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?

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?

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?

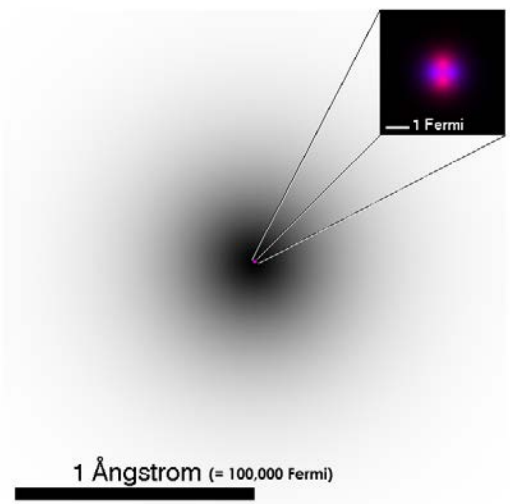
natural elements: **Pu** (Z=94) ⟶ a tiny amount in nature
U (Z=92)

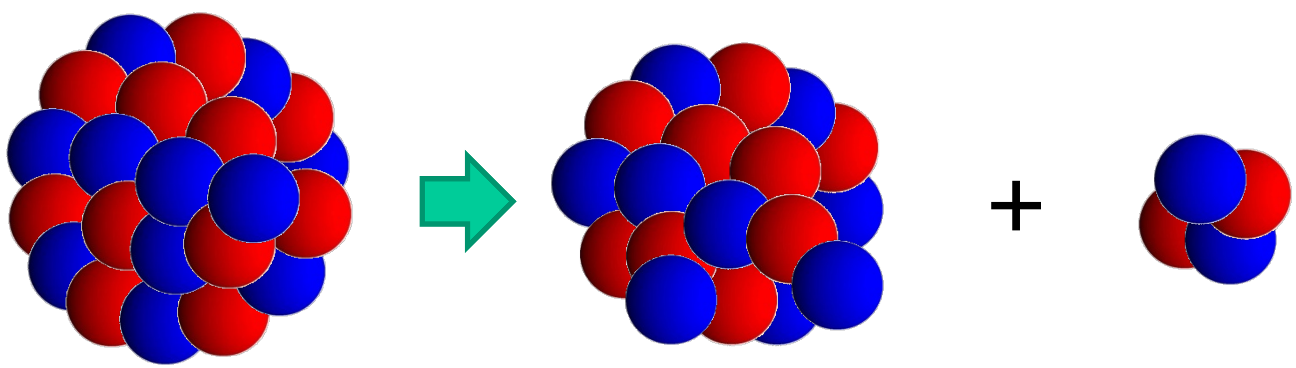
What determines these numbers??

heavy nuclei ⟶ large Coulomb repulsion

↓

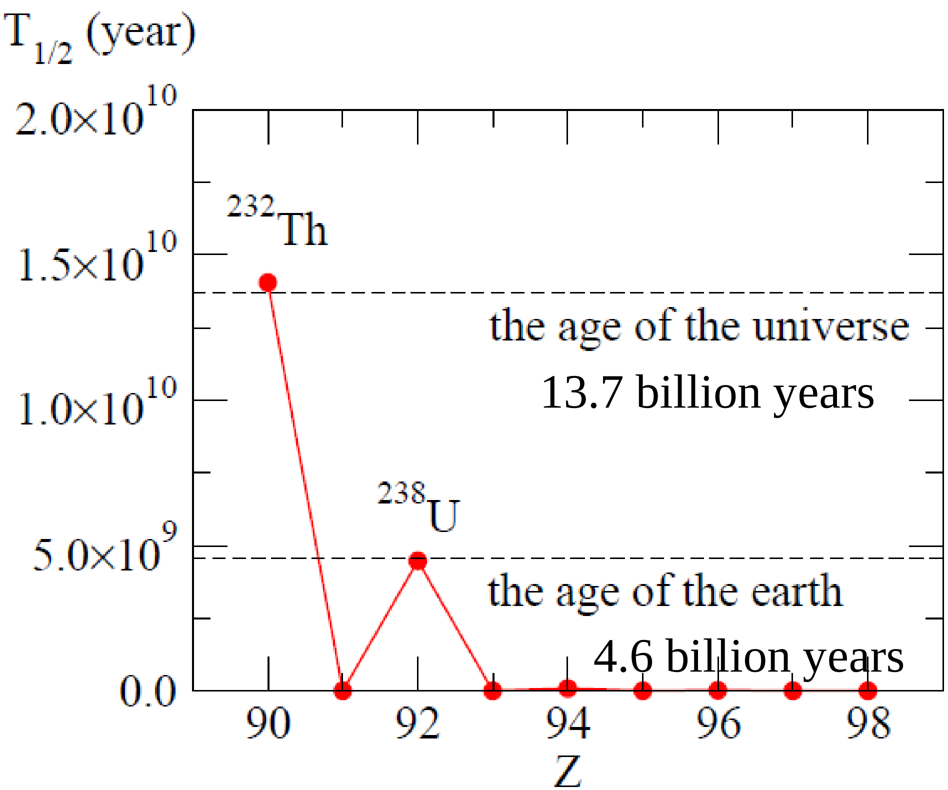
unstable against α decay

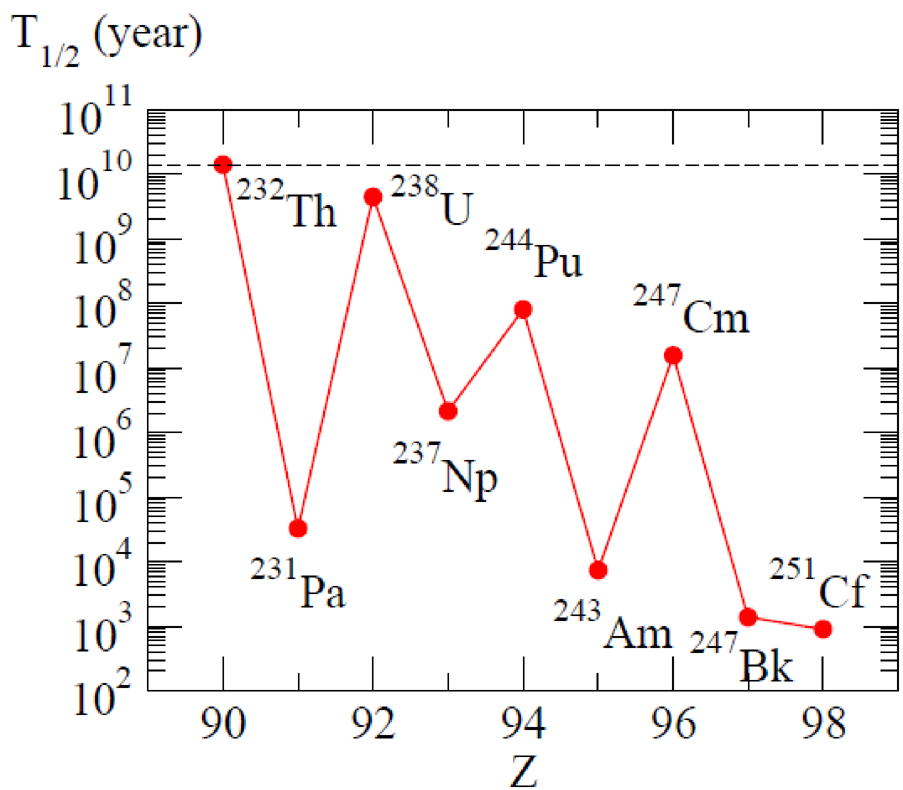




(Z,N) (Z-2,N-2) (Z=2,N=2)

