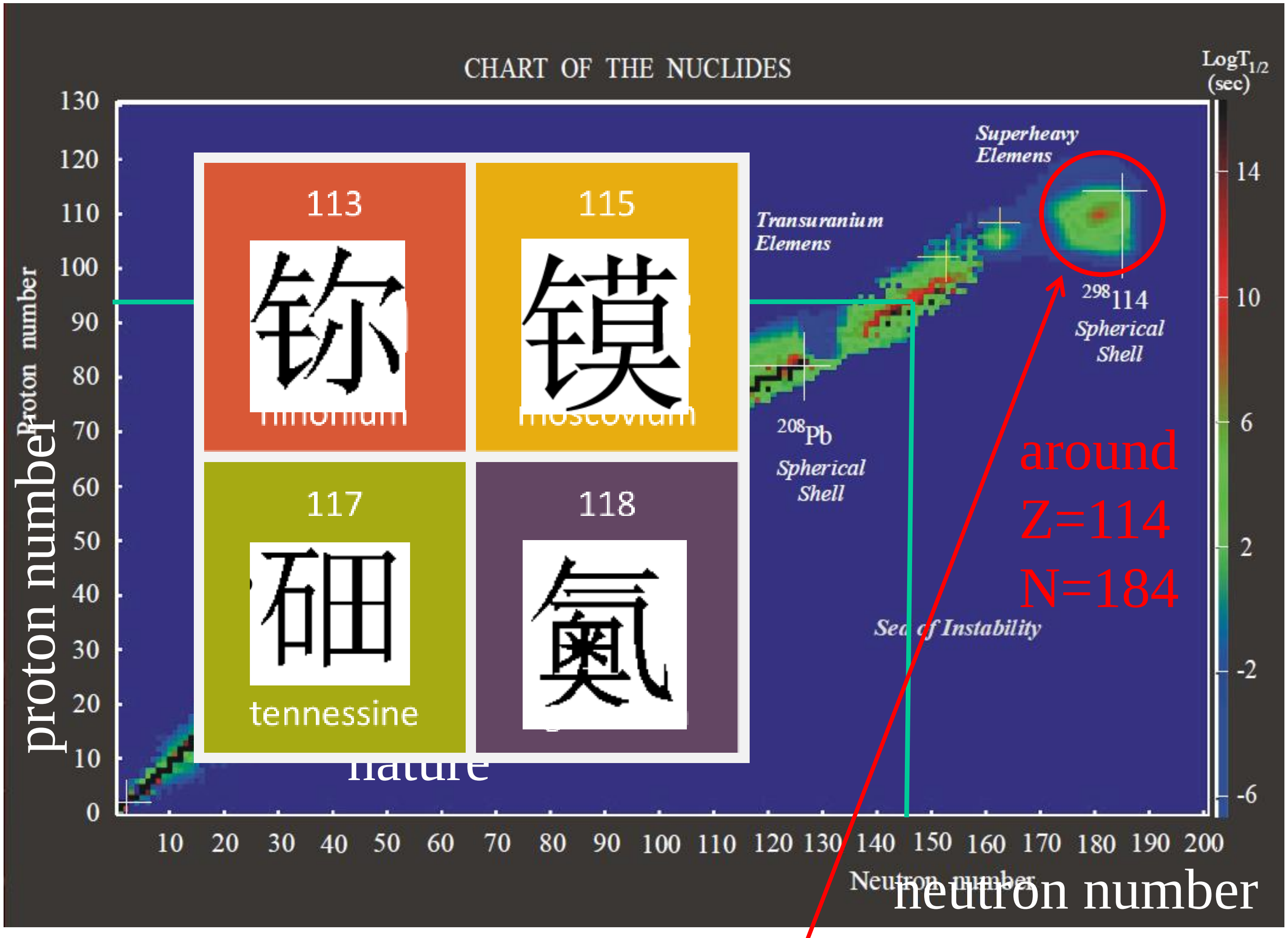


TDGCM:
a promising microscopic theory
for many-body tunneling



Fusion for superheavy elements

超重元素



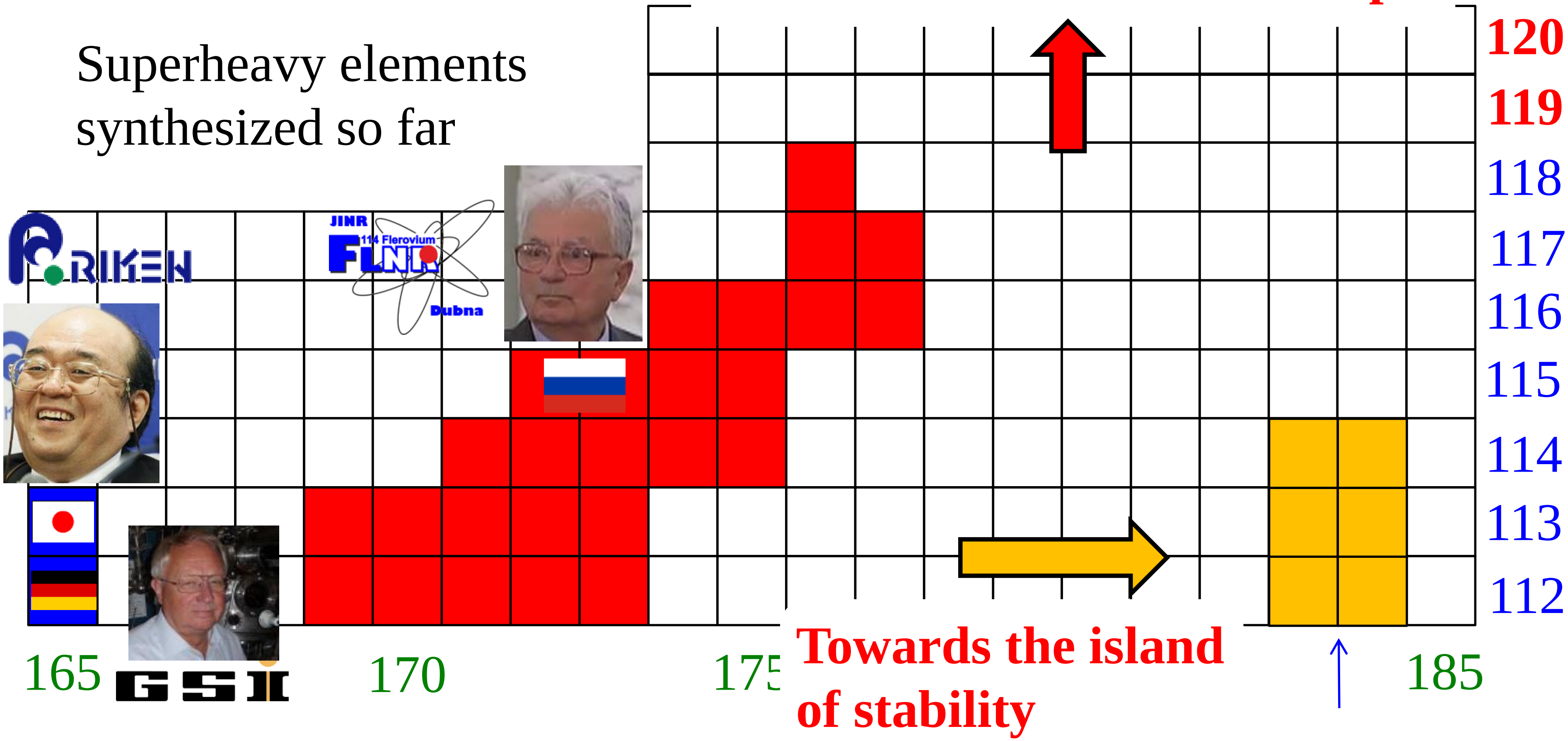
Yuri Oganessian

a prediction of island of stability

(Swiatecki et al., 1966)

Future directions of SHE

Towards Z=119 and 120 isotopes



the island
of stability?

