Physics of superheavy elements

Periodic table of chemical elements

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	

What is the heaviest element?

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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
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**				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	

What is the heaviest element?

natural elements: **Pu** (Z=94) ⟶ a tiny amount in nature

U (Z=92)

What determines these numbers??

Lanthanides	57 La	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
Actinides	89 Ac	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

What is the heaviest element?

natural elements: **Pu** (Z=94) ⟶ a tiny amount in nature

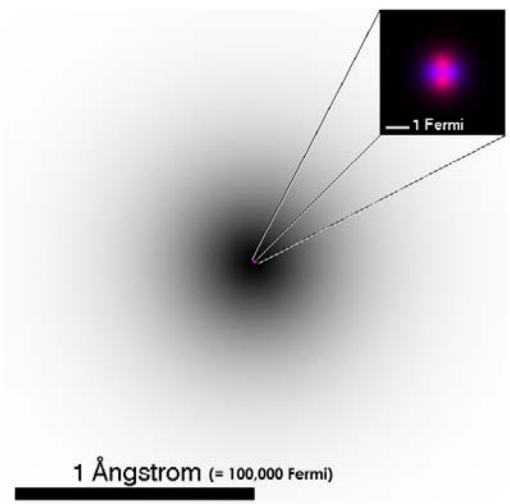
U (Z=92)

What determines these numbers??

heavy nuclei ⟶ large Coulomb repulsion

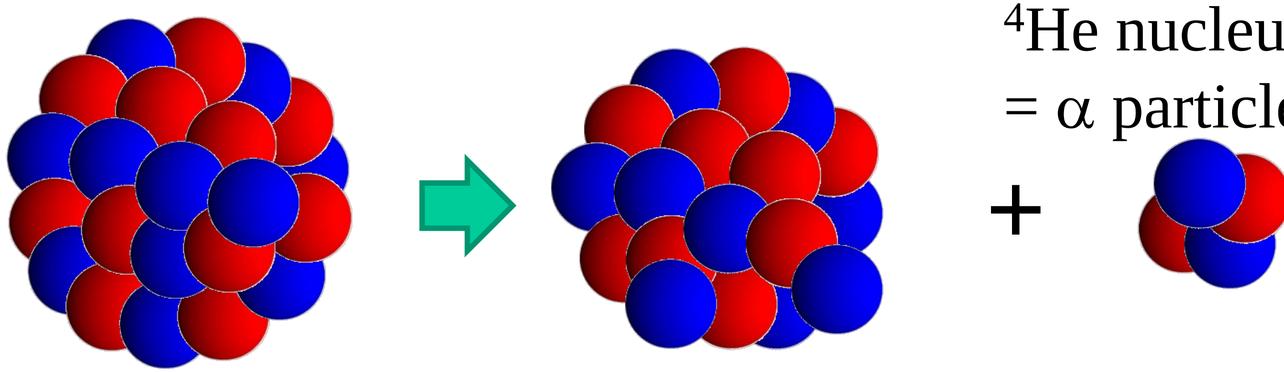
↓

unstable against α decay



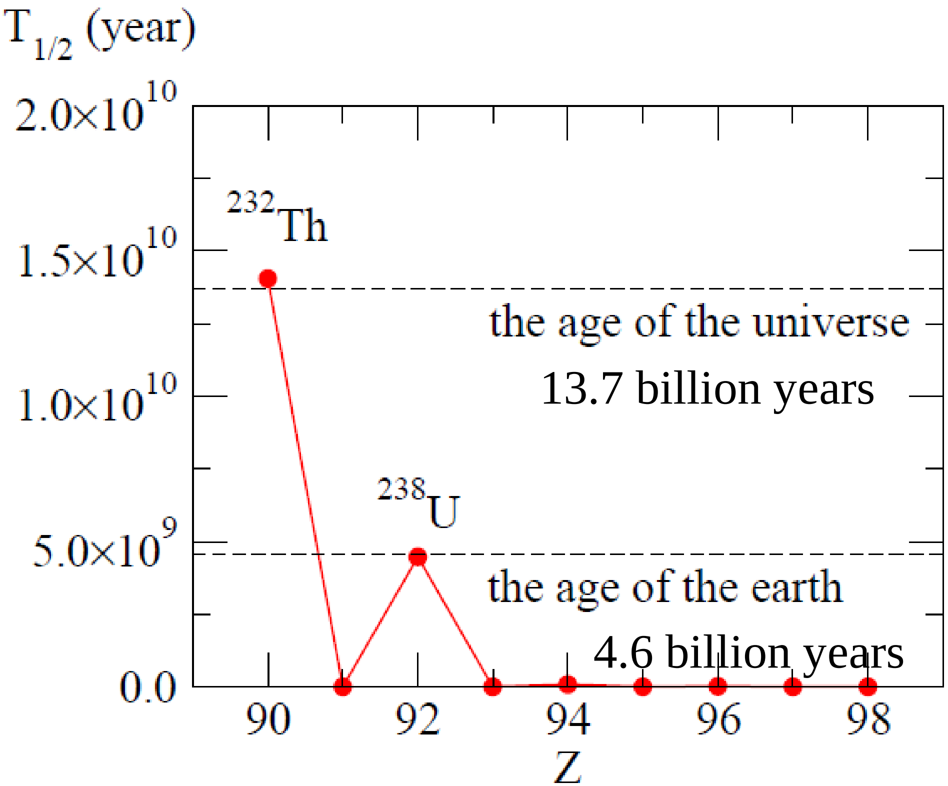
^{4}He nucleus

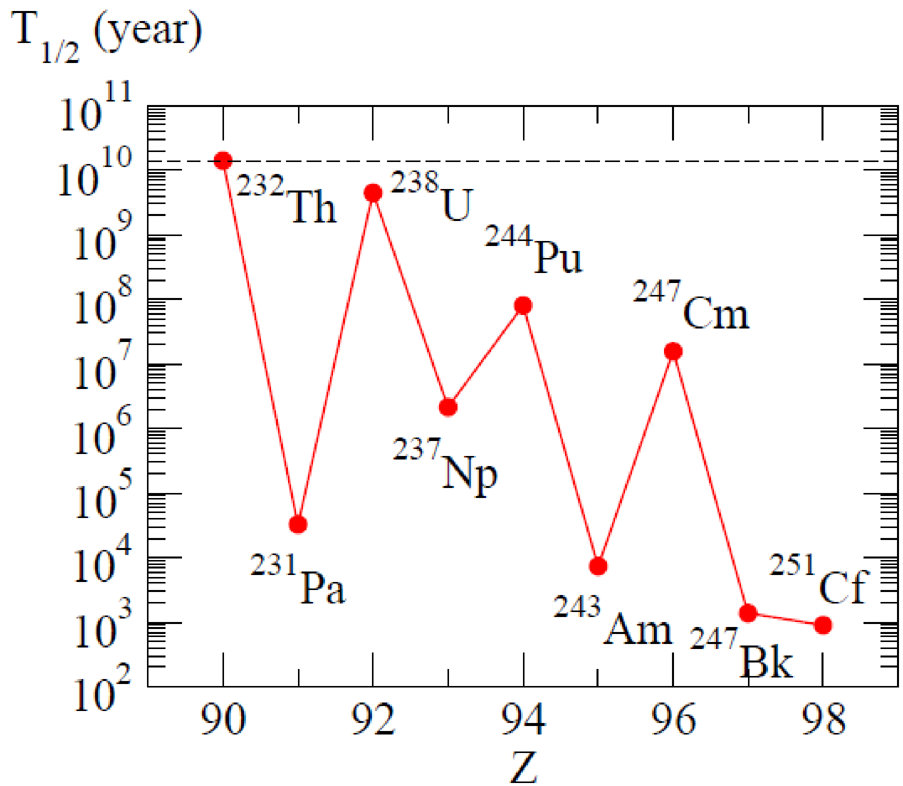
= α particle



(Z,N) (Z-2,N-2) (Z=2,N=2)