Decay half-lives of heavy nuclei





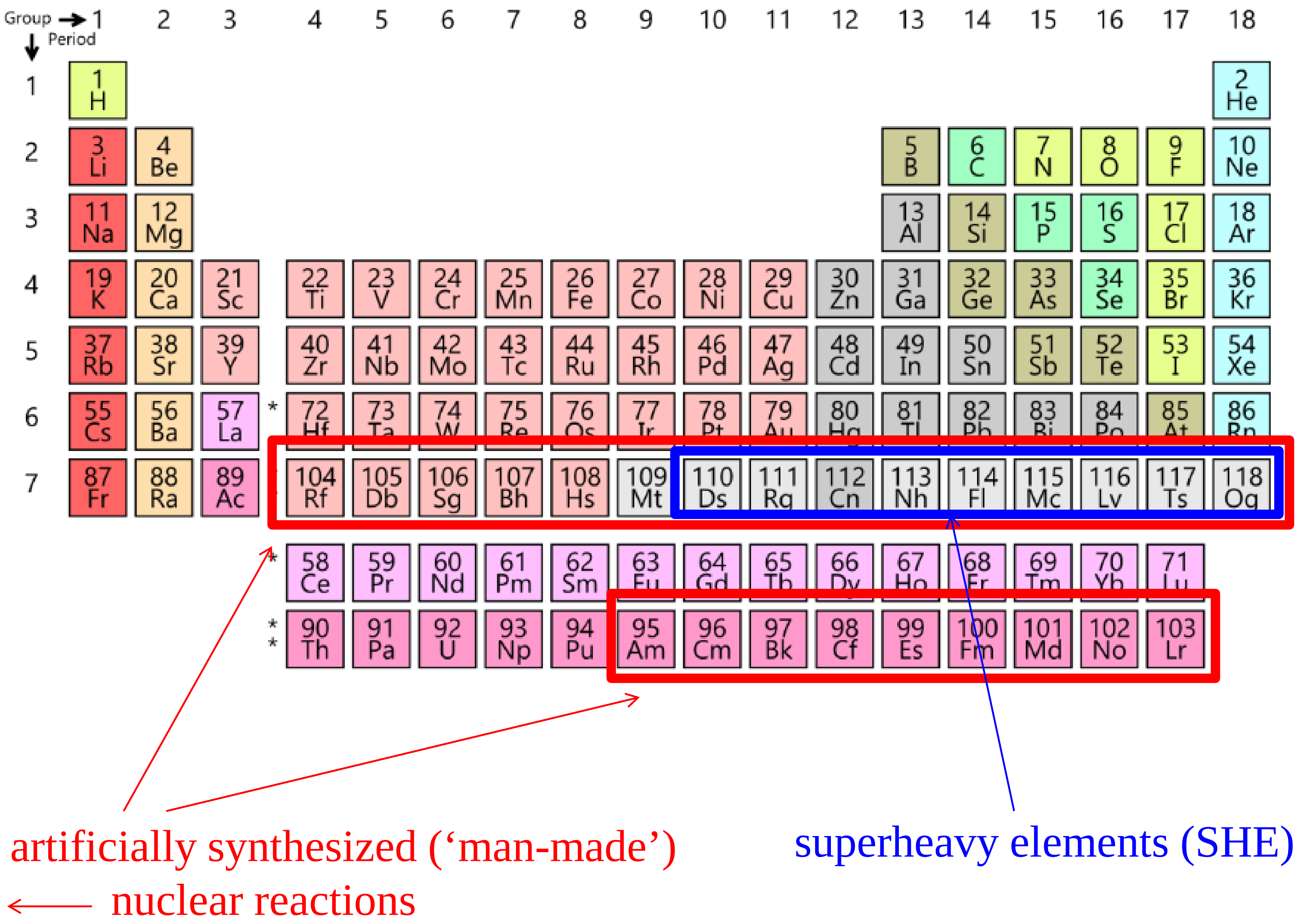
^{232}Th 1.405 x 10^{10} years

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

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

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

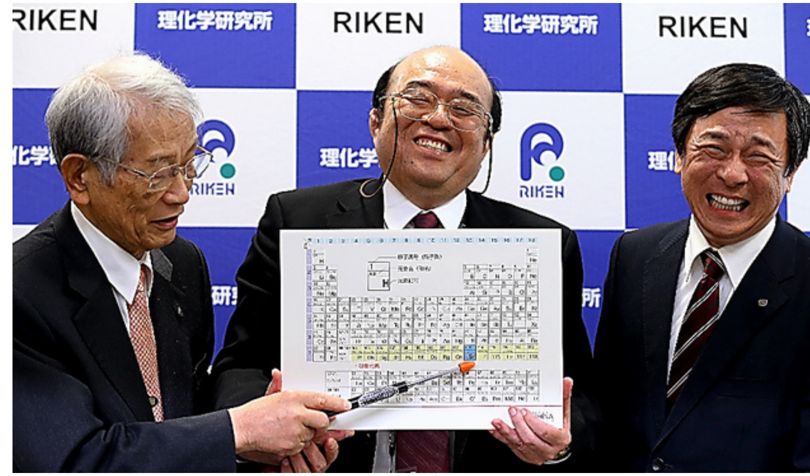
Periodic table of chemical elements

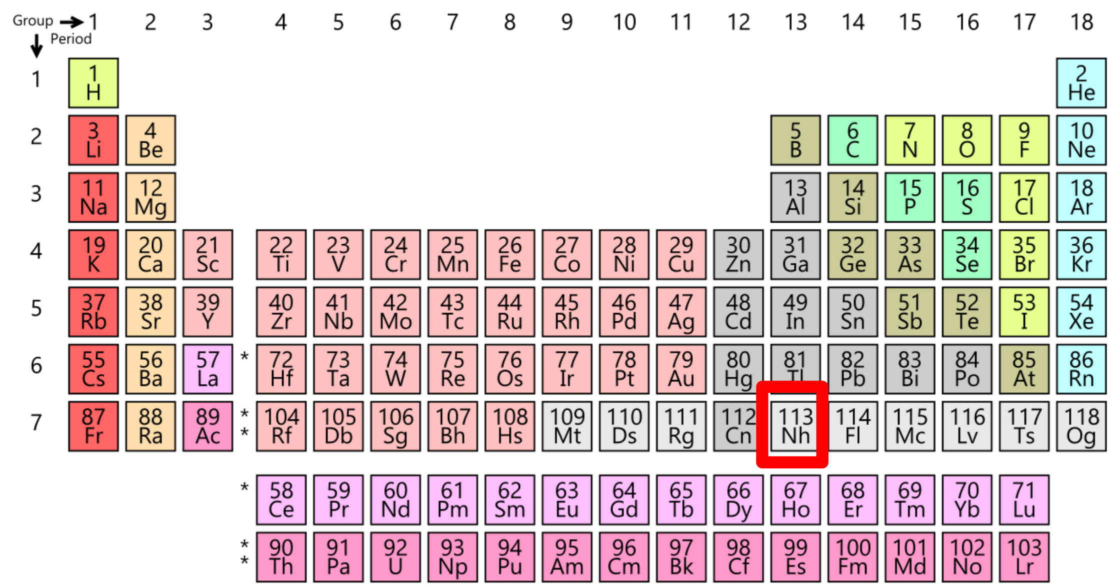


Fusion reactions for SHE

the element 113: Nh

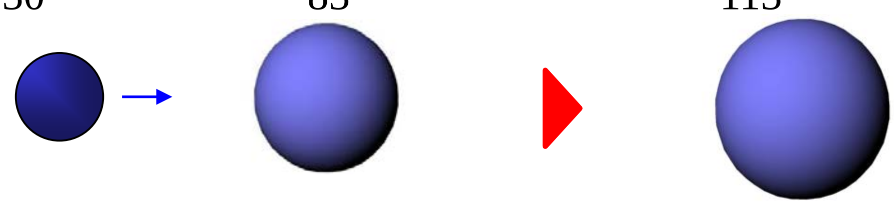
November, 2016





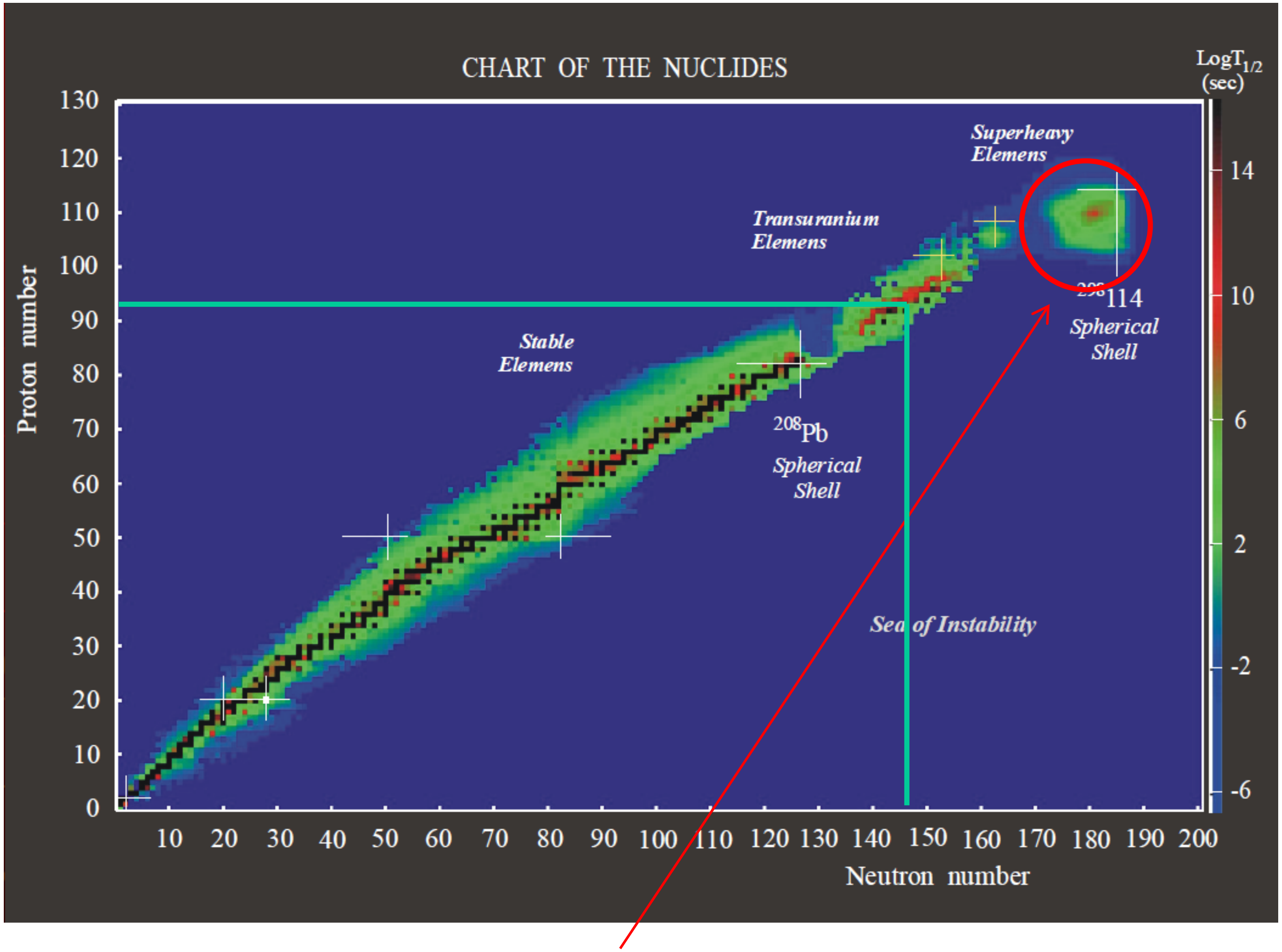
Wikipedia

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



Heavy-ion fusion reaction

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

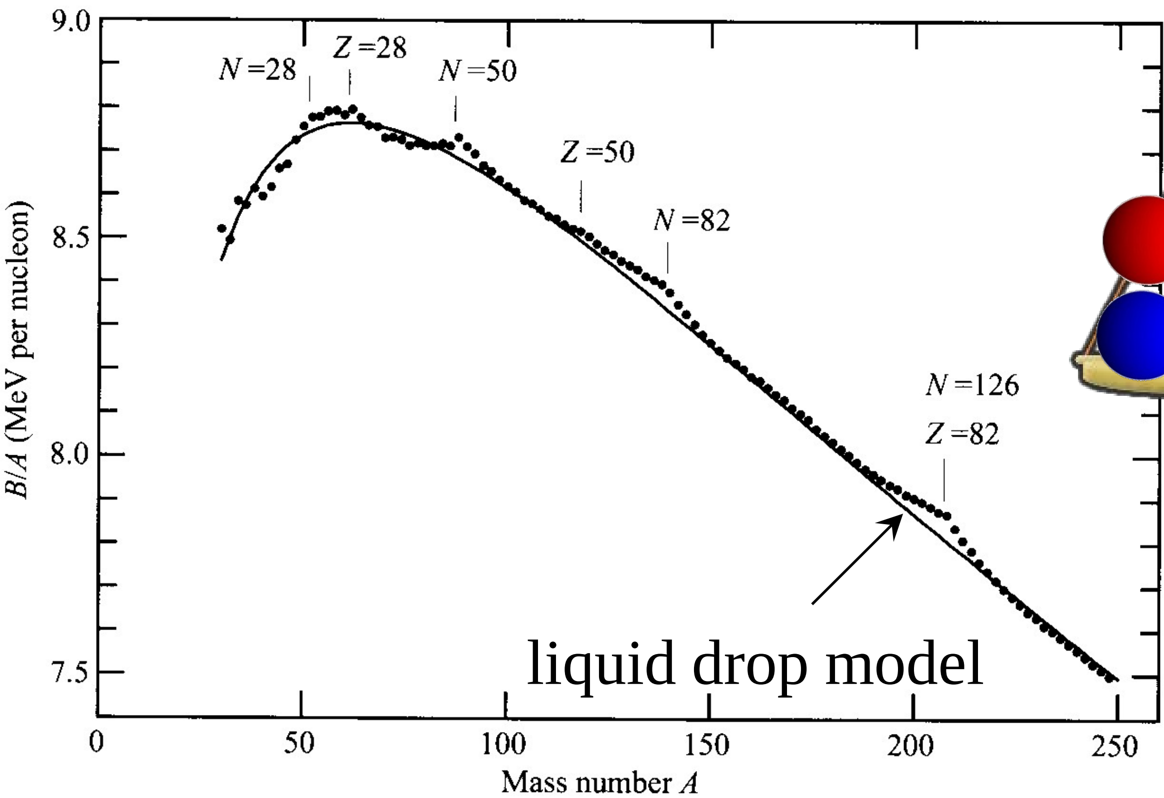


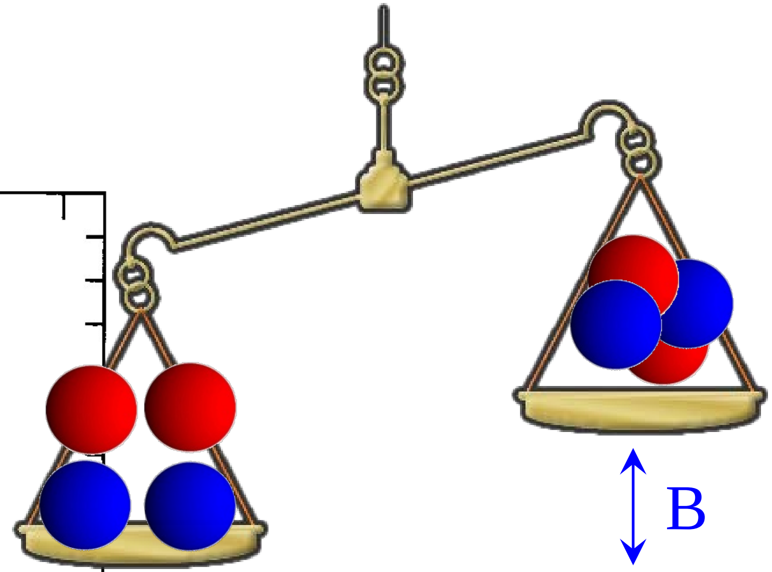
Yuri Oganessian

island of stability around Z=114, N=184

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

shell energy

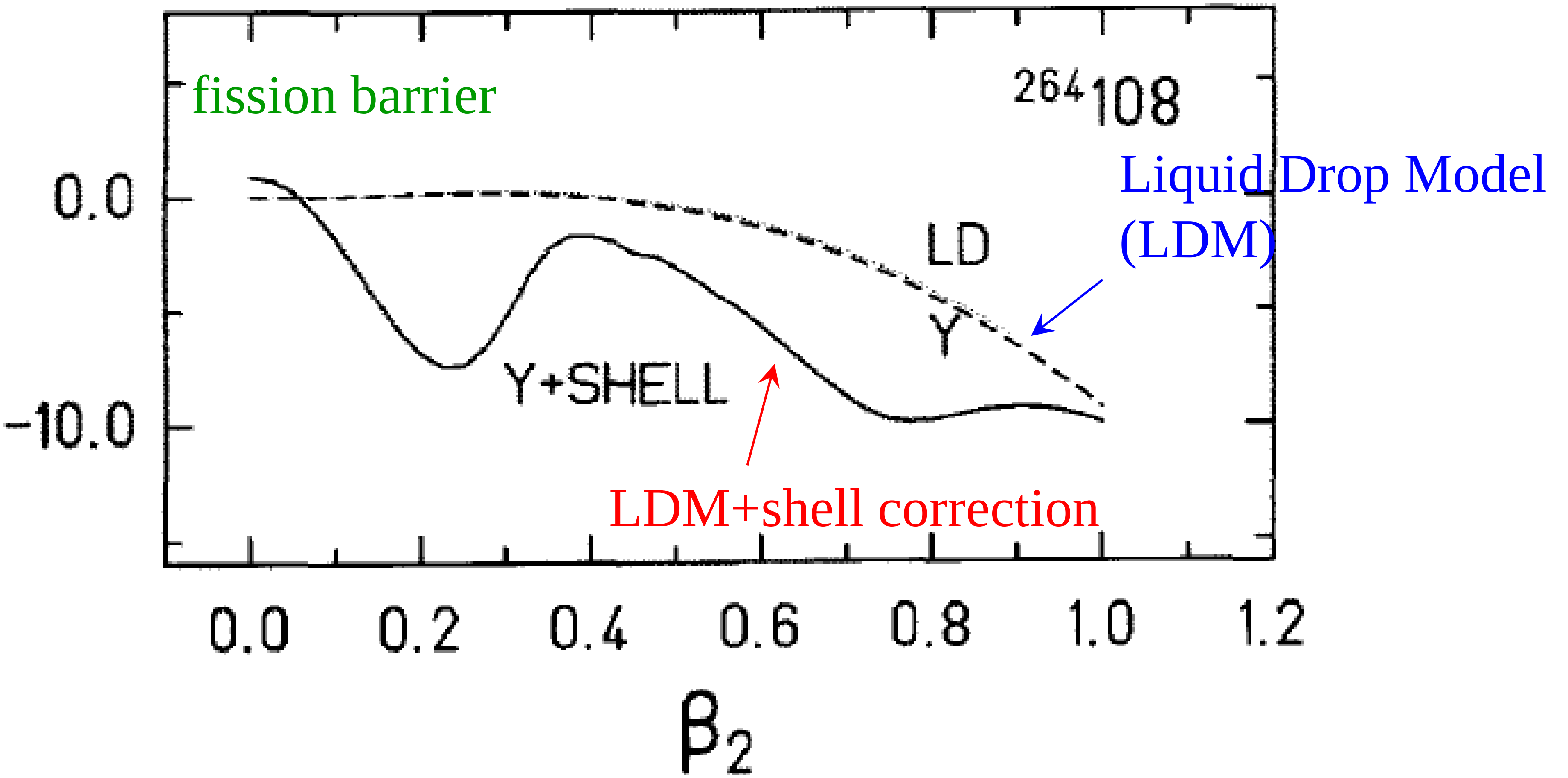




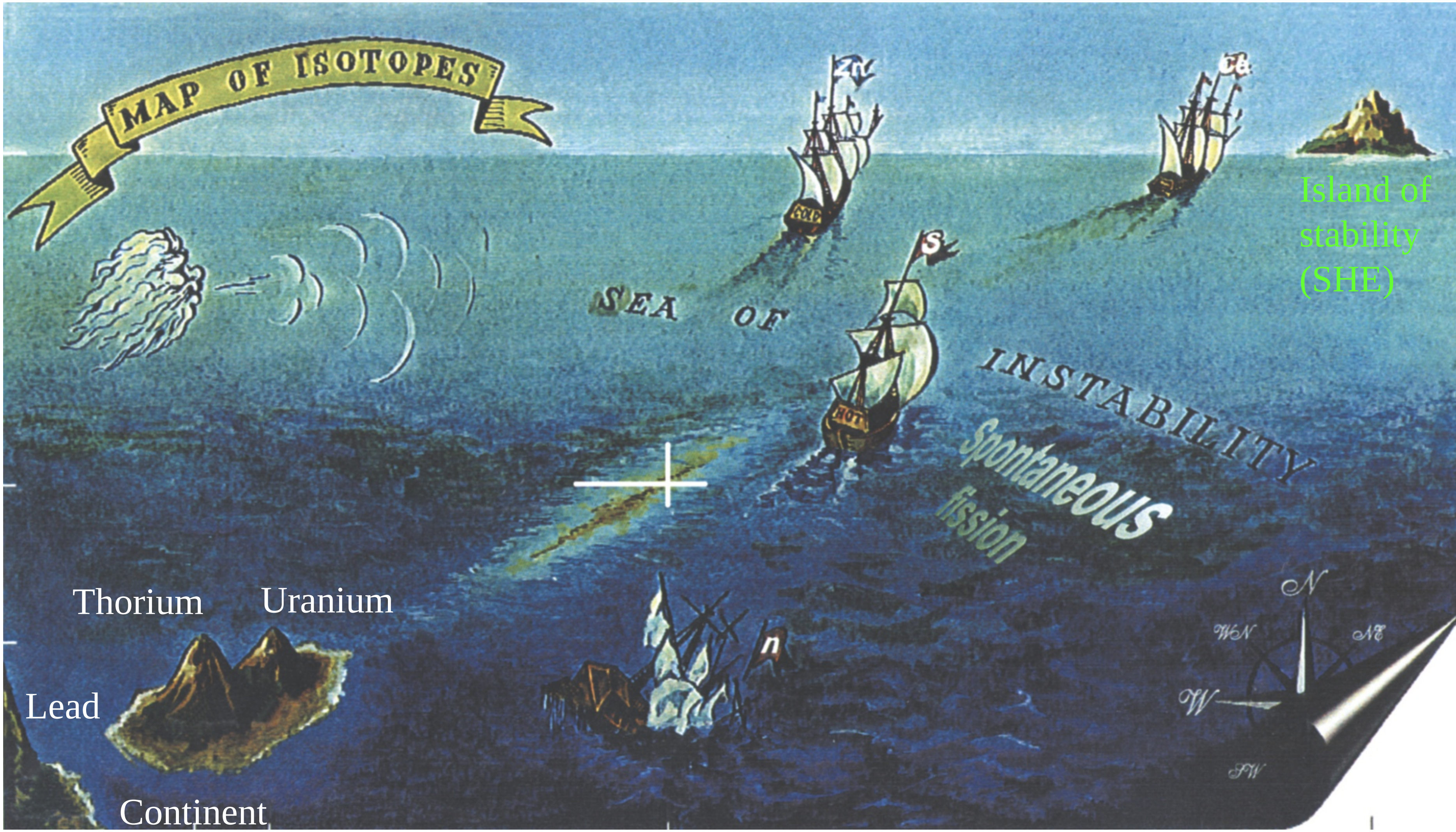
Extra binding for N or Z = 2, 8, 20, 28, 50, 82, 126 (magic numbers)

