Theoretical issues in physics of SHE : nuclear reaction perspectives

2019 IYPT
International Year
of the Periodic Table
of Chemical Elements

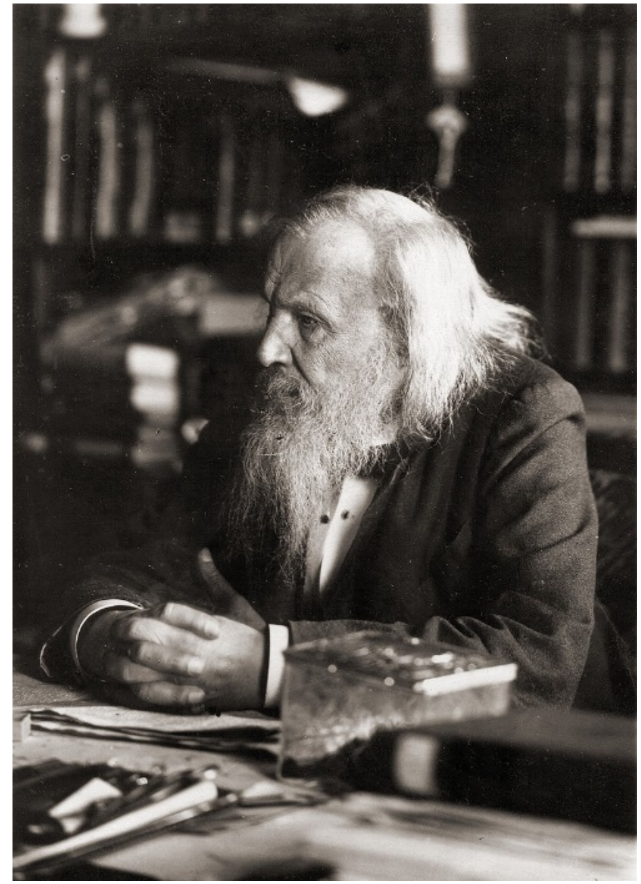
Kouichi Hagino
Kyoto University

1. Introduction-1: periodic tables
2. Introduction-2: superheavy elements
3. Formation reactions
4. Theoretical issues
5. Physics of neutron-rich nuclei
6. Summary

Periodic table of elemetns (1869)

2019 IYPT

International Year
of the Periodic Table
of Chemical Elements



Mendereev
(1834-1907)

Periodic table of elemetns (1869)

2019 IYPT

International Year
of the Periodic Table
of Chemical Elements

closing ceremony (2019/12/5, Tokyo)

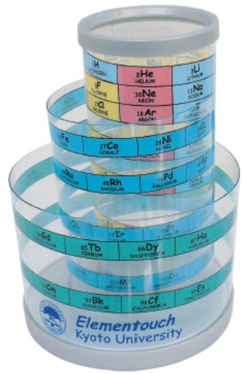
periodic table of elements

noble gas

Group → / Period ↓	1	2	3		4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc		22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y		40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
				*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
				**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

periodic table of elements

noble gas



"elementouch"
(Y. Maeno, 2001)

Group → / Period ↓	1	2						7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
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5	37 Rb	38 Sr	39 Y		40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87	88	89	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
				*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
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Prof. Yoshiteru Maeno (Kyoto U., cond. matt. expt.)

periodic table of ~~elements~~ nuclei?

proton magic # ← noble gas

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1	1 H																		2 He
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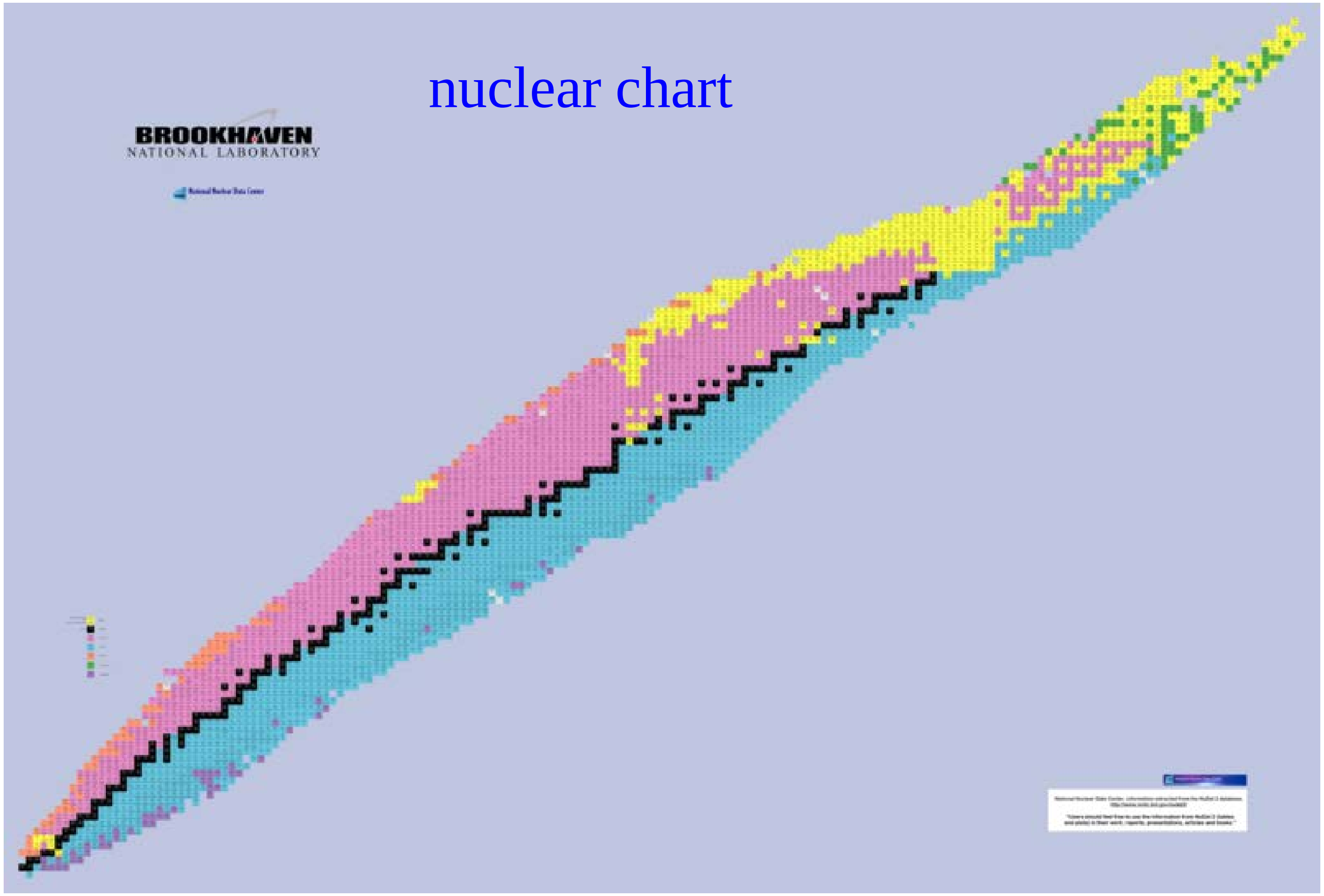
Prof. Yoshiteru Maeno (Kyoto U., cond. matt. expt.)

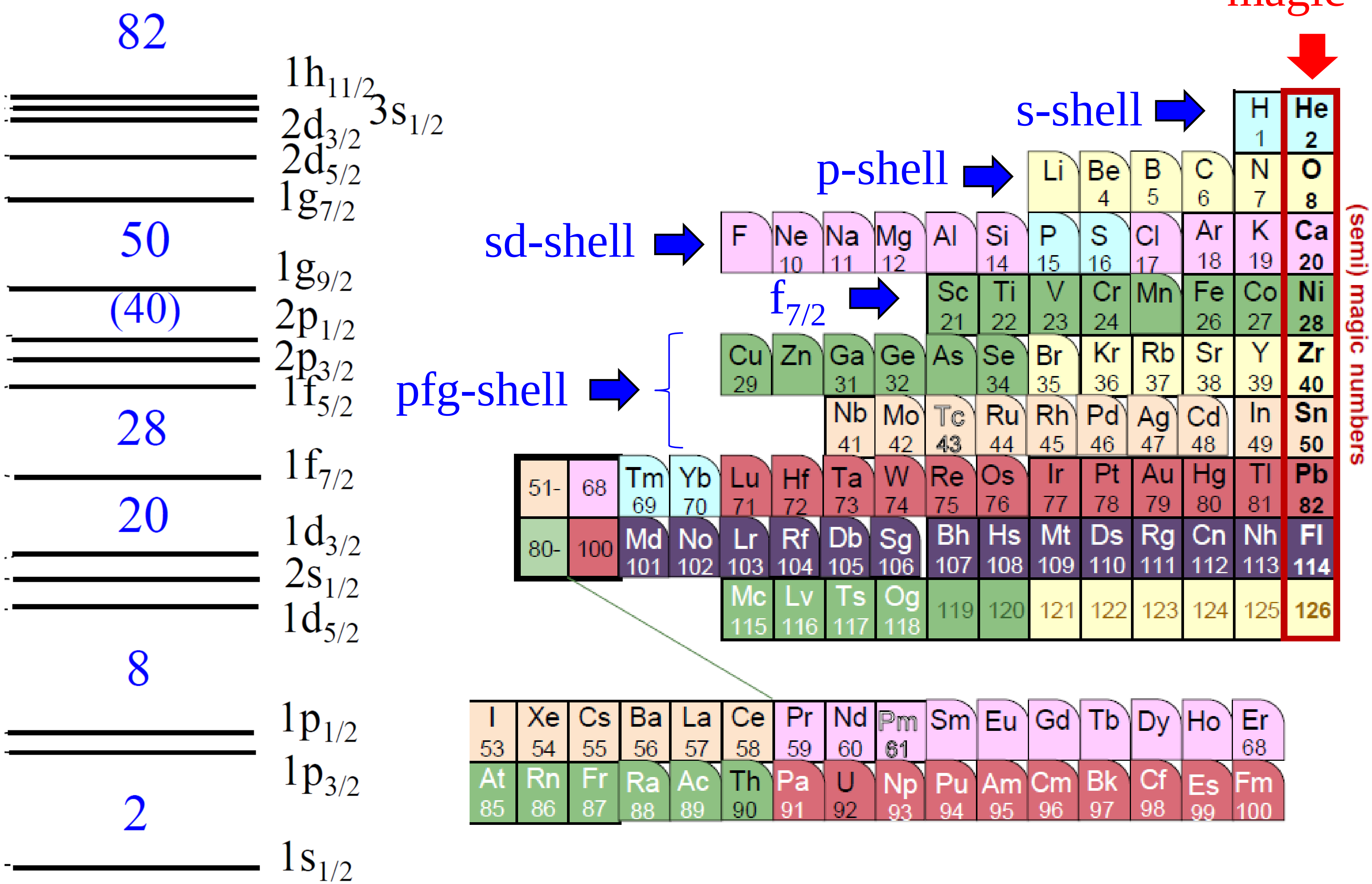
Nuclear periodic table



Yet, a pedagogical significance
(to familiarize nuclear physics)

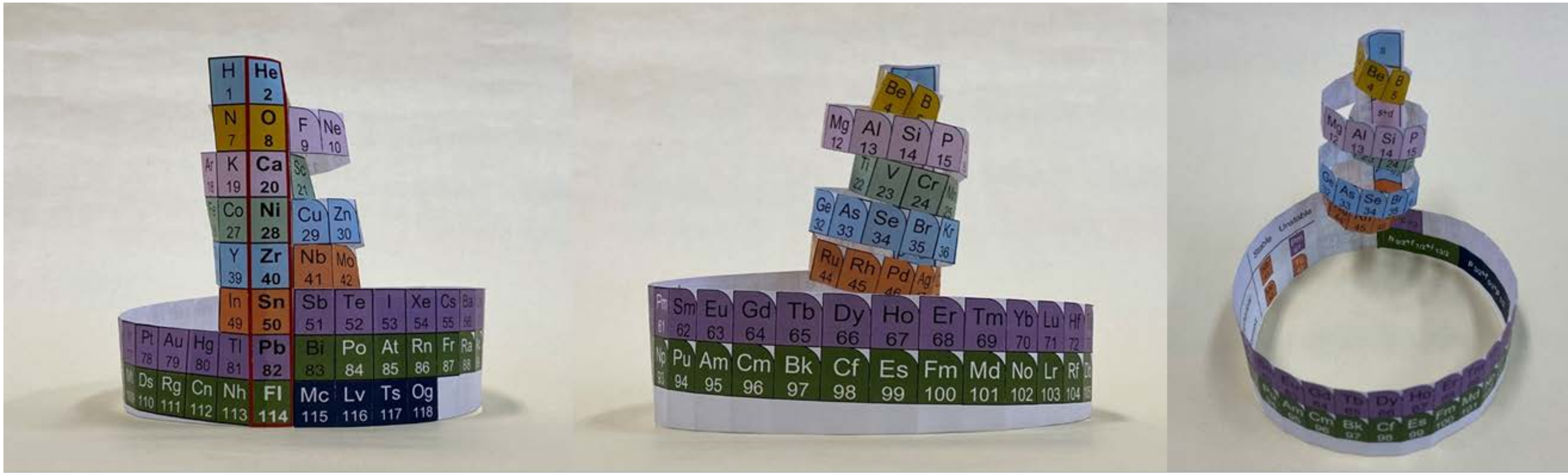
Nuclear periodic table

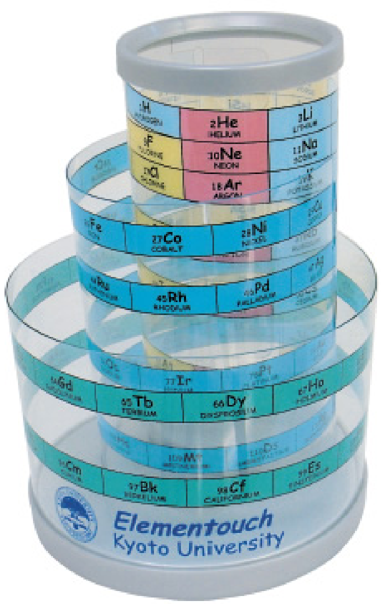
K. Hagino and Y. Maeno, Found. of Chem. 22, 267 (2020).



Nuclear periodic table

“nucletouch” (a 3D model)





cf. “elementouch”
(Y. Maeno, 2001)

mug cup

towel

T-shirt
(Kyoto-U. coop)

購読はこちら [1週間無料]

讀賣新聞 オンライン

ログイン　新規登録

ニュース　> 科学・IT

「すいへーりーべ」でおなじみの元素周期表、新パターン提案…京大が原子核の状態着目

2020/04/22 23:41

日本經濟新聞

朝刊・夕刊　ストーリー　Myニュース　日

トップ　速報　マネー　経済・金融　政治　ビジネス　マーケット　テクノロジー

新しい周期表を考案 京大、原子核の性質を表現

2020/5/3付 | 日本経済新聞　朝刊

保存　共有

京都大学の前野悦輝教授と萩野浩一教授は、原子核の性質をわかりやすく表い周期表を考案した。従来の周期表が元素の化学的な性質を知るのに役立て、新しい周期表は元素の原子核の性質を知るのに使える。

NEWS RELEASE 27-MAY-2020

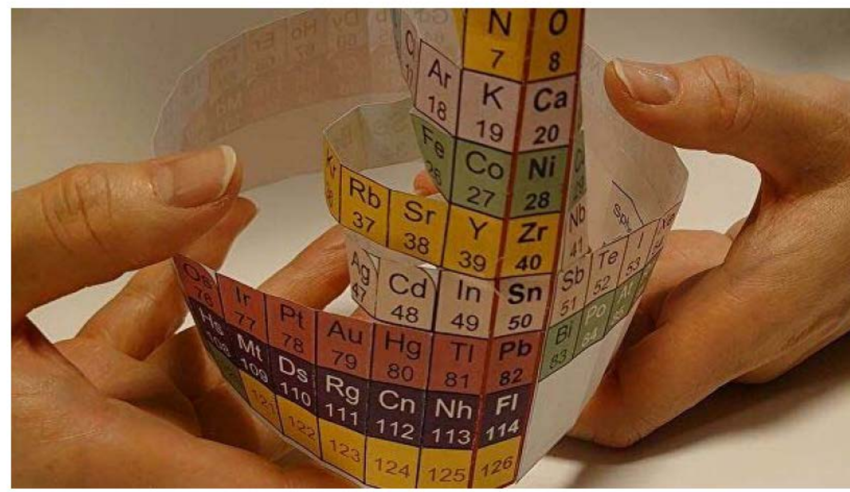
A special elemental magic

Kyoto scientists announce a 'nuclear' periodic table

KYOTO UNIVERSITY

Японские физики представили новую периодическую таблицу элементов

19:34 27.05.2020　58122



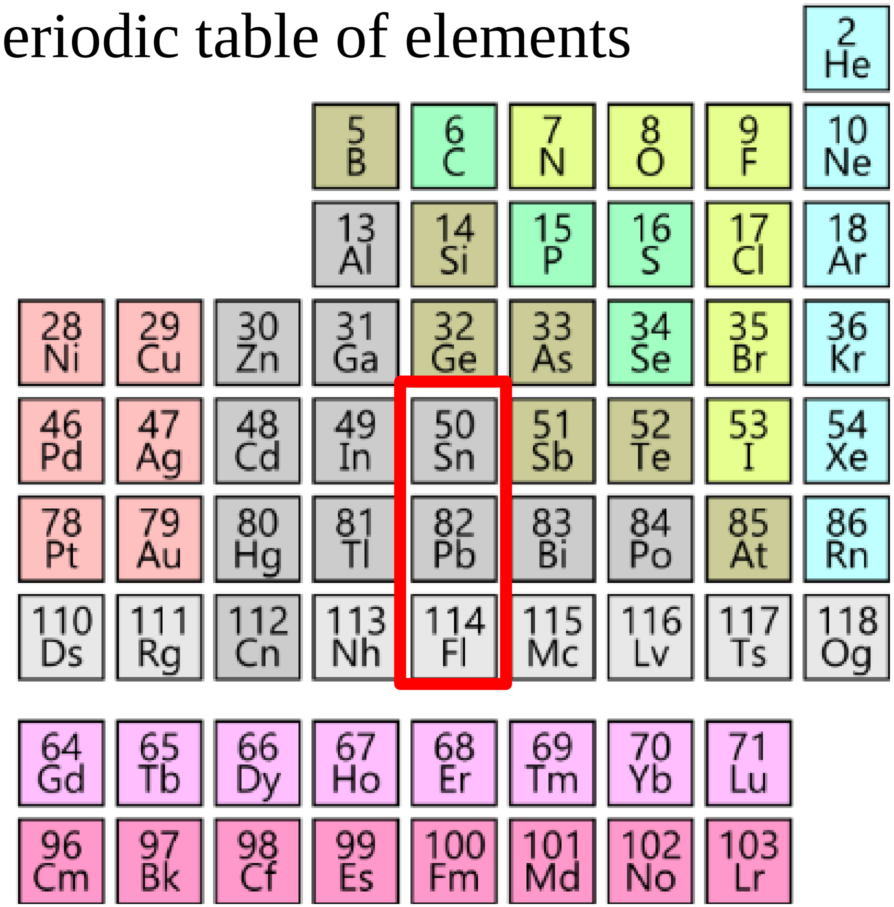
© Фото : Kyoto University/Yoshiteru Maeno/Kouichi Hagino

МОСКВА, 27 мая — РИА Новости. Ученые из Киотского университета представили периодическую таблицу элементов, которая в отличие от таблицы Менделеева, где за основу взяты электроны в атоме, основана на

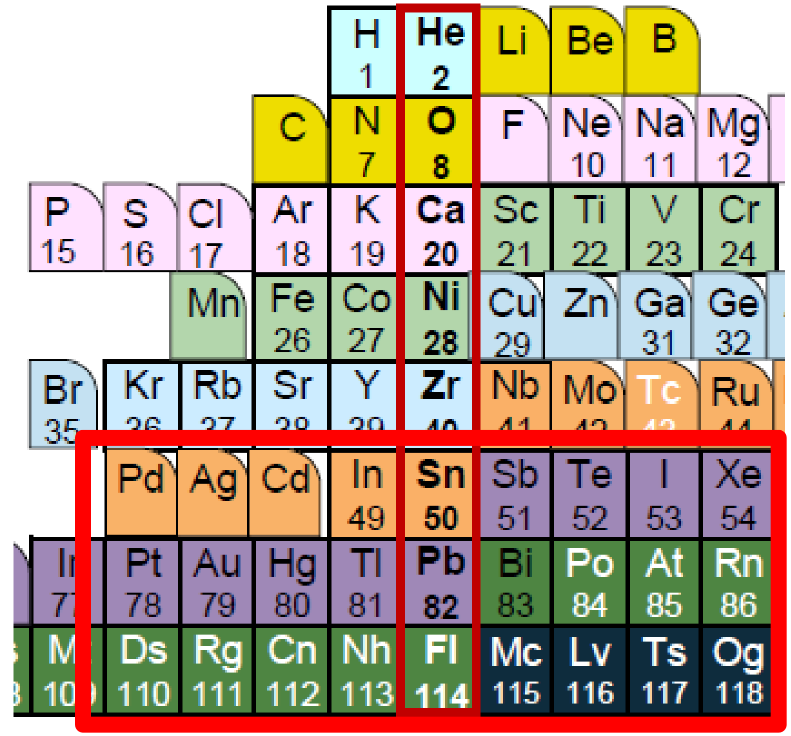
[a magical coincidence]

Y. Maeno, K. Hagino, and T. Ishiguro,
Found. of Chem., in press.

periodic table of elements



nuclear periodic table



the nuclear magic numbers are there in the same column!
(the same elements around them)

a magical coincidence which can be recognized only after making a nuclear periodic table