Decay half-lives of heavy nuclei





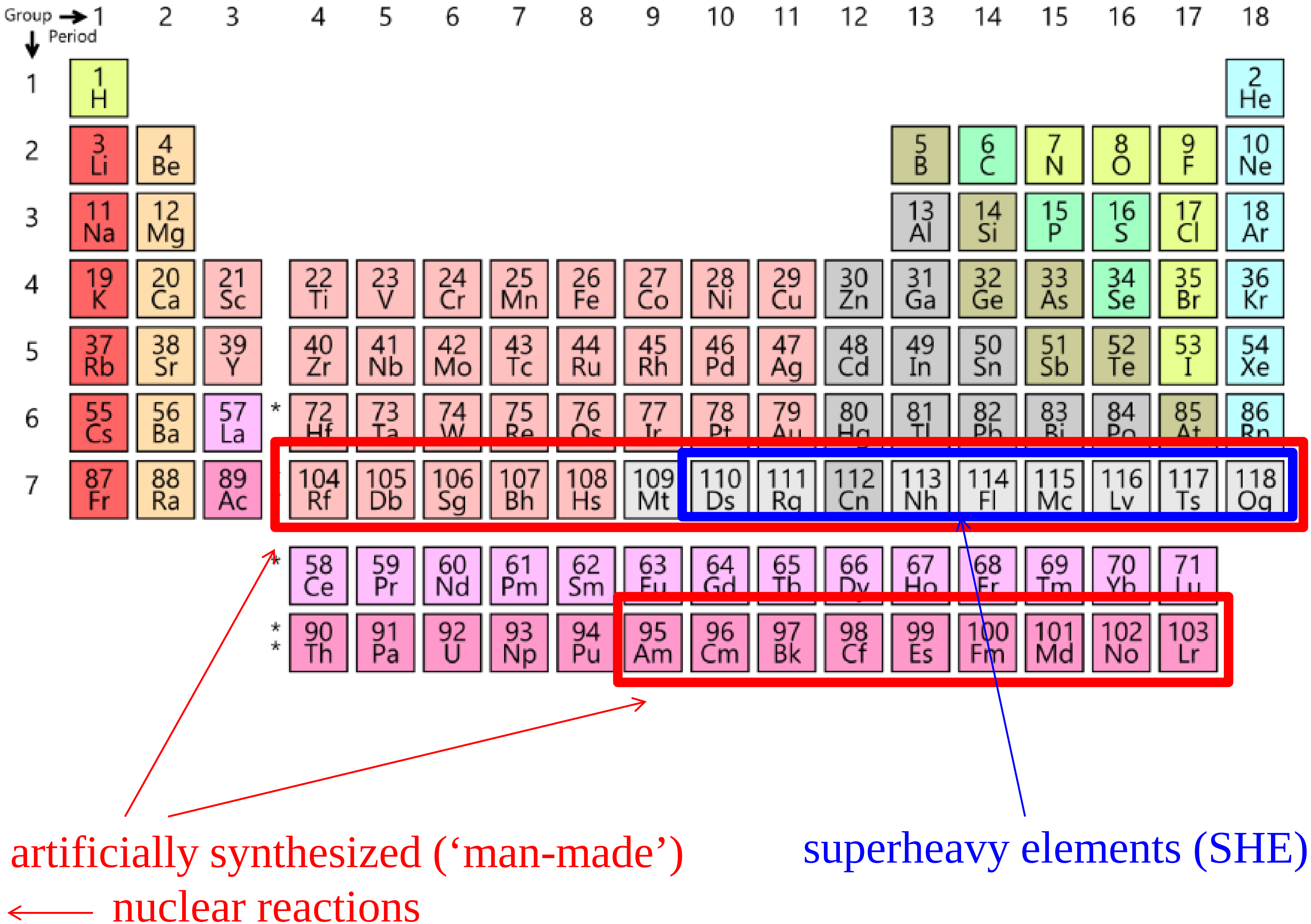
^{232}Th 1.405 x 10^{10} years

^{238}U 4.468 x 10^{9} years

^{244}Pu 8.08 x 10^{7} years

^{247}Cm 1.56 x 10^{7} years

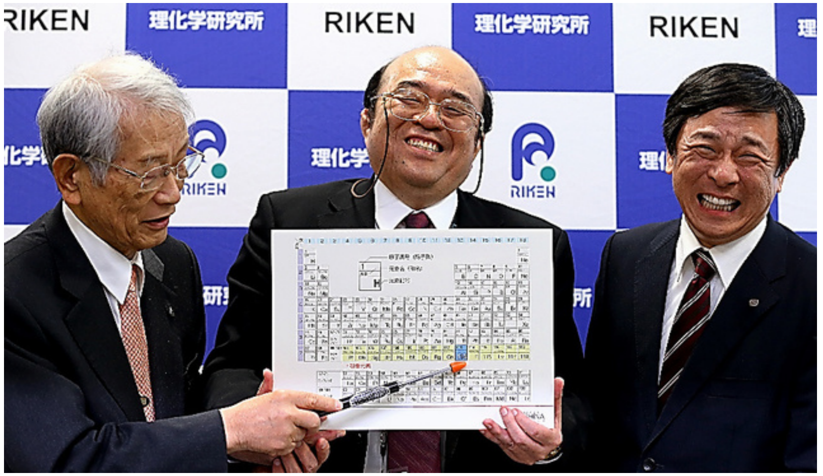
Periodic table of chemical elements

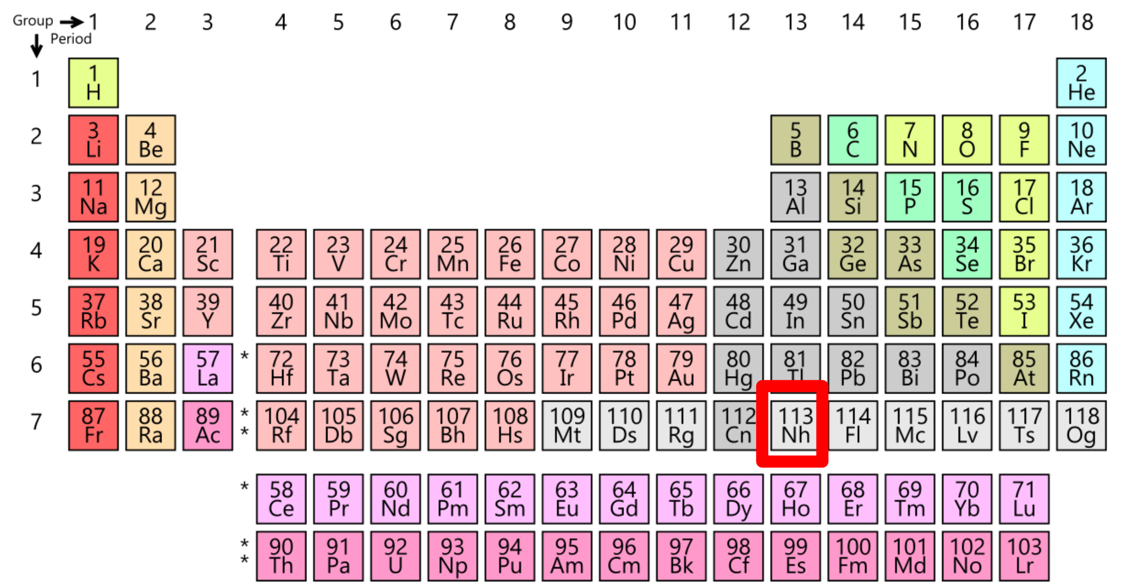


Fusion reactions for SHE

the element 113: Nh

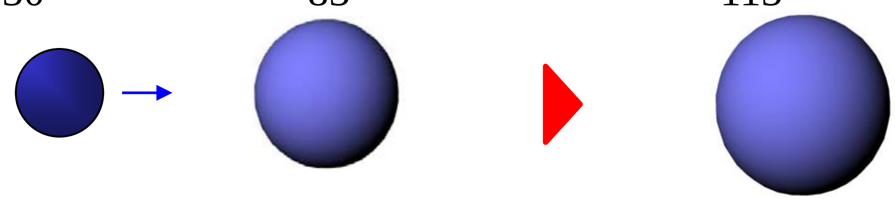
November, 2016





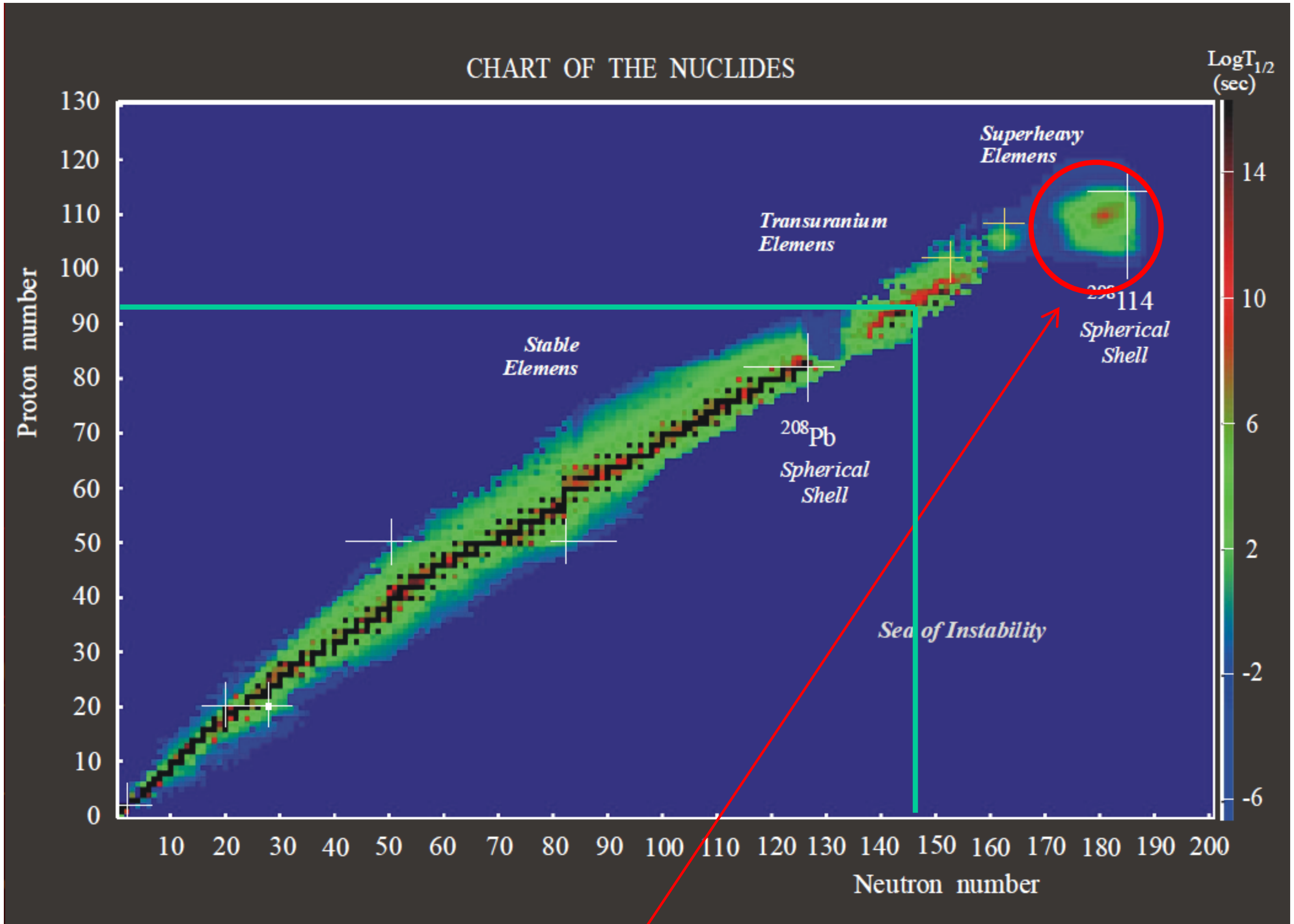
Wikipedia

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



Heavy-ion fusion reaction

Prediction of island of stability: an important motivation of SHE study

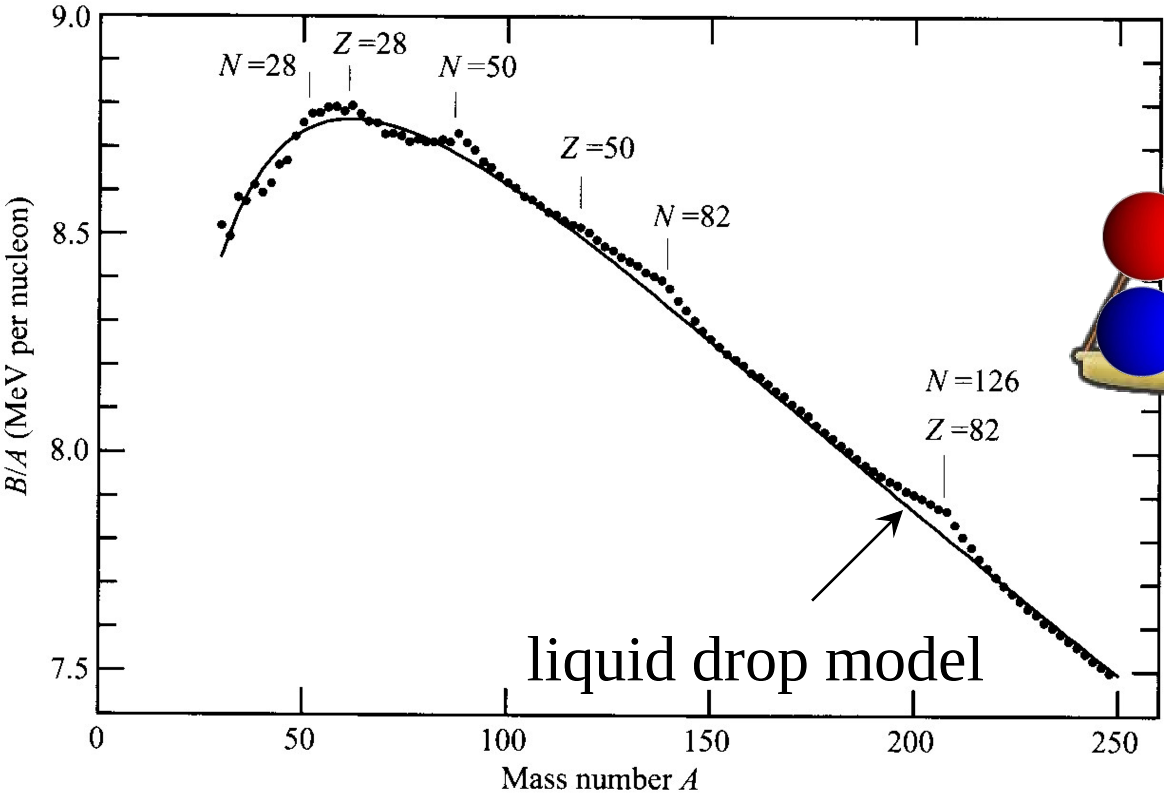


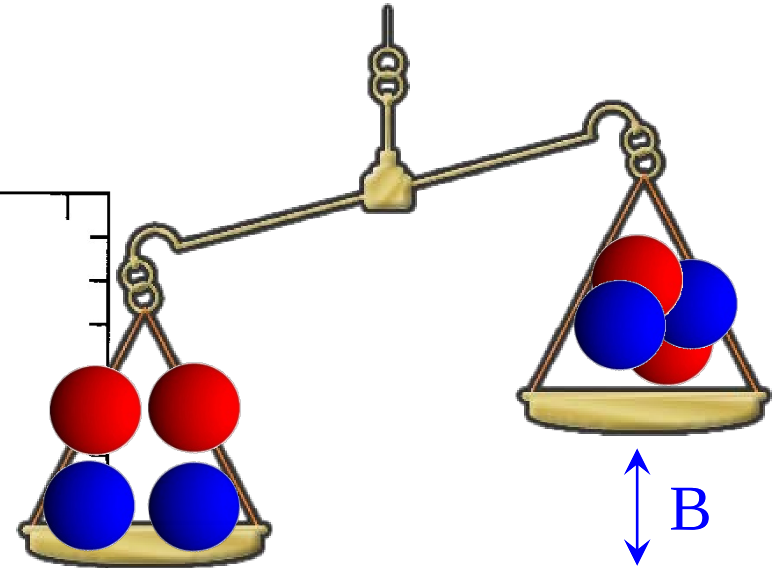
Yuri Oganessian

island of stability around Z=114, N=184

W.D. Myers and W.J. Swiatecki (1966), A. Sobiczewski et al. (1966)

