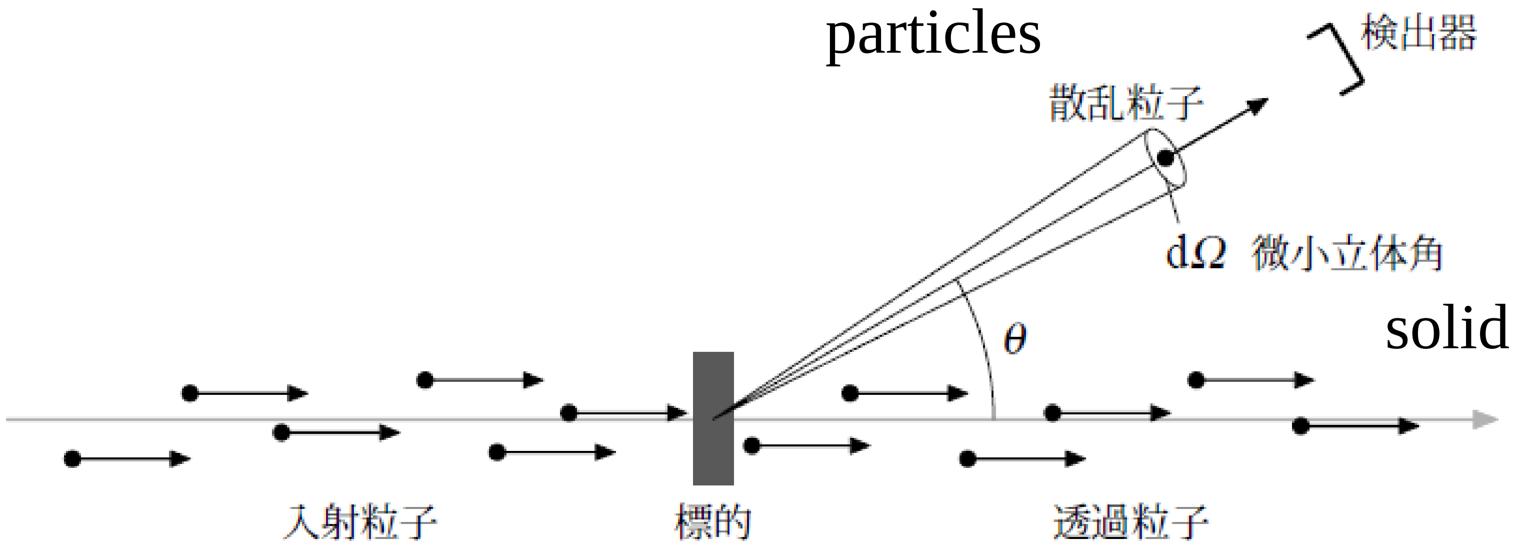
Nuclear Reactions

Shape, interaction, and excitation structures of nuclei $\longleftarrow$ scattering expt.

cf. Experiment by Rutherford (α scatt.)

scattered particles

detector



solid angle

projectile

target

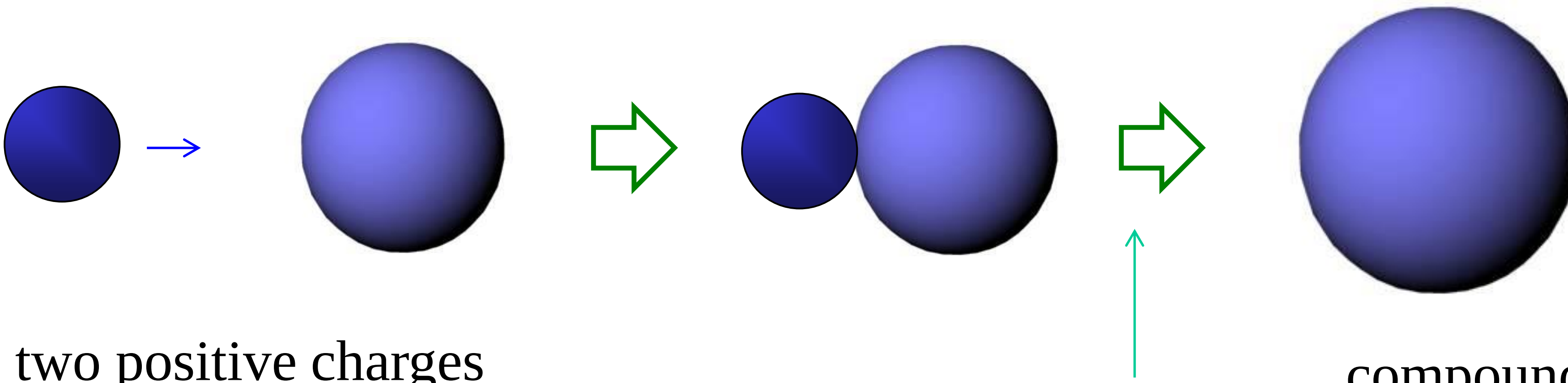
transmitted particles

図 21.1: 散乱実験

http://www.th.phys.titech.ac.jp/~muto/lectures/QMII11/QMII11_chap21.pdf

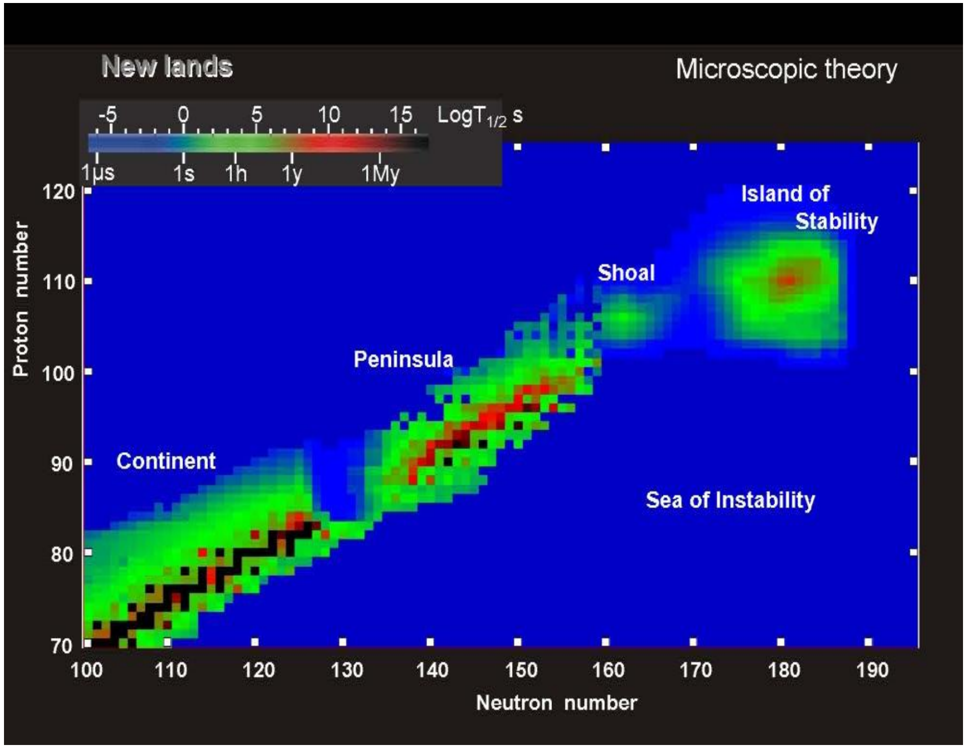
K. Muto (TIT)

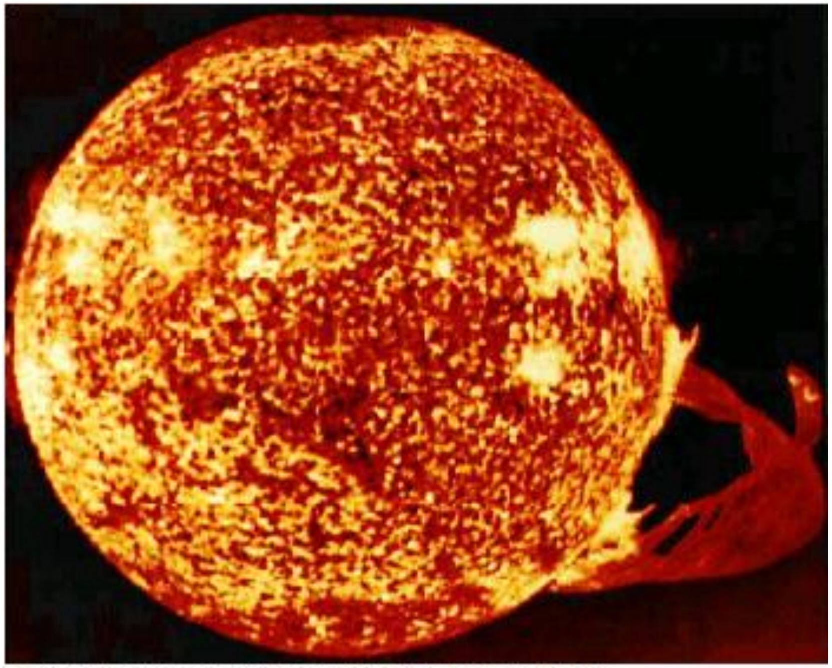
Nuclear fusion reactions



Why subbarrier fusion?

Two obvious reasons:





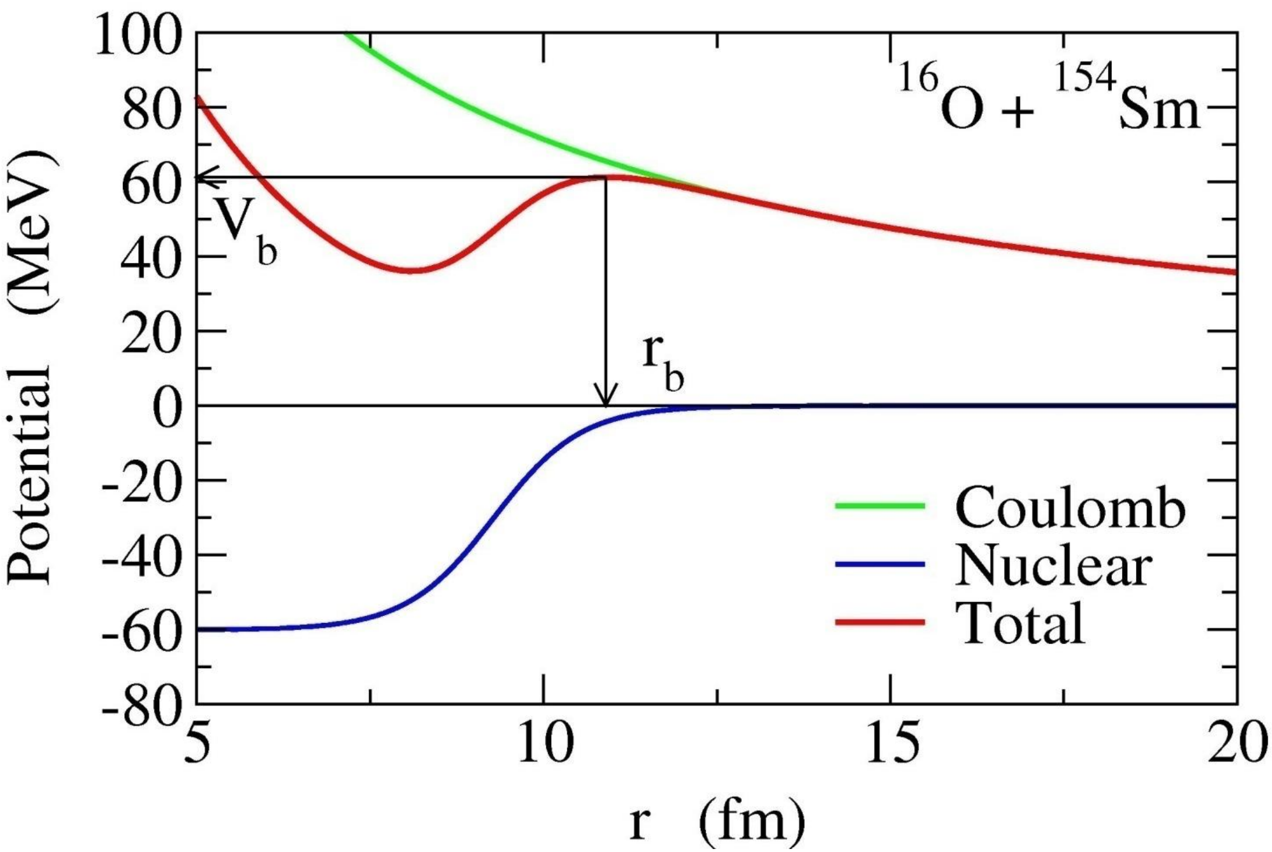
NASA, Skylab space station December 19. 1973, solar flare reaching 588 000 km off solar surface

discovering new elements
(SHE by cold fusion reactions)

nuclear astrophysics
(fusion in stars)

Heavy-ion subbarrier fusion reactions

Inter-nucleus potential



Two forces:

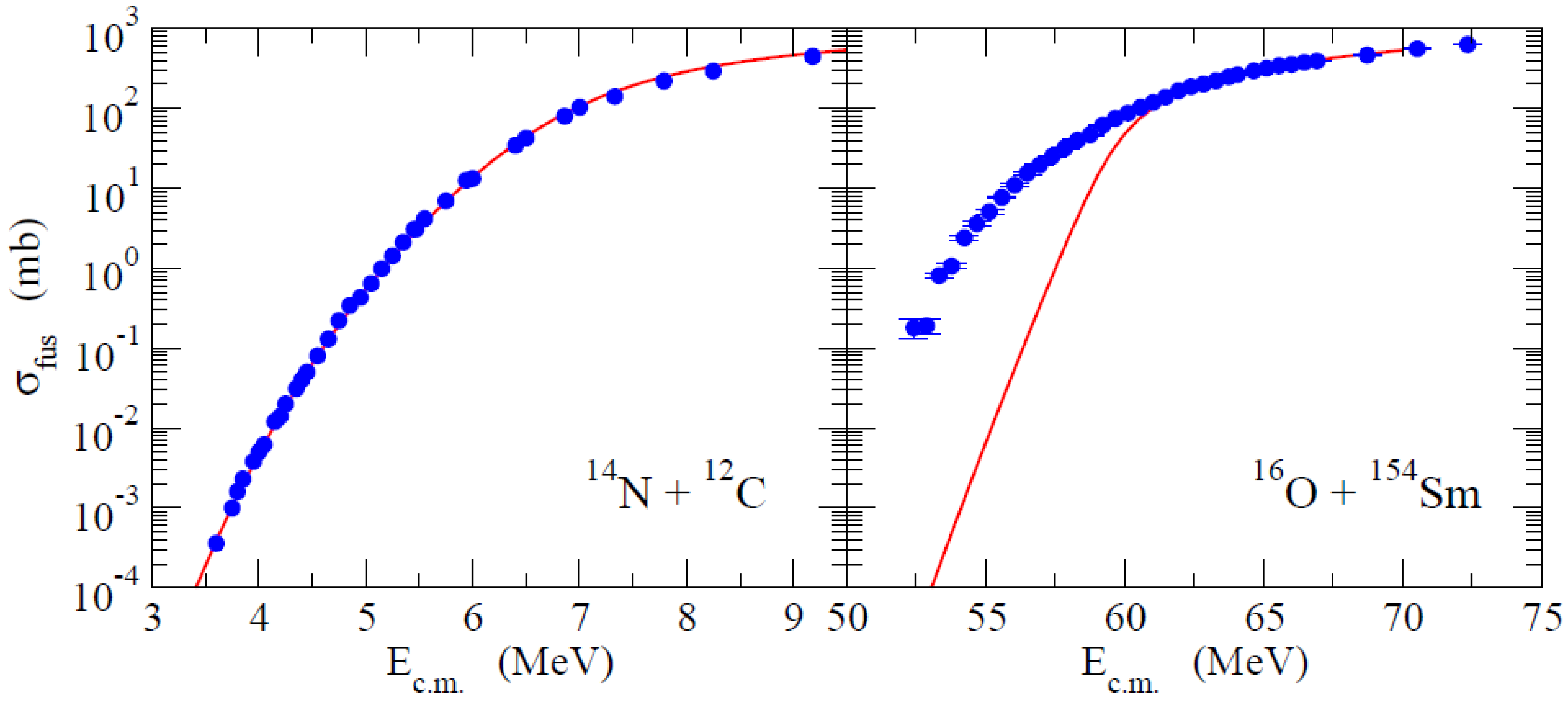
1. Coulomb force
   Long range, repulsive
2. Nuclear force
   Short range, attractive

Potential barrier due to the compensation between the two (Coulomb barrier)