原子核の周期表――Magic な関係

前野悦輝　〈京都大学大学院理学研究科　maeno.yoshiteru.2e@kyoto-u.ac.jp〉
萩野浩一　〈京都大学大学院理学研究科　hagino.kouichi.5m@kyoto-u.ac.jp〉

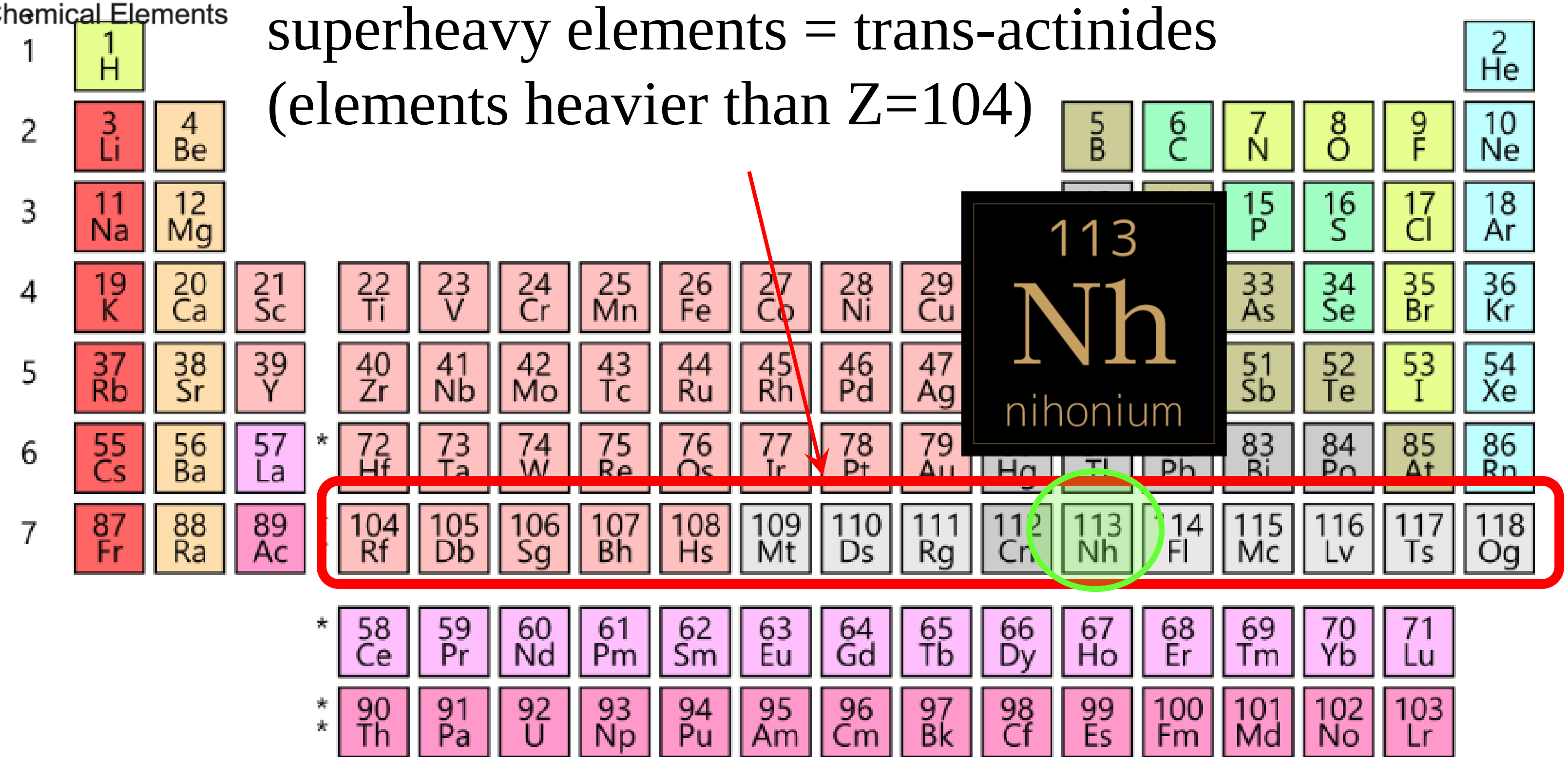
Superheavy elements and Neutron-rich Nuclei

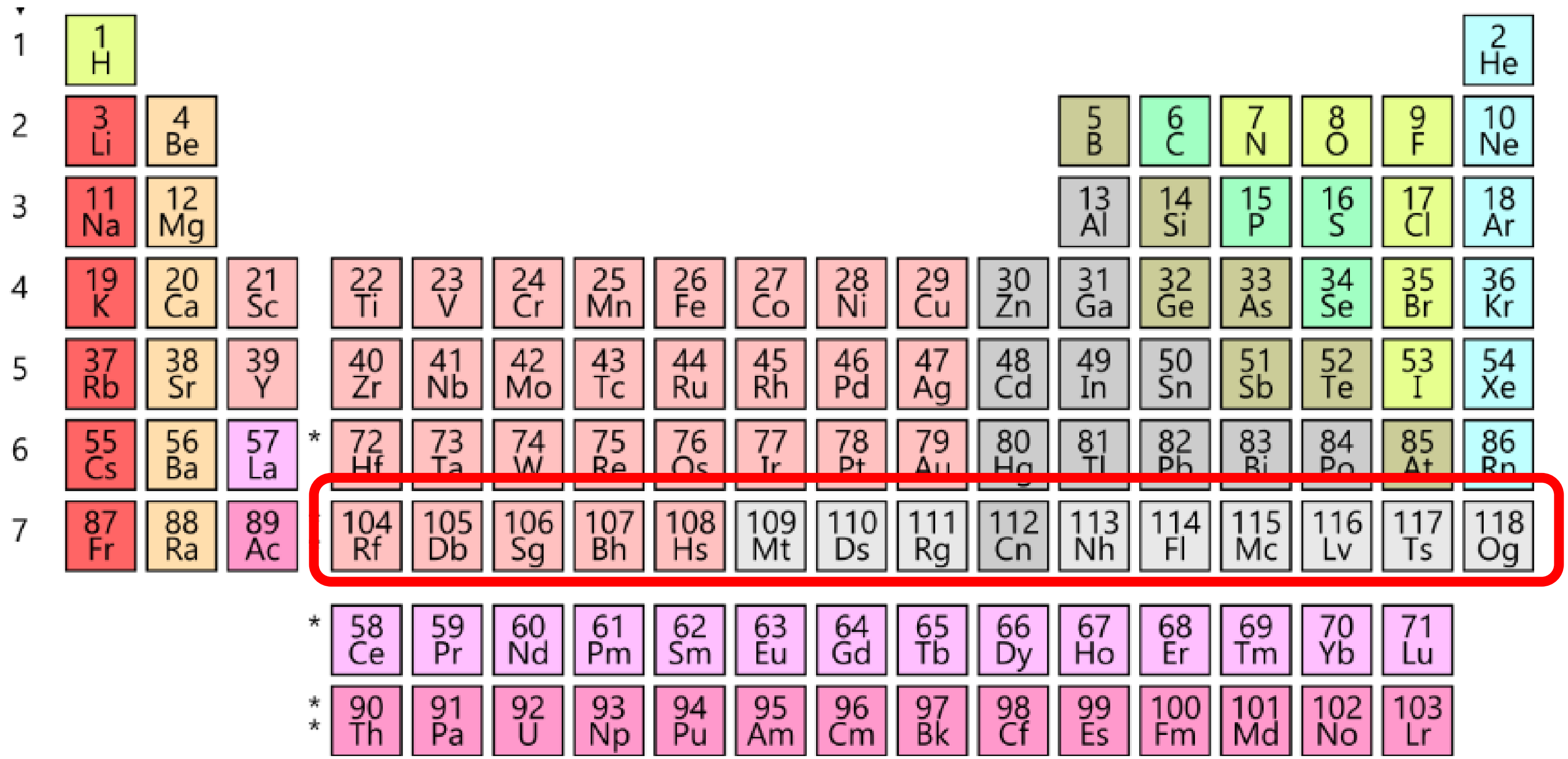
2019 IYPT

International Year of the Periodic Table of Chemical Elements

Definition: superheavy elements

superheavy elements = trans-actinides
(elements heavier than Z=104)





Interests in physics and chemistry of superheavy elements

- what is the heaviest element? → atomic property
- what is the double magicu nucleus next to ^{208}Pb? → nuclear property
- should the periodic table be changed or not? → chemical property
- how do superheavy elements influence the r-process nucleosynthesis?
  → astrophysics

what determines the limit of existence of elements?

INTERNATIONAL YEAR OF THE PERIODIC TABLE 2019

I 53 Iodine | Y 39 Yttrium | Pt 78 Platinum | Ca 20 Calcium | K 19 Potassium

possibilities to be considered:

- ✓ electron orbitals in atom
- ✓ stability of nucleus in atom (← magic number)

what determines the limit of existence of elements?

INTERNATIONAL YEAR OF THE PERIODIC TABLE 2019

possibilities to be considered:

let’s first discuss

- ✓ electron orbitals in atom
- ✓ stability of nucleus in atom (← magic number)

what determines the limit of existence of elements? (i) electron orbits

hydrogen-like atom

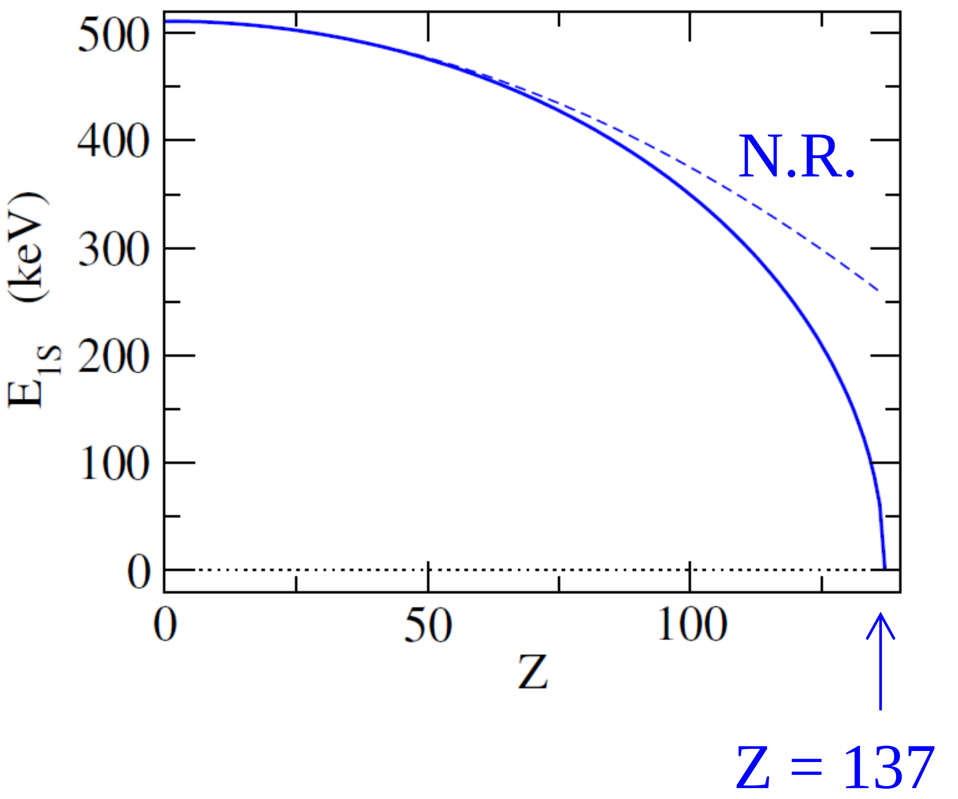
$$V(r) = -\frac{Ze^2}{r}$$

1S state (Dirac equation)

$$E_{1S} = mc^2\sqrt{1-(Z\alpha)^2}$$

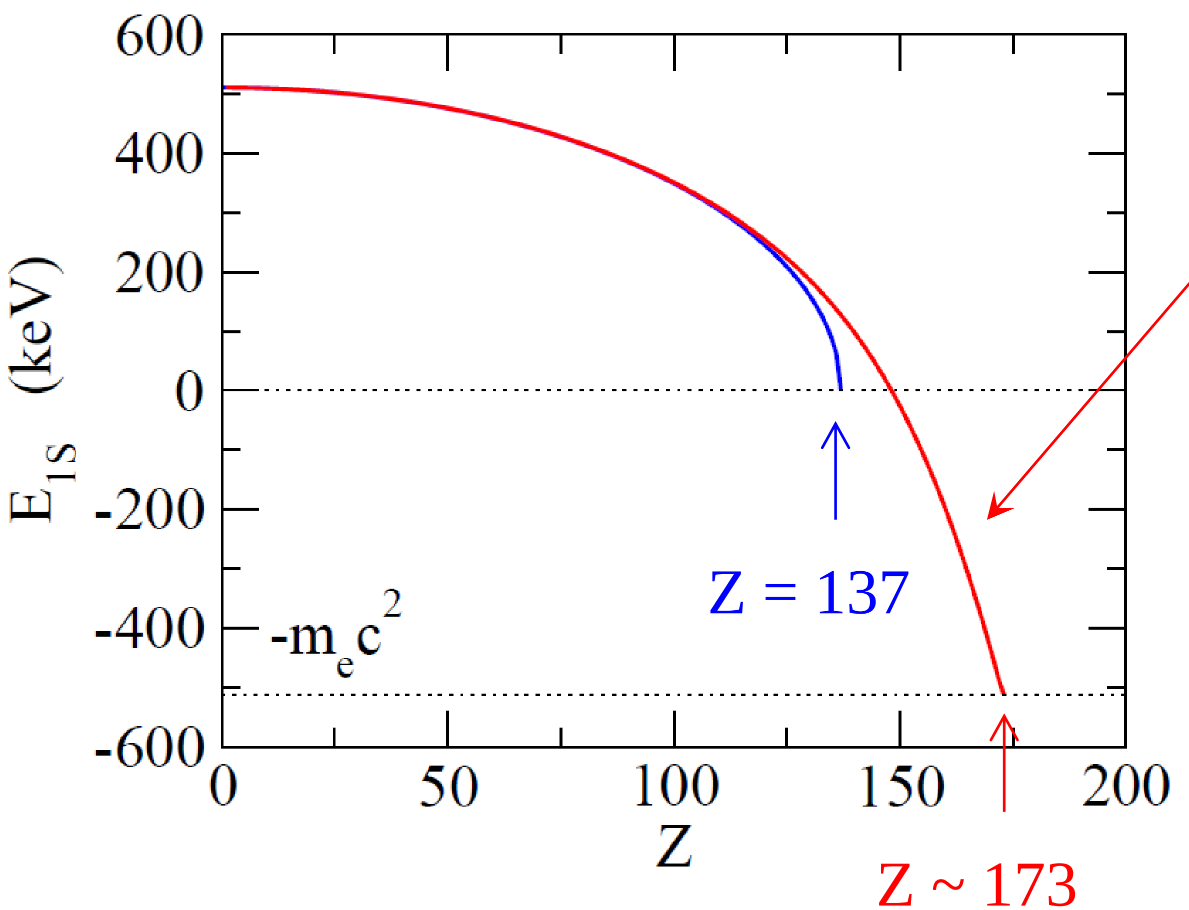
$$\alpha = \frac{e^2}{\hbar c} \sim \frac{1}{137}$$

Z > 137 → no solution



what determines the limit of existence of elements? (i) electron orbits

hydrogen-like atom



$R_N \sim 10^{-4}$ Å
rms $\sim 10^{-3}$ Å
(A=173)

cf. W. Pieper and W. Greiner, Z. Physik 218 (1969) 327 what determines the limit of existence of elements?

INTERNATIONAL YEAR OF THE PERIODIC TABLE 2019

I 53 Iodine | Y 39 Yttrium | Pt 78 Platinum | Ca 20 Calcium | K 19 Potassium

possibilities to be considered:

