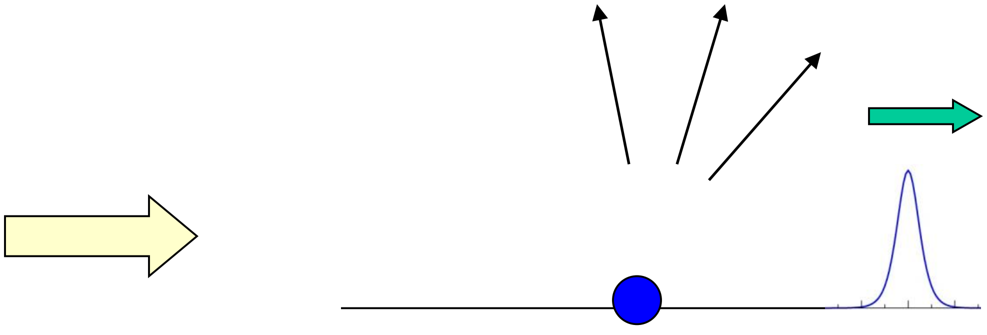
Absorption cross sections

Reaction processes

- Elastic scatt.
- Inelastic scatt.
- Transfer reaction
- Compound nucleus formation (fusion)



Loss of incident flux (absorption)

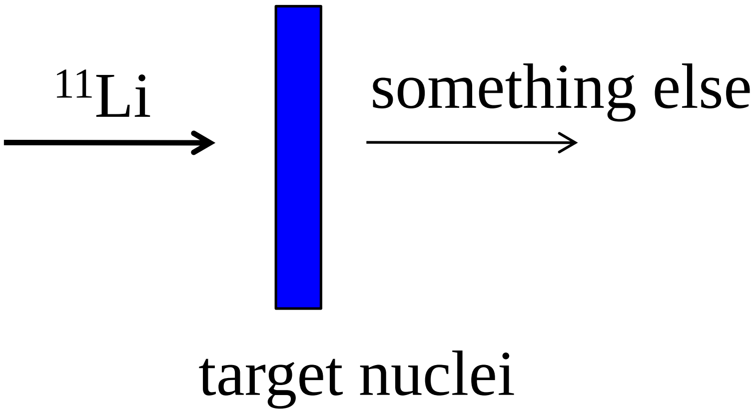
reaction cross sections

total scattering cross section - elastic cross section

$$\sigma_R = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}}$$

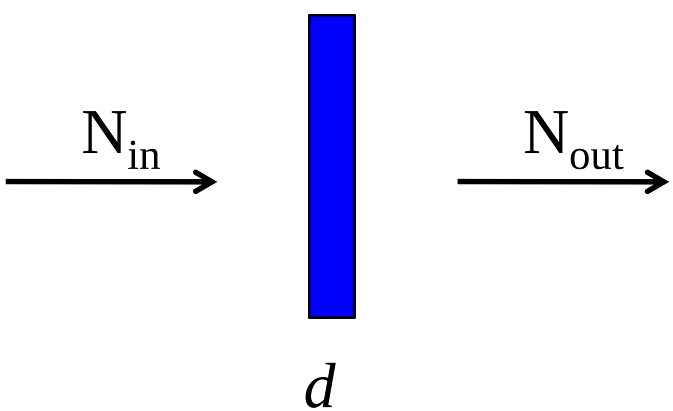
- fusion
- inelastic
- transfer

Interaction cross sections and halo nuclei



interaction cross section σ_I
= cross section for the change
of Z a/o N in the incident nucleus

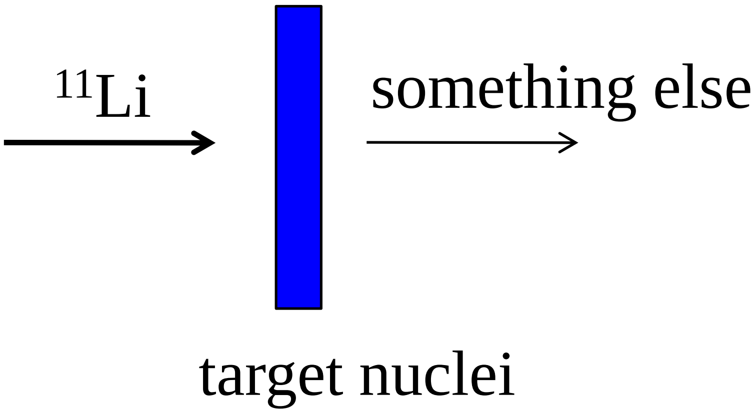
transmission method



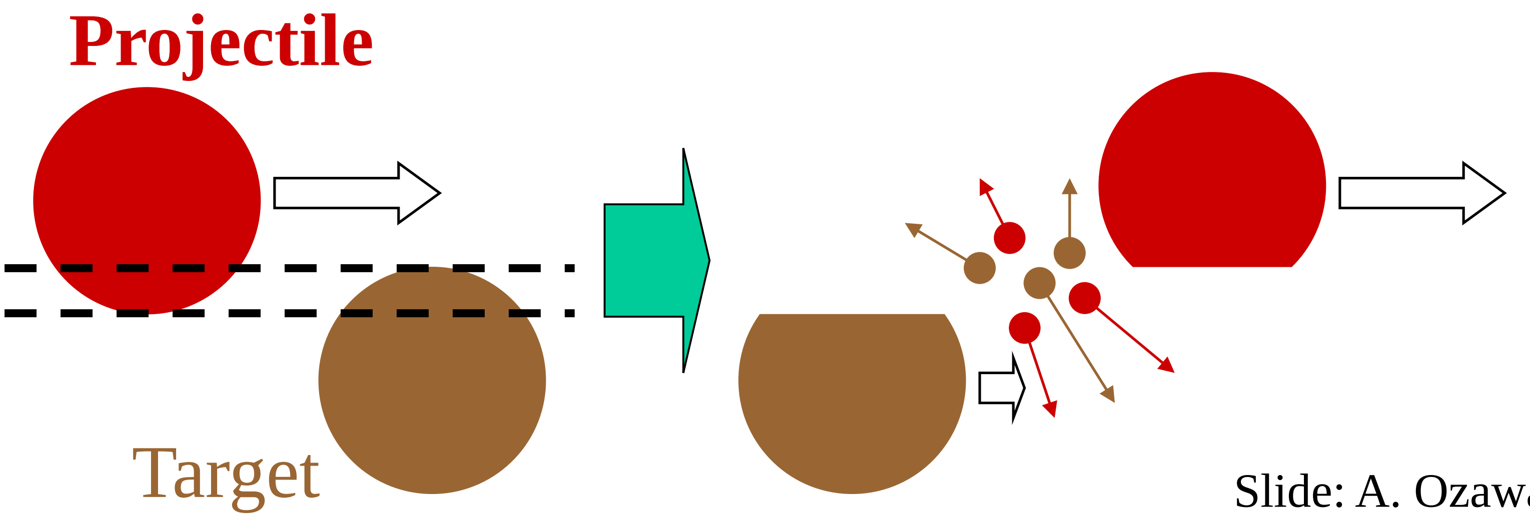
$$\sigma_R = -\frac{1}{t} \ln\left(\frac{N_{\text{out}}}{N_{\text{in}}}\right)$$

$$t = \rho_T \cdot d \cdot \epsilon$$

Interaction cross sections and halo nuclei



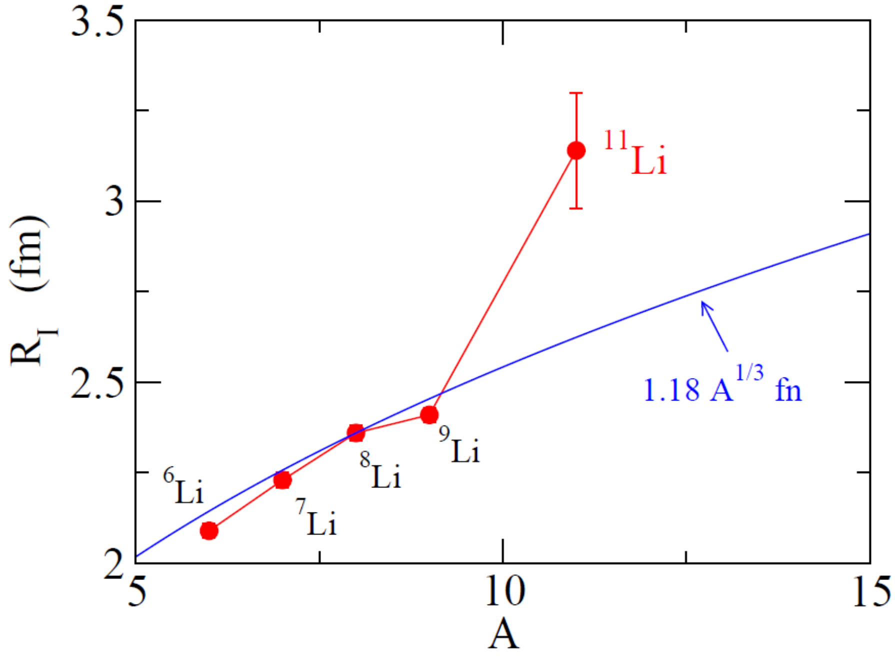
interaction cross section σ_I
= cross section for the change of Z a/o N in the incident nucleus

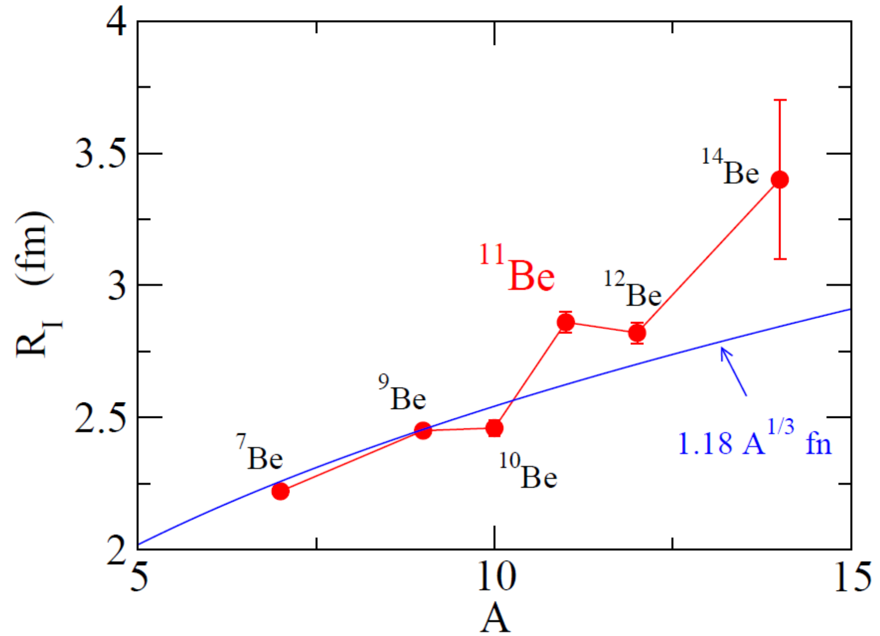


Slide: A. Ozawa

$$\sigma_I \sim \pi[R_I(P) + R_I(T)]^2 \longrightarrow R_I(P)$$

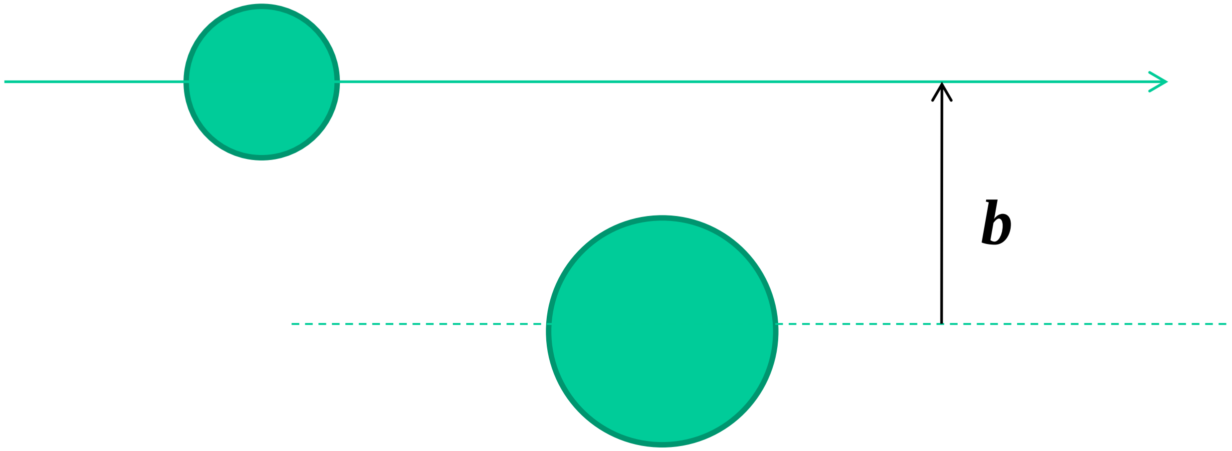
Discovery of **halo nuclei**





I. Tanihata, T. Kobayashi, O. Hashimoto et al., PRL55('85)2676; PLB206('88)592

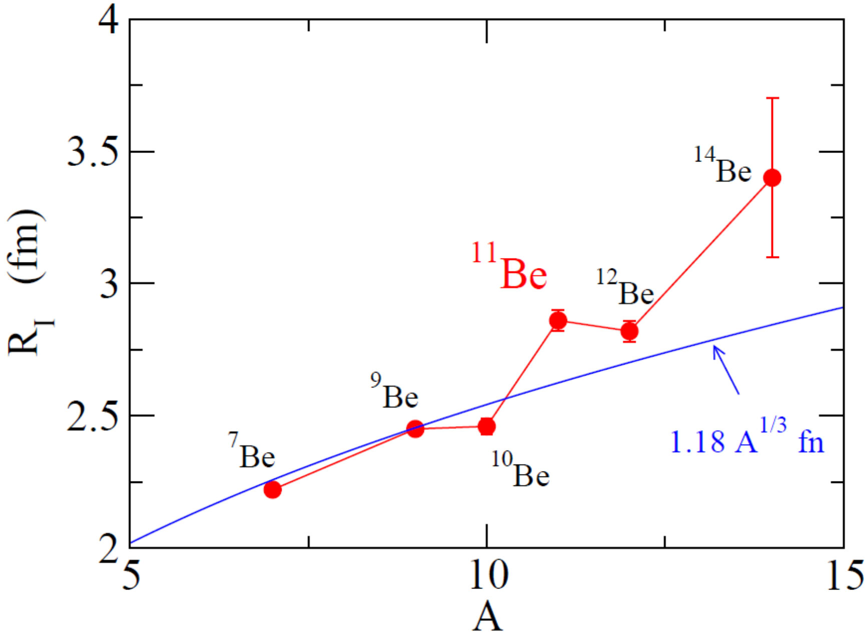
Reaction cross sections



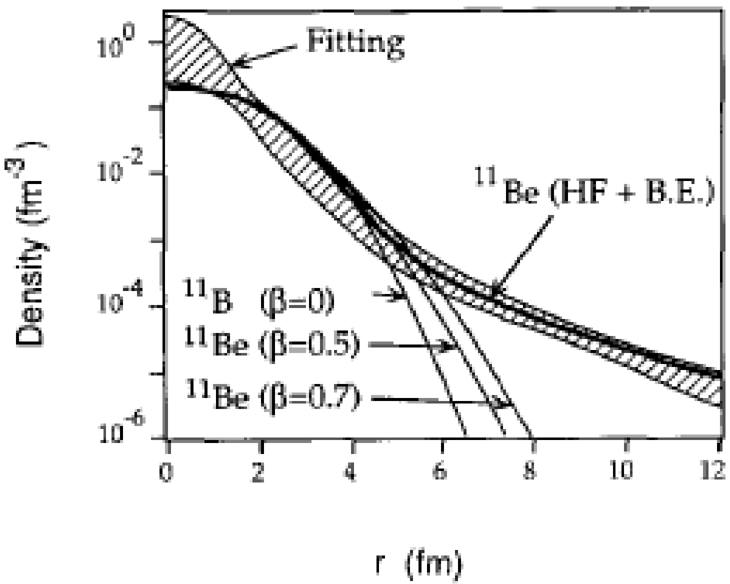
Glauber theory (optical limit approximation : OLA)

$$\sigma_R \sim 2\pi \int_0^\infty bdb \left[1 - \exp\left(-\sigma_{NN} \int d^2 s \rho_P^{(z)}(\boldsymbol{s}) \rho_T^{(z)}(\boldsymbol{s} - \boldsymbol{b})\right)\right]$$

- straight-line trajectory (high energy scattering)
- adiabatic approximation
- simplified treatment for multiple scattering: $(1-x)^N \to e^{-Nx}$