- above barrier
- sub-barrier
- deep subbarrier

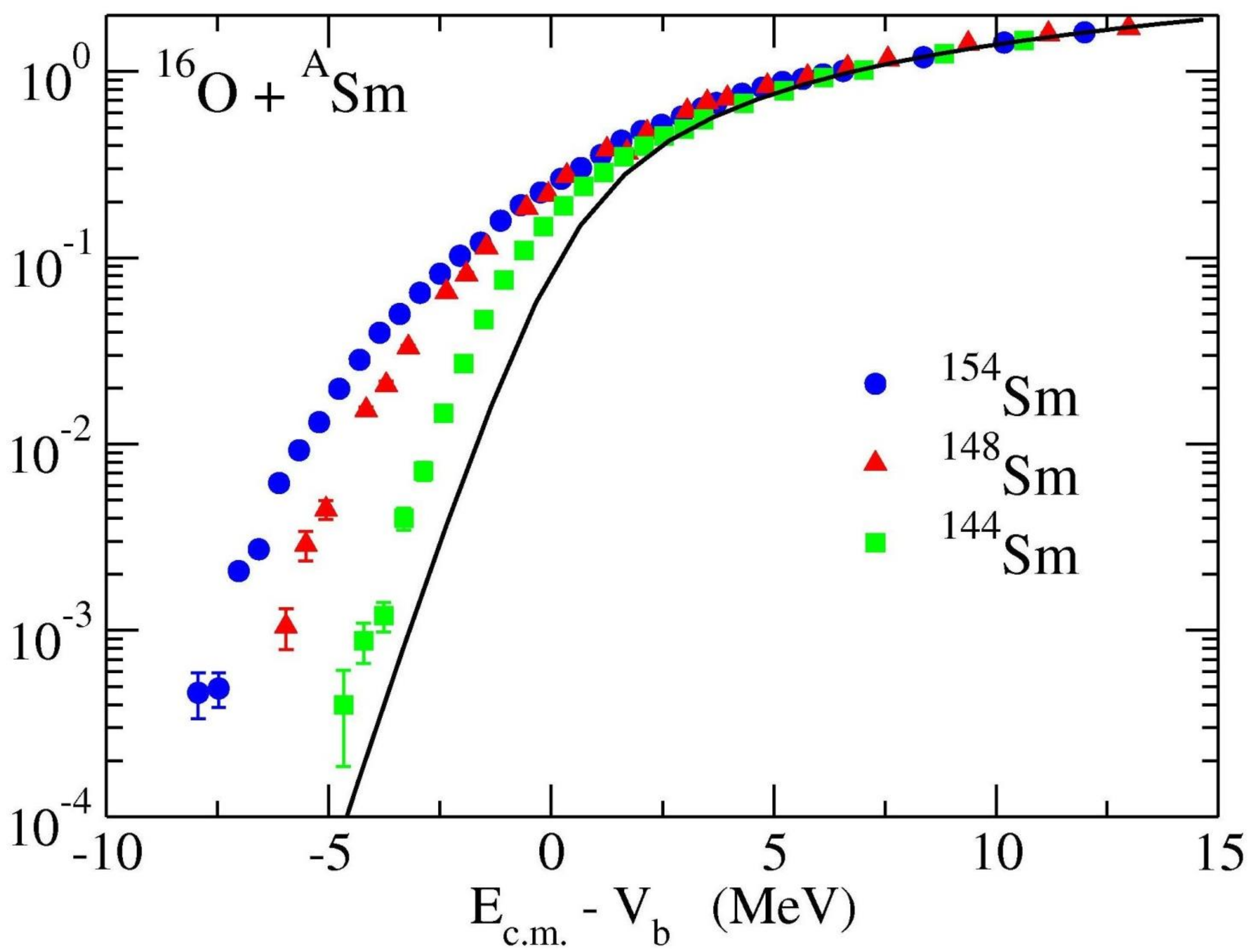
Fusion cross sections at subbarrier energies

Fusion cross sections of structure-less nuclei (a potential model)



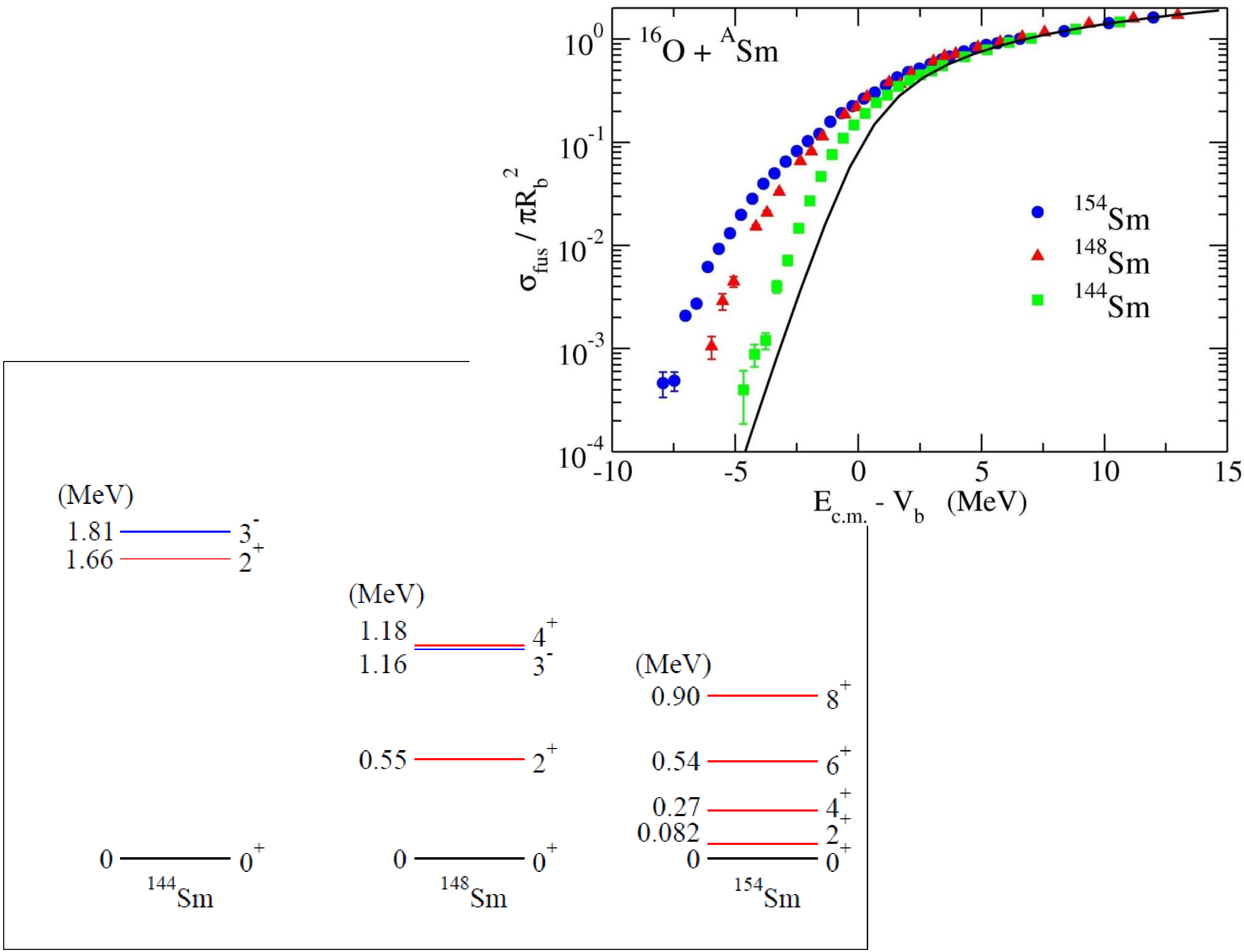
Simple potential model:

- OK for relatively light systems
- underestimates σ_{fus} for heavier systems at subbarrier energies



Strong target dependence at $E < V_b$

low-lying collective excitations?



$^{16}O + ^{A}Sm$
$\sigma_{fus} / \pi R_b^2$
$E_{c.m.} - V_b$ (MeV)
^{154}Sm
^{148}Sm
^{144}Sm
(MeV)
1.81 3-
1.66 2+
0 0+
^{144}Sm
(MeV)
1.18 4+
1.16 3-
0.55 2+
0 0+
^{148}Sm
(MeV)
0.90 8+
0.54 6+
0.27 4+
0.082 2+
0 0+
^{154}Sm

Effect of deformation on subbarrier fusion

Excitation spectra of ^{154}Sm

0.903 (MeV) —— 8^+

0.544 —— 6^+

0.267 —— 4^+

0.082 —— 2^+

0 —— 0^+

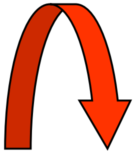
^{154}Sm

$$E_I \sim \frac{I(I+1)\hbar^2}{2\mathcal{J}}$$

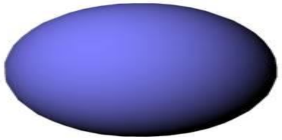
cf. Rotational energy of a rigid body
(Classical mechanics)

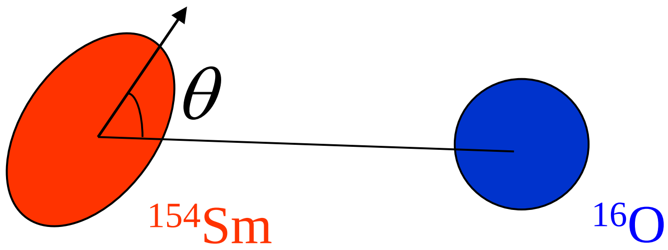
$$E = \frac{1}{2}\mathcal{J}\omega^2 = \frac{I^2}{2\mathcal{J}}$$

$$(I = \mathcal{J}\omega, \;\; \omega = \dot{\theta})$$

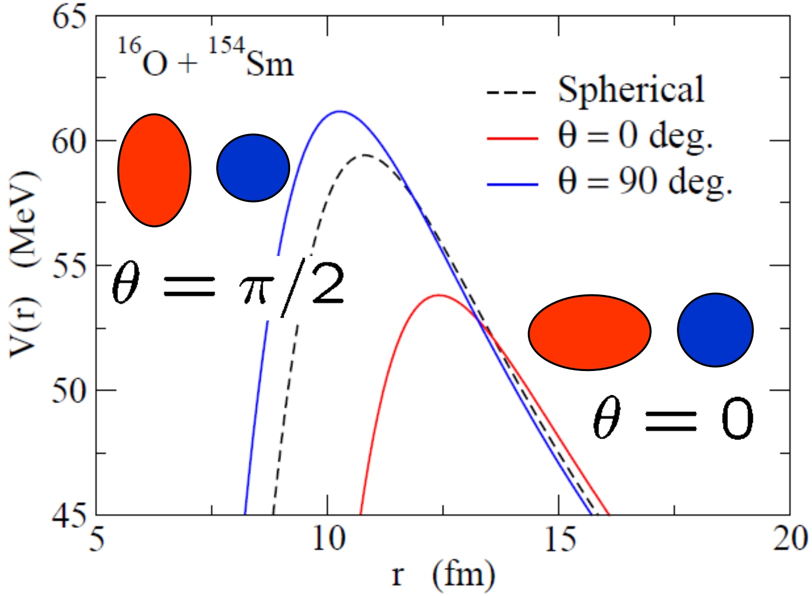


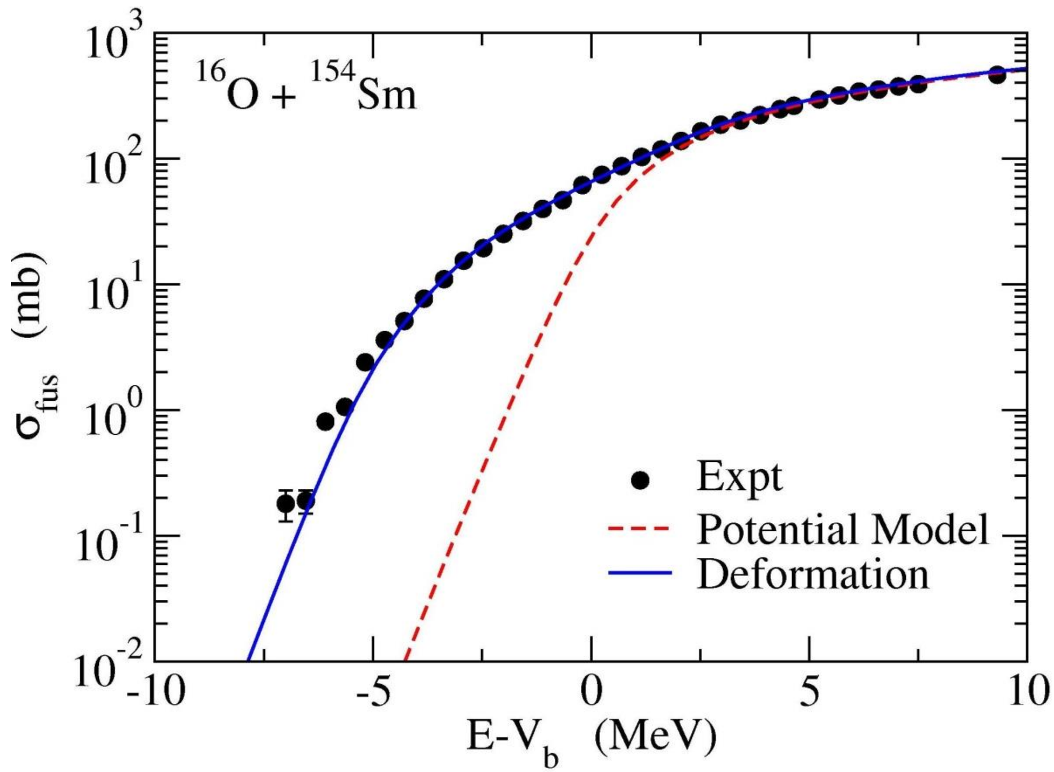
^{154}Sm is deformed





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





The barrier is lowered for θ=0
because an attraction works from large distances.

The barrier increases for θ=π/2.
because the rel. distance has
to get small for the attraction to work

Def. Effect: enhances σ_{fus} by a factor of 10 ~ 100

Fusion: interesting probe for nuclear structure

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		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

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
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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

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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?

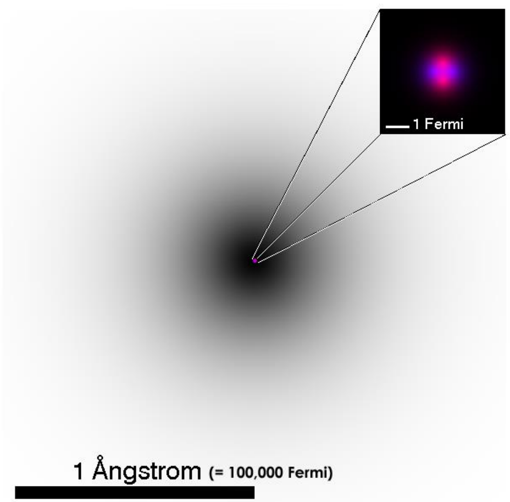
natural elements: **Pu** (Z=94) $\longrightarrow$ a tiny amount in nature
U (Z=92)

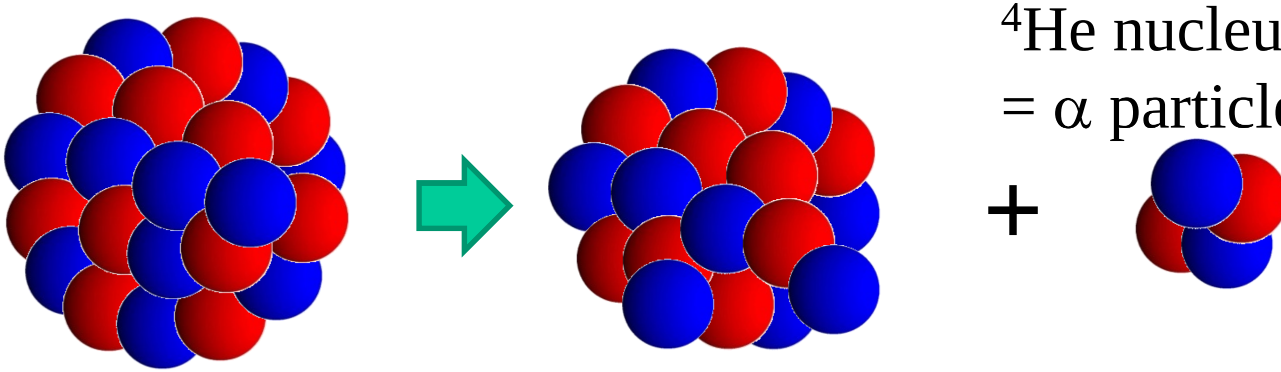
What determines these numbers??