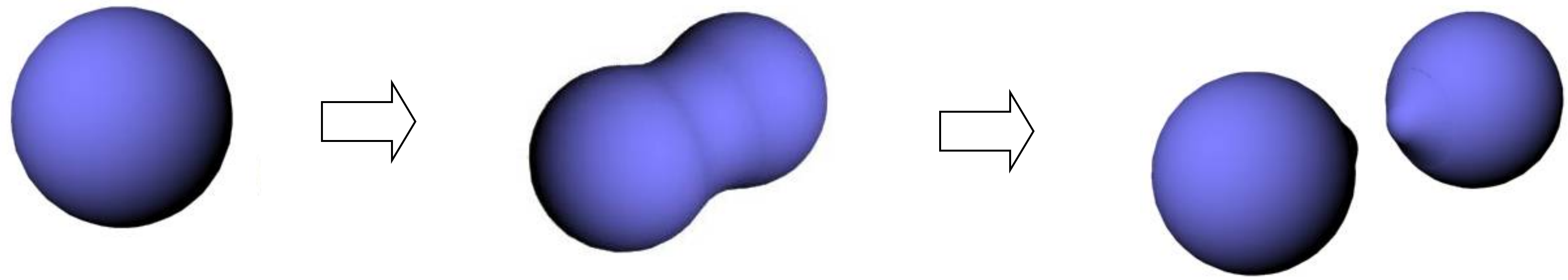
let's next discuss

✓ electronic orbitals in atom

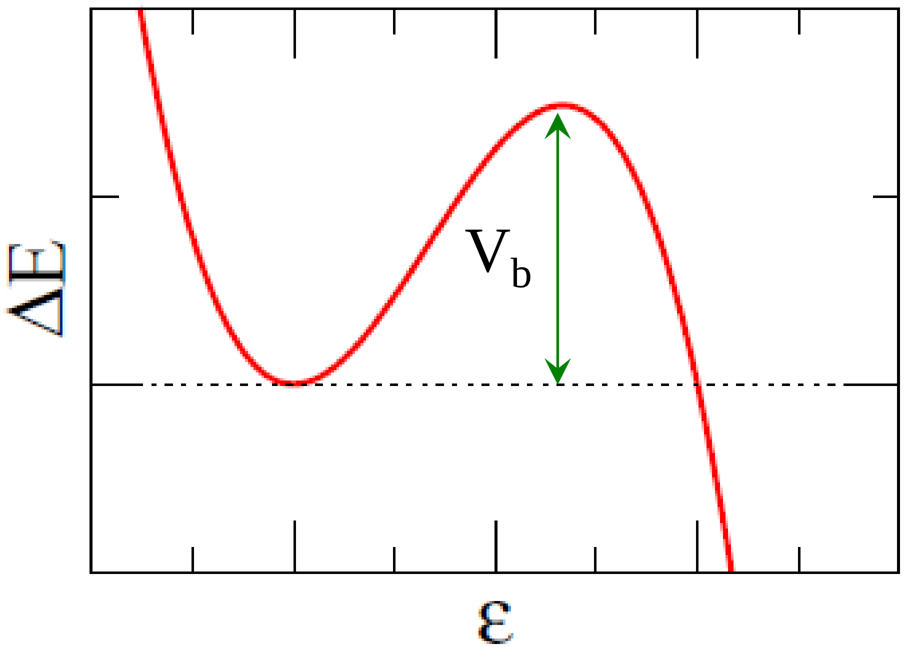
✓ stability of nucleus in atom

what determines the limit of existence of elements? (ii) atomic nucleus

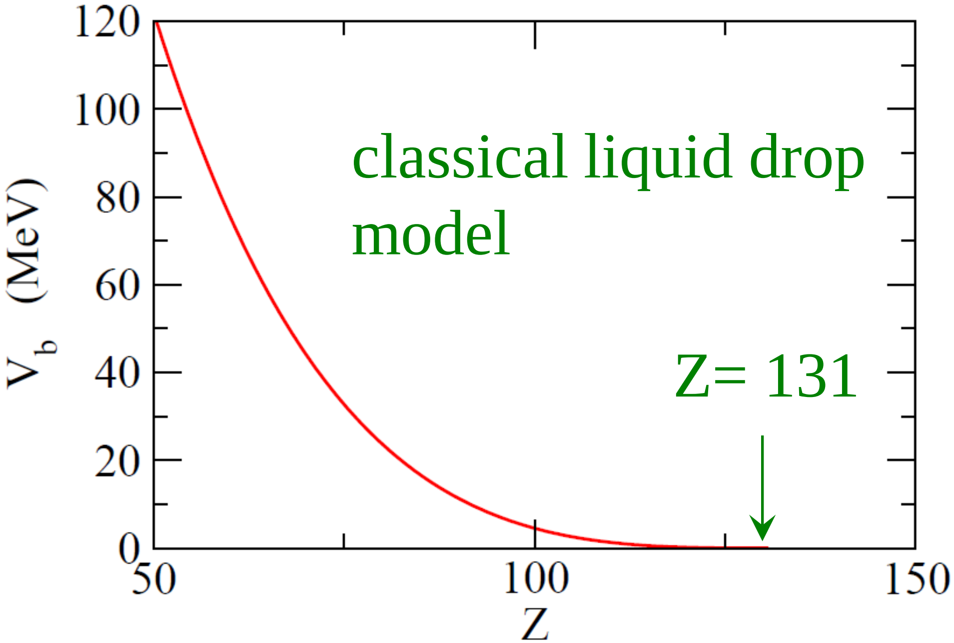
heavy nuclei → unstable against fission



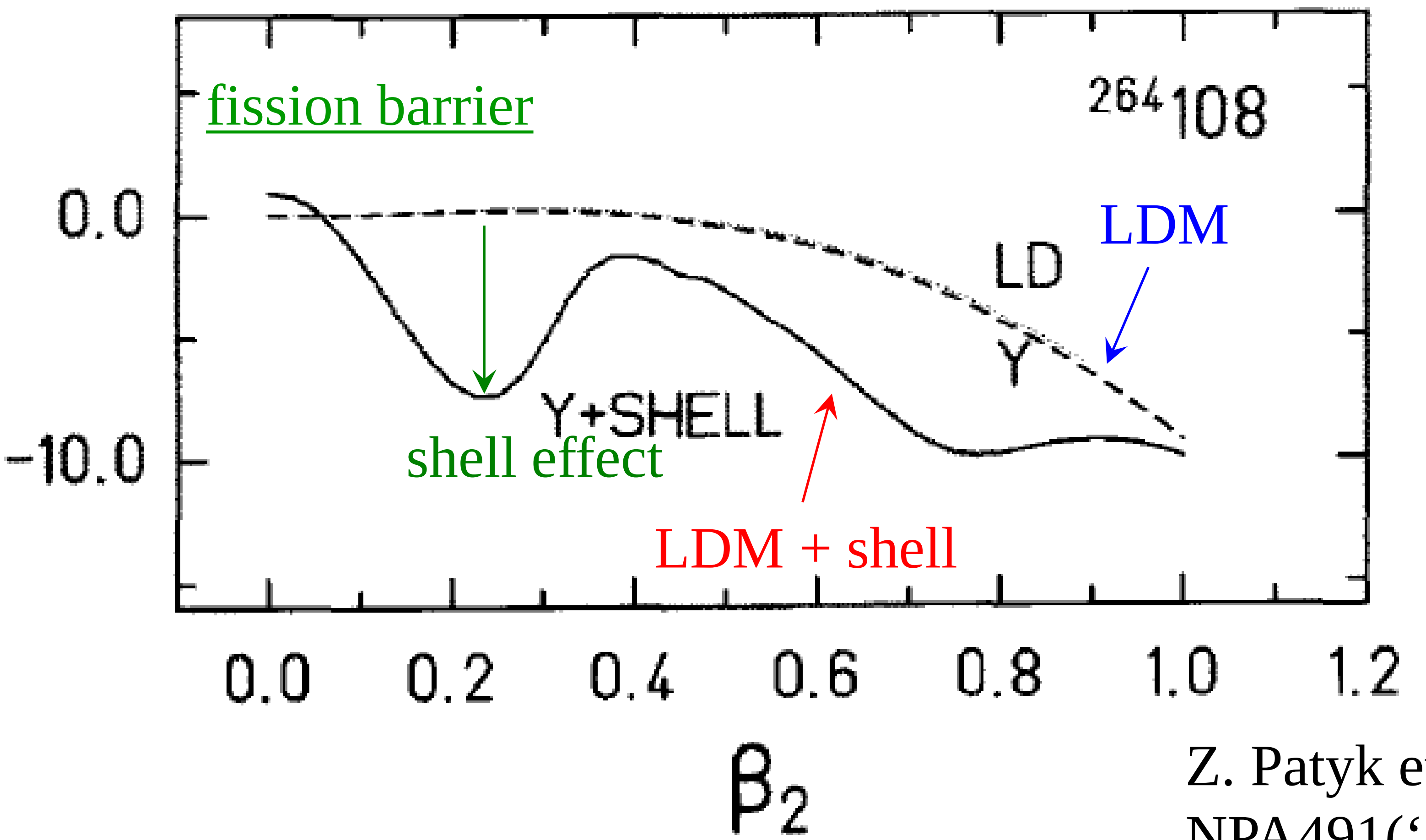
fission barrier



barrier height



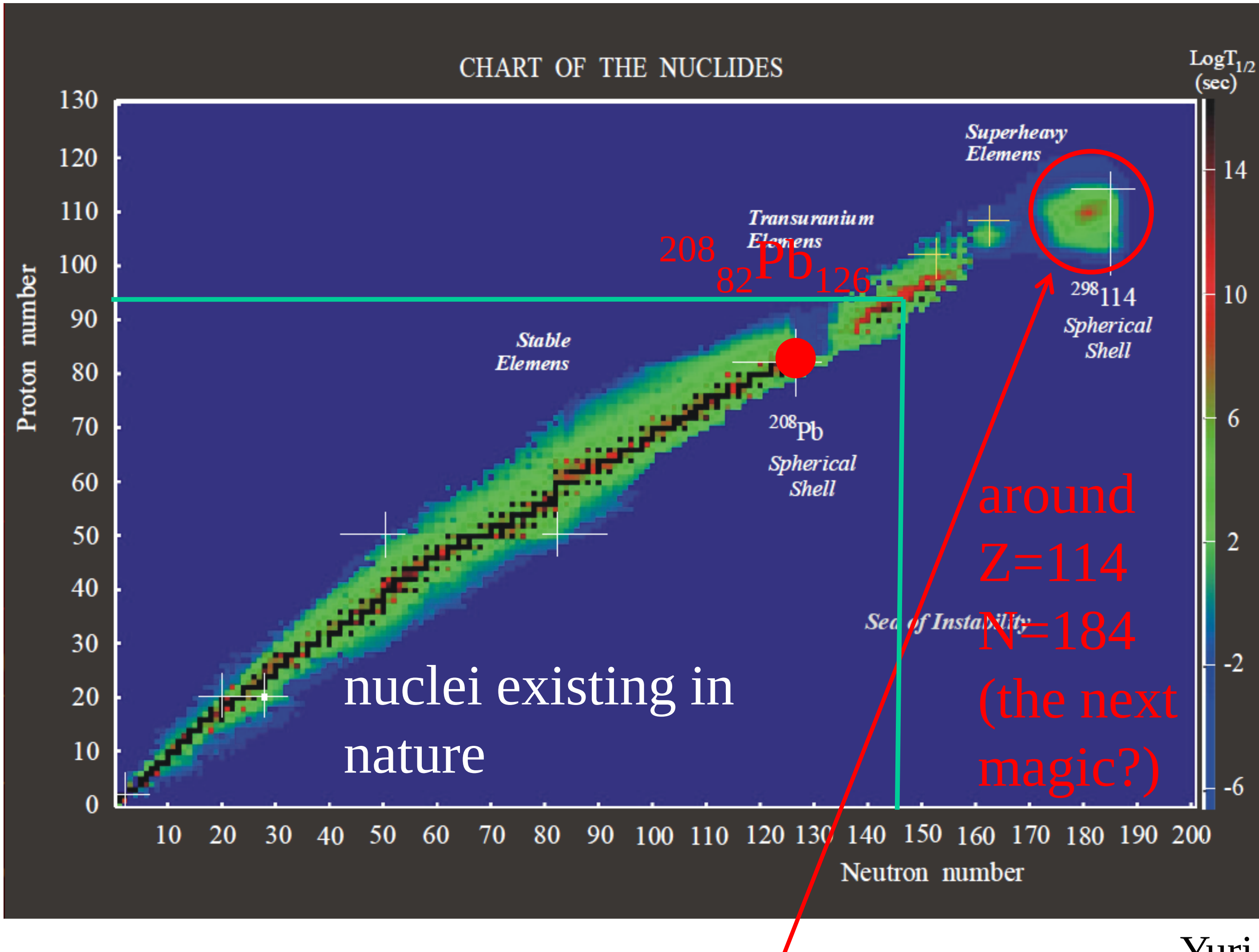
what determines the limit of existence of elements? (ii) atomic nucleus



Z. Patyk et al., NPA491('89) 267

QM shell effect (magic numbers) raises B_{fiss} and stabilizes a nucleus

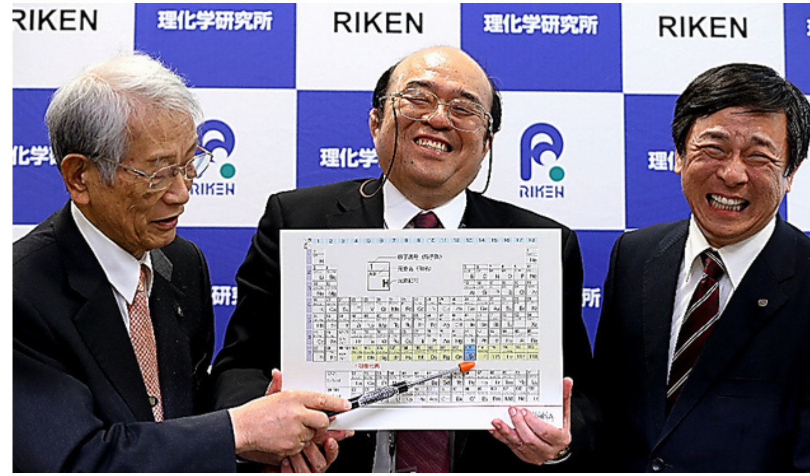
Superheavy elements (the island of stability)



Yuri Oganessian

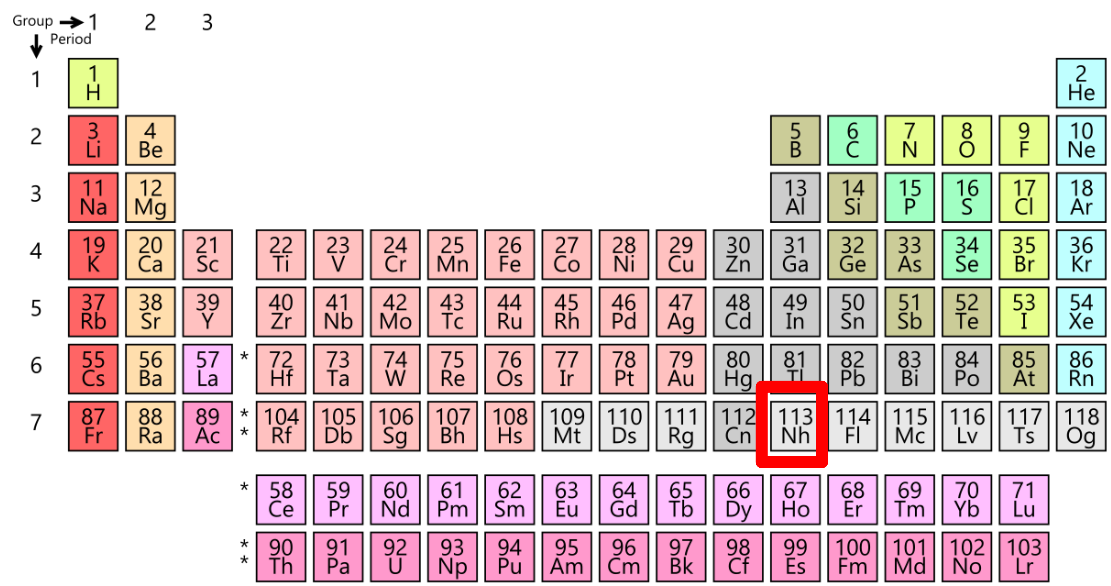
long-lived with $10^{3\text{-}5}$ years

Fusion reactions for SHE



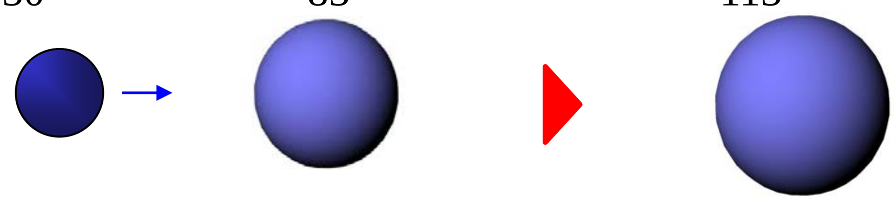
the element 113: Nh

November, 2016



Wikipedia

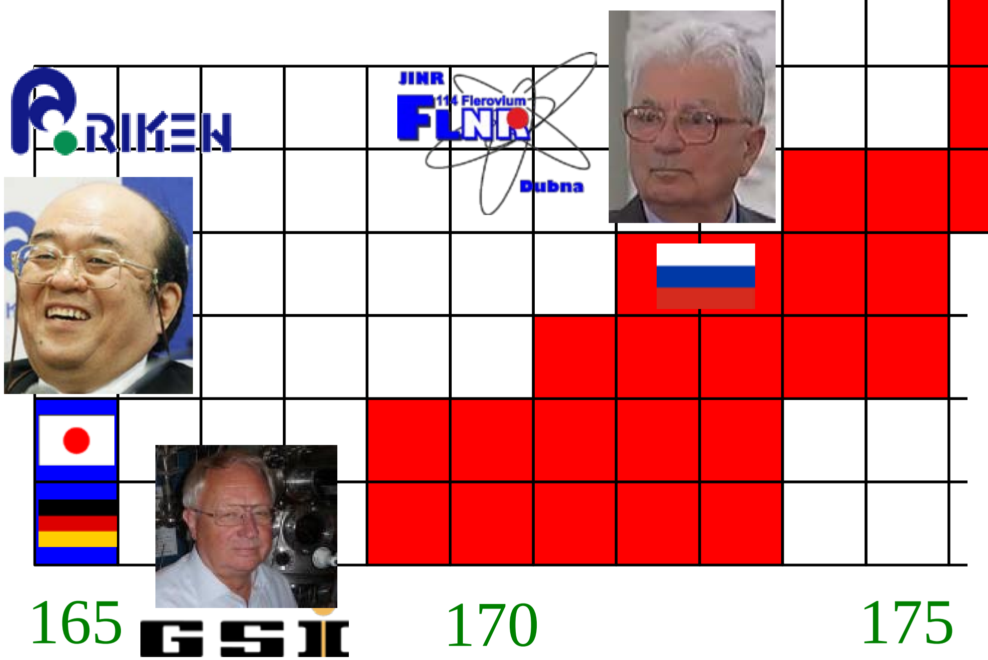
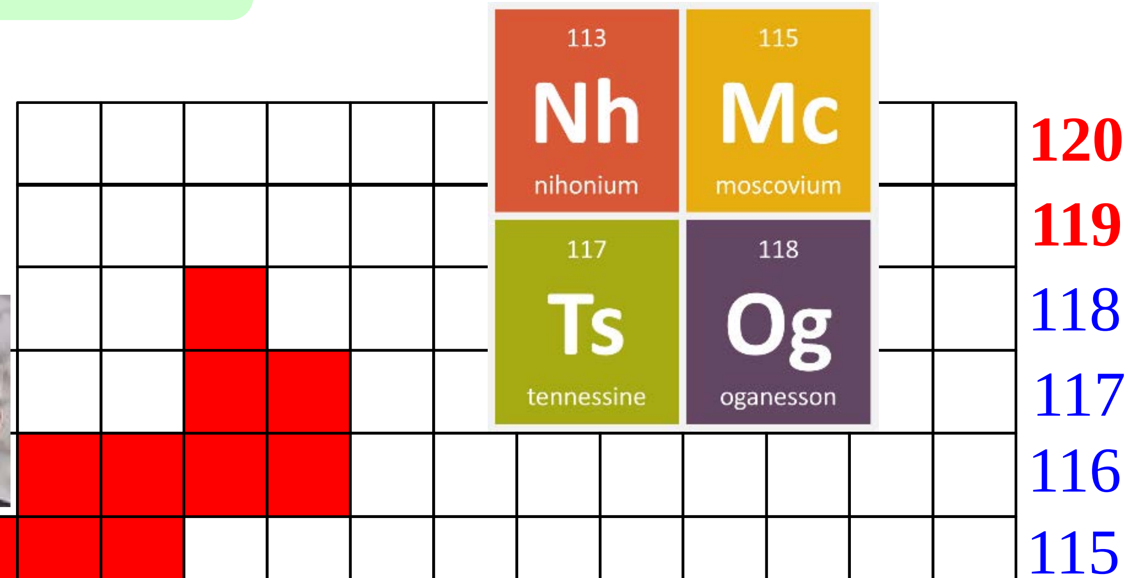
$^{70}_{30}$Zn $^{209}_{83}$Bi $^{279}_{113}$Nh*