Density distribution which explains the experimental σ_R

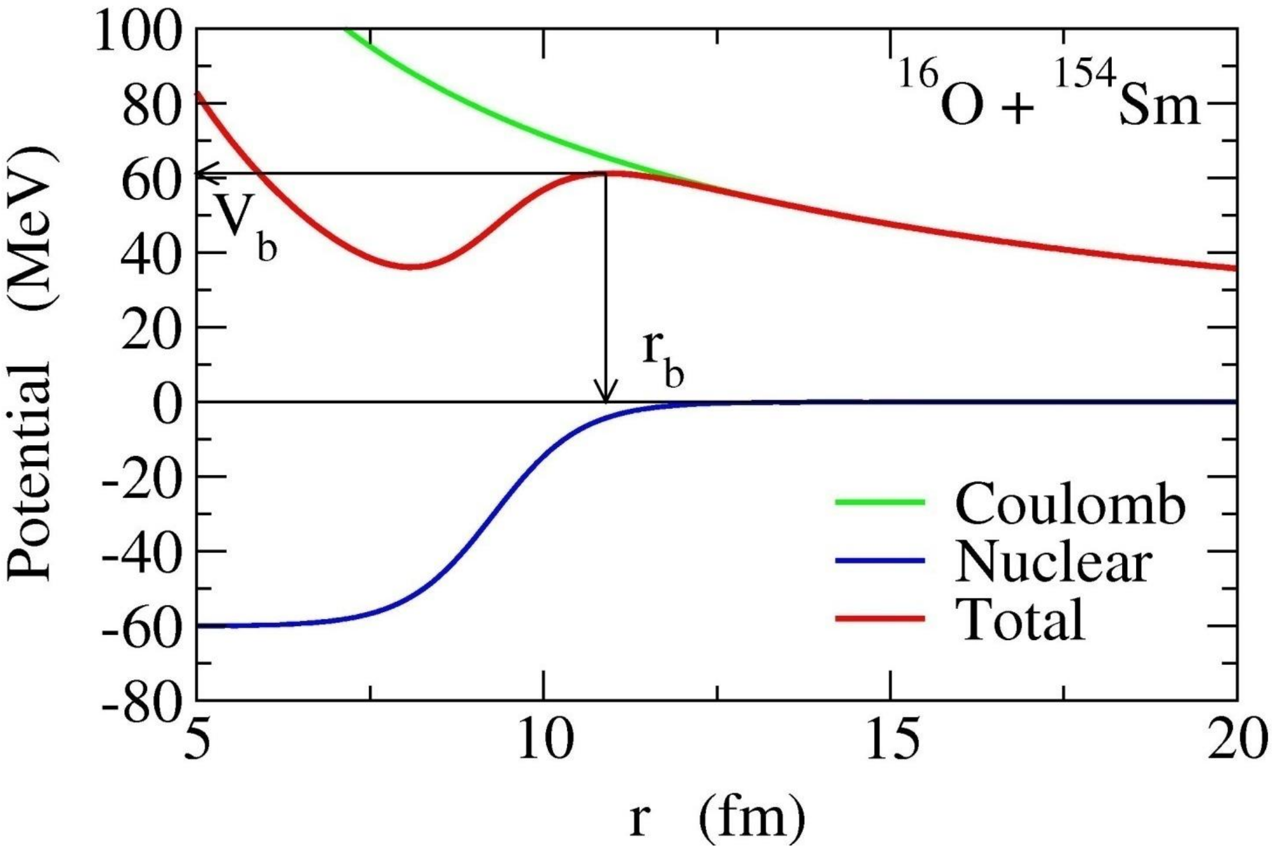


M. Fukuda et al., PLB268('91)339

$$\sigma_R \sim 2\pi \int_0^\infty bdb \left[1 - \exp\left(-\sigma_{NN} \int d^2 s \rho_P^{(z)}(\boldsymbol{s})\rho_T^{(z)}(\boldsymbol{s}-\boldsymbol{b})\right)\right]$$

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)

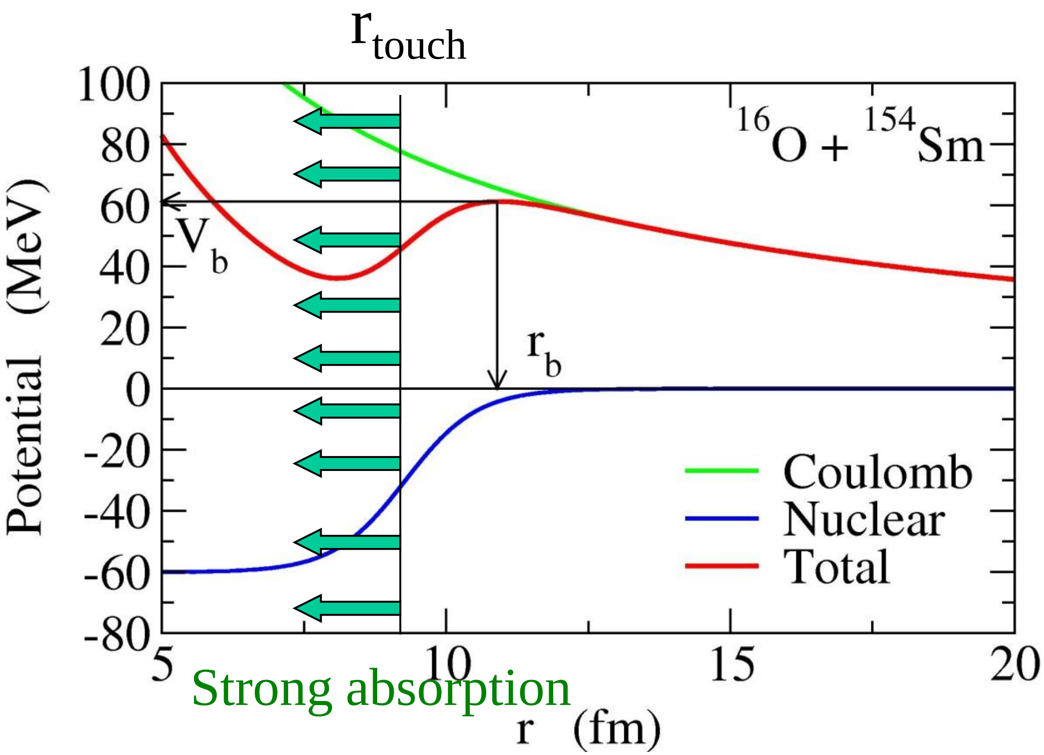
- above barrier
- sub-barrier
- deep subbarrier

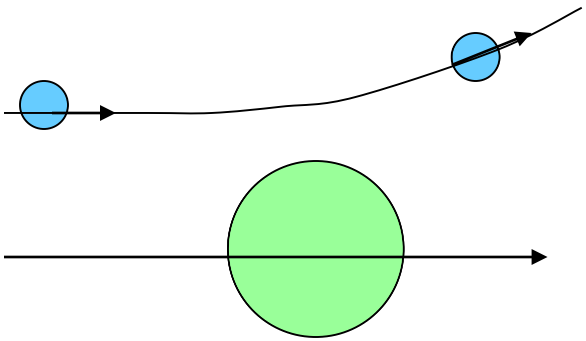
Three important features of heavy-ion reactions

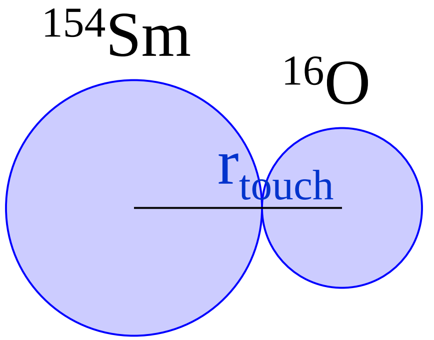
1. Coulomb interaction: important
2. Reduced mass: large → (semi-) classical picture
   concept of trajectory

$$\mu = \frac{m_T\, m_P}{m_T + m_P}$$

3. Strong absorption inside the Coul. barrier

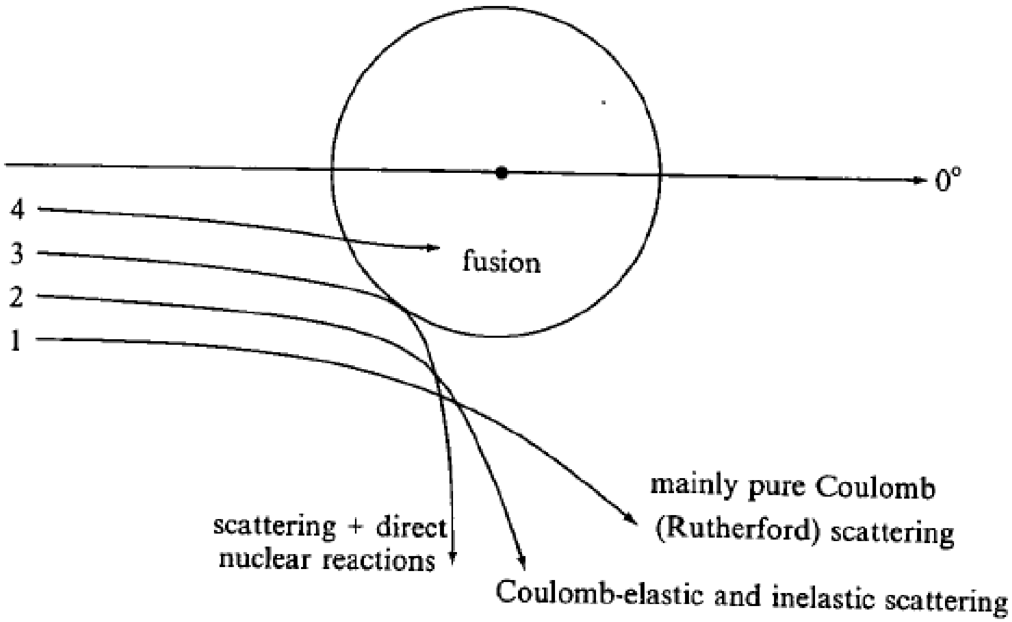


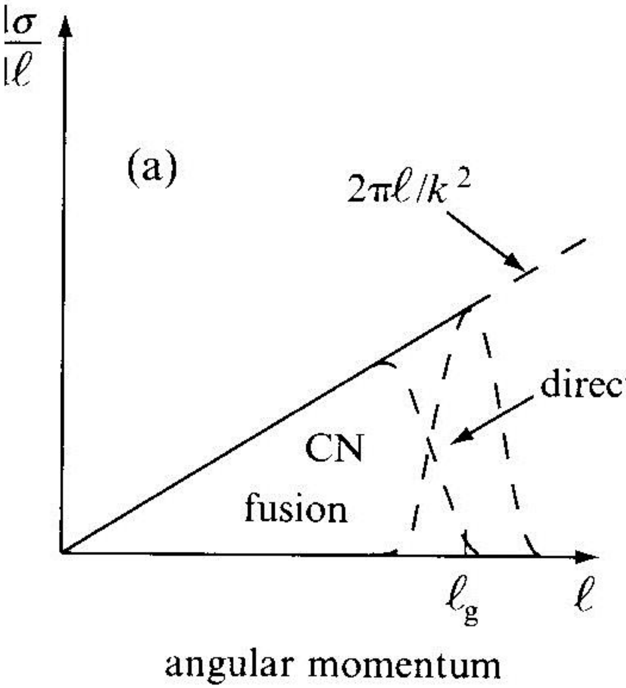




Automatic compound nucleus formation once touched (assumption of strong absorption)

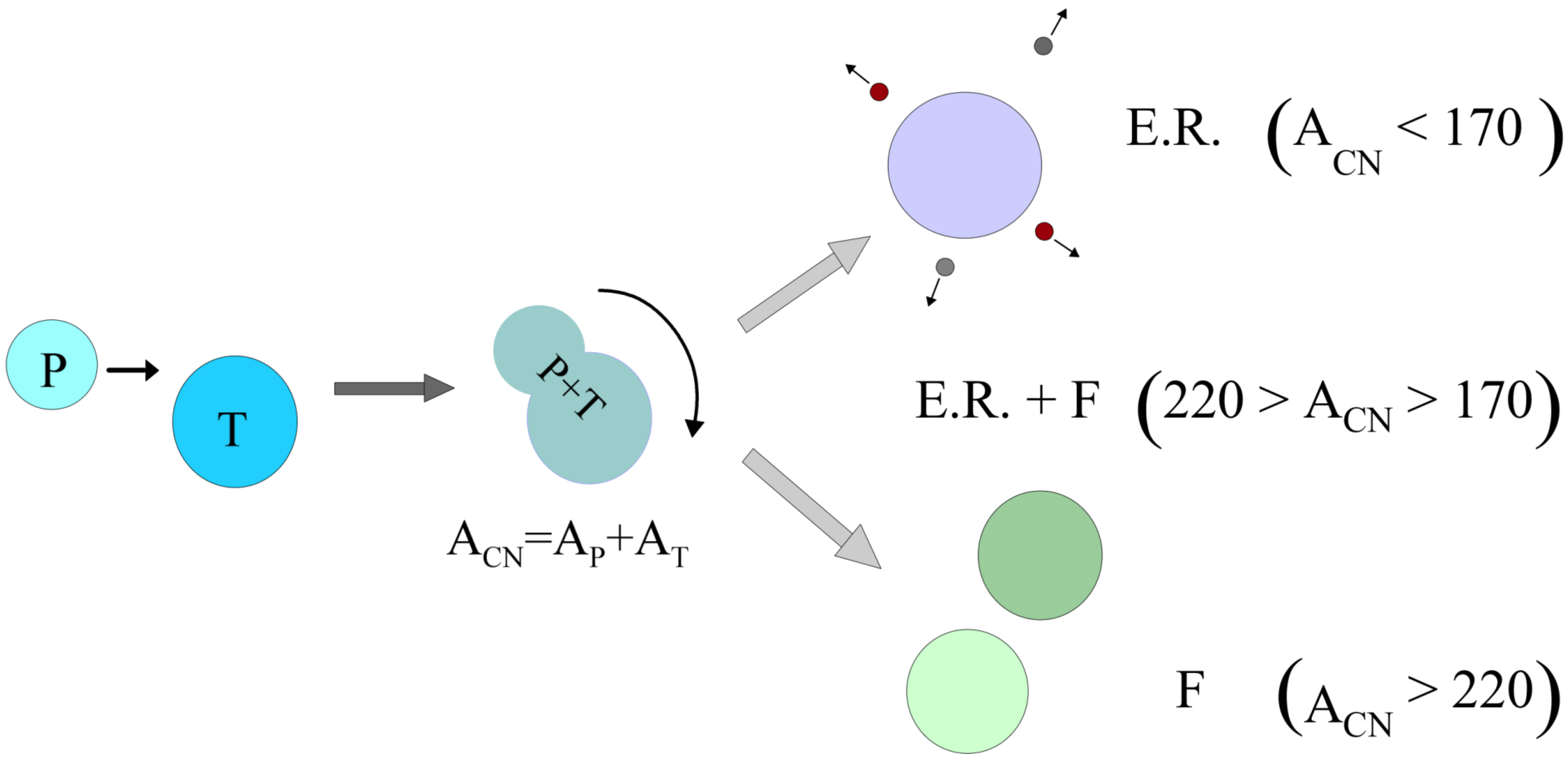
Partial decomposition of reaction cross section





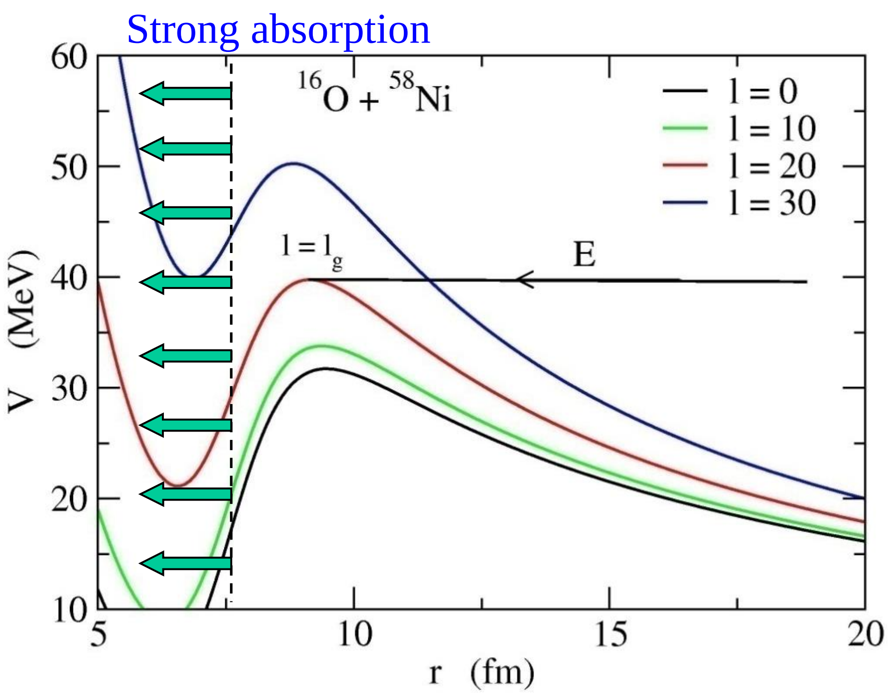
Taken from J.S. Lilley,
"Nuclear Physics"