heavy nuclei $\longrightarrow$ large Coulomb repulsion

$\downarrow$

unstable against α decay

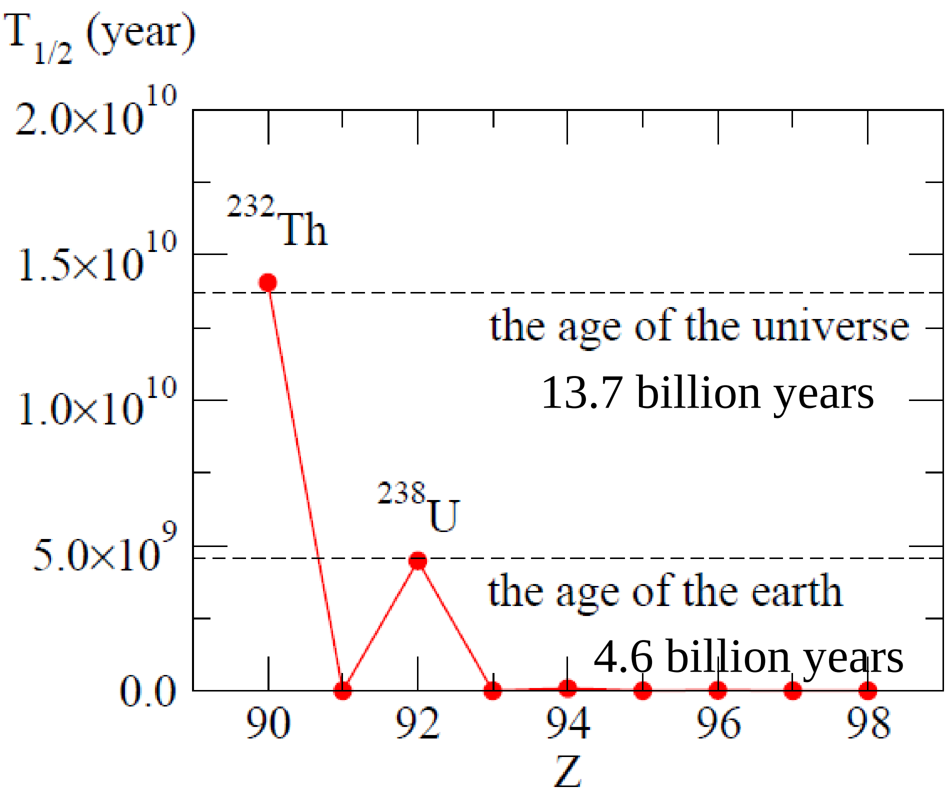


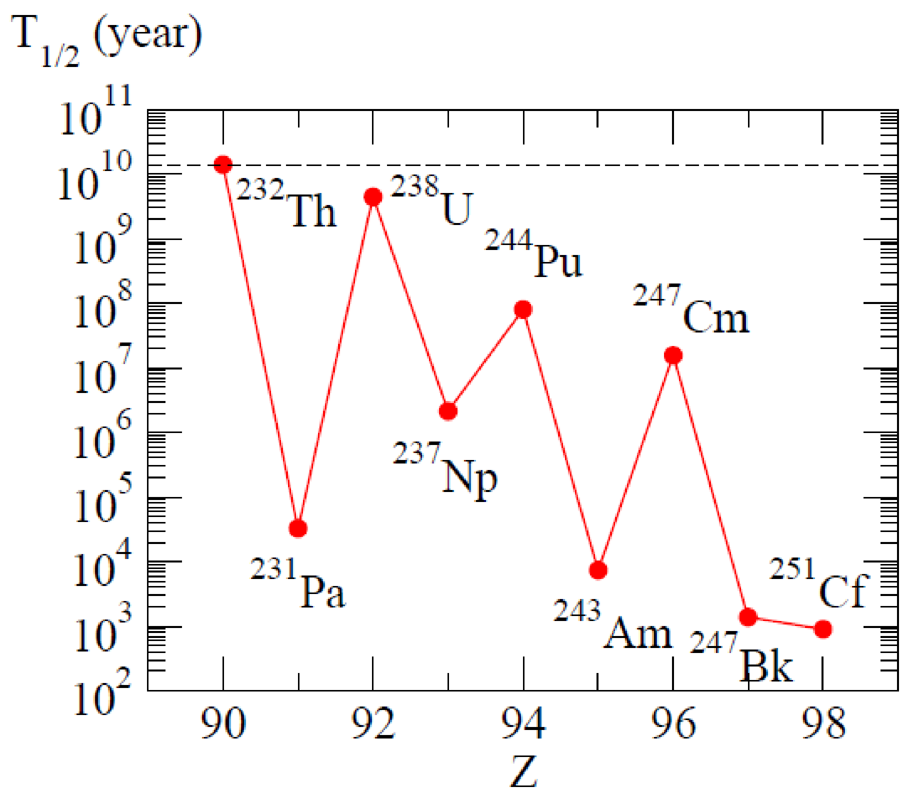


^{4}He nucleus
= α particle

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

Decay half-lives of heavy nuclei





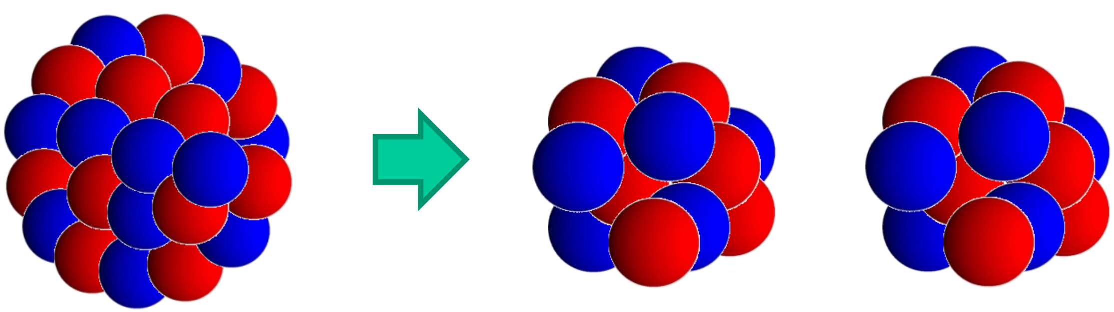
^{232}Th 1.405 x 10^{10} years

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

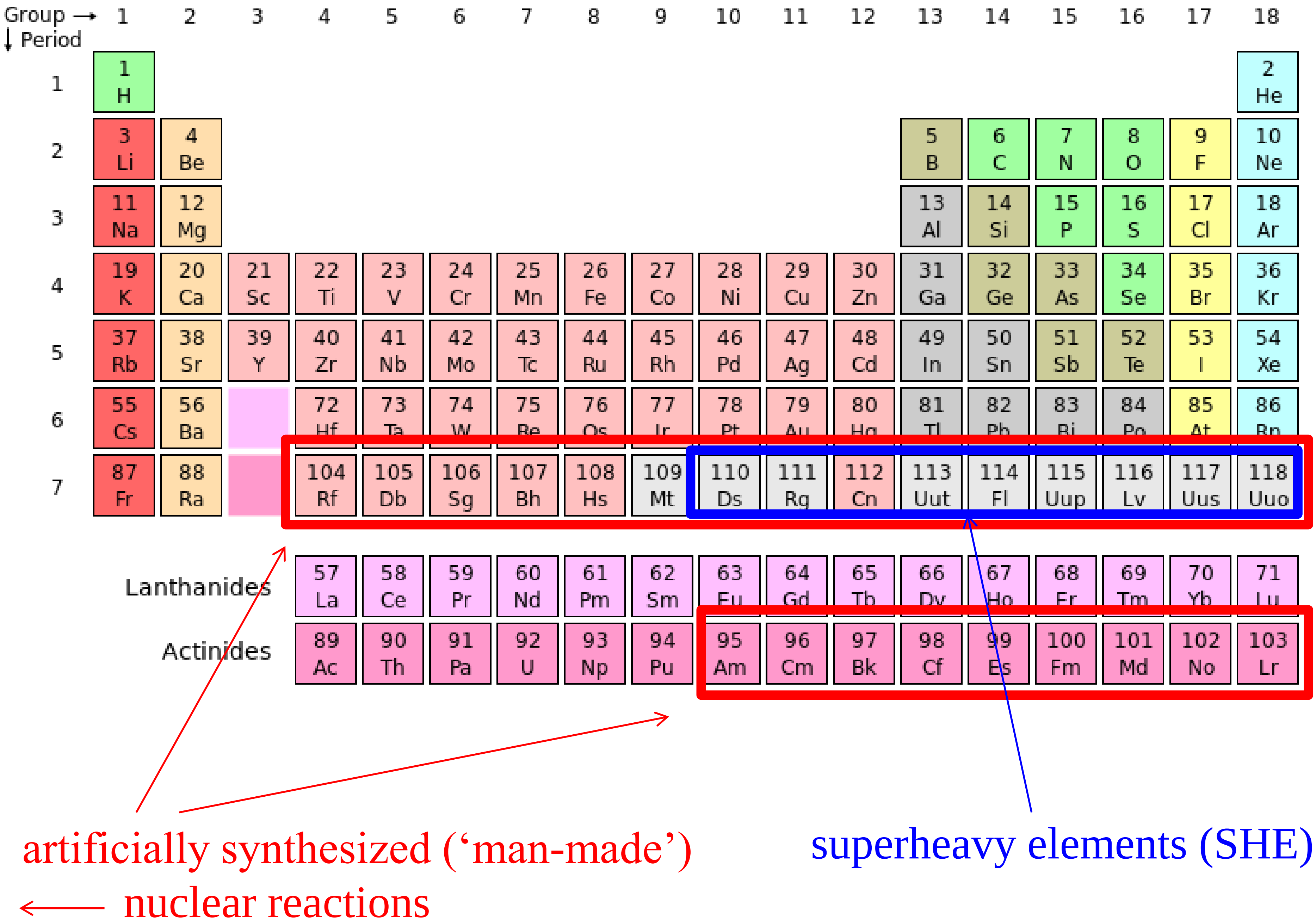
^{244}Pu 8.08 x 10^{7} years

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

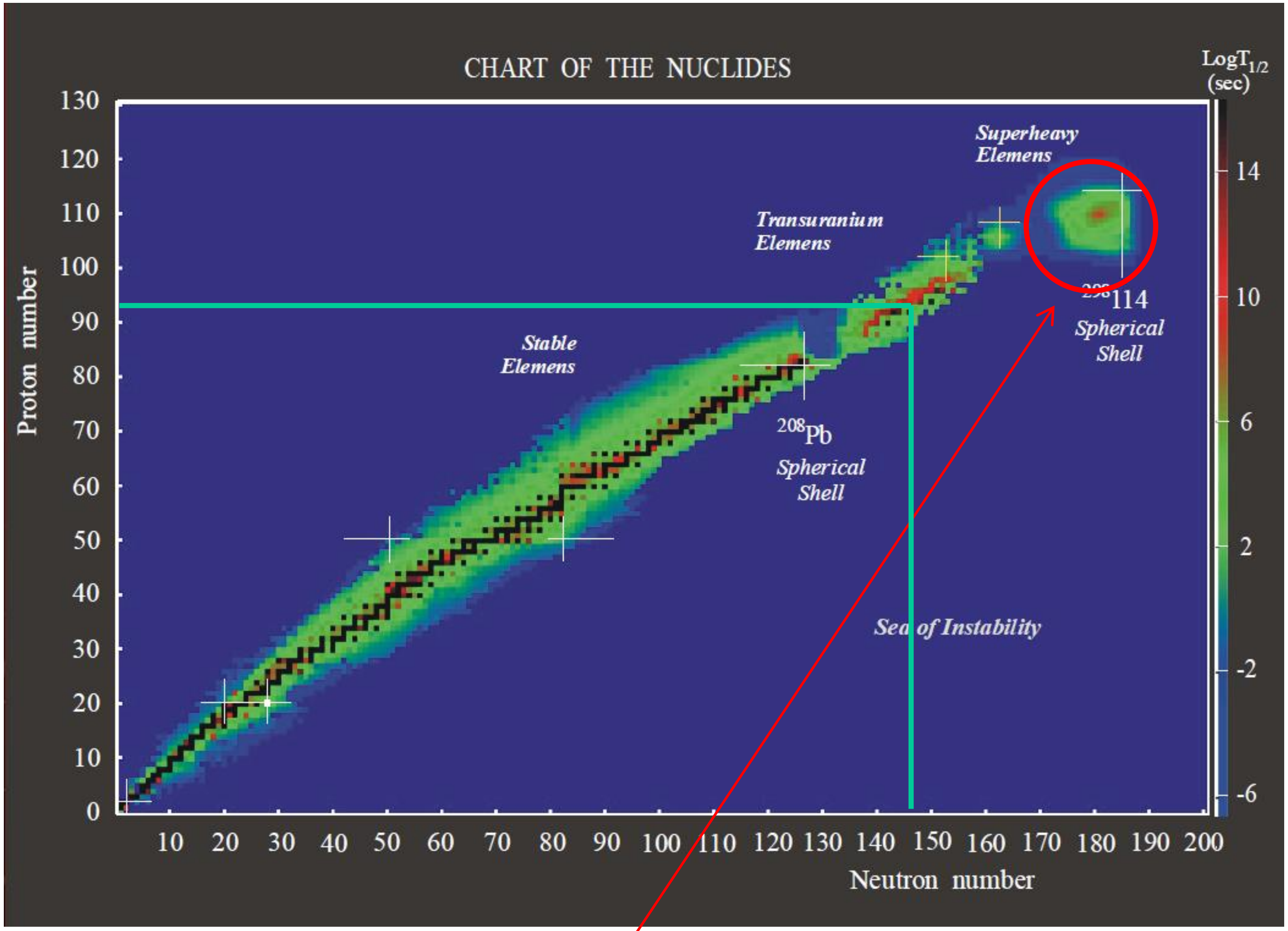
Heavier nuclei: unstable against fission



Periodic table of chemical elements



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



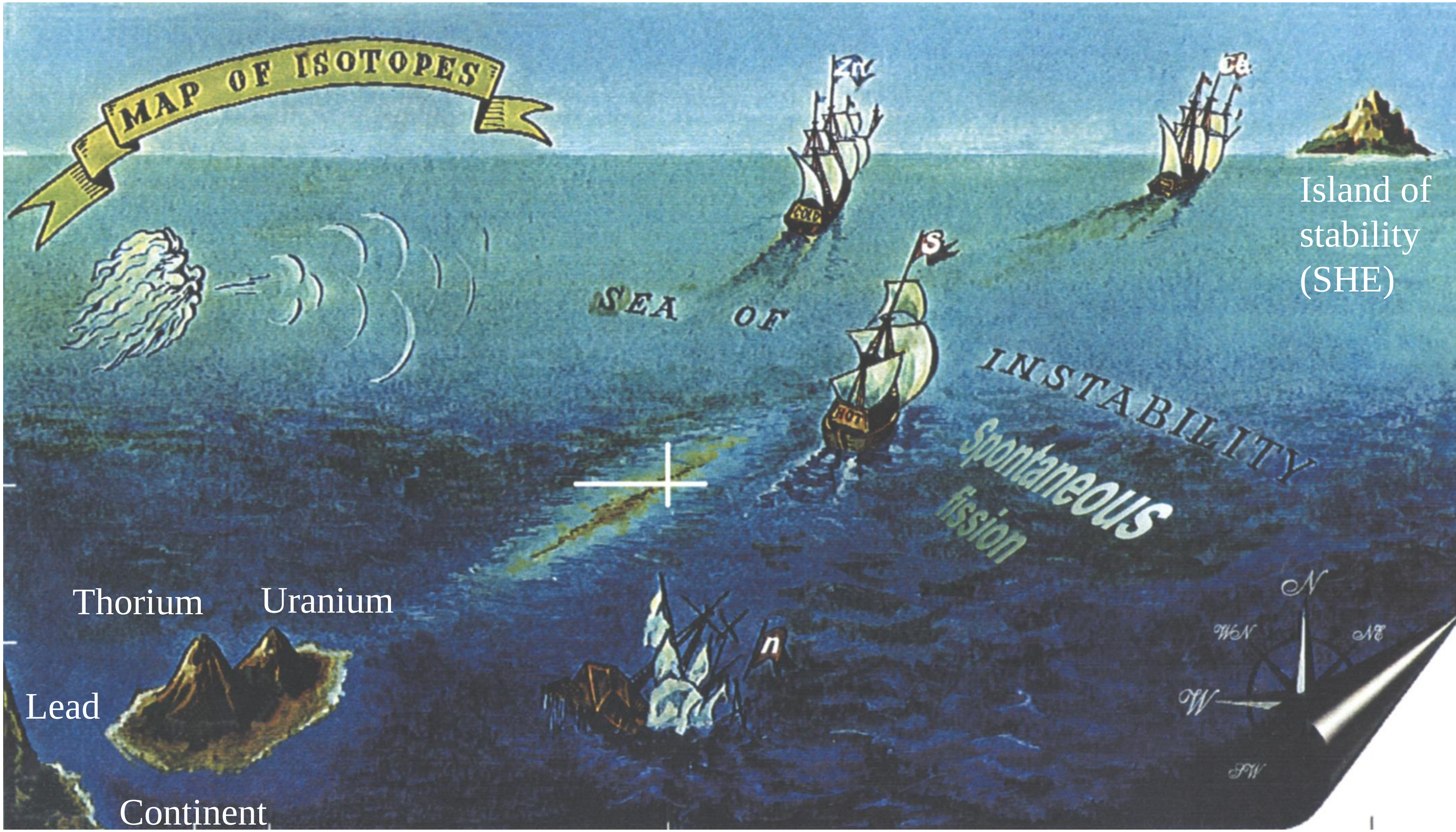
Yuri Oganessian

island of stability around Z=114, N=184

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

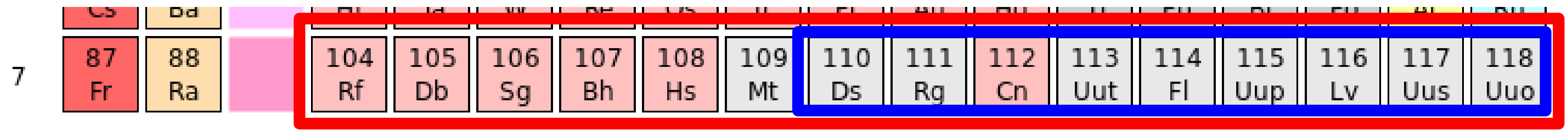
⟶ modern calculations: Z=114,120, or 126, N=184

e.g., H. Koura et al. (2005)



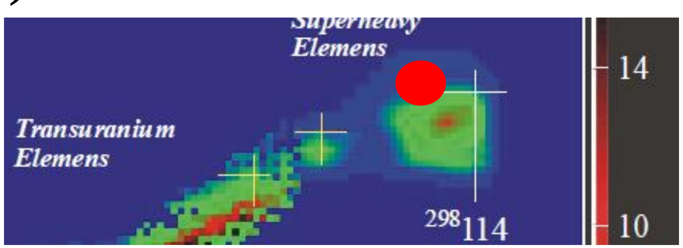
Yuri Oganessian

who is she?