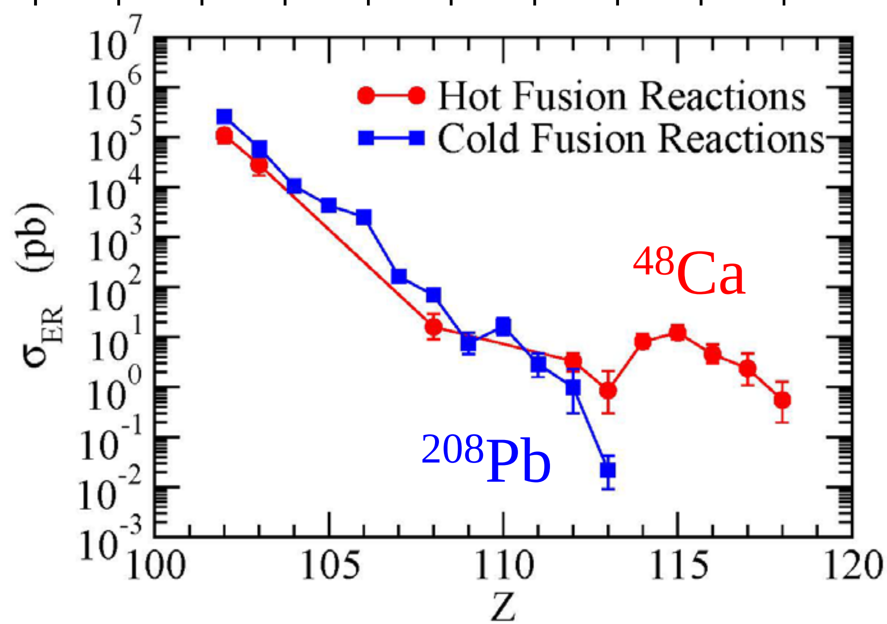


Heavy-ion fusion reaction

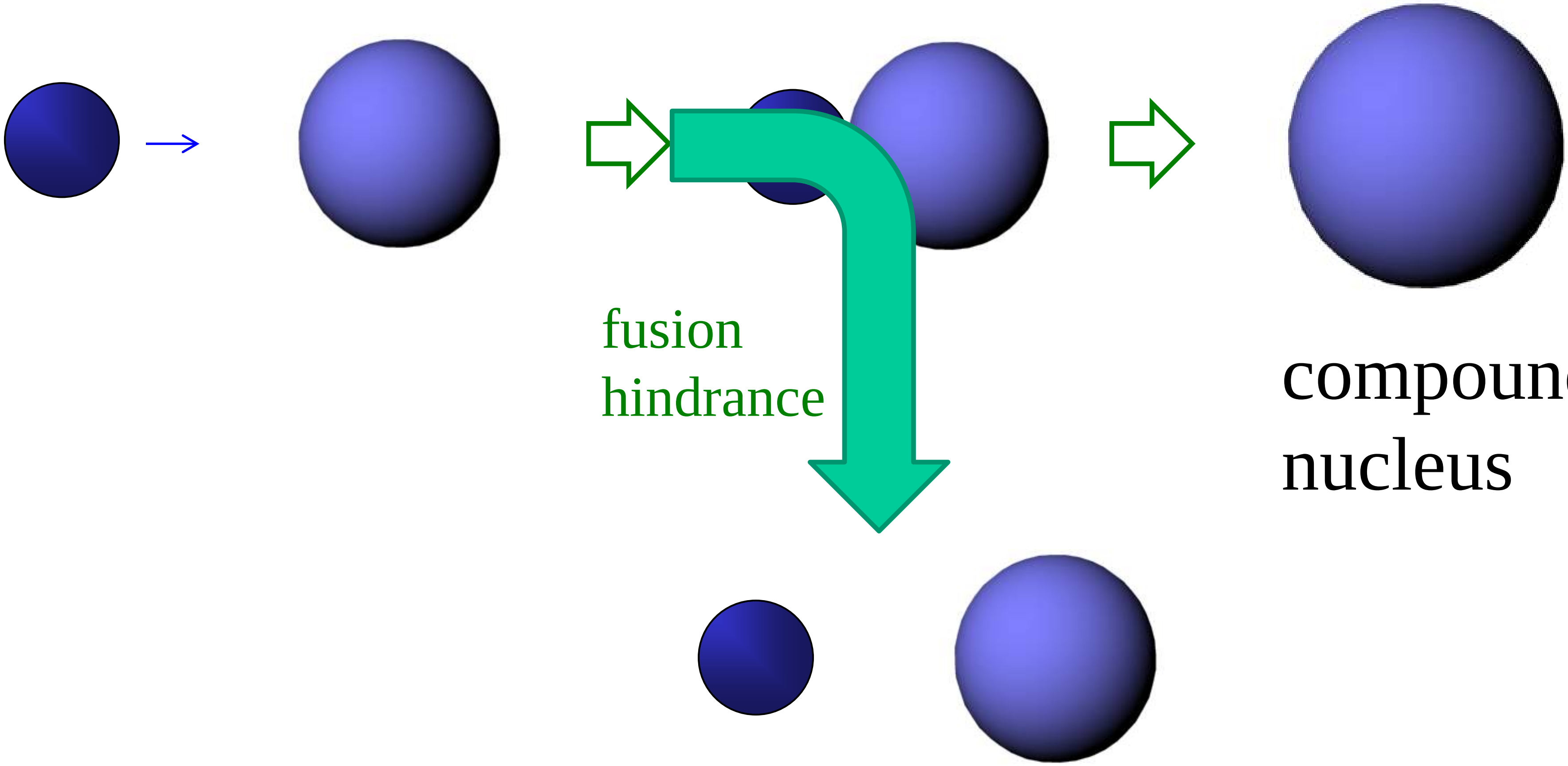
Fusion for superheavy elements

Superheavy elements synthesized so far

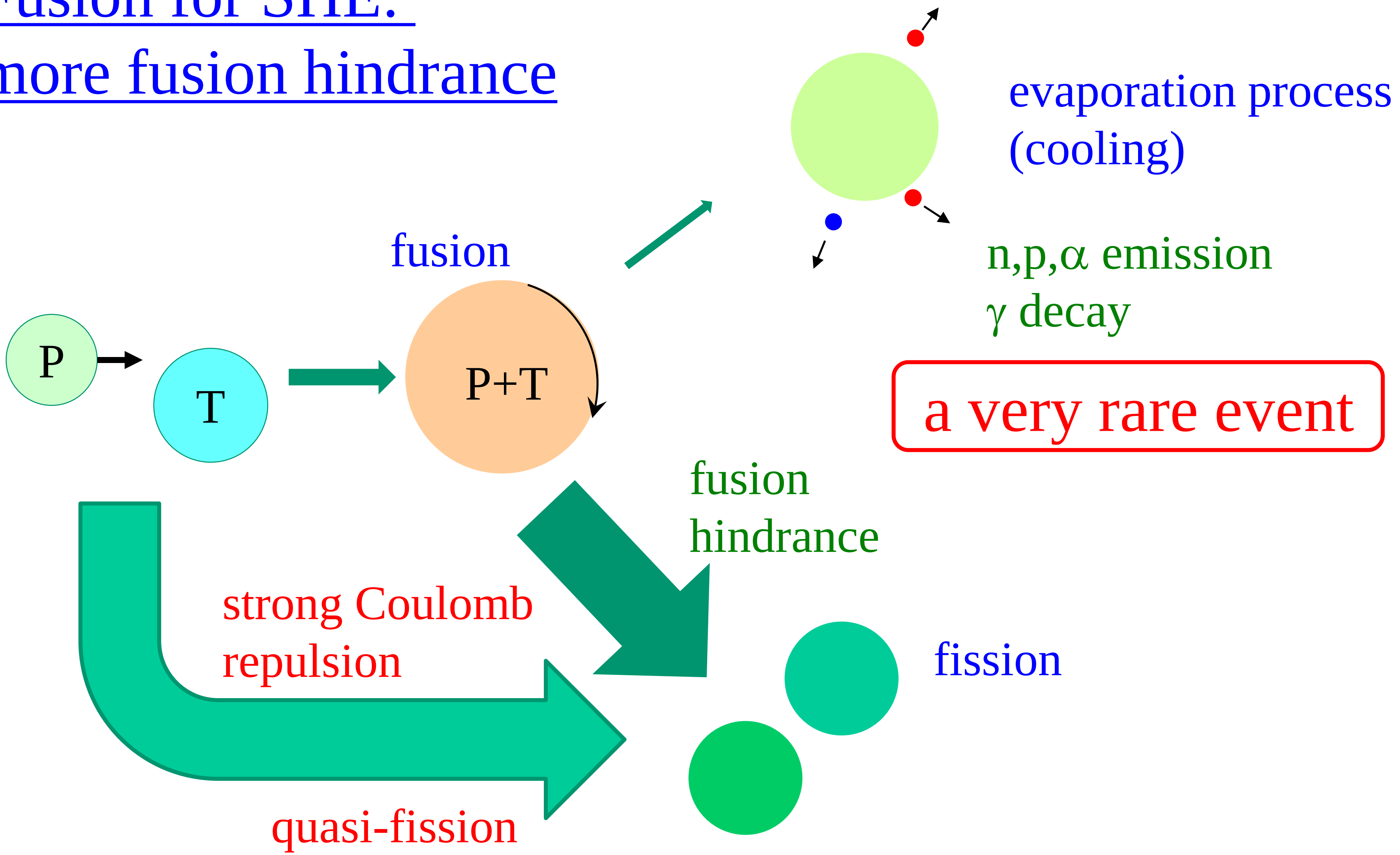


Fusion for SHE: fusion hindrance

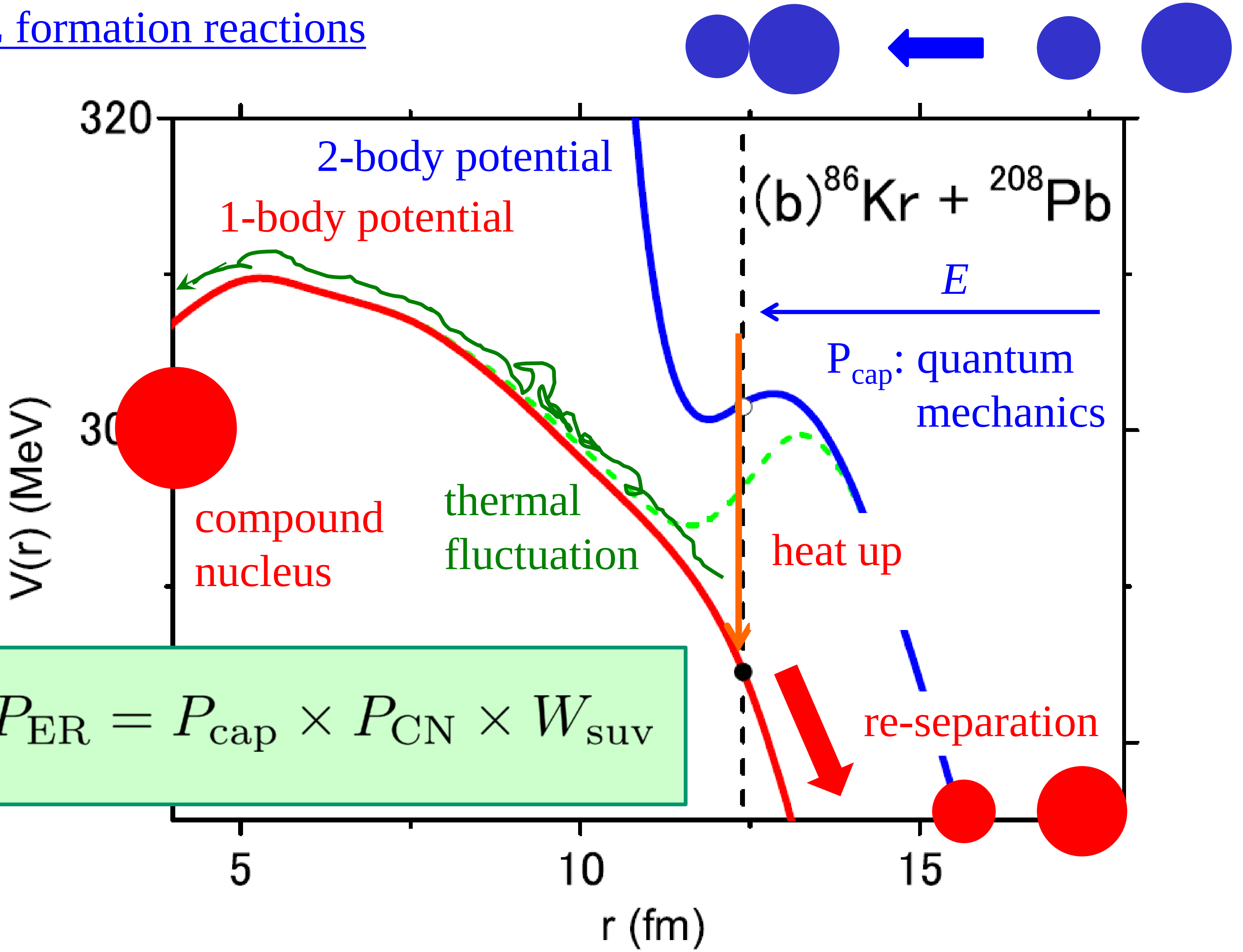


strong Coulomb repulsion
→ re-separation

Fusion for SHE: more fusion hindrance



SHE formation reactions



$$P_{\rm ER} = P_{\rm cap} \times P_{\rm CN} \times W_{\rm suv}$$

Theoretical challenges

formation of SHE: very rare

→ a large theoretical uncertainty

$$P_{\mathrm{ER}} = P_{\mathrm{cap}} \cdot P_{\mathrm{CN}} \cdot W_{\mathrm{suv}}$$

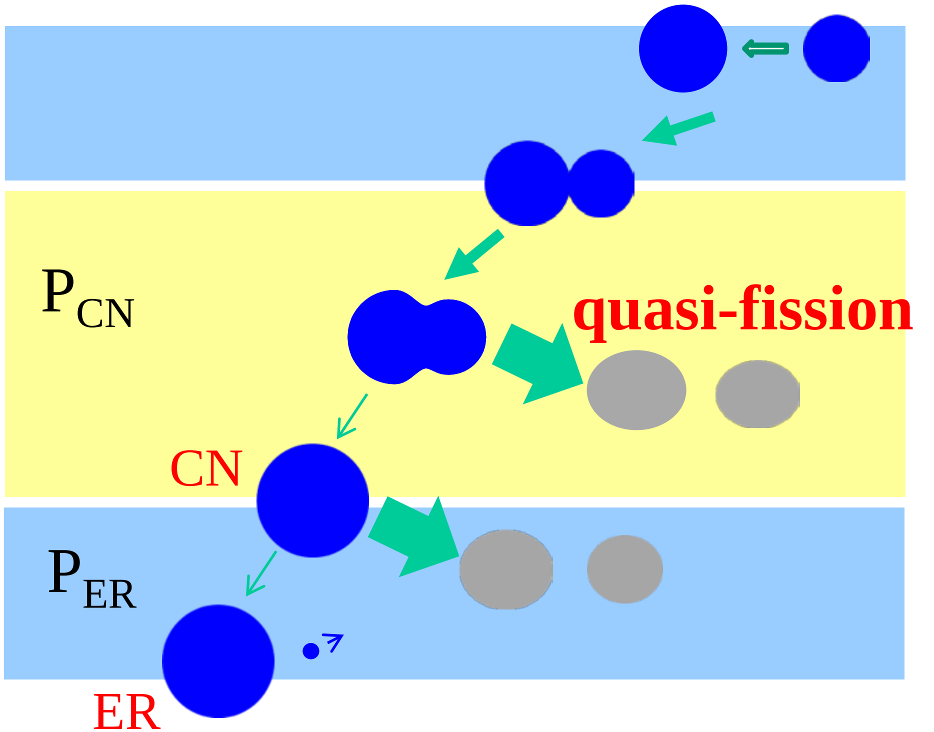
✓no exp. data for P_{CN}

✓exp. data: P_{ER} only

CN＝複合核、ER=蒸発残留核

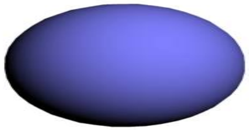
theoretical challenges:
to reduce the uncertainties and
make reliable predictions

fusion hindrance

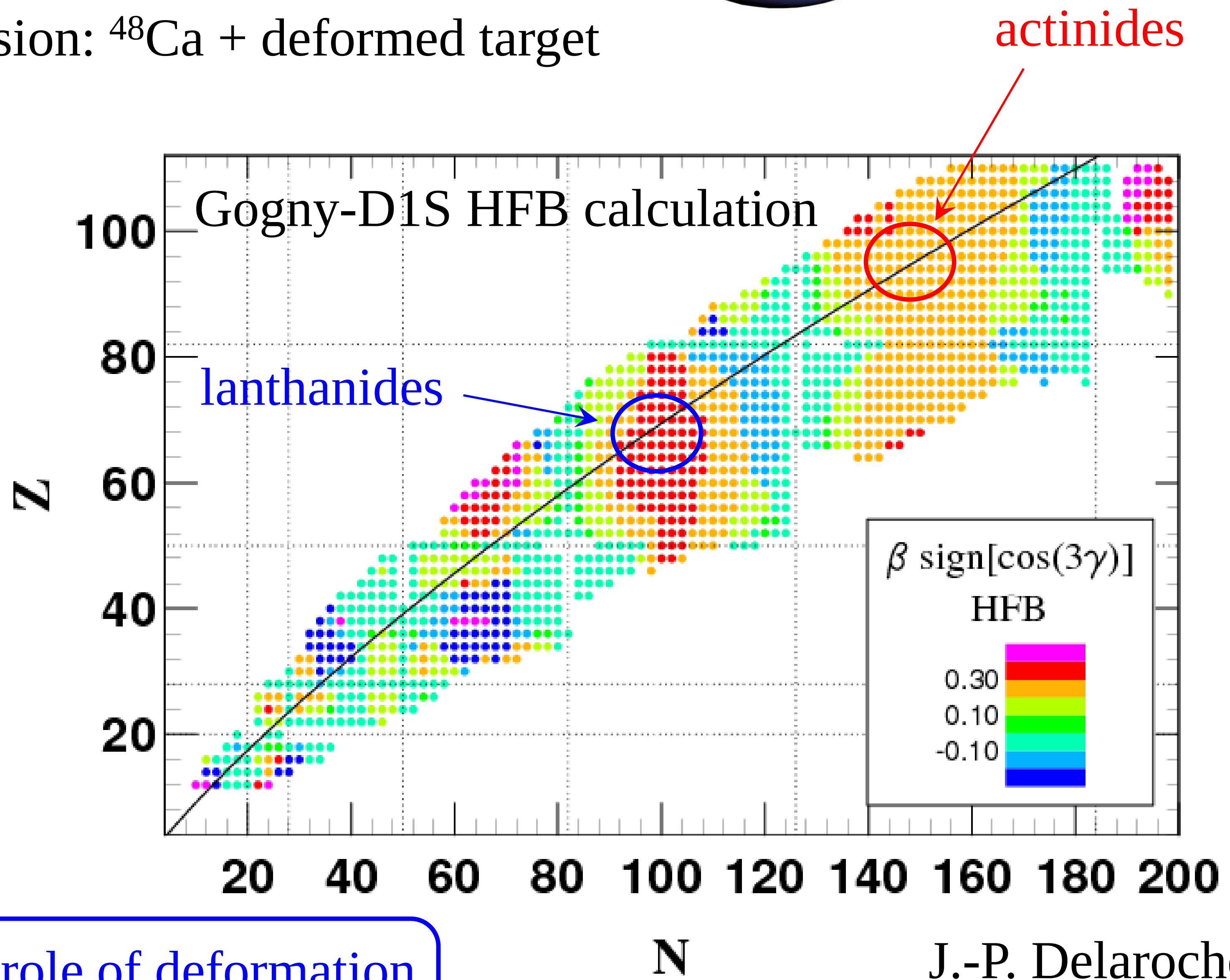


➡ Physics of open quantum systems
量子開放系の物理

hot fusion: Nuclear Deformation



hot fusion: ^{48}Ca + deformed target



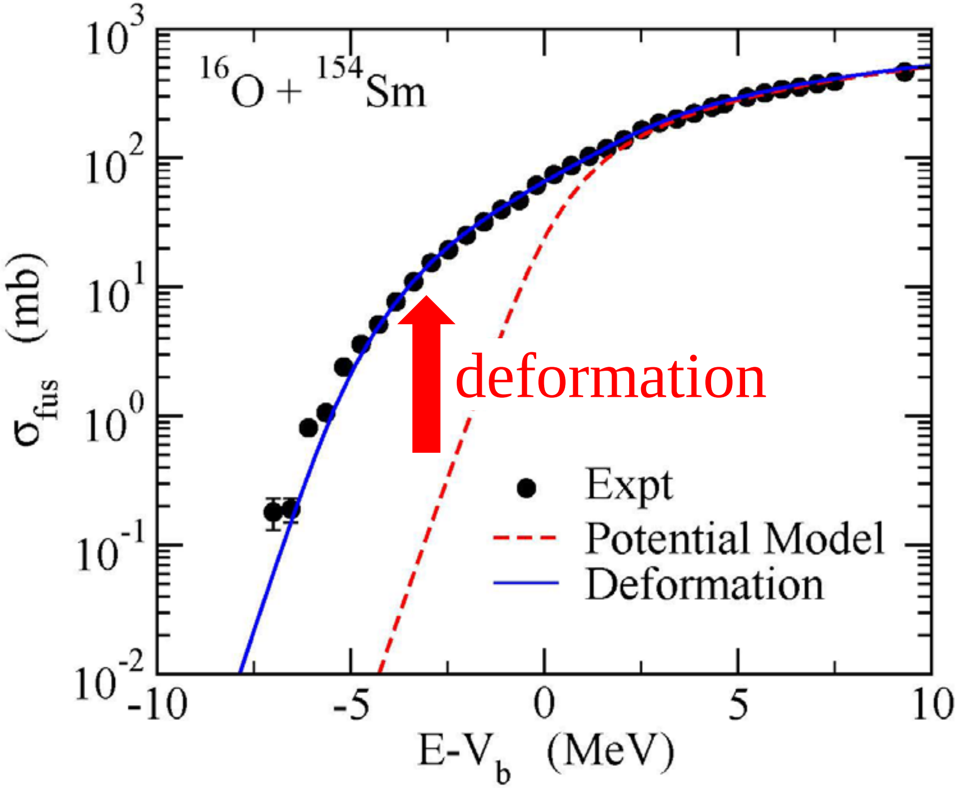
J.-P. Delaroche et al., PRC81 (‘10) 014303

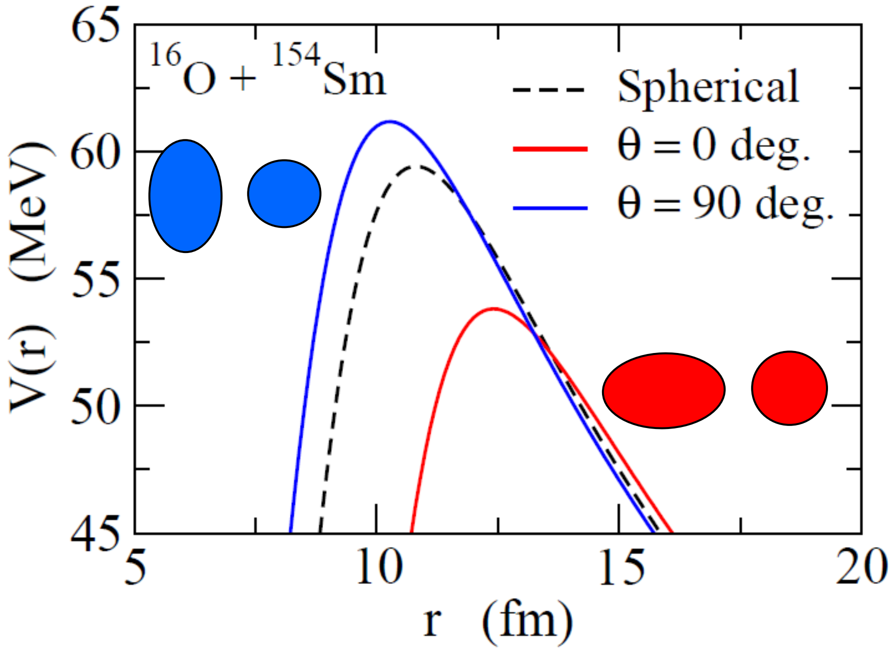
the role of deformation in heavy-ion reactions?

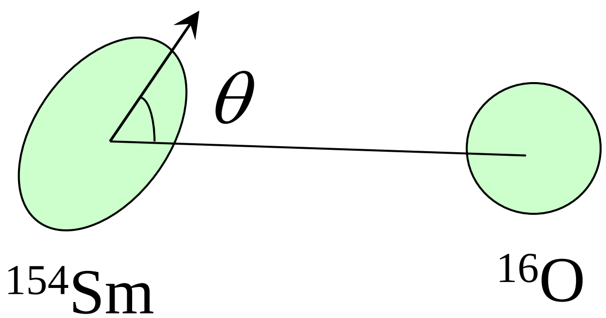
Nuclear deformation and barrier distribution

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

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





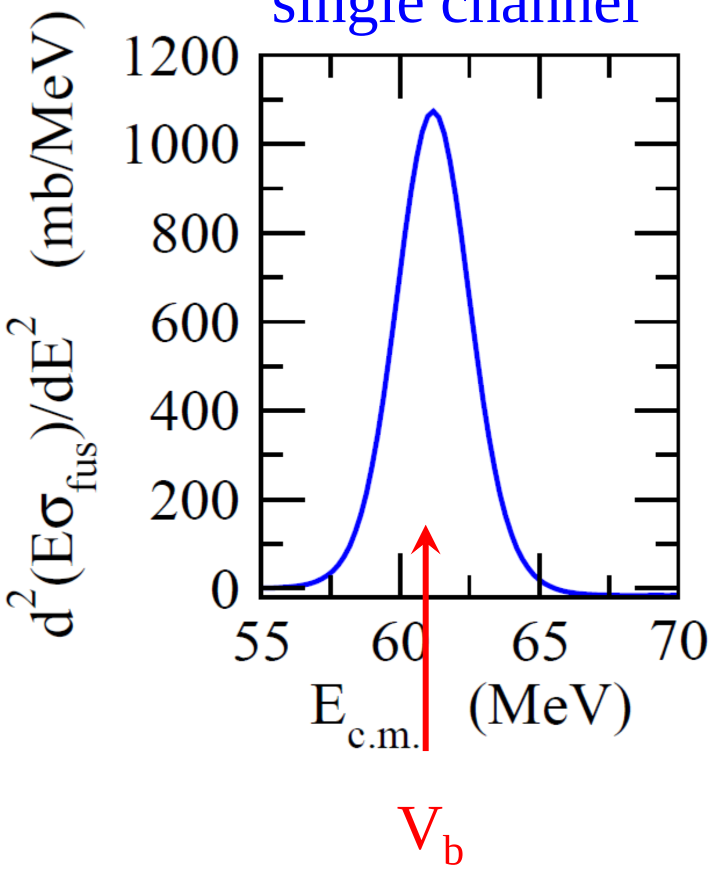


K.H., N. Takigawa, PTP128 (‘12) 1061

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

$$D_{\rm fus}(E) = \frac{d^2(E\sigma_{\rm fus})}{dE^2} \propto \frac{dP_{l=0}}{dE}$$