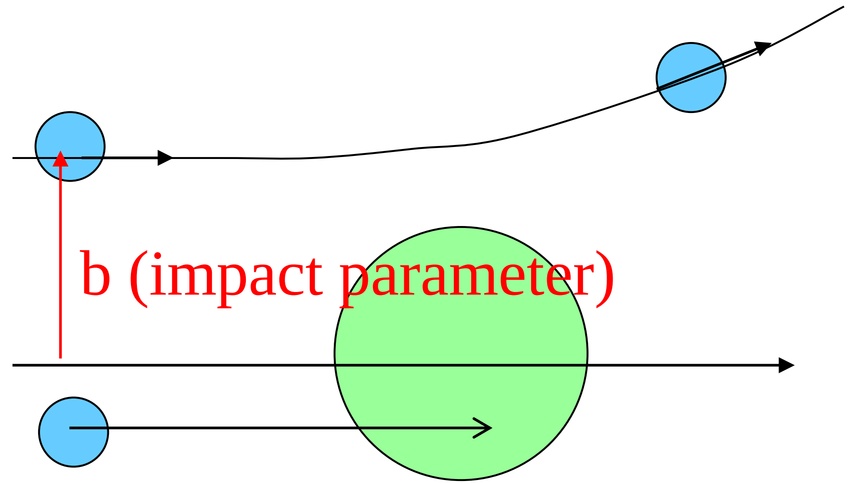
Fusion: compound nucleus formation



courtesy: Felipe Canto

classical fusion cross sections





$$l_{cl} = kb \qquad k = \sqrt{2\mu E/\hbar^2}$$

$l < l_g$: can access to the strong absorption region classically

$$\Rightarrow \quad b_g = l_g/k$$

$$\sigma^{cl} = 2\pi \int_0^{b_g} b\,db = \pi\, b_g^2$$

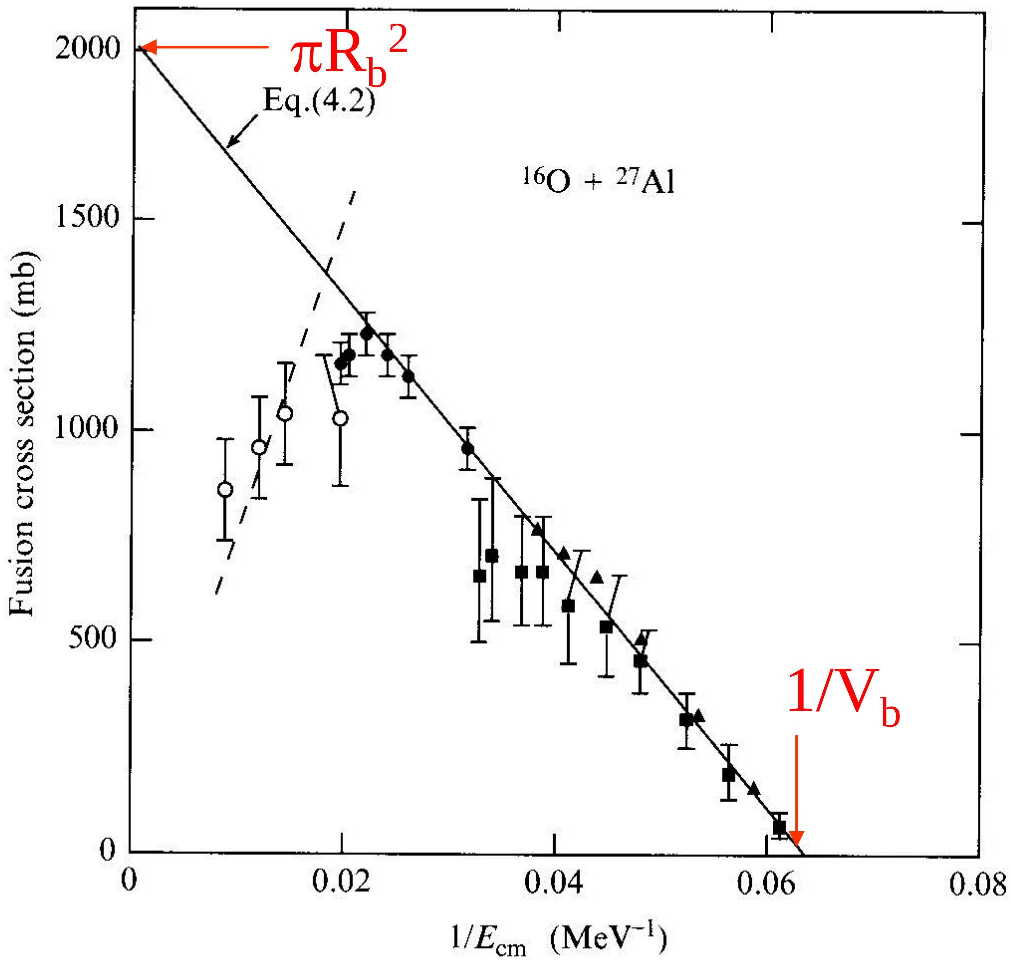
$$V_b + \frac{(kb_g)^2\hbar^2}{2\mu R_b^2} = E$$

$$\sigma_{\rm fus}^{cl}(E) = \pi R_b^2 \left(1 - \frac{V_b}{E}\right)$$

σ_{fus} vs 1/*E* (~70's)

Classical fusion cross section is proportional to $1/E$:

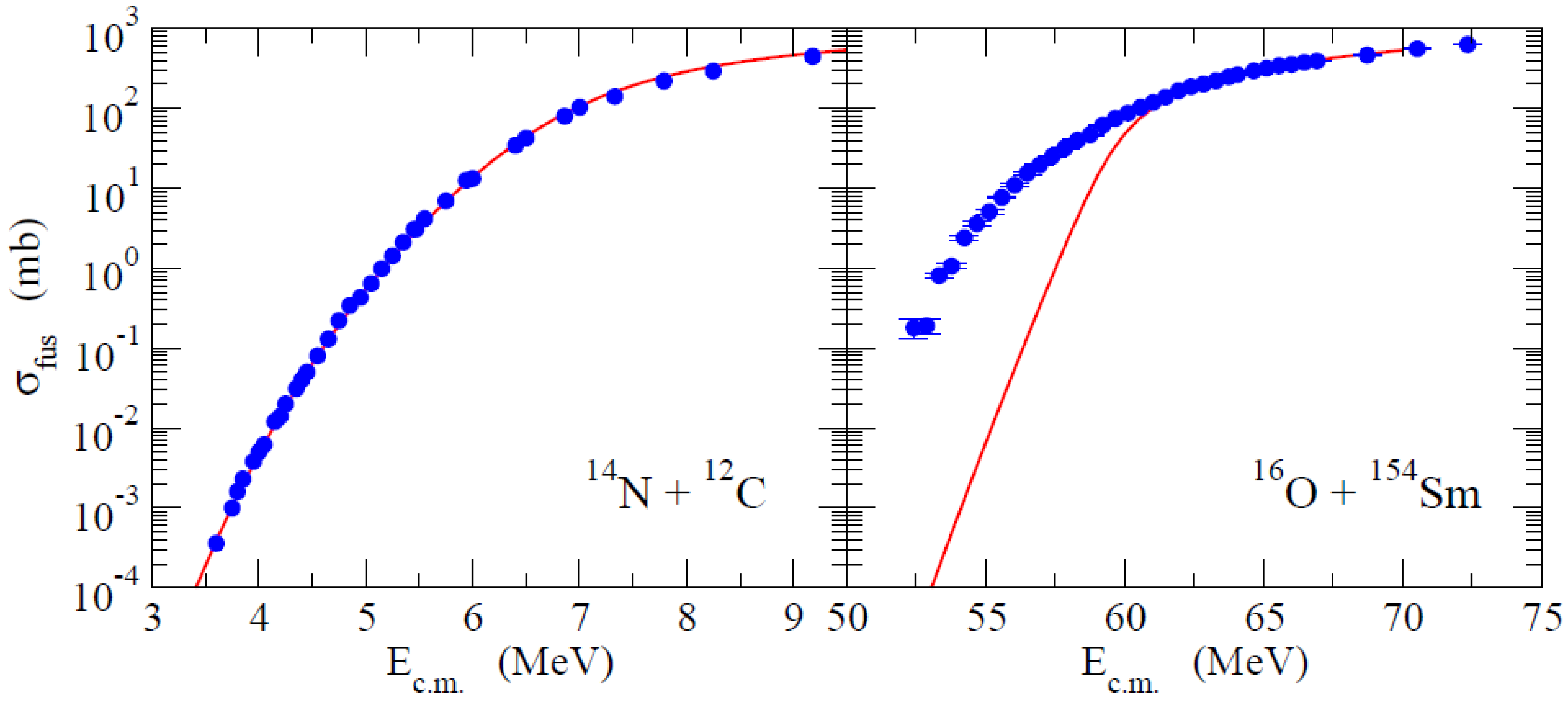
$$\sigma^{cl}_{\mathrm{fus}}(E) = \pi R_b^2 \left(1 - \frac{V_b}{E}\right)$$



Taken from J.S. Lilley, "Nuclear Physics"

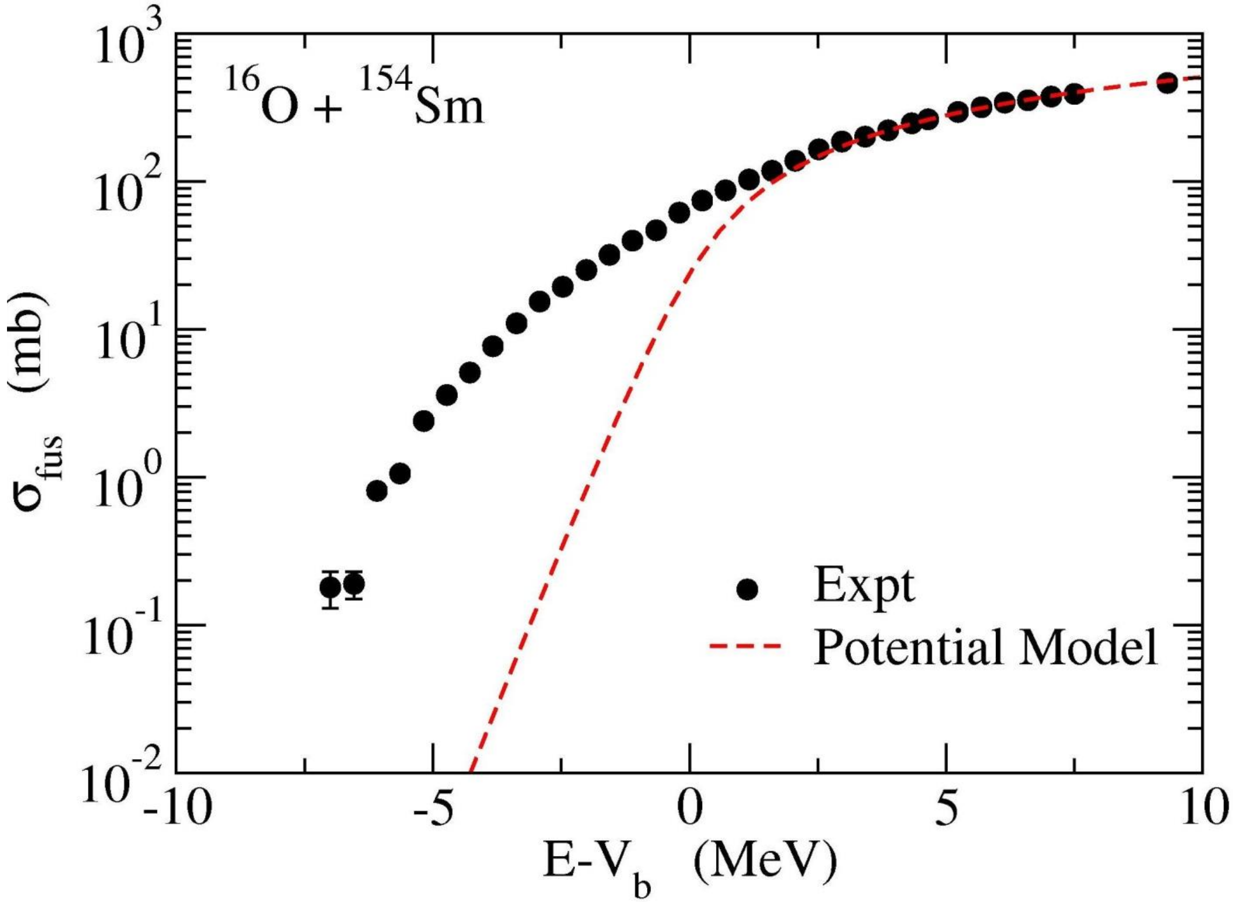
Fusion cross sections at subbarrier energies

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



Simple potential model:

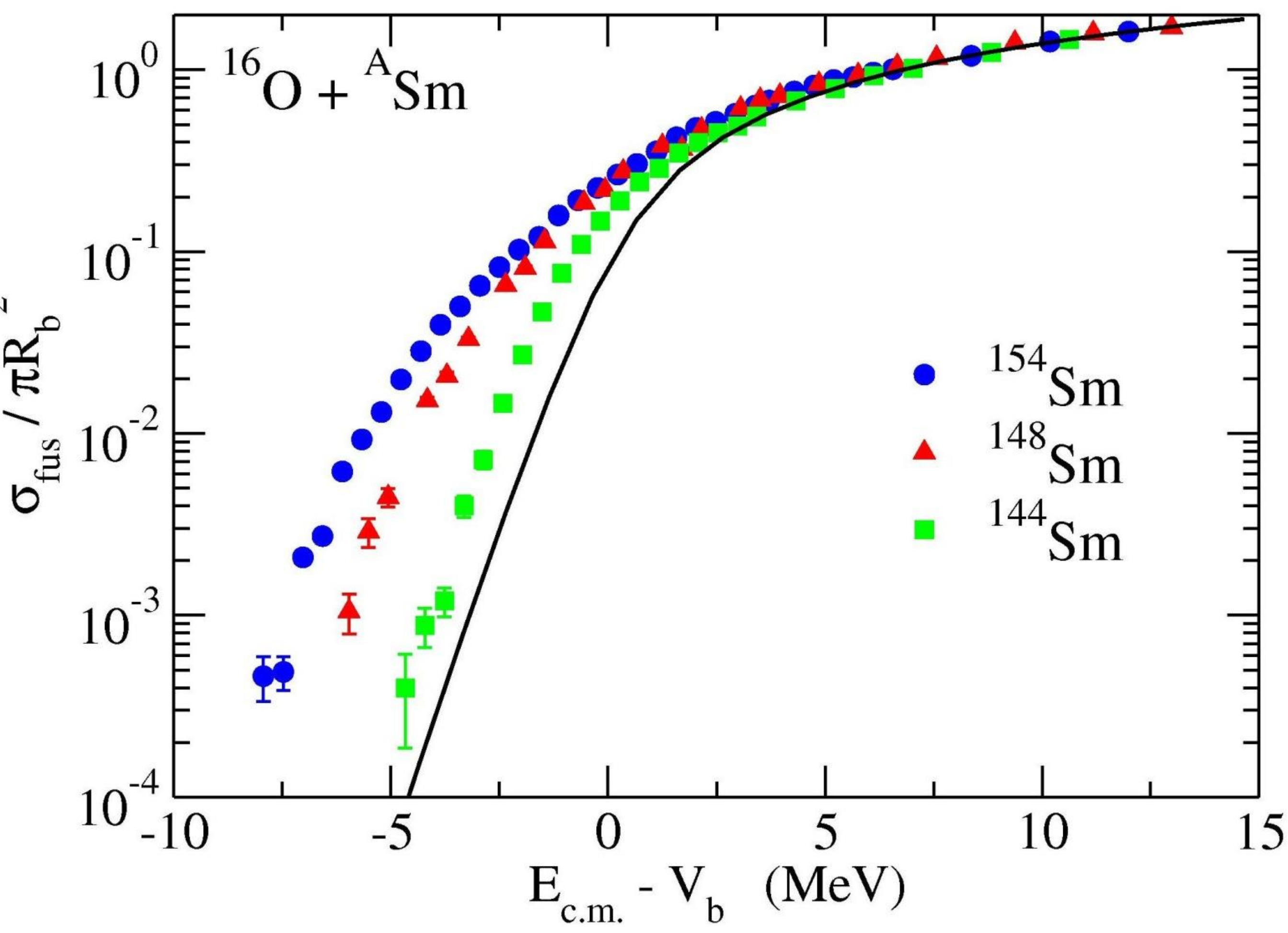
- ➢OK for relatively light systems
- ➢underestimates σ_{fus} for heavier systems at subbarrier energies