⇨ Very stable

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



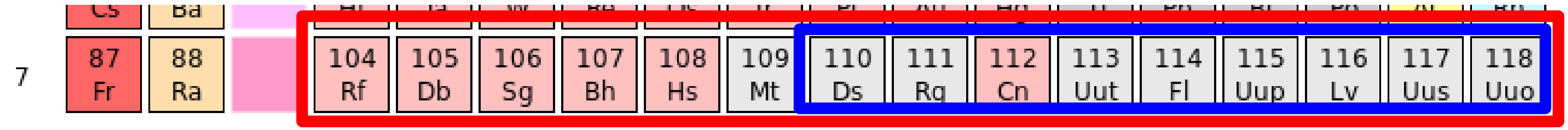
Z. Patyk et al., NPA491('89) 267



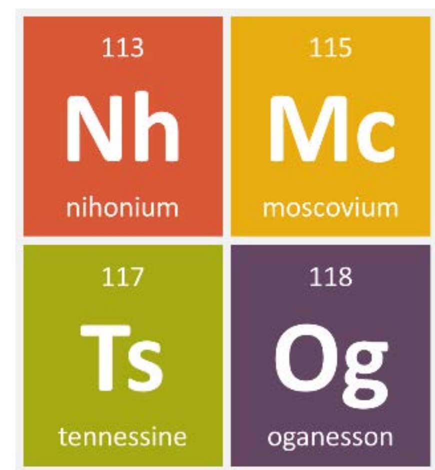
118
Og
oganesson

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

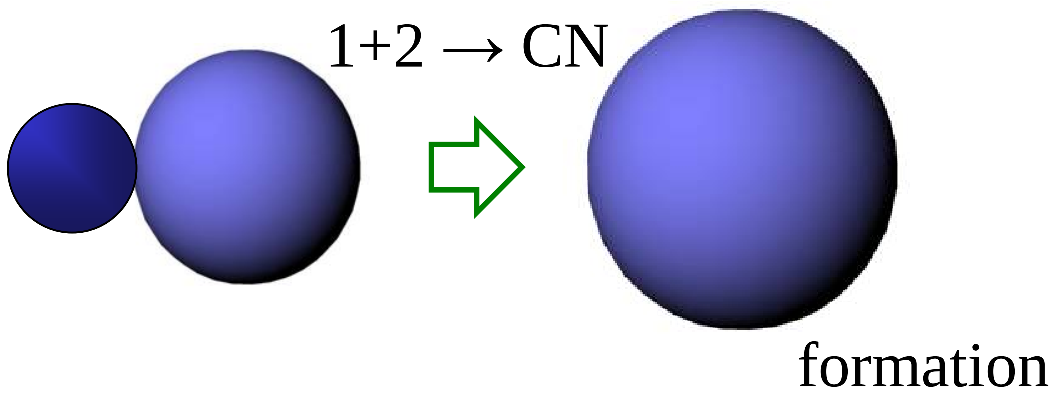


Germany, Japan: cold fusion reactions

Russia: hot fusion reactions

Germany, Japan: cold fusion reactions

Russia: hot fusion reactions

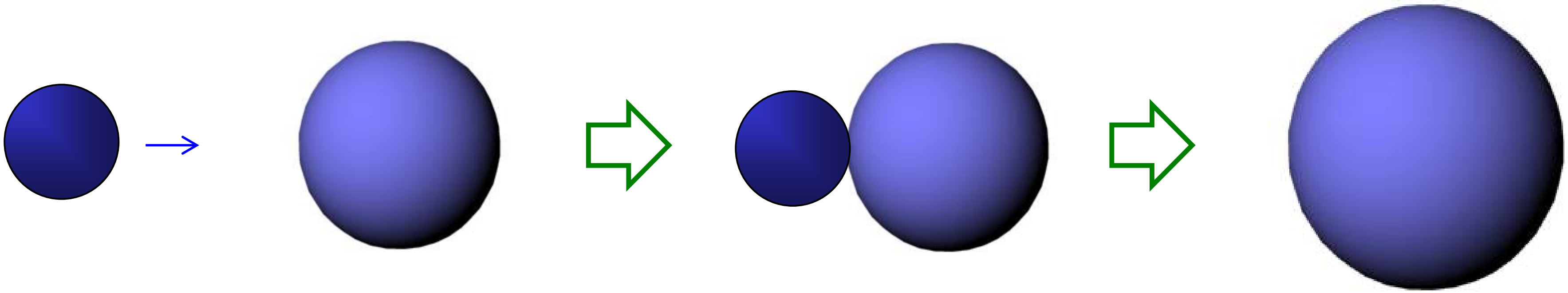


	Hot Fusion	**Cold Fusion**
Example	$^{48}Ca + {}^{243}Am \rightarrow {}^{187}Nh + 4n$	$^{70}Zn + {}^{209}Bi \rightarrow {}^{278}Nh + 1n$
asymmetry	large	small
	hot CN	cold CN

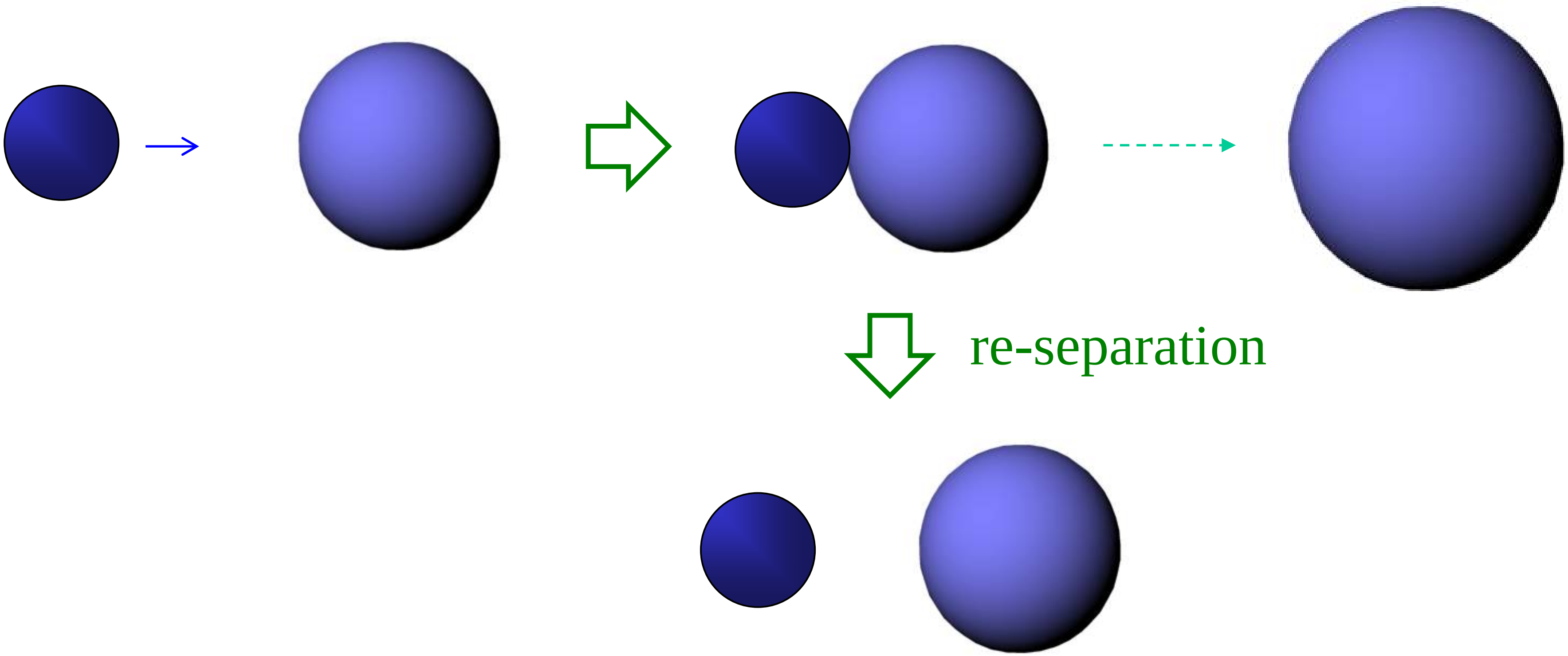
<u>How to synthesize SHE?</u>

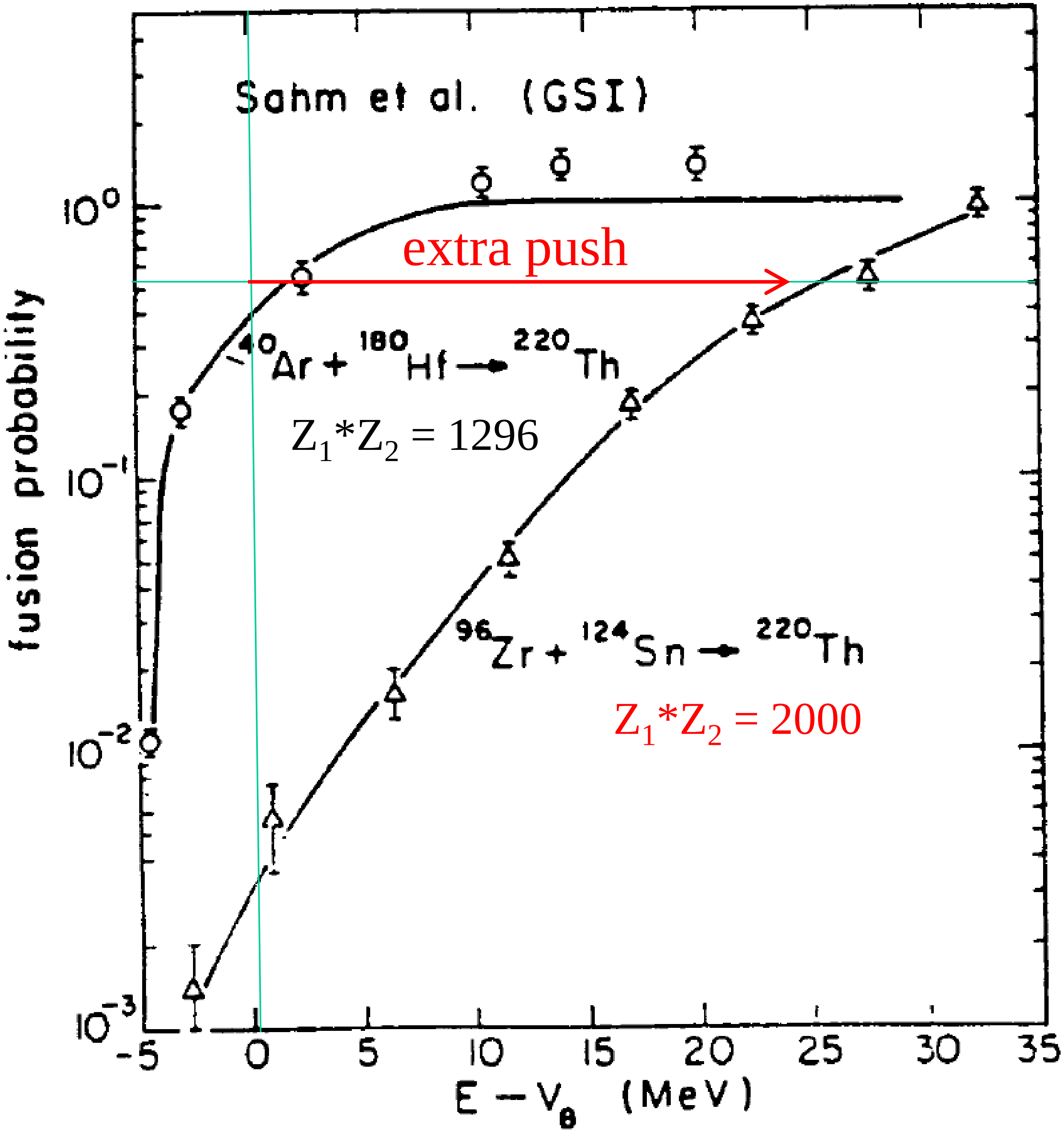
Nuclear fusion reactions

- Fusion of medium-heavy systems:

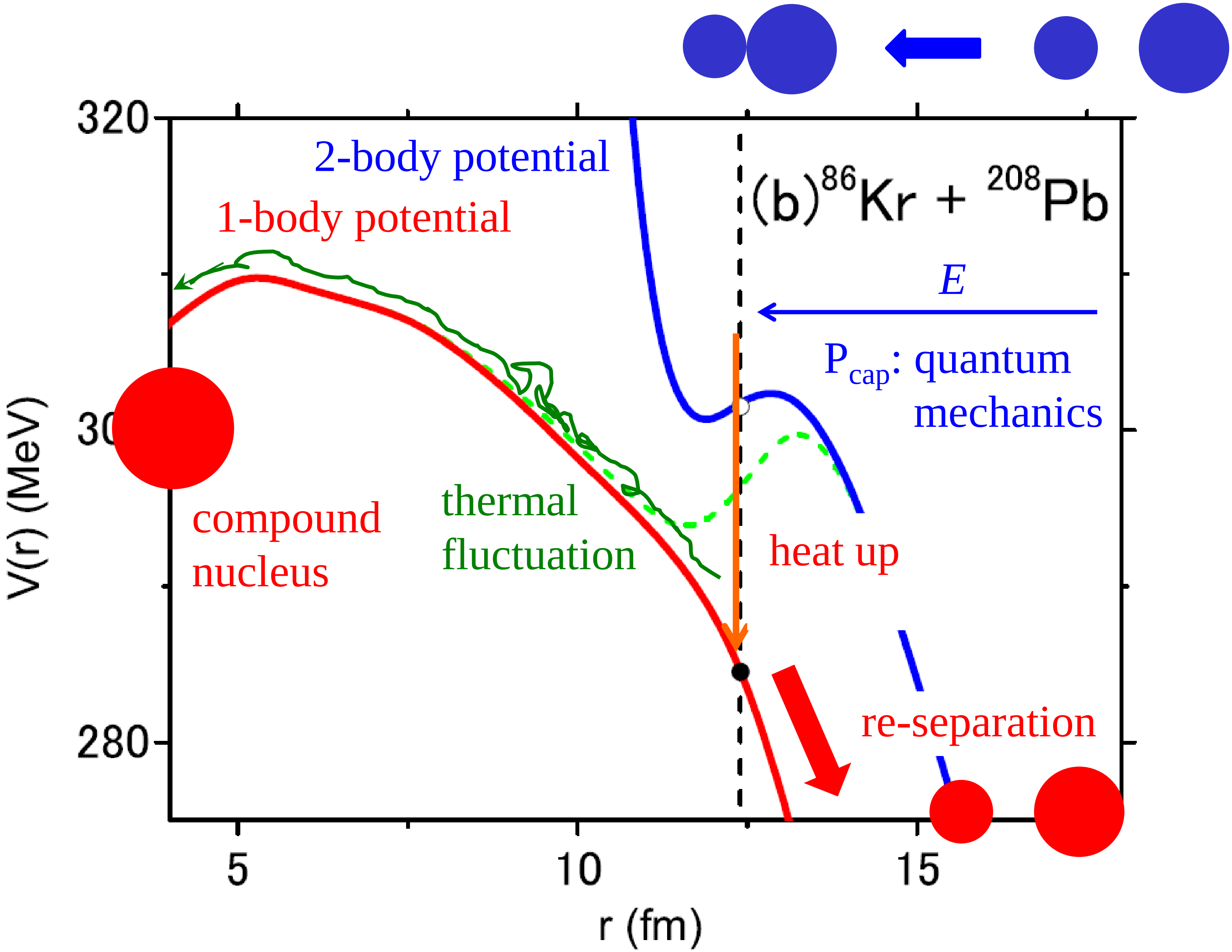


- Fusion of heavy and super-heavy systems:





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



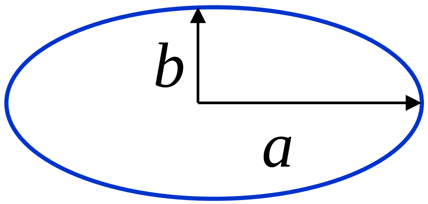
2-body potential
1-body potential
(b)^{86}Kr + ^{208}Pb
E
Pcap: quantum mechanics
compound nucleus
thermal fluctuation
heat up
re-separation
320
300
280
V(r) (MeV)
5
10
15
r (fm)

（復習）

$$B(N,Z) = a_v A - a_s A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_{\rm sym}\frac{(N-Z)^2}{A}$$

原子核を体積一定のまま変形してみる

例）回転楕円体



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

$ab^2 = R^3 =$ 一定

変形したときのエネルギー変化:

- 体積項、対称エネルギー項:変化せず
- クーロン項
- 表面項

（クーロン項・表面項）→ 変化

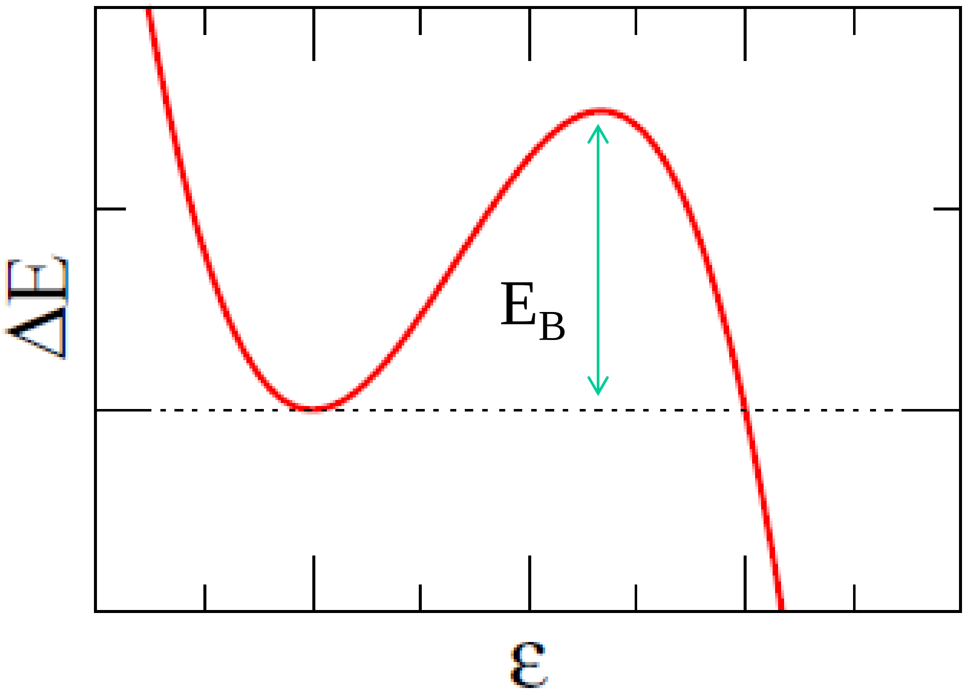
表面項 → 球形になる傾向
クーロン項 → 変形になる傾向

→ 2つの力の競合

（復習）

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

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



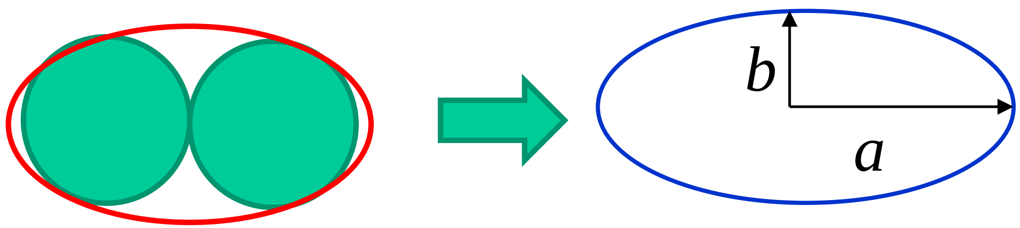
$$E_B = \frac{98}{15} \cdot \frac{(1-x)^3}{(1+2x)^2} \cdot E_S^{(0)}$$