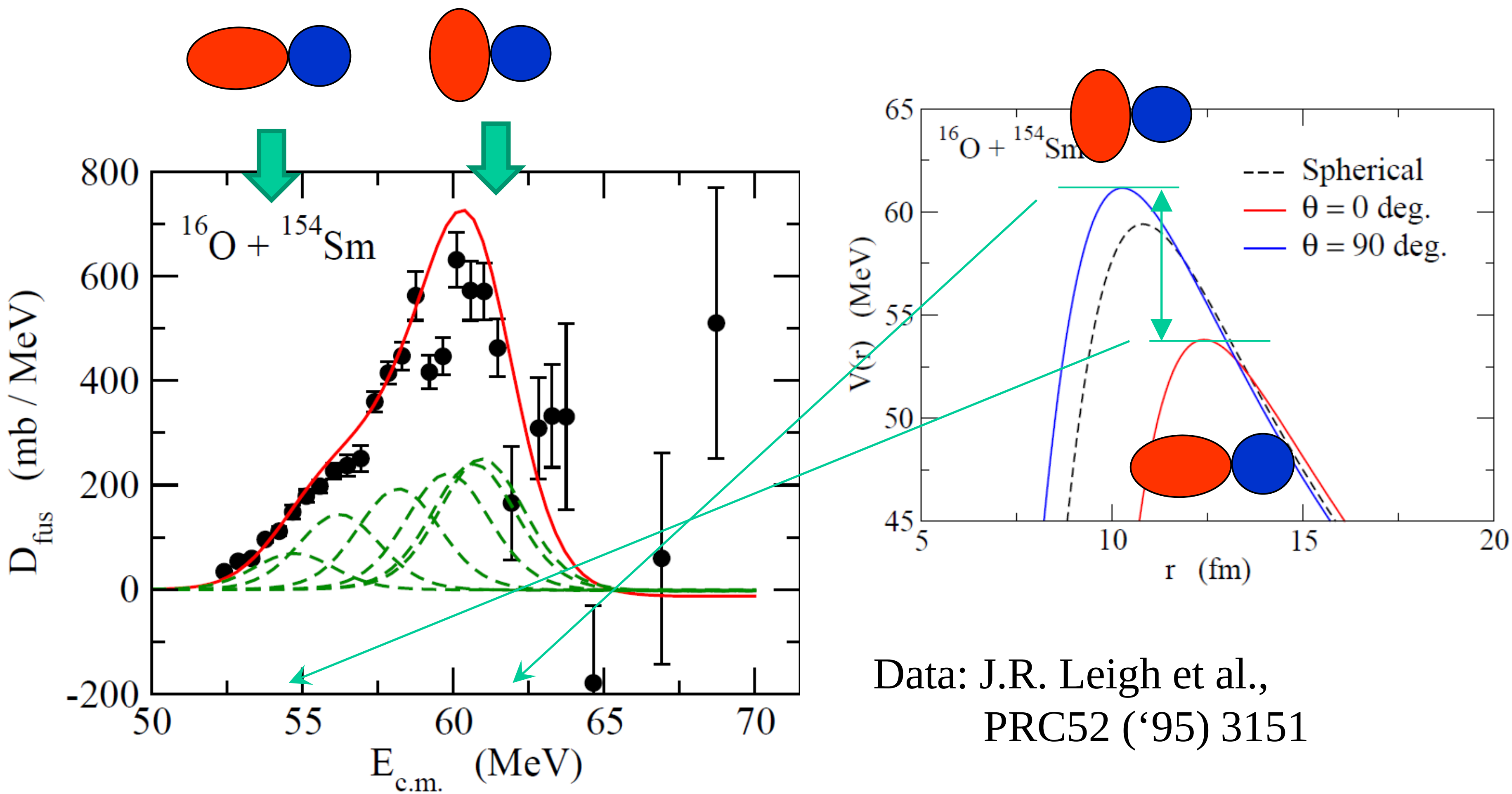
single channel



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

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

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

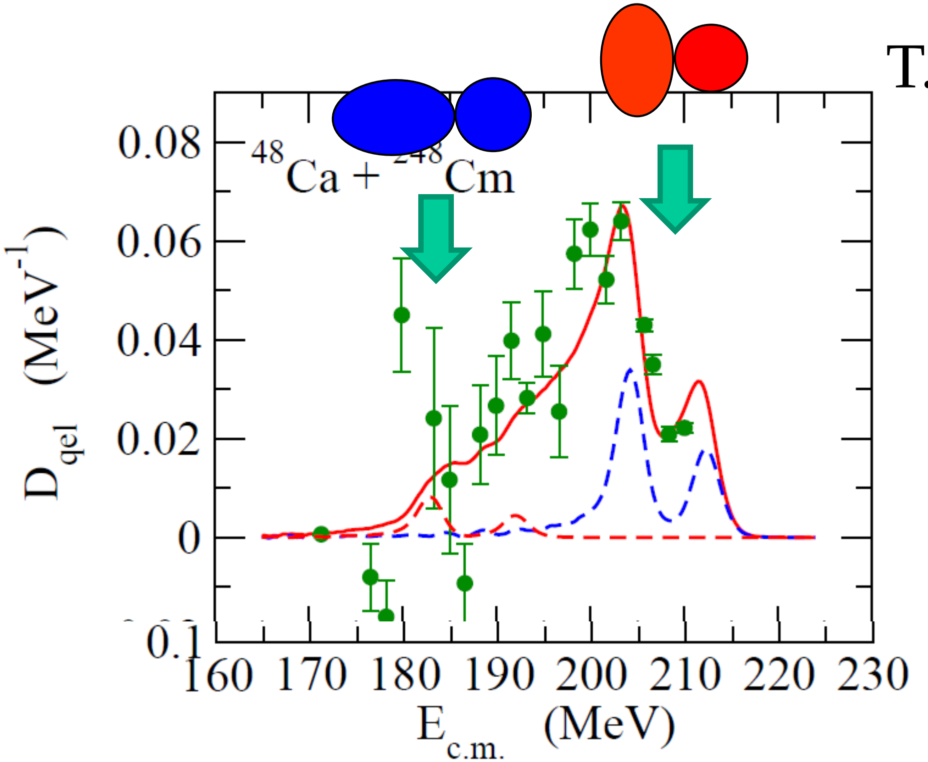


Data: J.R. Leigh et al.,
PRC52 ('95) 3151

can be used to identify
the side/tip collisions

Application to hot fusion reactions

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

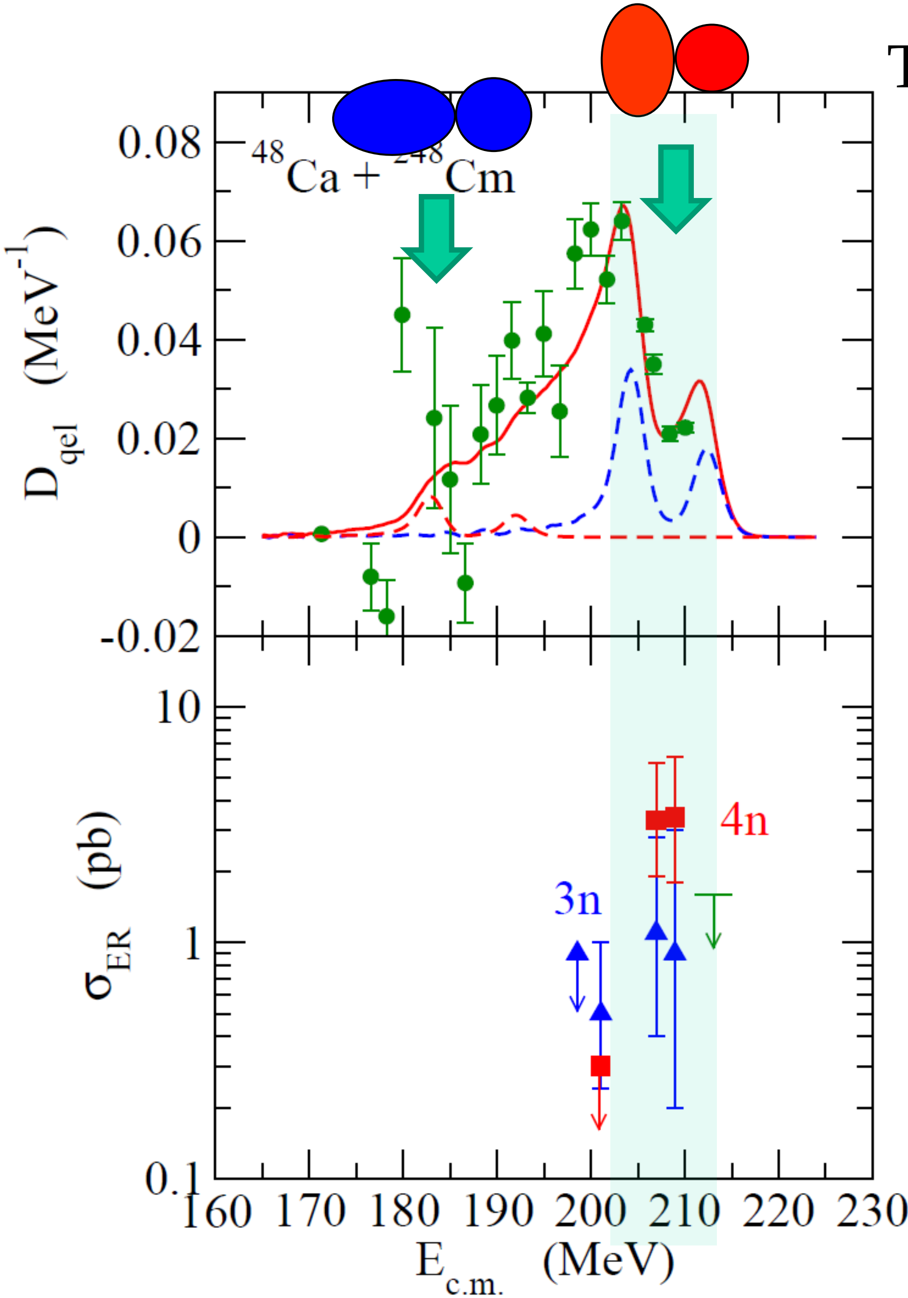


T. Tanaka,…, K.H., et al.,
JPSJ 87 (‘18) 014201
PRL124 (‘20) 052502

capture barrier distribution

Application to hot fusion reactions

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

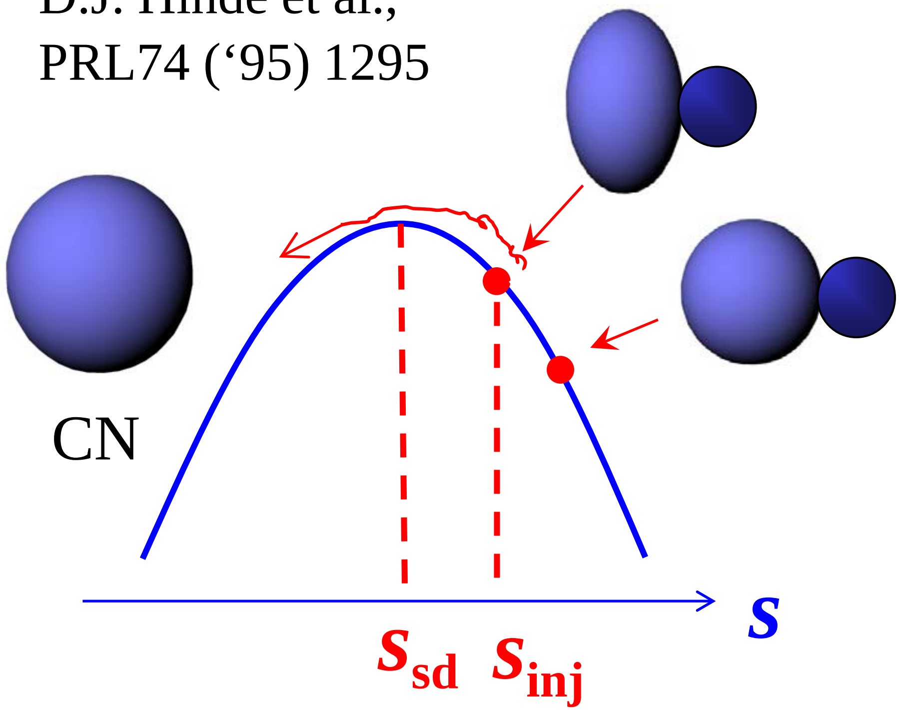


T. Tanaka,..., K.H., et al.,
JPSJ 87 ('18) 014201
PRL124 ('20) 052502

capture barrier distribution

cf. notion of compactness:

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



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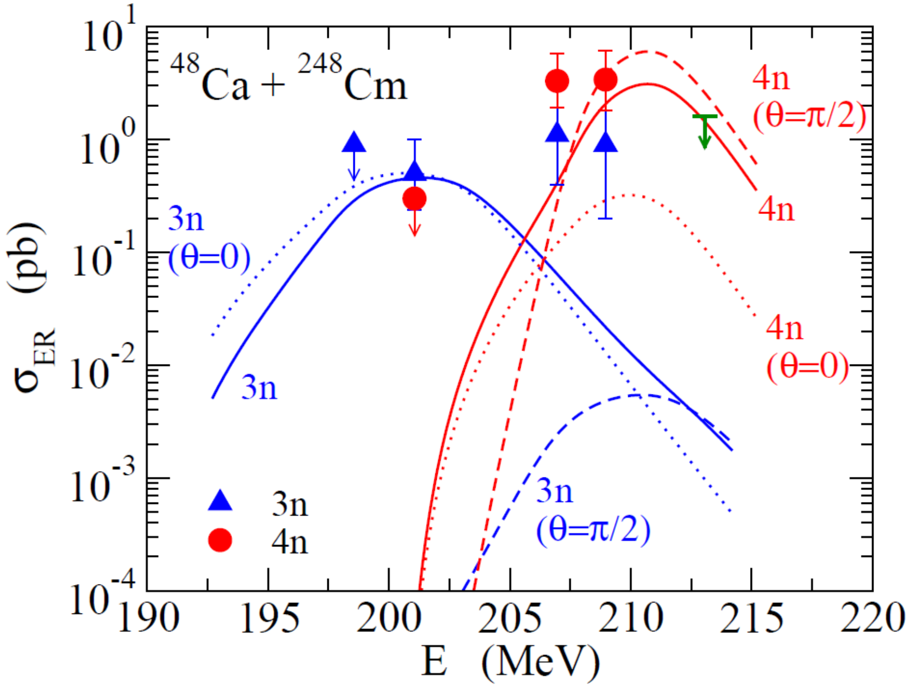

capture barrier distribution

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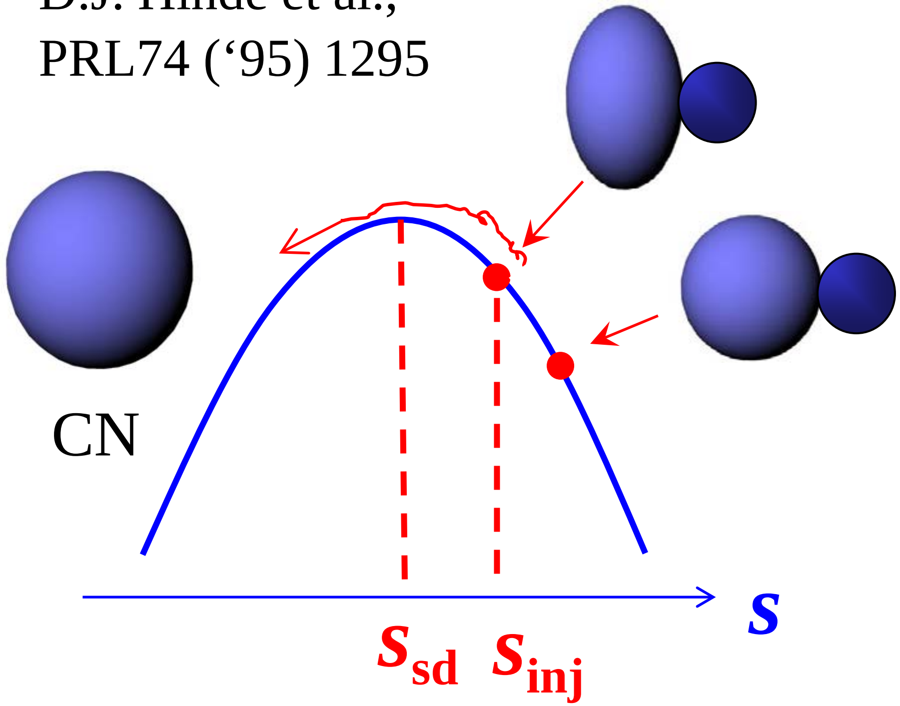
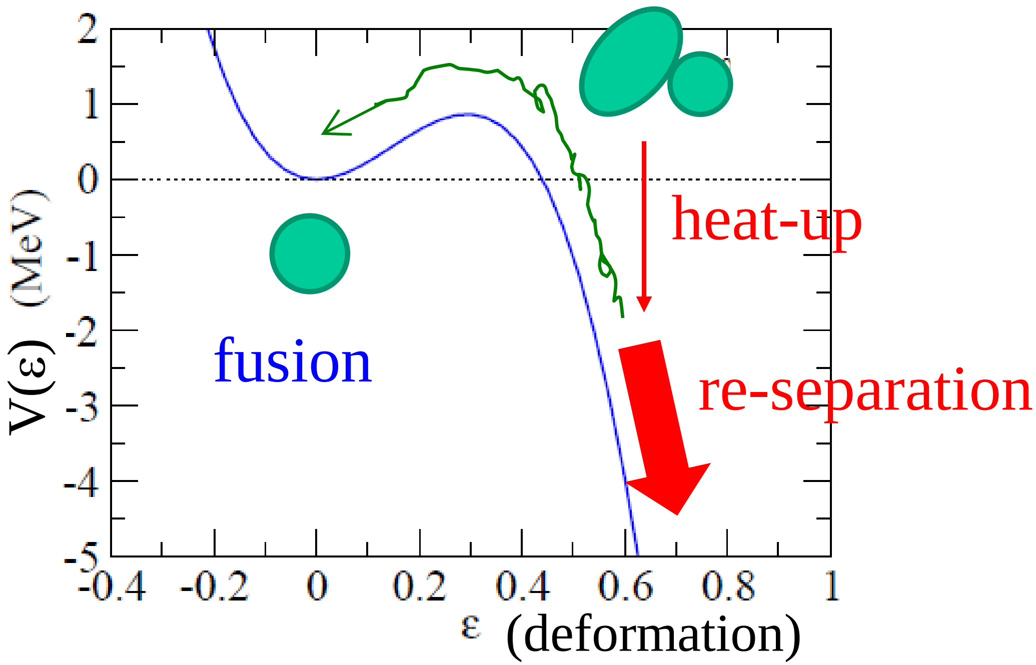
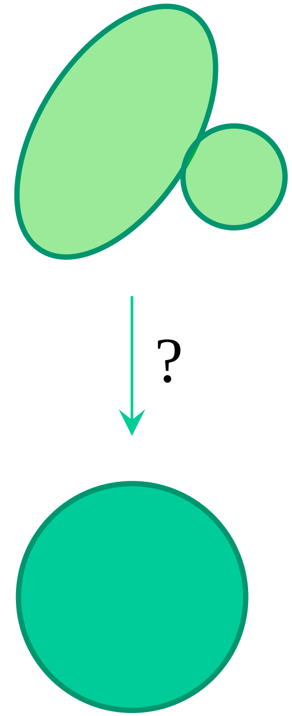
D.J. Hinde et al.,
PRL74 ('95) 1295



K. Hagino, PRC98 ('18) 014607

open problems





- how is the shape evolved to a compound nucleus?
- Deformation: a quantum effect

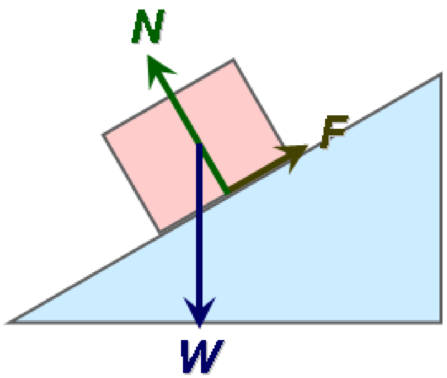
  how does the deformation disappear during heat-up?

quantum friction/open quantum systems

M. Tokieda and K.H., Ann. of Phys. 412 (‘20) 168005.

Front. in Phys. 8 (‘20) 8.

quantum friction



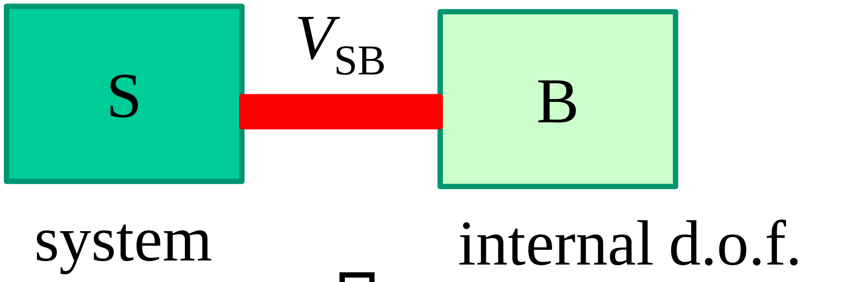
heat generation when a rigid body stops

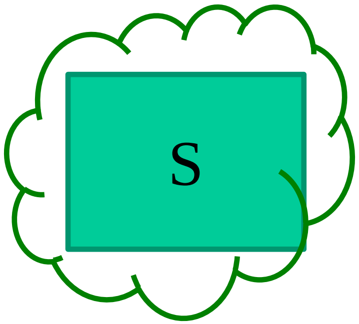
⇩

the energy conversion from the rigid body to intrinsic d.o.f. (atoms)

quantum Langevin?

in quantum mechanics :