shell energy

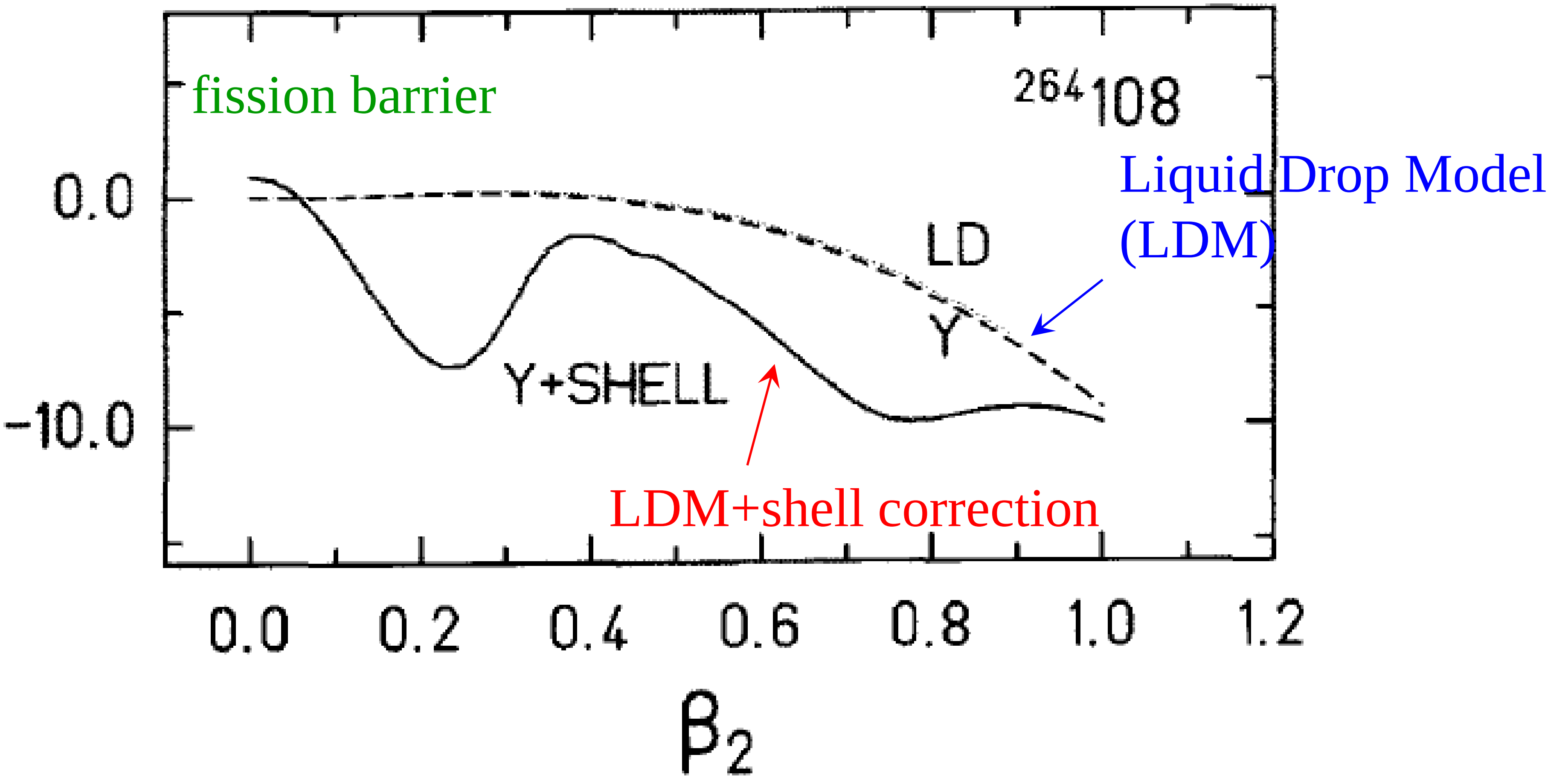




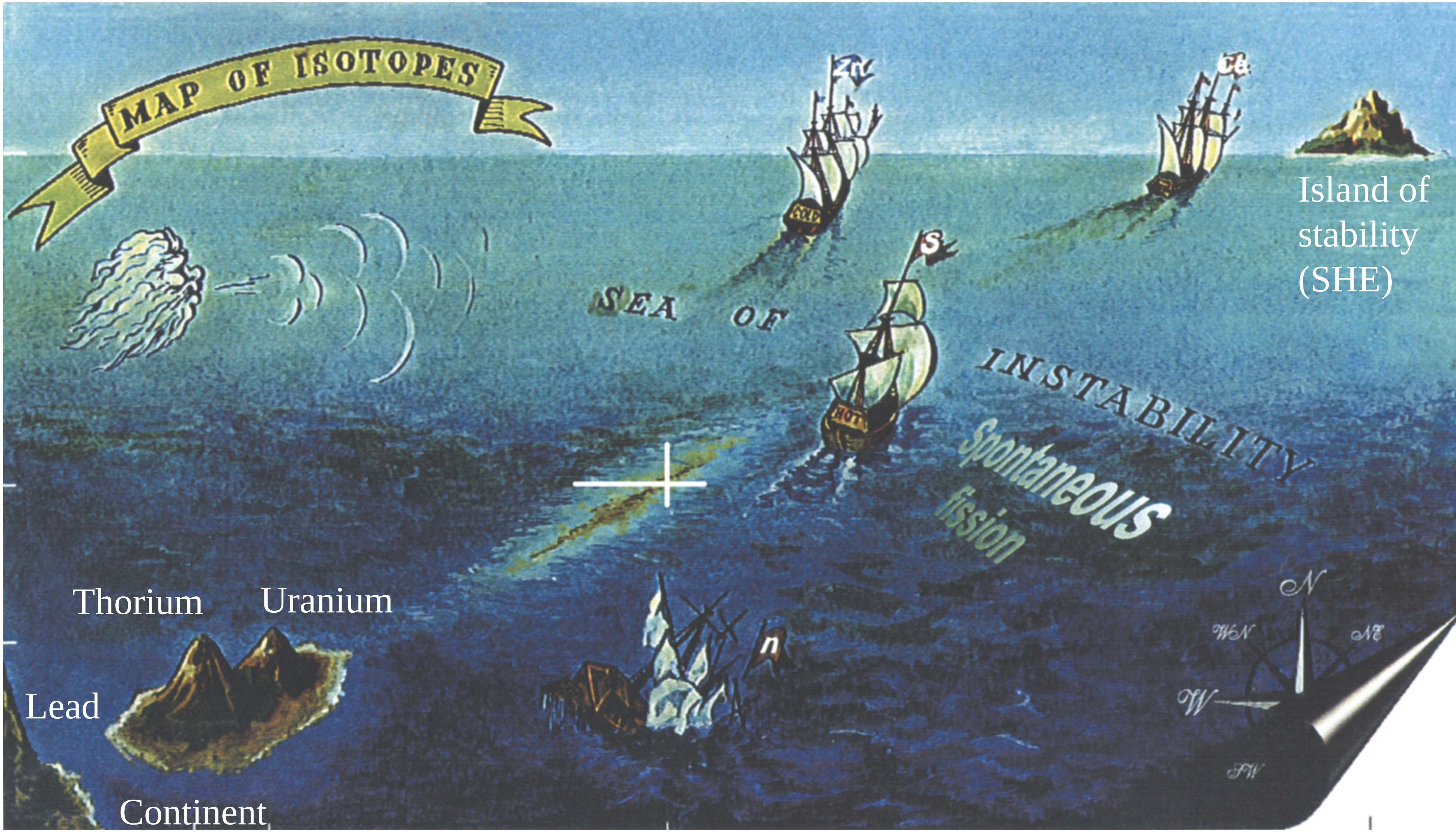
Extra binding for N or Z = 2, 8, 20, 28, 50, 82, 126 (magic numbers)

⇨ Very stable

${}^{4}_{2}He_{2}, {}^{16}_{8}O_{8}, {}^{40}_{20}Ca_{20}, {}^{48}_{20}Ca_{28}, {}^{208}_{82}Pb_{126}$

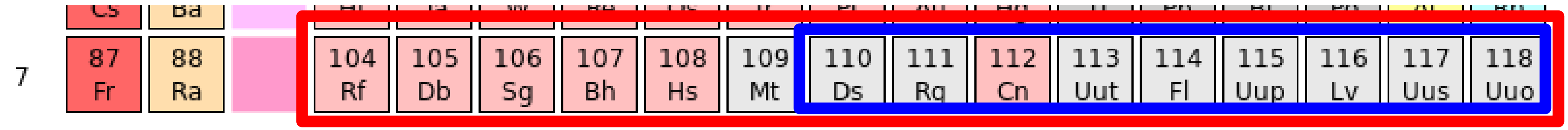


Z. Patyk et al., NPA491('89) 267



Yuri Oganessian

who is she?



Z=110 Darmstadtium (Ds) 1994 Germany

Z=111 Roentgenium (Rg) 1994 Germany

Z=112 Copernicium (Cn) 1996 Germany

Z=113 **Nihonium (Nh)** 2003 Russia / 2004 Japan

Z=114 Flerovium (Fl) 1999 Russia

Z=115 **Moscovium (Mc)** 2003 Russia

Z=116 Livermoriun (Lv) 2000 Russia

Z=117 **Tennessine (Ts)** 2010 Russia

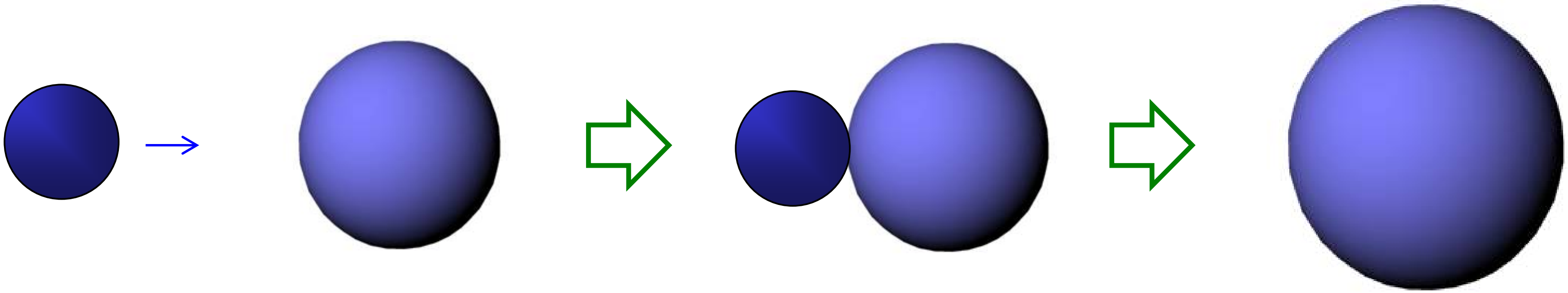
Z=118 **Oganesson (Og)** 2002 Russia

Germany, Japan: cold fusion reactions

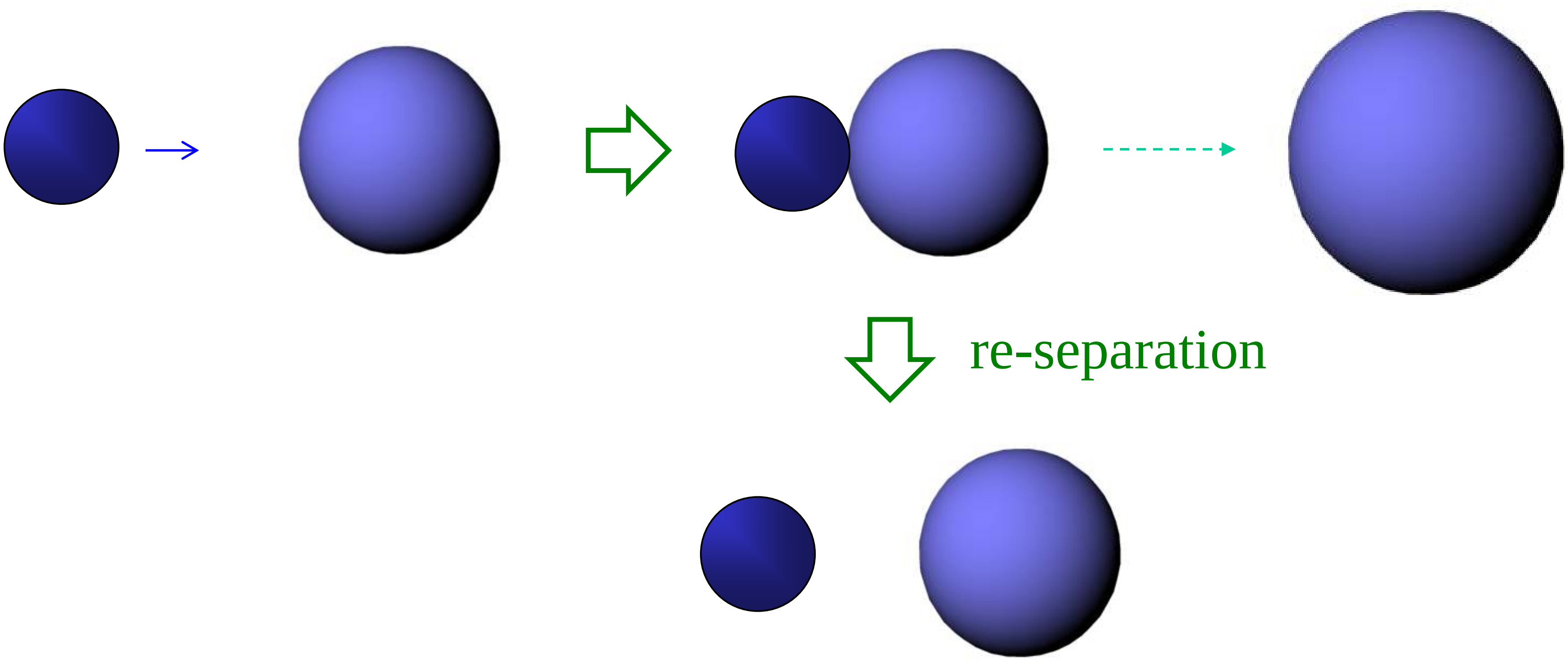
Russia: hot fusion reactions

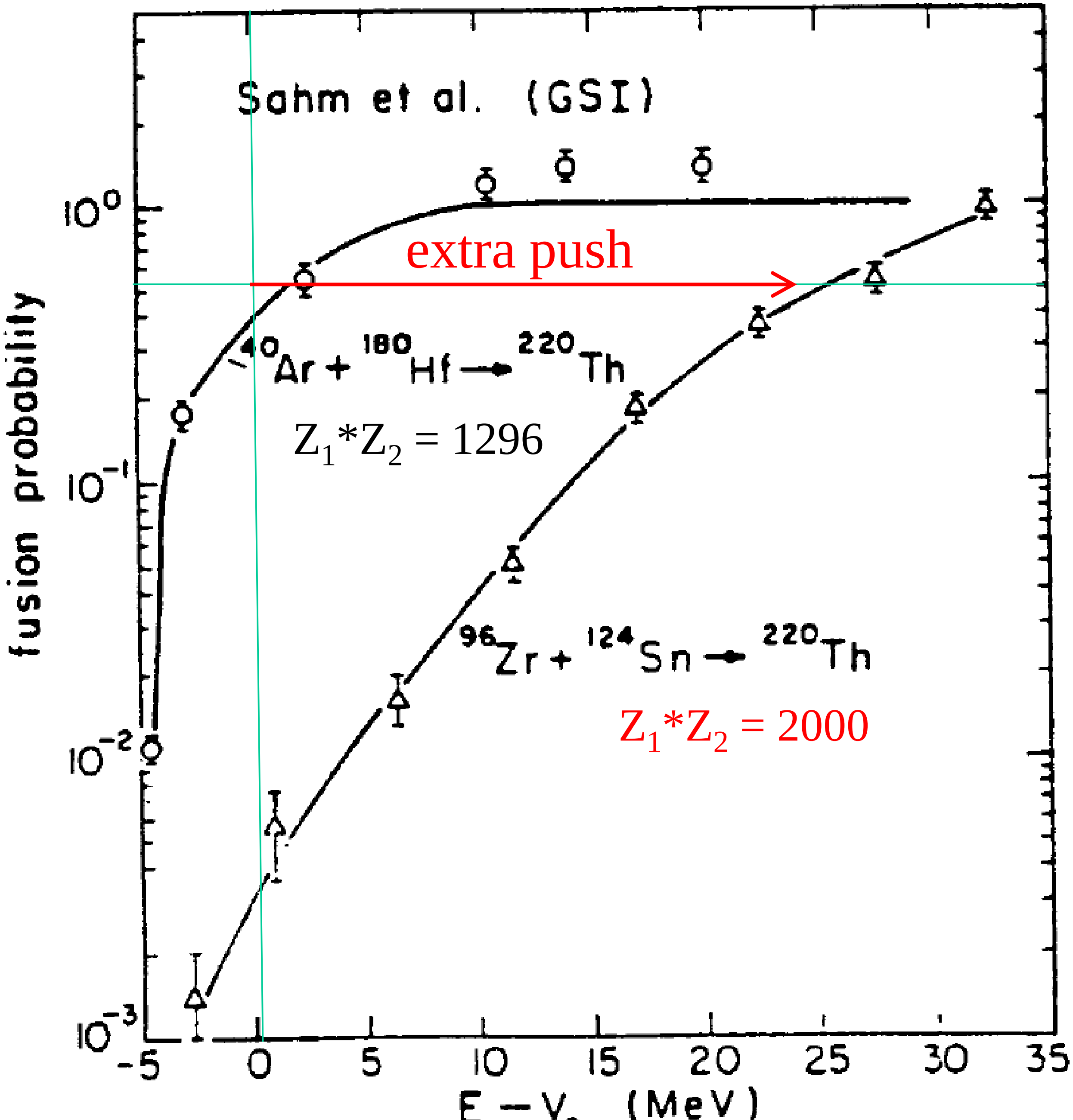
How to synthesize SHE? Nuclear fusion reactions

- Fusion of medium-heavy systems:

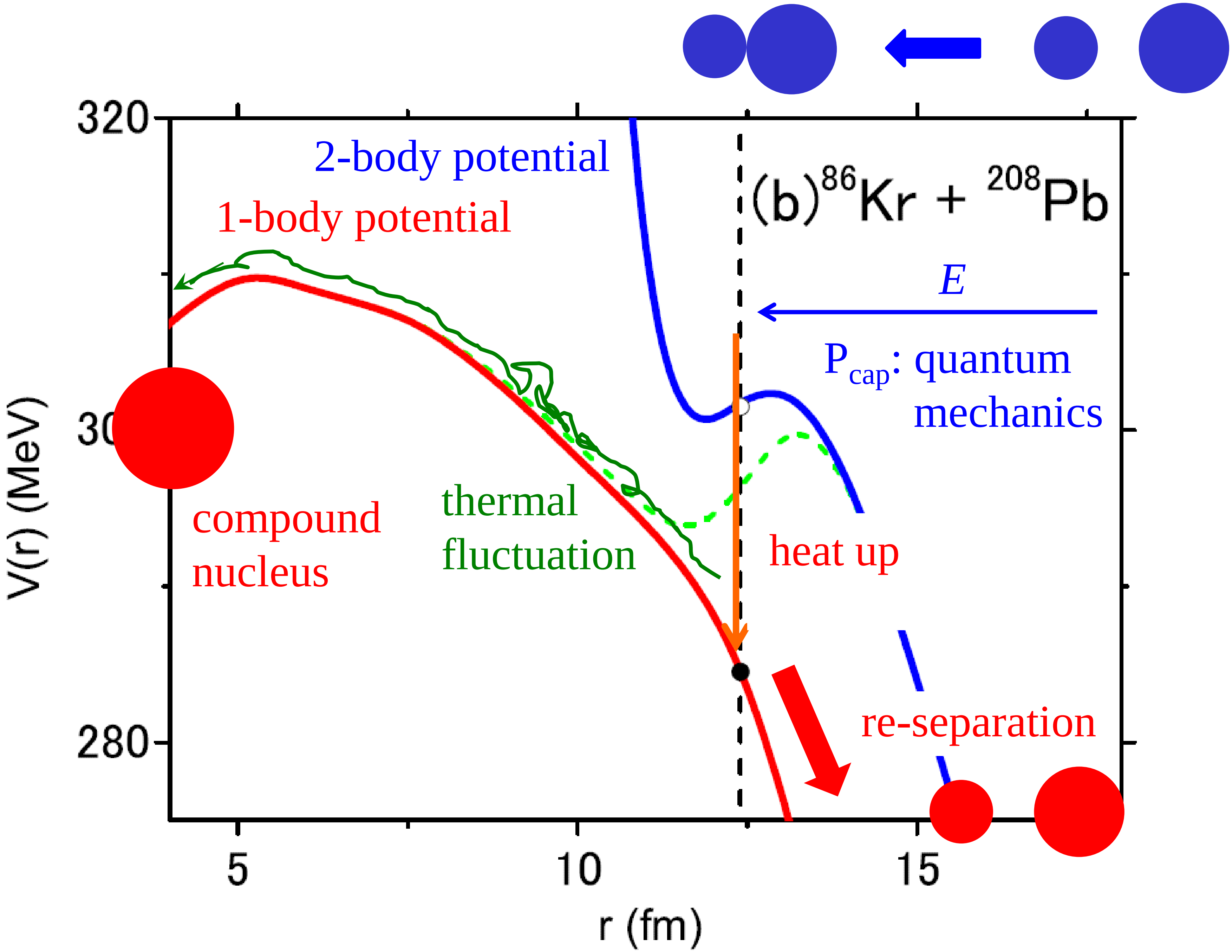


- Fusion of heavy and super-heavy systems:



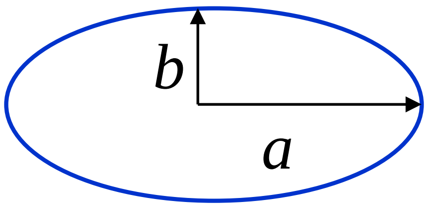


C.-C. Sahm et al.,
Z. Phys. A319('84)113



320
300
280
5
10
15
V(r) (MeV)
r (fm)
2-body potential
1-body potential
(b) 86Kr + 208Pb
E
Pcap: quantum mechanics
compound nucleus
thermal fluctuation
heat up
re-separation

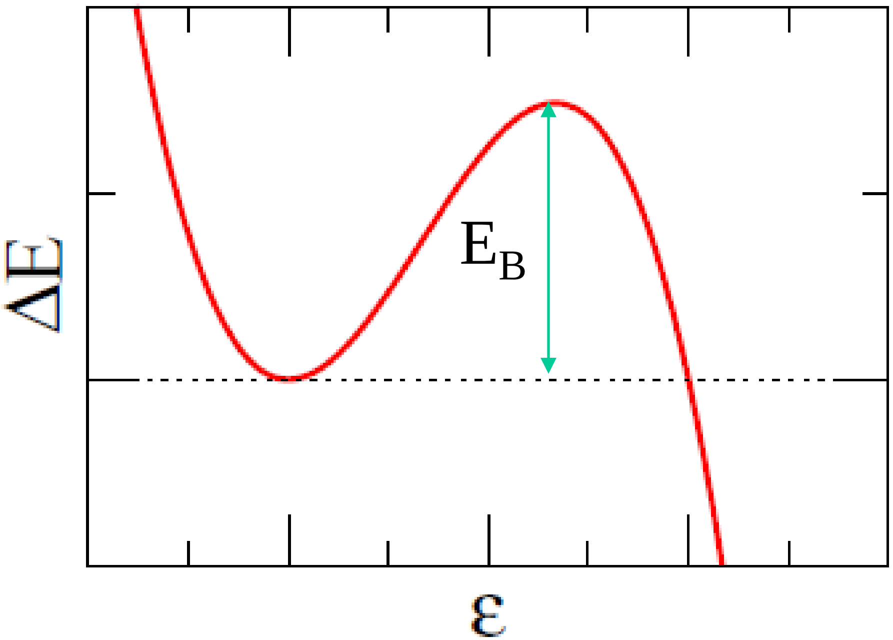
(note) fission barrier in the liquid drop model



$$a = R \cdot (1+\epsilon)$$
$$b = R \cdot (1+\epsilon)^{-1/2}$$

$$ab^2 = R^3 = \text{constant}$$

$$\Delta E = \Delta E_{\text{surf}} + \Delta E_{\text{coul}}$$
$$= E_S^{(0)} \left\{ \frac{2}{5}(1-x)\epsilon^2 - \frac{4}{105}(1+2x)\epsilon^3 + \cdots \right\}$$

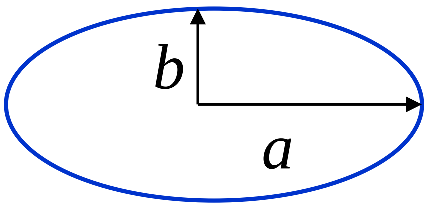


$$E_S^{(0)} = +a_S A^{2/3}$$

$$x \equiv \frac{E_C^{(0)}}{2E_S^{(0)}} = \frac{a_C}{2a_S} \cdot \frac{Z^2}{A} \sim \frac{1}{53.3} \cdot \frac{Z^2}{A}$$

$$E_C^{(0)} = a_C Z(Z-1)/A^{1/3}$$

(note) fission barrier in the liquid drop model



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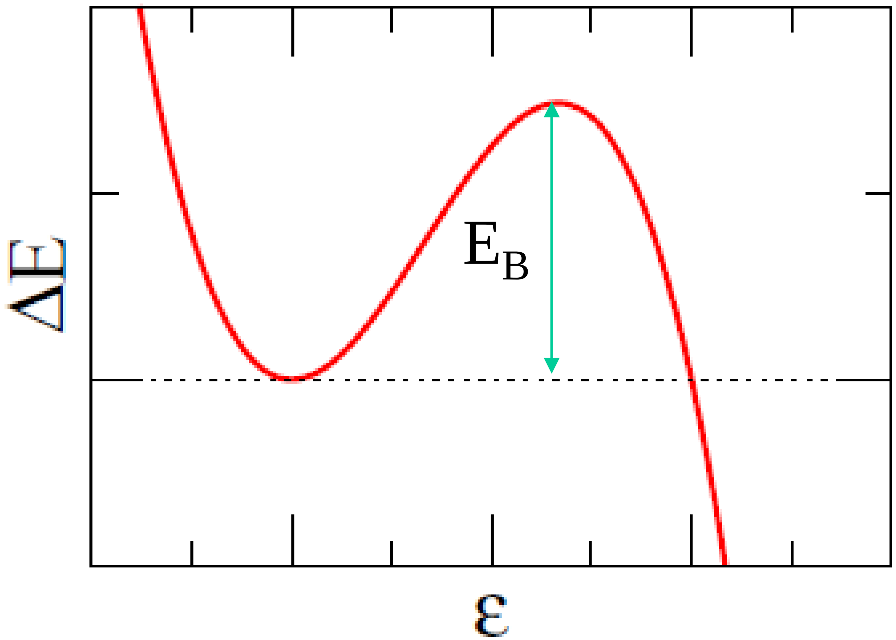
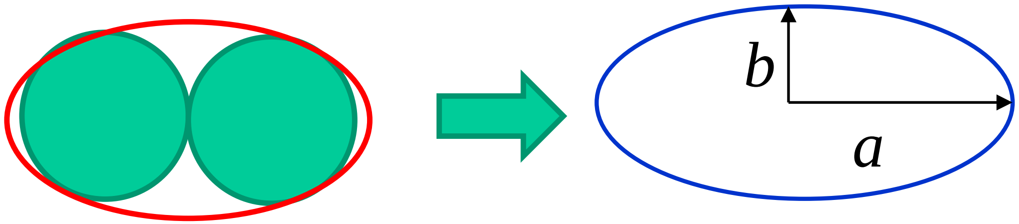


fission barrier:

$$\epsilon_B = \frac{21(1-x)}{3(1+2x)}$$

$$E_B = \frac{98}{15}\cdot\frac{(1-x)^3}{(1+2x)^2}\cdot E_S^{(0)}$$

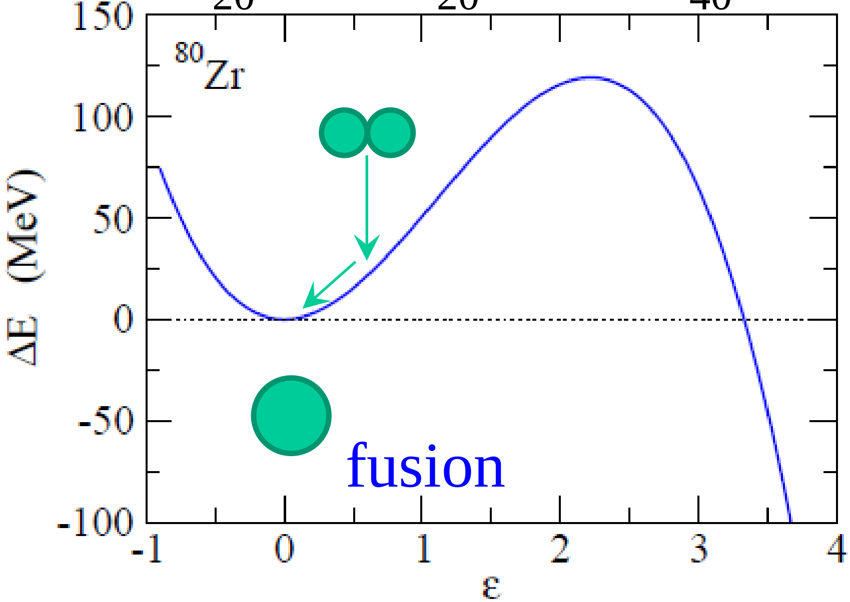
if two identical nuclei contact :



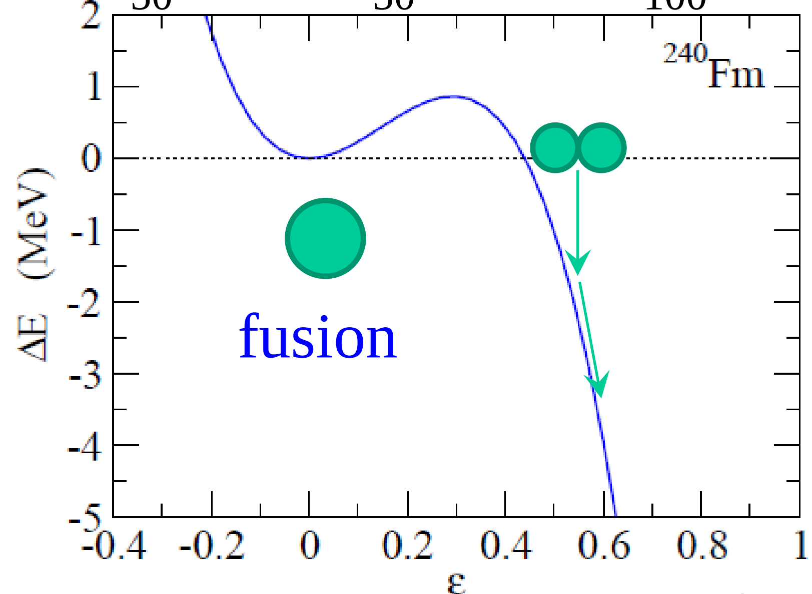
$$a = R_0 \cdot (1+\epsilon)$$
$$b = R_0 \cdot (1+\epsilon)^{-1/2}$$

