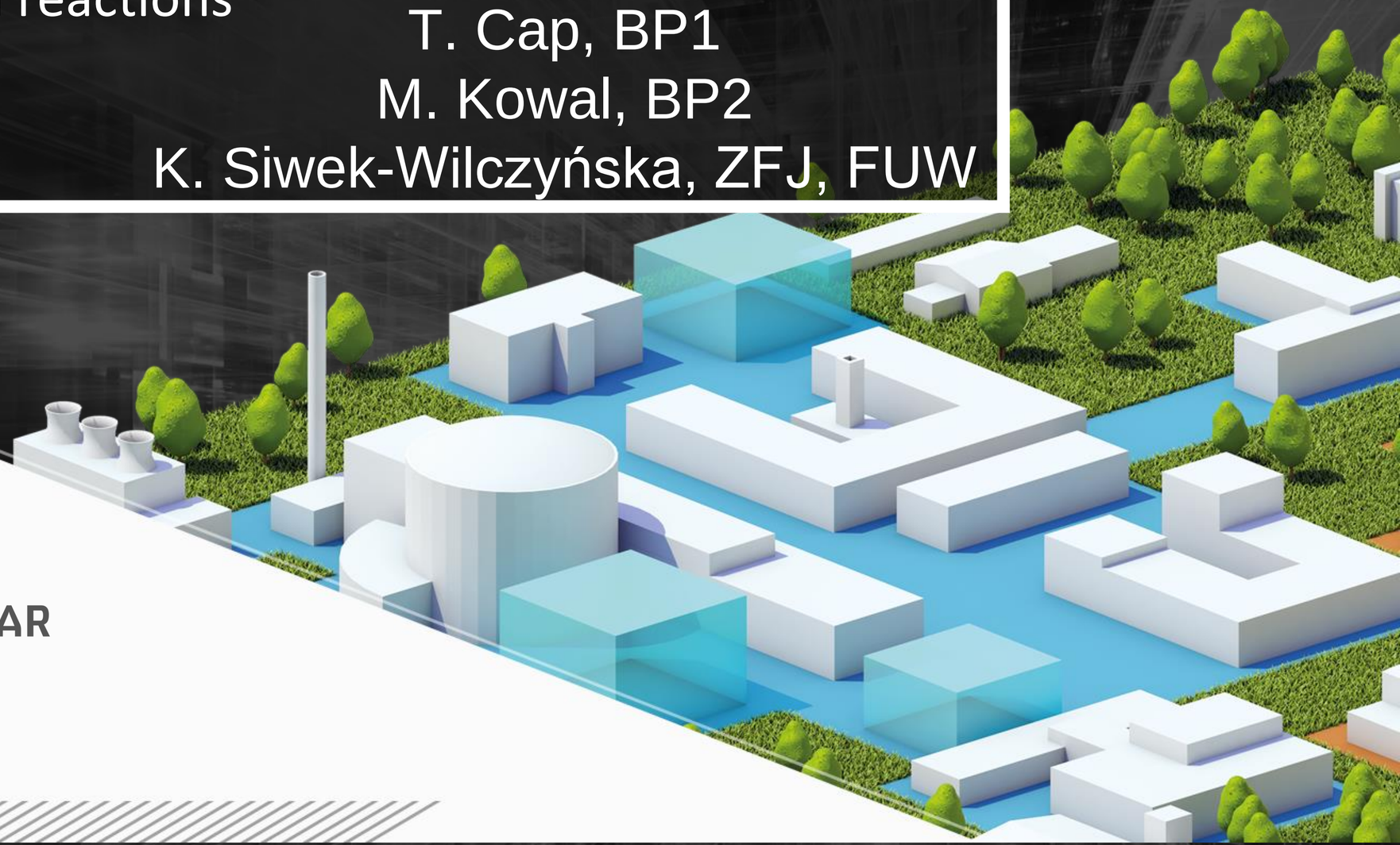
Diffusion as a possible mechanism controlling the production of superheavy nuclei in cold fusion reactions

T. Cap, BP1
M. Kowal, BP2
K. Siwek-Wilczyńska, ZFJ, FUW



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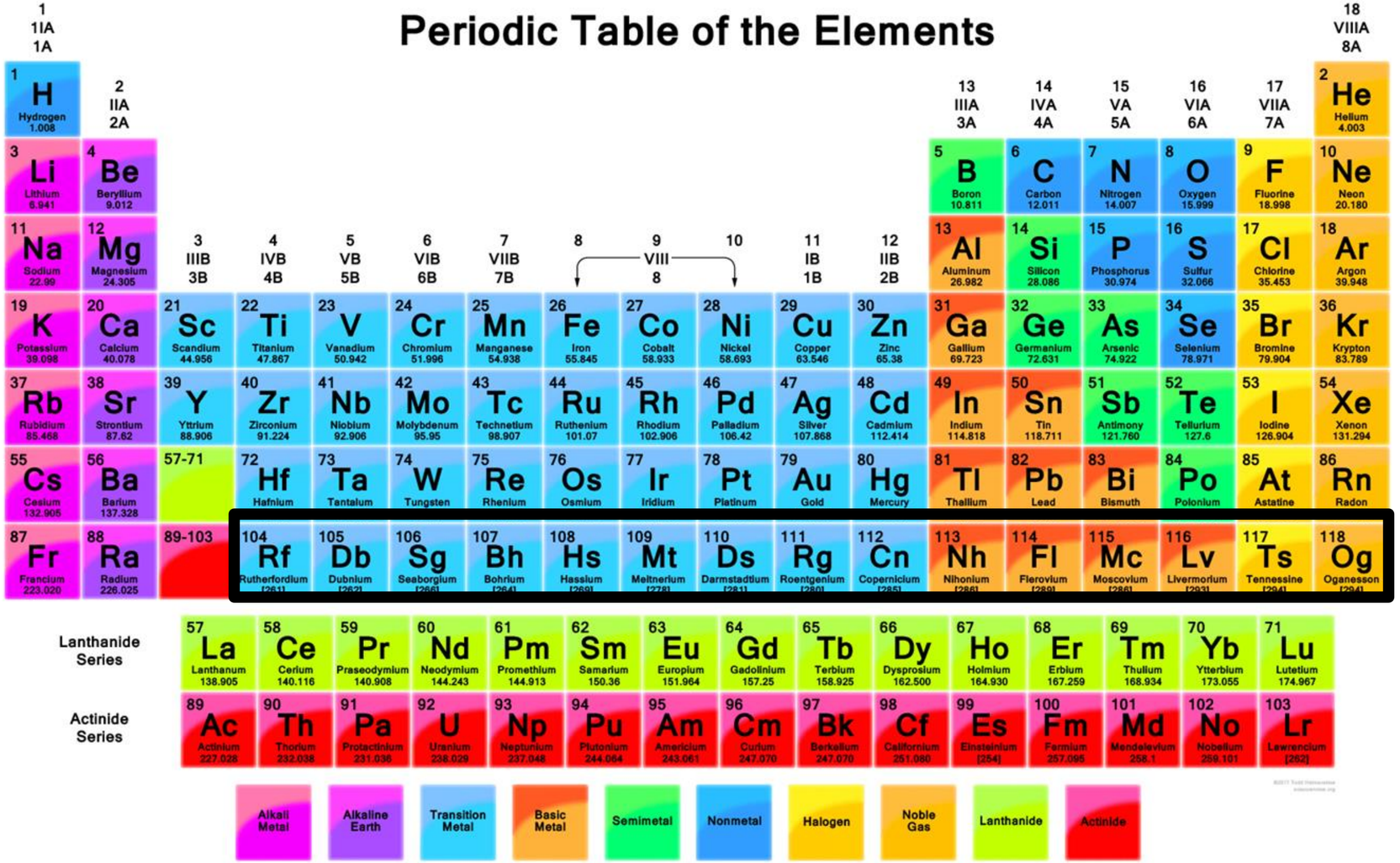


Superheavy elements (Transactinides)

SHE = TAN ($Z \geq 104$)

15 elements discovered in 50 years

138 nuclides (SHN)

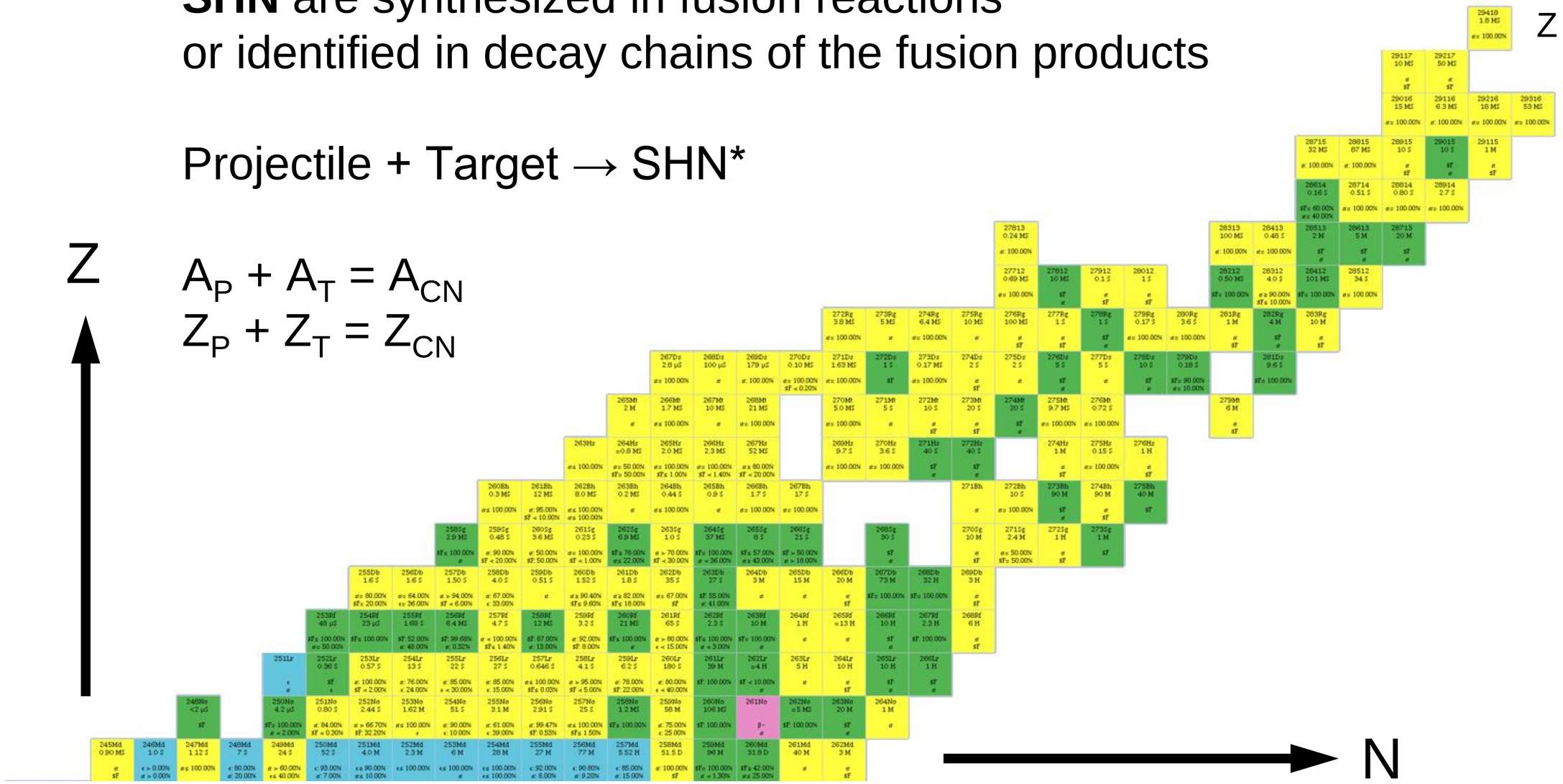
8th row: 119 (ongoing exp. at RIKEN), 120 (ongoing exp. at DUBNA)

SHN are synthesized in fusion reactions
or identified in decay chains of the fusion products