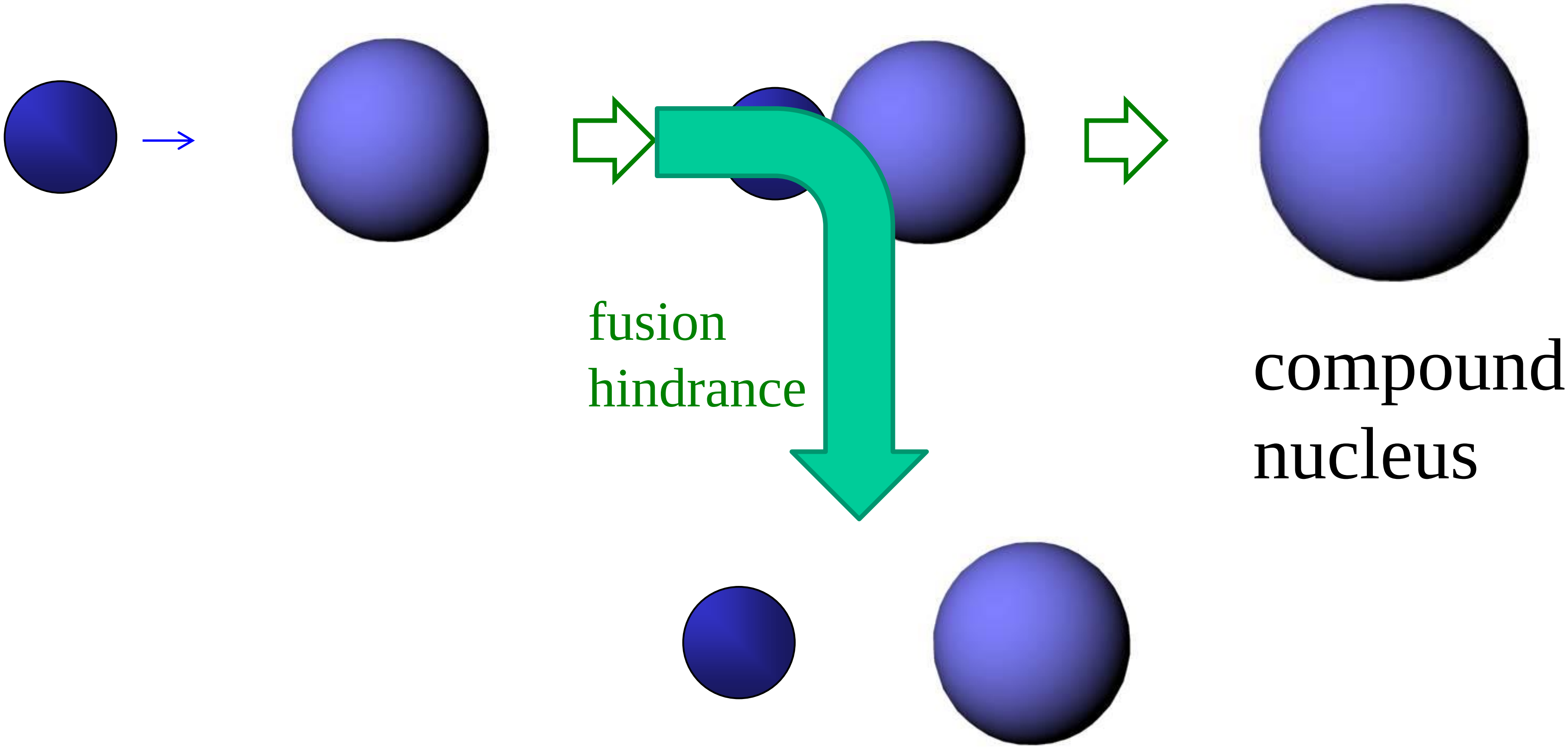
➢Towards Z=119 and 120 isotopes

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

➢Towards the island of stability

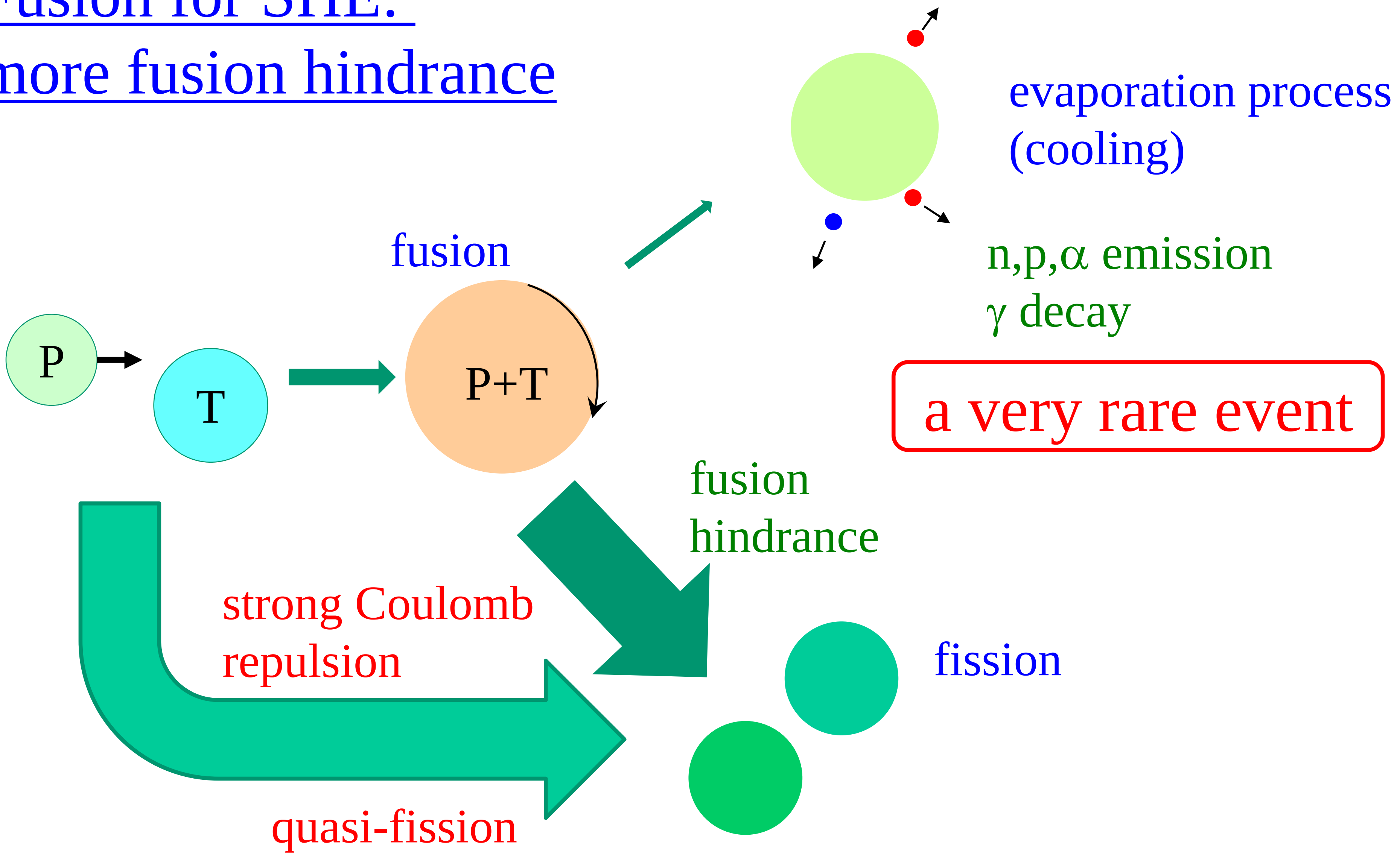
neutron-rich beams: indispensable → reaction dynamics?