重い核ほど障壁は低くなる

$$\epsilon_B = 7 \cdot \frac{(1-x)}{(1+2x)}$$

重い核ほど障壁での変形度は小さくなる

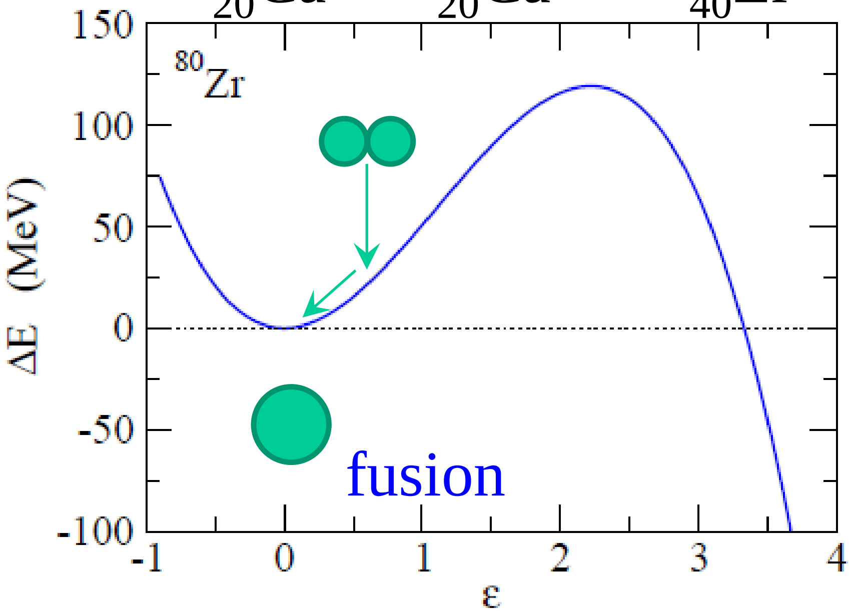
if two identical nuclei contact :



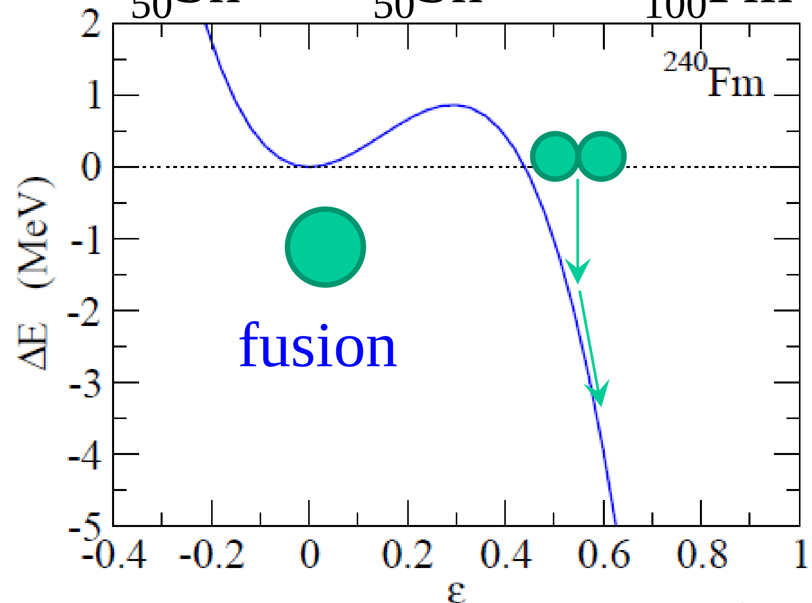
$$a = R_0 \cdot (1+\epsilon)$$
$$b = R_0 \cdot (1+\epsilon)^{-1/2}$$

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

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

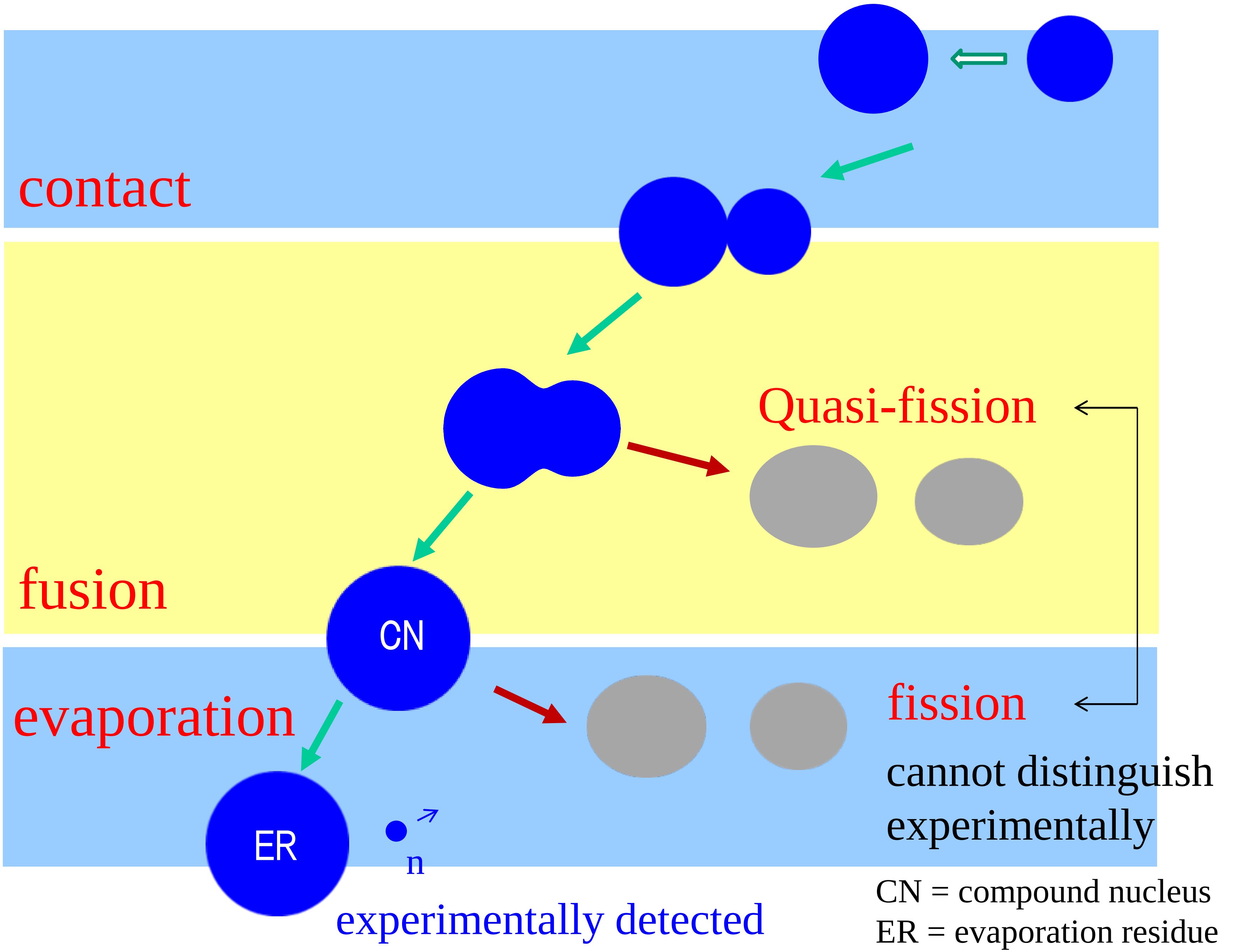


$^{120}_{50}Sn + ^{120}_{50}Sn \longrightarrow ^{240}_{100}Fm$



threshold: $Z_1 * Z_2 = 1600 \sim 1800$

$a_S = 16.8$ MeV
$a_C = 0.72$ MeV

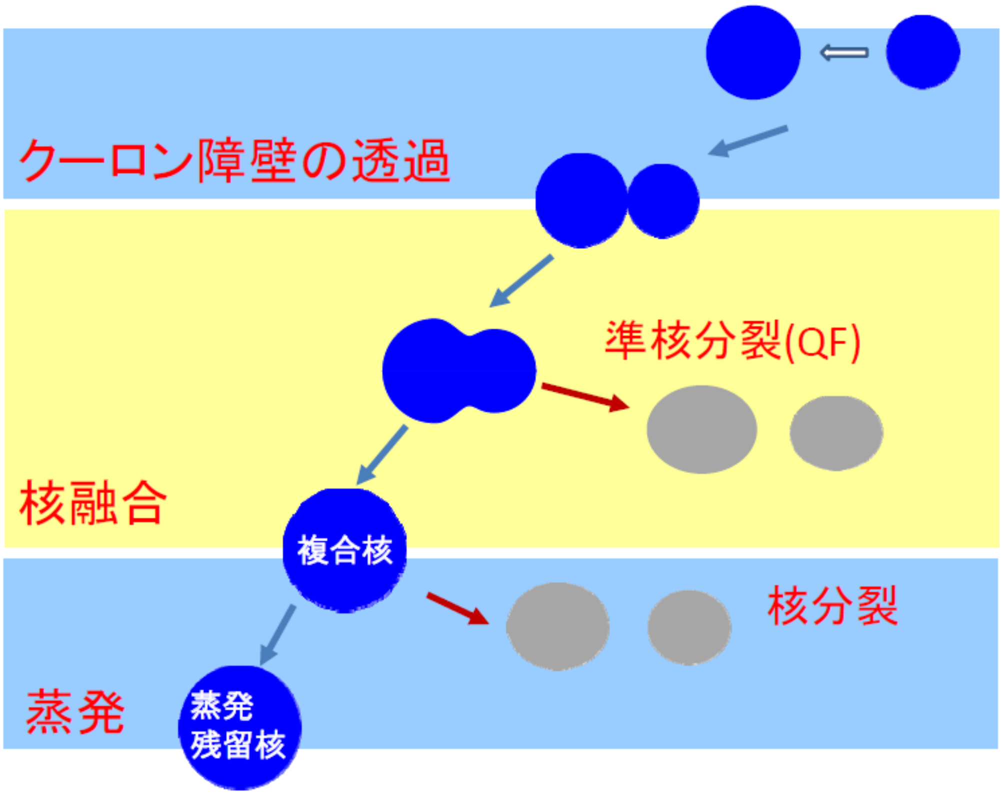

contact
Quasi-fission
fusion
CN
evaporation
fission
cannot distinguish
experimentally
ER
n
experimentally detected
CN = compound nucleus
ER = evaporation residue

＊どのように核融合反応断面積を測定するのか?

➢ 中重核領域の場合：

✓核融合生成物の直接測定（蒸発残留核＋核分裂）

➢ 重核・超重核領域の場合：



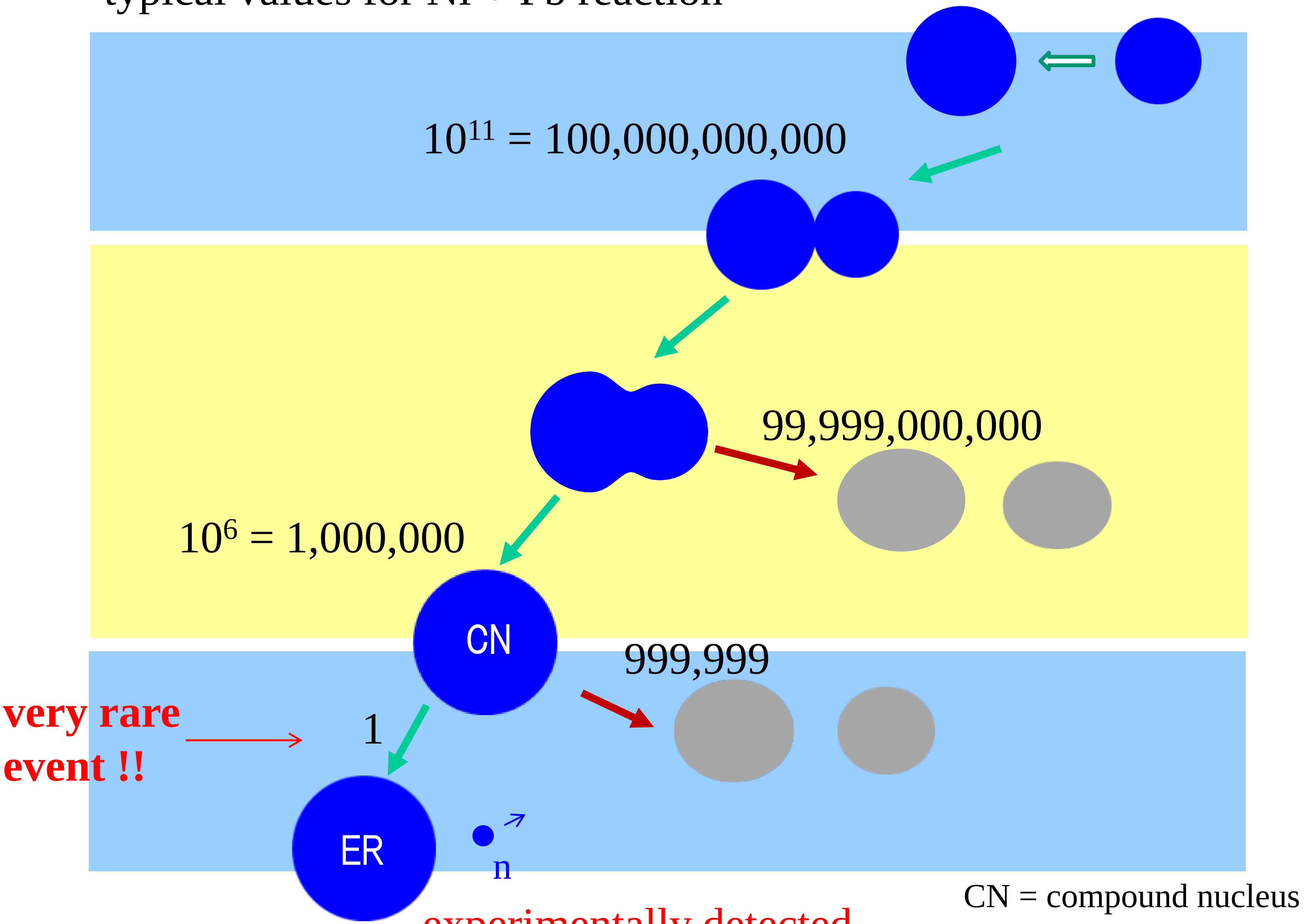
大きな準核分裂の確率のため、核分裂片の測定は複合核形成を意味しない（QFとFFの区別は実験的に困難）