Z=110	Darmstadtium (Ds)	1994 Germany
Z=111	Roentgenium (Rg)	1994 Germany
Z=112	Copernicium (Cn)	1996 Germany
Z=113	No name yet	2003 Russia / 2004 Japan
Z=114	Flerovium (Fl)	1999 Russia (*)
Z=115	No name yet	2003 Russia
Z=116	Livermoriun (Lv)	2000 Russia
Z=117	No name yet	2010 Russia
Z=118	No name yet	2002 Russia

(*)



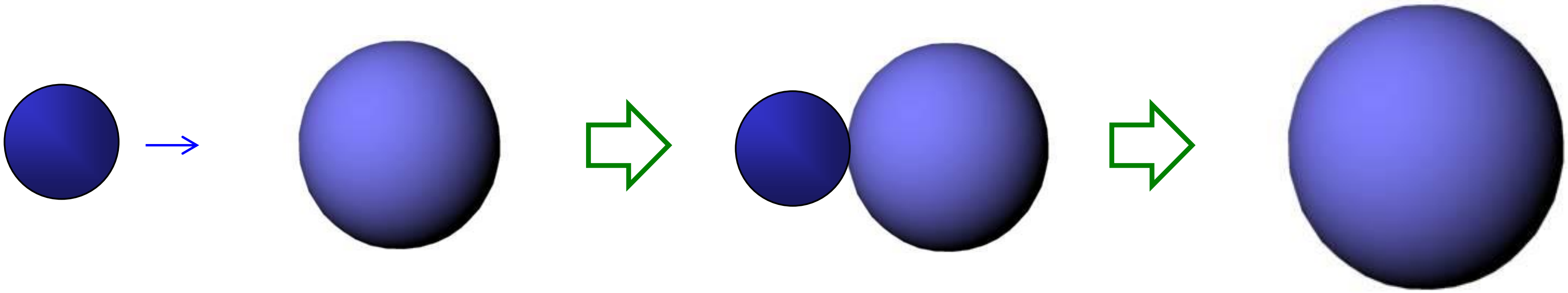
island of stability: Z=114, N=184

Fl discovered: Z=114, N=174-175

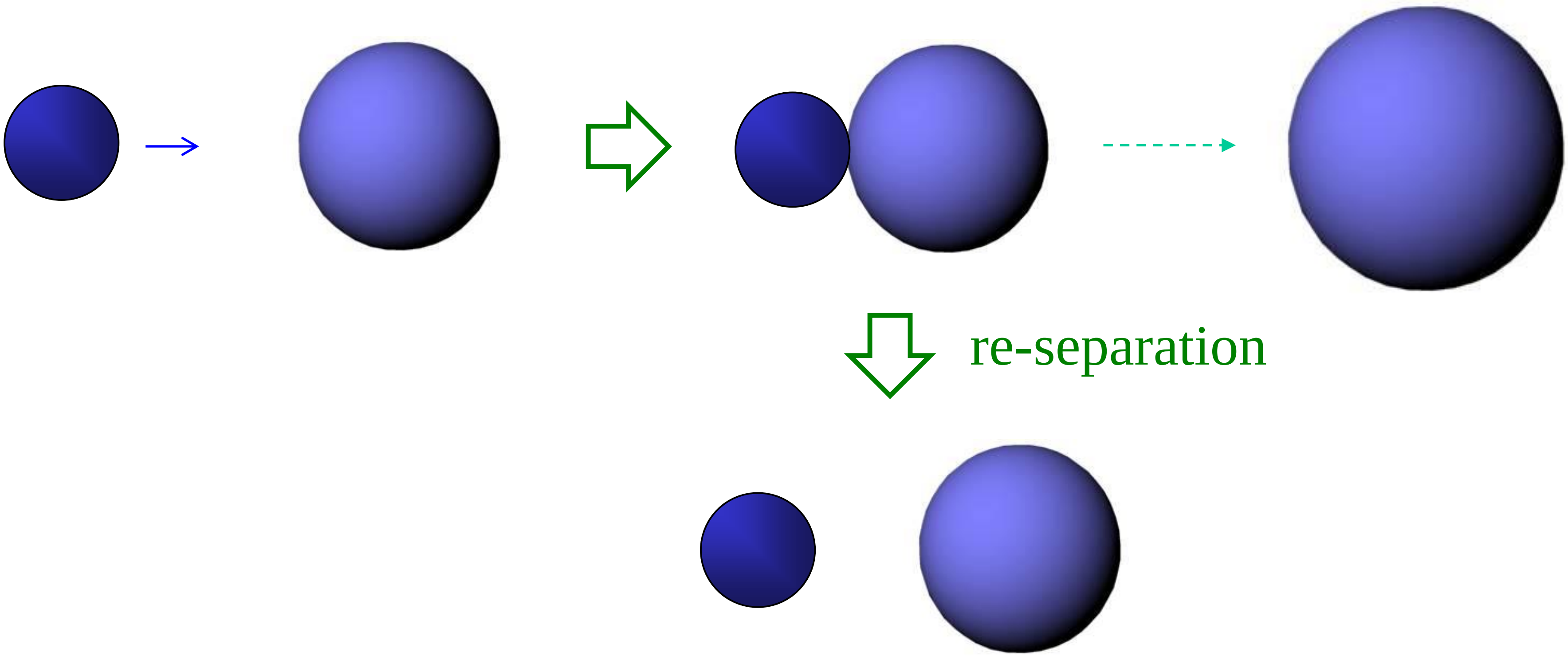
⟶ island not yet confirmed

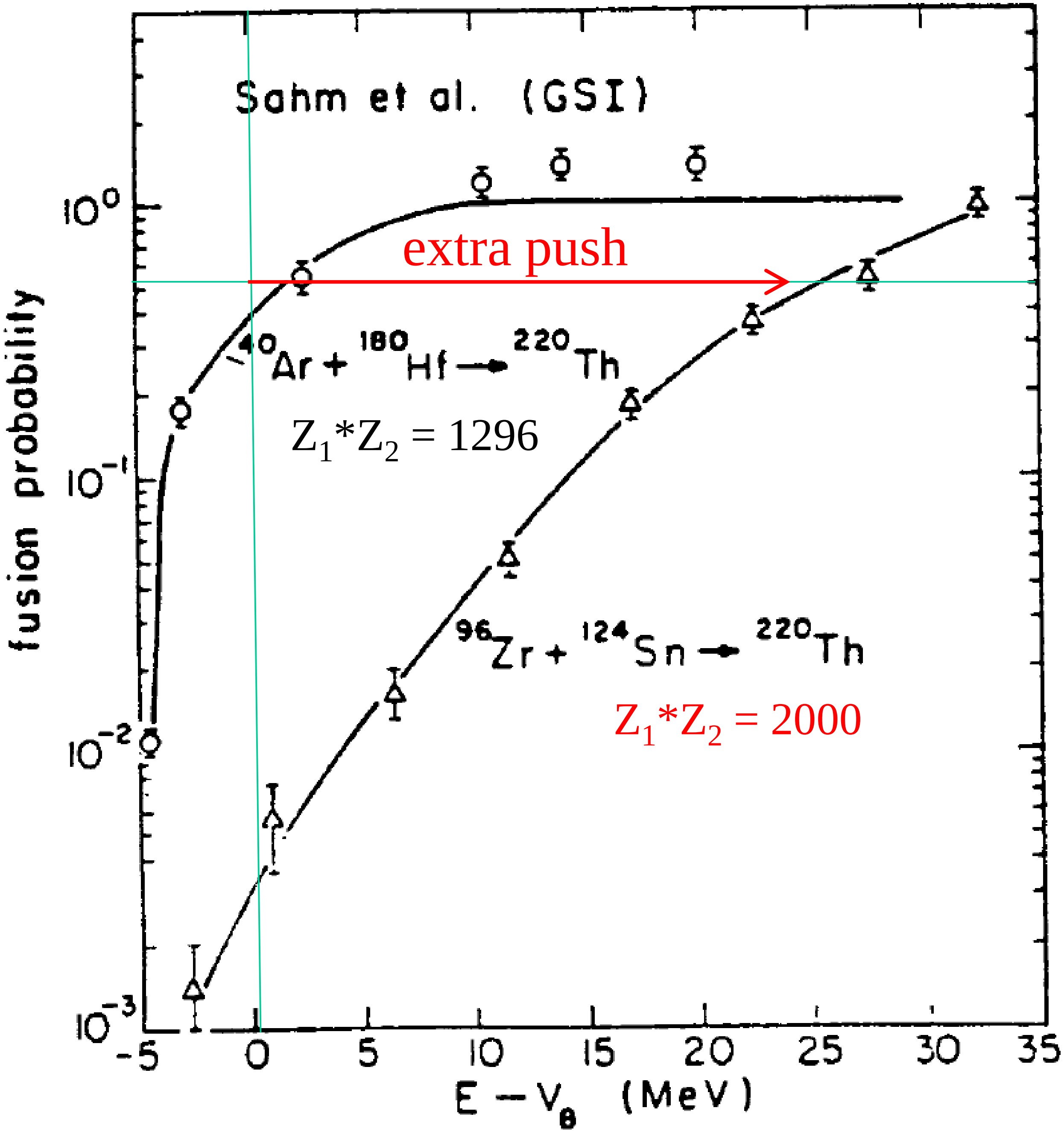
How to synthesize SHE? Nuclear fusion reactions

- Fusion of medium-heavy systems:

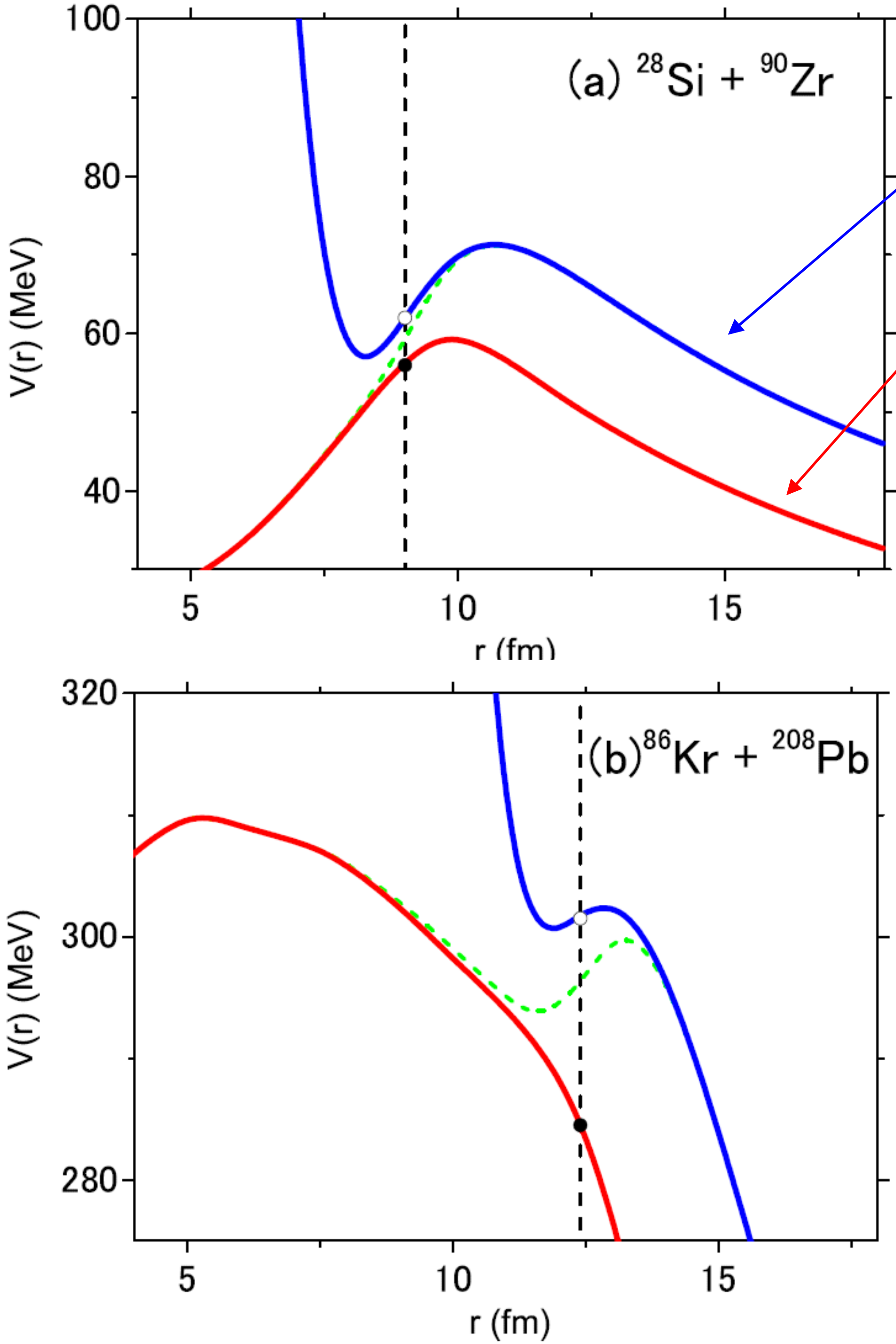


- Fusion of heavy and super-heavy systems:





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



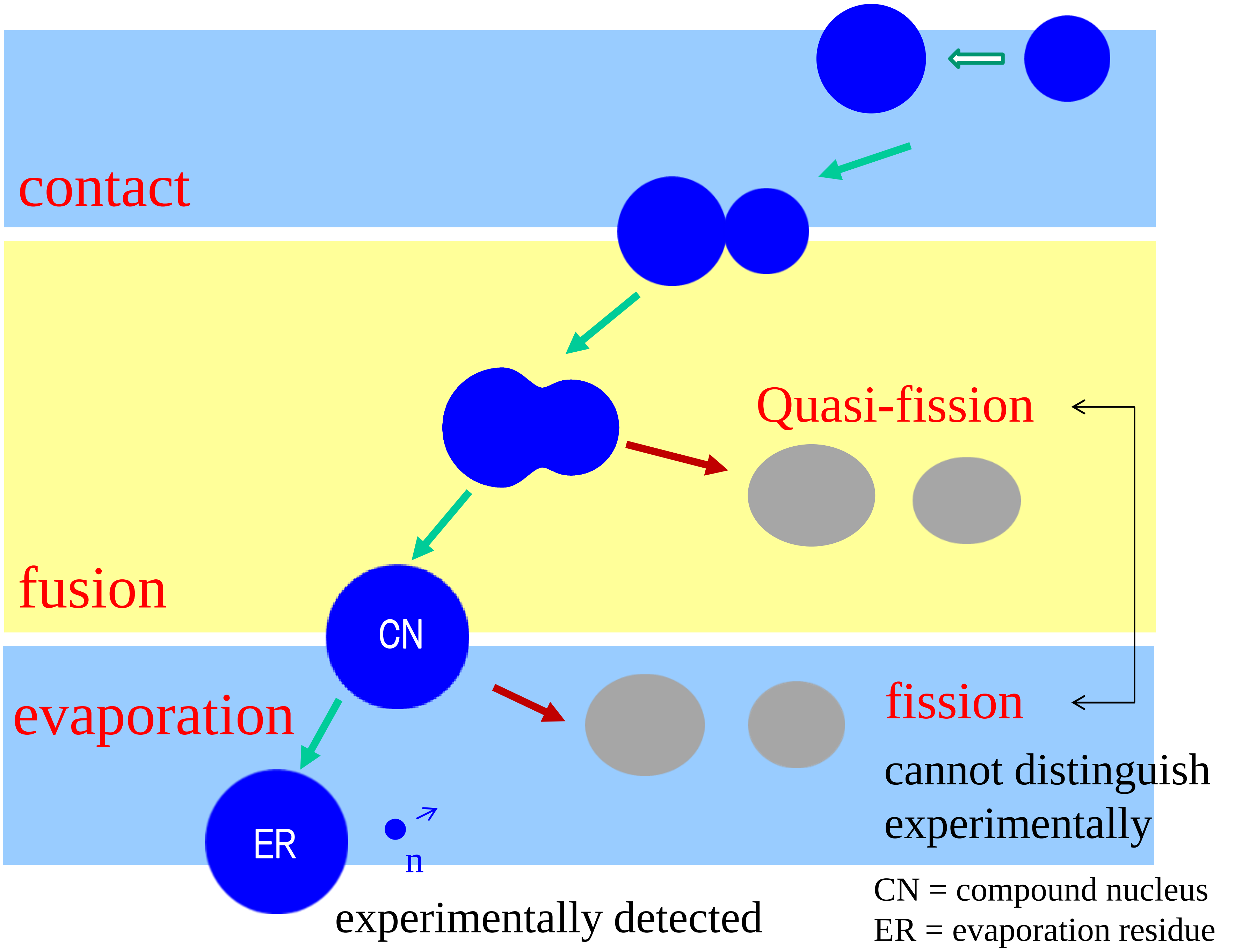
2-body potential before touching

1-body potential after touching

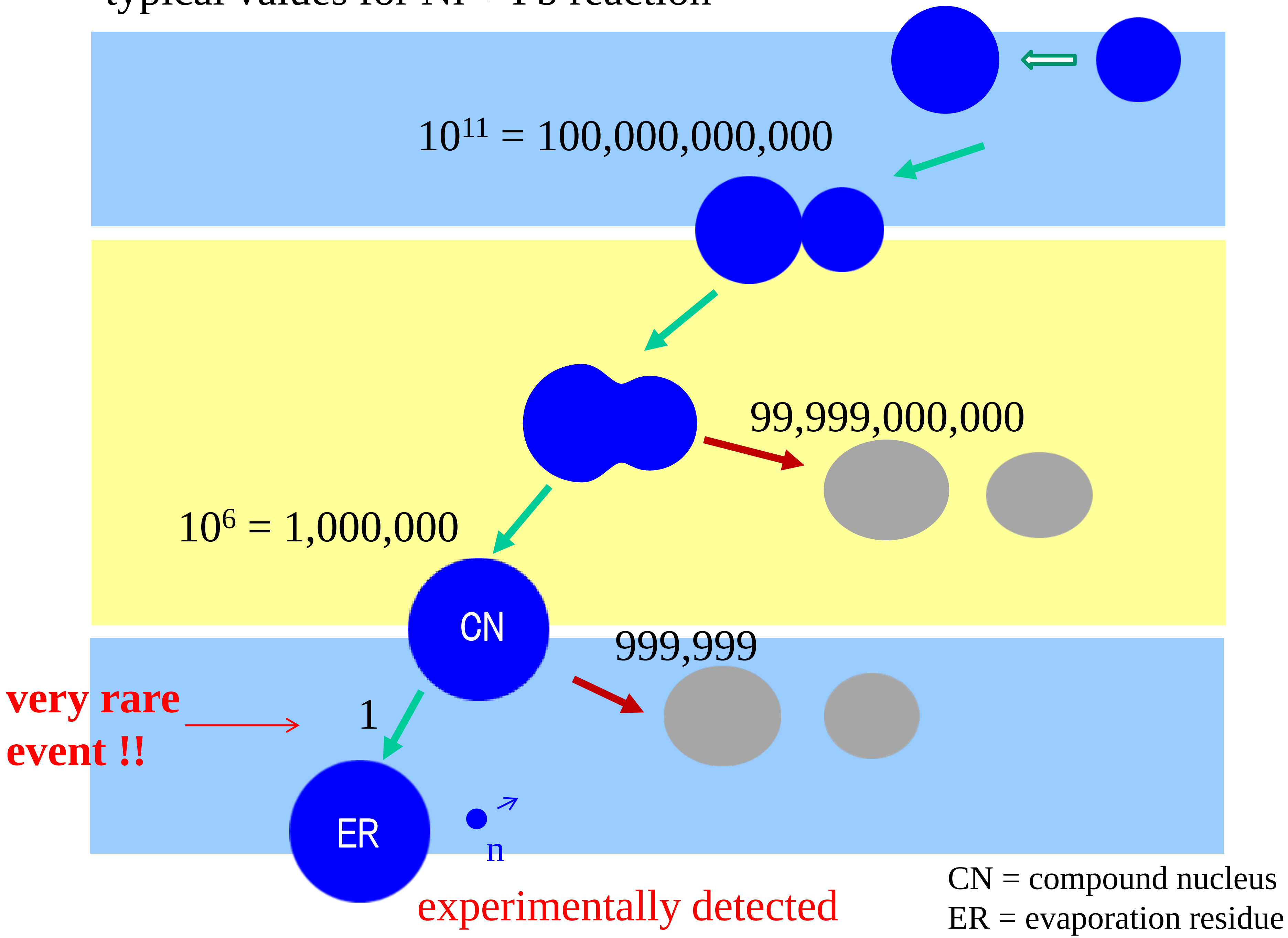
The red potential has to be overcome even if the blue potential has been overcome.

↓

Re-separation if failed (quasi-fission)

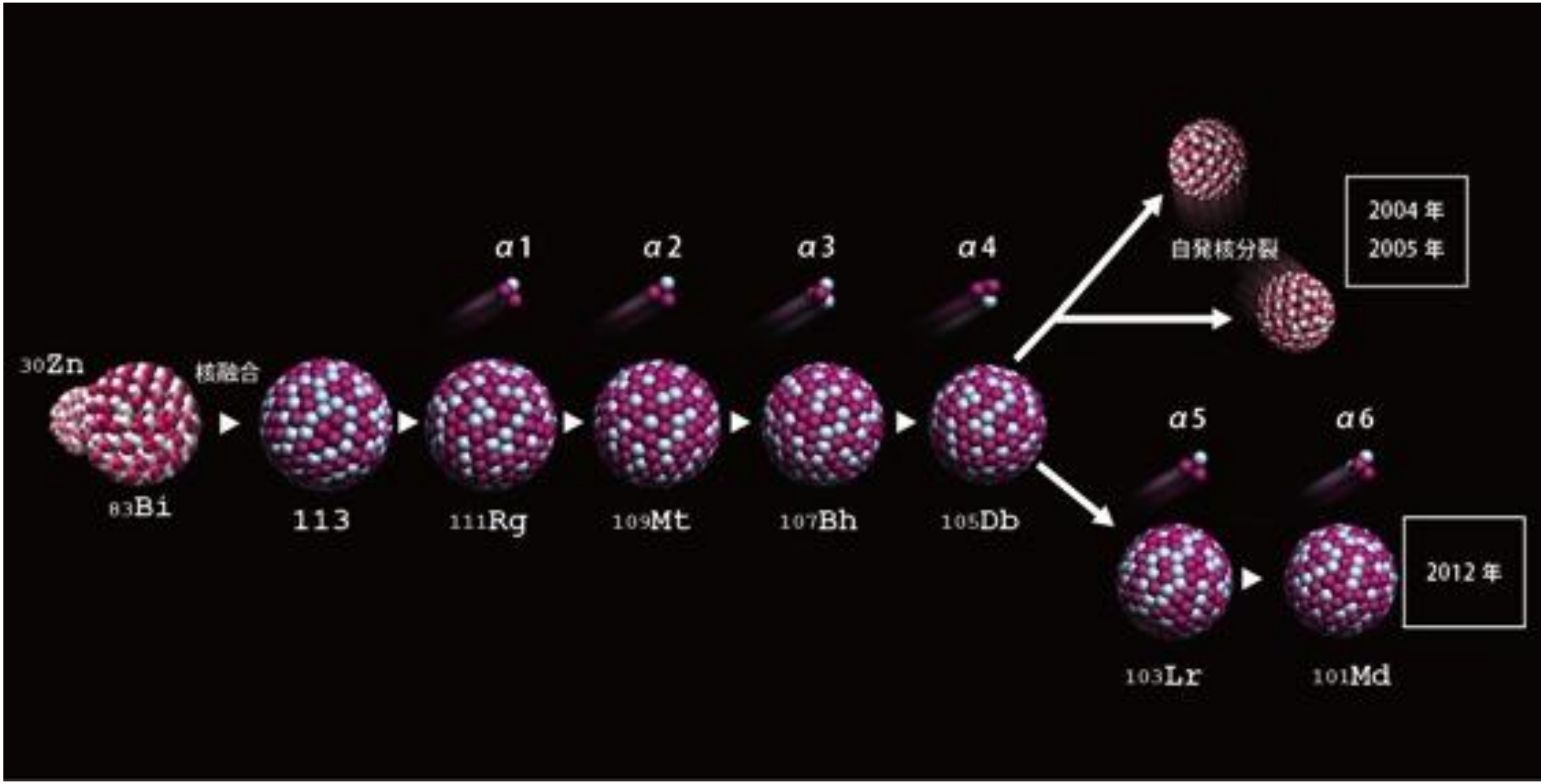

contact
Quasi-fission
fusion
CN
evaporation
fission
cannot distinguish
experimentally
ER
n
experimentally detected
CN = compound nucleus
ER = evaporation residue