Fusion for SHE: fusion hindrance



strong Coulomb repulsion
→ re-separation

Fusion for SHE: more fusion hindrance



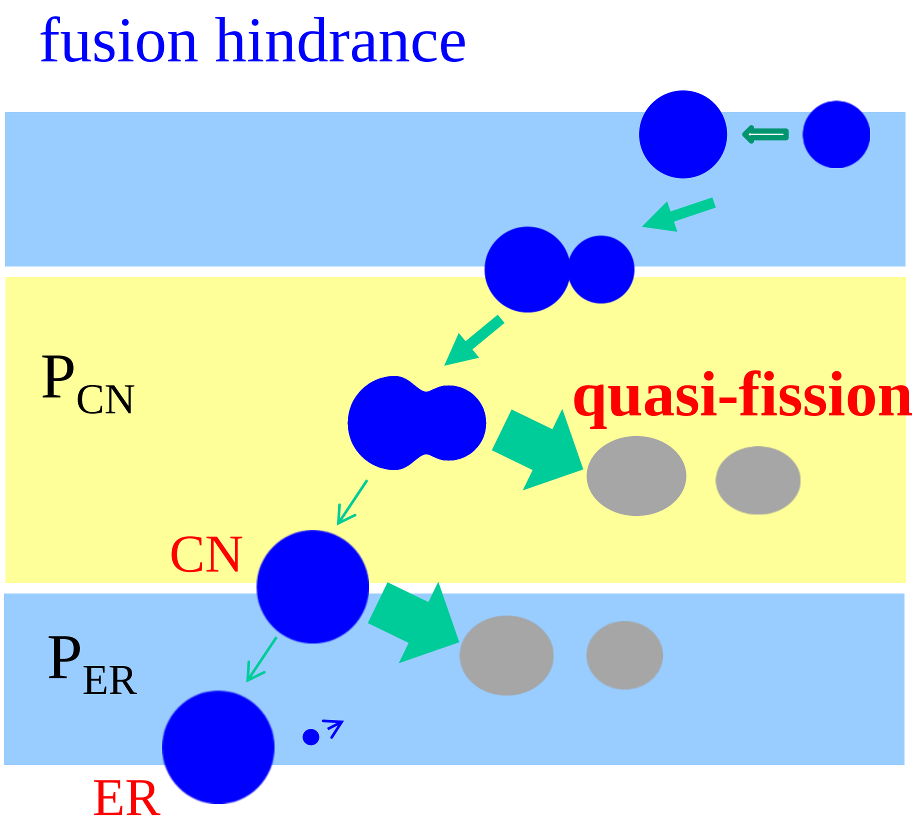
Theoretical challenges

formation of SHE: very rare

→ a large theoretical uncertainty

✓no exp. data for P_{CN}
✓exp. data: P_{ER} only

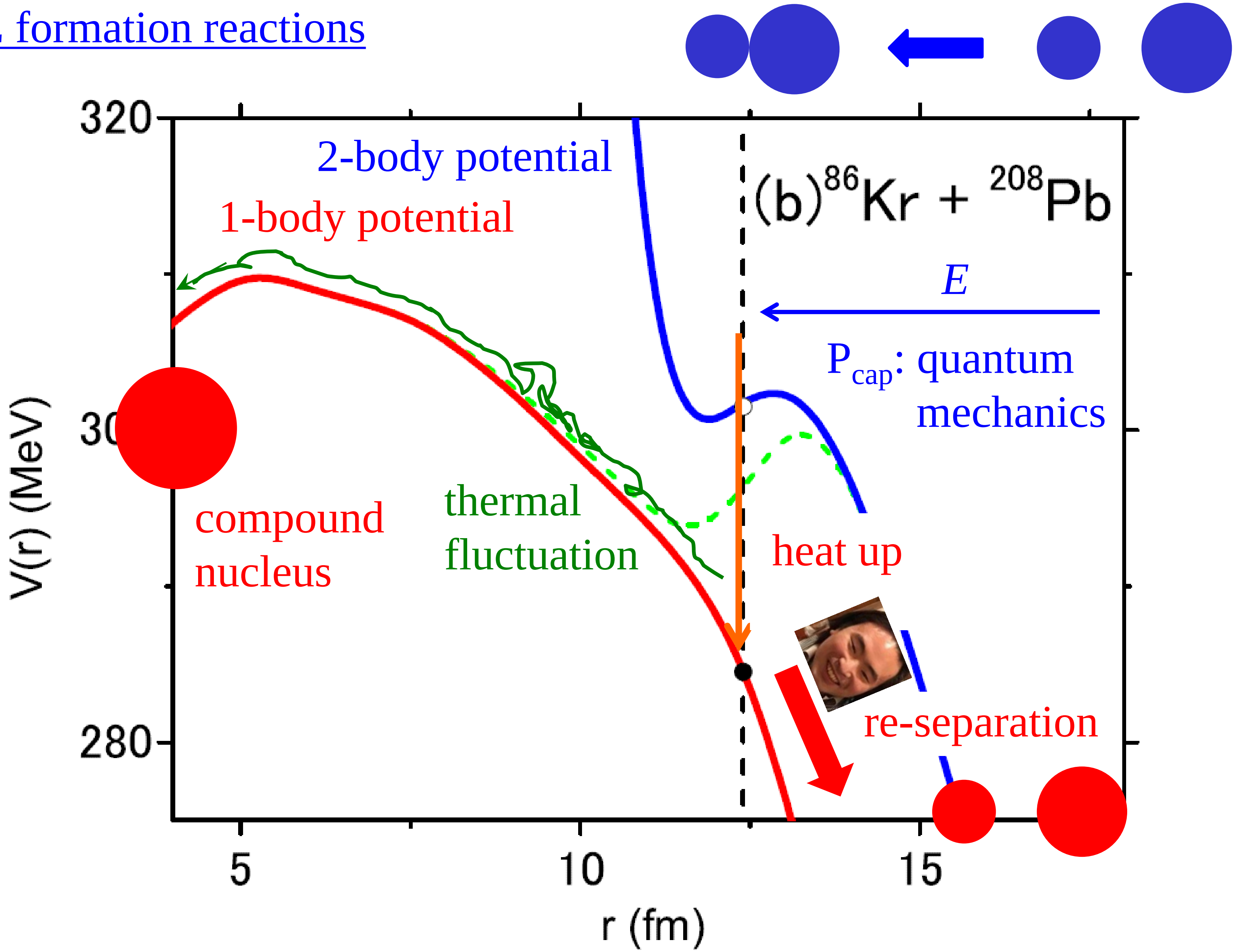
CN＝複合核、ER=蒸発残留核



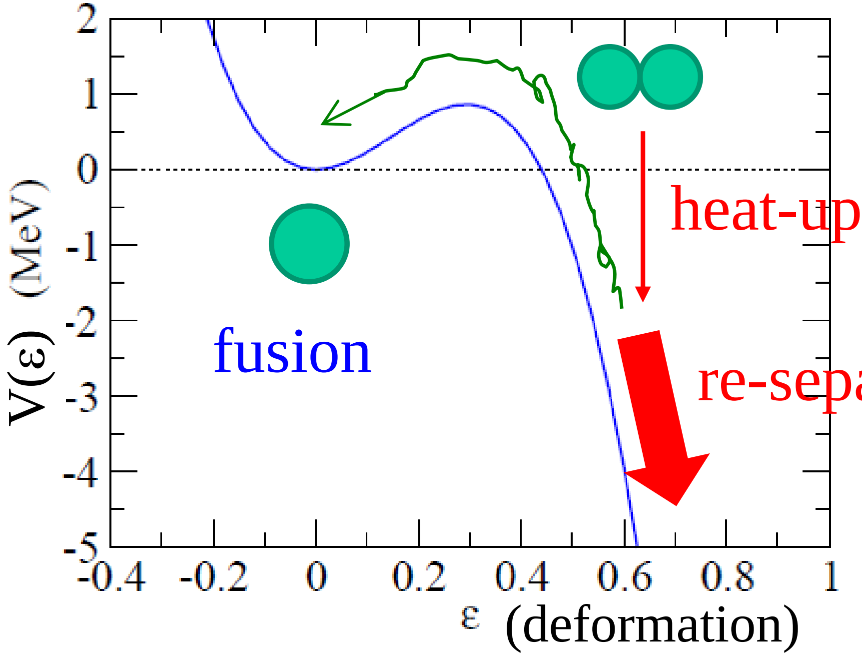