"quasi" particle

solve the whole H without introducing the quasi-particle

M. Tokieda and K.H. (2020)

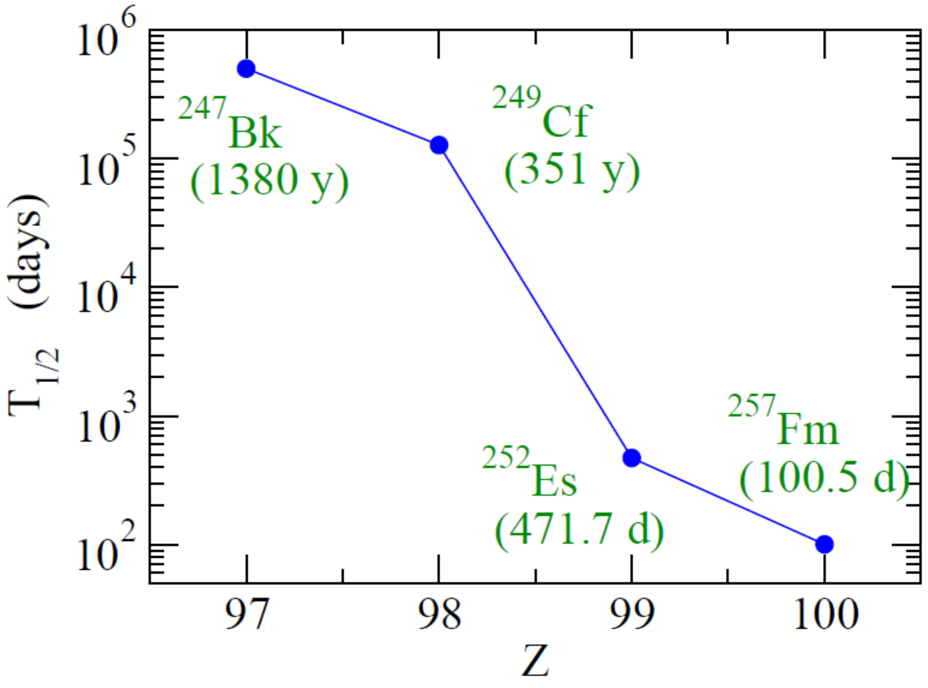
Hot fusion towards Z=119 and 120 nuclei

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



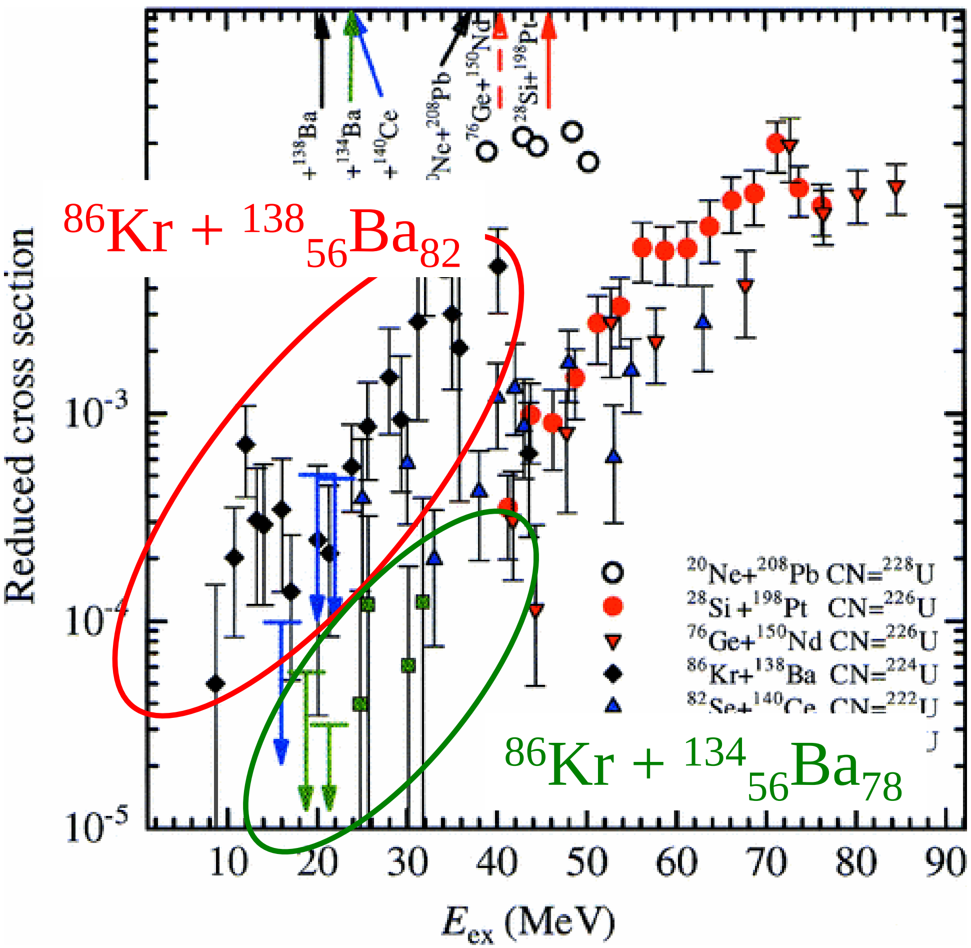
$^{48}Ca \rightarrow {}^{50}_{22}Ti$, $^{51}_{23}V$, $^{54}_{24}Cr$ projectiles

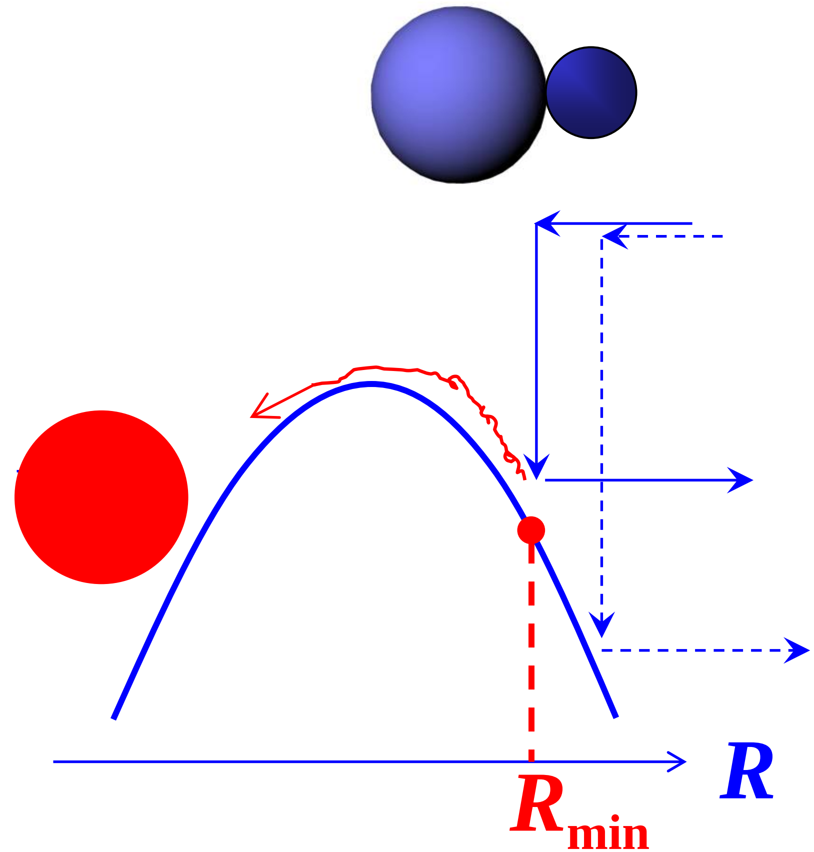
closed shell → open shells

how much will cross sections be affected?

Role of magicity

can proceed deeper
with less friction





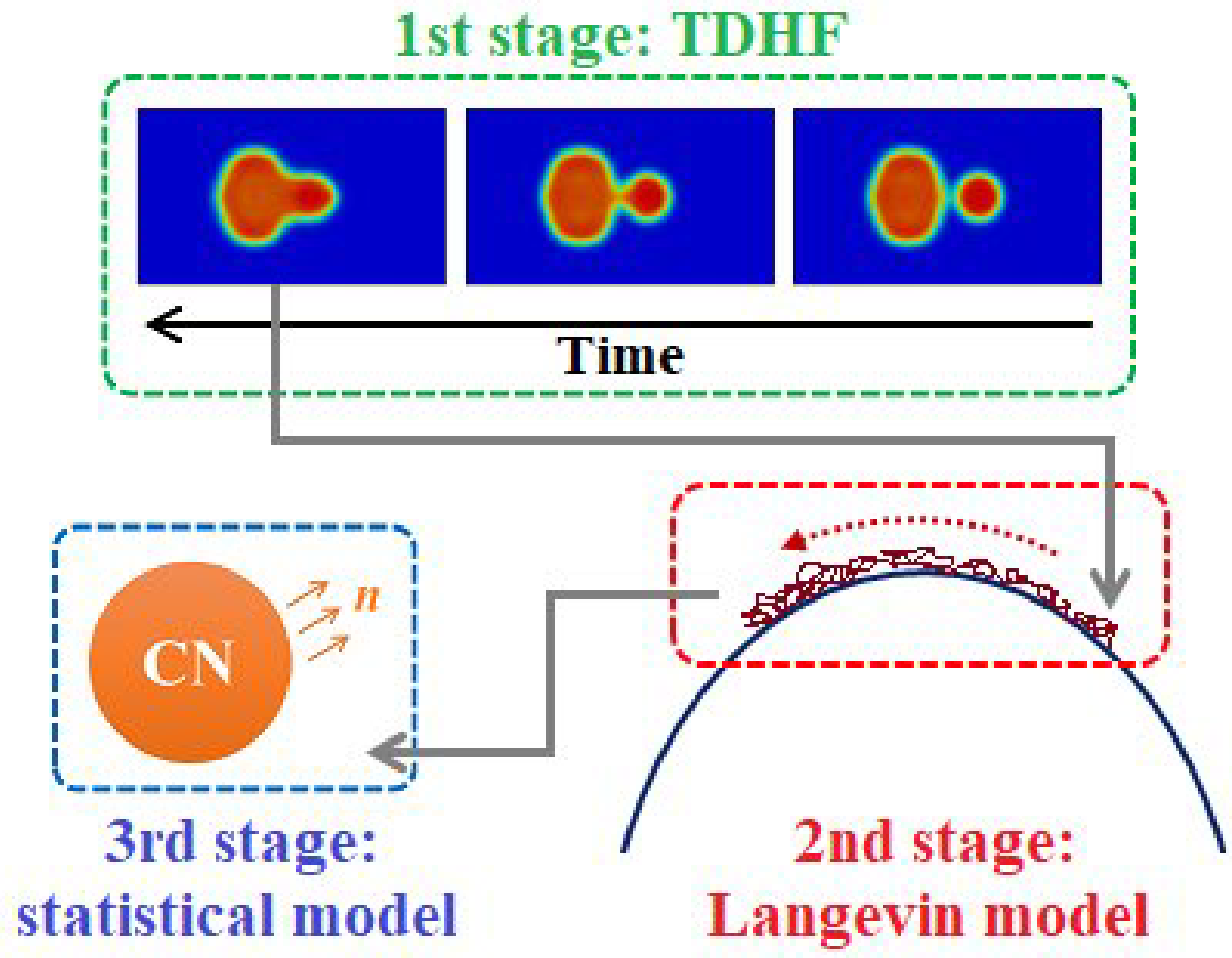
K. Satou, H. Ikezoe et al.,
PRC73 (‘06) 034609

cf. P. Moller et al.,
Z. Phys. A359 (‘97) 251.

similar effect for ^{48}Ca?

New hybrid model: TDHF + Langevin approach

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

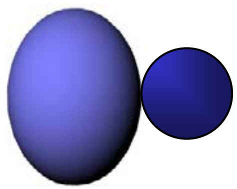


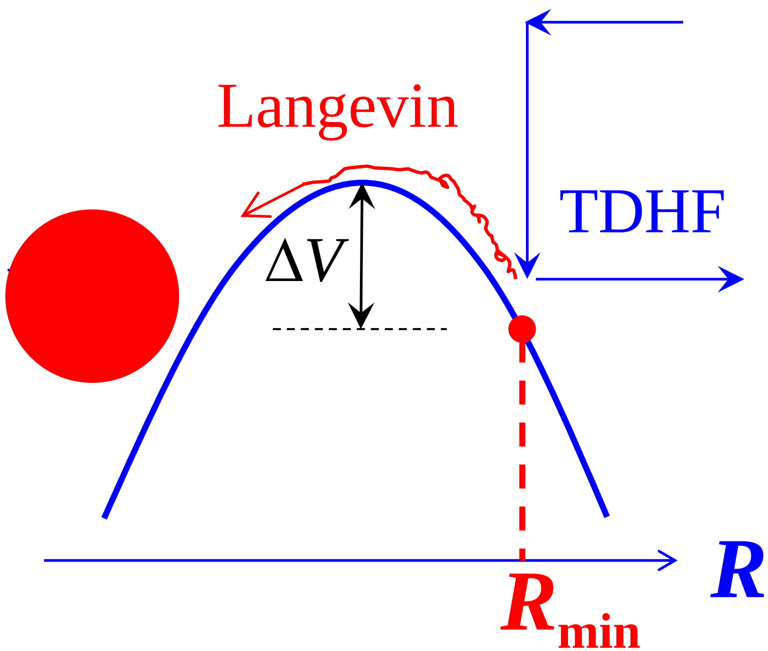
Furthermore : TDHF + Langevin approach and quantum friction

TDHF + Langevin approach :

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

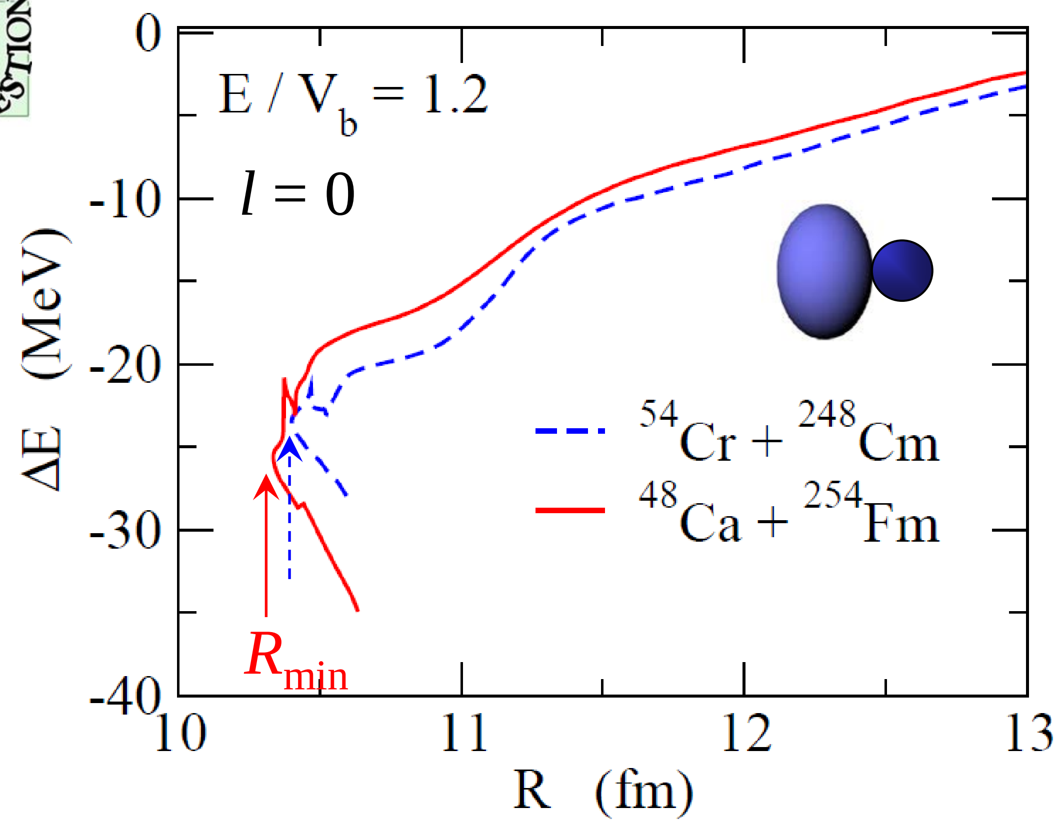
side
collision



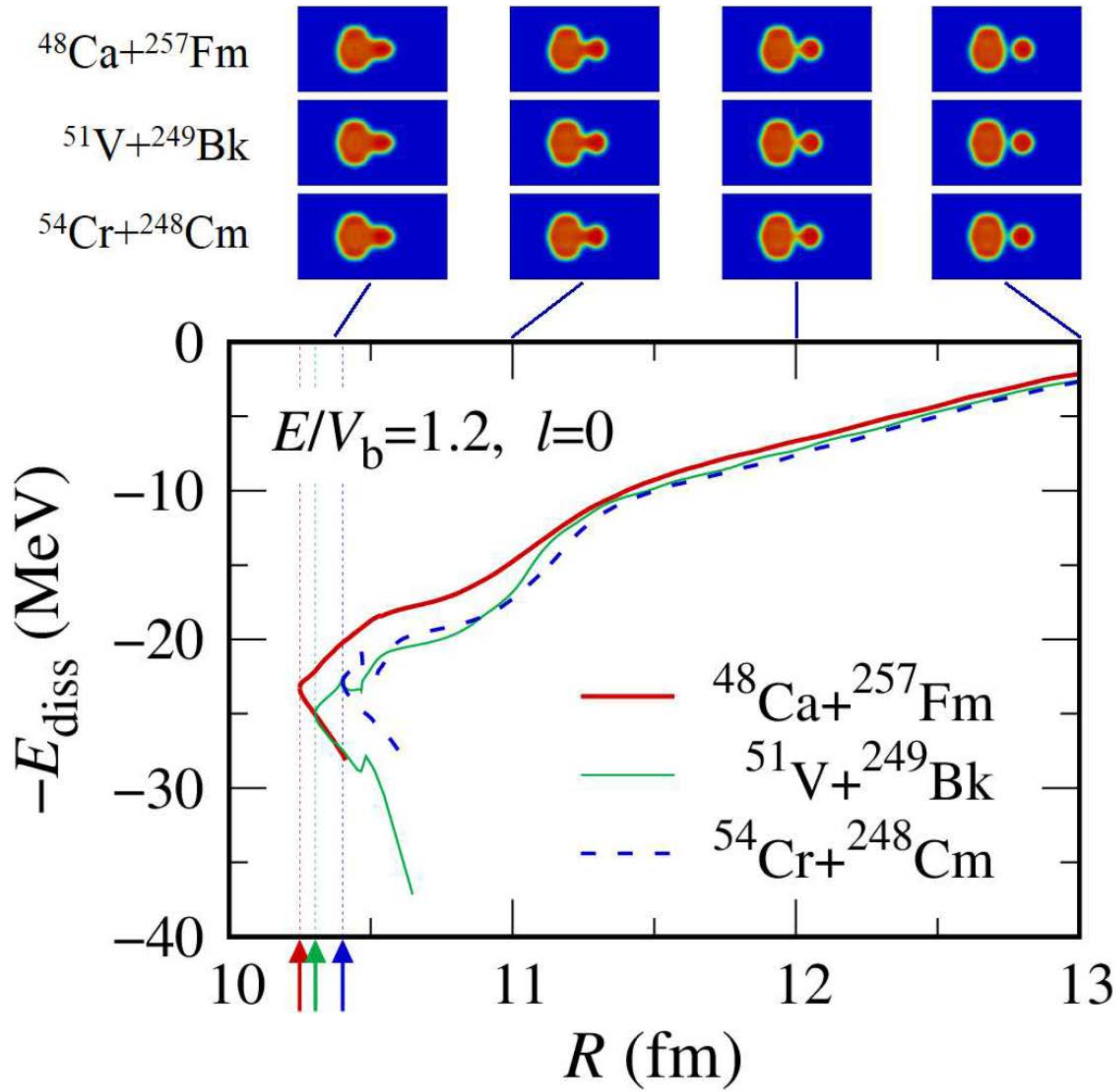


$^{54}Cr + ^{248}Cm \rightarrow ^{302}120$

$^{48}Ca + ^{254}Fm \rightarrow ^{302}120$



→ Langevin caluclation



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)

how special is ^{48}Ca ?