Projectile + Target → SHN*

$A_P + A_T = A_{CN}$

$Z_P + Z_T = Z_{CN}$



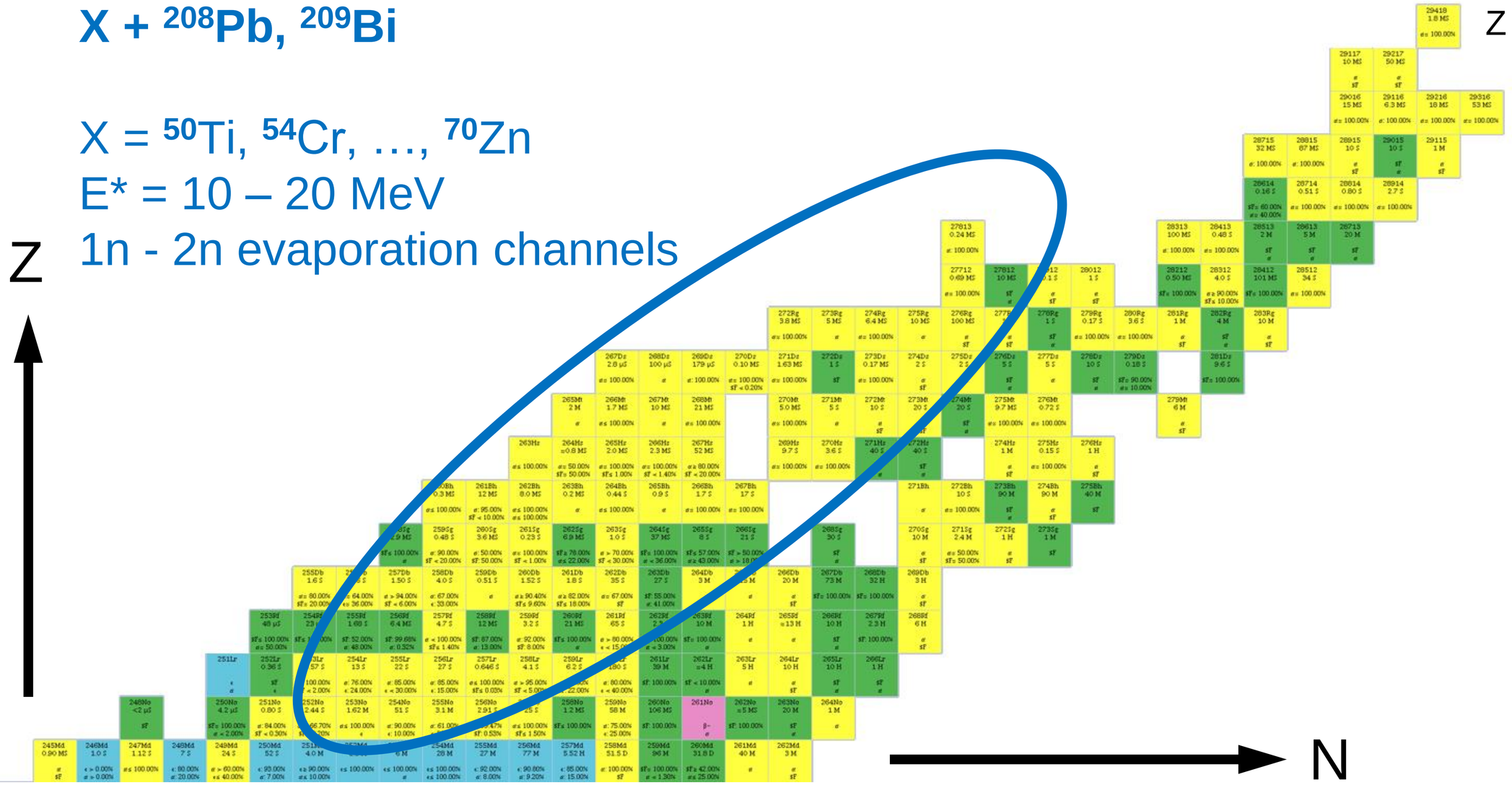
Cold Fusion Reactions

X + ^{208}Pb, ^{209}Bi

X = ^{50}Ti, ^{54}Cr, …, ^{70}Zn

E* = 10 – 20 MeV

1n - 2n evaporation channels



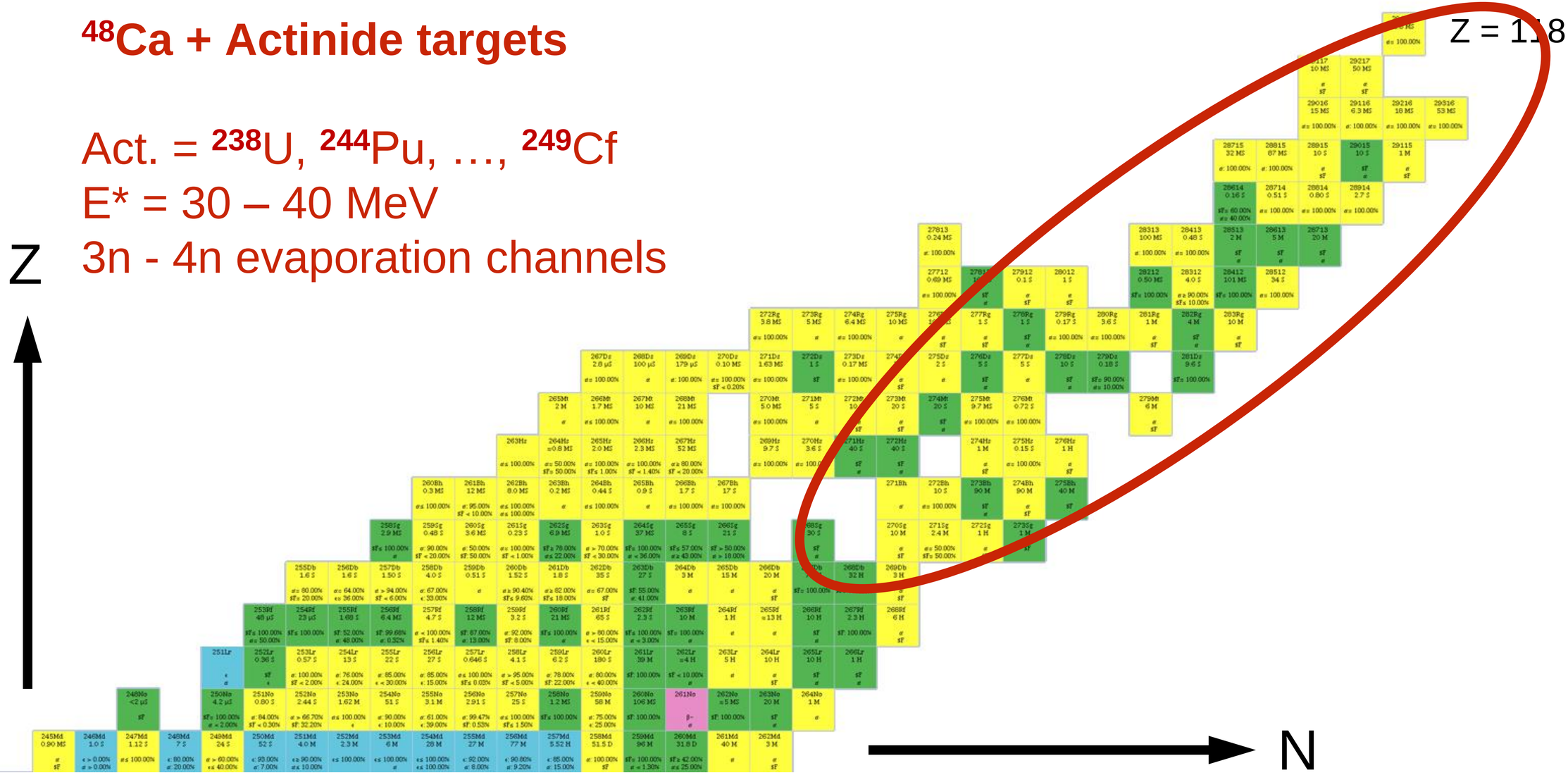
Hot Fusion Reactions

^{48}Ca + Actinide targets

Act. = ^{238}U, ^{244}Pu, …, ^{249}Cf

E* = 30 – 40 MeV

3n - 4n evaporation channels



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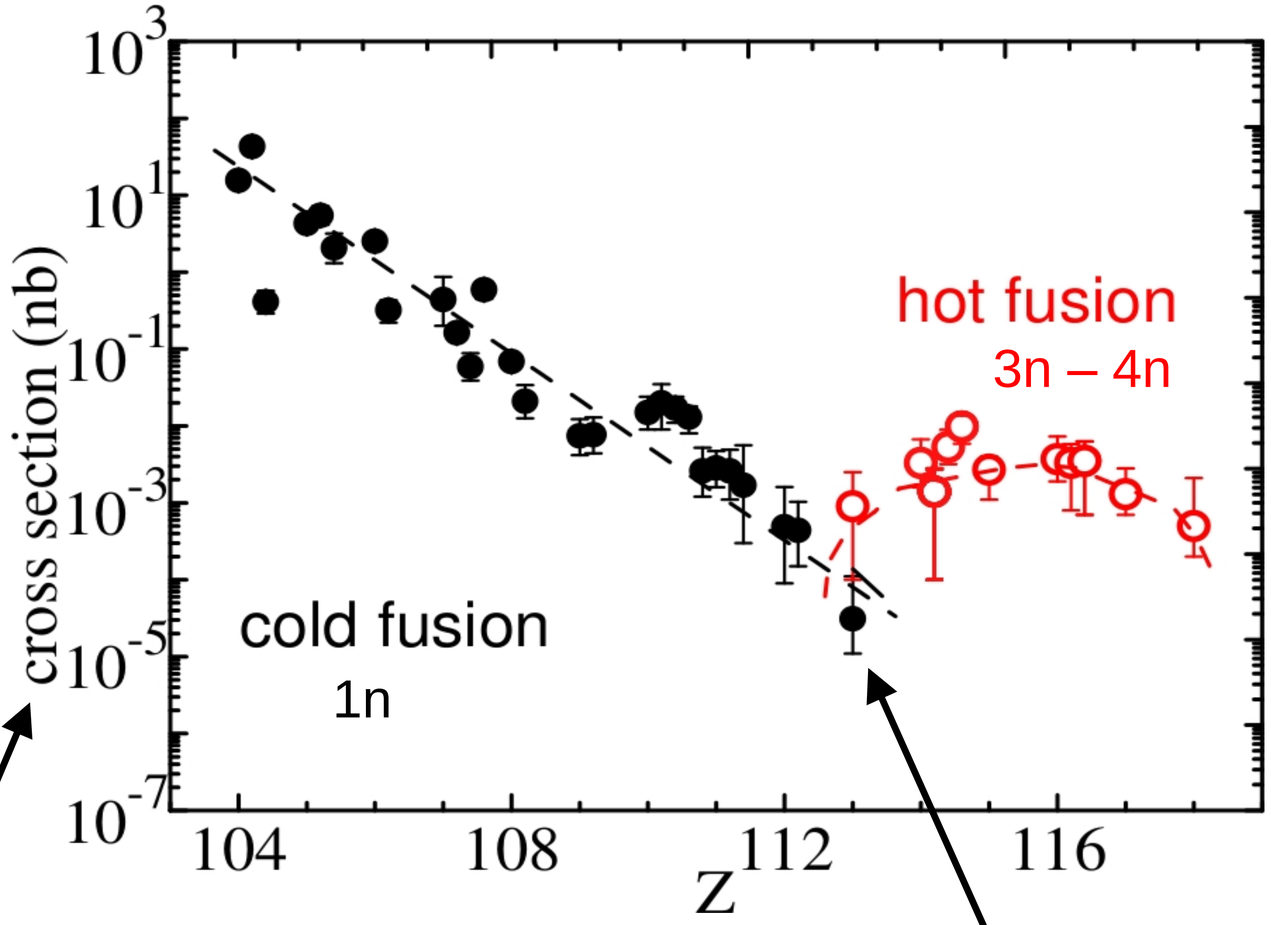


Highest measured cross section for a given element

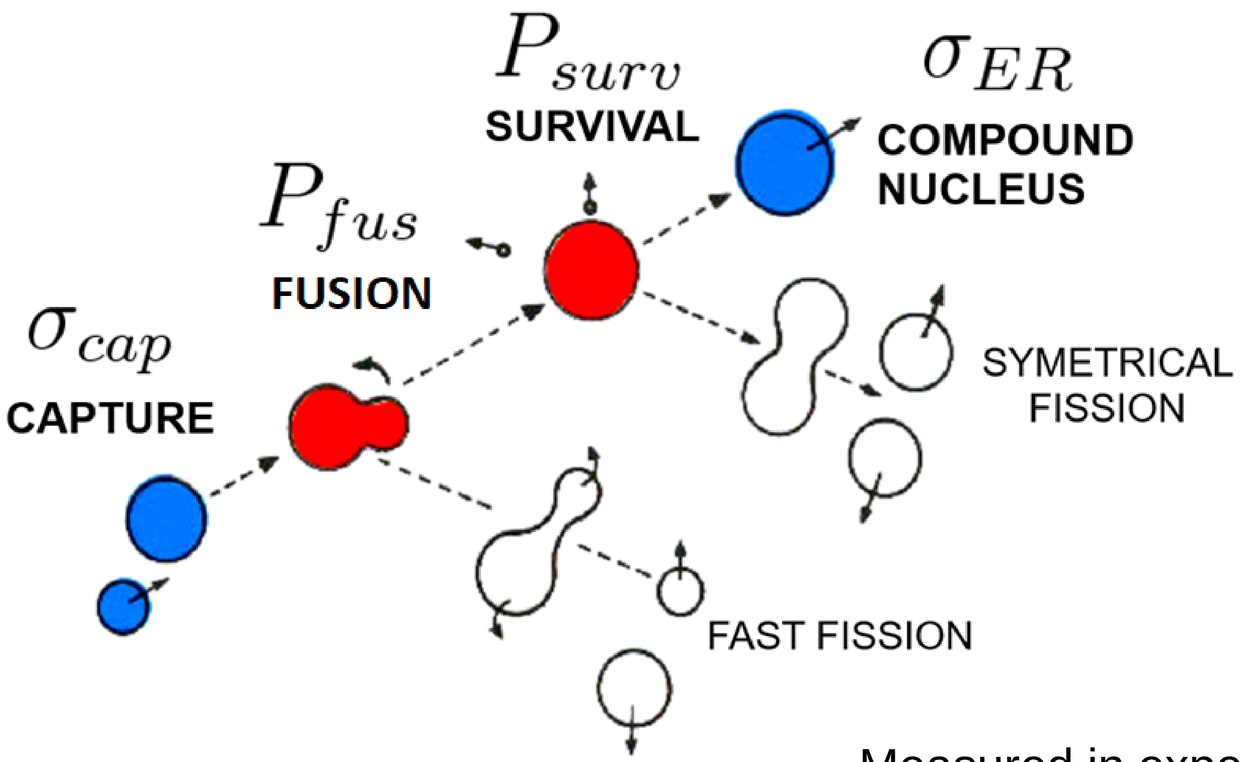
Z=113, 22 fb, only 3 atoms in 576 days of irradiation

No heavier target than Cf (Z=98) is available

Es (Z=99) is too radioactive

Experiments with ^{51}V, ^{50}Ti, ^{54}Cr, and ^{56}Fe beams gave no results so far

Most of the experiments are focused on studying SHN properties and (recently) fusion reaction mechanisms.