theoretical challenges:
to reduce the uncertainties and
make reliable predictions

⇒ Physics of open quantum systems

SHE formation reactions

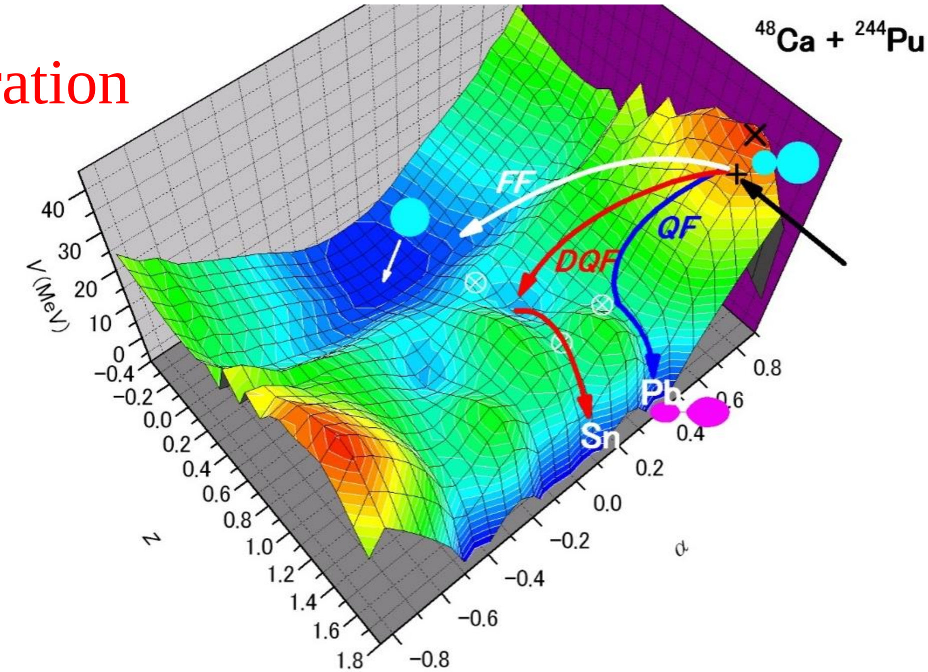


Langevin approach



multi-dimensional extention

q: ▪ internuclear separation,
▪ deformation,
▪ asymmetry of the two fragments



thermal fluctuation

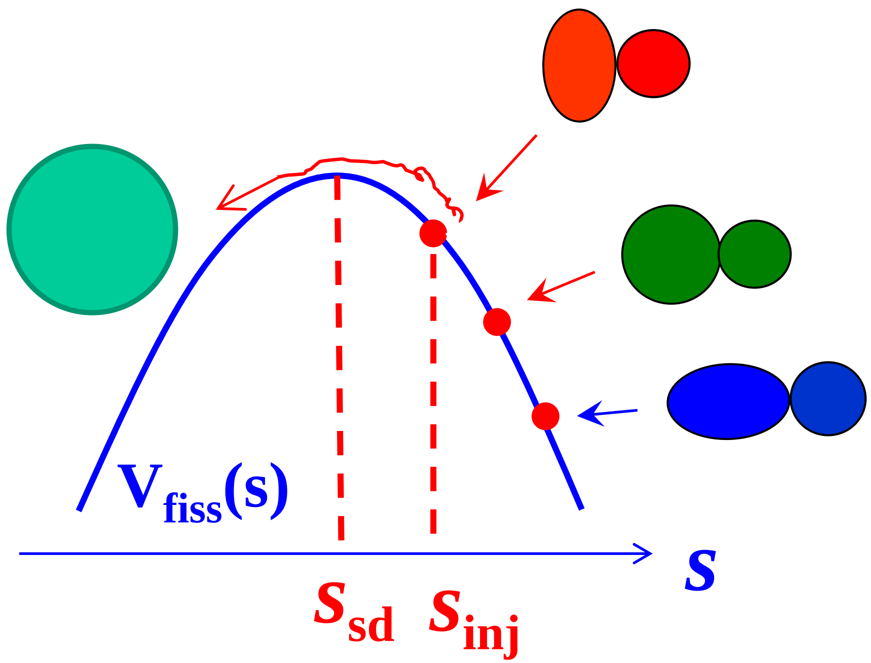
⟶ Langevin method
(Brownian method)