typical values for Ni + Pb reaction



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

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

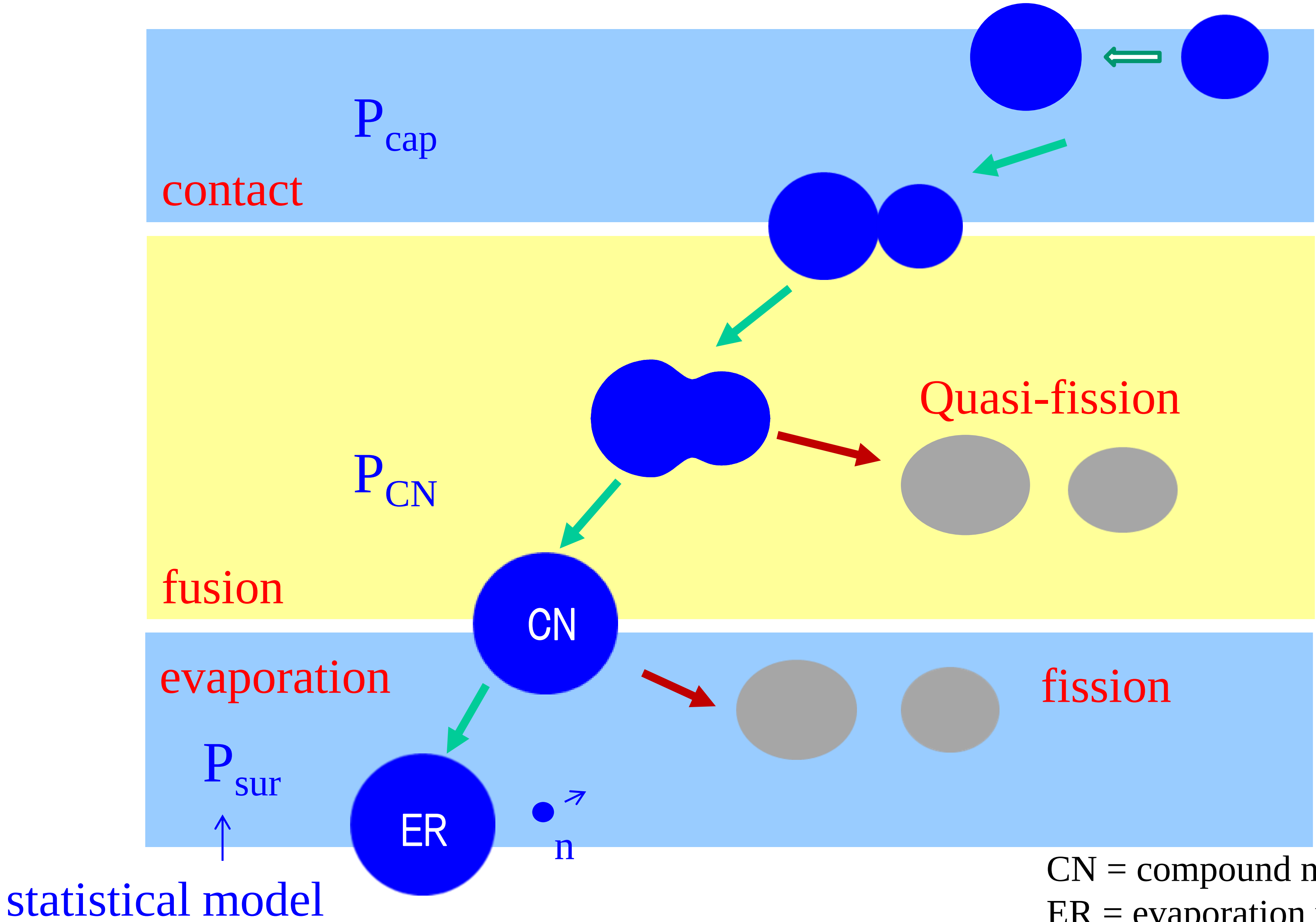


K. Morita et al., J. Phys. Soc. Jpn. 81('12)103201

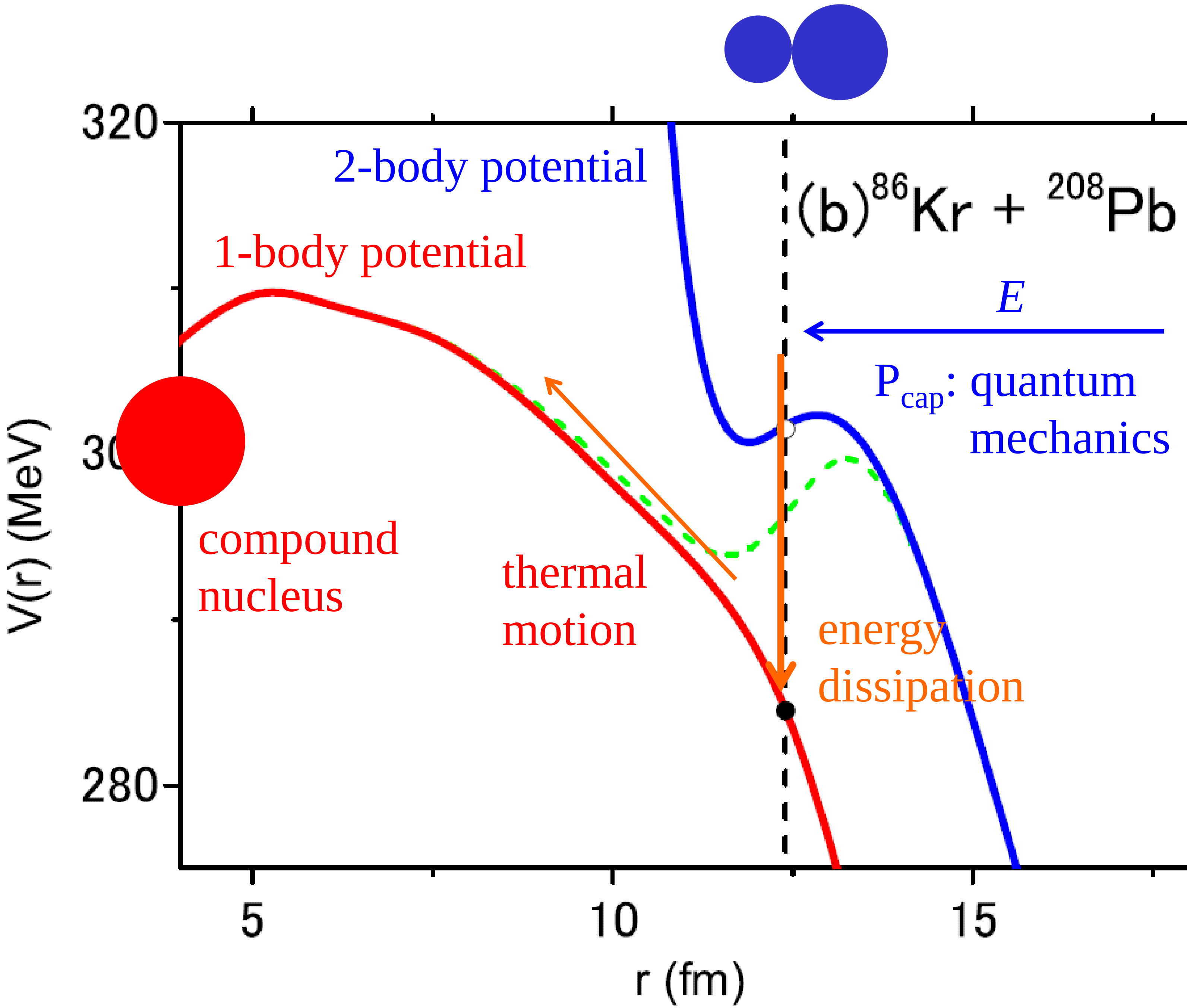
only 3 events for 553 days experiment

Theoretical treatment

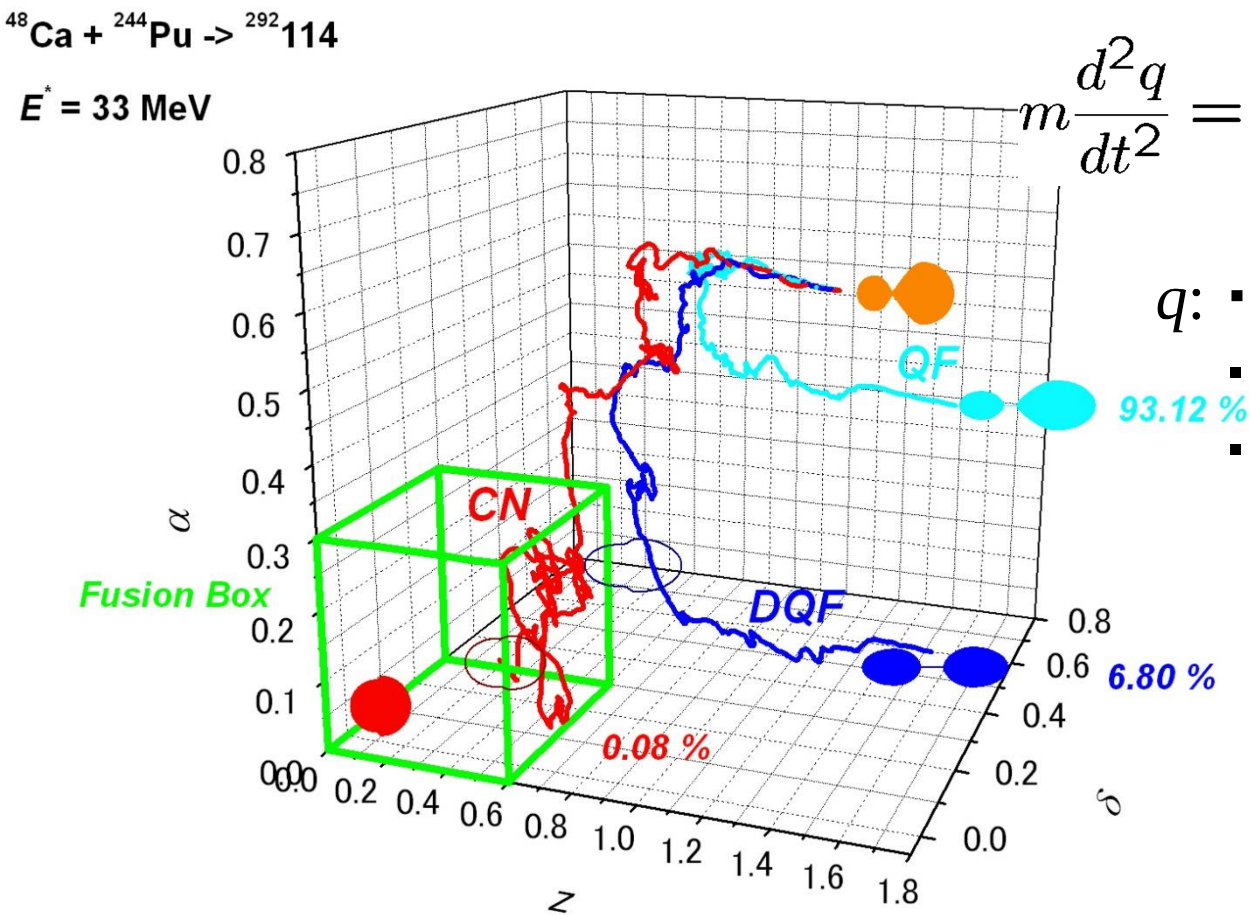
$$P_{ER} = P_{cap} \cdot P_{CN} \cdot P_{sur}$$



CN = compound nucleus
ER = evaporation residue


2-body potential
(b) 86Kr + 208Pb
1-body potential
E
Pcap: quantum mechanics
compound nucleus
thermal motion
energy dissipation
320
300
280
V(r) (MeV)
5
10
15
r (fm)

Theory: Lagenvin approach

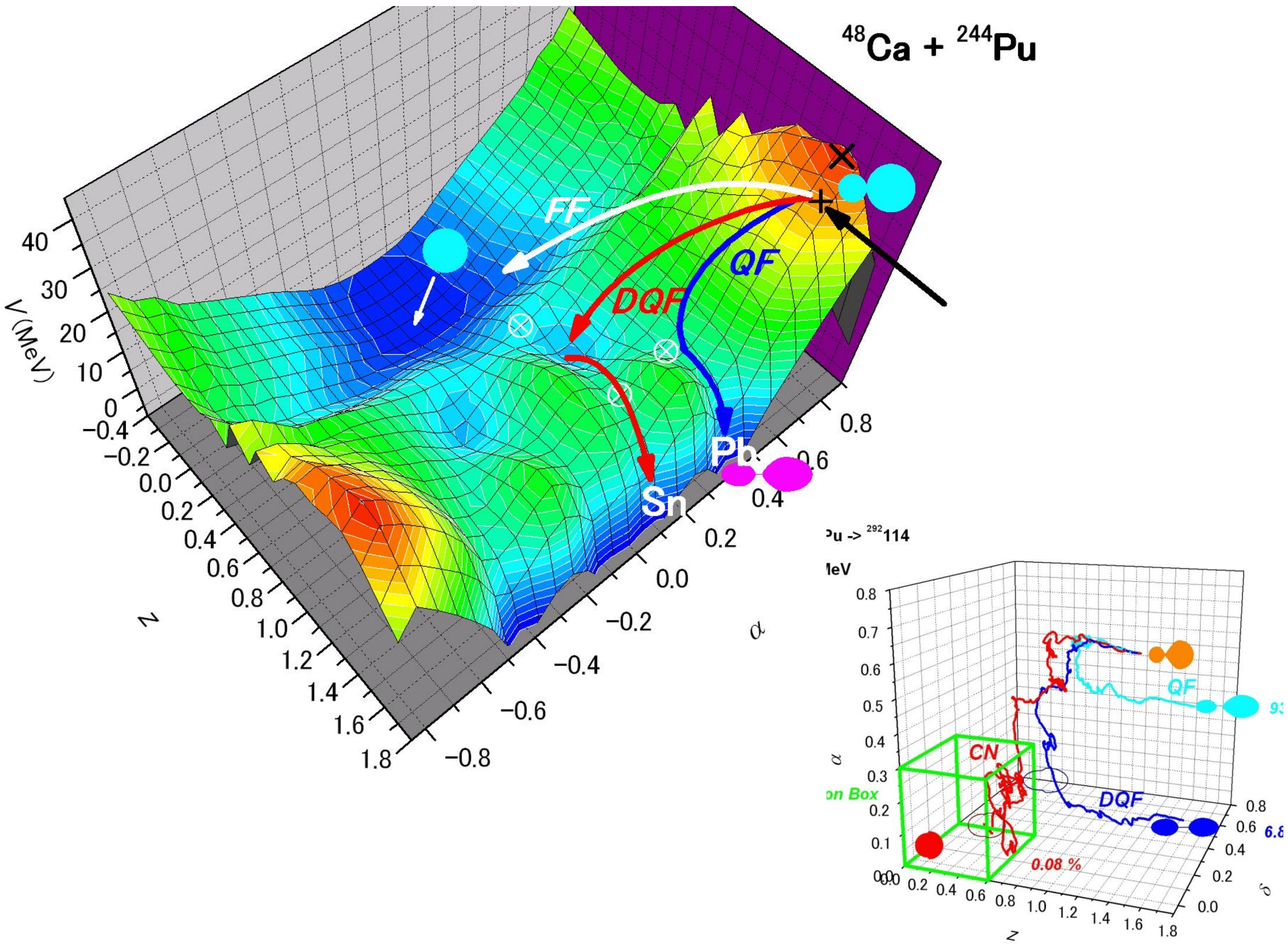


multi-dimensional extension of:

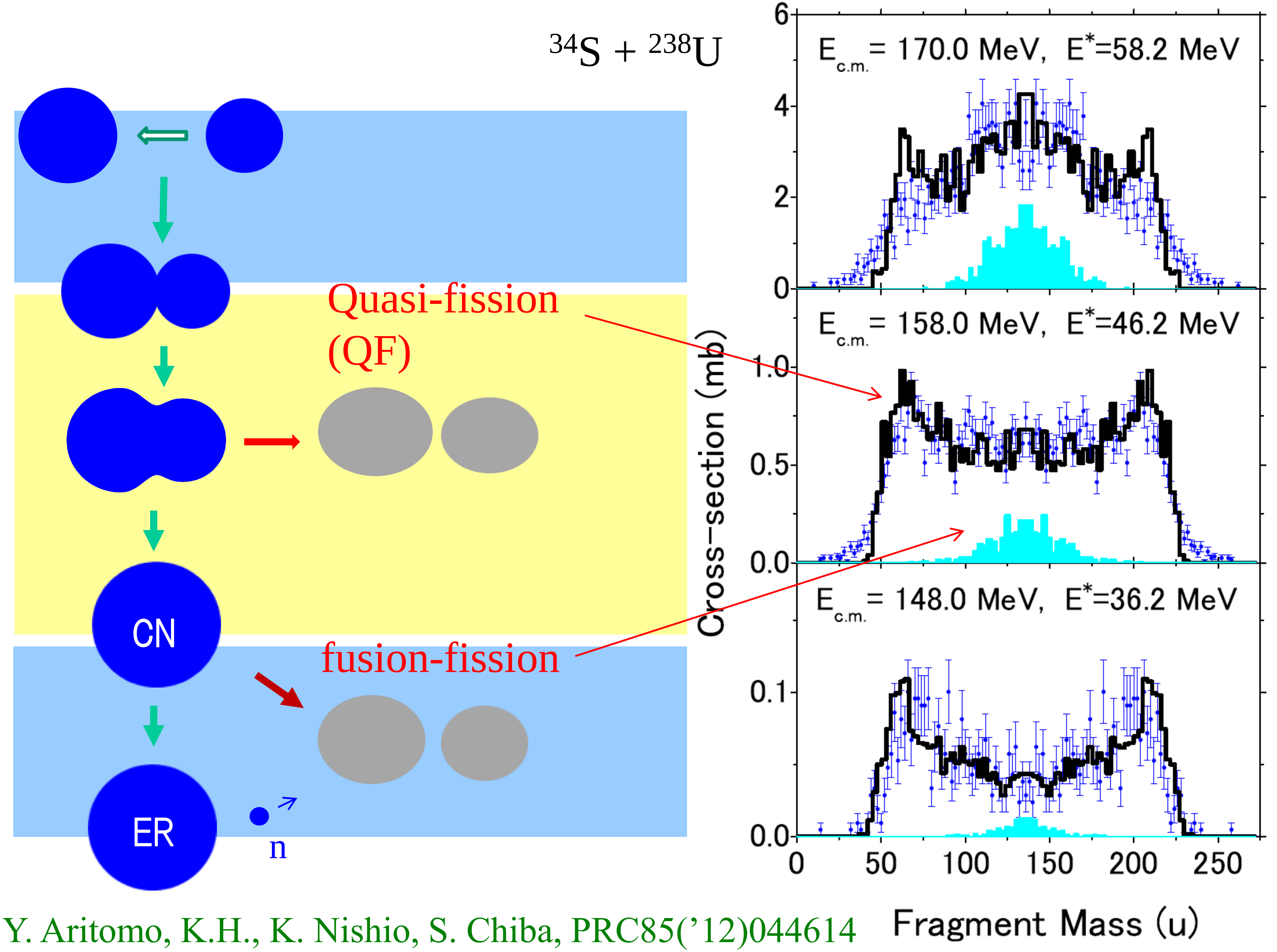
$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$

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

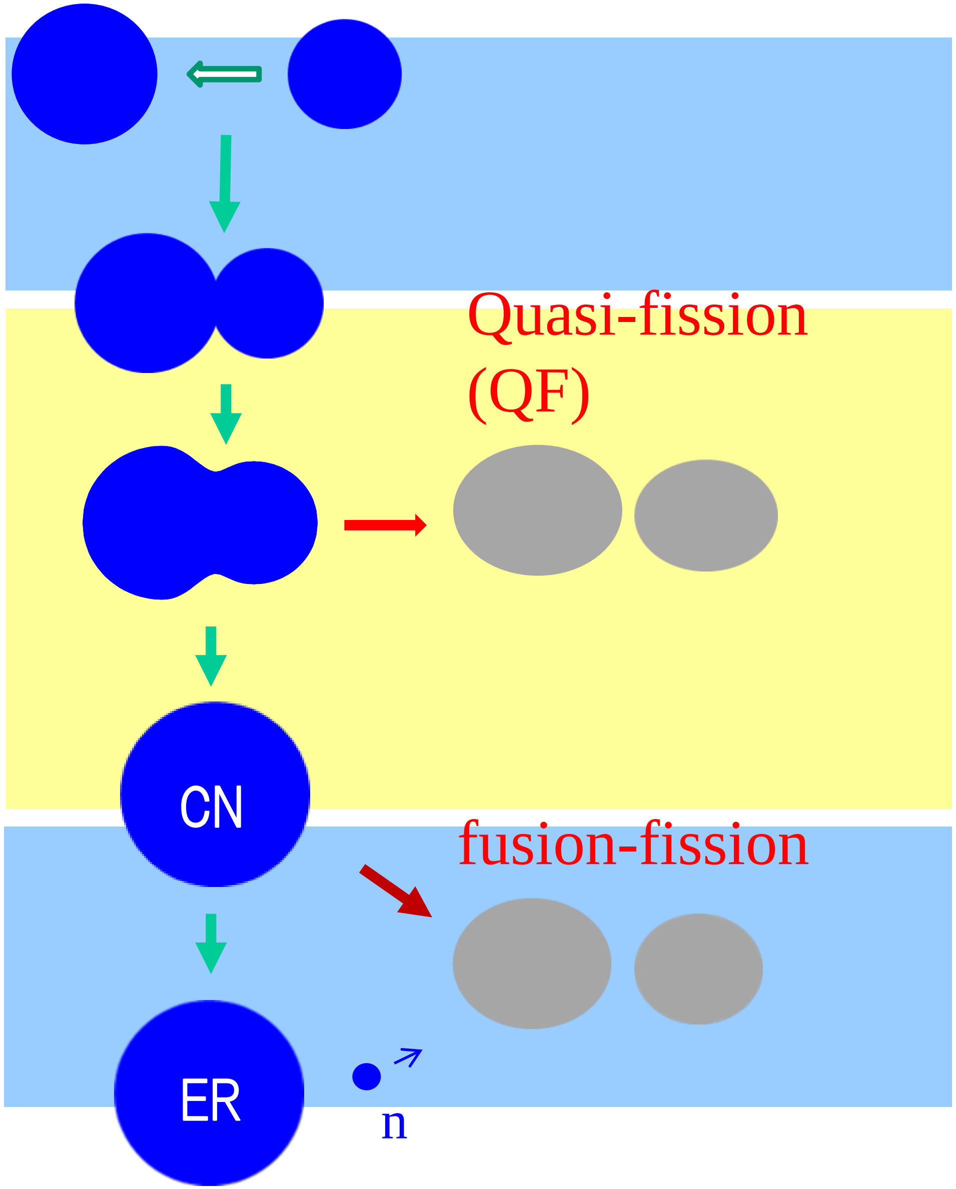
γ: friction coefficient
R(*t*): random force