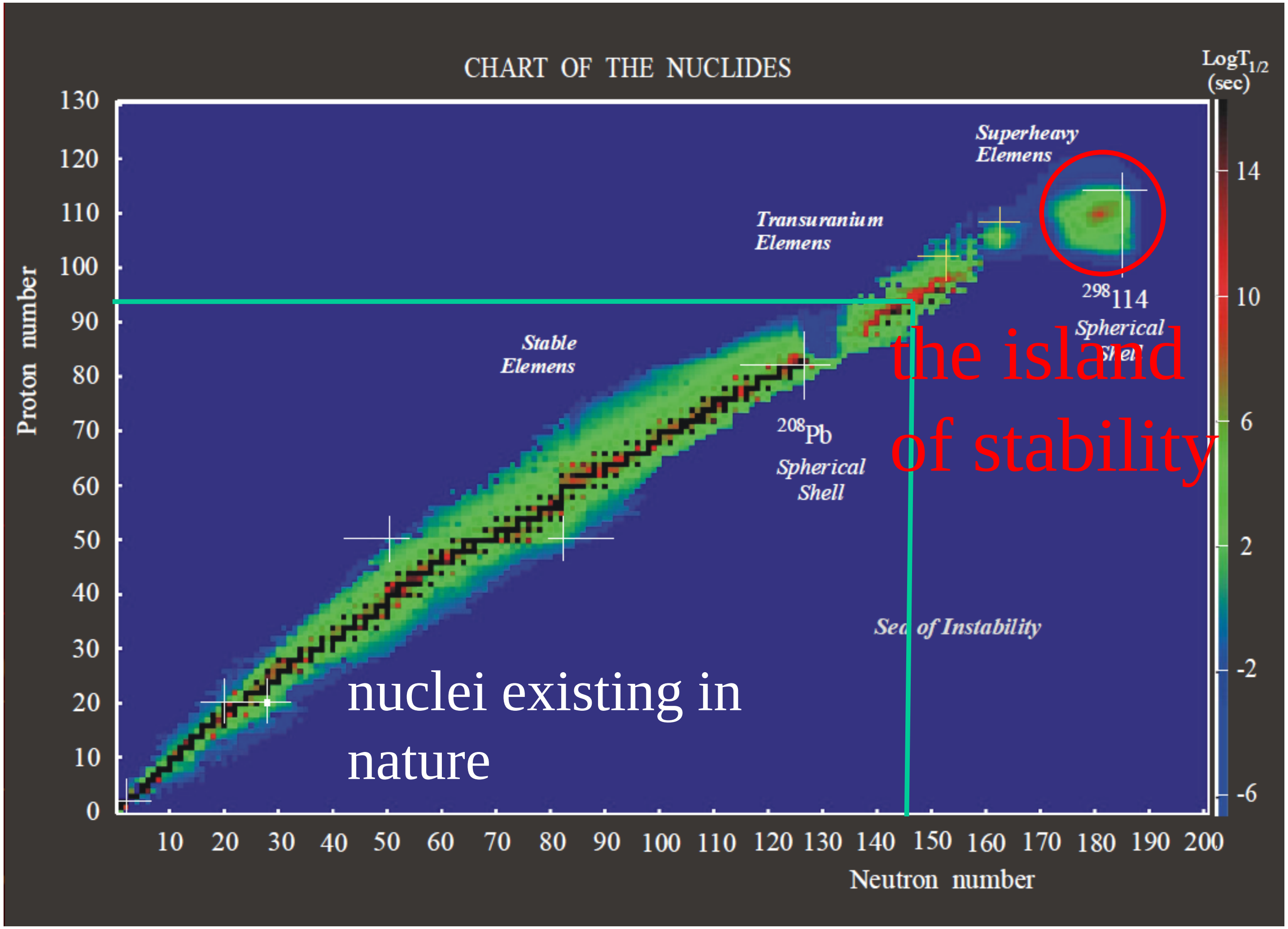
System	CN	E^* (MeV)	$R_{\rm min}$ (fm)	$P_{\rm CN}$ ($\times 10^4$)	$W_{\rm sur}$ ($\times 10^9$)	$P_{\rm CN}\, W_{\rm sur}$ ($\times 10^{13}$)
^{48}Ca + ^{254}Fm	^{302}120	29.0	12.93	1.72	176	302
^{54}Cr + ^{248}Cm	^{302}120	33.2	13.09	1.89	1.31	2.47
^{51}V + ^{249}Bk	^{300}120	37.0	12.94	3.95	0.117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

$$P_{\rm ER} = P_{\rm cap} \cdot P_{\rm CN} \cdot W_{\rm suv}$$

similar $P_{\rm CN}$

- ✓ no special role of ^{48}Ca in the entrance channel
- ✓ non-^{48}Ca proj.: about 2 order of magnitude smaller due mainly to $W_{\rm sur}$

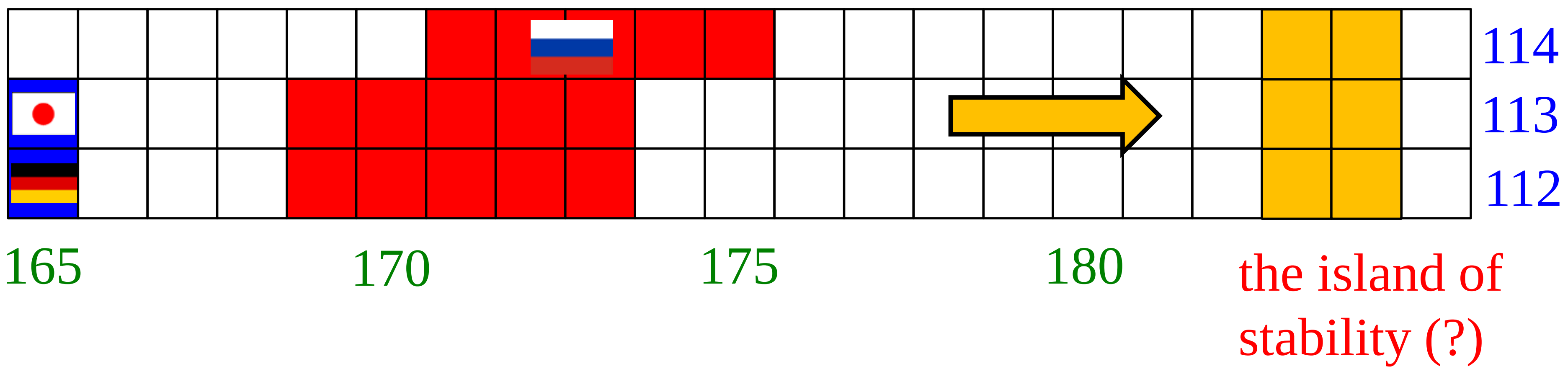
Another important issue: physics of neutron-rich nuclei



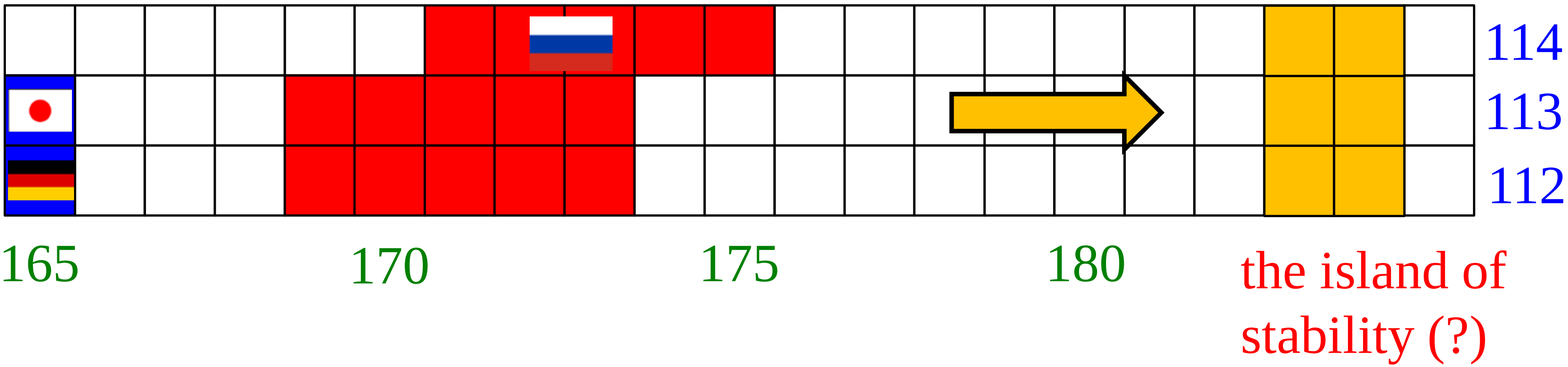
Yuri Oganessian

how to reach the island of stability?

Fusion of unstable nuclei



Fusion of unstable nuclei



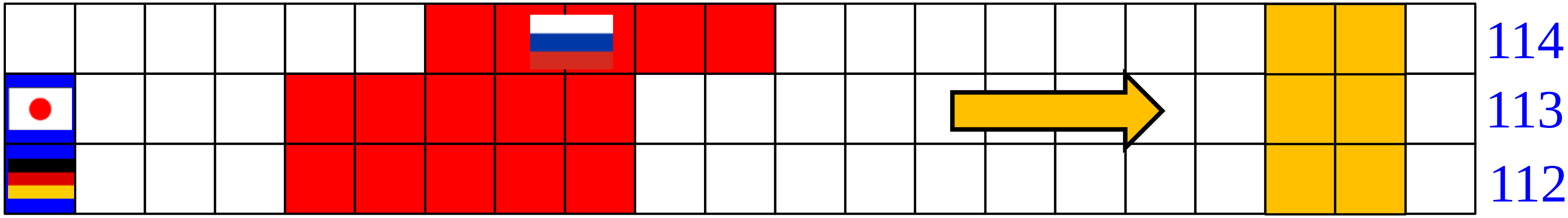
neutron-rich beams: indispensable

- how to deal with low beam intensity?
- reaction dynamics of neutron-rich beams?
  - ✓ capture: role of breakup and (multi-neutron) transfer?
  - ✓ diffusion: neutron emission during a shape evolution?
  - ✓ survival: validity of the statistical model?

structure of exotic nuclei

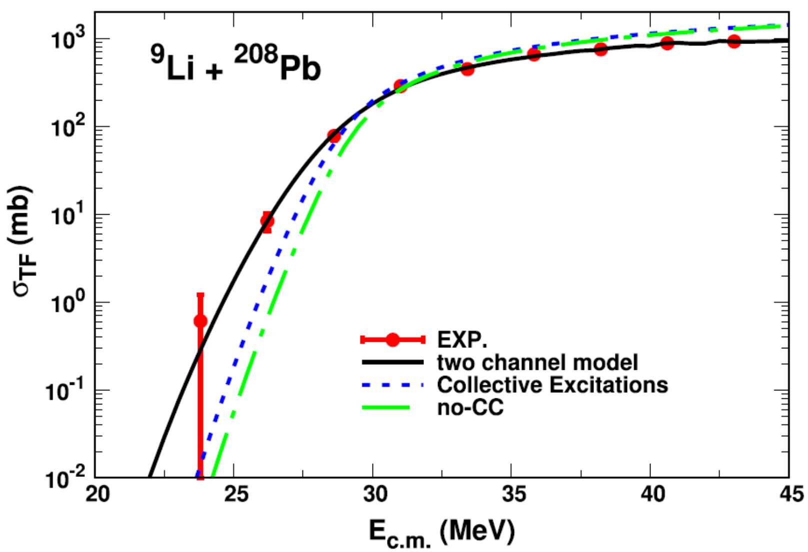
more studies are required

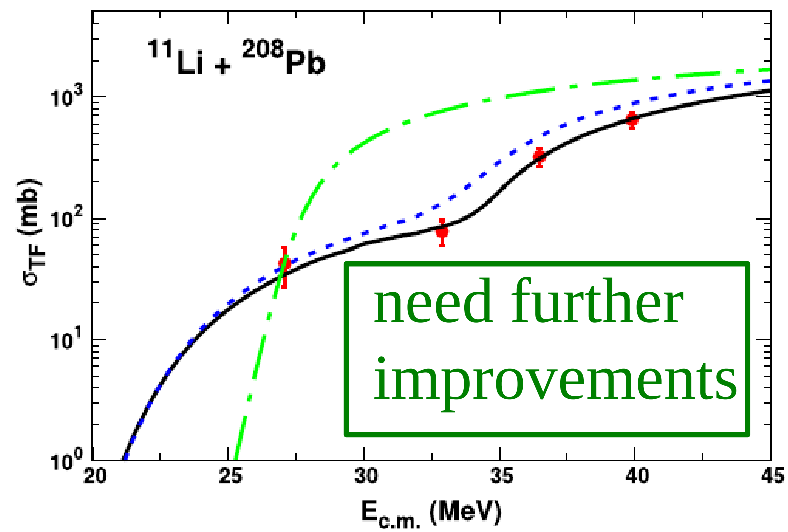
Fusion of unstable nuclei



neutron-rich beams: indispensable
→reaction dynamics?

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

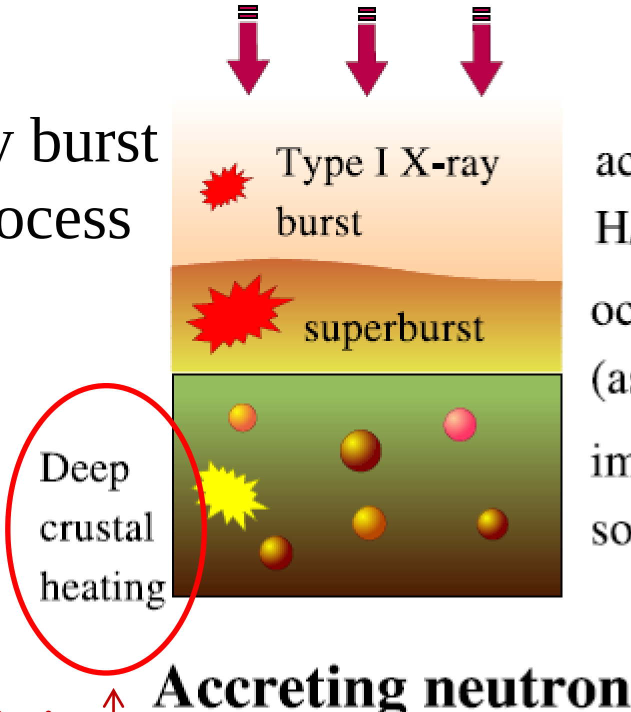




simultaneous explanation for ^{9}Li+^{208}Pb and ^{11}Li+^{208}Pb with:
^{11}Li+^{208}Pb ⟵⟶ ^{9}Li+^{210}Pb ⟵⟶ ^{7}Li+^{212}Pb transfer couplings

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

X-ray burst
rp-process



accreted
H/He
ocean
(ashes)
impure
solid crust

electron capture

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

towards neutron-rich nuclei

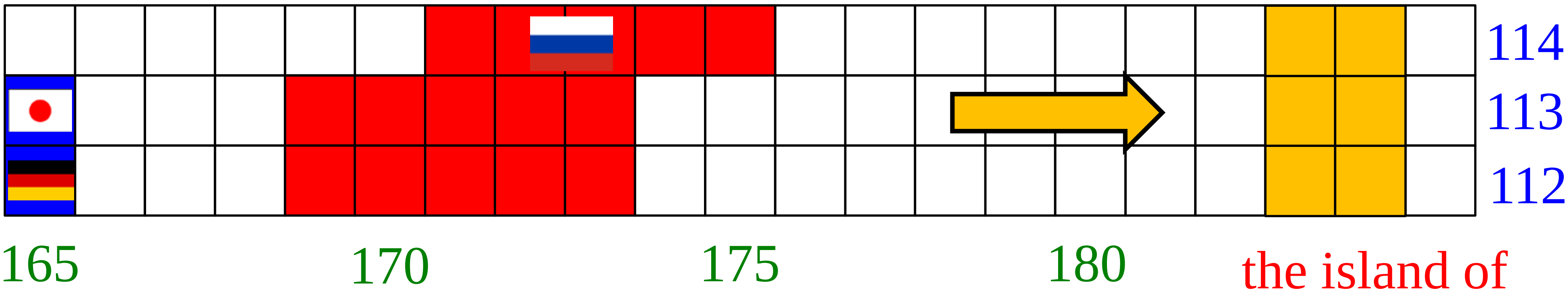
origin ↑

fusion of neutron-rich nuclei
when Z becomes small enough

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

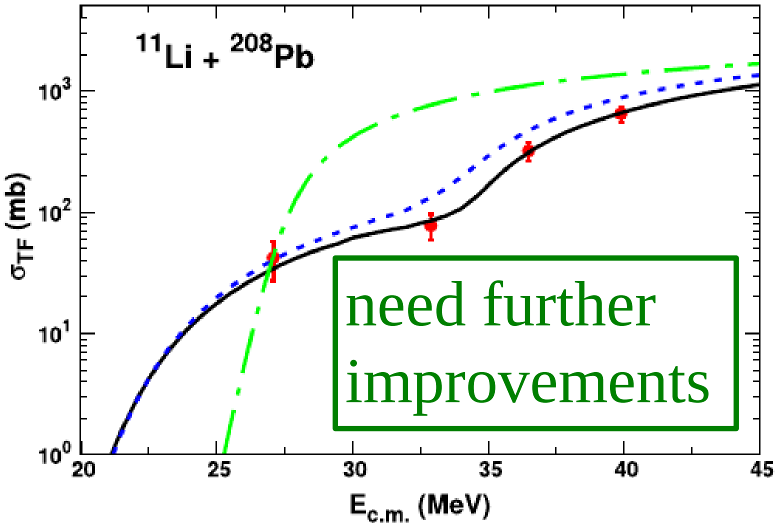
N. Chamel and P. Haensel,
Living Rev. Relativity, 11 ('08) 10.

Fusion of unstable nuclei

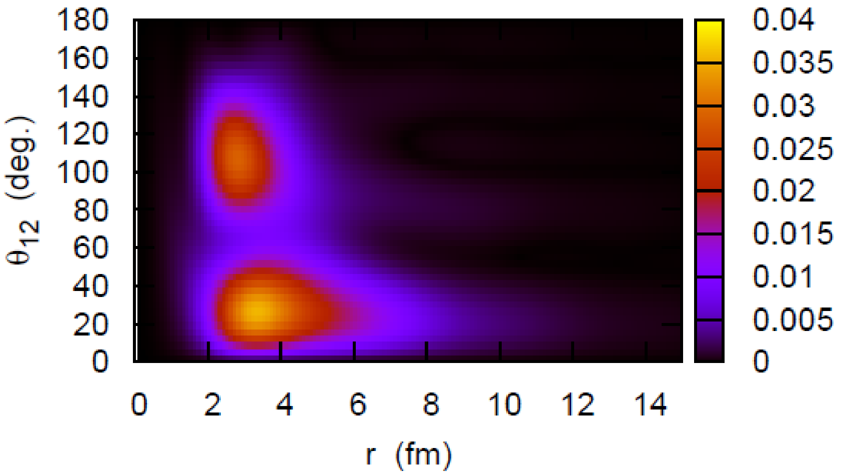


the island of stability

neutron-rich beams: indispensable→reaction dynamics?



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



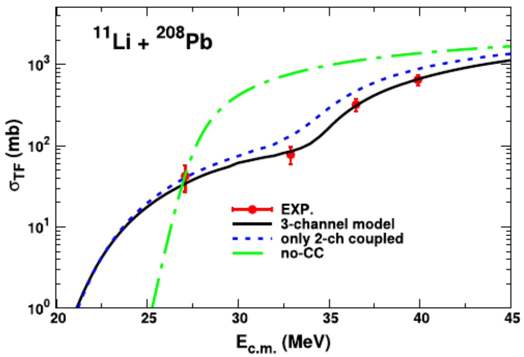
K.H. and H. Sagawa, PRC72('05)044321

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

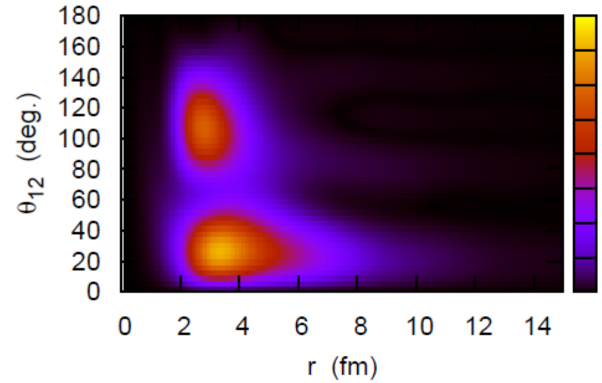
Summary

Physics of SHE

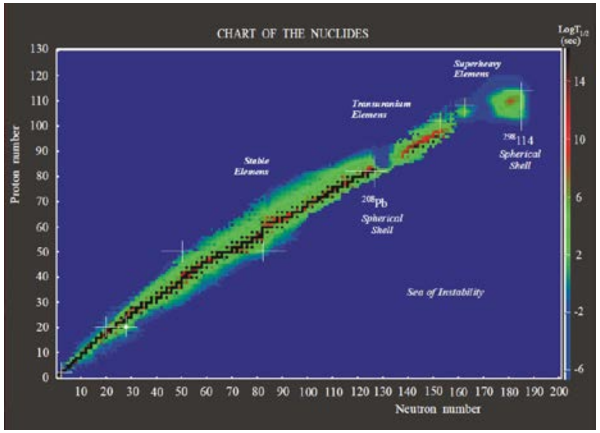
Reactions of n-rich nucl.



Structure of n-rich nucl.