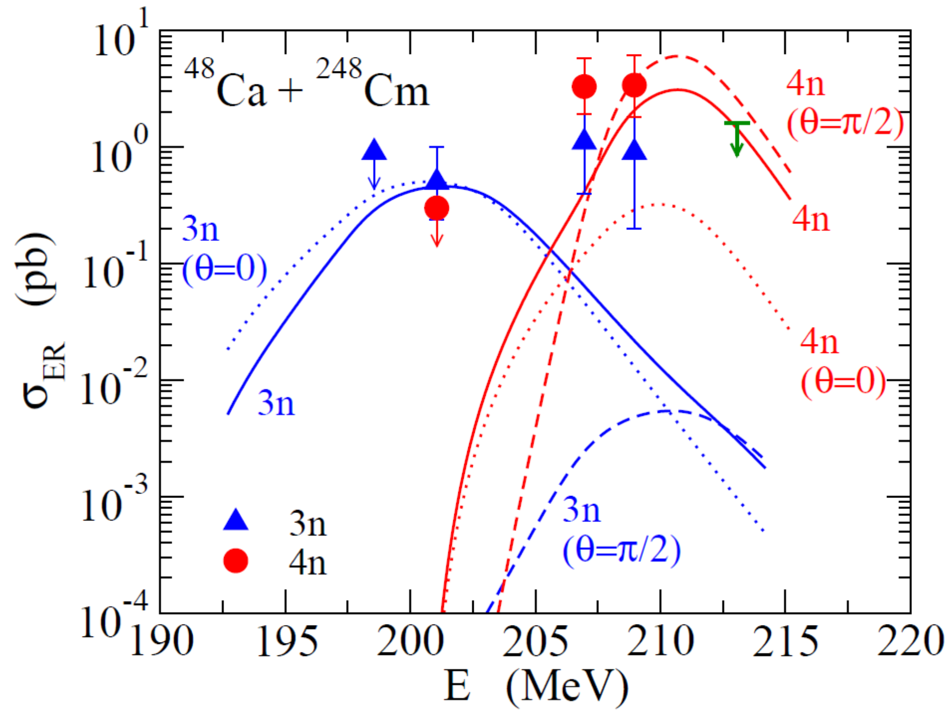
$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$

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

Extension of fusion-by diffusion model

K. Hagino, PRC98 (‘18) 014607

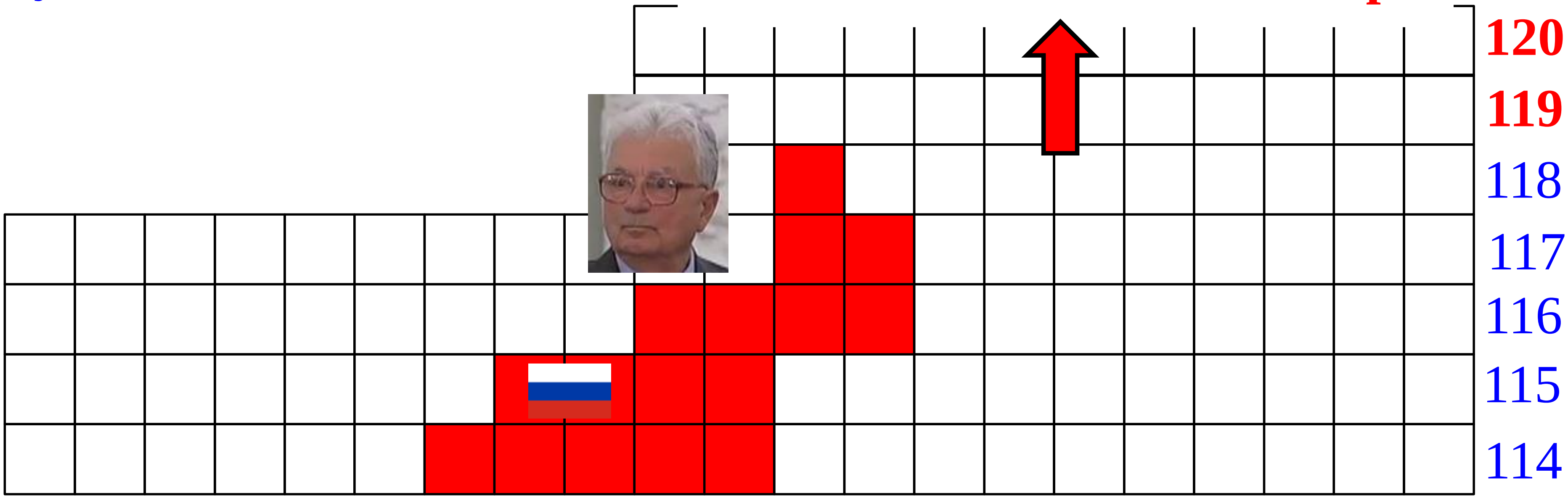




cf. barrier distribution measurements by Tanaka et al.

Synthesis of Z=119 and 120

Towards Z=119 and 120 isotopes



hot fusion reactions with ^{48}Ca:

$^{48}_{20}Ca + {}_{99}Es \rightarrow 119$

$^{48}_{20}Ca + {}_{100}Fm \rightarrow 120$

short lived →not available with sufficient amounts

$^{48}Ca \rightarrow {}^{50}_{22}Ti,\ {}^{51}_{23}V,\ {}^{54}_{24}Cr$ projectiles

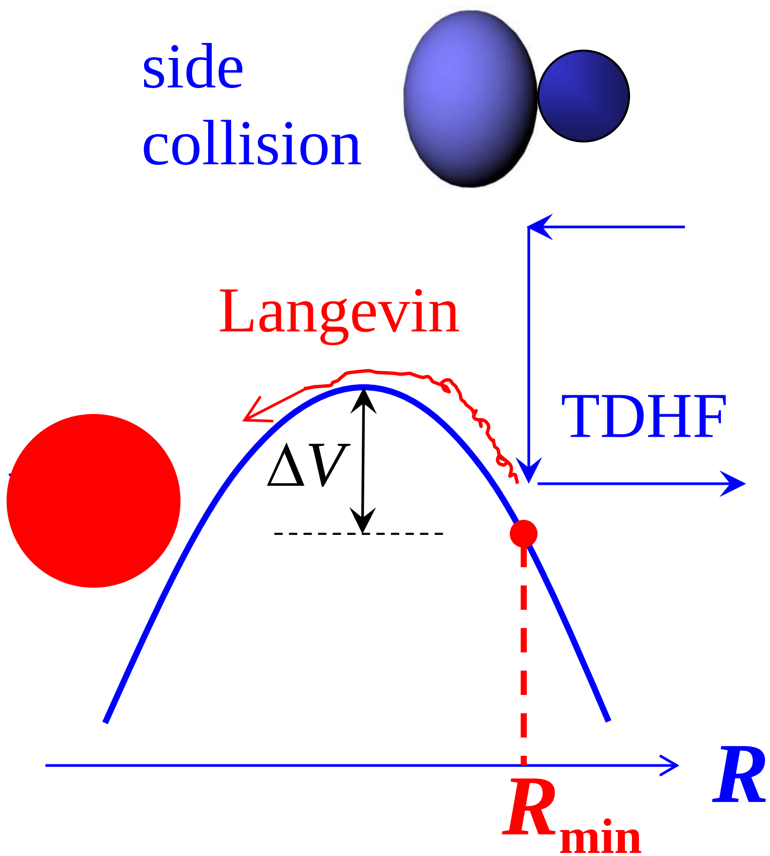
closed shell → open shells

how much will cross sections be affected?