蒸発残留核の測定をもって複合核形成とみなす

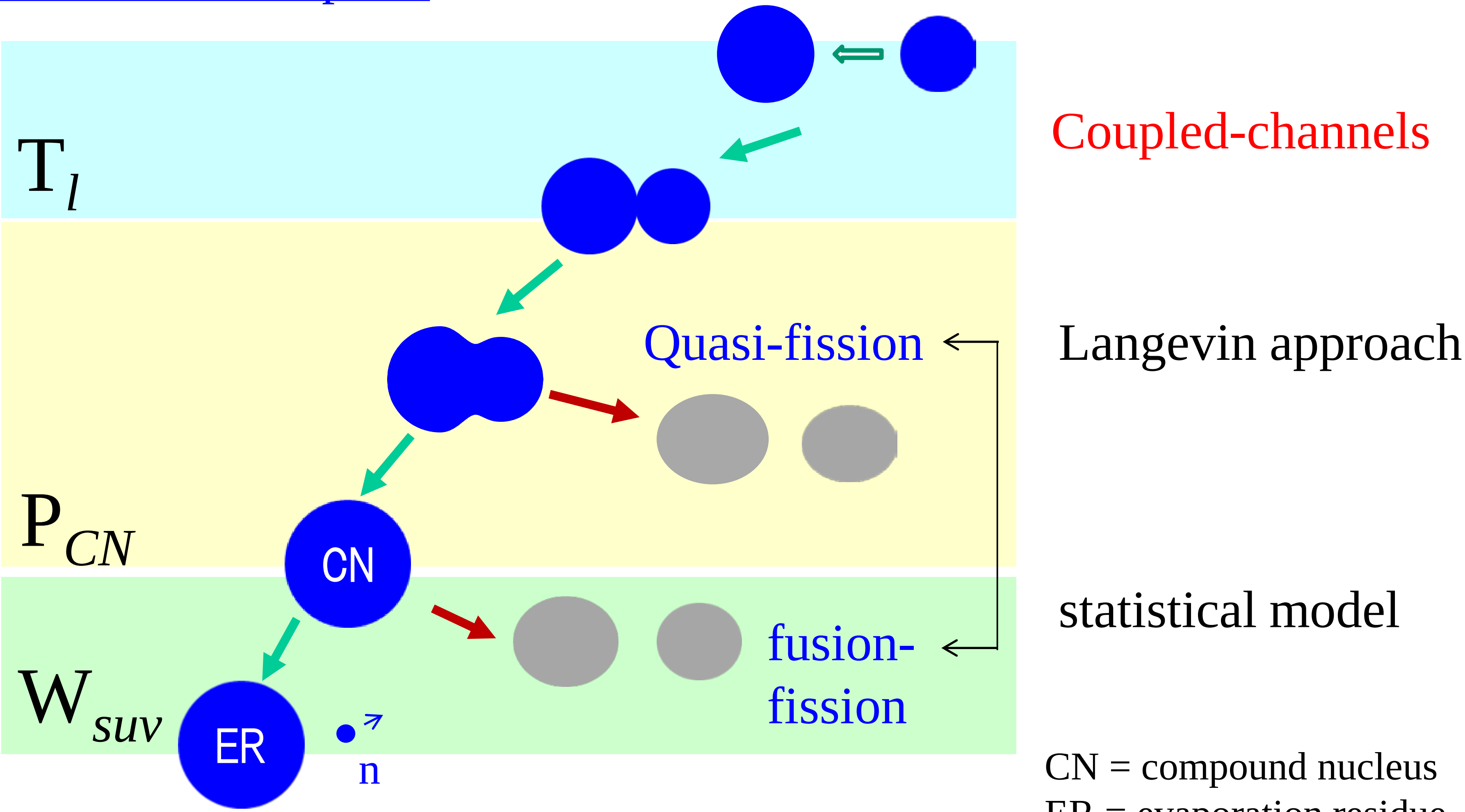
重い複合核：
圧倒的な確率で核分裂
（例：^{58}Fe + ^{208}Pb 反応では
核分裂しない確率は
$P_{suv} \sim 10^{-6}$ 程度）

準核分裂＋生き残りの2重苦

typical values for Ni + Pb reaction



Theoretical description



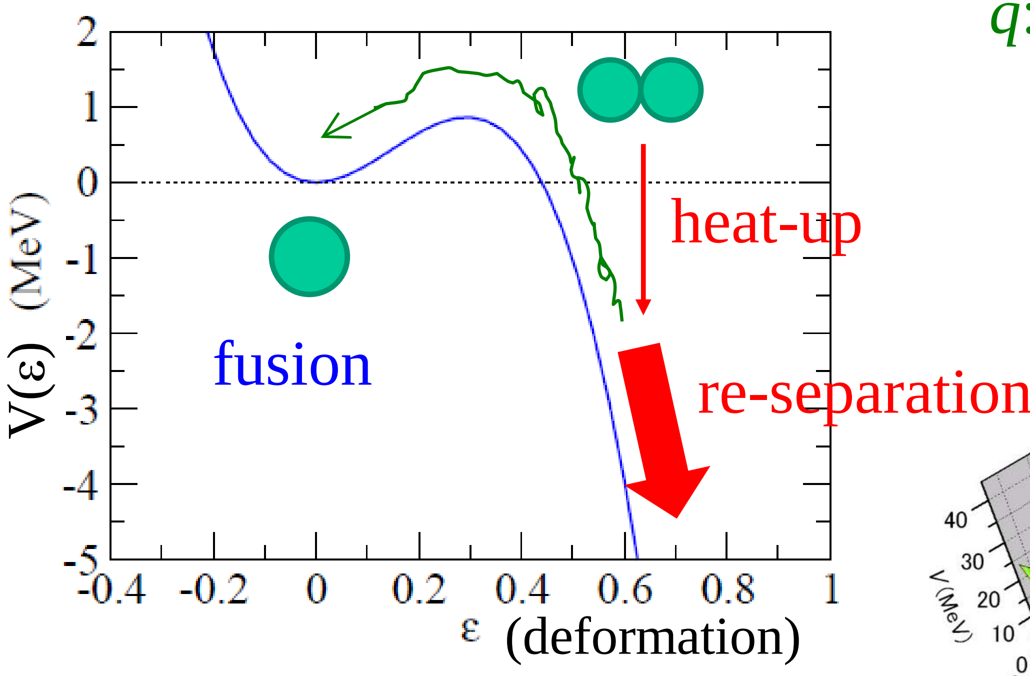
CN = compound nucleus
ER = evaporation residue

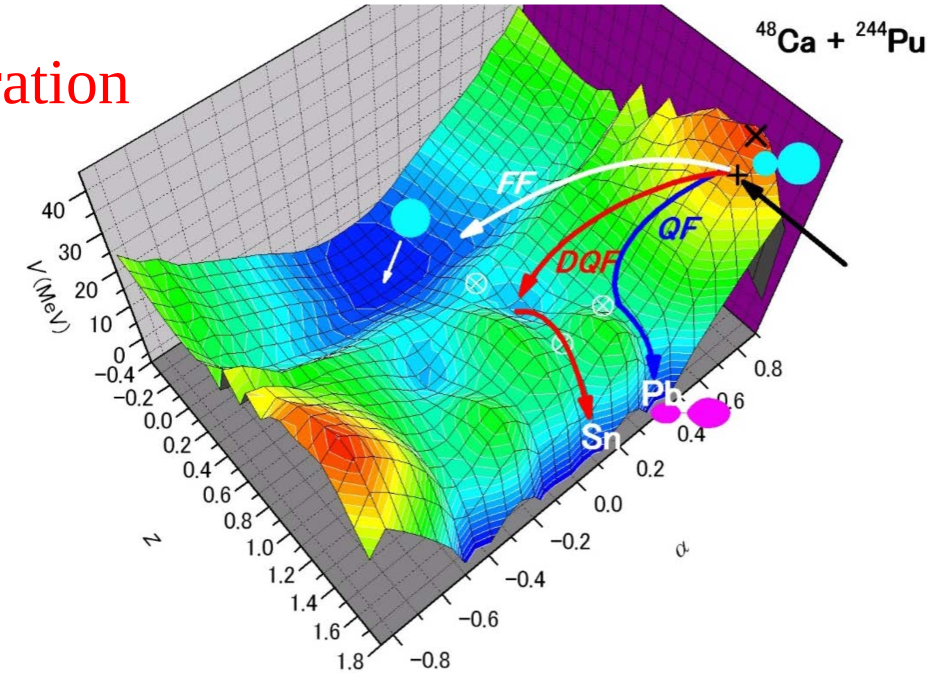
$$\sigma_{\mathrm{ER}}(E) = \frac{\pi}{k^2}\sum_l (2l+1) T_l(E)\, P_{\mathrm{CN}}(E,l)\, W_{\mathrm{suv}}(E^*,l)$$

Langevin approach

multi-dimensional extention

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





thermal fluctuation

⟶ Langevin method
(Brownian method)

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

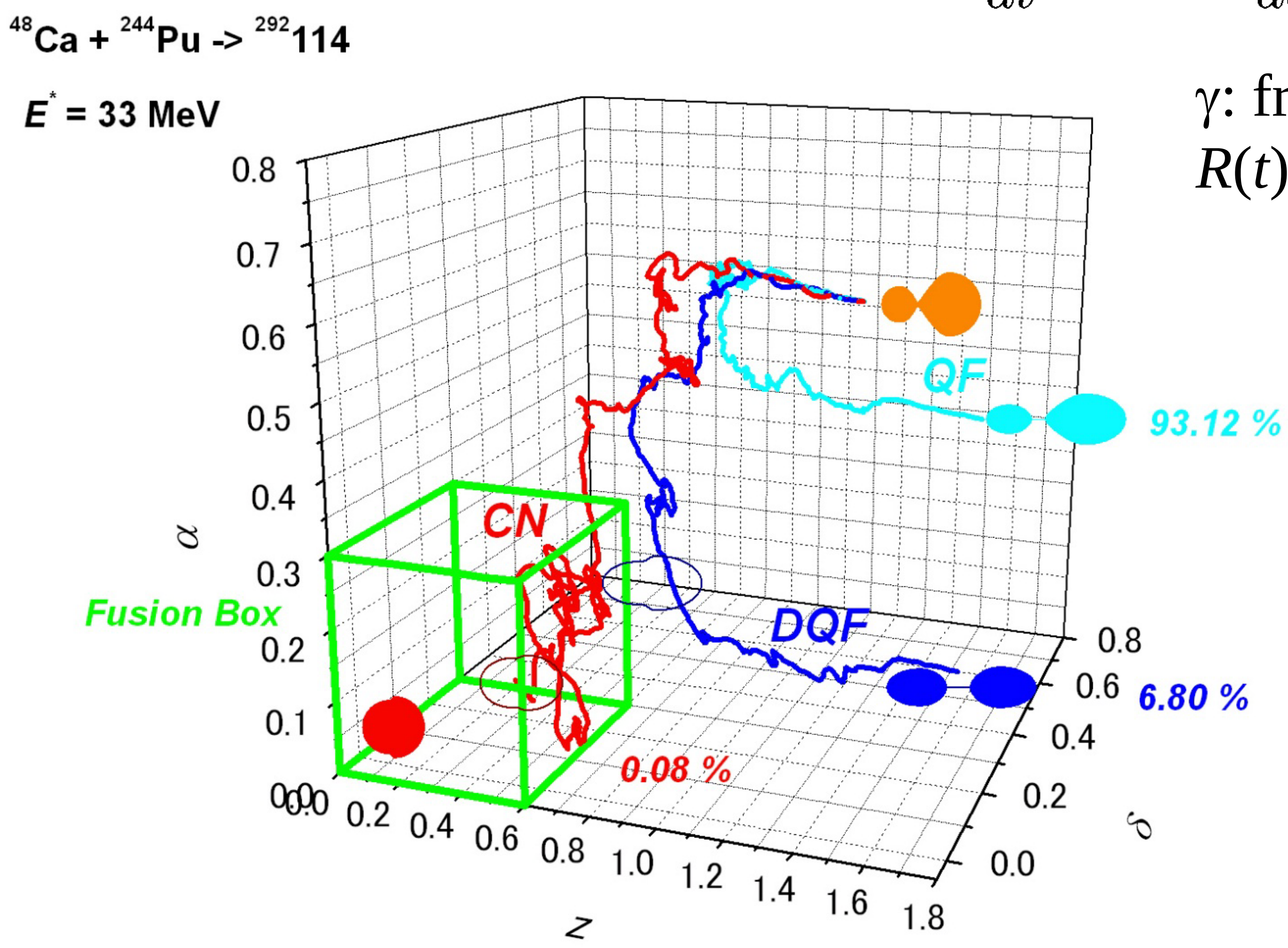
γ: friction coefficient
R(*t*): random force

Theory: Lagenvin approach

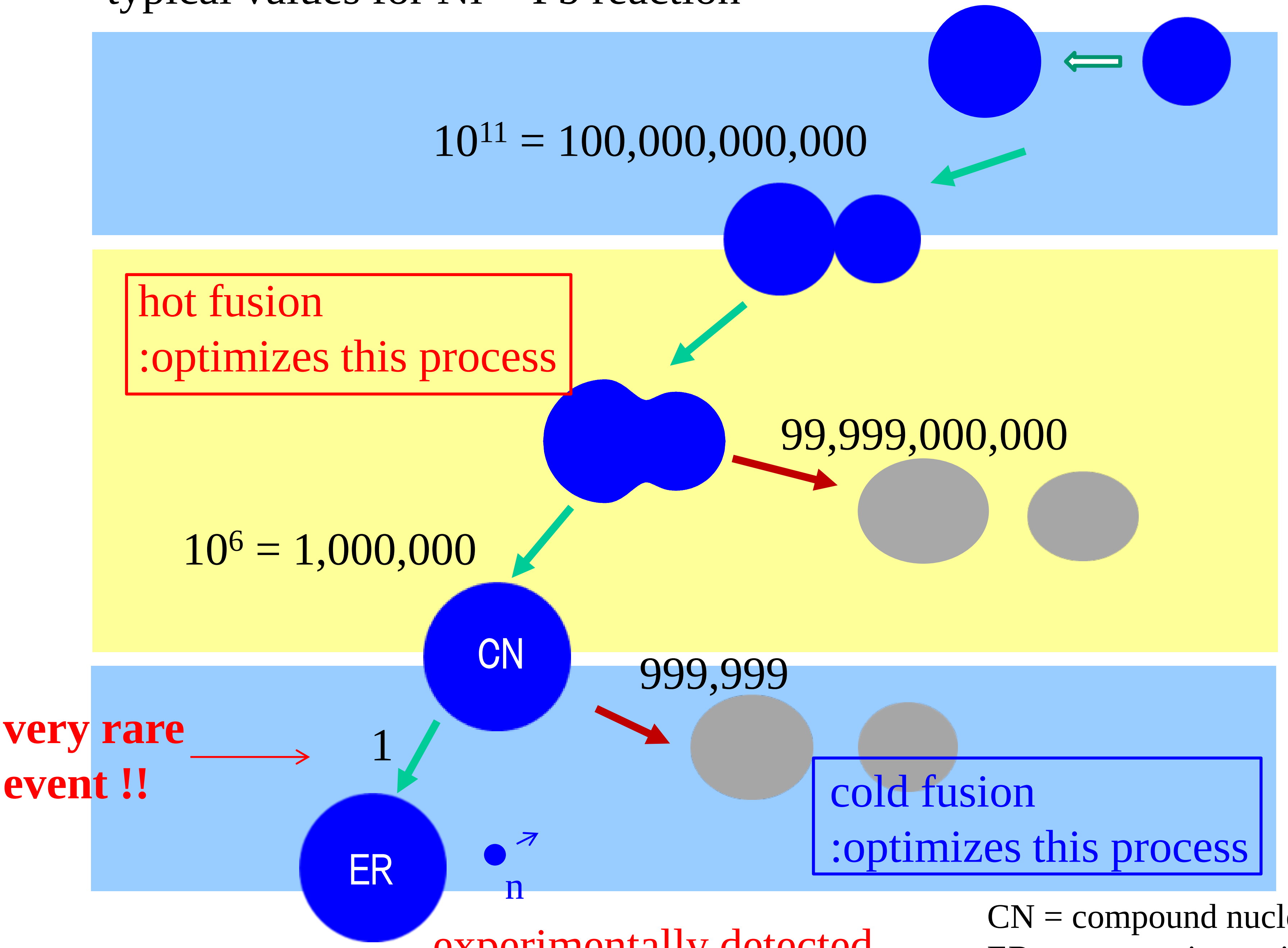
multi-dimensional extension of:

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

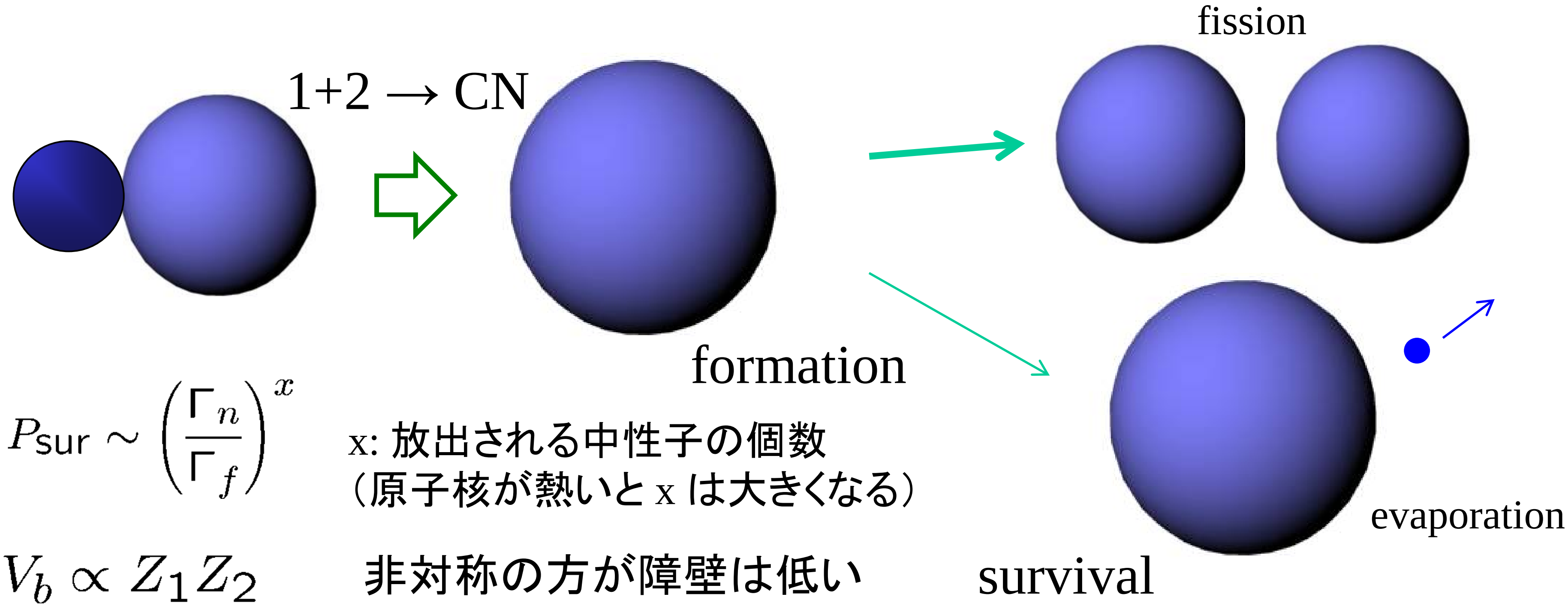
γ: friction coefficient
$R(t)$: random force



typical values for Ni + Pb reaction



CN = compound nucleus
ER = evaporation residue



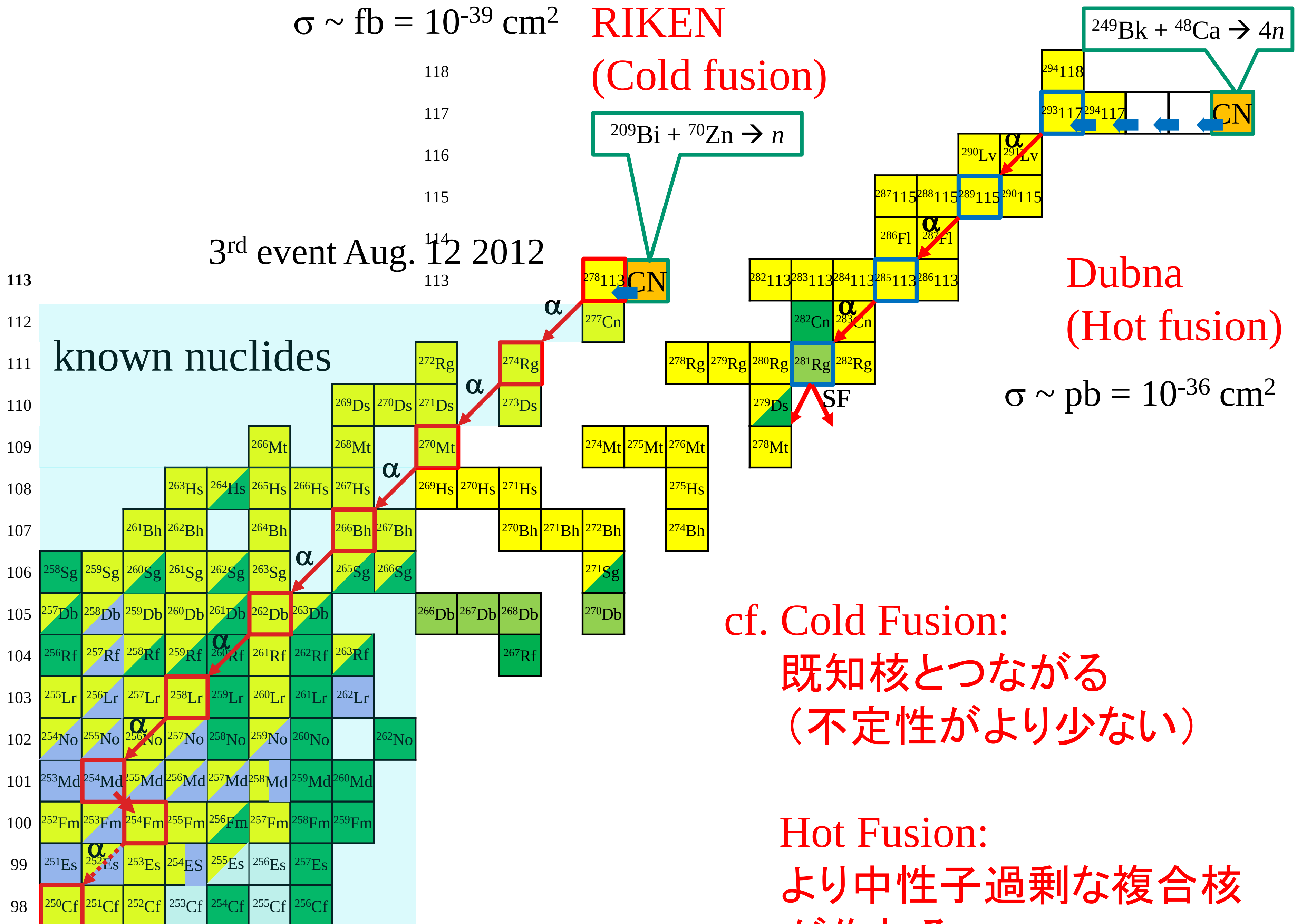
$$P_{\rm sur} \sim \left(\frac{\Gamma_n}{\Gamma_f}\right)^x$$

x: 放出される中性子の個数
（原子核が熱いと x は大きくなる）

$$V_b \propto Z_1 Z_2$$

非対称の方が障壁は低い

	Hot Fusion	**Cold Fusion**
Example	^{48}Ca + ^{243}Am → ^{187}Nh + 4n	^{70}Zn+^{209}Bi → ^{278}Nh + 1n
asymmetry	large	small
Capture	large	small
Survival	small	large



cf. Cold Fusion:

既知核とつながる

（不定性がより少ない）

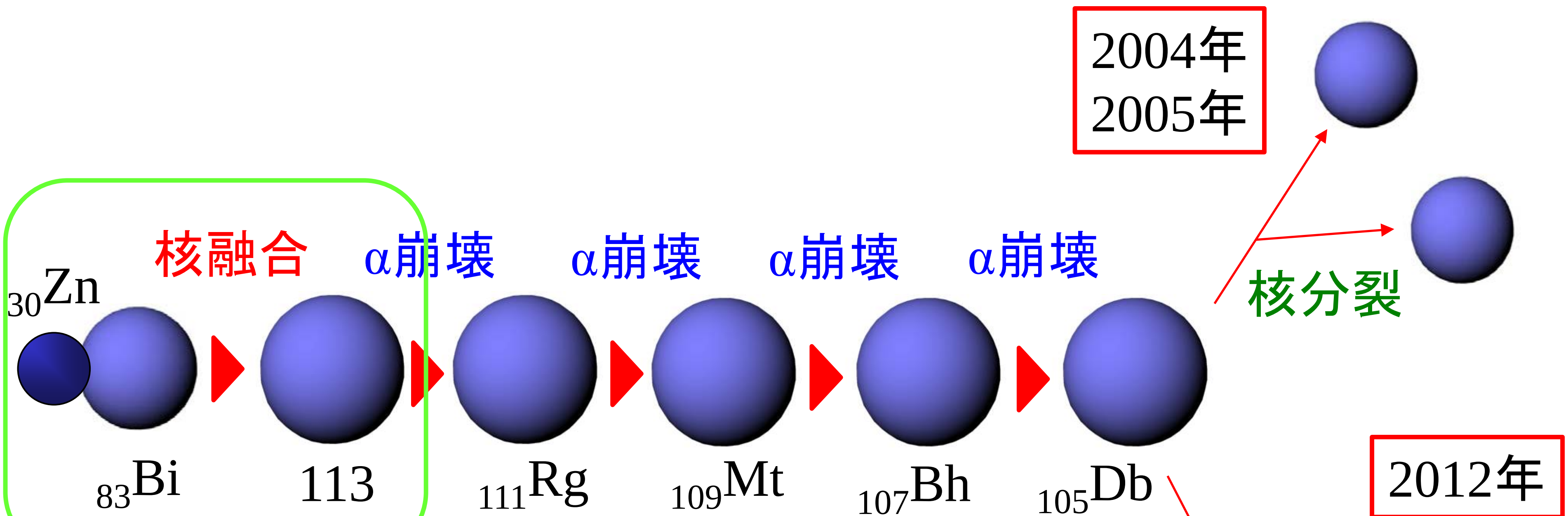
Hot Fusion:

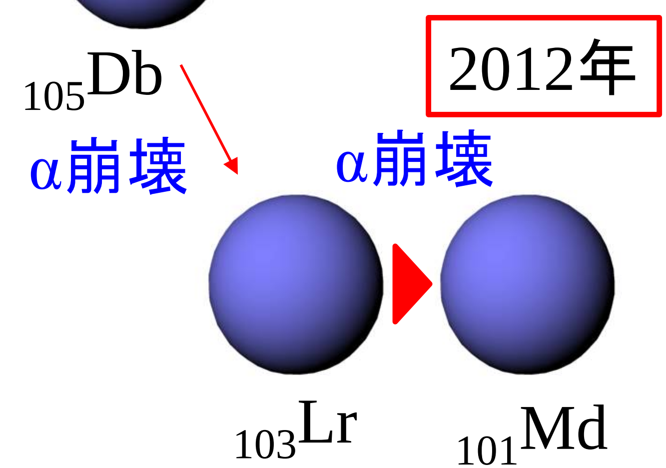
より中性子過剰な複合核

が作れる。

新元素113番　ニホニウム(Nh)

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





553 日間の実験で
たったの3例の発見

→ 日本に命名権
ニホニウム　Nh

Campus Map
東北大学 大学院 理学研究科・理学部
青葉山北キャンパスマップ
Graduate School of Science and Faculty of Science, Tohoku University
H-41
H-26
H-25
H-23
H-24
H-21
H-22
H-17
H-18
H-14
H-15
H-12
H-16
H-13
H-02
H-05
H-03
H-01
H-04
H-11
H-32
H-33
H-31
I-01
I-02
I-03
I-04
中央広場
Central Plaza
北青葉山憩い公園
Kita-Aobayama Park
薬学研究科
Graduate School of Pharmaceutical Science
サイクロトロン・ラジオアイソトープセンター
Cyclotron and Radioisotope Center
入口
北1出入口
至宮城教育大学
至工学部
至川内キャンパス
コンビニ
Convenience Store
車いす対応トイレ
Disabled Toilet
購買
University Shop
公衆電話
Public Phone
食堂・喫茶
Dining / Cafeteria
一方通行
One-way
タクシー乗り場
Taxi Stand

幻の元素、ニッポニウム（Np）

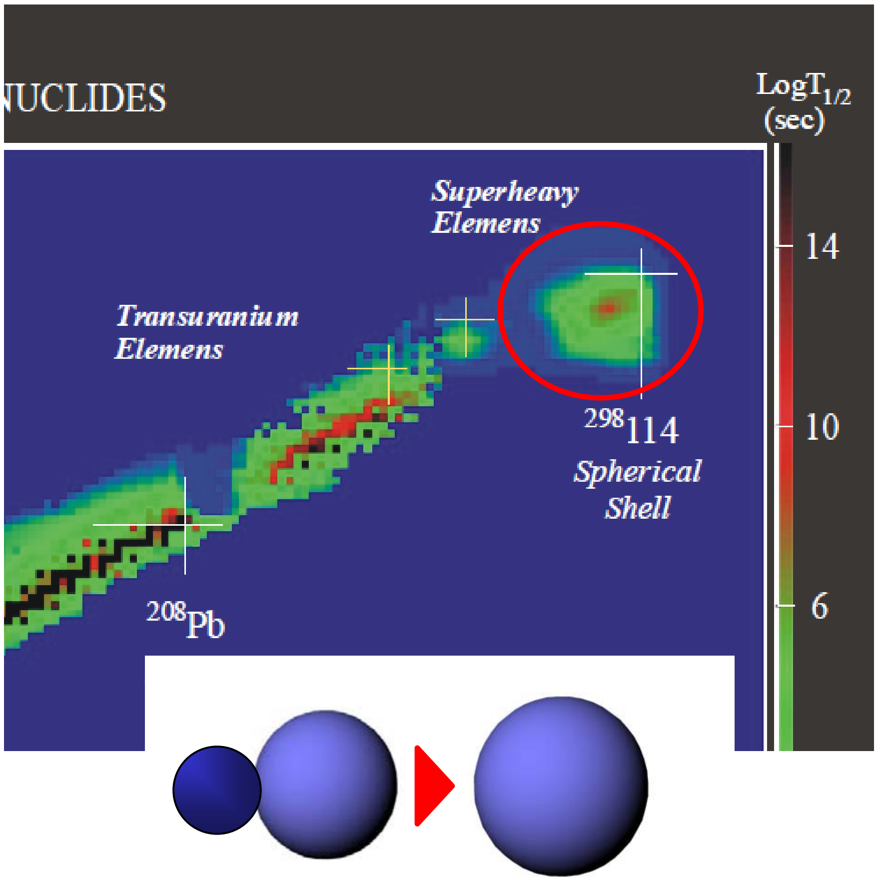
1908 年:「43番目の元素」として新元素を発見し
ニッポニウム（Np）と命名したと発表。
⟶ その後疑問視され、周期表からは落とされる
（実は75番元素レニウム（当時未発見）だった）

小川正孝
(1865－1930)