Potential model:
Reproduces the data reasonably well for
$E > V_b$

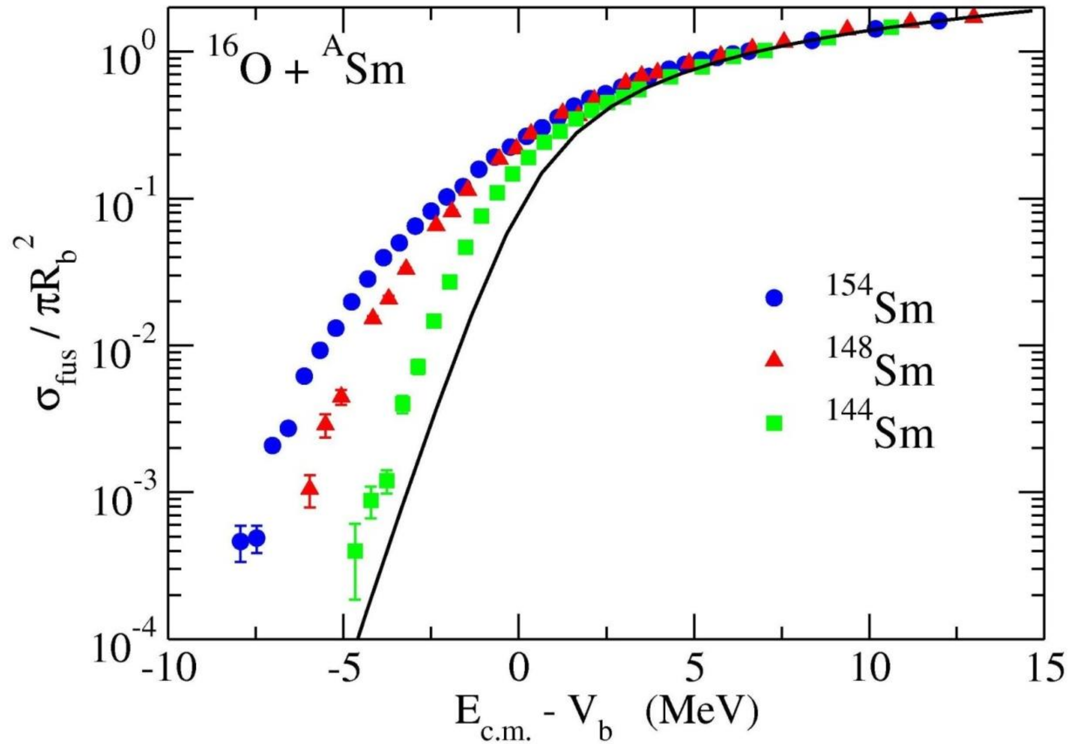
Underpredicts σ_{fus} for
$E < V_b$

cf. seminal work:
R.G. Stokstad et al., PRL41('78)465
PRC21('80)2427

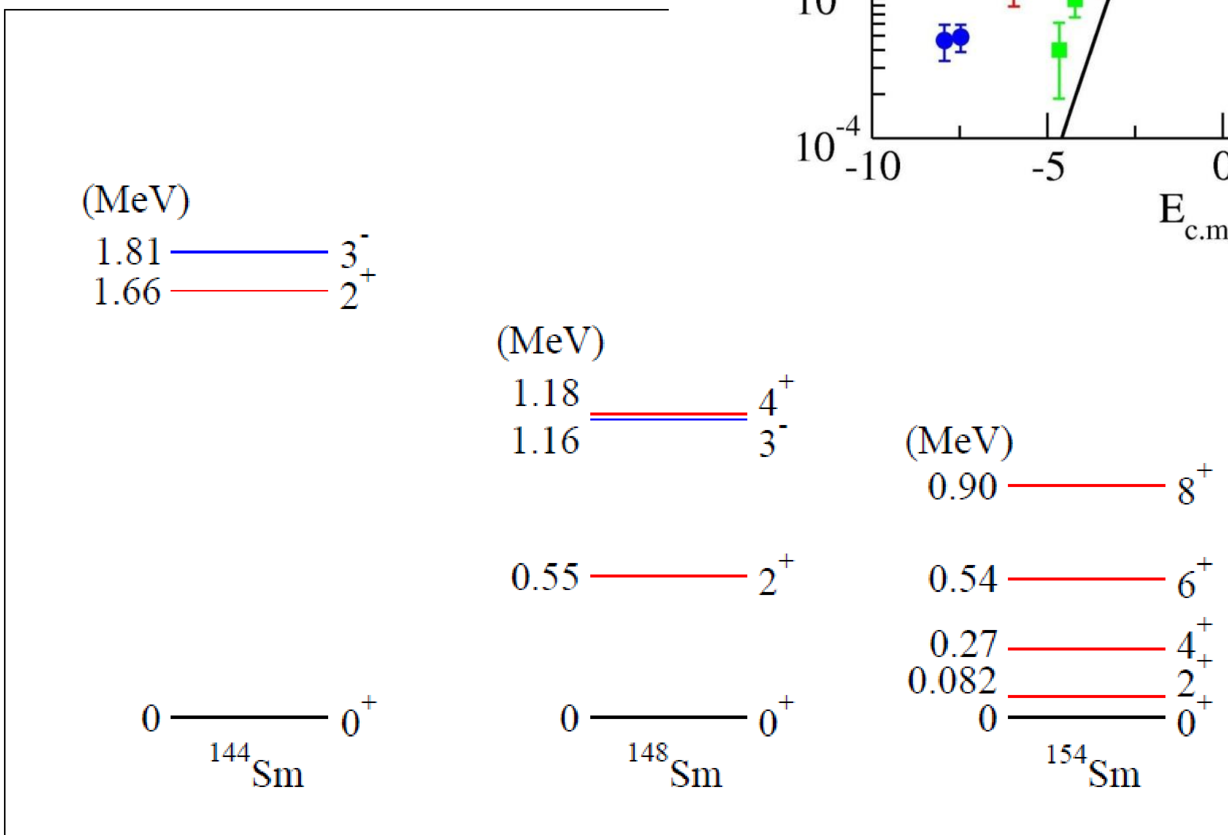


Strong target dependence at $E < V_b$

low-lying collective excitations?



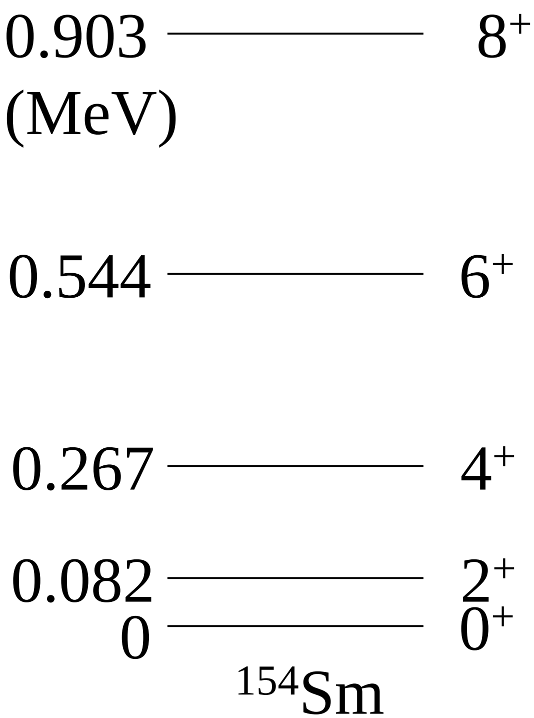
$^{16}O + {}^{A}Sm$
$\sigma_{fus} / \pi R_b^2$
$E_{c.m.} - V_b$ (MeV)
^{154}Sm
^{148}Sm
^{144}Sm



(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

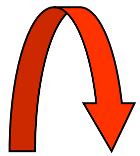


$$E_I \sim \frac{I(I+1)\hbar^2}{2\mathcal{J}}$$

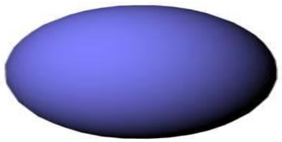
cf. Rotational energy of a rigid body
(Classical mechanics)

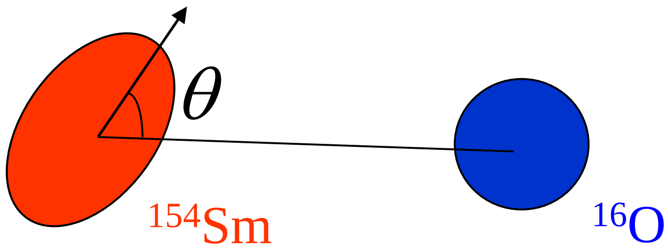
$$E = \frac{1}{2}\mathcal{J}\omega^2 = \frac{I^2}{2\mathcal{J}}$$

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

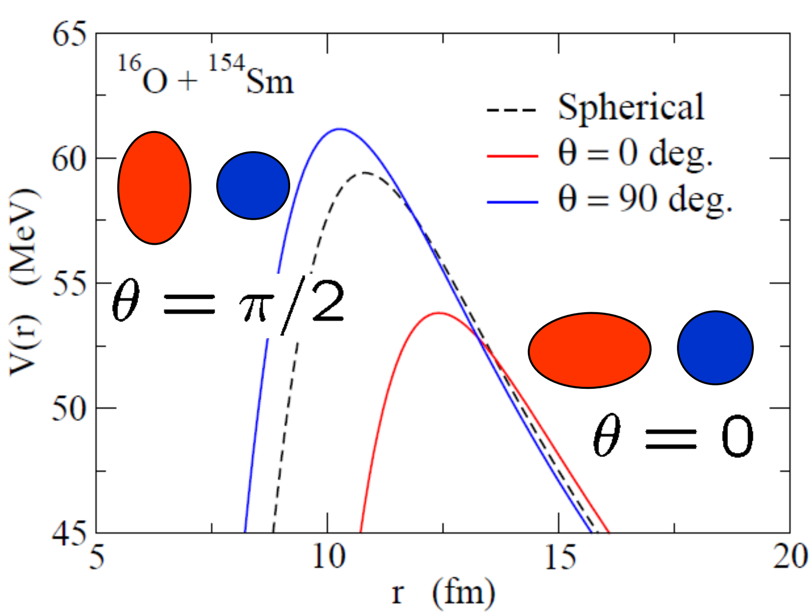


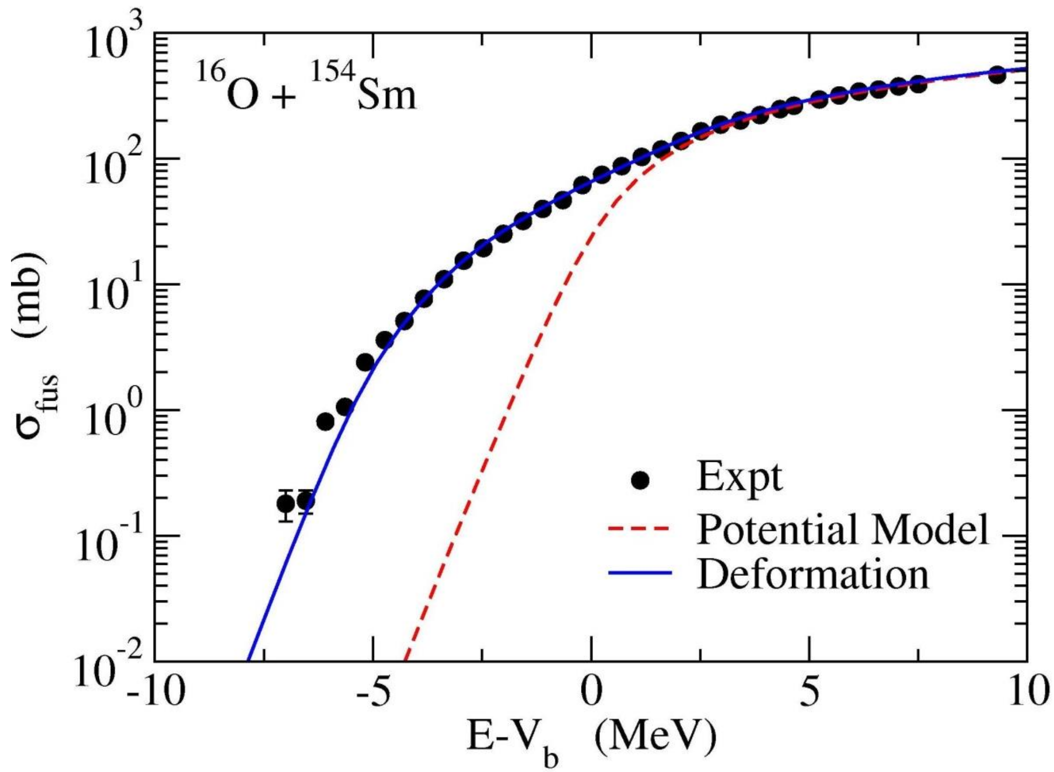
^{154}Sm is deformed





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





The barrier is lowered for θ=0

because an attraction works from large distances.

The barrier increases for θ=π/2.

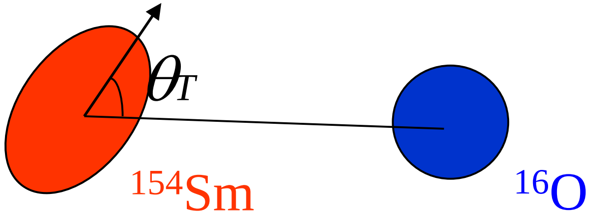
because the rel. distance has to get small for the attraction to work

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

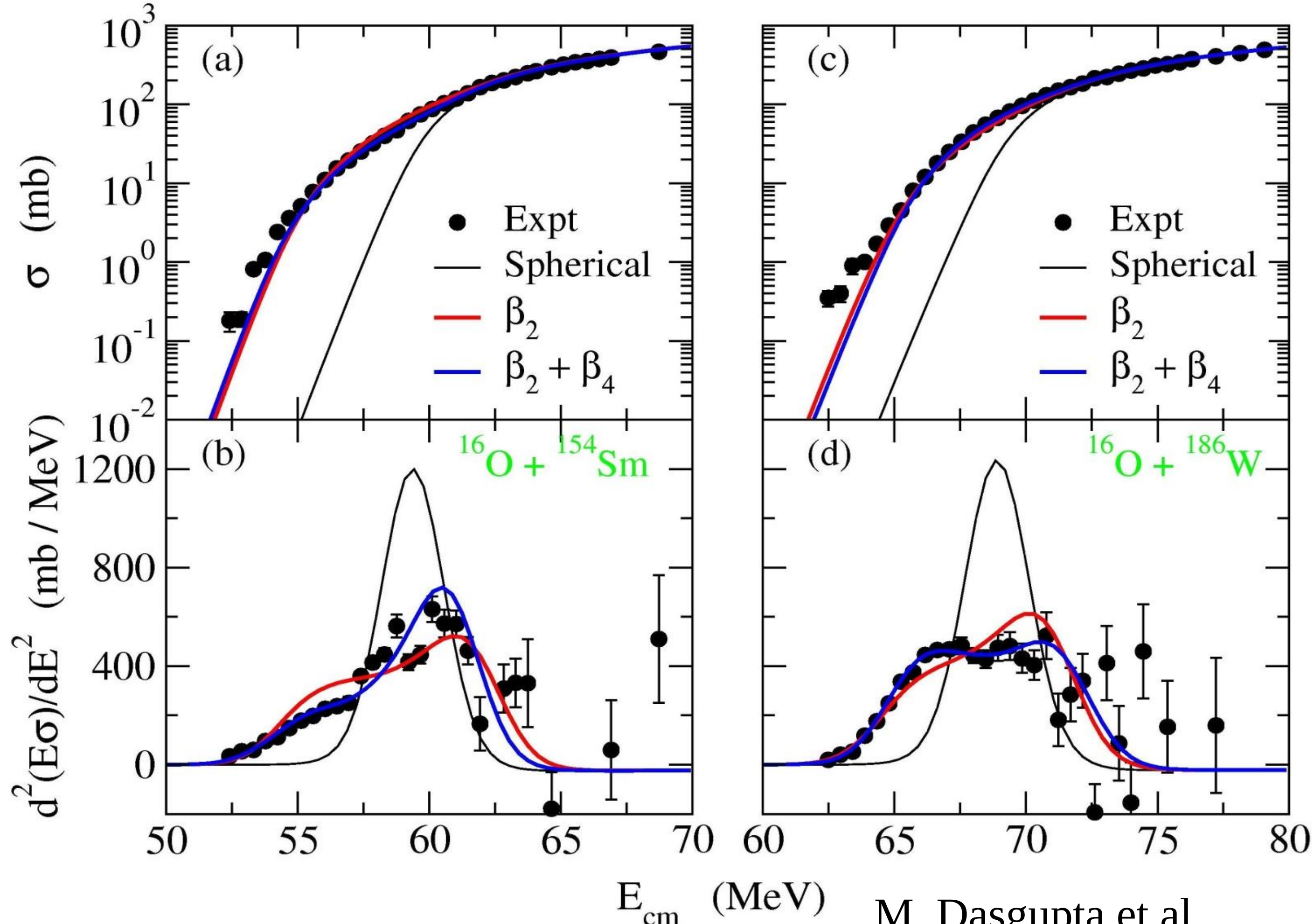
Fusion: interesting probe for nuclear structure