W. J. Świątecki, K. Siwek-Wilczyńska, J. Wilczyński, PRC 2005

T. Cap et al., PRC 2011
K. Siwek-Wilczyńska et al. PRC 2012
T. Cap et al., PRC 2013
K. Siwek-Wilczyńska et al. PRC 2019

FBD (fusion-by-diffusion)

Synthesis of SHN can be described as a 3 step process:

$$\sigma_{ER} = \sigma_{cap}\ P_{fus}\ P_{surv}$$

Measured in experiments, can be calculated using various models

Diffussed barrier formula (Gaussian distribution around mean entrance channel barrier *B0*)

Not measured directly
Difficult to calculate

Smoluchowski Diffusion equation

Well established theory and formulas
Psurv << 1

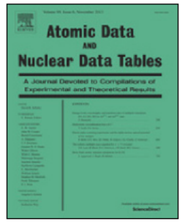
masses, fission barriers, deformations from Warsaw Micro-Macro model

Atomic Data and Nuclear Data Tables 138 (2021) 101393

Contents lists available at ScienceDirect

Atomic Data and Nuclear Data Tables

journal homepage: www.elsevier.com/locate/adt



Properties of heaviest nuclei with $98 \leq Z \leq 126$ and $134 \leq N \leq 192$

P. Jachimowicz [a], M. Kowal [b,*], J. Skalski [b]

[a] Institute of Physics, University of Zielona Góra, Szafrana 4a, 65-516 Zielona Góra, Poland
[b] National Centre for Nuclear Research, Pasteura 7, 02-093 Warsaw, Poland

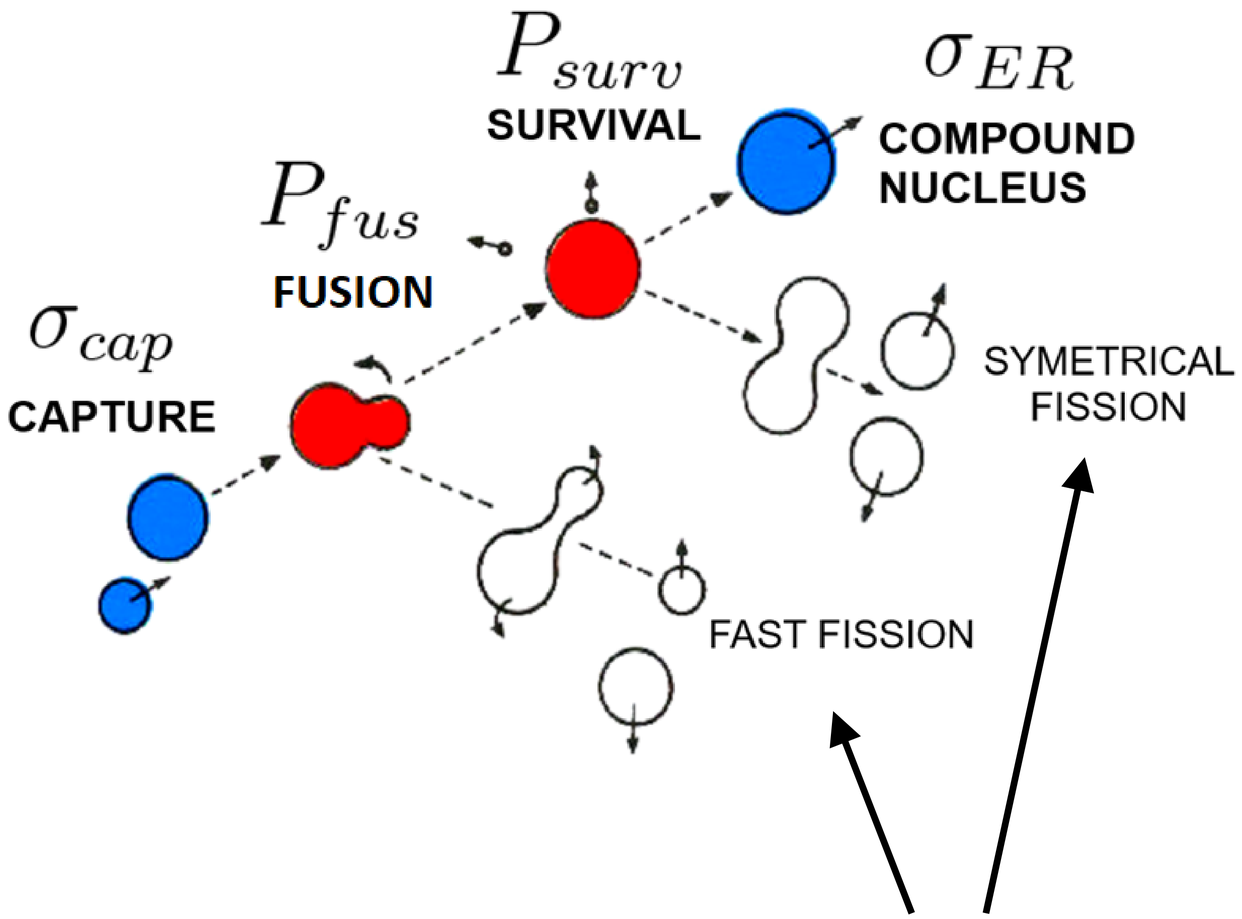
Ground-state and saddle-point shapes and masses for 1305 heavy and superheavy nuclei including odd-A and odd–odd systems. Static fission barrier heights, one- and two-nucleon separation energies, and Qα values.

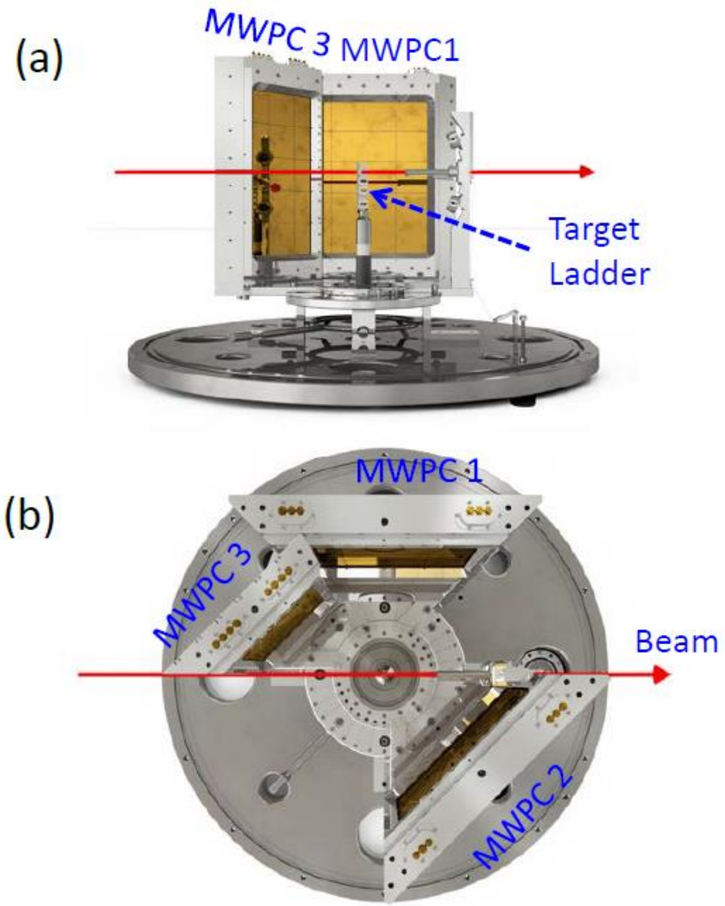
Microscopic–macroscopic method with the deformed Woods–Saxon single-particle potential and the Yukawa-plus-exponential macroscopic energy taken as the smooth part.

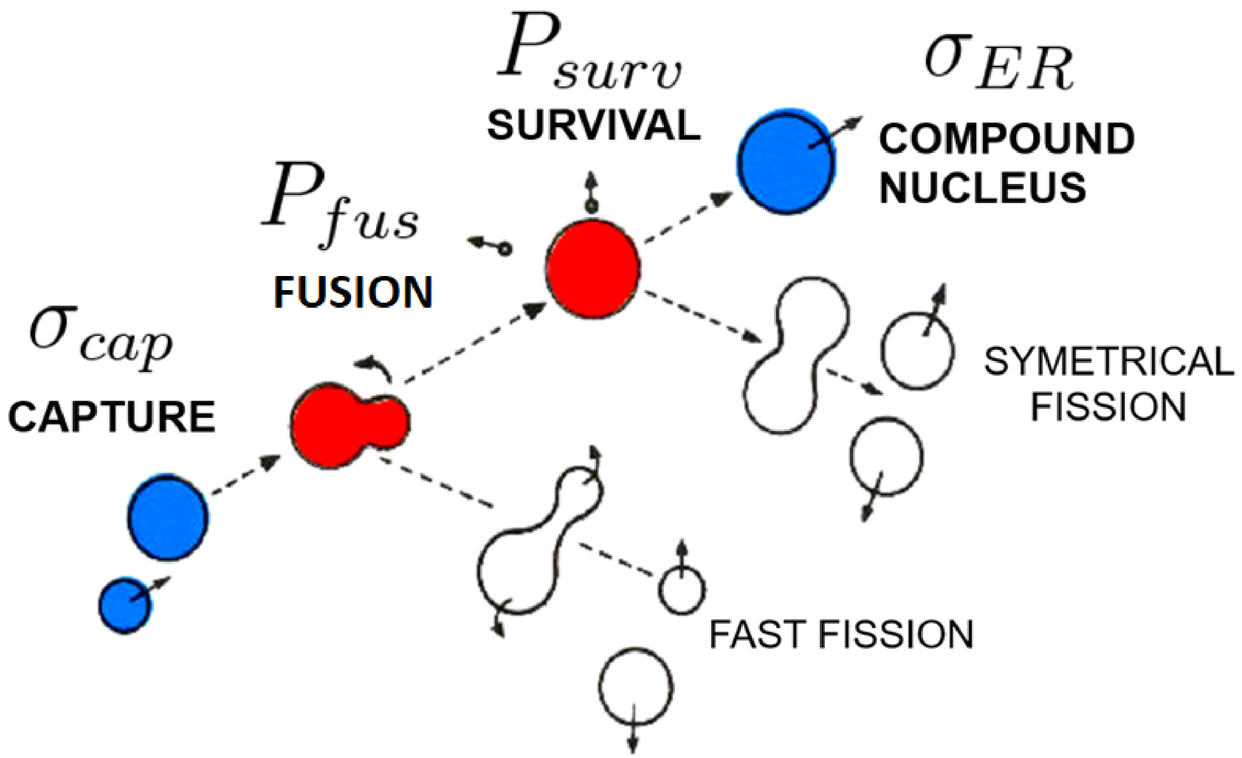
Ground-state shapes and energies are found by the minimization over **seven axially-symmetric deformations**. A search for saddle-points was performed by using the "imaginary water flow" method in three consecutive stages, using five- (for nonaxial shapes) and seven-dimensional (for reflection-asymmetric shapes) deformation spaces.

Good agreement with the experimental data for actinides.

Mechanisms Suppressing Superheavy Element Yields in Cold Fusion Reactions
Banerjee et al., PRL 122, 232503 (2019)





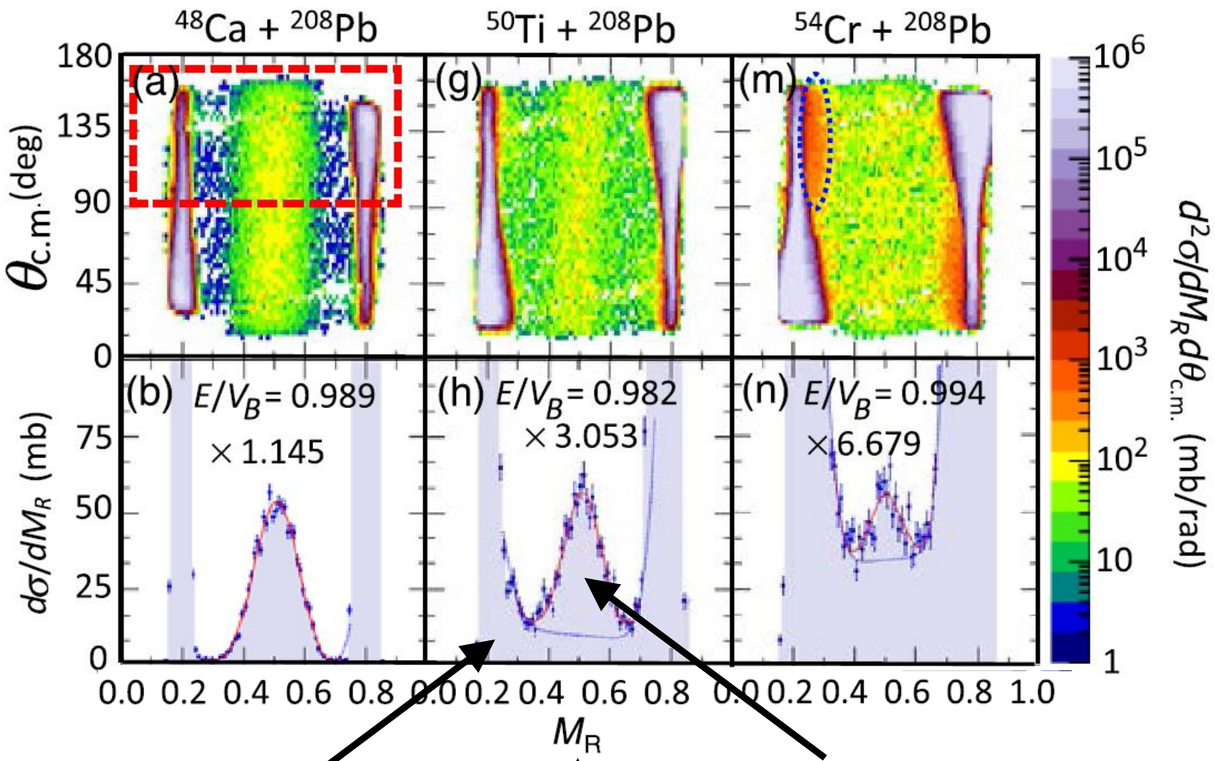


Pfus can be experimentally estimated:

$$Psym = \frac{\textbf{Fusion−Fission} \text{ cross section}}{\textbf{Capture} \text{ cross section}}$$