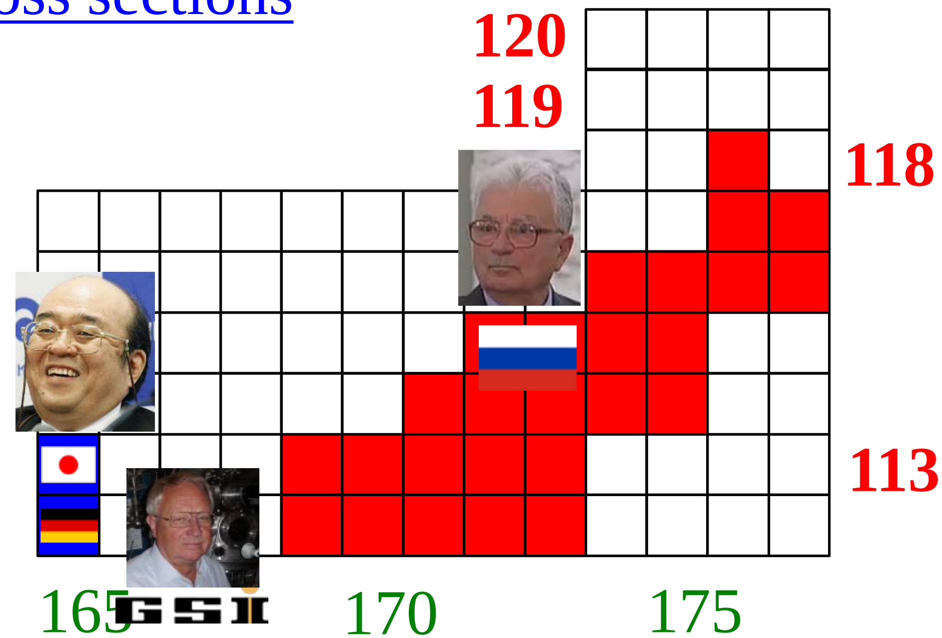
東北大学第4代総長
（1919－1928）

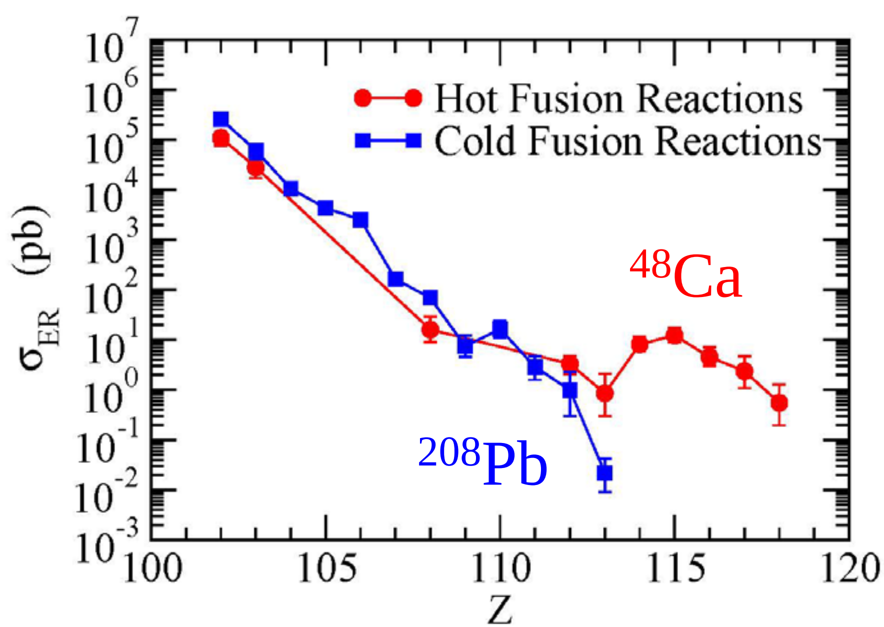
ニホニウム Nh は
この時以来の悲願
達成！

hot/cold fusion: a comparison of cross sections



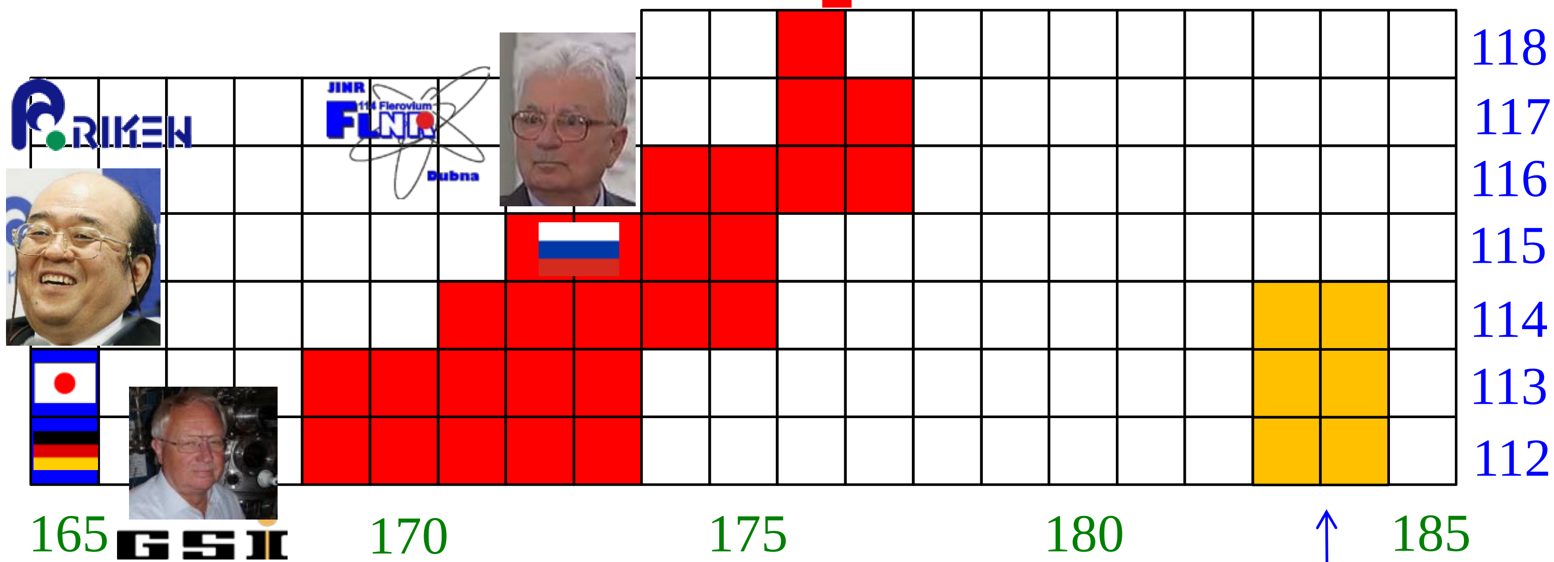
fusion reaction



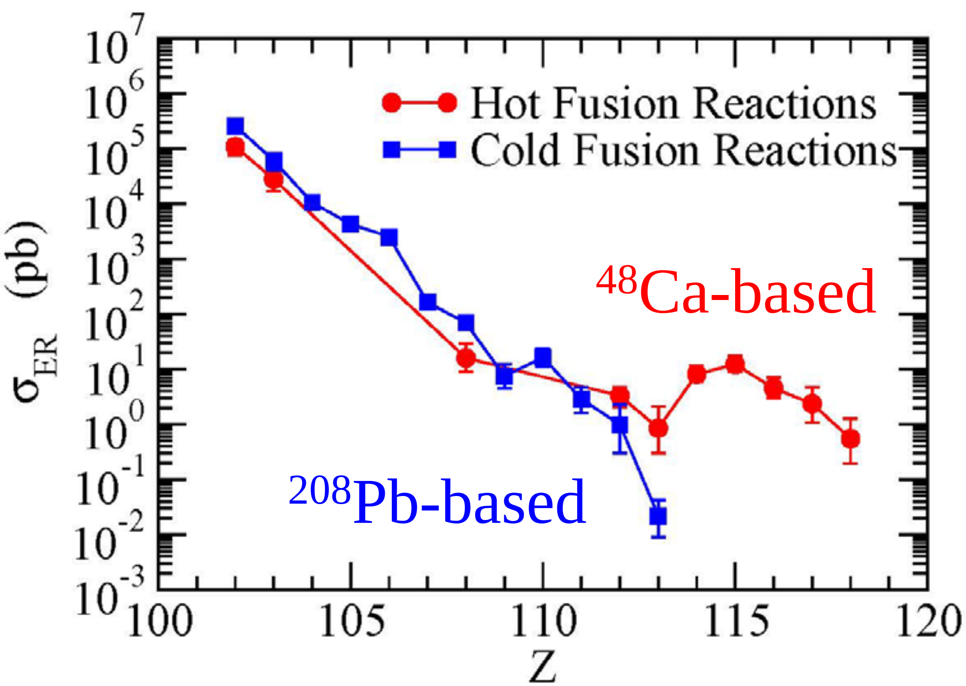


Hot fusion reactions: ^{48}Ca+actinides

Z = 119 and 120



the island of stability?



Hot fusion for Z = 119 and 120

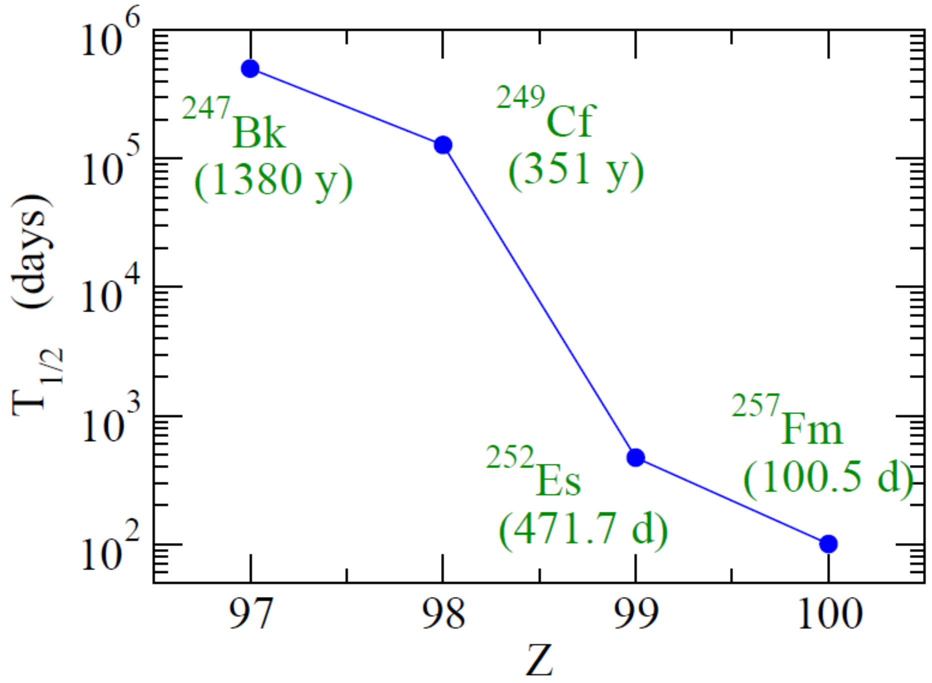
Towards Z=119 and 120 nuclei

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

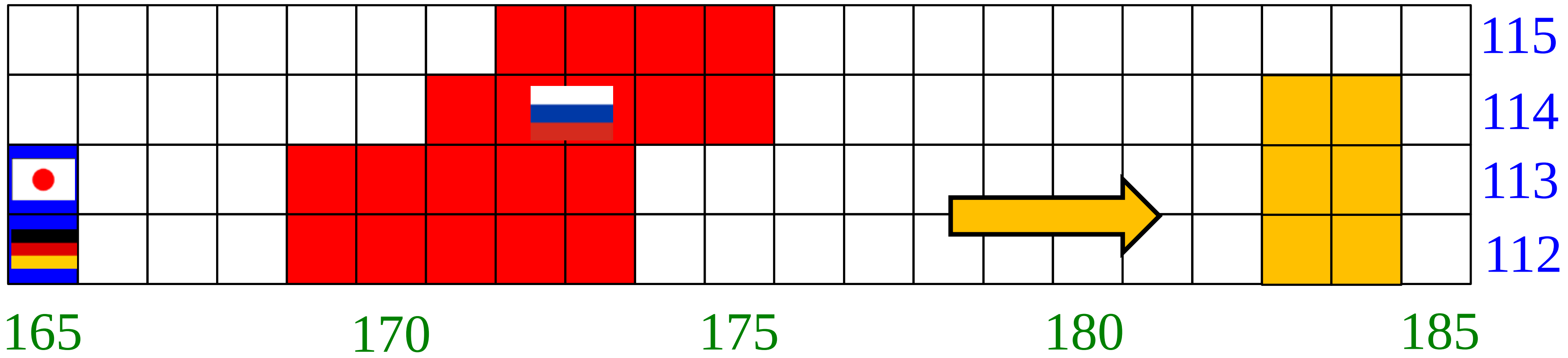


$^{48}Ca \rightarrow {}^{50}_{22}Ti,\ {}^{51}_{23}V,\ {}^{54}_{24}Cr$ projectiles

closed shell → open shells

how much will cross sections be affected?

Towards the island of stability



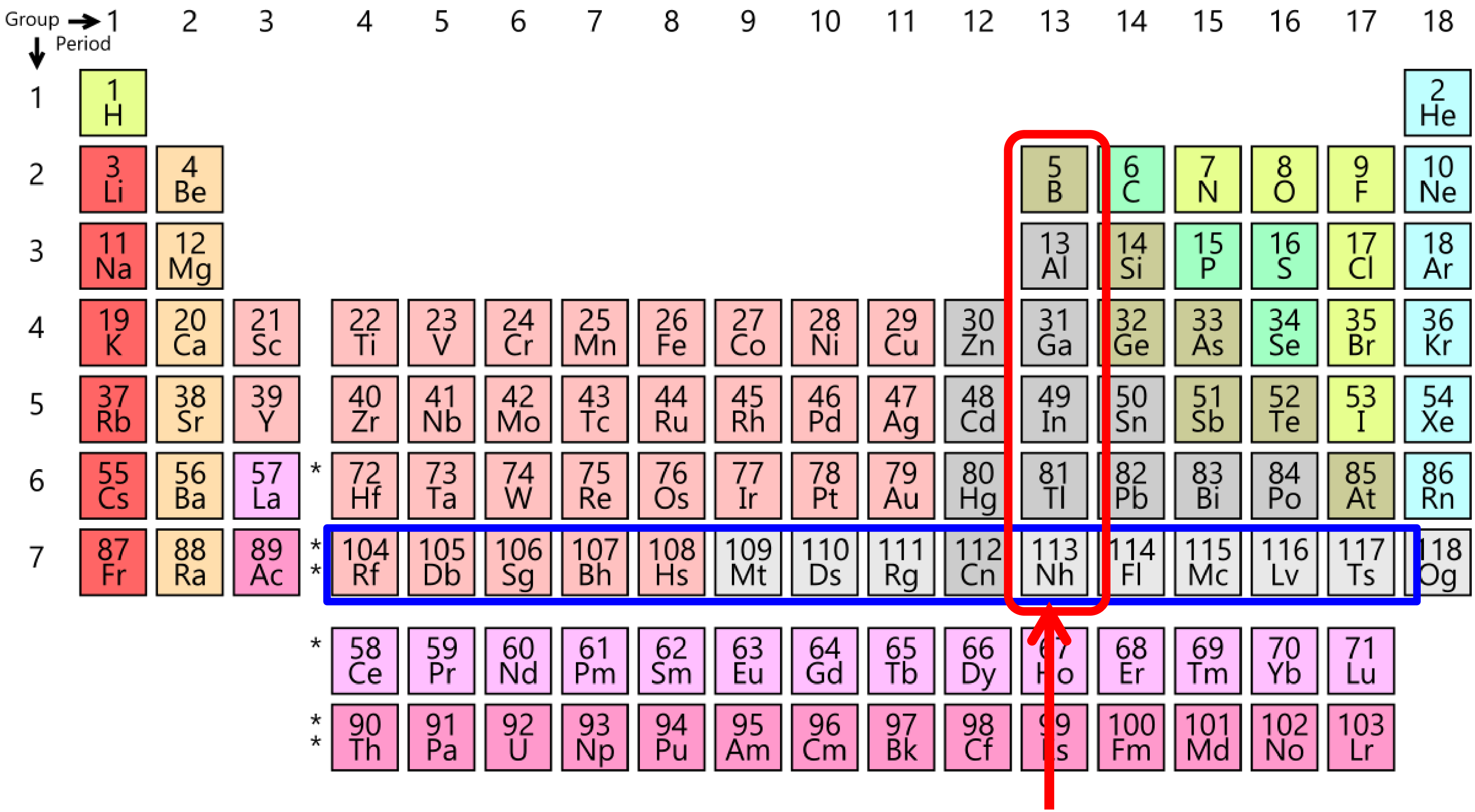
neutron-rich beams: indispensable

- ➢ 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

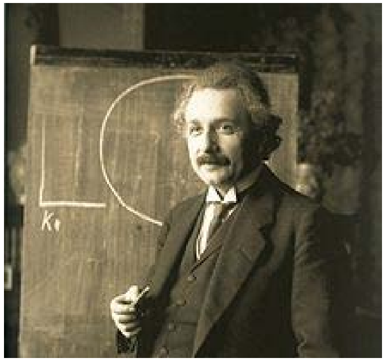
Chemistry of superheavy elements



- 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

$E = mc^2$

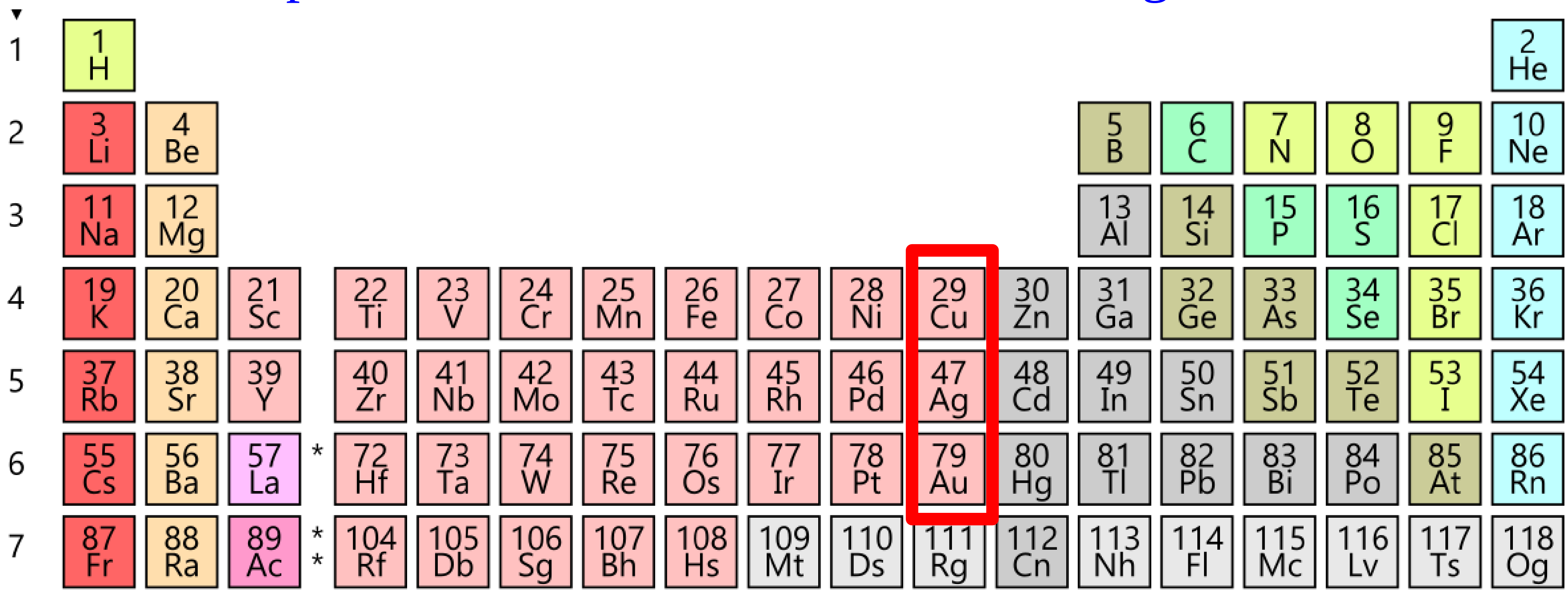


Solution of the Dirac equation (relativistic quantum mechanics) for a hydrogen-like atom:

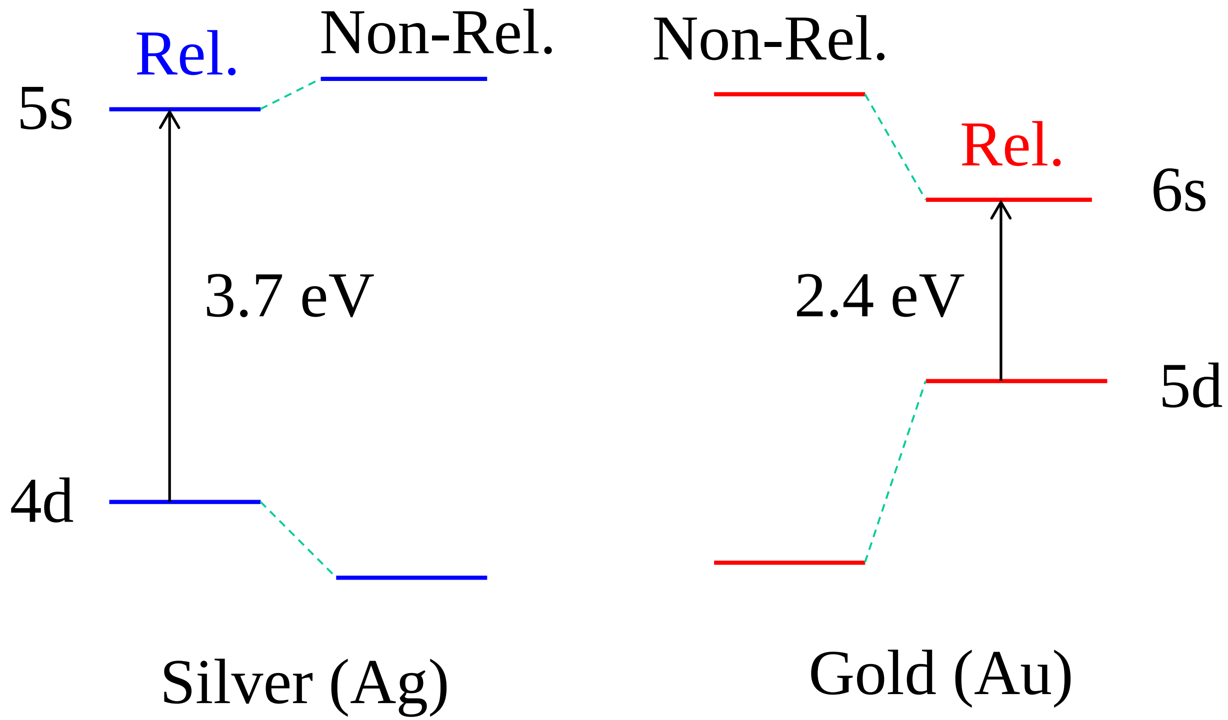
$$E_{1S} = mc^2\sqrt{1-(Z\alpha)^2} \sim mc^2\left(1 - \frac{(Z\alpha)^2}{2} \underbrace{- \frac{(Z\alpha)^4}{8} + \cdots}_{\text{relativistic effect}}\right)$$

relativistic effect

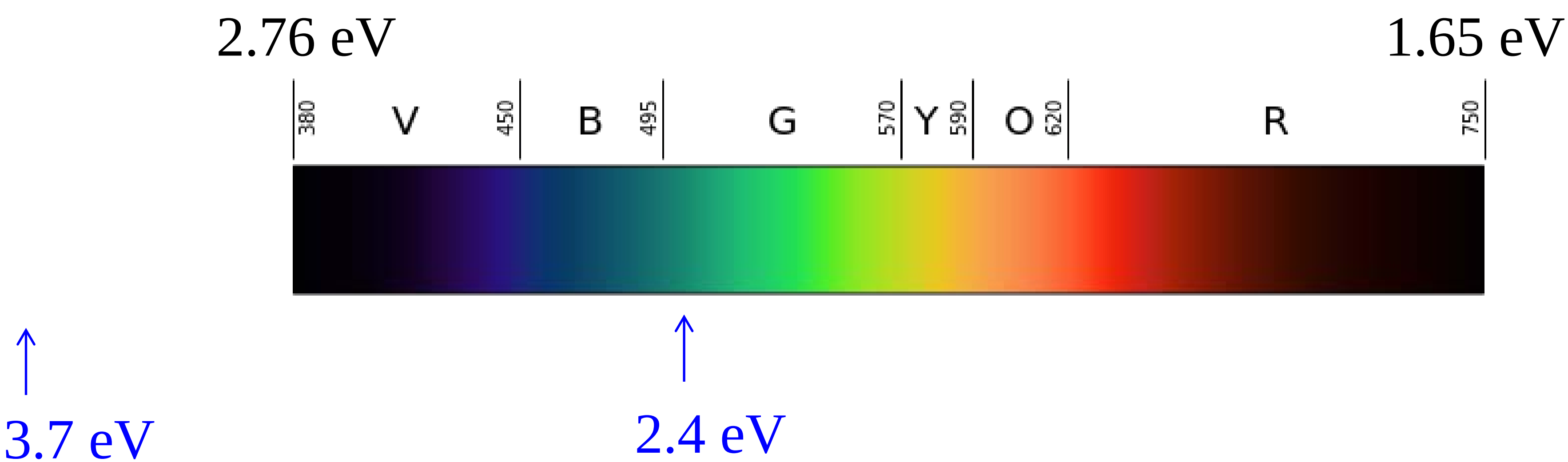
Famous example of relativistic effects: the color of gold

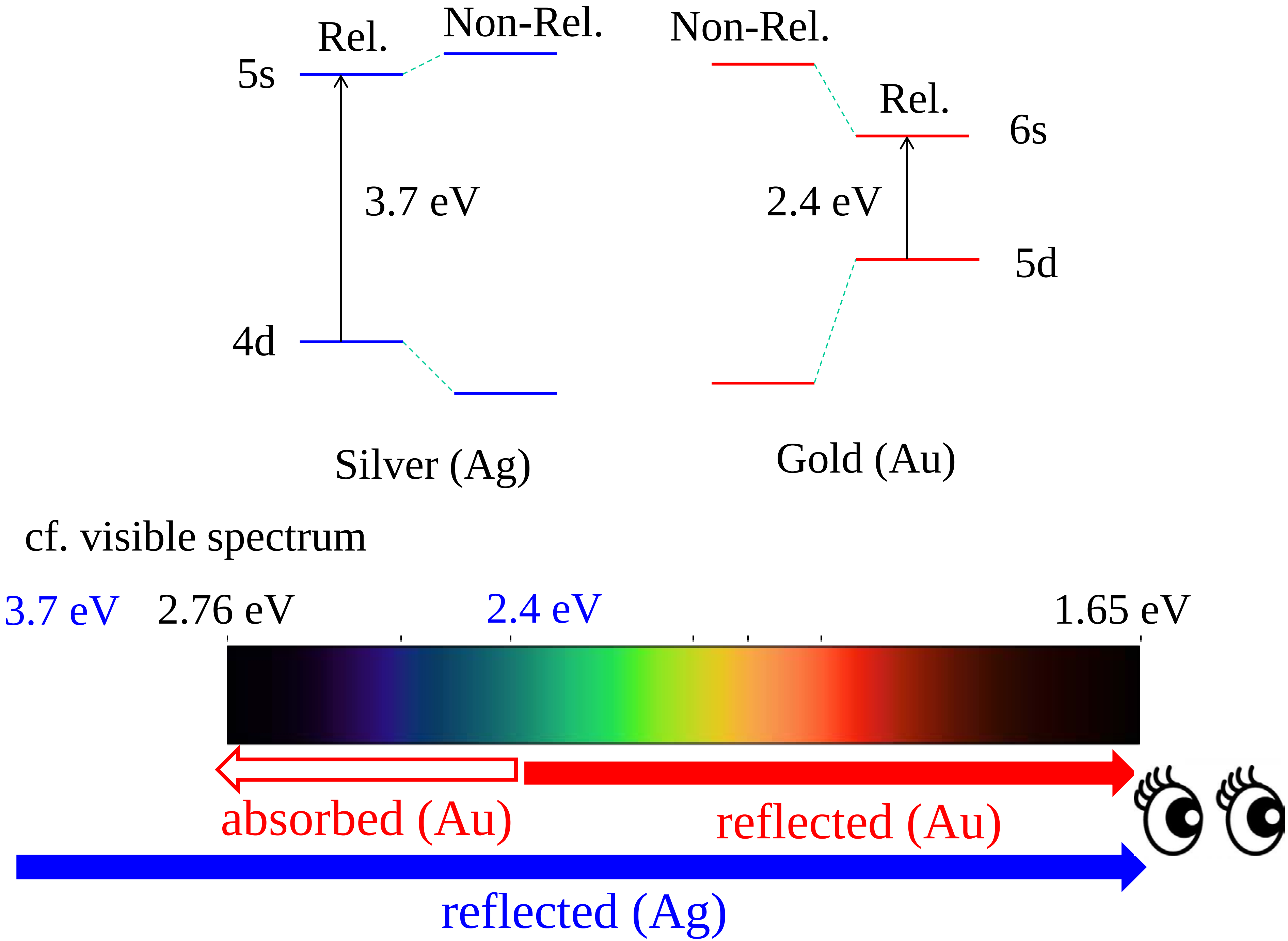


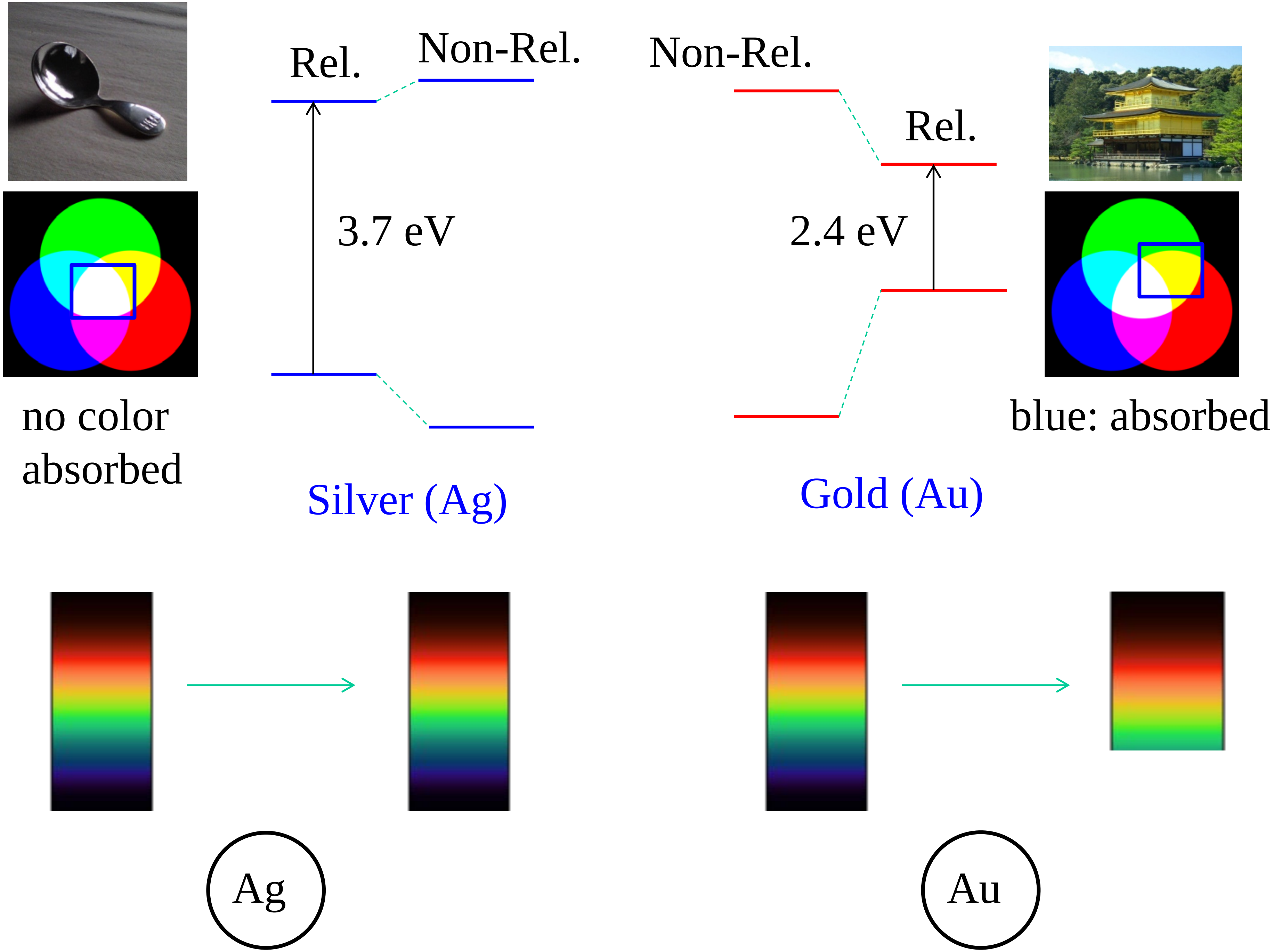
Gold looked like silver if there was no relativistic effects!



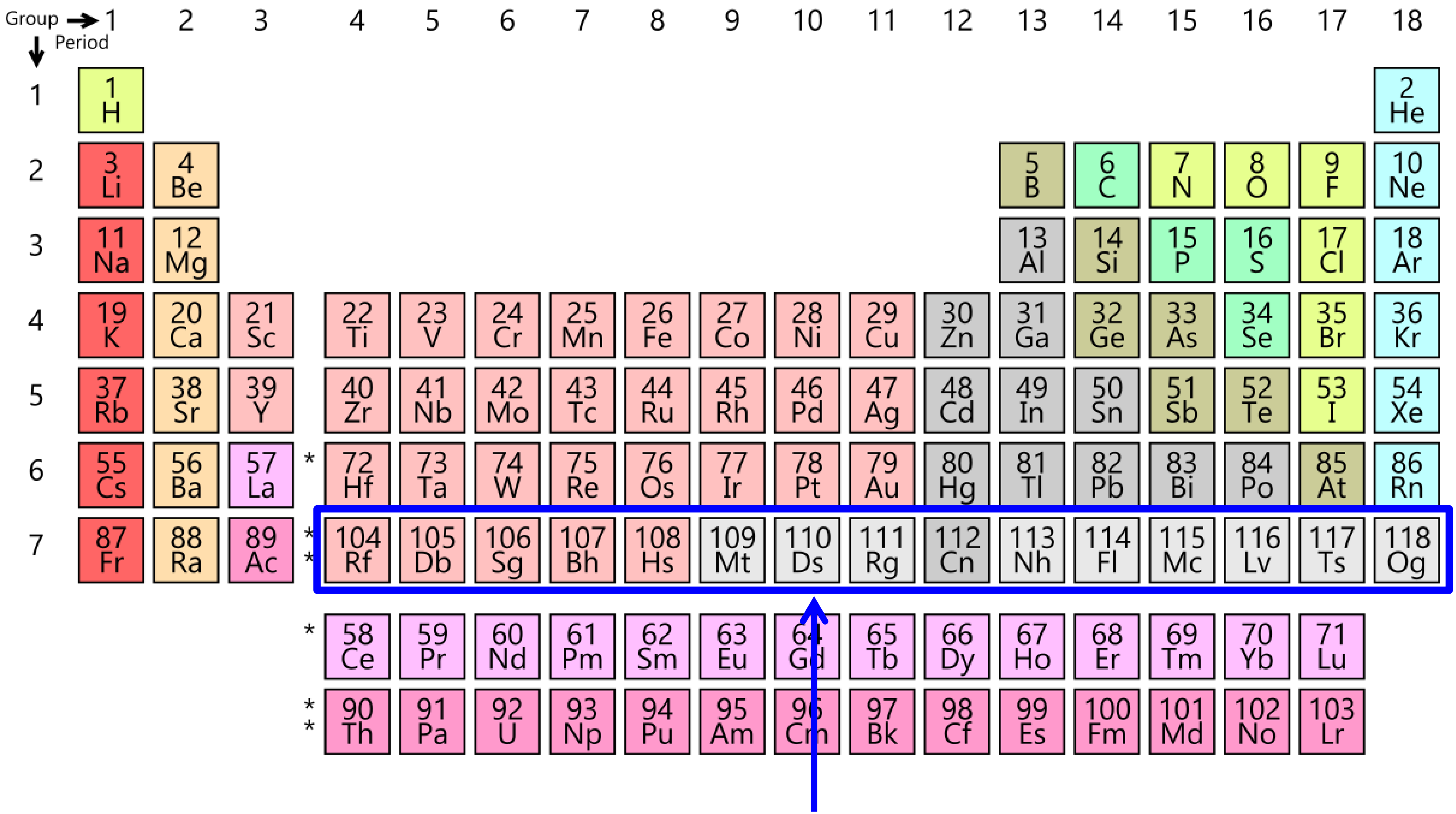
cf. visible spectrum




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



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

⟶ a big open question