Fusion barrier distributions

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

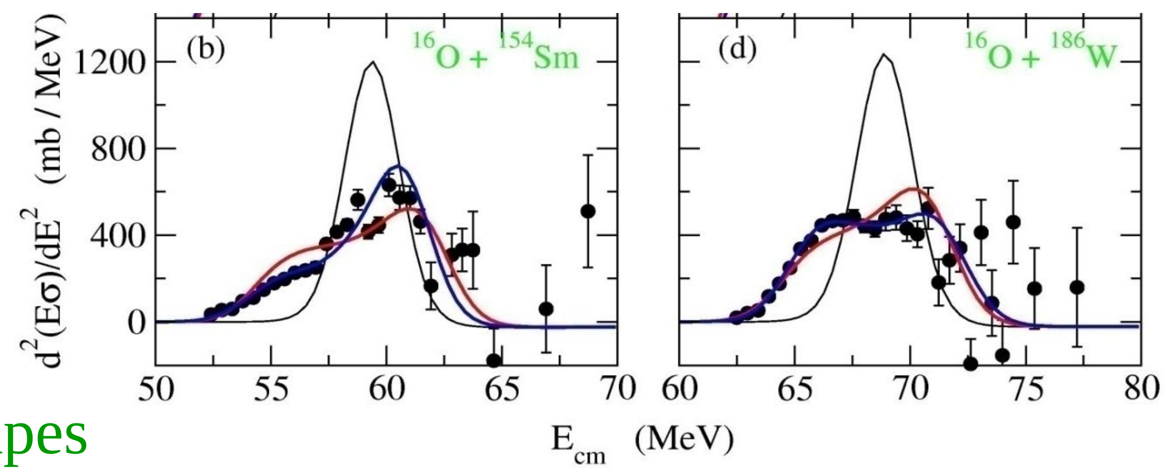


$$\sigma_{\text{fus}}(E) = \int_0^1 d(\cos\theta_T)\sigma_{\text{fus}}(E;\theta_T)$$



M. Dasgupta et al.,
Annu. Rev. Nucl. Part. Sci. 48('98)401

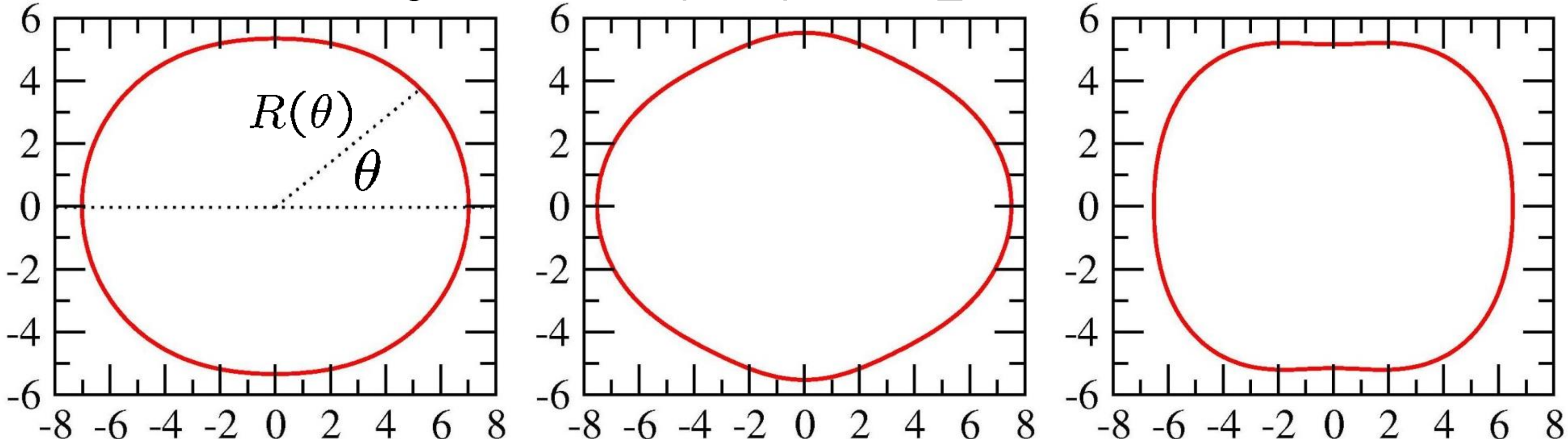
Investigate nuclear shape through barrier distribution



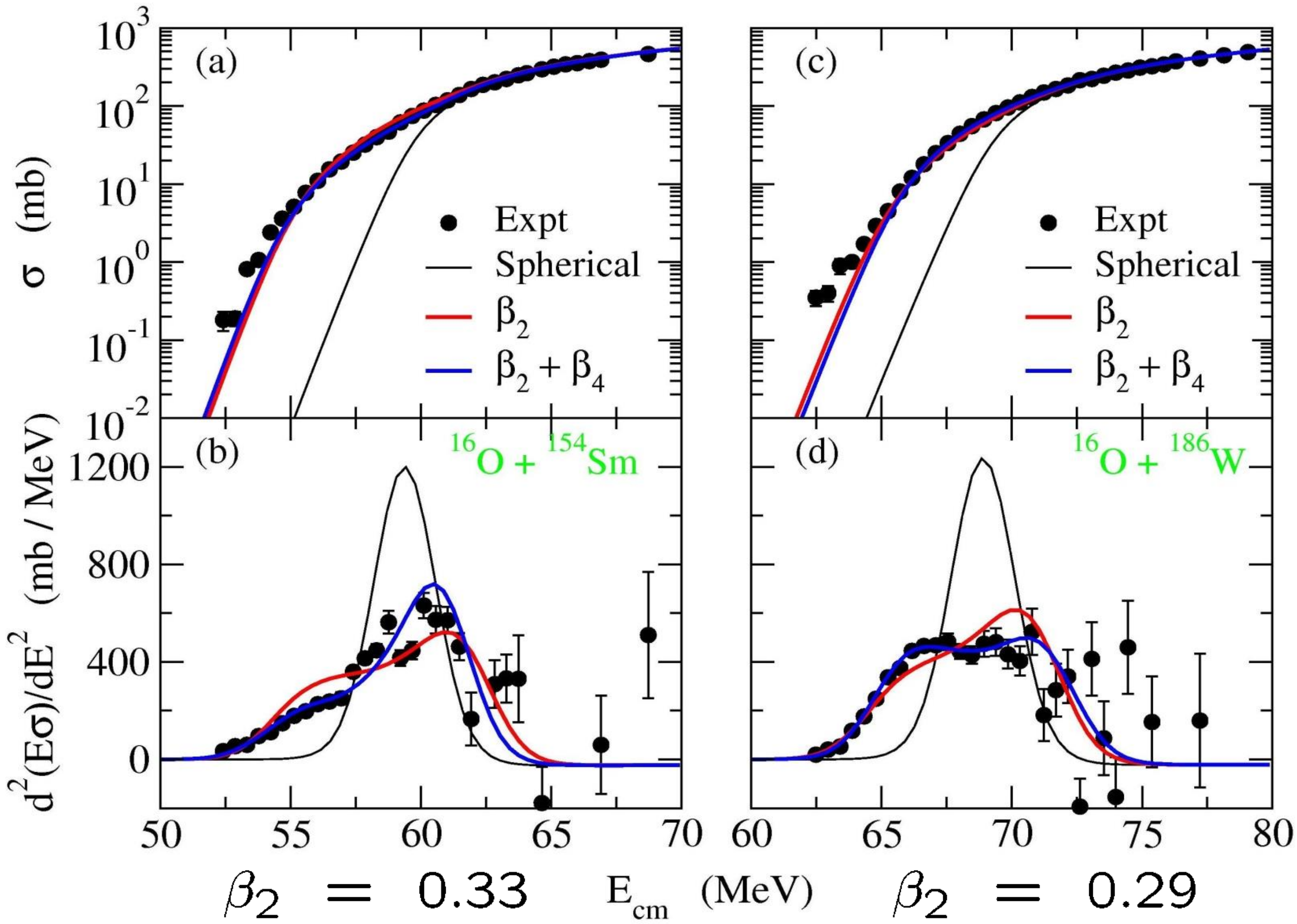
Nuclear shapes

$$R(\theta) = R_0(1 + \beta_2 Y_{20}(\theta) + \beta_4 Y_{40}(\theta) + \cdots)$$

$$R_0 = 5.9 \text{ (fm)}, \quad \beta_2 = 0.3$$

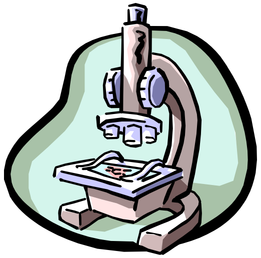


$\beta_4 = 0$ $\beta_4 = 0.1$ $\beta_4 = -0.1$



$\beta_2 = 0.33$ $\beta_2 = 0.29$

$\beta_4 = +0.05$ $\beta_4 = -0.03$

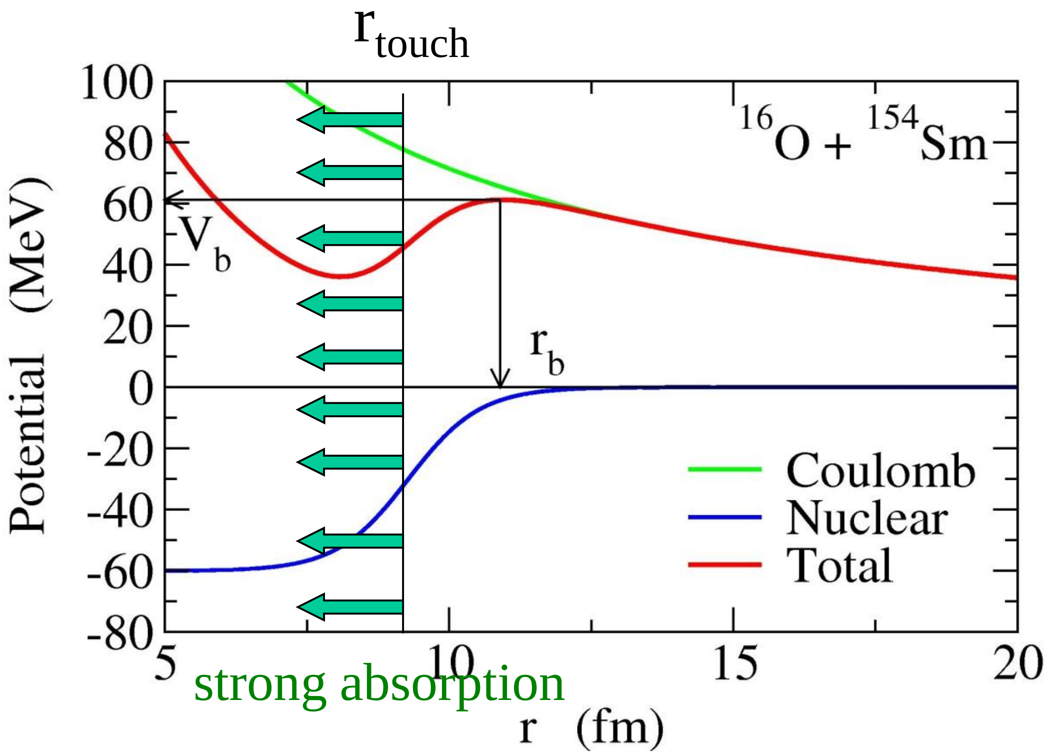


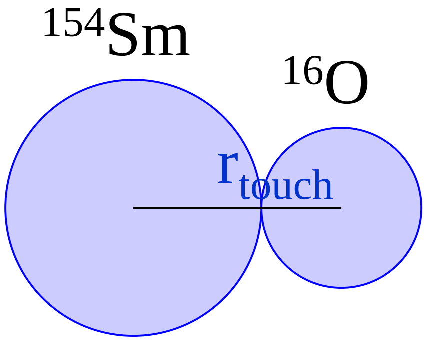
By taking the barrier distribution, one can very clearly see the difference due to β_4!

→ Fusion as a quantum tunneling microscope for nuclei

Heavy-ion subbarrier fusion reactions in the SHE region

- Fusion of medium-heavy systems:



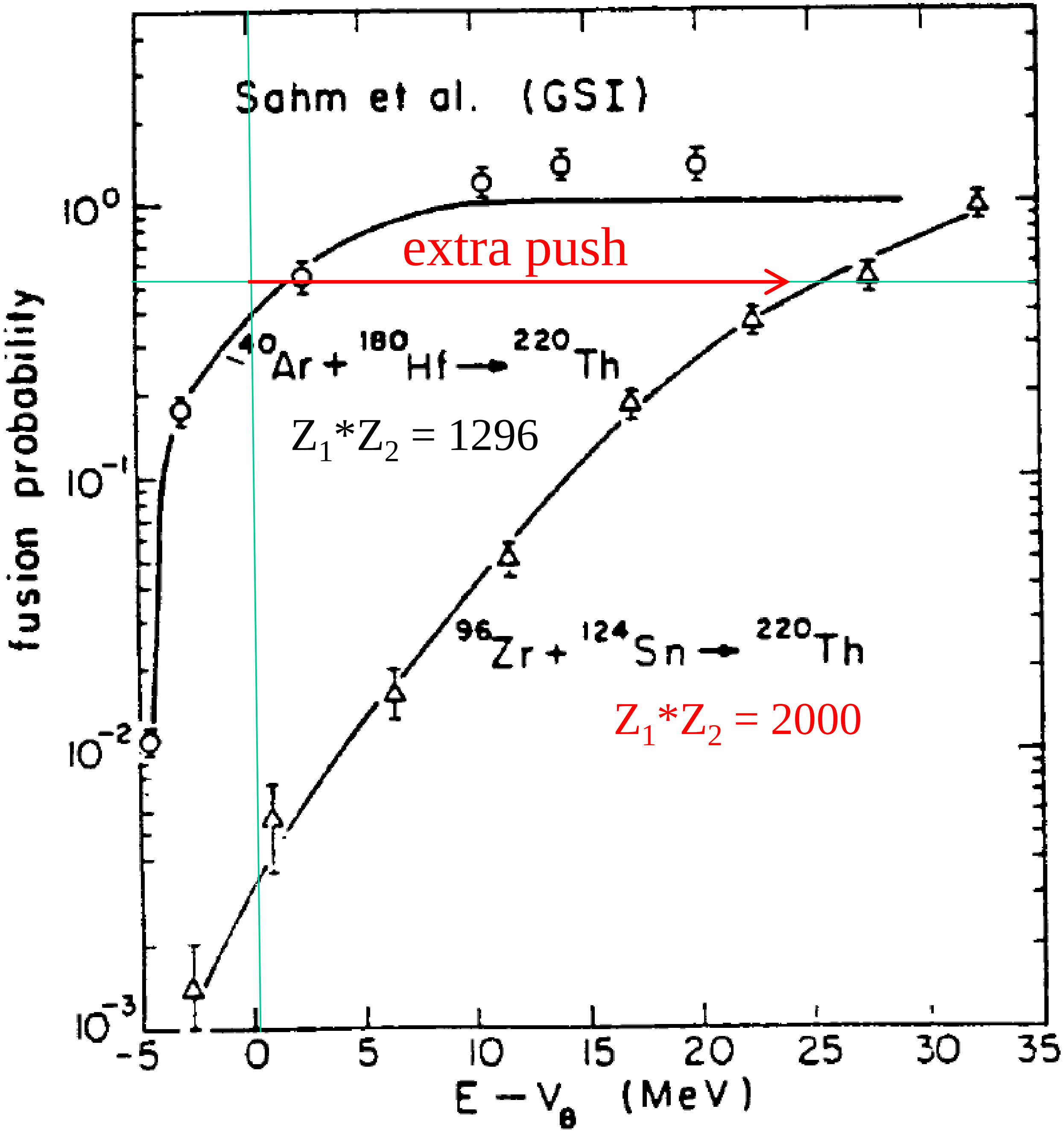


Compound nucleus: automatically formed once touched (strong absorption)

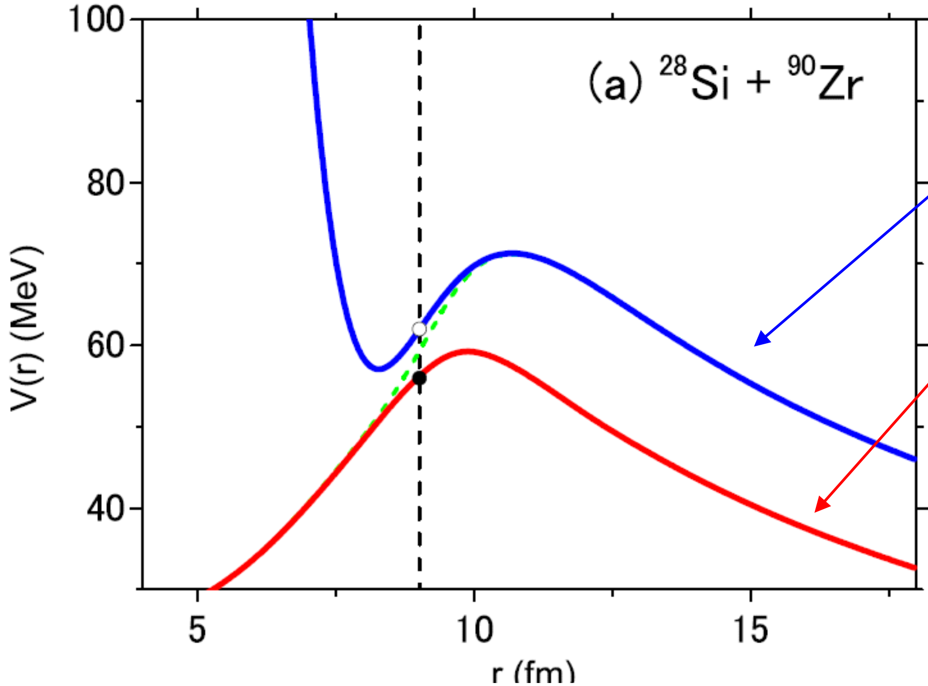
- Fusion of heavy and super-heavy systems

Large probability of re-separation (due to the strong Coulomb repulsion)

[This happens for $Z_1 * Z_2 > 1600 \sim 1800$.]