Mechanisms Suppressing Superheavy Element Yields in Cold Fusion Reactions

Banerjee et al., PRL 122, 232503 (2019)



Fast Fission cross section

Mass ratio, symmetric split M_R = 0.5

Fusion-Fission cross section (symmetrical fission)

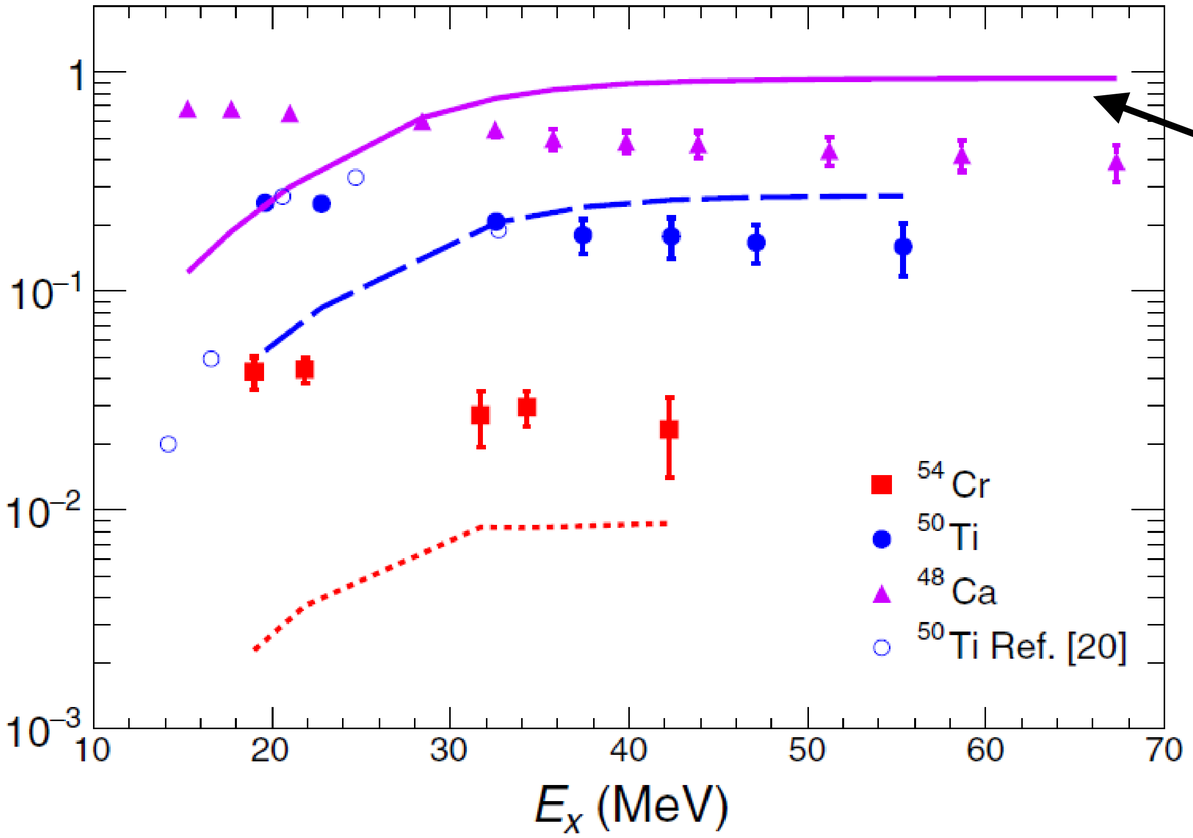
Banerjee et al., PRL 122, 232503 (2019)

Reactions:

$^{48}Ca + {}^{208}Pb \rightarrow {}^{256}No^*$

$^{50}Ti + {}^{208}Pb \rightarrow {}^{258}Rf^*$

$^{54}Cr + {}^{208}Pb \rightarrow {}^{262}Sg^*$



Upper limit for Fusion Probability

Excitation energy

Difusion model calculations by V. Zagrebaev and W. Greiner PRC 78, 034610 (2008).

The experimental trend is different than the model predictions for all 3 reactions.

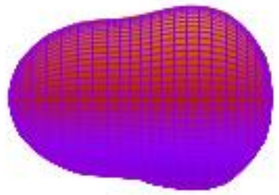
The conclusion was that diffusion is not the main mechanism responsible for the synthesis of SHN.

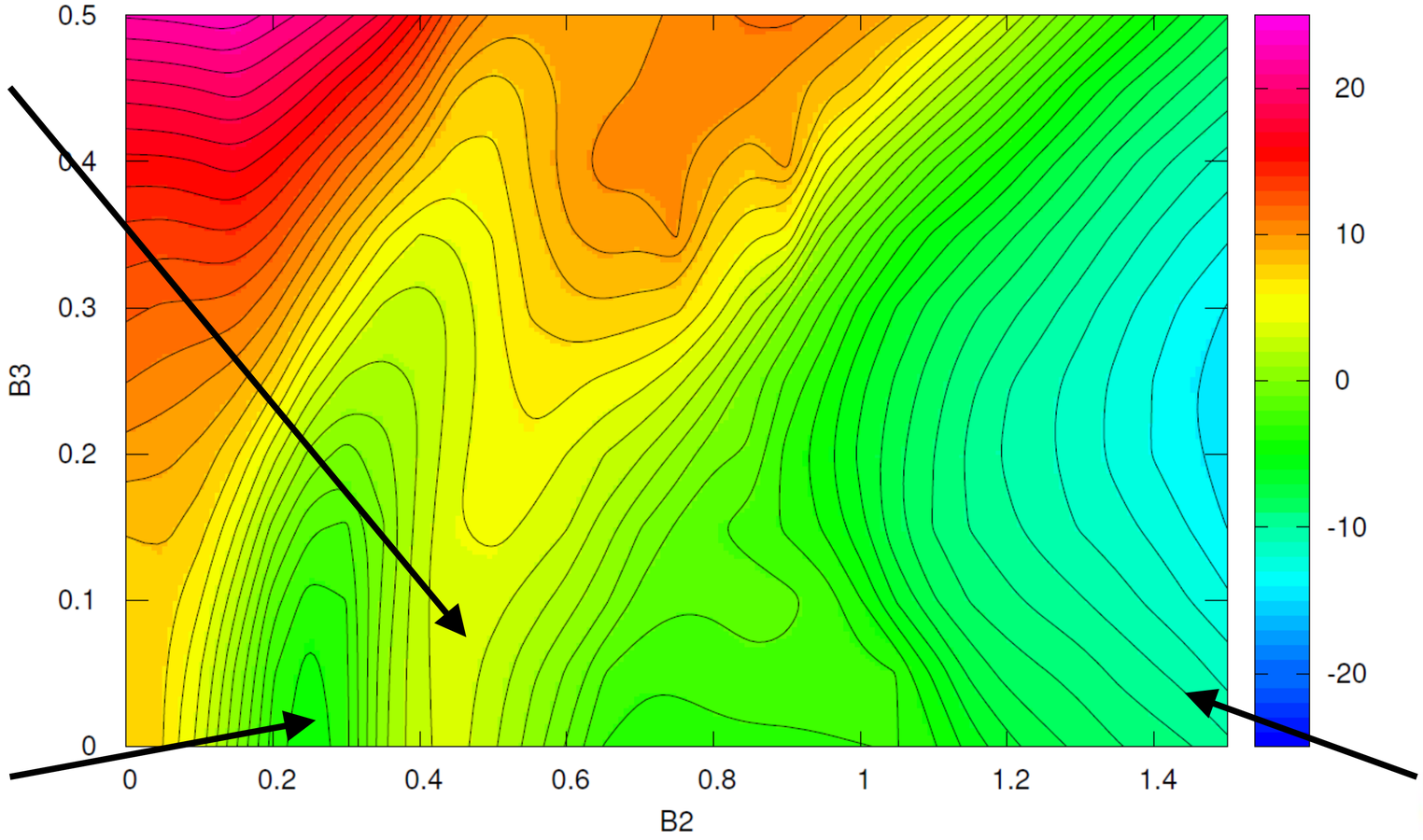
Questions:
Can the diffusion approach (FBD) describe the experimental results?
What is the fusion mechanism?

Fusion process on the Potential Energy Surface (PES)

Fission saddle point

$M(A,Z) = (A\text{-}Z)m_n + Zm_p$ + Binding Energy



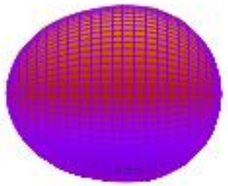


Map for ^{256}No (Z=102)

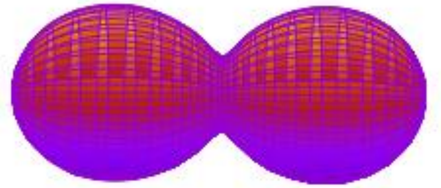
Based on
P. Jachimowicz, M. Kowal and J. Skalski
ADNDT 138, 101393 (2021)

Calculations done by
Aleksander Augustyn in CIŚ

3D representation
of 8D space (200M point)



Ground state

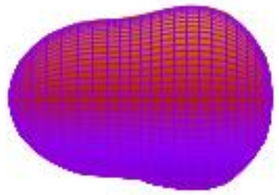


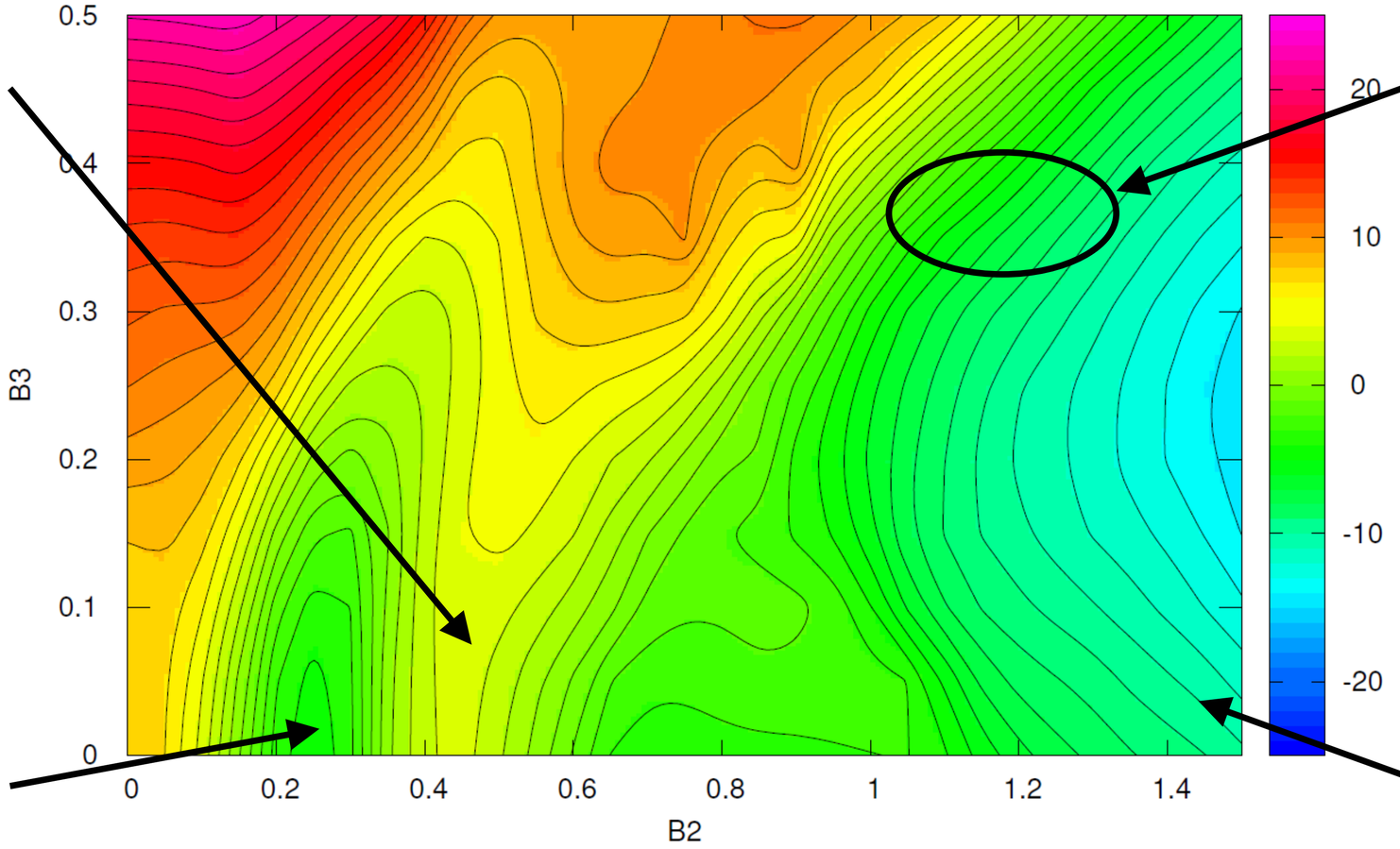
Scission point → Fission

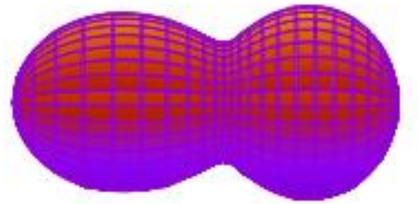
Fusion process on the Potential Energy Surface (PES)

Fission saddle point

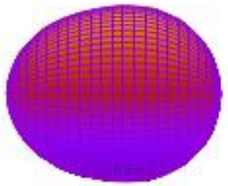
$M(A,Z) = (A\text{-}Z)m_n + Zm_p$ + Binding Energy