$$\frac{a}{b} \sim \frac{2R}{R} = 2 \rightarrow \epsilon \sim 0.587$$

$^{40}_{20}Ca + ^{40}_{20}Ca \rightarrow ^{80}_{40}Zr$

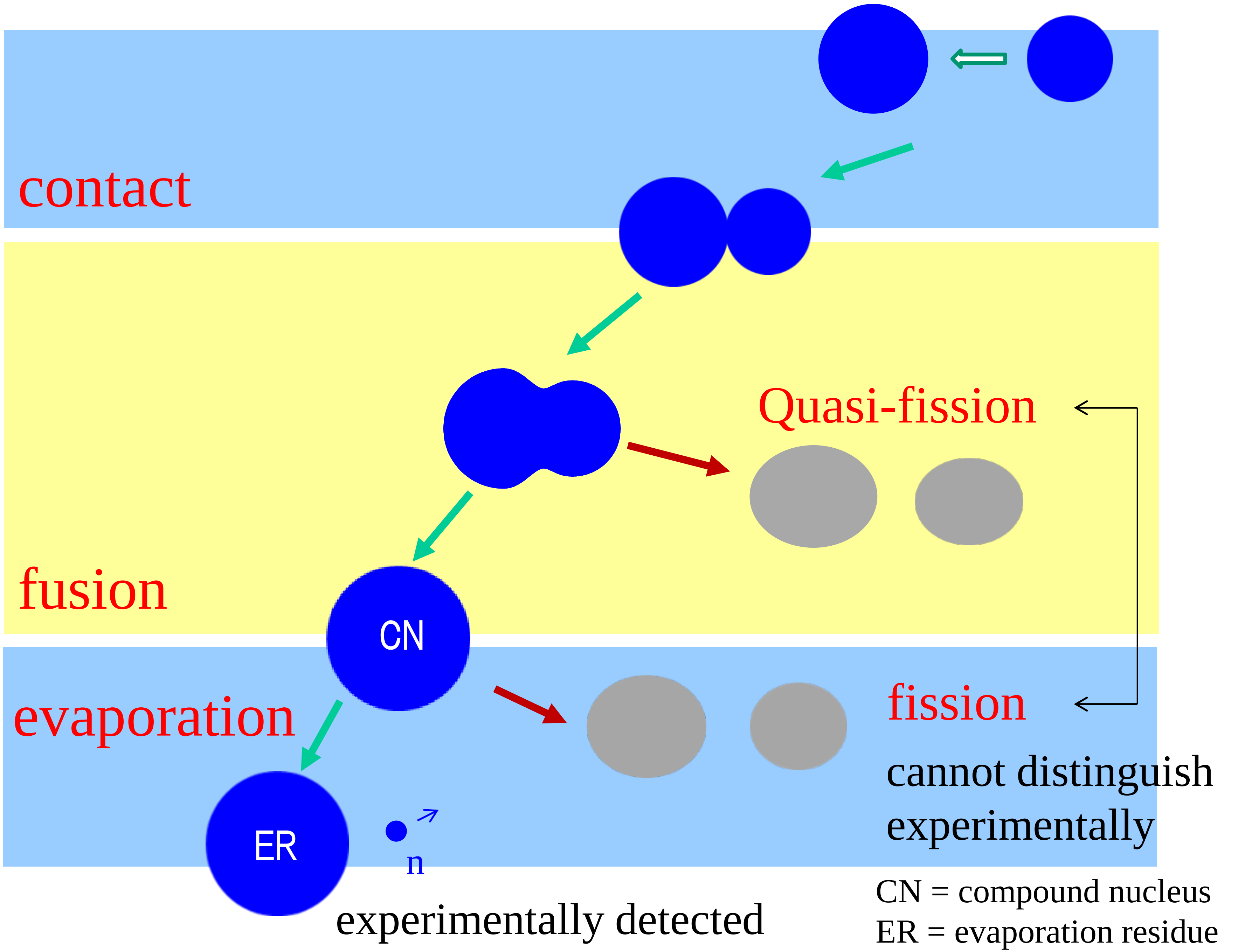


$^{120}_{50}Sn + ^{120}_{50}Sn \rightarrow ^{240}_{100}Fm$

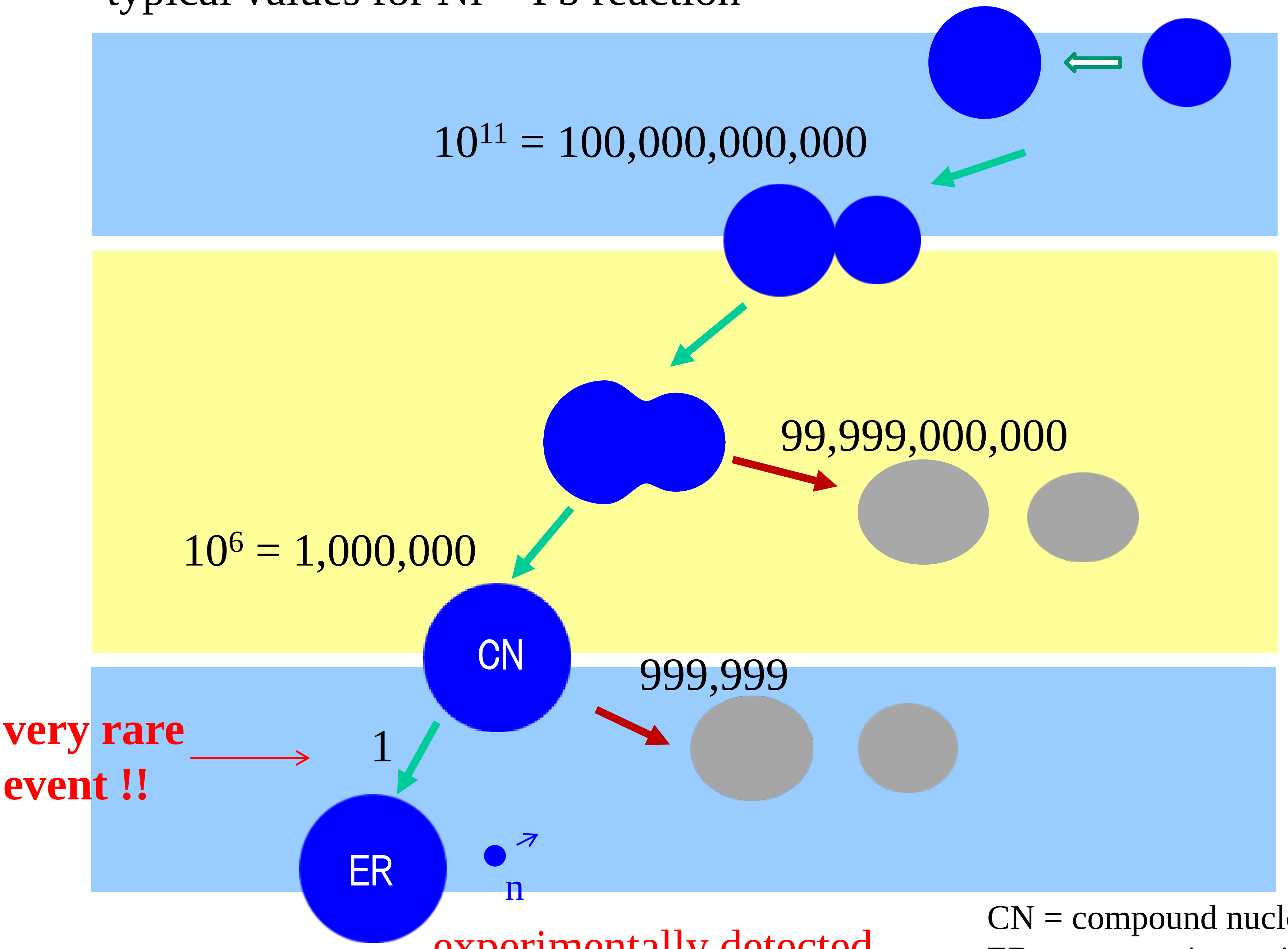


a_S = 16.8 MeV
a_C = 0.72 MeV

threshold: $Z_1 * Z_2$ = 1600 ~ 1800


contact
fusion
evaporation
Quasi-fission
CN
fission
cannot distinguish
experimentally
ER
n
experimentally detected
CN = compound nucleus
ER = evaporation residue

typical values for Ni + Pb reaction



CN = compound nucleus
ER = evaporation residue

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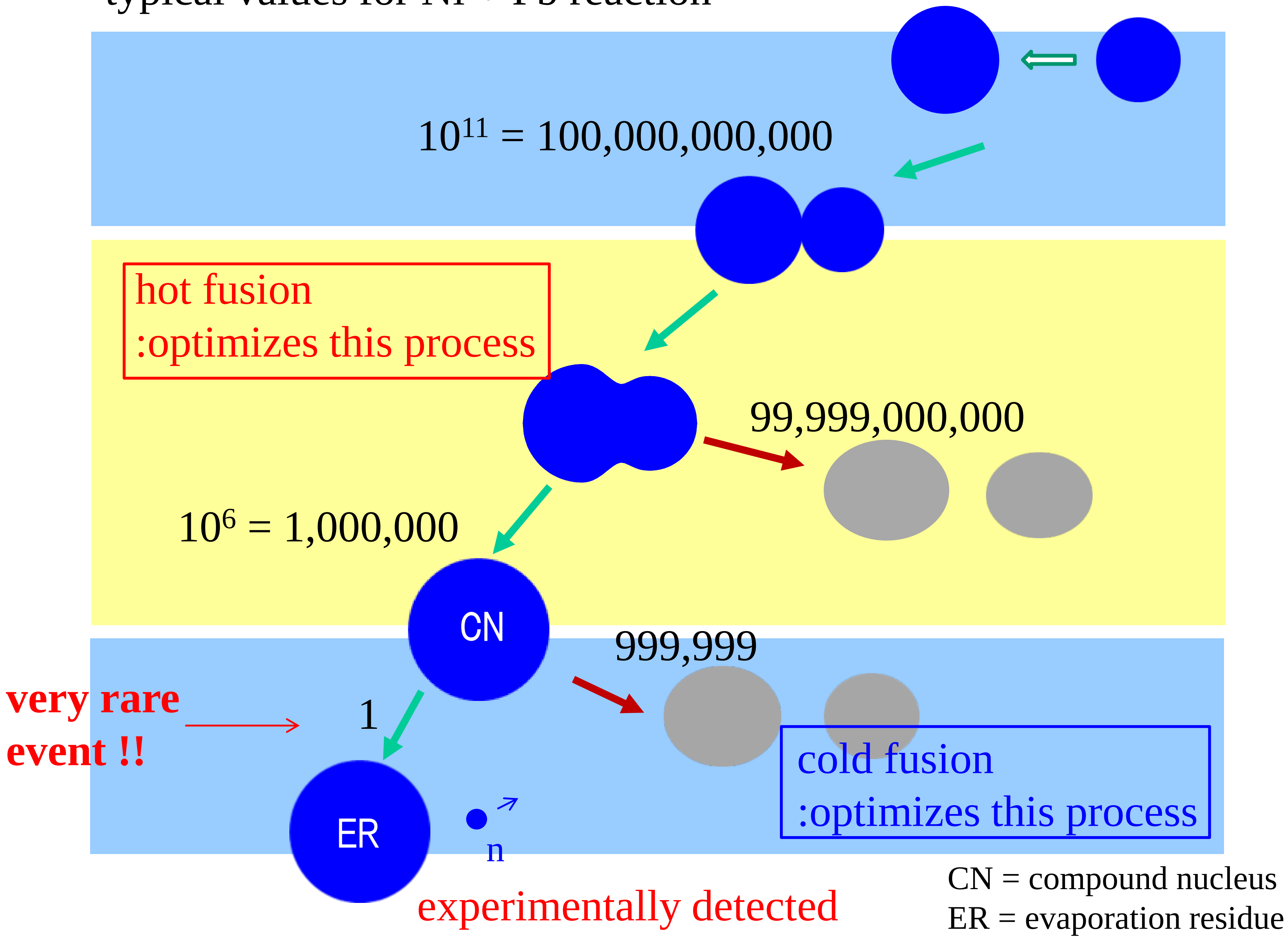
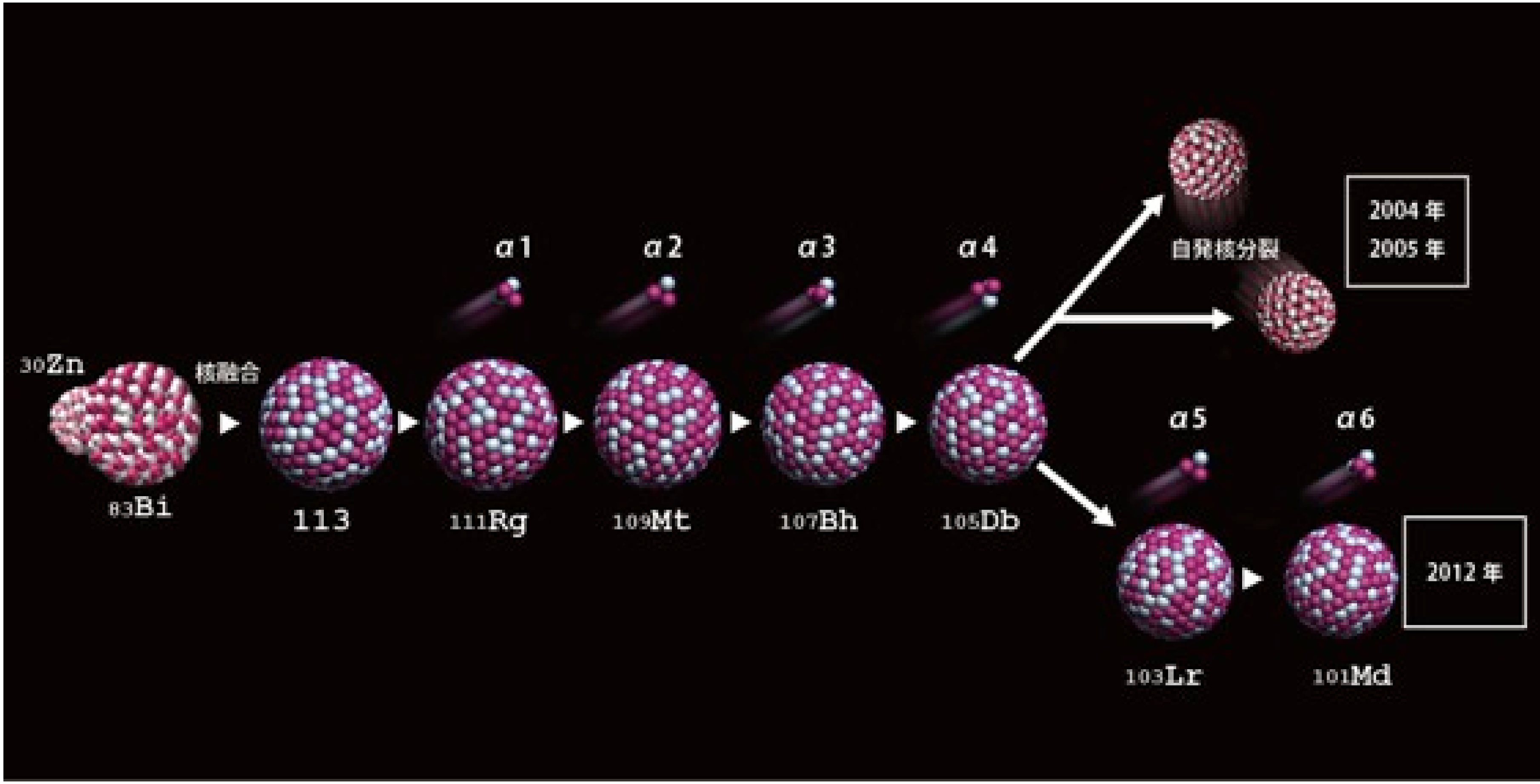