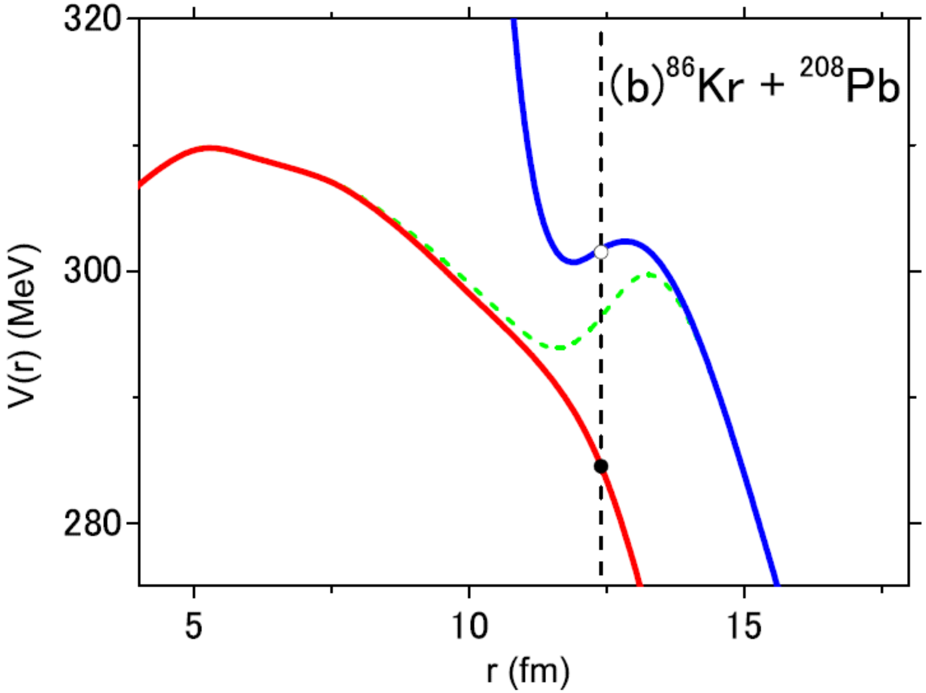


C.-C. Sahm et al.,
Z. Phys. A319('84)113



2-body potential before touching

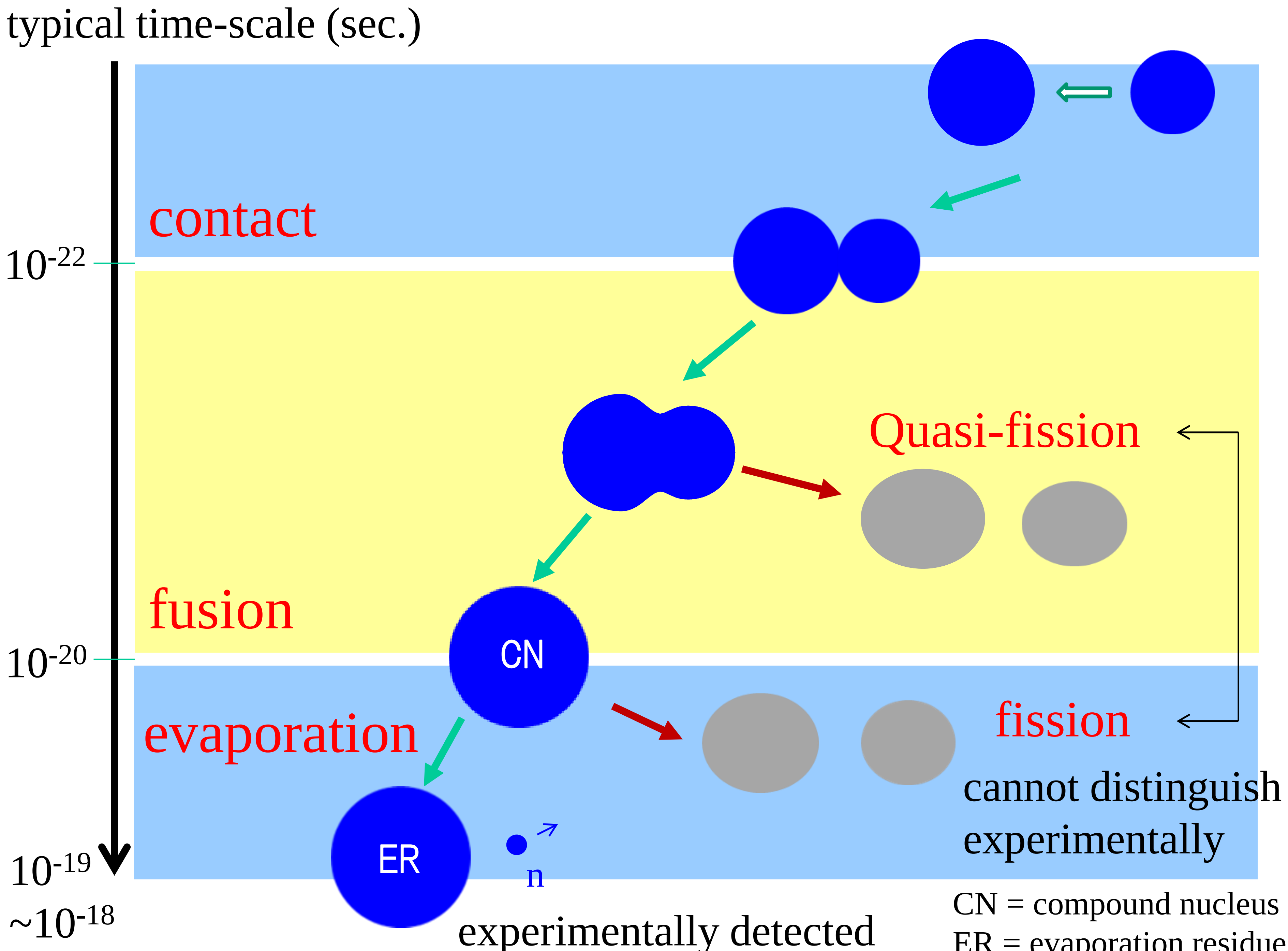
1-body potential after touching



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

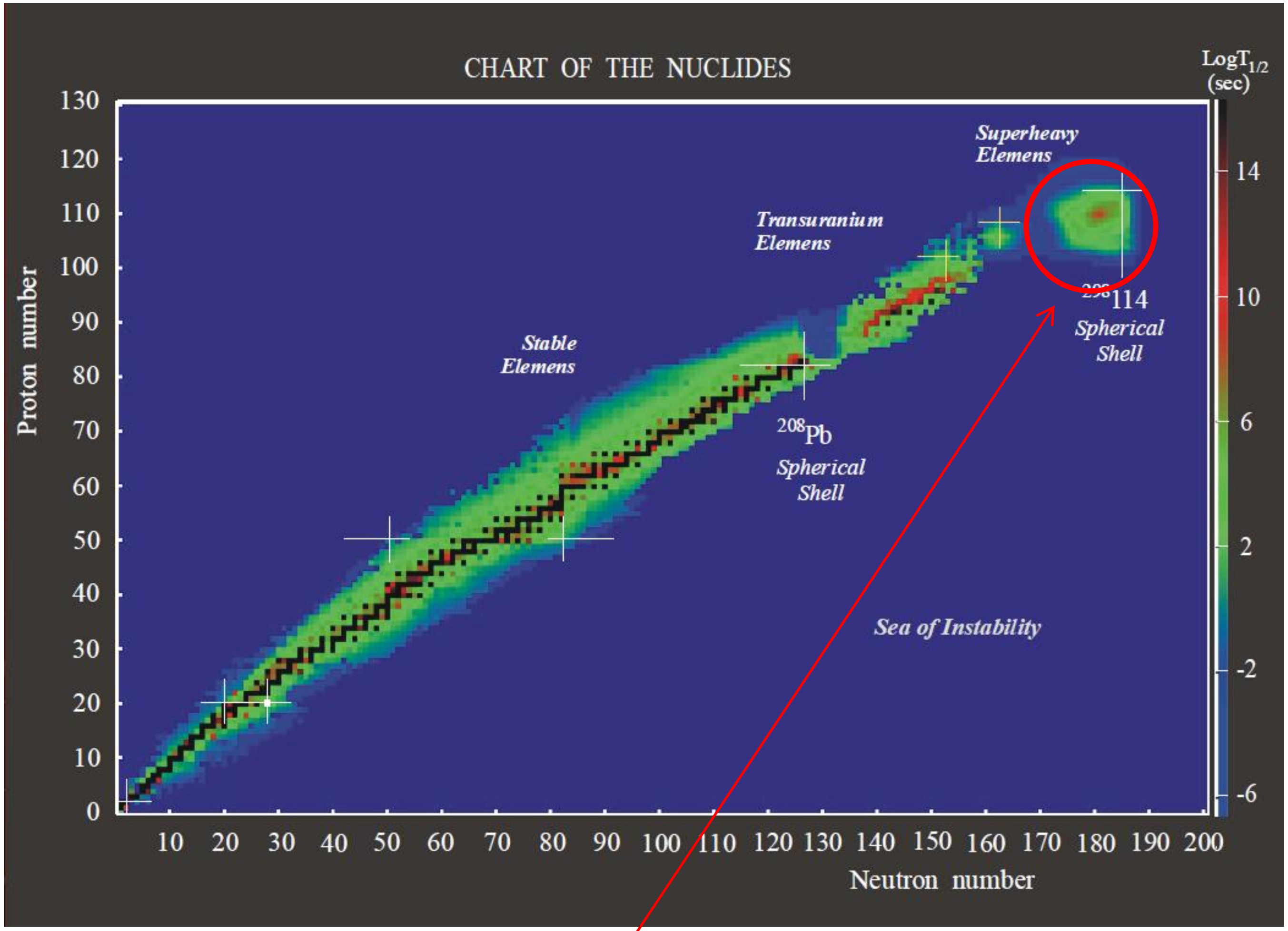
↓

Re-separation if failed (quasi-fission)



typical time-scale (sec.)
contact
10^{-22}
Quasi-fission
fusion
CN
10^{-20}
evaporation
fission
cannot distinguish experimentally
ER
n
10^{-19}
$\sim10^{-18}$
experimentally detected
CN = compound nucleus
ER = evaporation residue