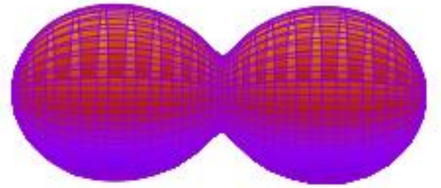


Starting point
(injection point)
$^{48}Ca + {}^{208}Pb \rightarrow {}^{256}No$



Ground state

β2 ≈ elongation

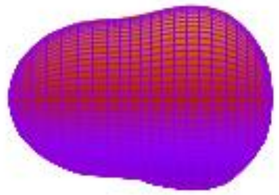


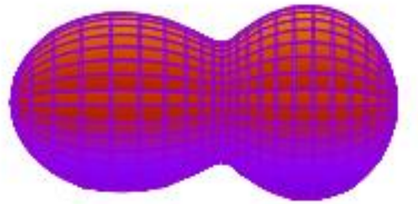
Scission point → Fission

Fusion process on the Potential Energy Surface (PES)

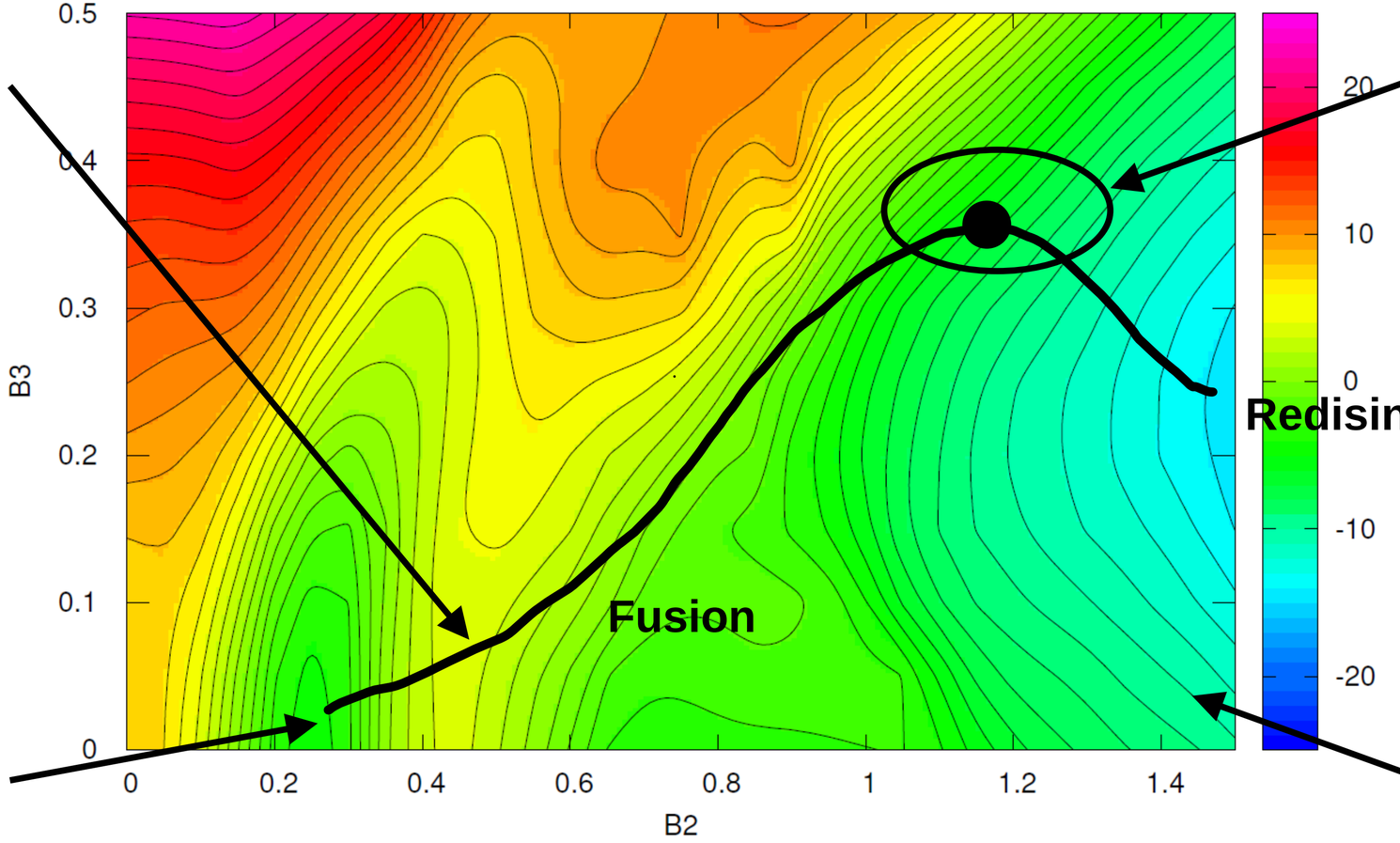
Fission saddle point

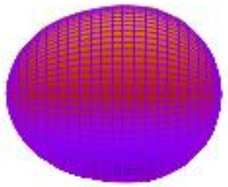
$M(A,Z) = (A\text{-}Z)m_n + Zm_p$ + Binding Energy



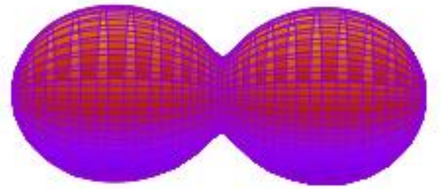


Starting point
(injection point)
$^{48}Ca + {}^{208}Pb \rightarrow {}^{256}No$





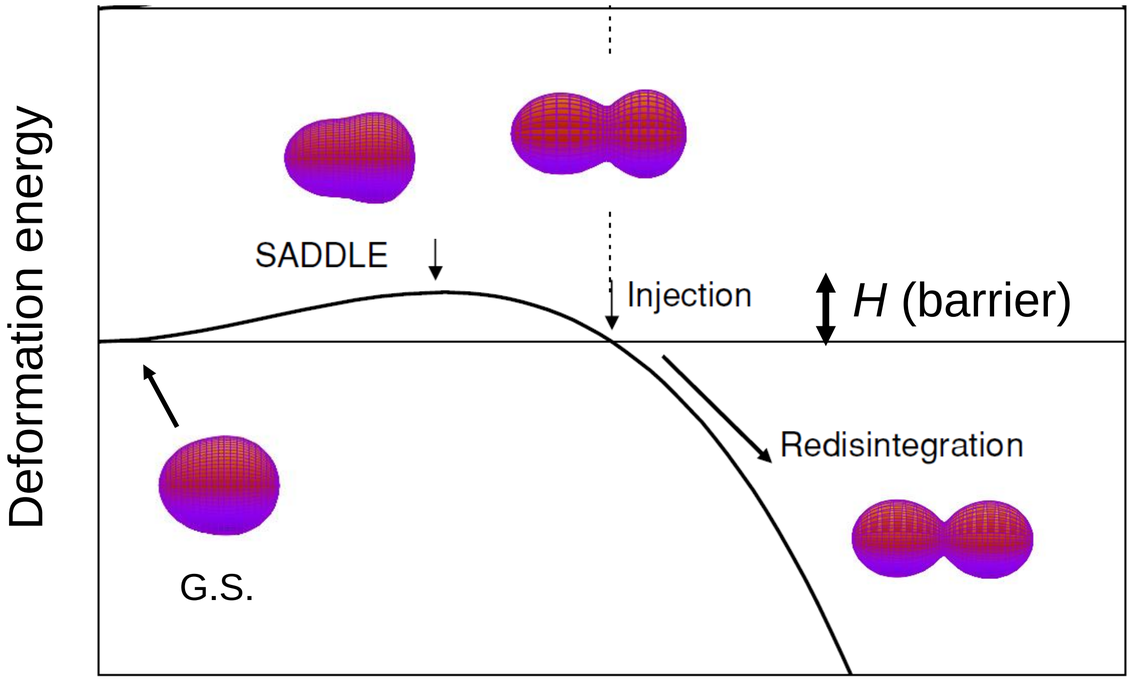
Ground state



Scission point → Fission

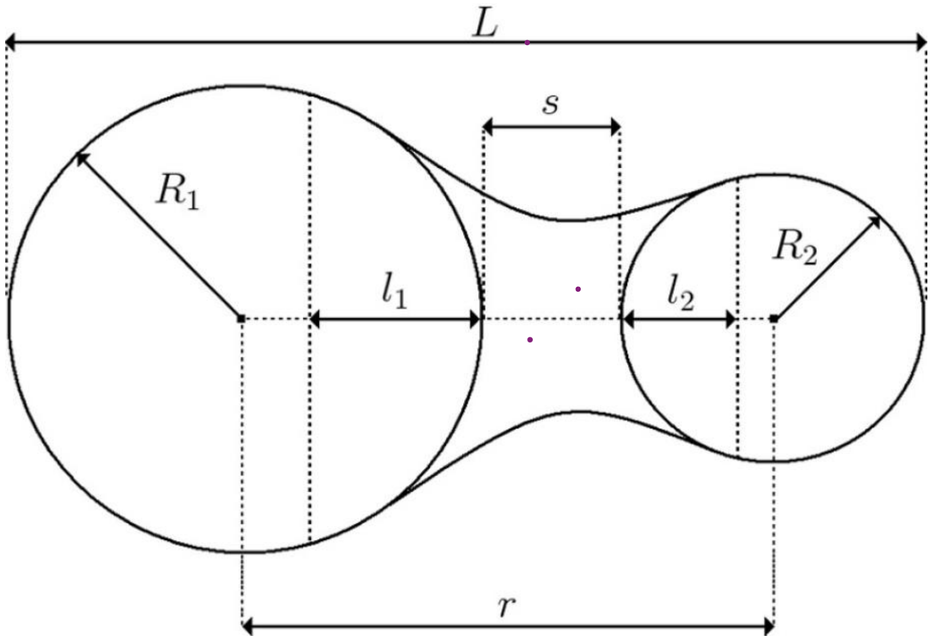
In the FBD model we use 1D motion approximation

The system must overcome an internal barrier *H* to fuse.



L is the effective elongation (along the fusion path)

Macroscopic deformation energies are calculated using the parameterization of the nuclear shapes by two spheres joined smoothly by a third quadratic surface of revolution.

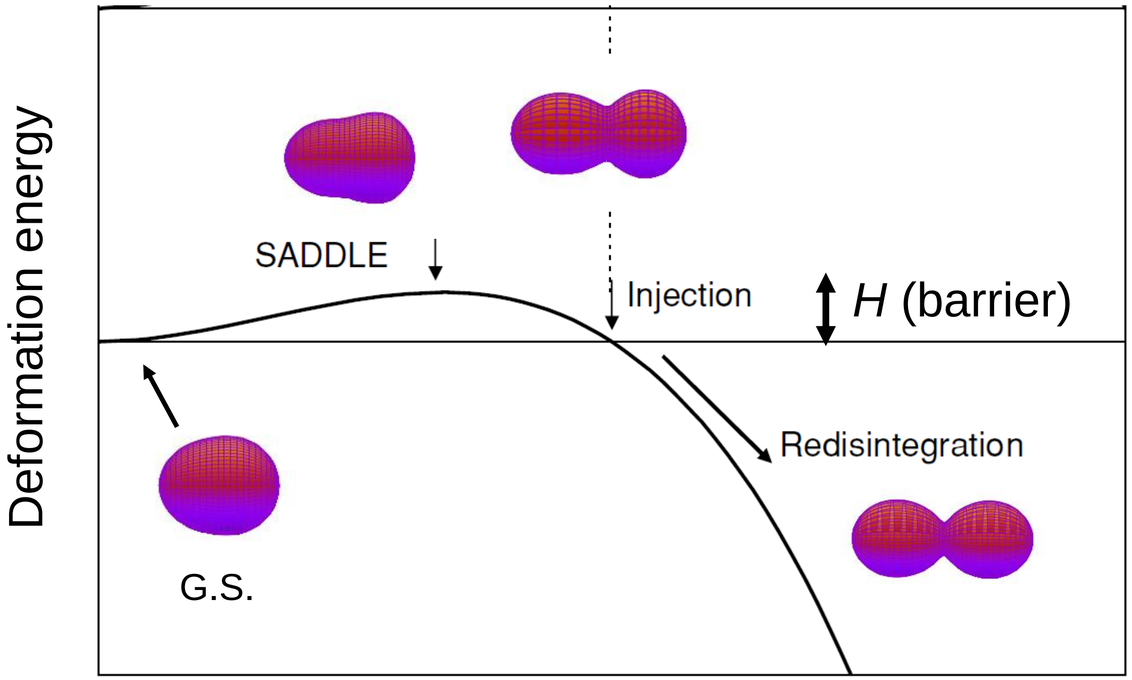


The distance between the nuclear surfaces of two colliding nuclei at the **injection** point, s_{inj}, is the only adjustable parameter of the model.

s_{inj} distance was parametrized by analyzing 27 cold fusion reactions.

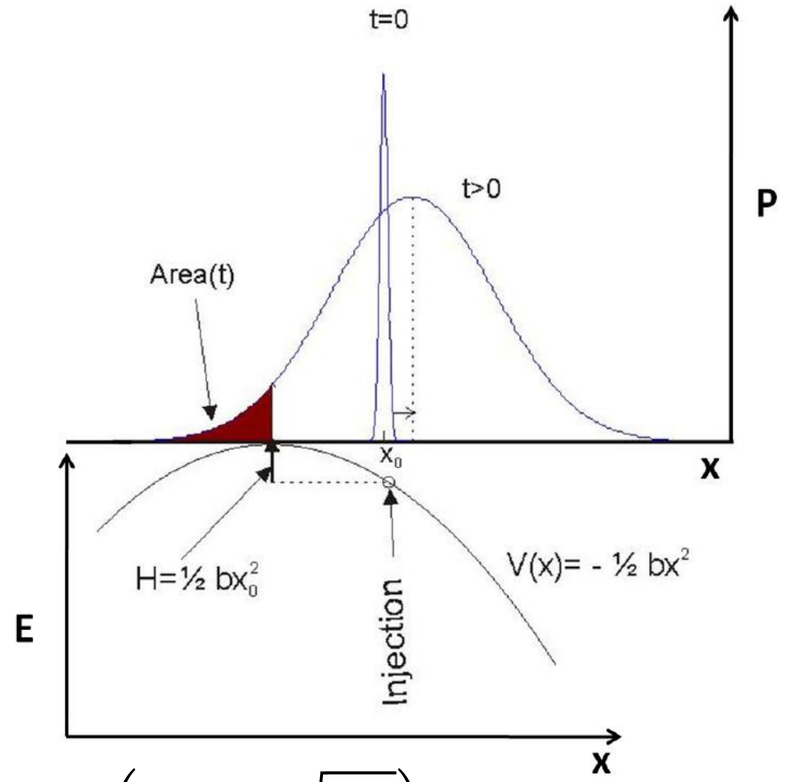
In the FBD model we use
1D motion approximation

The system must overcome an internal barrier *H* to fuse.