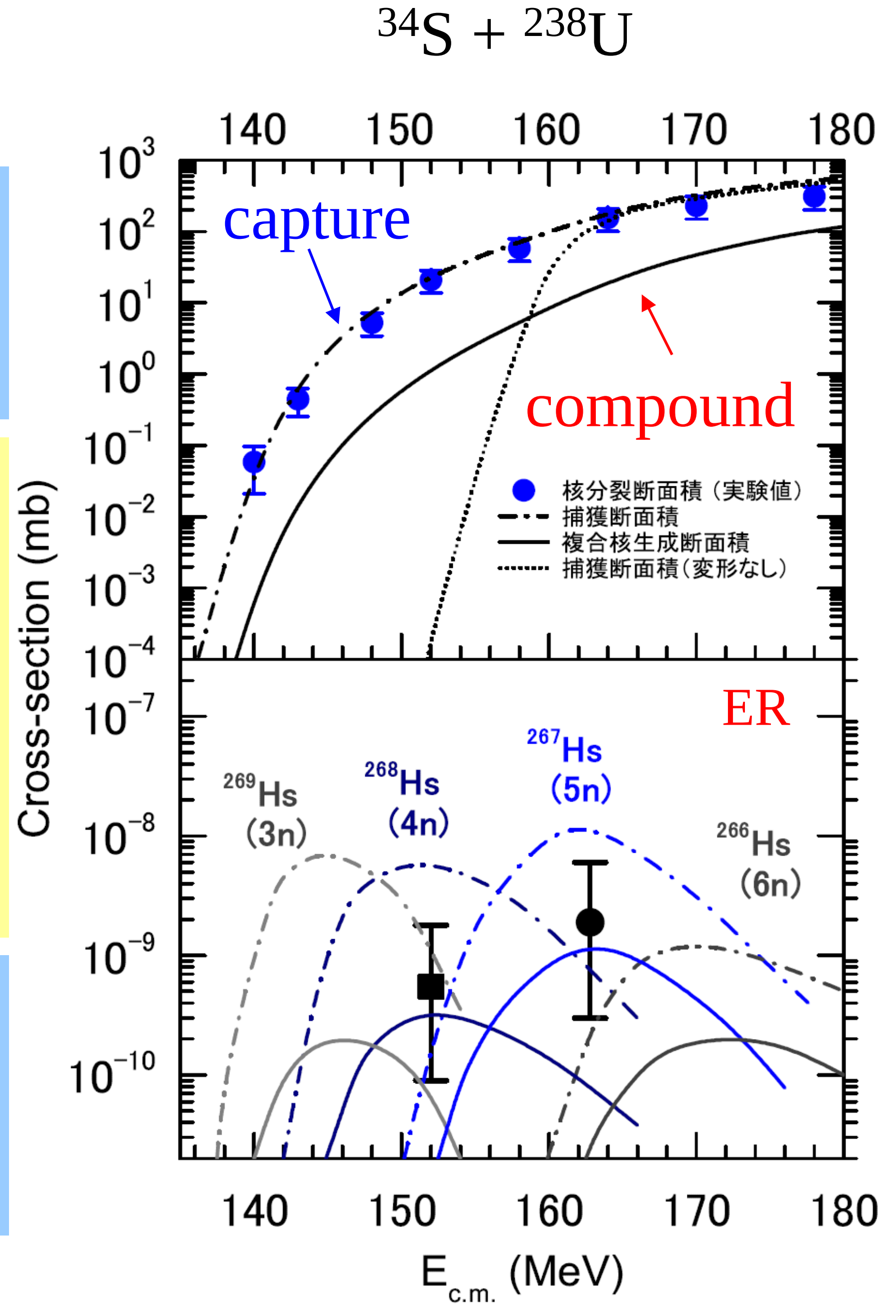


48Ca + 244Pu
FF
QF
DQF
Pb
Sn
V (MeV)
40
30
20
10
0
z
α
u -> 292114
MeV
CN
QF
DQF
on Box
0.08 %
δ



Y. Aritomo, K.H., K. Nishio, S. Chiba, PRC85('12)044614





Y. Aritomo, K.H., K. Nishio, S. Chiba, PRC85('12)044614

Element 113

- Dubuna

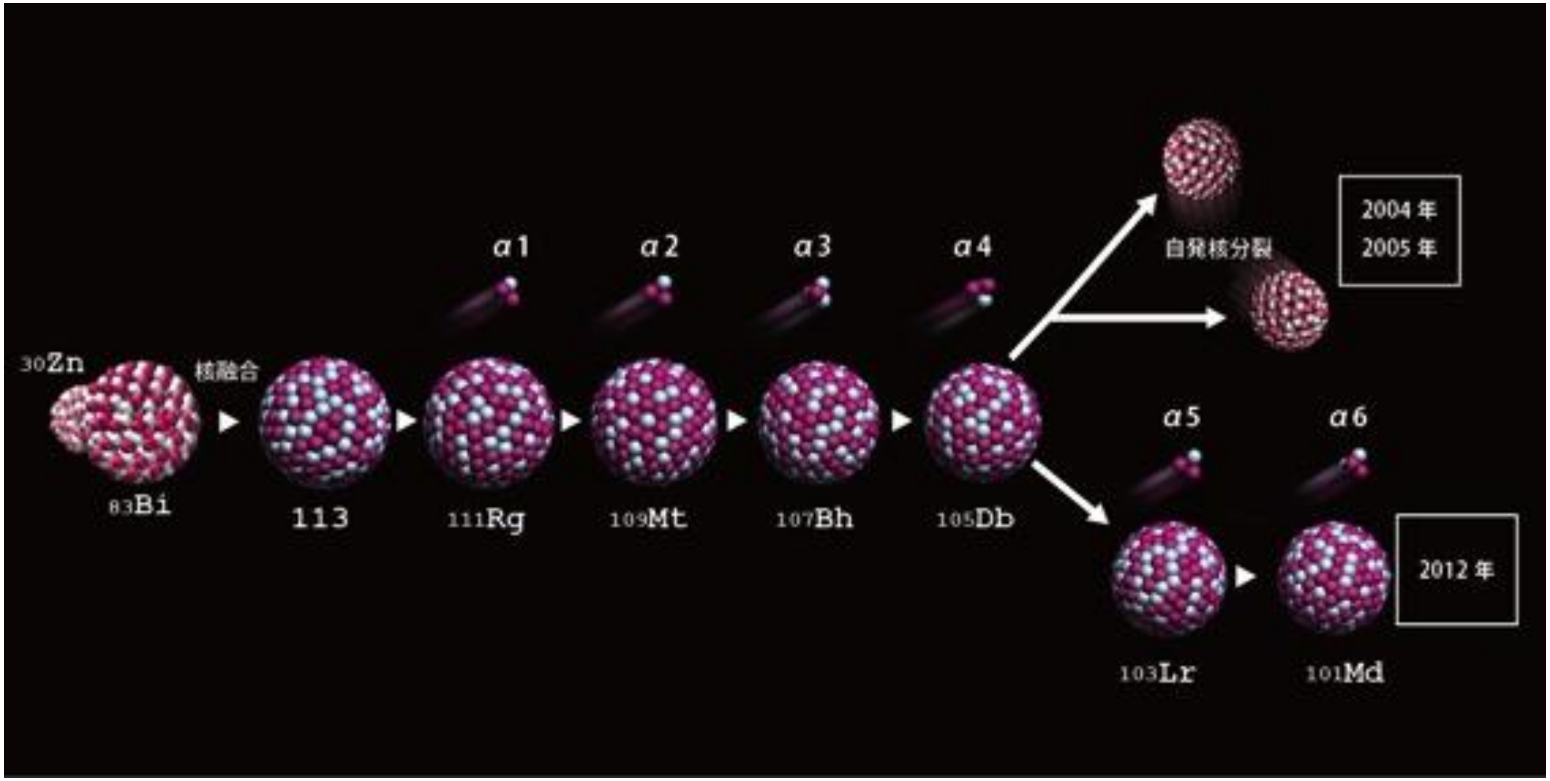
  $^{48}Ca + ^{243}Am \rightarrow ^{288}115 + 3n \rightarrow ^{284}113 + \alpha$ (2003)

  $^{48}Ca + ^{249}Bk \rightarrow ^{293}117 + 4n \rightarrow ^{189}115 + \alpha \rightarrow ^{285}113 + \alpha$ (2010)

  etc. Hot Fusion: ^{48}Ca projectile

- RIKEN

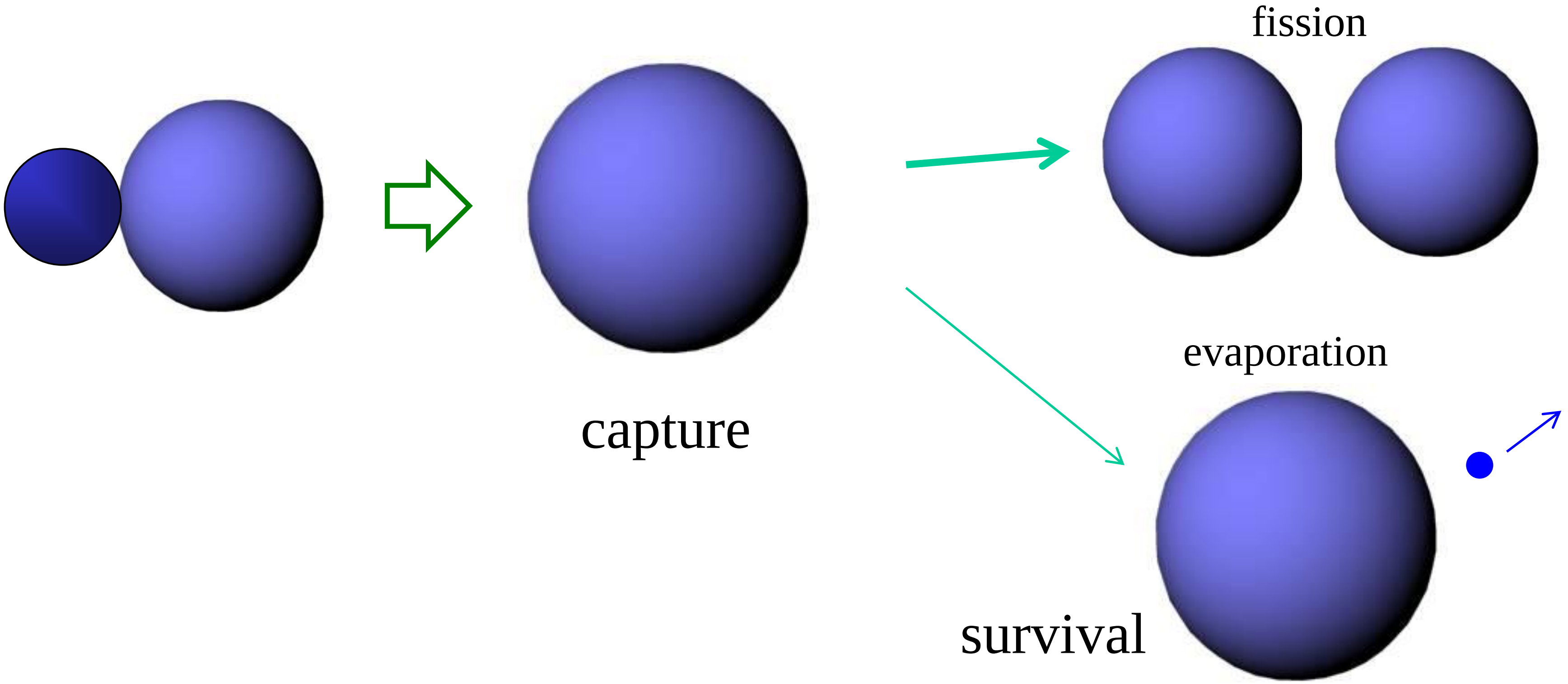
  $^{70}Zn + ^{209}Bi \rightarrow ^{278}113 + n$ (2004) Cold Fusion: ^{208}Pb or ^{209}Bi target



Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia

about 120 km north of Moscow

$_{105}$Db (Dubnium)

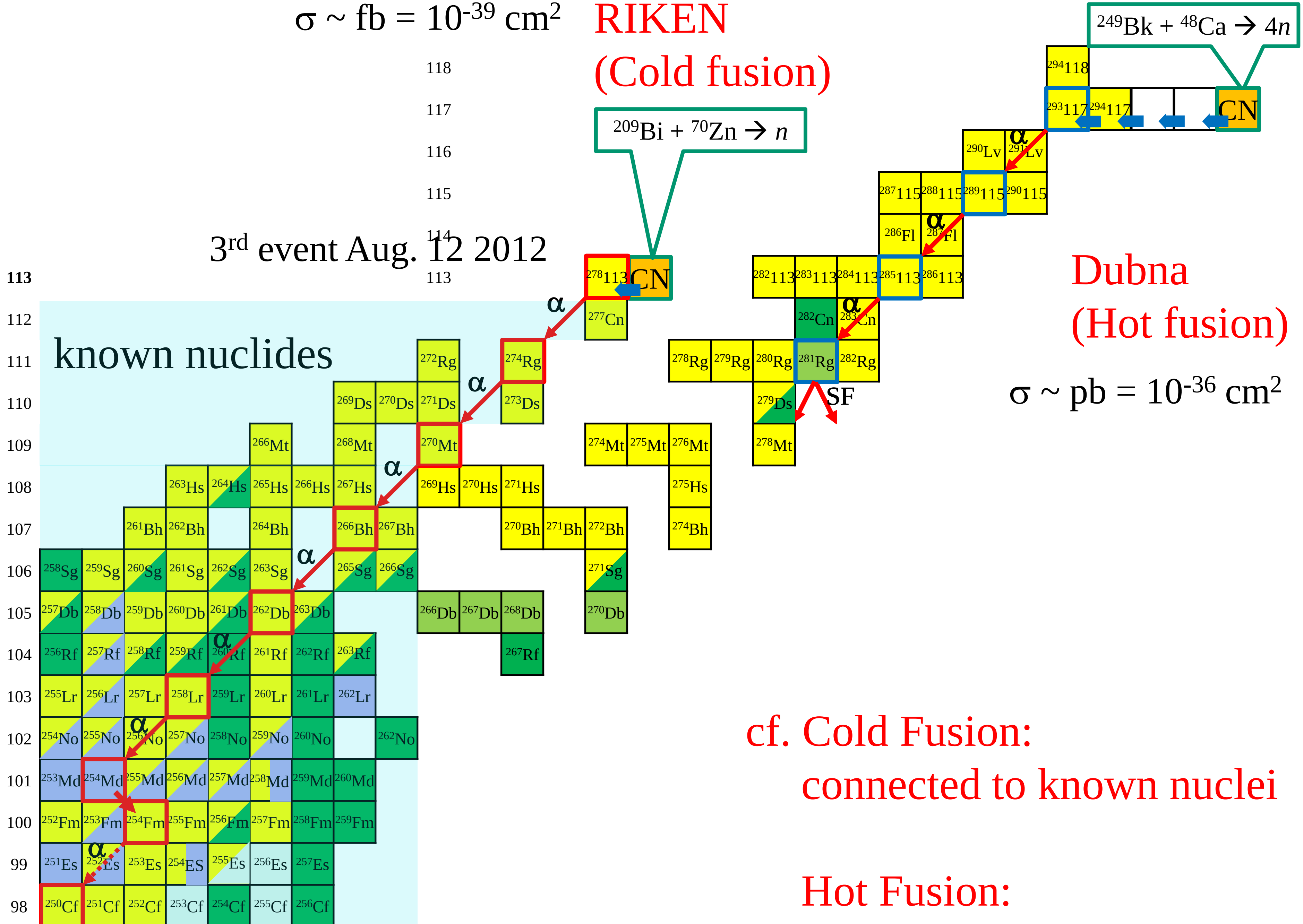


	Hot Fusion	**Cold Fusion**
Example	$^{48}Ca + ^{243}Am \rightarrow 4n$	$^{70}Zn + ^{209}Bi \rightarrow 1n$
asymmetry	large	small
Capture	large	small
Survival	small	large

$\sigma \sim fb = 10^{-39}\ cm^2$

RIKEN
(Cold fusion)

3rd event Aug. 12 2012



Dubna
(Hot fusion)

$\sigma \sim pb = 10^{-36}\ cm^2$

cf. Cold Fusion:
connected to known nuclei

Hot Fusion:
neutron-richer CN

Naming rights?