Heavy-ion fusion for SHE



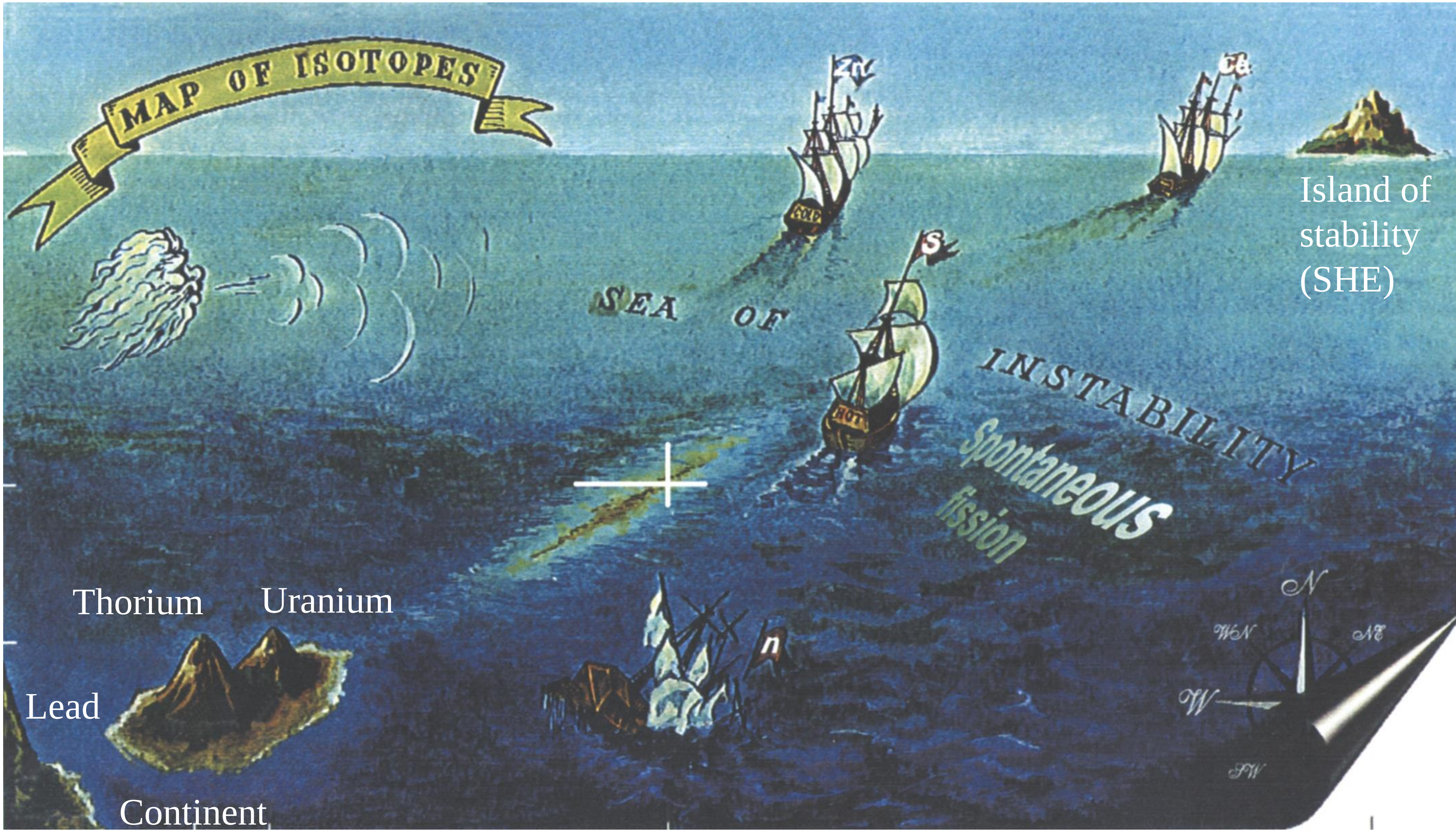
Yuri Oganessian

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

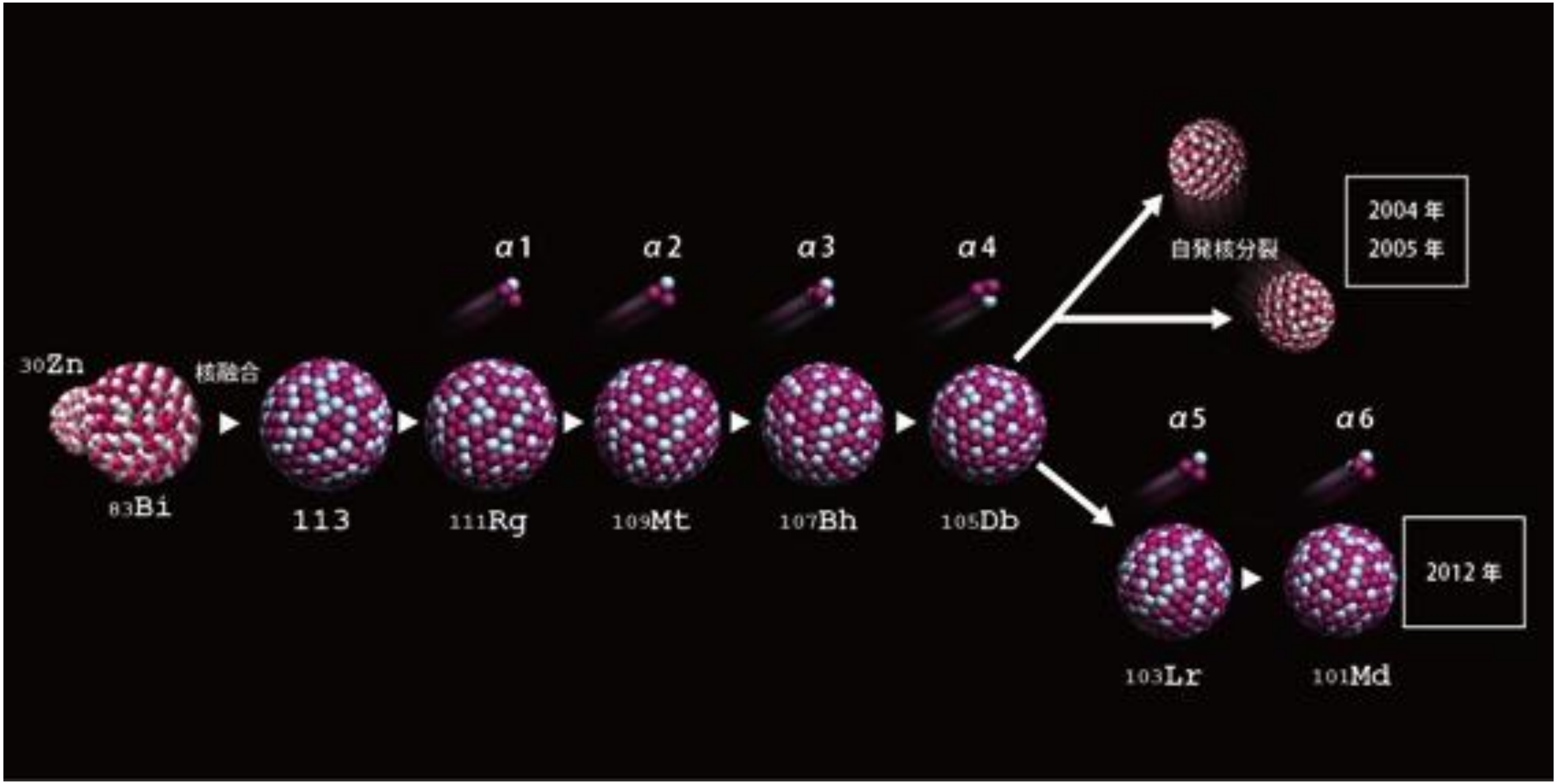
e.g., H. Koura et al. (2005)



Yuri Oganessian

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

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



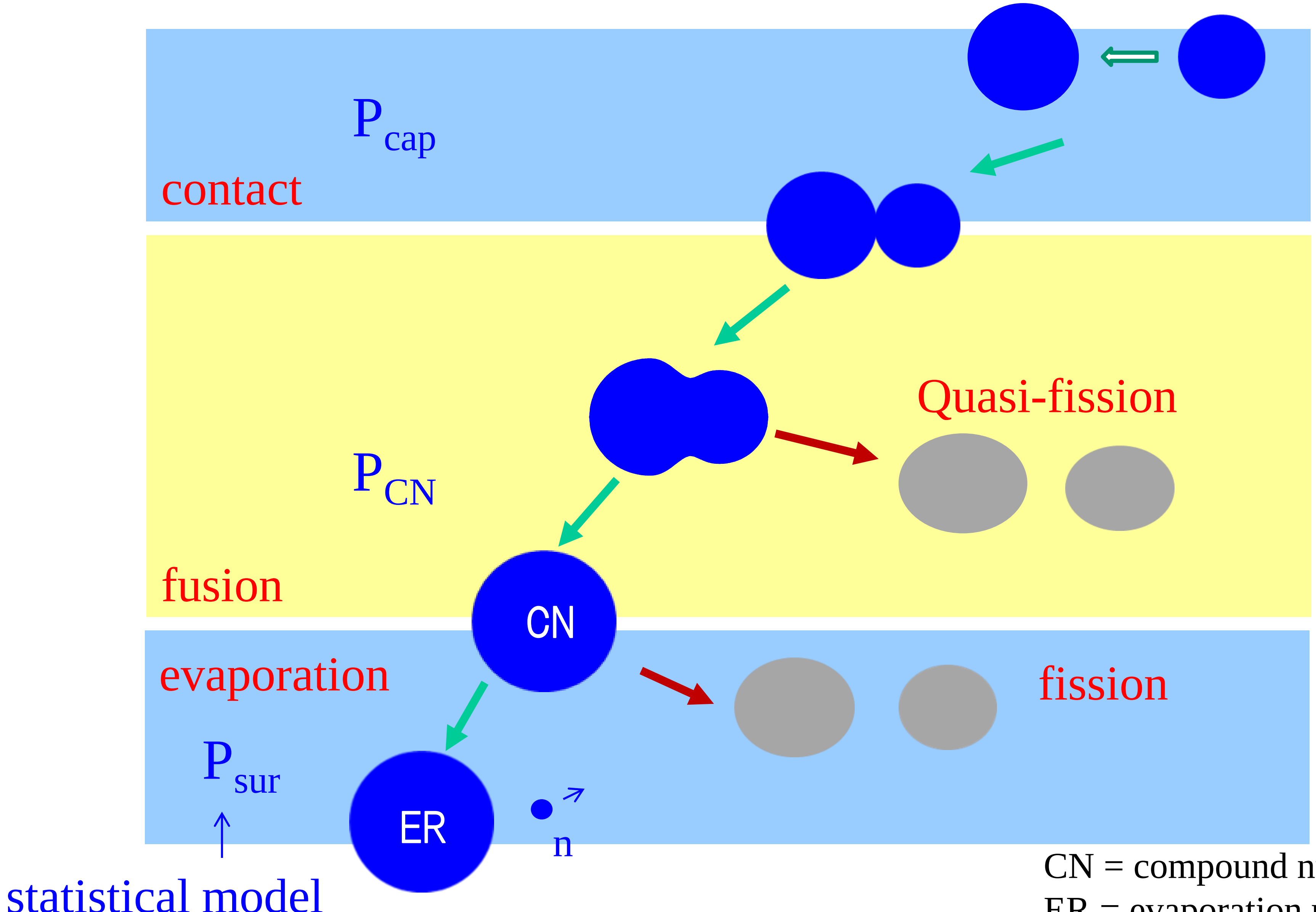
K. Morita et al., J. Phys. Soc. Jpn. 81('12)103201

$$\sigma_{ER} = 22^{+20}_{-13}\ \text{fb}$$

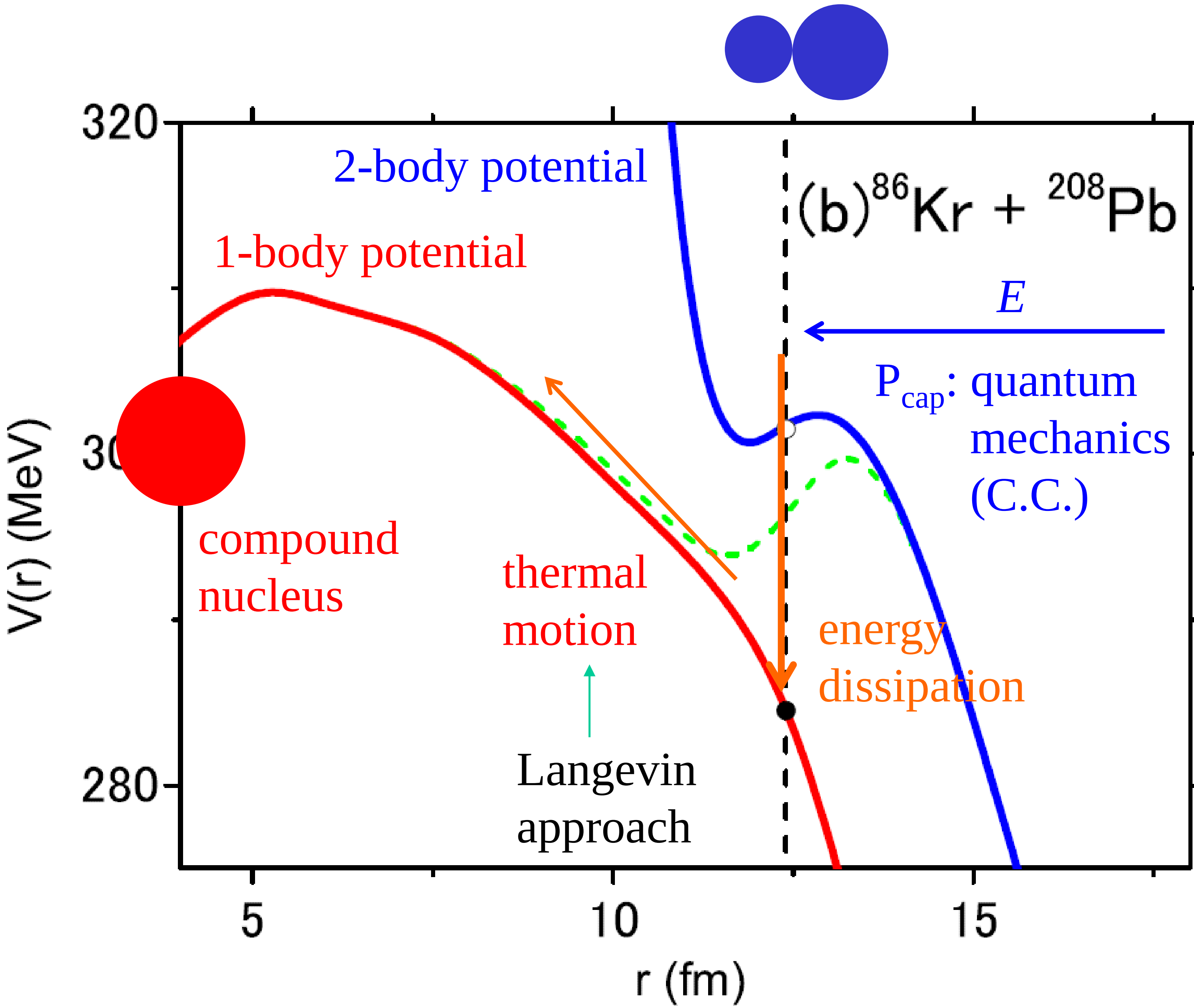
only 3 events for 553 days experiment

Theoretical treatment

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

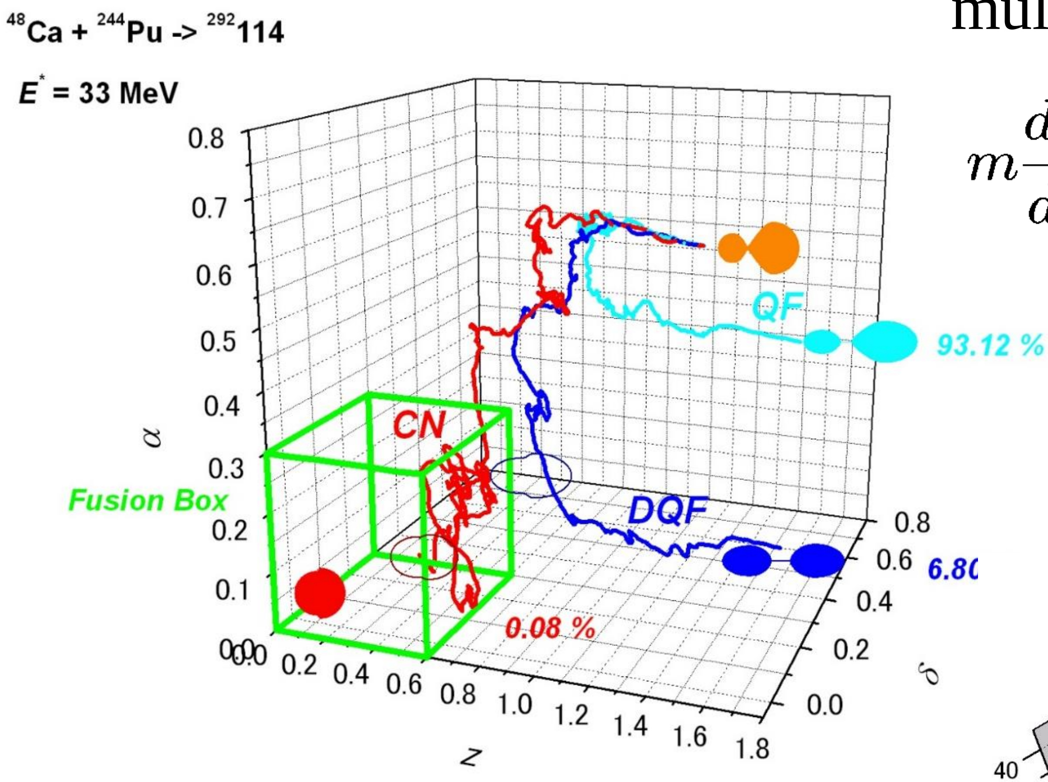


CN = compound nucleus
ER = evaporation residue



320
30
280
5
10
15
r (fm)
V(r) (MeV)
2-body potential
(b)^{86}Kr + ^{208}Pb
1-body potential
E
P_{cap}: quantum mechanics (C.C.)
compound nucleus
thermal motion
energy dissipation
Langevin approach

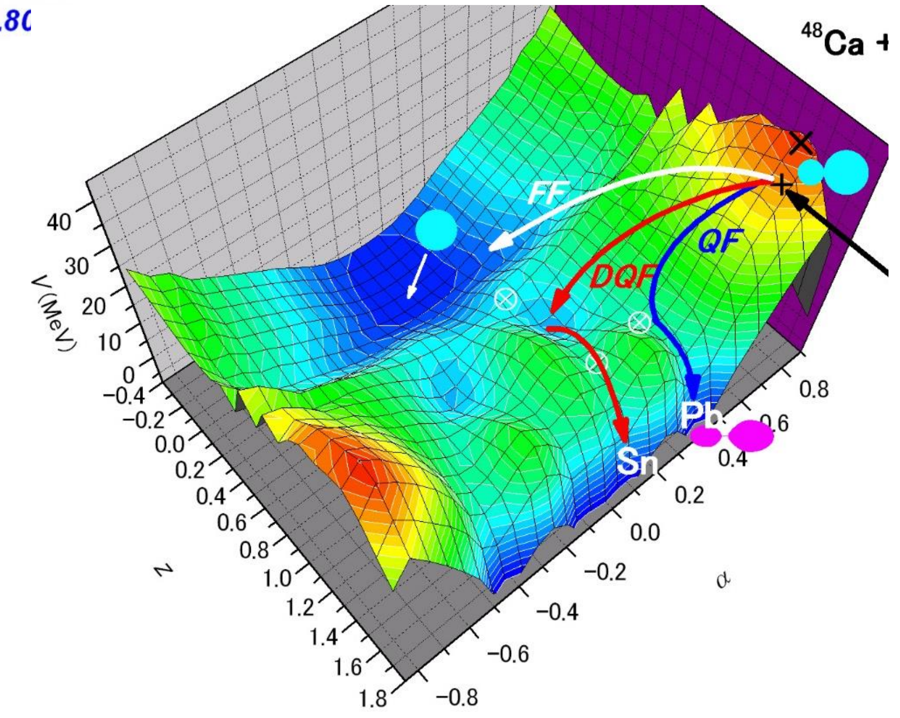
Theory: Lagenvin approach



multi-dimensional extension of:

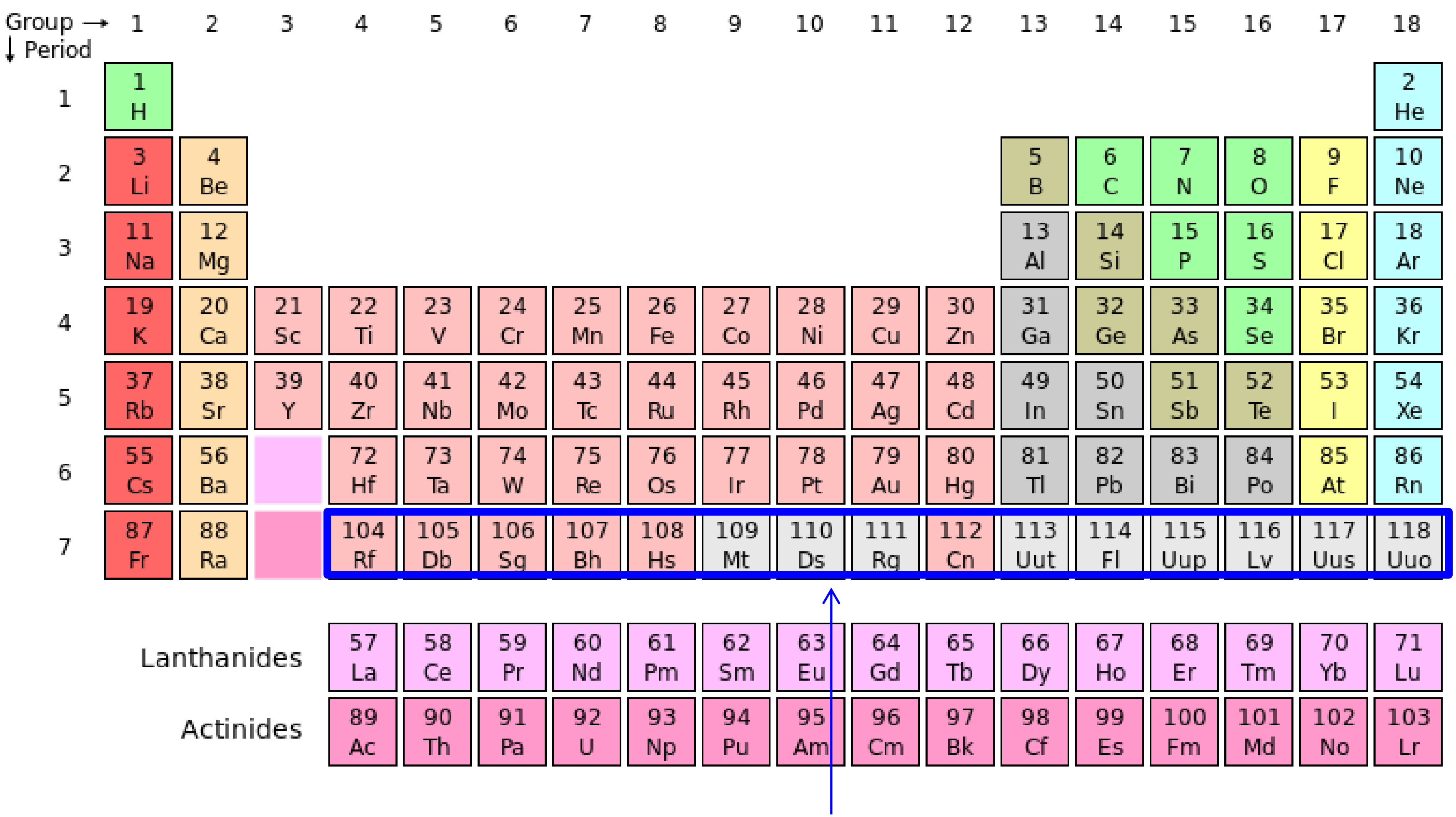
$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$

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



q: ▪ internuclear separation (*z*),
▪ deformation (δ),
▪ asymmetry of the two fragments (α)

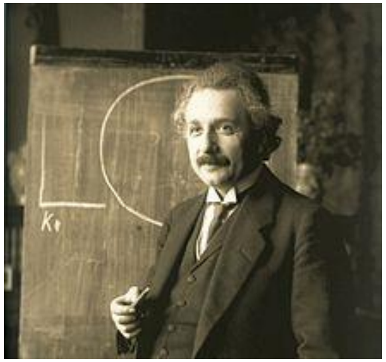
Chemistry of superheavy elements



- 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:

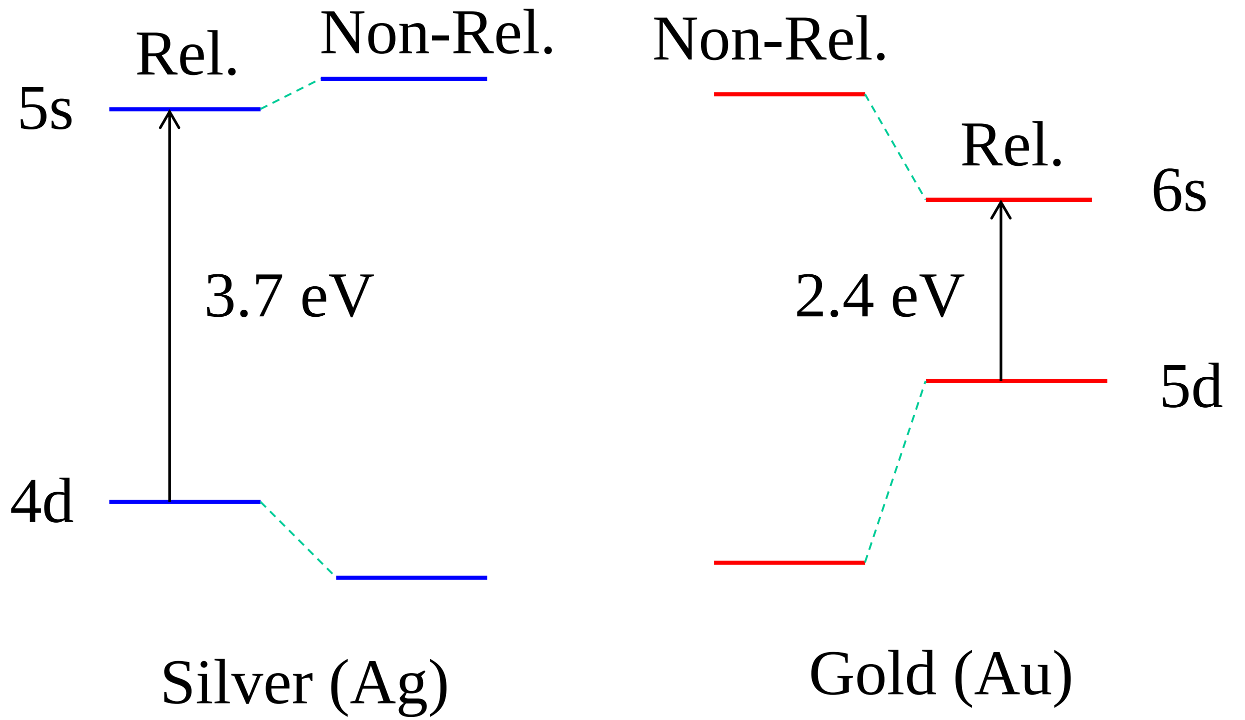
$$E_{1S} = mc^2\sqrt{1-(Z\alpha)^2} \sim mc^2\left(1 - \frac{(Z\alpha)^2}{2} \underbrace{- \frac{(Z\alpha)^4}{8} + \cdots}\right)$$

relativistic effect

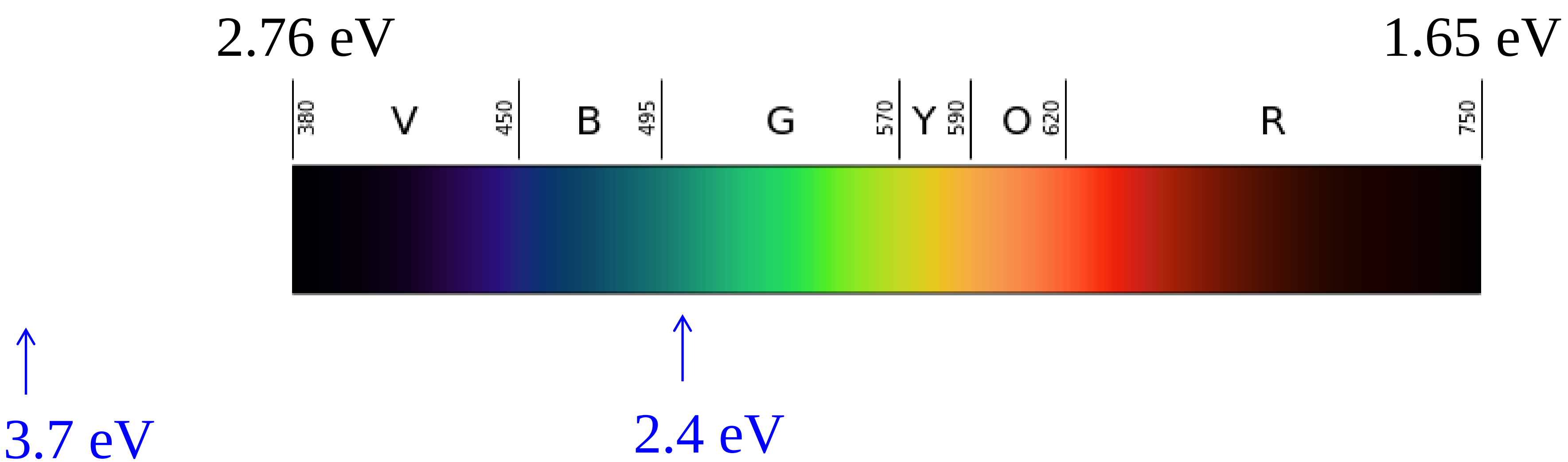
Famous example of relativistic effects: the color of gold

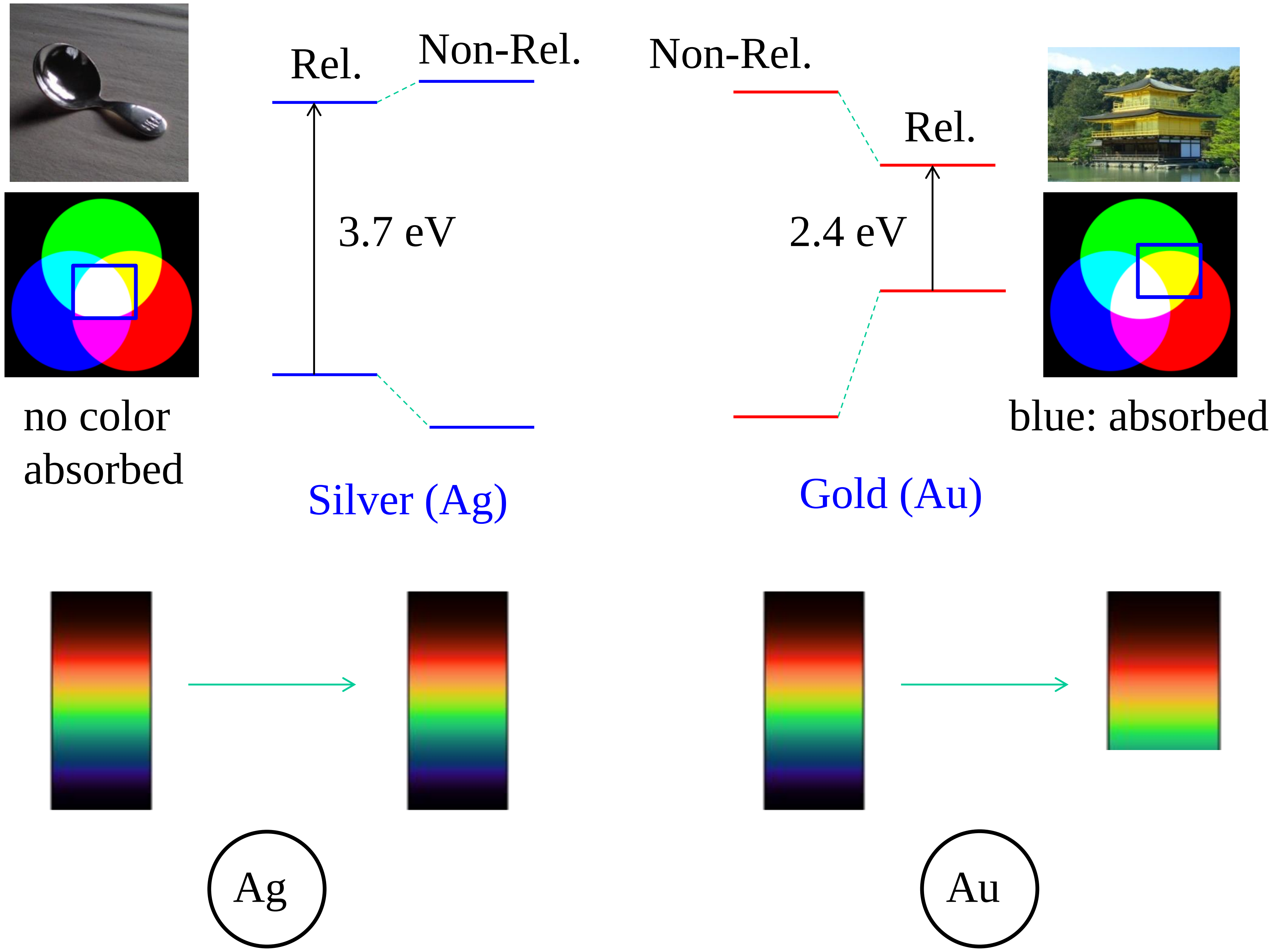
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd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

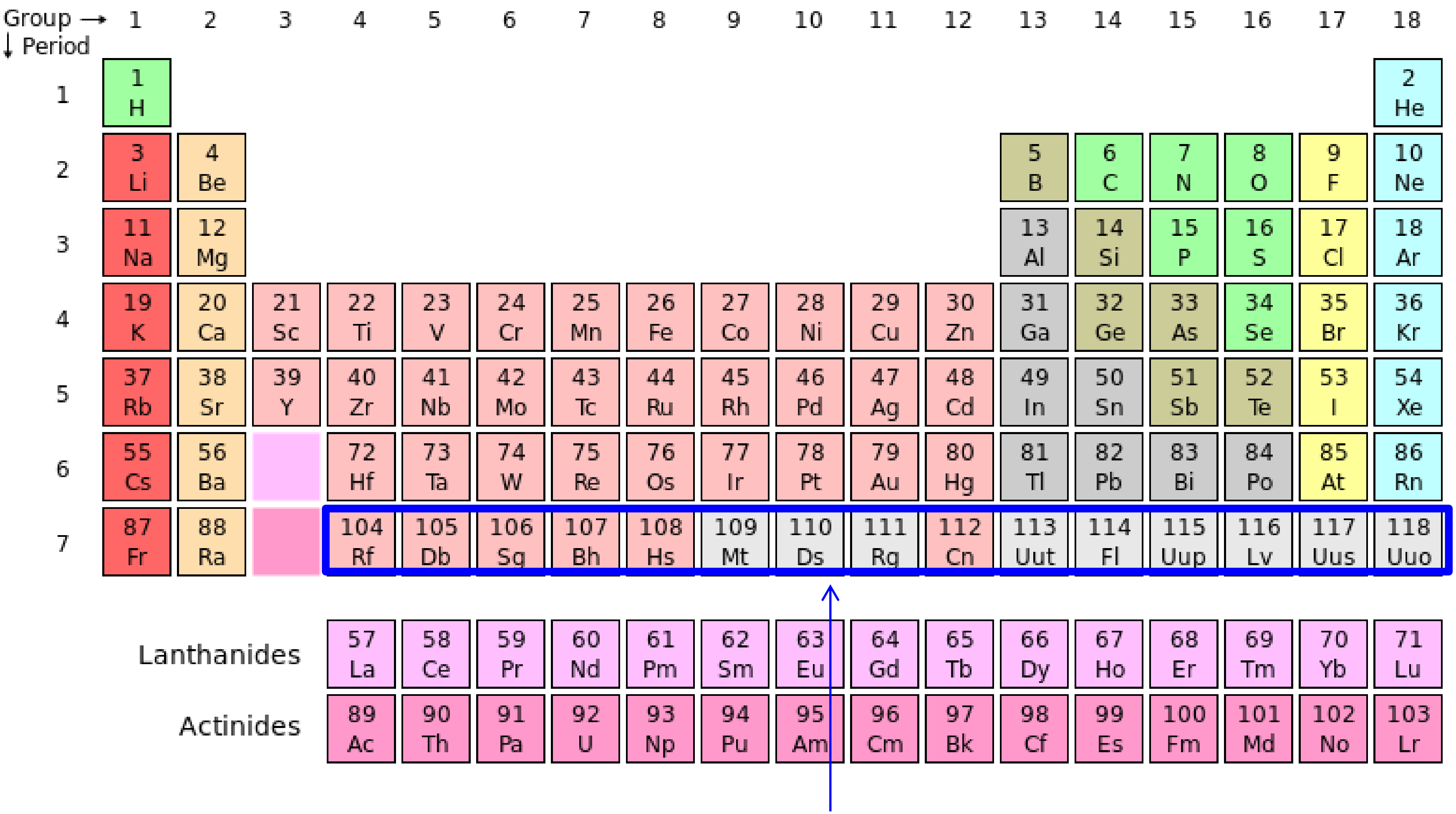


cf. visible spectrum




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

Chemistry of superheavy elements



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

⟶ a big open question