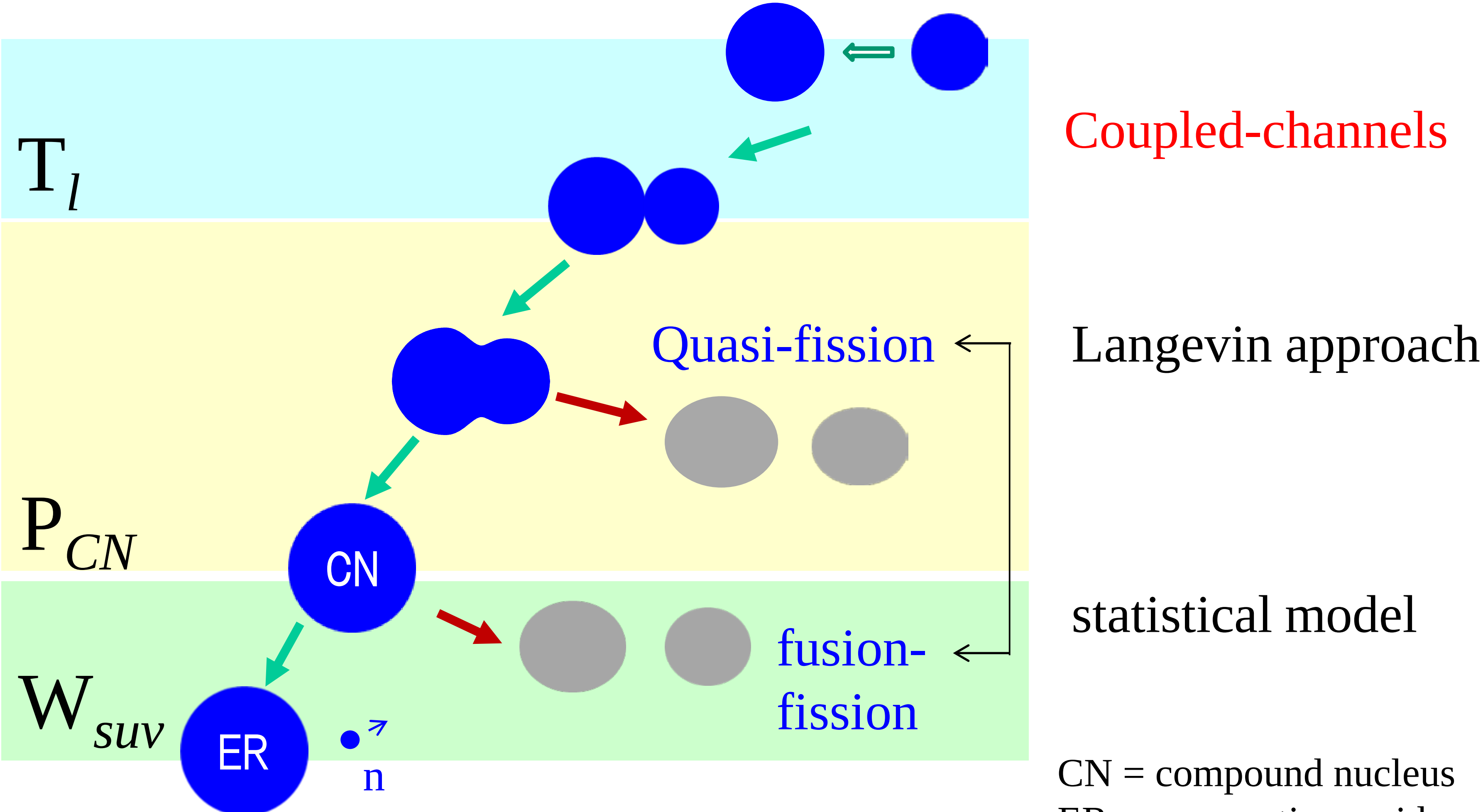
Element 113 (RIKEN, K. Morita et al.)

$$^{70}\mathrm{Zn}\ (Z=30) + {}^{209}\mathrm{Bi}\ (Z=83) \longrightarrow {}^{278}113 + n$$



K. Morita et al., J. Phys. Soc. Jpn. 81('12)103201

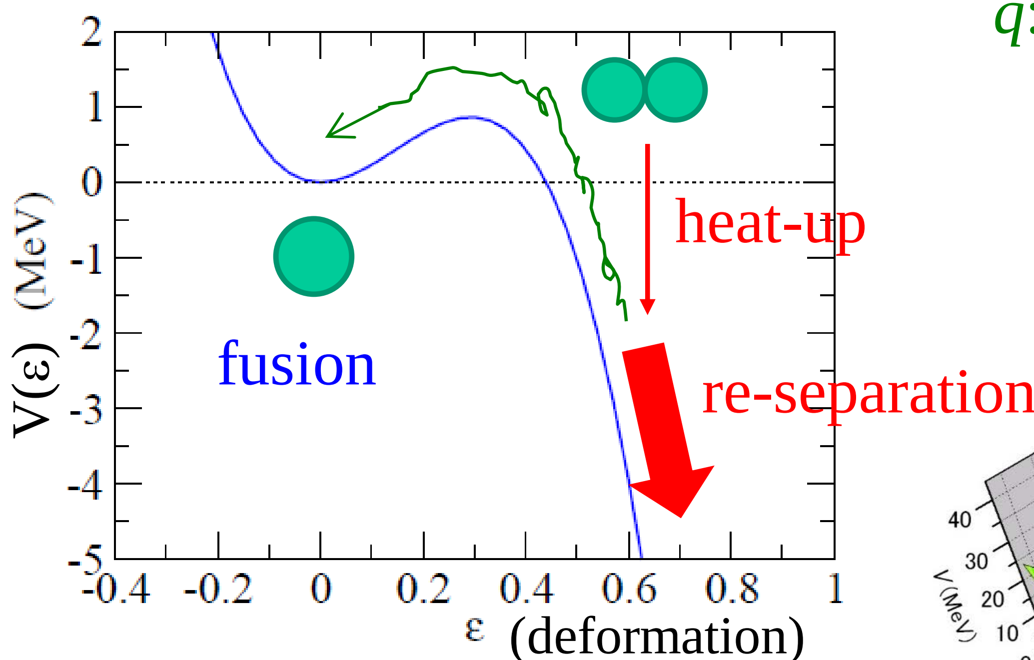
only 3 events for 553 days experiment



CN = compound nucleus
ER = evaporation residue

$$\sigma_{\mathrm{ER}}(E) = \frac{\pi}{k^2}\sum_l (2l+1) T_l(E)\, P_{\mathrm{CN}}(E,l)\, W_{\mathrm{suv}}(E^*,l)$$

Langevin approach



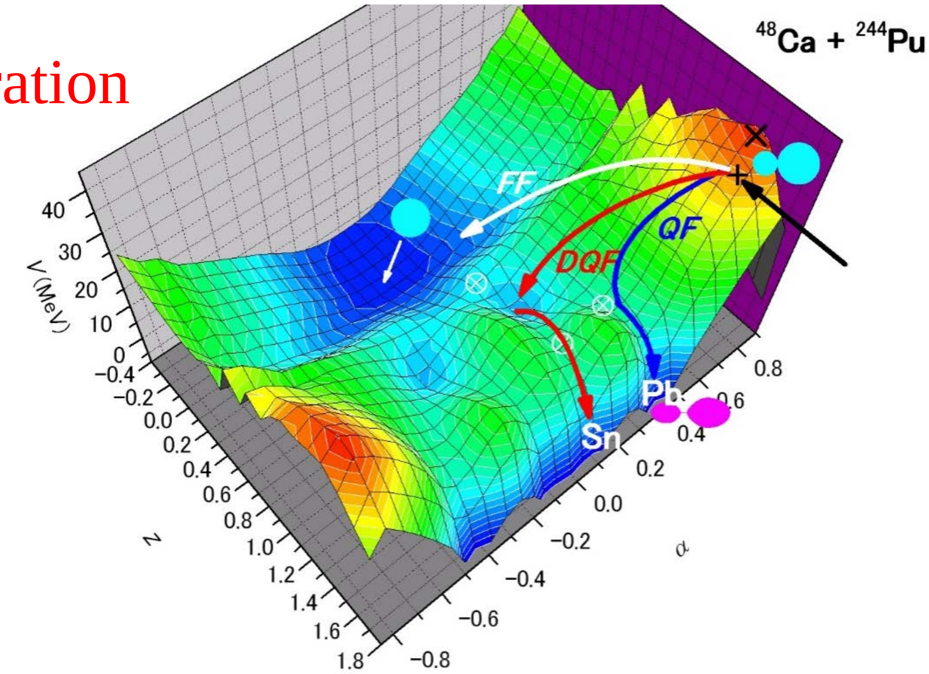
thermal fluctuation

→ Langevin method
(Brownian method)

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

multi-dimensional extention

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



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

Theory: Lagenvin approach

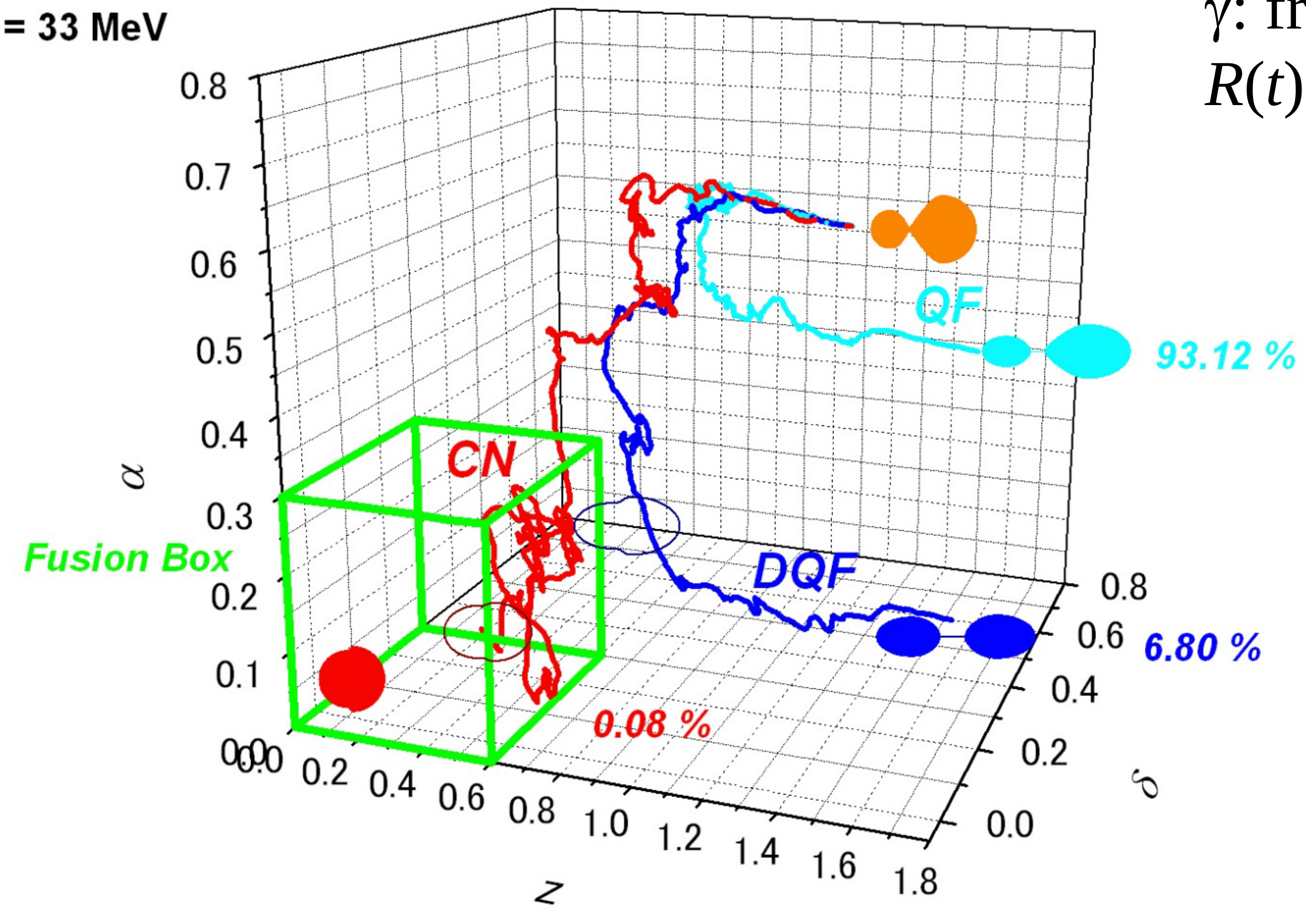
multi-dimensional extension of:

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

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

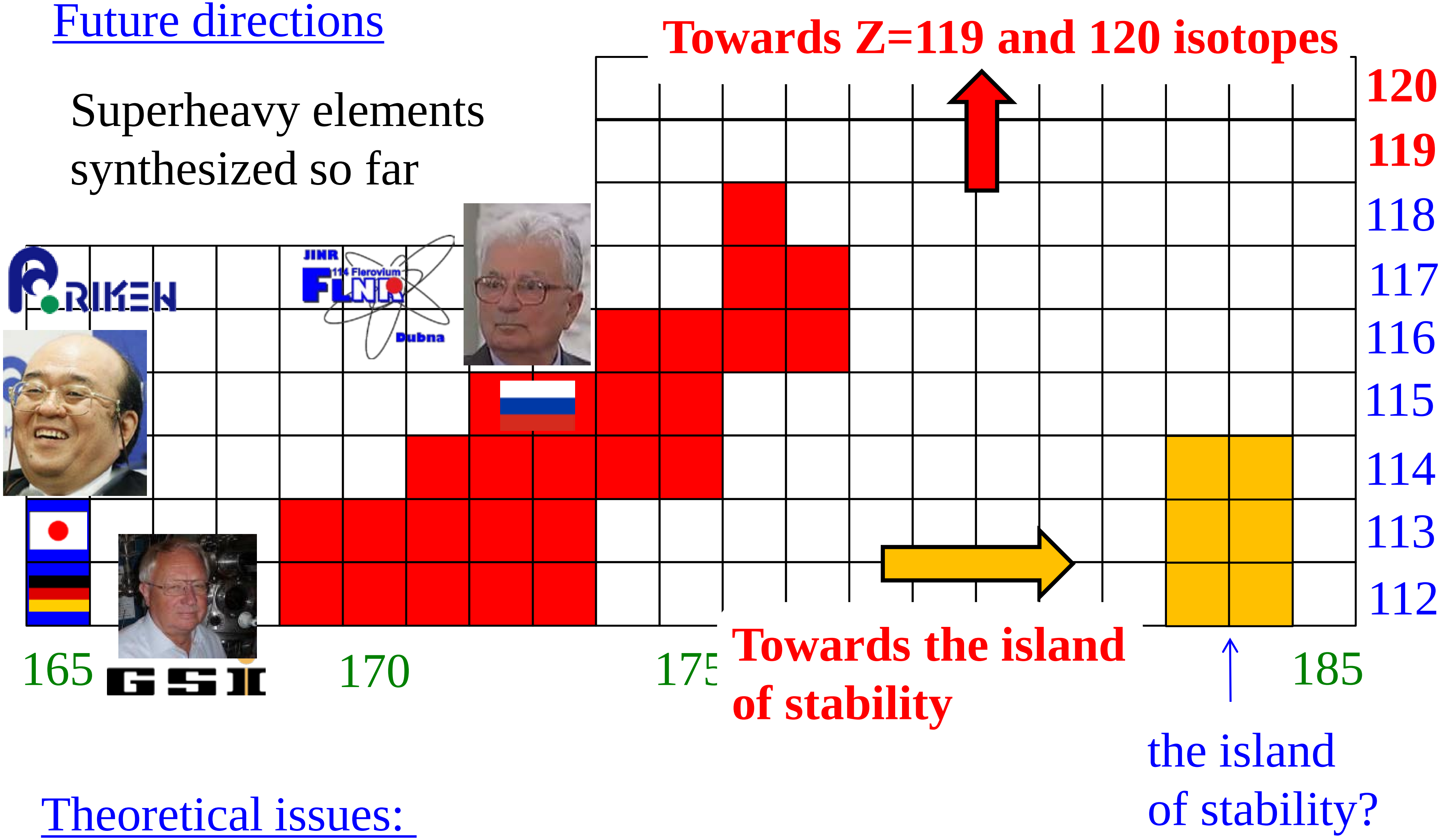
$^{48}Ca + ^{244}Pu \rightarrow ^{292}114$