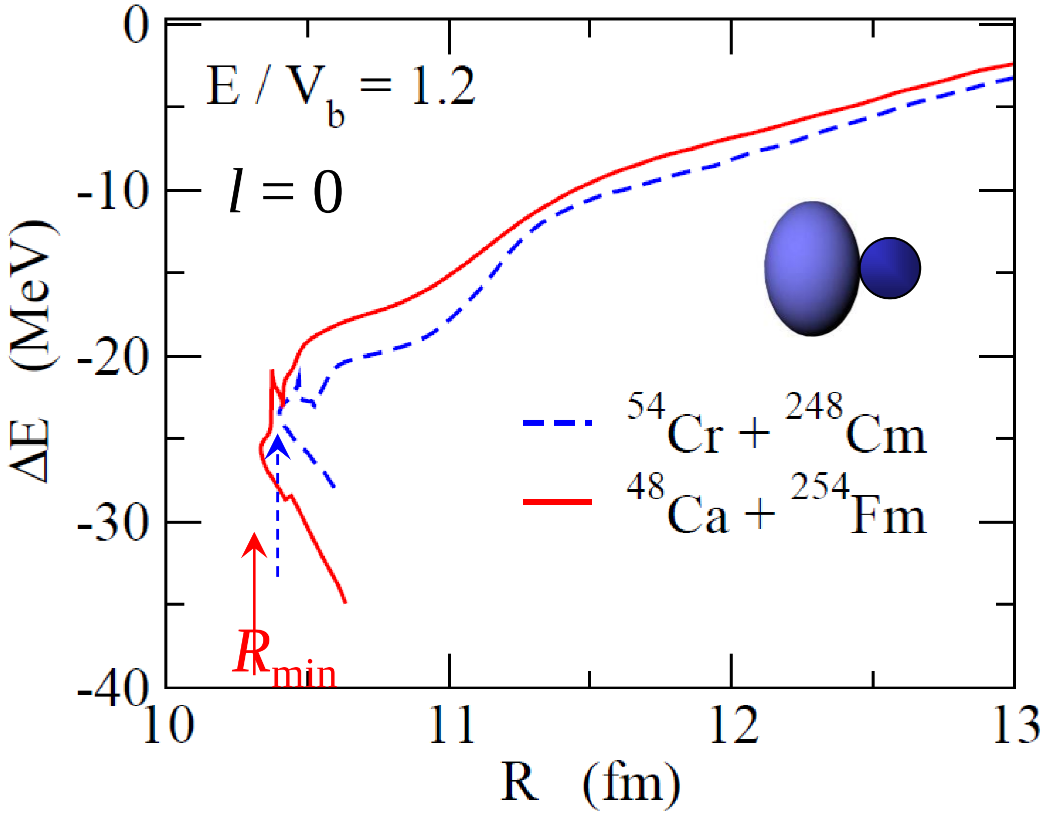
TDHF + Langevin approach

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

SUGGESTION



$^{54}Cr + ^{248}Cm \rightarrow\ ^{302}120$
$^{48}Ca + ^{254}Fm \rightarrow\ ^{302}120$