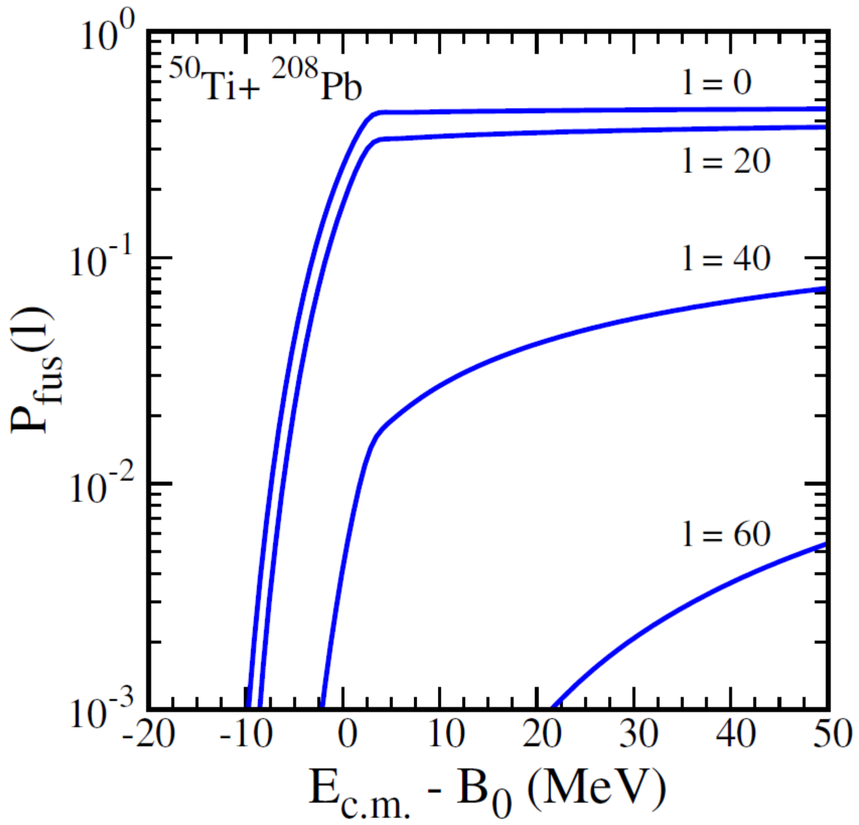
L is the effective elongation (along the fusion path)

Pfus is calculated by solving
1D Smoluchowski Diffusion Equation



$$P_{fus}(l) = \frac{1}{2}\left(1 - \mathrm{erf}\sqrt{\frac{H(l)}{T}}\right) \text{ when } L_{inj} \geq L_{saddle}$$

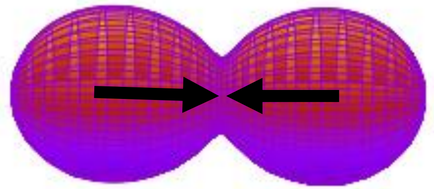
H(l) – the function of angular momentum and bombarding energy
T – the temperature depends on available energy



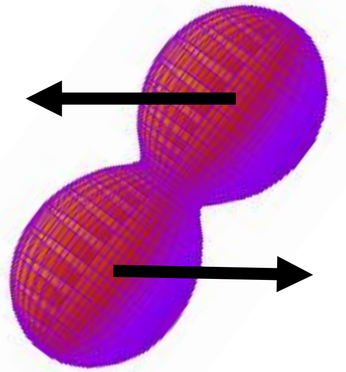
Available energy with respect to the entrance channel barrier *B0*

B0 = 191.3 MeV
*E**($E_{c.m.}$ = *B0*) = 21.7 MeV

l = 0
Central collision

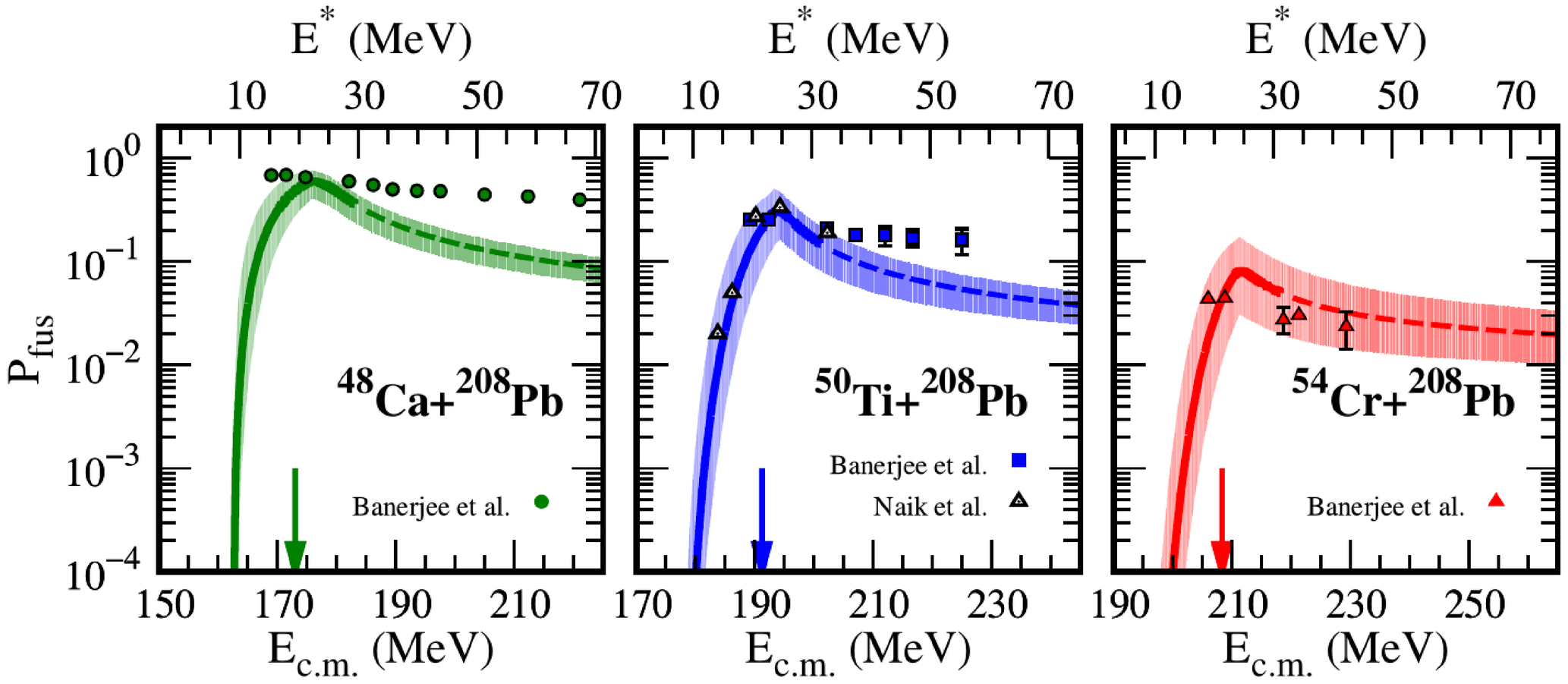


Peripheral collisions



Higer partial waves l
=
Higher rotational Energy
=
Lower *Pfus*

$$P_{fus}(E_{c.m.}) = \frac{\sum_{l=0}^{lmax}(2l+1)P_{fus}(l)}{(2l_{max}+1)^2}$$ Fusion probability averaged over l

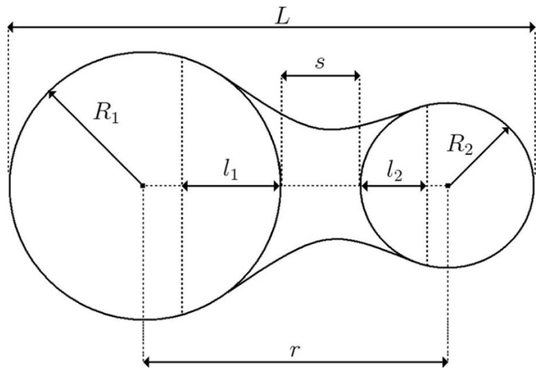


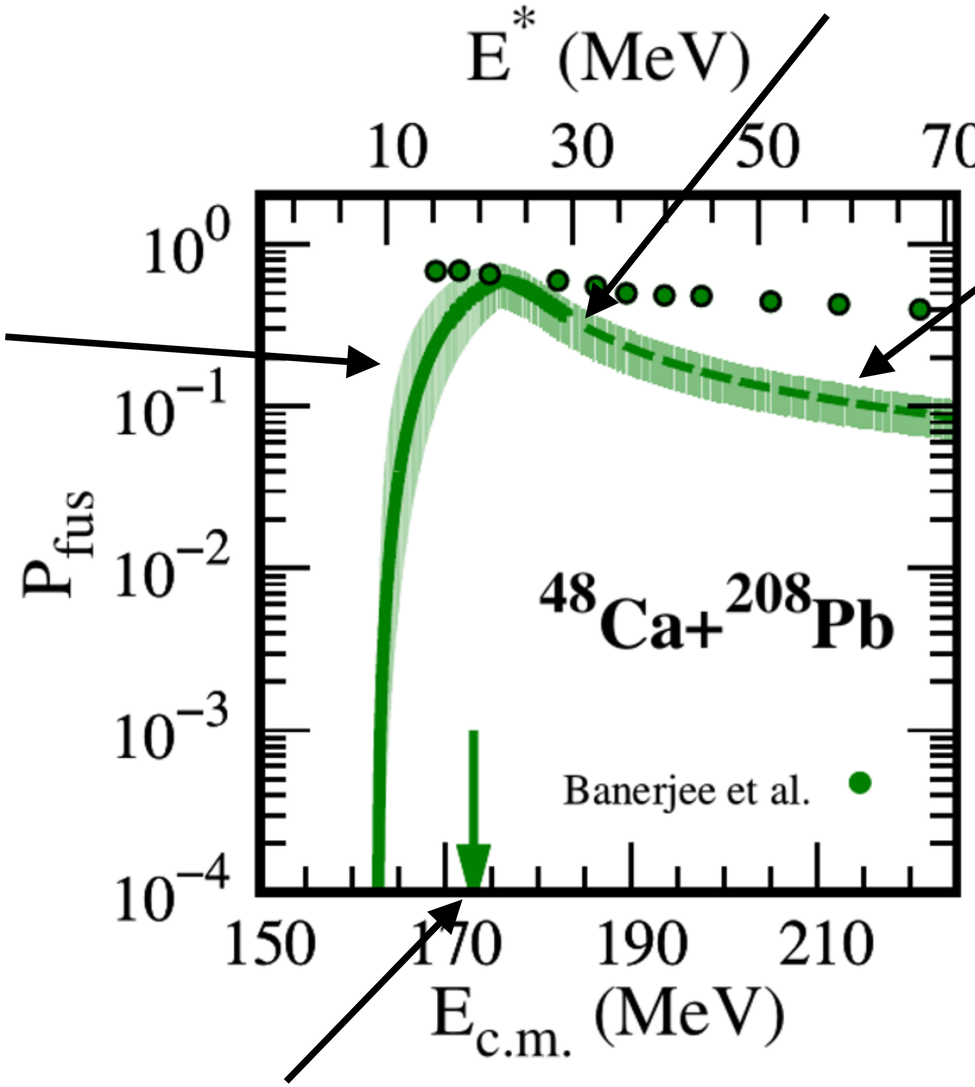
Submitted to PLB, available at: arXiv:2107.00579

Tangent configuration of projectile and target
($s_{injection}$ = 0 fm)

Below *B0*, the *Pfus* growth comes from the reduction in the height of the internal barrier opposing fusion.