- SHE
- the island of stability

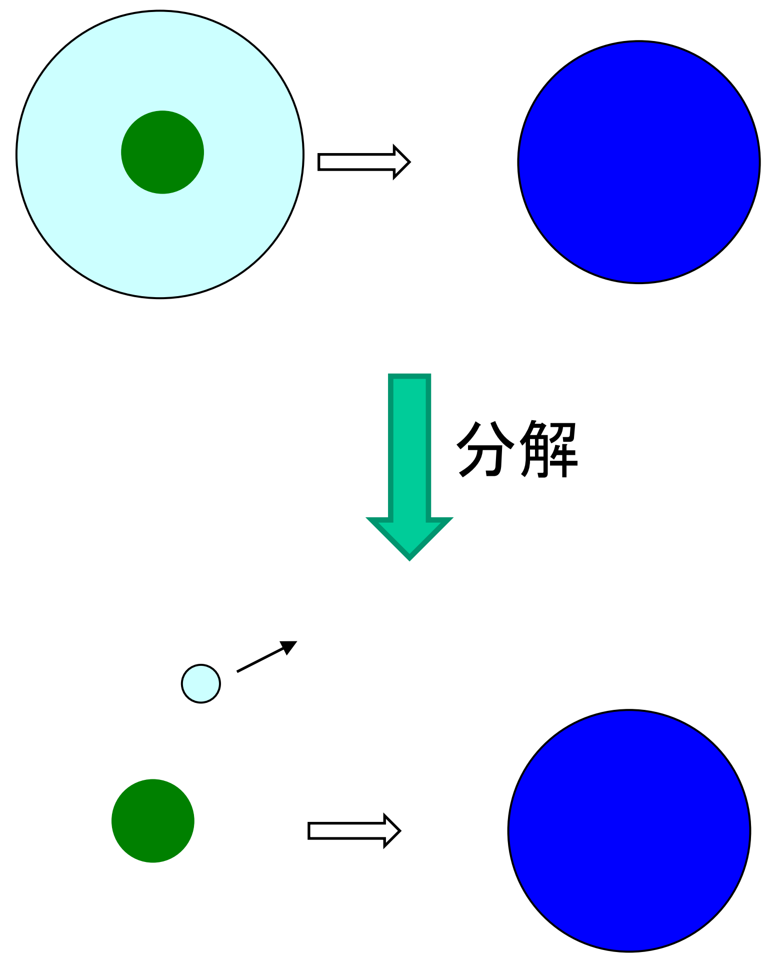


open quantum systems (OQS)

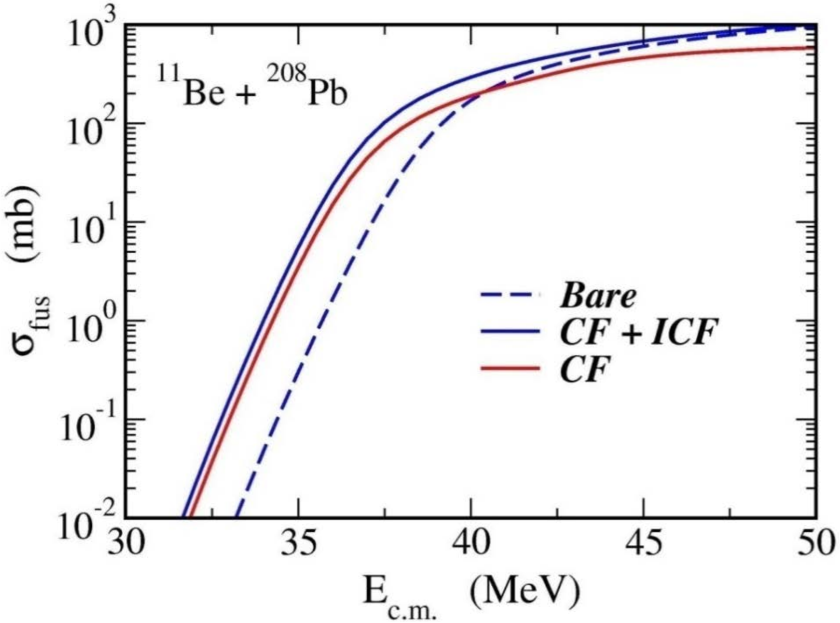
SHE + neutron-rich nuclei + OQS → new direction

➢安定の島に向けて

中性子過剰核=弱束縛



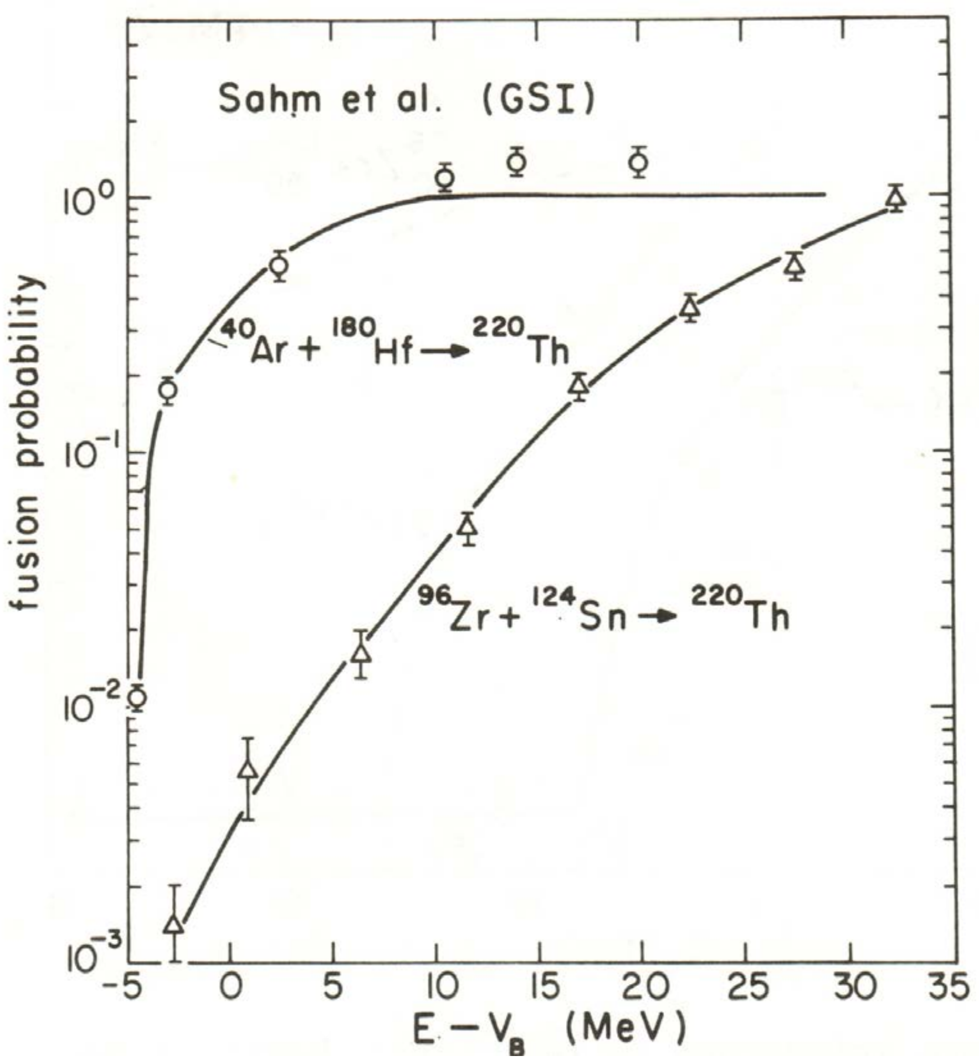
中性子過剰核ビームを用いた
実験が必要不可欠



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

反応機構の理解(分解、核子移行、融合)

fusion hindrance



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

New method for open quantum systems

M. Tokieda and K.H., Ann. of Phys., in press ('19)

$$H_{\rm tot} = \underbrace{H_S}_{\text{system}} + \underbrace{\sum_i \hbar\omega_i a_i^\dagger a_i}_{\text{environment}} + \underbrace{h(q)\sum_i d_i(a_i^\dagger + a_i)}_{\text{coupling}}$$

naiive coupled-channels equations:

$$\Psi_{\rm tot}(q,t) = \sum_{\{n_i\}} \psi_{\{n_i\}}(q,t)\,|\{n_i\}\rangle; \quad |\{n_i\}\rangle = \prod_i \frac{1}{\sqrt{n_i!}}\left(a_i^\dagger\right)^{n_i}|0\rangle$$

$$\Longrightarrow \quad \langle\{n_i\}|i\hbar\frac{\partial}{\partial t}|\Psi_{\rm tot}\rangle = \langle\{n_i\}|H_{\rm tot}|\Psi_{\rm tot}\rangle$$

$\longrightarrow$ coupled-channels eqs. for $\psi_{\{n_i\}}(q,t)$

difficult when the number of environmental osc. modes is large

$$H_{\text{tot}} = H_S + \sum_i \hbar\omega_i a_i^\dagger a_i + h(q)\sum_i d_i(a_i^\dagger + a_i)$$

→ introduce more efficient basis

$$e^{-i\omega t} \sim \sum_{k=1}^{K} \underline{\eta_k(\omega)}\,\underline{u_k(t)}$$

exp. coef. — basis

cf. correlation function

$$L(t) = \int_{-\infty}^{\infty} d\omega \frac{J(\omega)}{1-e^{-\beta\hbar\omega}} e^{-i\omega t}$$

cf. 階層型運動方程式

Y. Tanimura and R. Kubo,
J. Phys. Soc. Jpn 58 ('89)101

→

$$b_k^\dagger = \sum_i \frac{d_i}{\hbar}\eta_k(\omega_i) a_i^\dagger$$

cf. Lanczos method

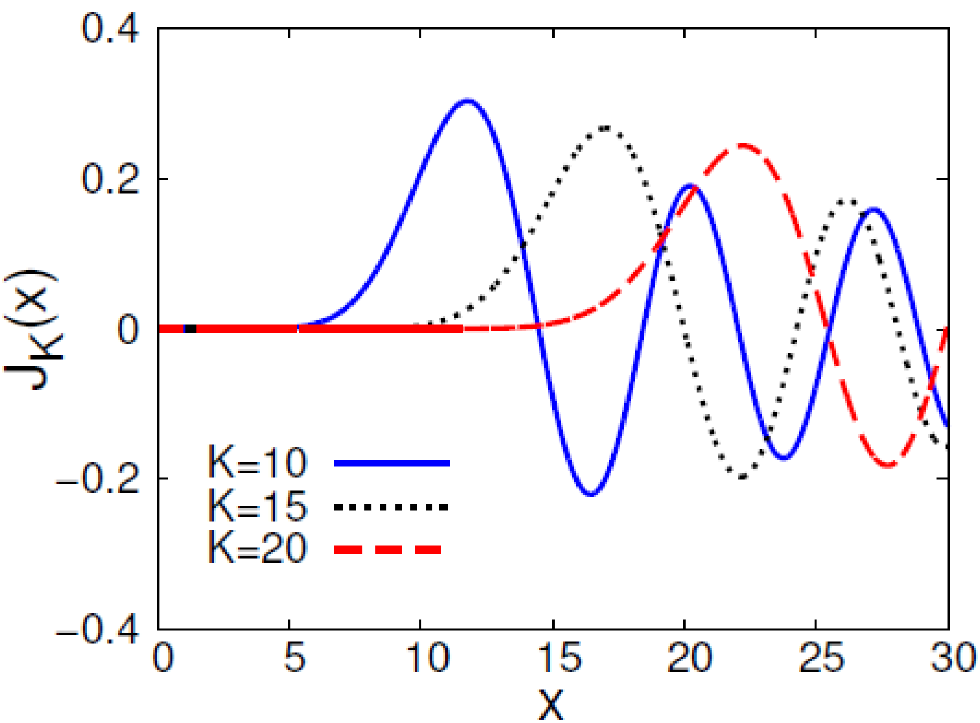
$$\Psi_{\text{tot}}(q,t) = \sum_{\{\tilde{n}_k\}} \tilde{\psi}_{\{\tilde{n}_k\}}(q,t)\,|\{\tilde{n}_k\}\rangle; \quad |\{\tilde{n}_k\}\rangle = \prod_{k=1}^{K} \frac{1}{\sqrt{\tilde{n}_k!}} \left(b_k^\dagger\right)^{\tilde{n}_k} |0\rangle$$

$$e^{-i\omega t} \sim \sum_{k=1}^{K} \eta_k(\omega) u_k(t) \quad \Longrightarrow \quad b_k^\dagger = \sum_i \frac{d_i}{\hbar} \eta_k(\omega_i) a_i^\dagger$$

in actual calc.: expansion with Bessel function (Jacobi-Anger identity):

$$e^{-i\omega t} = J_0(\Omega t) + 2 \sum_{k=1}^{\infty} (-i)^k T_k\left(\frac{\omega}{\Omega}\right) J_k(\Omega t)$$

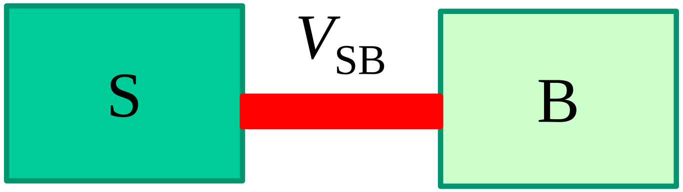
Chebyshev polynomials



large k: does not contribute when t is small

$$J_k(x) = \sum_{s=0}^{\infty} \frac{(-1)^2}{s!(s+k)!} \left(\frac{x}{2}\right)^{k+2s}$$

modelling of open quantum systems



i) system + bath

$$H = H_S + H_B + V_{SB}$$

✓ Caldeira-Leggett
✓ Feynmann-Vernon

solution:

a) eliminate B (bath)
$\rightarrow$ eff. action for S
(influence functional)

b) $\rho_S = Tr_B[\rho]$

$$\rightarrow i\hbar\dot{\rho}_S = \cdots$$

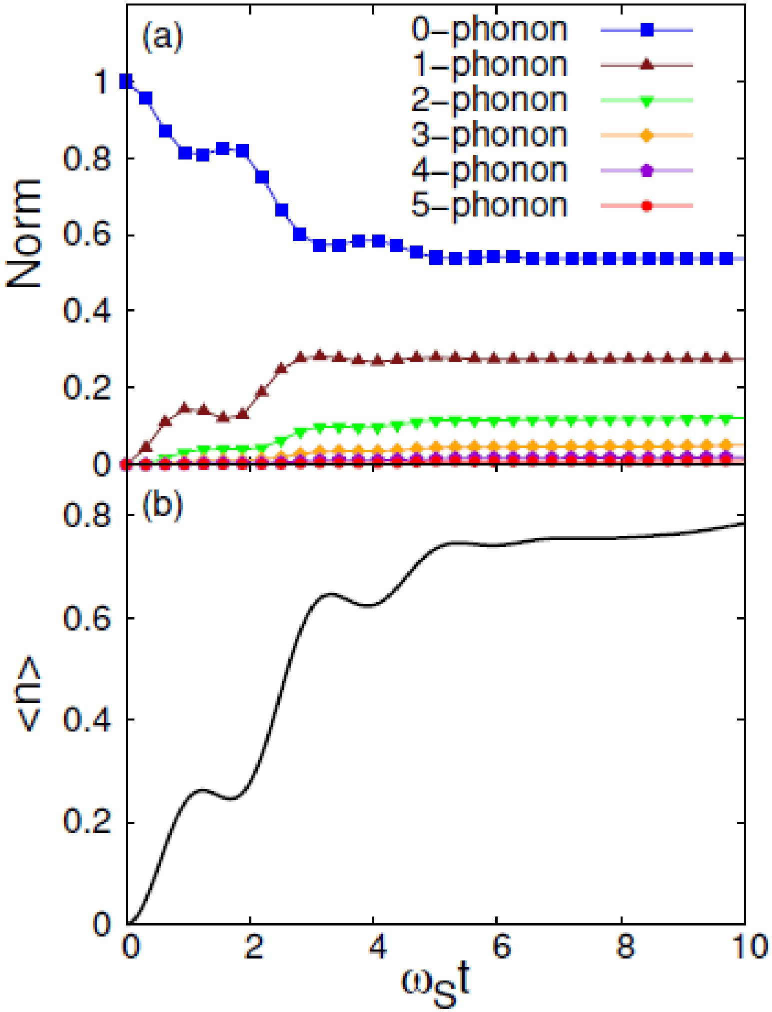
Markovian approximation
$\rightarrow$ Lindblad equation

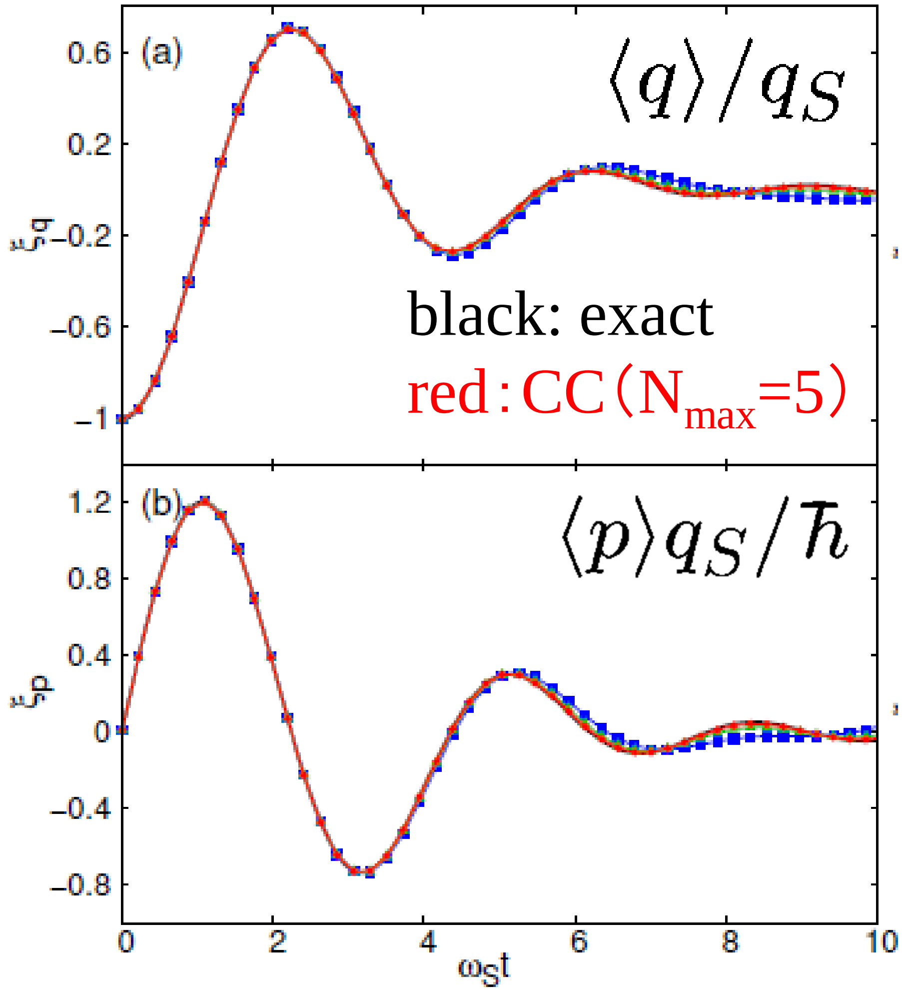
c) expand the tot. wf with the eigen states of H_B (coupled-channels eq.)

M. Tokieda and K.H.,
Ann. of Phys. 412 ('20) 168005.
Front. in Phys. 8 ('20) 8.

application to damped oscillation: HO + environment (conti. spectrum)

expansion with Bessel functions up to K=20





M. Tokieda and K. Hagino, Ann. of Phys. 412 ('20) 168005

modelling of open quantum systems

i) system + bath

$$H = H_S + H_B + V_{SB}$$

- ✓ Caldeira-Leggett
- ✓ Feynmann-Vernon

solution:

a) eff. action for S
(influence functional)

b) Lindlad eq.

c) coupled-channels eqs.

- microscopic
- but, hard to solve

ii) quantum friction model

construct a Hamiltonian which leads to

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

- ✓ E. Kanai, PTP 3 ('48)
- ✓ M.D. Kostin, JCP 57 ('72)
- ✓ K. Albrecht, PLB56 ('75)
- ✓ K.-K. Kan & J.-J. Griffin, PLB50 ('74)
- ✓ A. Bulgac, S. Jin, and I. Stetcu, PRC100, 014615 (2019)

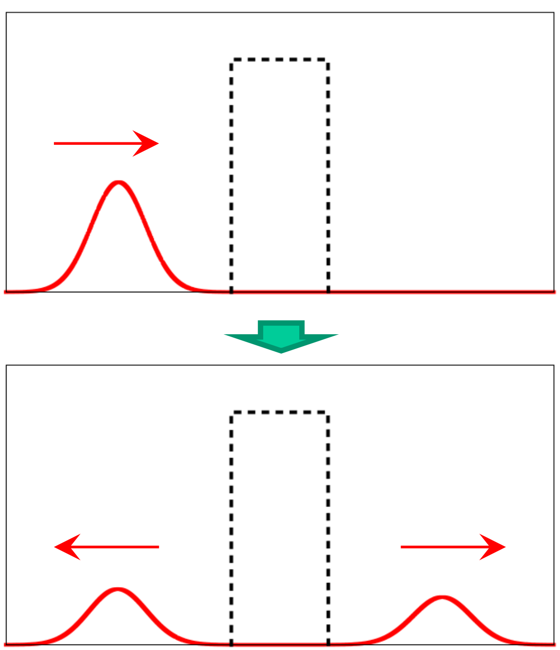
Quantum friction classical eq. of motion $\dot{p} = -V'(x) - \gamma p$

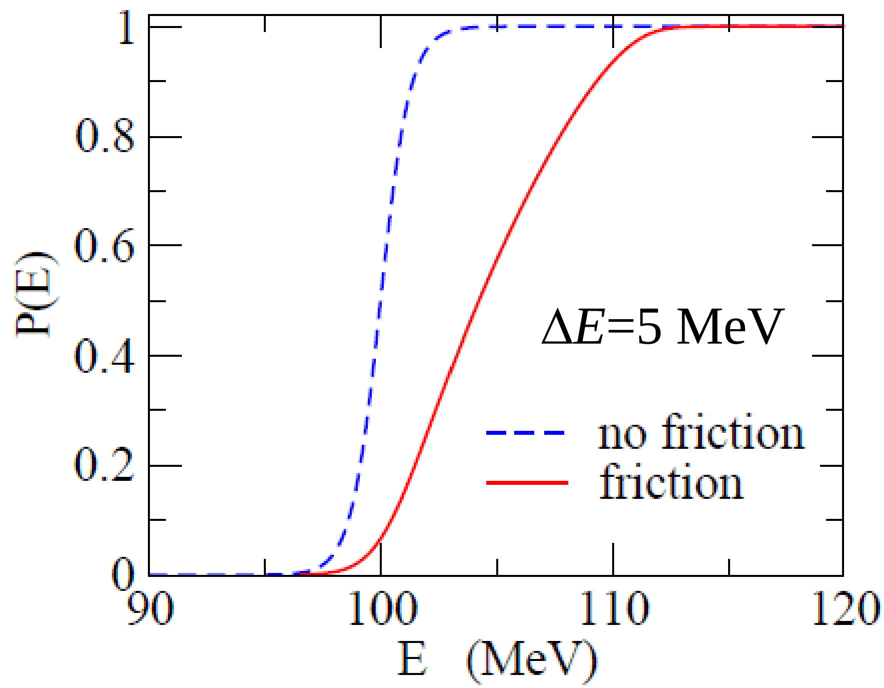
a quantization: Kanai model E. Kanai, PTP 3 (1948) 440

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

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

time-dep. wave packet approach





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

modelling of open quantum systems

i) system + bath

$$H = H_S + H_B + V_{SB}$$

✓ Caldeira-Leggett
✓ Feynmann-Vernon

- microscopic
- but, hard to solve

ii) quantum friction model

construct Hamiltonian which leads to

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

- phenomenological
- easy to solve