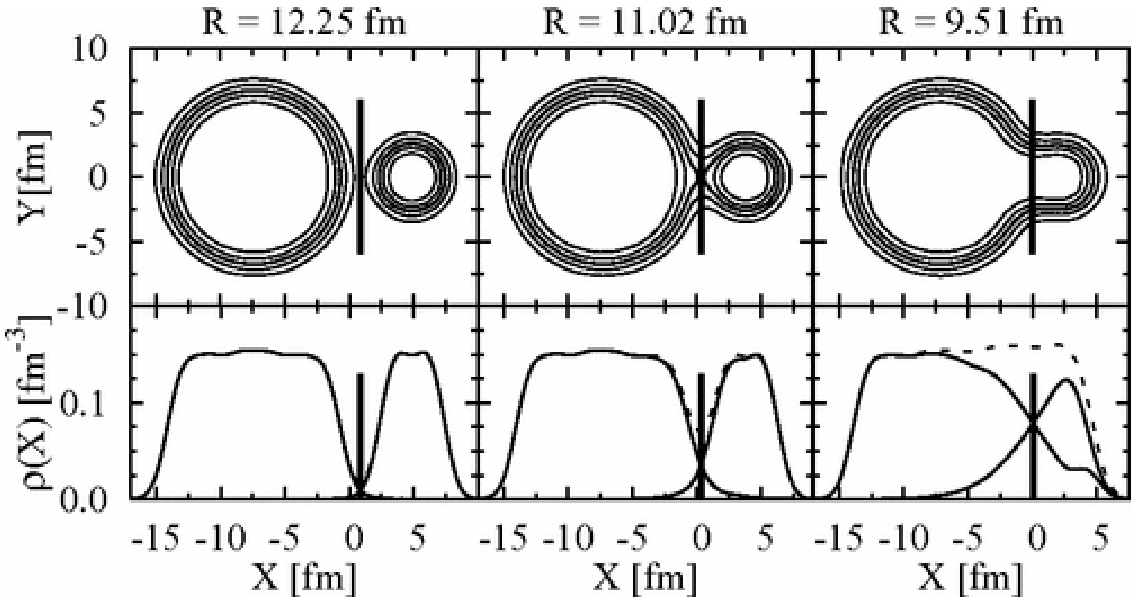


→ Langevin caluclation

Mapping TDHF onto a classical equation of motion

K. Washiyama and D. Lacroix, PRC78 ('08) 024610

TDHF simulations



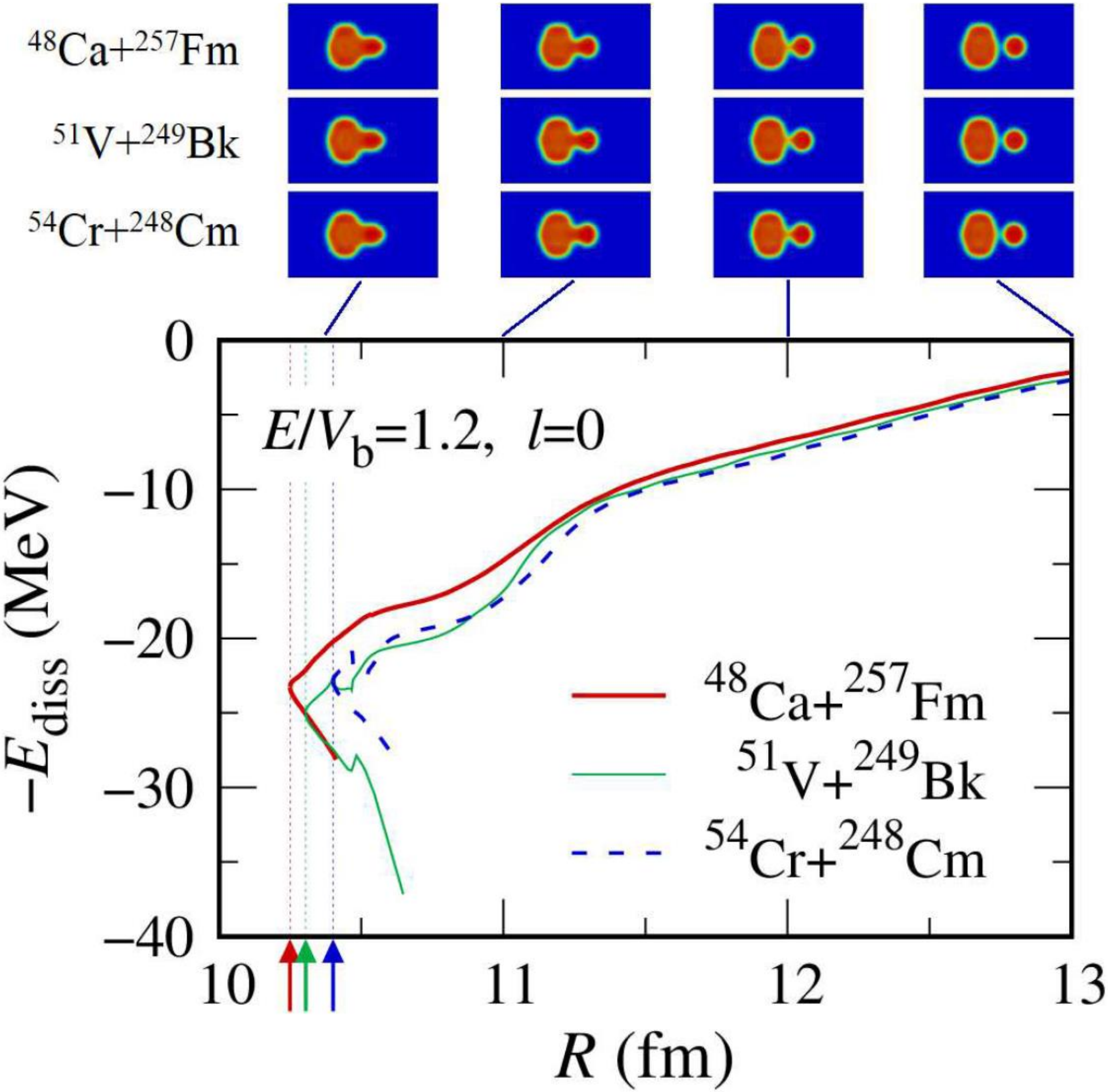
→ $R(t)$, $P(t)$

$$\dot{P} = -\frac{dV}{dR} - \frac{d}{dR}\left(\frac{P^2}{2\mu}\right) - \gamma\dot{R}$$

→ $V(R)$, $\gamma(R)$

→

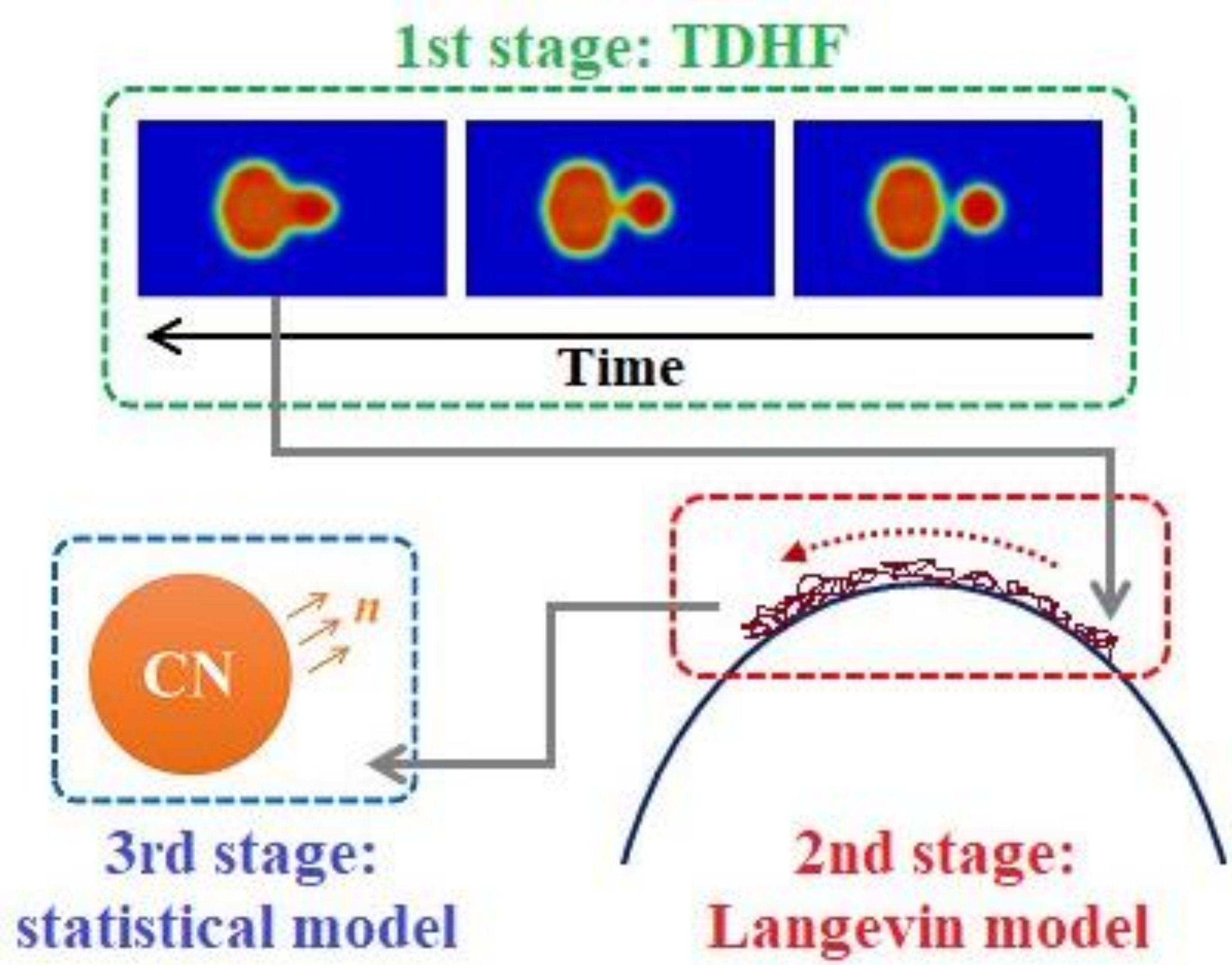
$$\Delta E(t) = -E_{\mathrm{diss}}(t) = \frac{P(t)^2}{2\mu(R(t))} + V(R(t)) - E_{\mathrm{ini}}$$



^{48}Ca+^{257}Fm
^{51}V+^{249}Bk
^{54}Cr+^{248}Cm
E/V_b=1.2, l=0
$-E_{diss}$ (MeV)
R (fm)
0
−10
−20
−30
−40
10
11
12
13

New hybrid model: TDHF + Langevin approach

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



New model for fusion for SHE: TDHF + Langevin approach

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

SUGGESTION

how special is ^{48}Ca ?