$s_{injection}$ > 0 fm

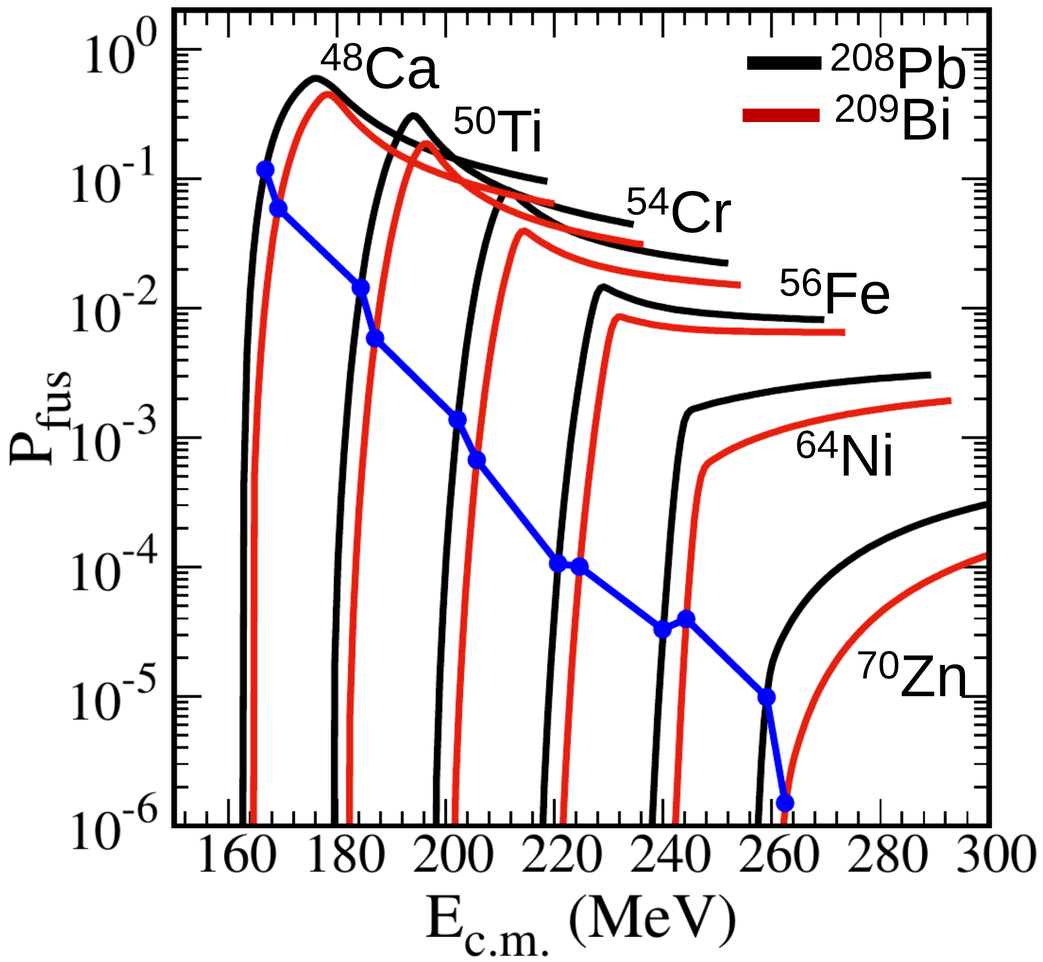




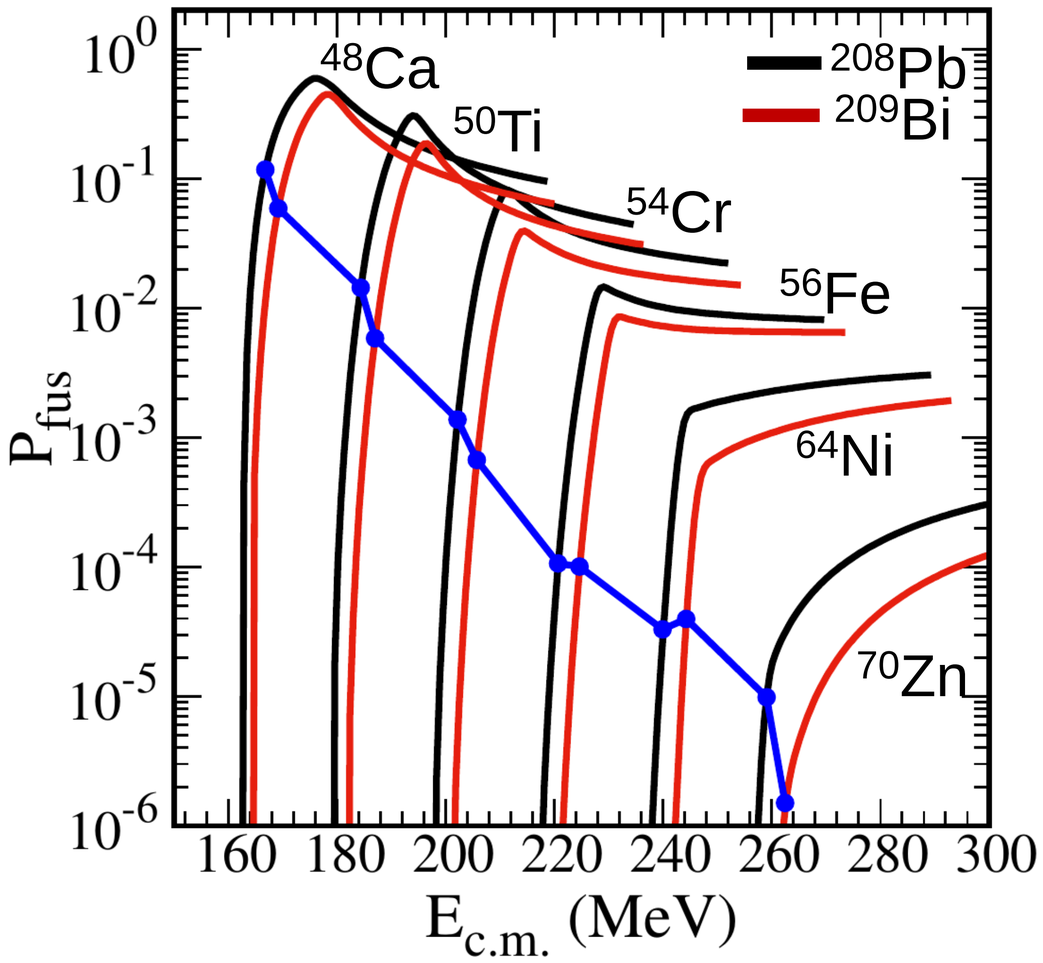
The *Pfus* saturation above *B0* results from suppression of the contributions from higher partial waves and can be linked to the critical angular momentum.

The difference between rotational energies in the fusion saddle and the contact (sticking) configuration plays a major role in compound nucleus formation at energies above *B0*.

B0 - entrance channel barrier (Coulomb+Nuclear potential)



Blue line – Maxima of the 1n channel cross section for cold Fusion reactions



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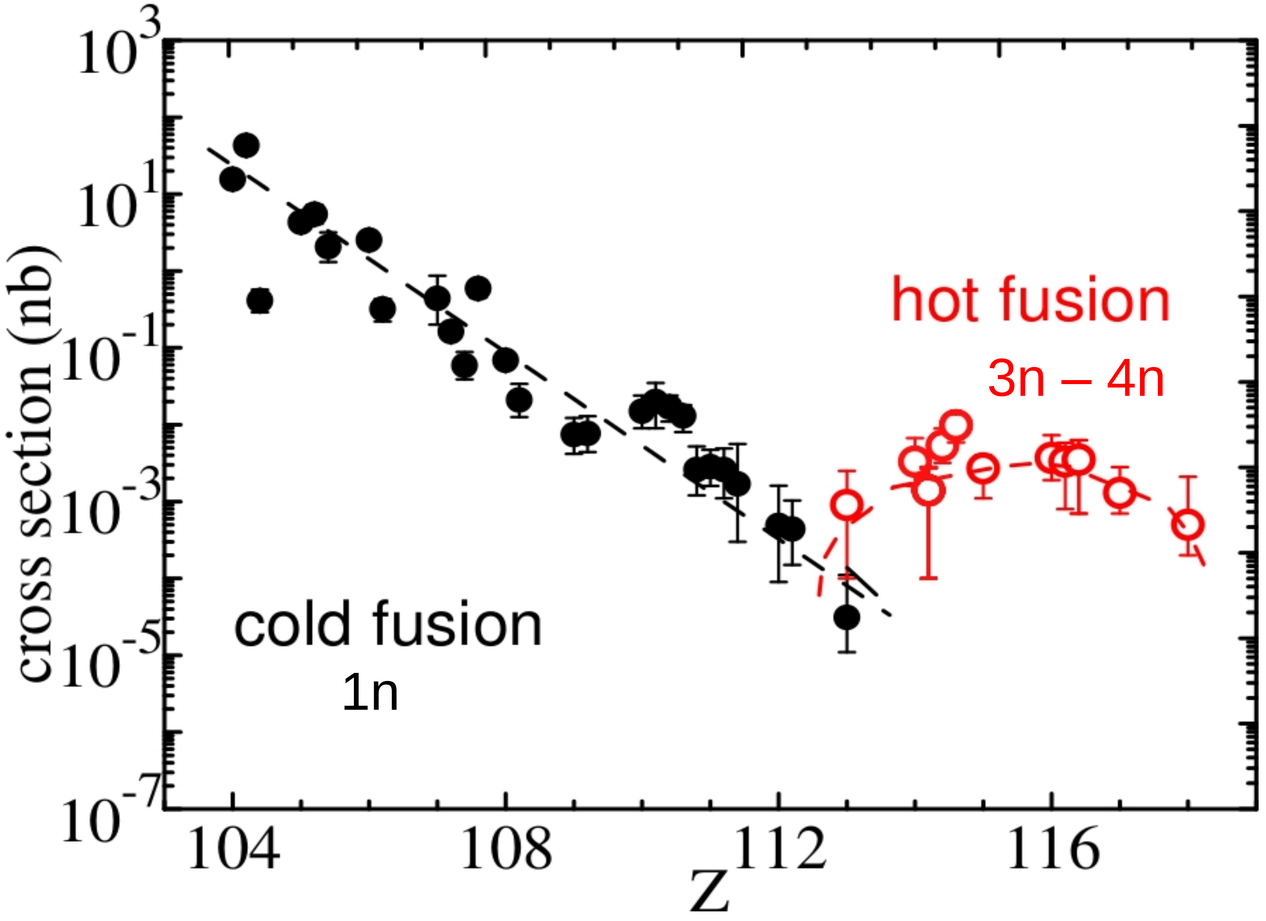
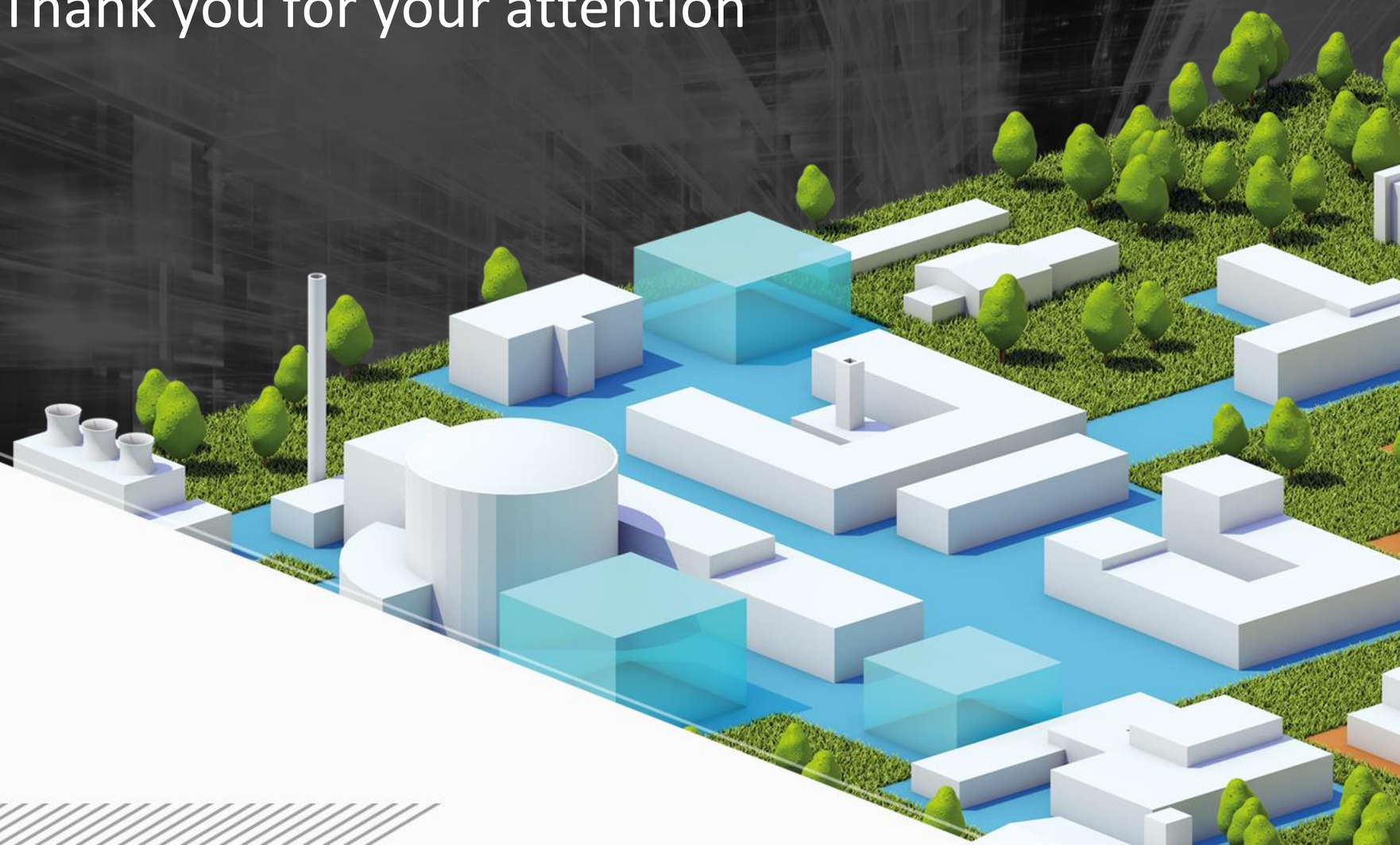