$E^* = 33$ MeV



Future directions

Superheavy elements synthesized so far

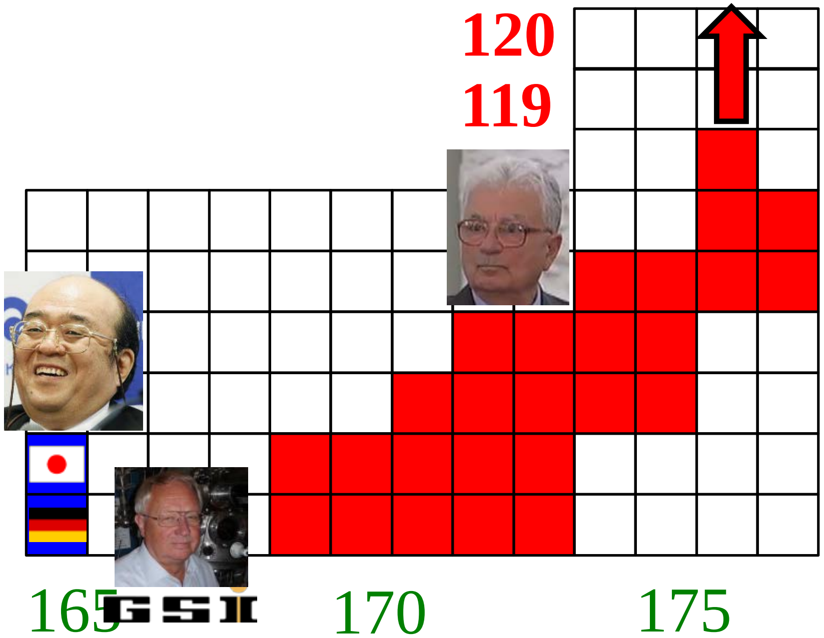


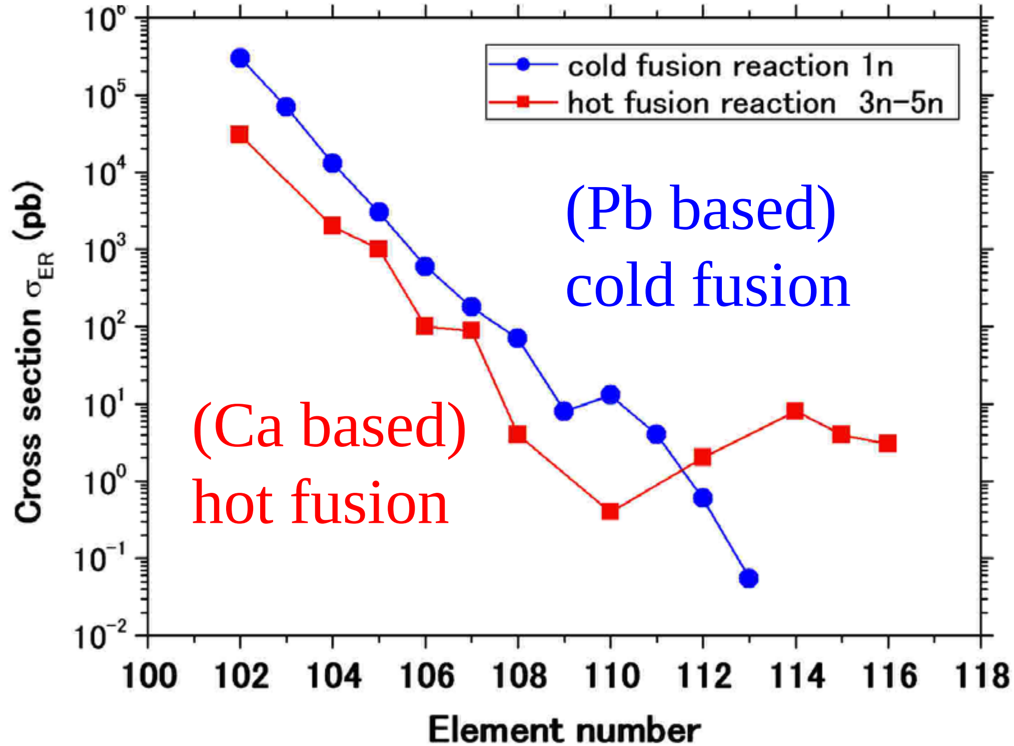
Theoretical issues:

- to understand the reaction dynamics
- to make a reliable theoretical prediction for fusion cross sections

Hot fusion for Z = 119 and 120

Towards Z=119 and 120 isotopes





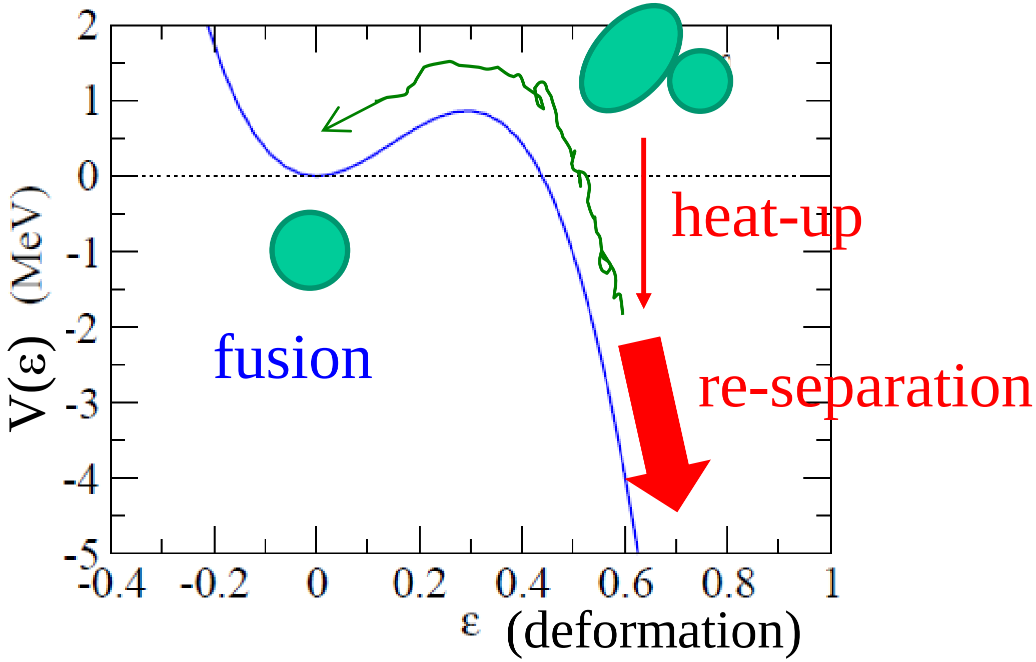
hot fusion: ^{48}Ca + actinide targets

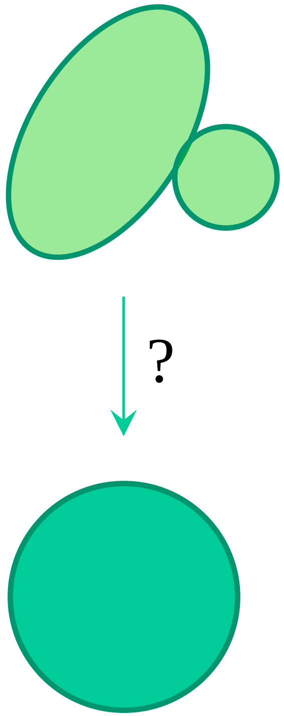
Dubna: ^{48}Ca + ^{249}Cf (β_2 = 0.235) $\longrightarrow$ $^{297\text{-}x}$Og (Z=118) + xn

role of deformation?

Hot fusion: ^{48}Ca + deformed actinide target

Effect of deformation





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?

➢Towards Z=119 and 120 nuclei

Another issue

$^{48}_{20}Ca + {}_{99}Es \longrightarrow 119$
$^{48}_{20}Ca + {}_{100}Fm \longrightarrow 120$

the targets: not available with sufficient amounts

Dubna: $^{48}Ca + {}^{249}_{98}Cf \longrightarrow {}^{297\text{-}x}Og$ (Z=118) + xn

$^{249}_{98}Cf$ (351 year)
$^{252}_{99}Es$ (471.7 day)
$^{257}_{100}Fm$ (100.5 day)

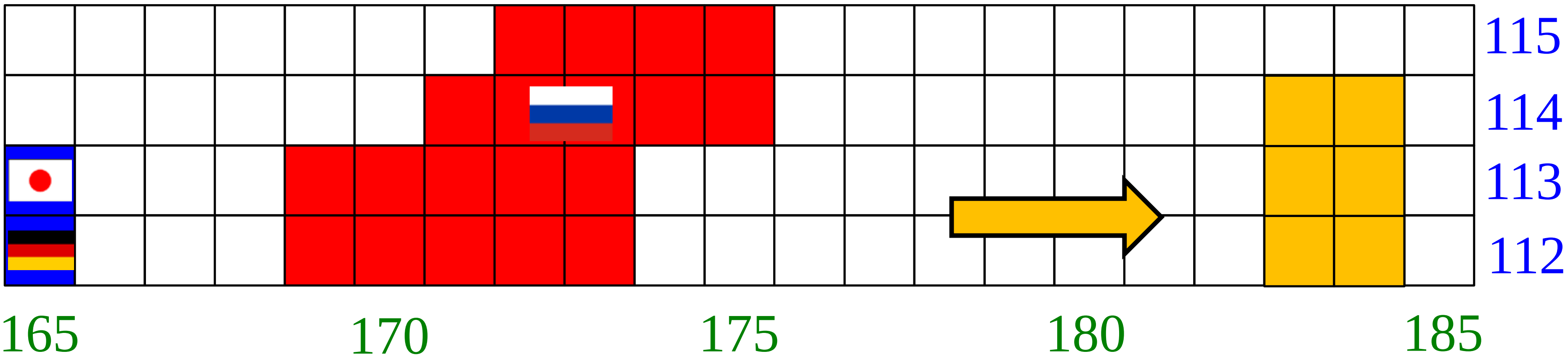
⇨ $^{48}Ca \longrightarrow {}^{50}_{22}Ti$, $^{51}_{23}V$, $^{54}_{24}Cr$ projectiles

cf. $^{46}_{21}Sc_{25}$: relatively small neutron number

how much will fusion cross sections be reduced?

nobody still knows

Towards the island of stability



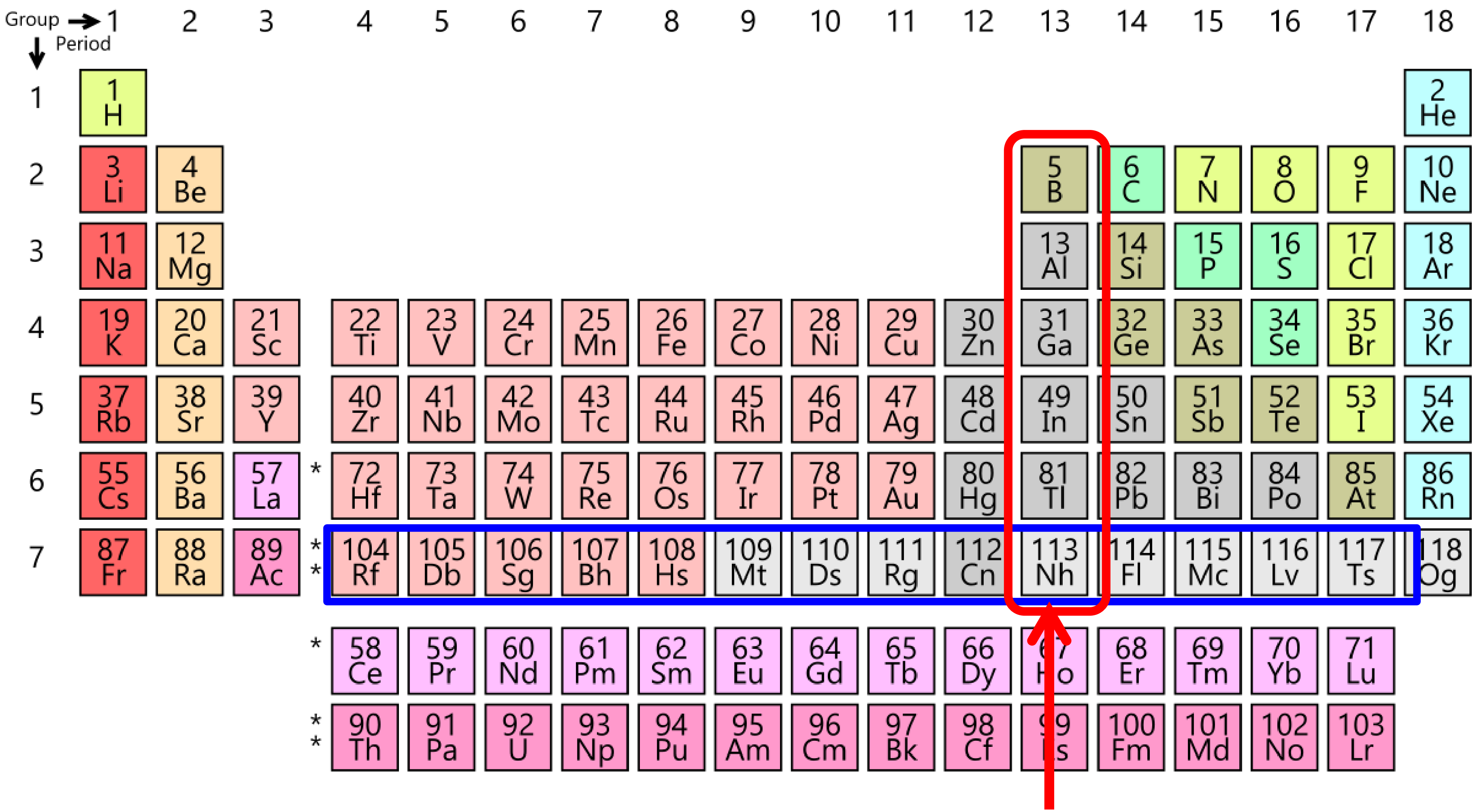
neutron-rich beams: indispensable

- ➢ how to deal with <u>low beam intensity</u>?
- ➢ 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