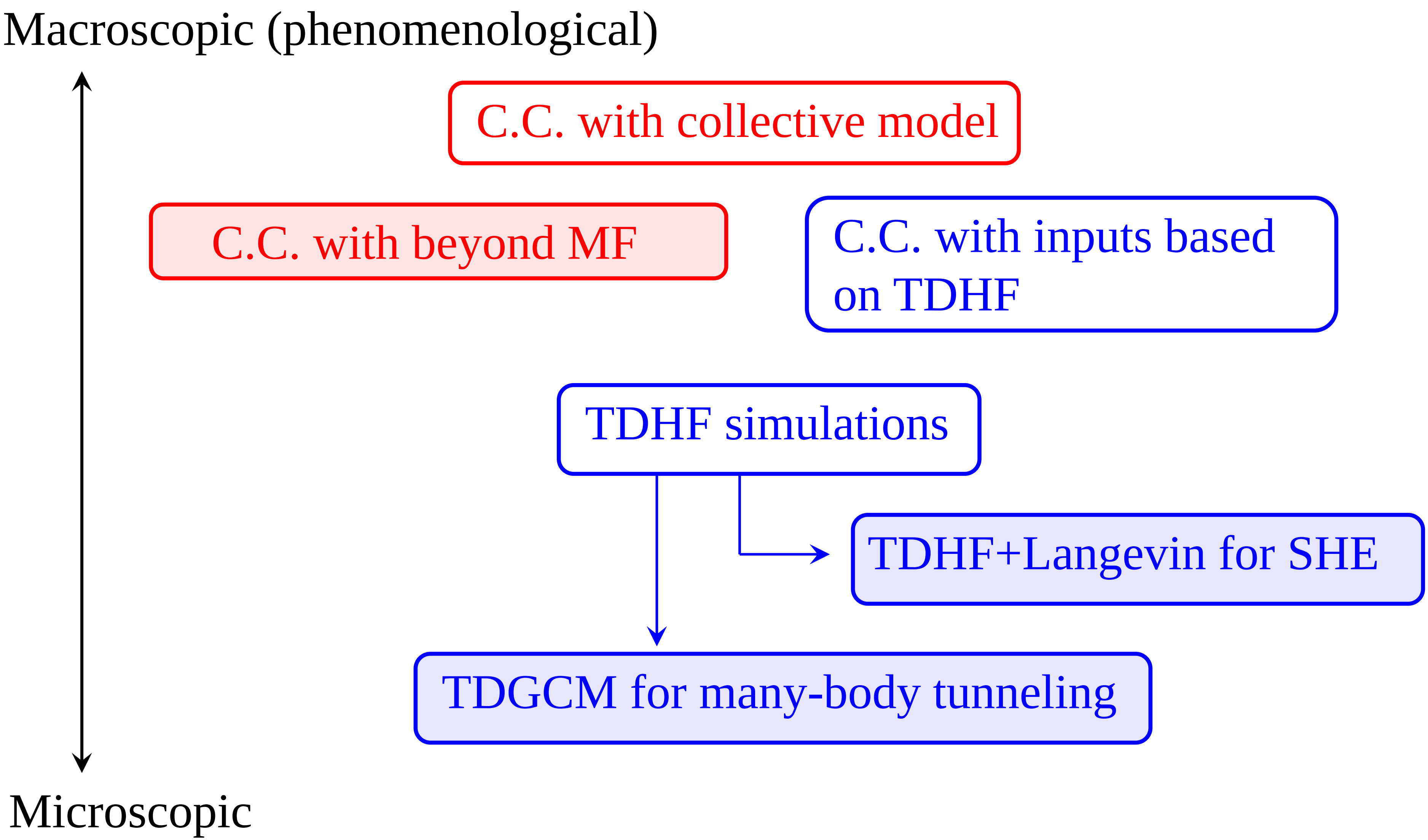
System	CN	E^* (MeV)	R_{min} (fm)	P_{CN} ($\times 10^4$)	W_{sur} ($\times 10^9$)	$P_{CN}\,W_{sur}$ ($\times 10^{13}$)
^{48}Ca + ^{254}Fm	^{302}120	29.0	12.93	1.72	176	302
^{54}Cr + ^{248}Cm	^{302}120	33.2	13.09	1.89	1.31	2.47
^{51}V + ^{249}Bk	^{300}120	37.0	12.94	3.95	0.117	0.461
^{48}Ca + ^{257}Fm	^{305}120	30.5	12.94	2.49	0.729	1.82

similar P_{CN}

no special role of ^{48}Ca in the entrance channel

Summary

From phenomenological to microscopic nuclear reaction theories



FUSION20

November 15-20, 2020
Shizuoka, Japan

Kouichi Hagino (co-chair) Kyoto University
Katsuhisa Nishio (co-chair) JAEA

Japan-China joint organization
Program Committee
Japanese members
+ L. Guo, X. Tang, S.G. Zhou

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Shizuoka Convention Beaureau: Taichiro Ishida

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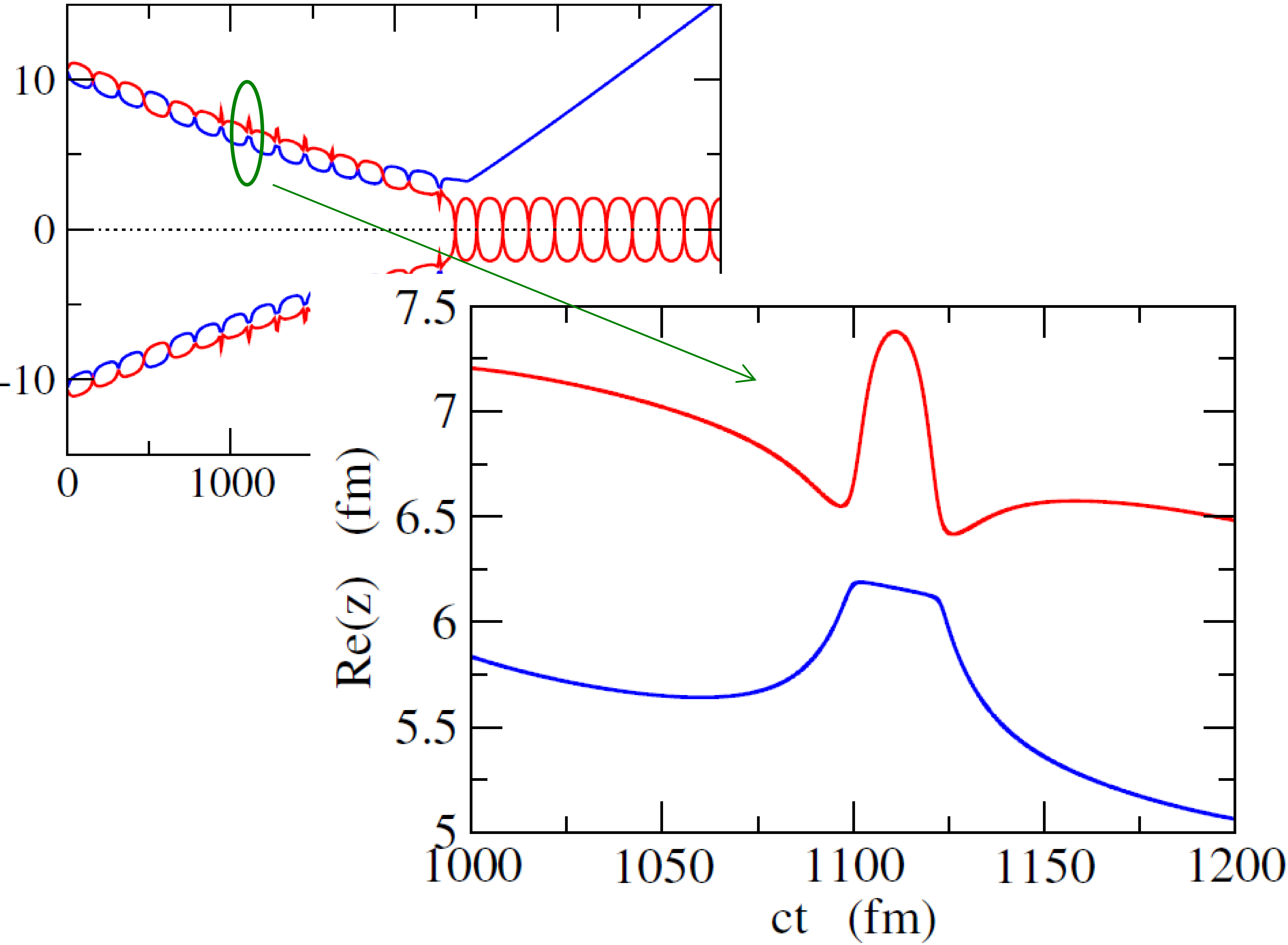
10
0
-10
0
1000
7.5
7
6.5
6
5.5
5
Re(z) (fm)
1000
1050
1100
1150
1200
ct (fm)