Next step – calculations for hot fusion reactions

Thank you for your attention



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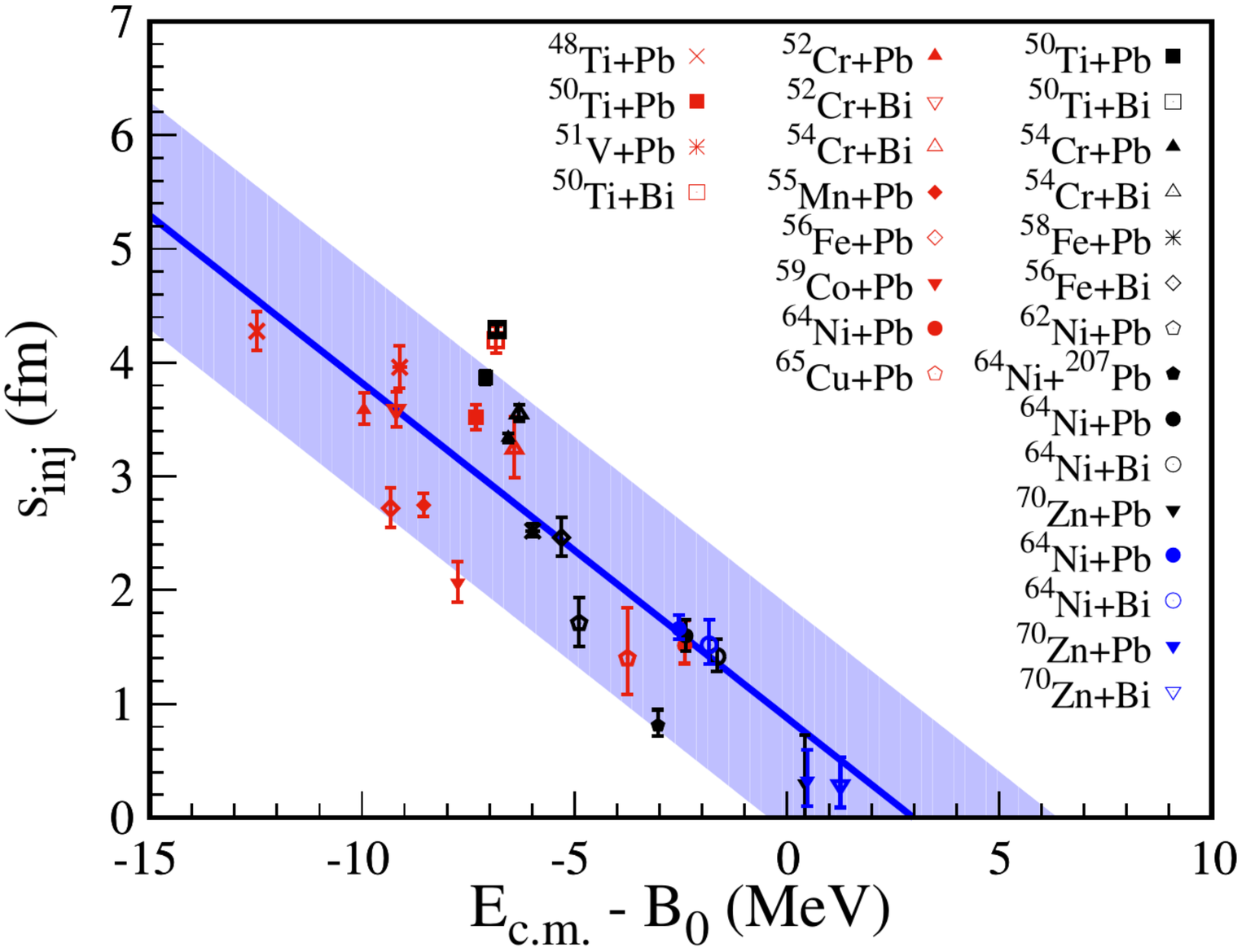
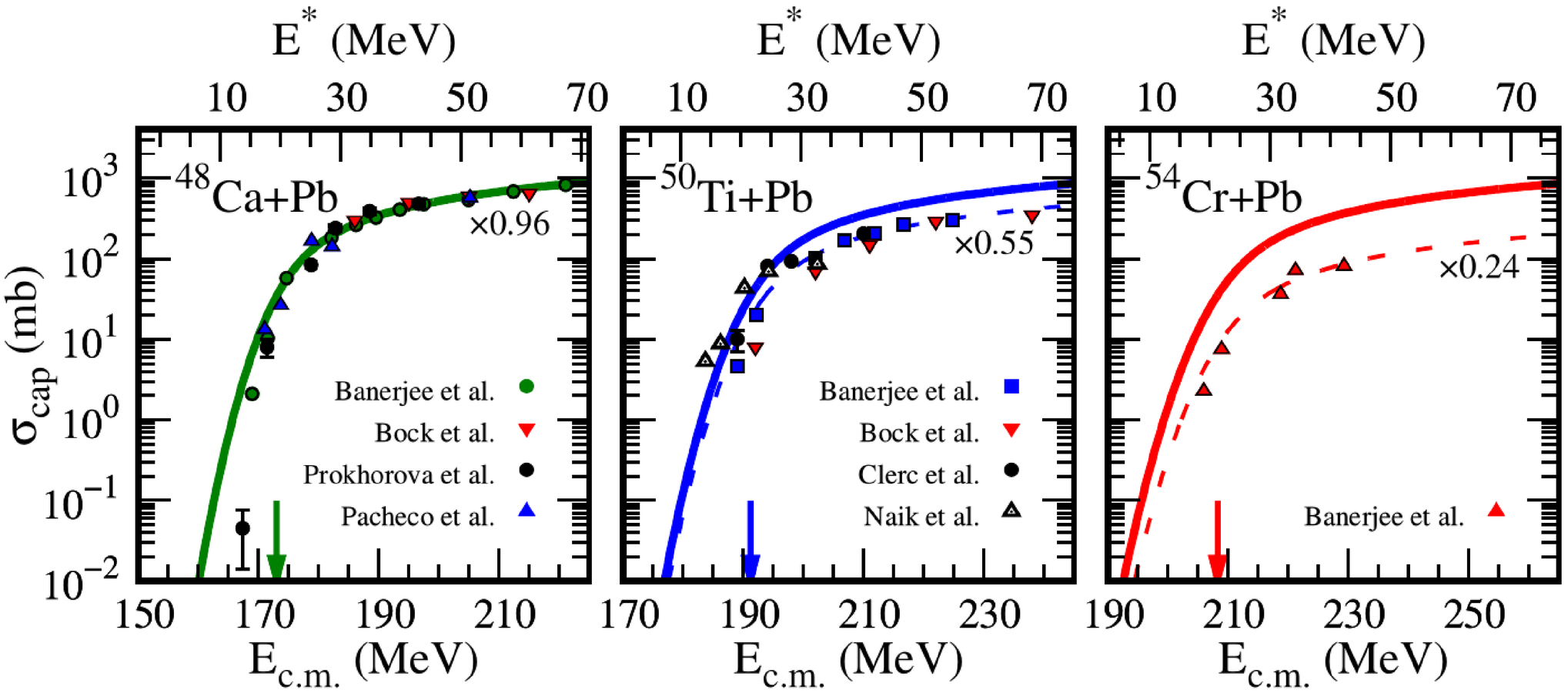

^{48}Ti+Pb
^{50}Ti+Pb
^{51}V+Pb
^{50}Ti+Bi
^{52}Cr+Pb
^{52}Cr+Bi
^{54}Cr+Bi
^{55}Mn+Pb
^{56}Fe+Pb
^{59}Co+Pb
^{64}Ni+Pb
^{65}Cu+Pb
^{50}Ti+Pb
^{50}Ti+Bi
^{54}Cr+Pb
^{54}Cr+Bi
^{58}Fe+Pb
^{56}Fe+Bi
^{62}Ni+Pb
^{64}Ni+^{207}Pb
^{64}Ni+Pb
^{64}Ni+Bi
^{70}Zn+Pb
^{64}Ni+Pb
^{64}Ni+Bi
^{70}Zn+Pb
^{70}Zn+Bi
s_{inj} (fm)
$E_{c.m.} - B_0$ (MeV)
0
1
2
3
4
5
6
7
-15
-10
-5
0
5
10


E* (MeV)
10
30
50
70
σ_{cap} (mb)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
^{48}Ca+Pb
×0.96
Banerjee et al.
Bock et al.
Prokhorova et al.
Pacheco et al.
^{50}Ti+Pb
×0.55
Banerjee et al.
Bock et al.
Clerc et al.
Naik et al.
^{54}Cr+Pb
×0.24
Banerjee et al.
150
170
190
210
230
250
$E_{c.m.}$ (MeV)

Smoluchowski Diffusion Equation

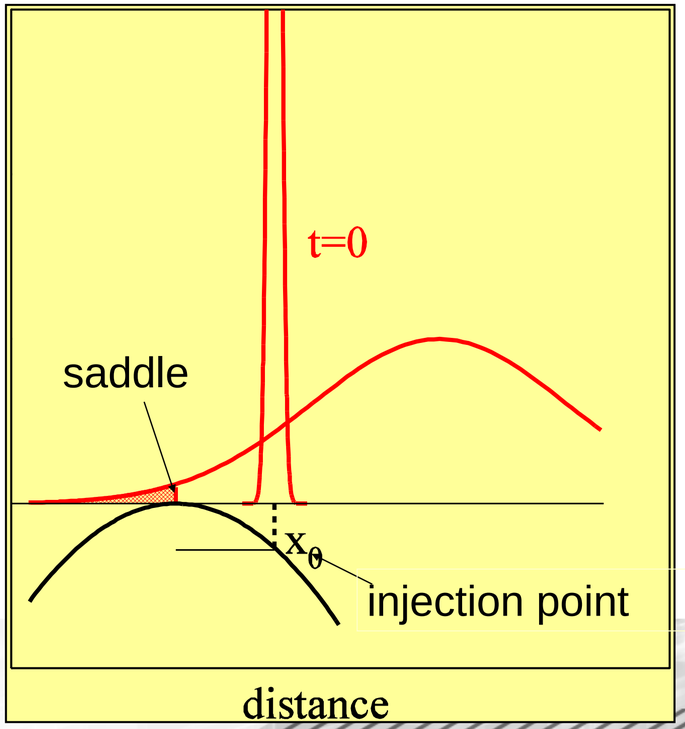
$$\gamma \frac{\partial W(x,t)}{\partial t} = -\frac{\partial}{\partial x}[bxW(x,t)] + T\frac{\partial^2}{\partial x^2}W(x,t)$$

$\propto$ Viscosity of fluid

Driving force

Temperature

W(x,t) = probability to find Brownian particle at position x at time t



Exact solution in a parabolic potential
$V(x) = -bx^2/2$ is a sliding, swelling Gaussian.

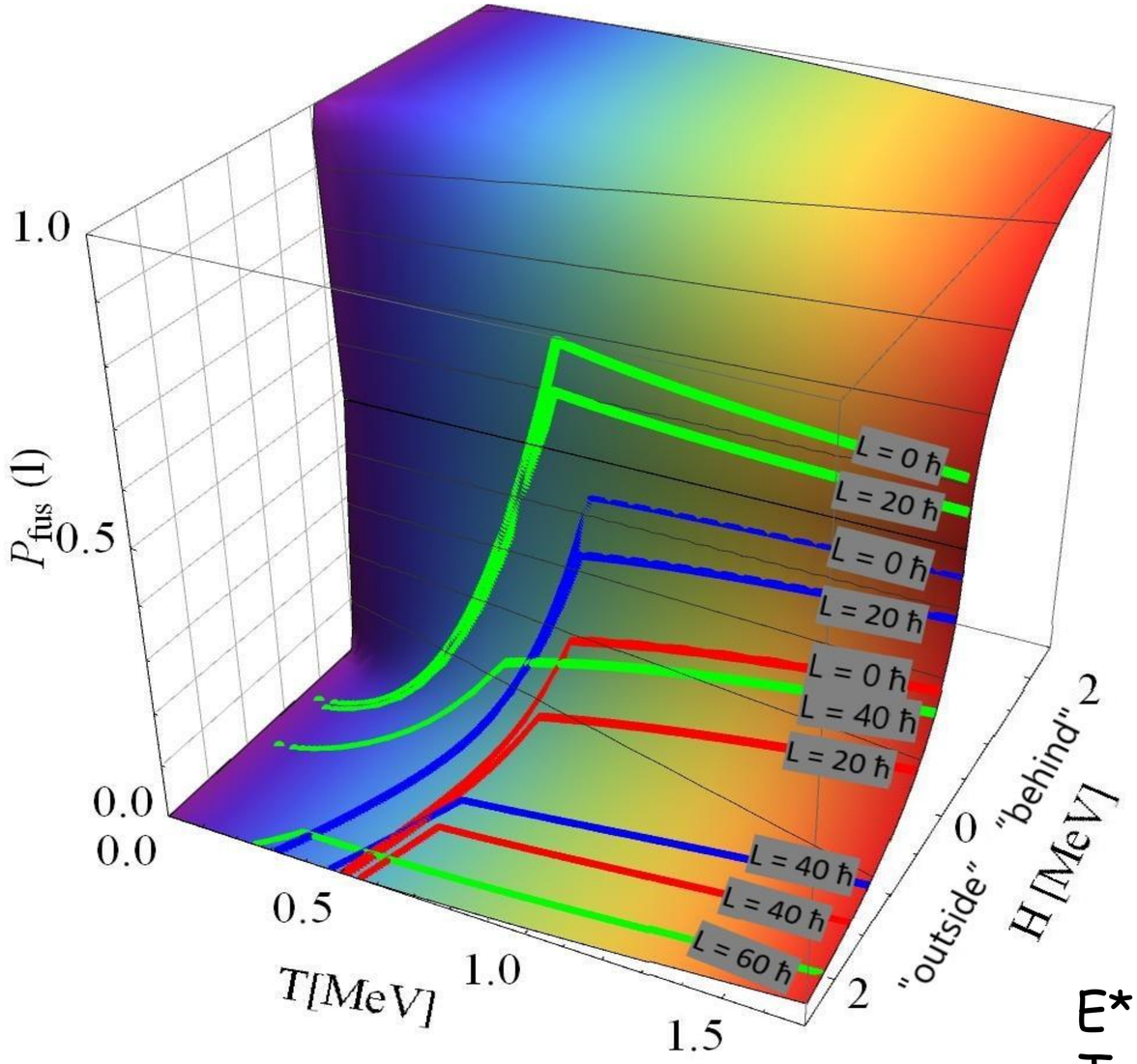
P(fusion) = fraction of Gaussian captured inside the barrier as $t \to \infty$

$$P(\text{fusion}) = \tfrac{1}{2}(1-\text{erf}\sqrt{B/T}) \qquad B = bx_0^2/2$$

if $x_0 \geq 0$ (injection point),

W.J. Świątecki, K. Siwek-Wilczyńska, J. Wilczyński
Acta Phys. Pol. B34 (2003)2049, IJMP E13 (2004) 261,
Phys.Rev.C71 (2005) 014602

^{48}Ca ^{50}Ti ^{54}Cr



$E^* = aT^2$

$T = 1$ MeV $E^* \approx 30$ MeV