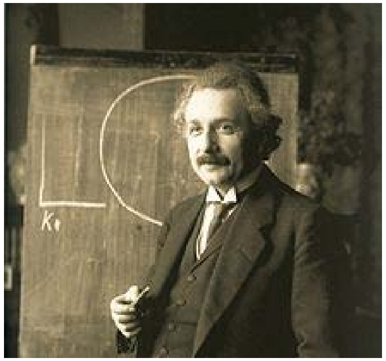
Chemistry of superheavy elements



- Are they here in the periodic table?
- Does Nh show the same chemical properties as B, Al, Ga, In, and Tl?

relativistic effect : important for large Z

$$E = mc^2$$



Solution of the Dirac equation (relativistic quantum mechanics) for a hydrogen-like atom:

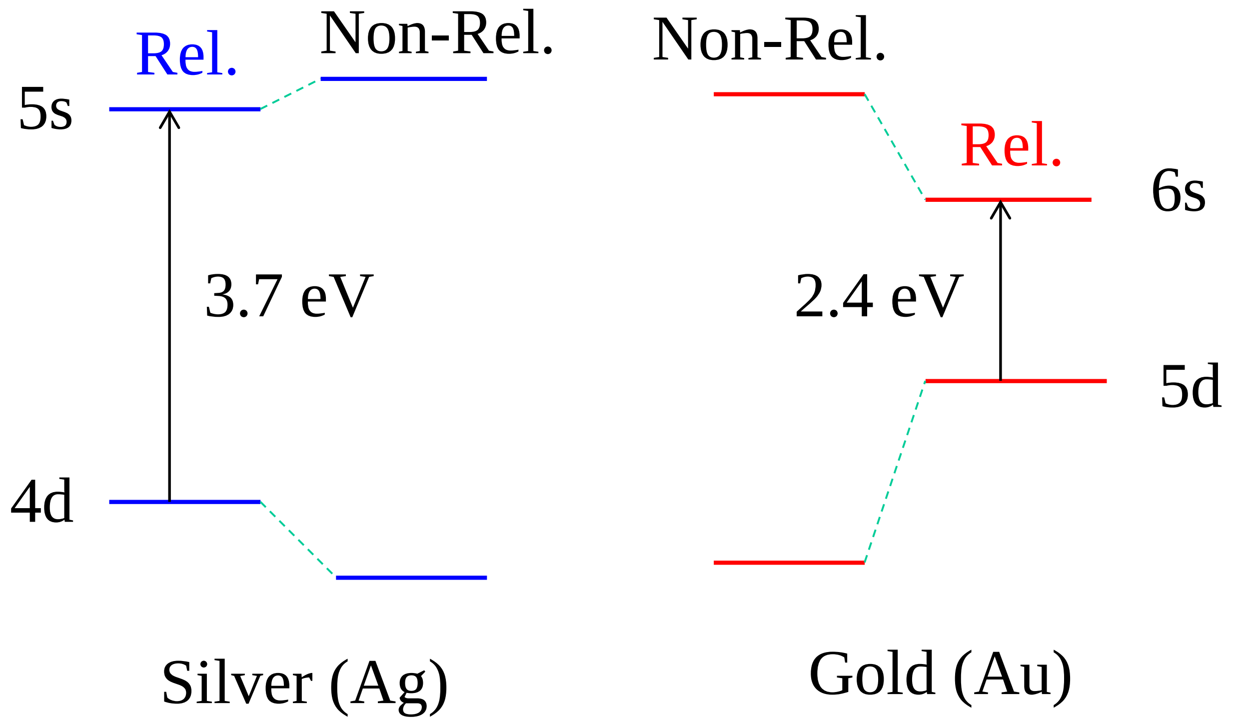
$$E_{1S} = mc^2\sqrt{1-(Z\alpha)^2} \sim mc^2\left(1 - \frac{(Z\alpha)^2}{2} \underbrace{- \frac{(Z\alpha)^4}{8} + \cdots}_{\text{relativistic effect}}\right)$$

relativistic effect

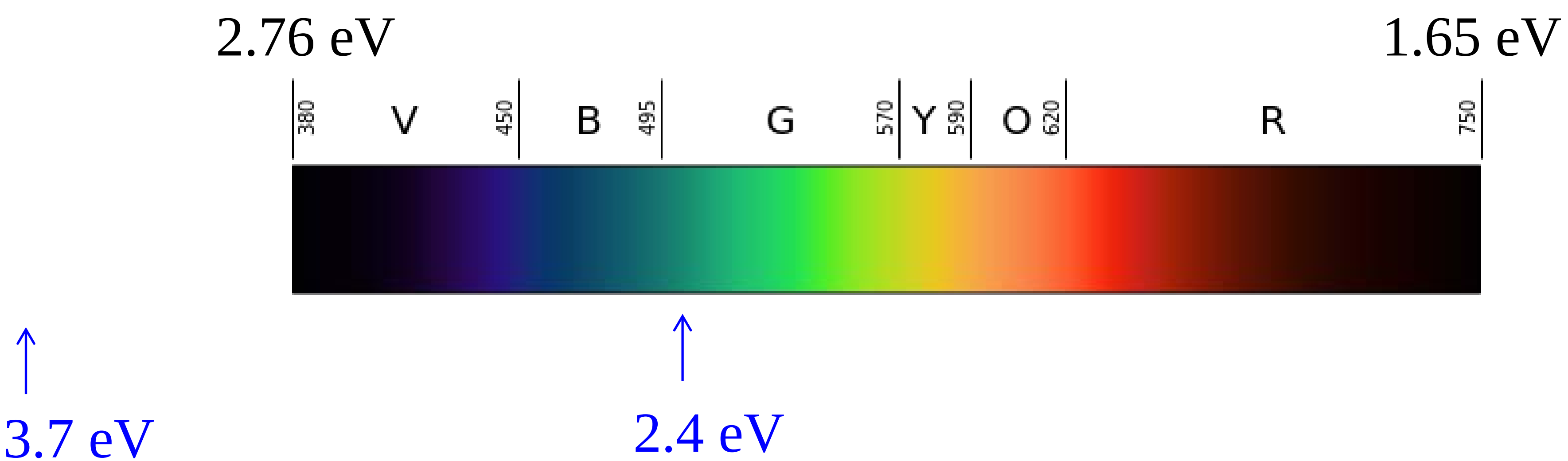
Famous example of relativistic effects: the color of gold

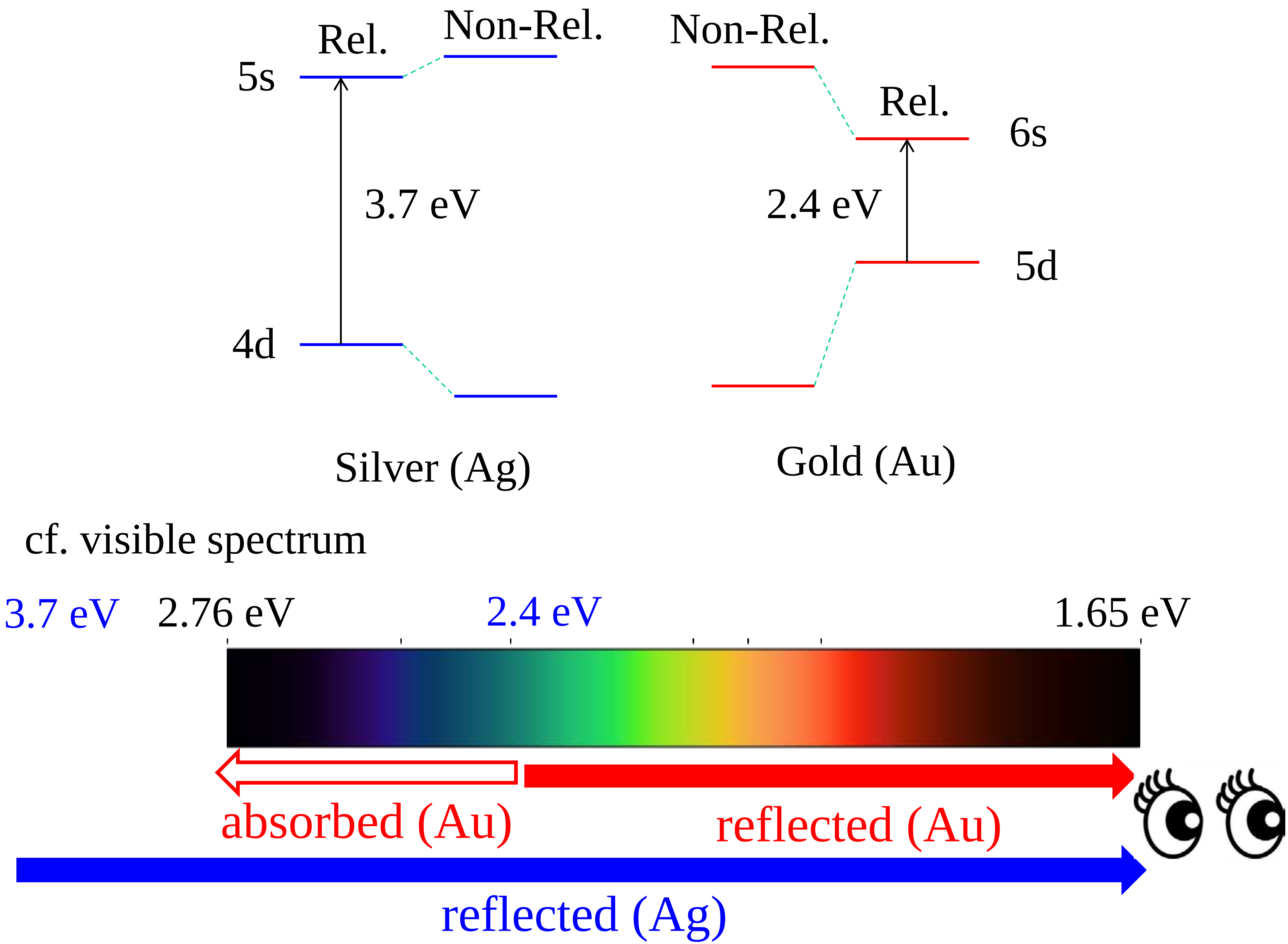
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		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		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

Gold looked like silver if there was no relativistic effects!

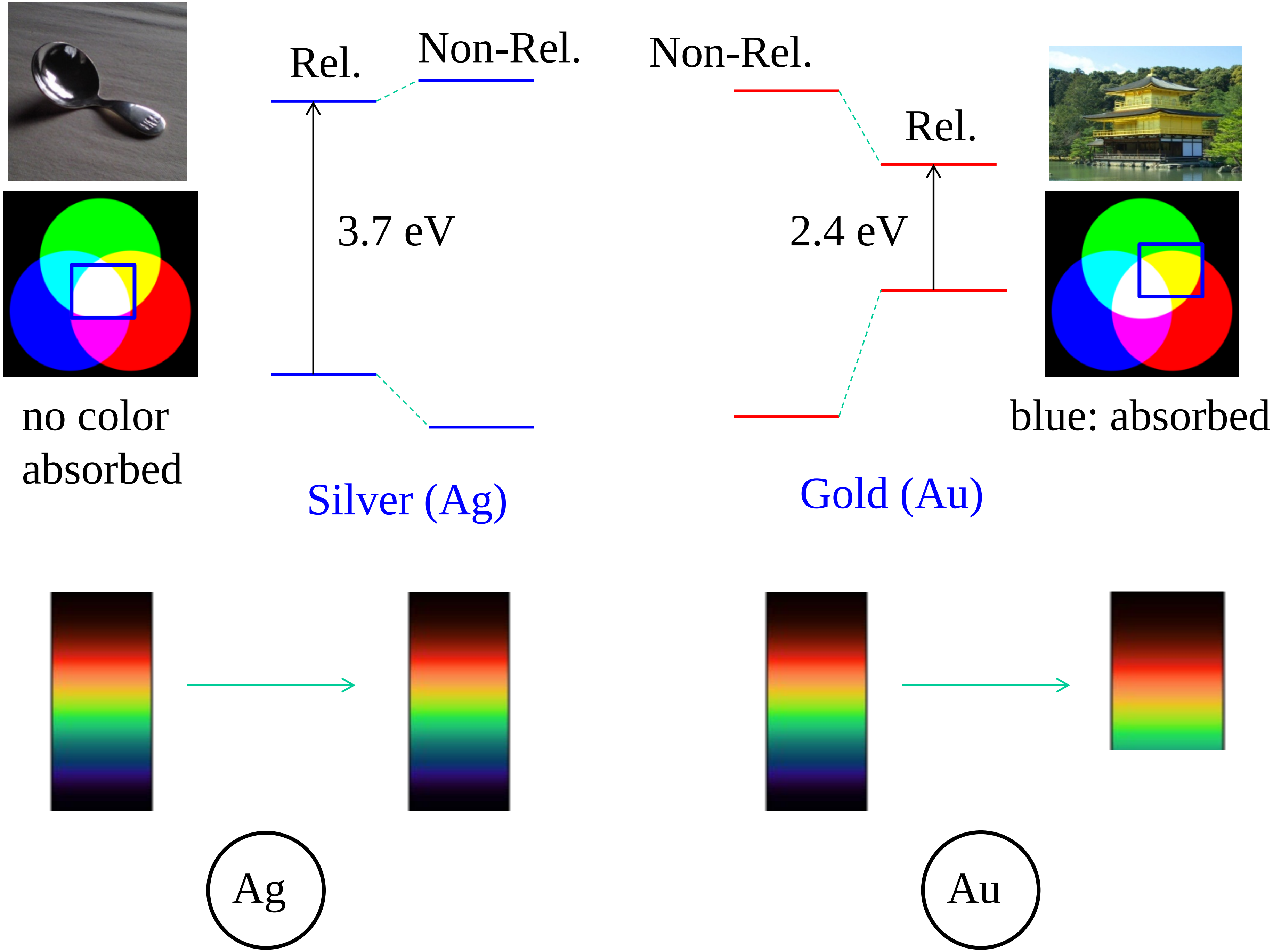


cf. visible spectrum





Rel.
Non-Rel.
Non-Rel.
5s
Rel.
6s
3.7 eV
2.4 eV
5d
4d
Silver (Ag)
Gold (Au)
cf. visible spectrum
3.7 eV
2.76 eV
2.4 eV
1.65 eV
absorbed (Au)
reflected (Au)
reflected (Ag)



Rel.
Non-Rel.
3.7 eV
no color
absorbed
Silver (Ag)
Non-Rel.
Rel.
2.4 eV
blue: absorbed
Gold (Au)
Ag
Au

Chemistry of superheavy elements

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		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		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

Lanthanides	57 La	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
Actinides	89 Ac	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

How do the relativistic effects alter the periodic table for SHE?

⟶ a big open question