Under discussions in the joint IUPAC/IUPAP Joint Working Party

IUPAC = International Union of Pure and Applied Chemistry
IUPAP = International Union of Pure and Applied Physics

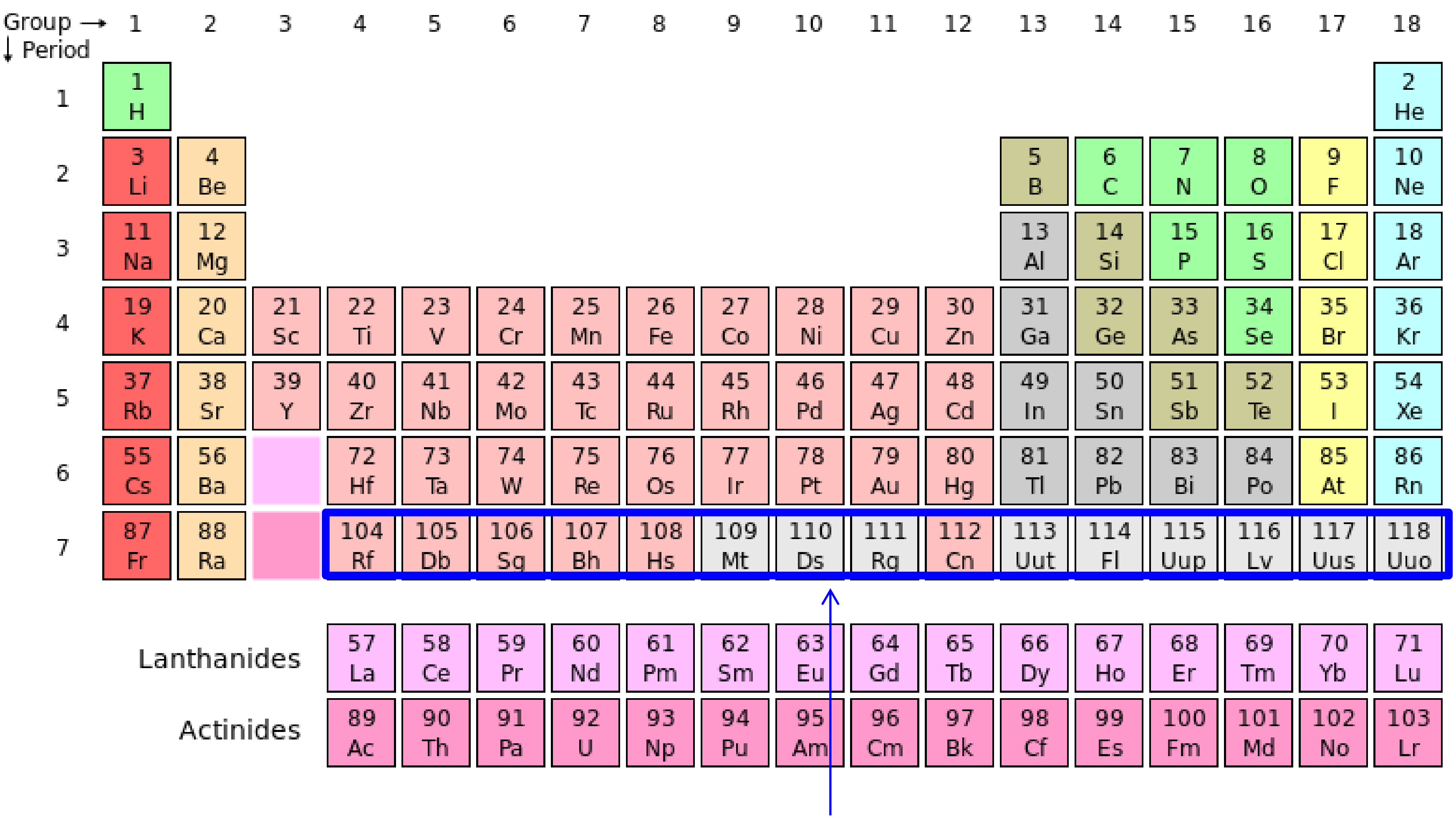
IUPAC

IUPAP

- RIKEN (Japan)
  much less ambiguity with cold fusion

- Dubna (Russia)
  much larger number of events

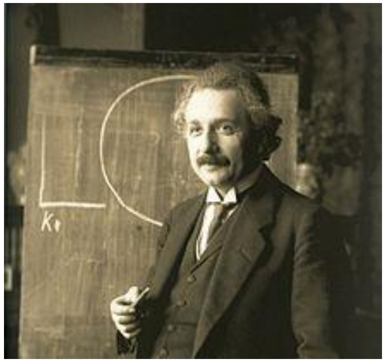
Chemistry of superheavy elements



- Are they here in the periodic table?
- That is, does e.g., Lv show the same chemical properties as O, S, Se, Te, and Po?

relativistic effect : important for large Z

$$E = mc^2$$



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

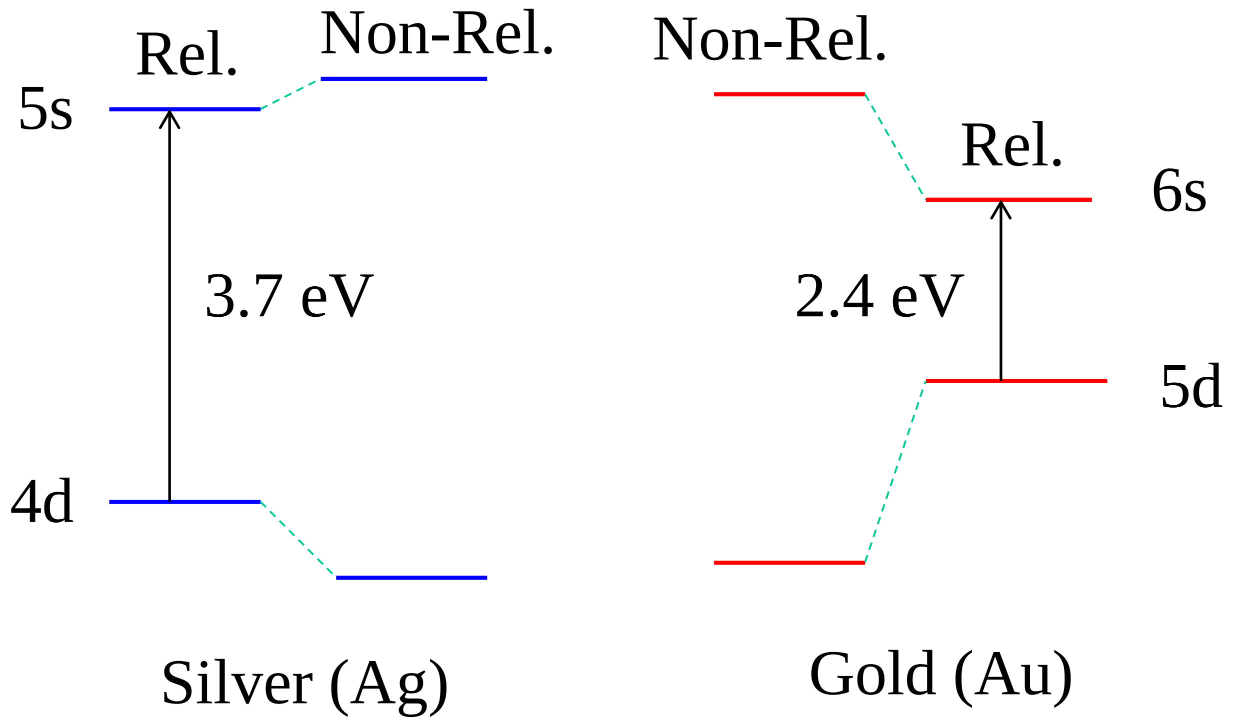
$$E_{1S} = mc^2\sqrt{1-(Z\alpha)^2} \sim mc^2\left(1 - \frac{(Z\alpha)^2}{2} \underbrace{- \frac{(Z\alpha)^4}{8} + \cdots}_{\text{relativistic effect}}\right)$$

relativistic effect

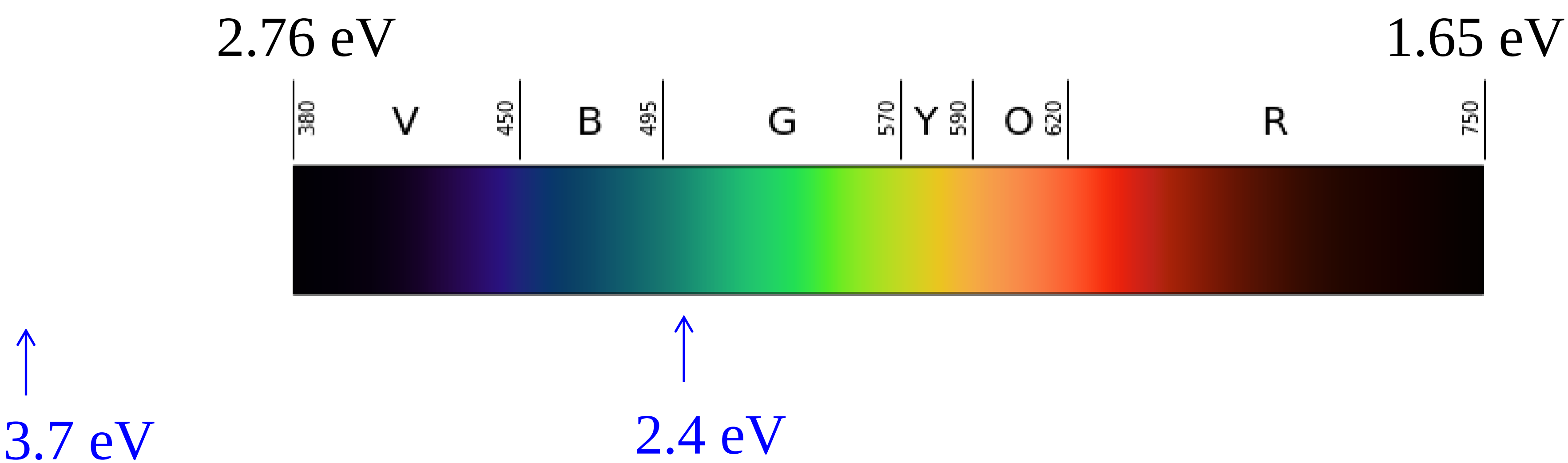
Famous example of relativistic effects: the color of gold

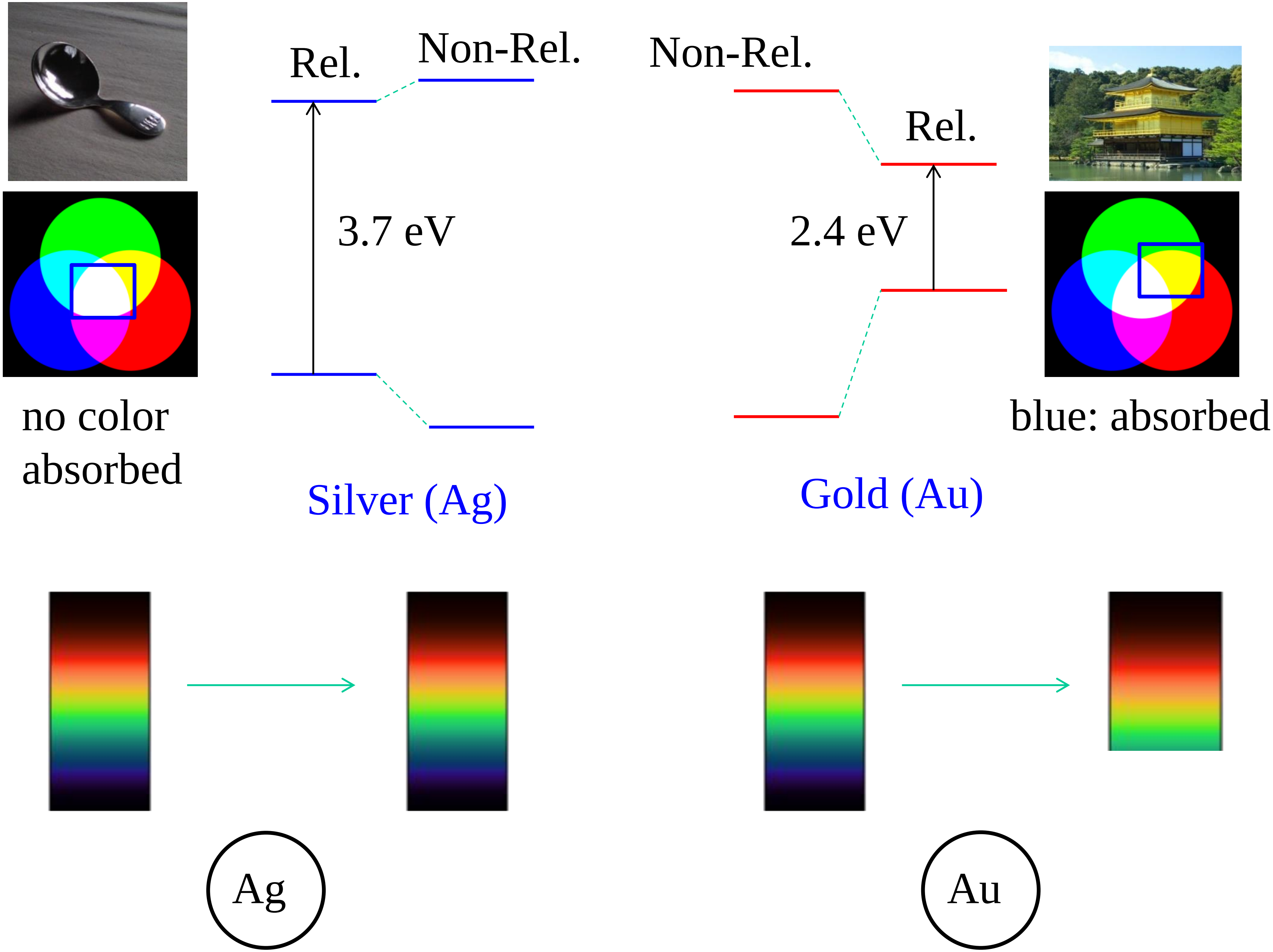
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	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!



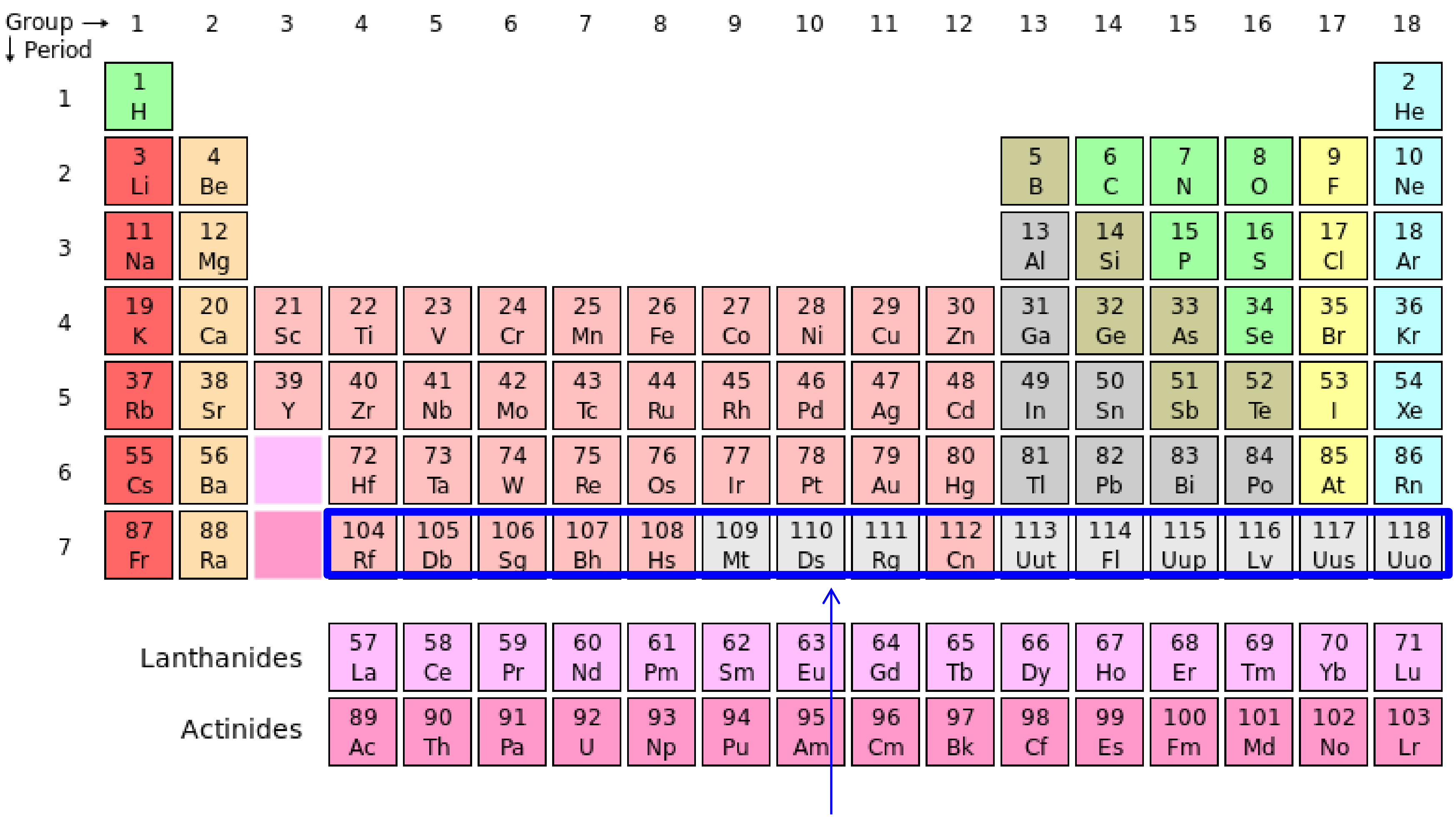
cf. visible spectrum





Rel.
Non-Rel.
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