WYBRANE PROBLEMY SYNTEZY JĄDER SUPERCIĘŻKICH

Michał Kowal, NCBJ

NATIONAL
CENTRE
FOR NUCLEAR
RESEARCH
ŚWIERK

SEMINARIUM FIZYKI JĄDRA ATOMOWEGO - FUW
23.03.2023

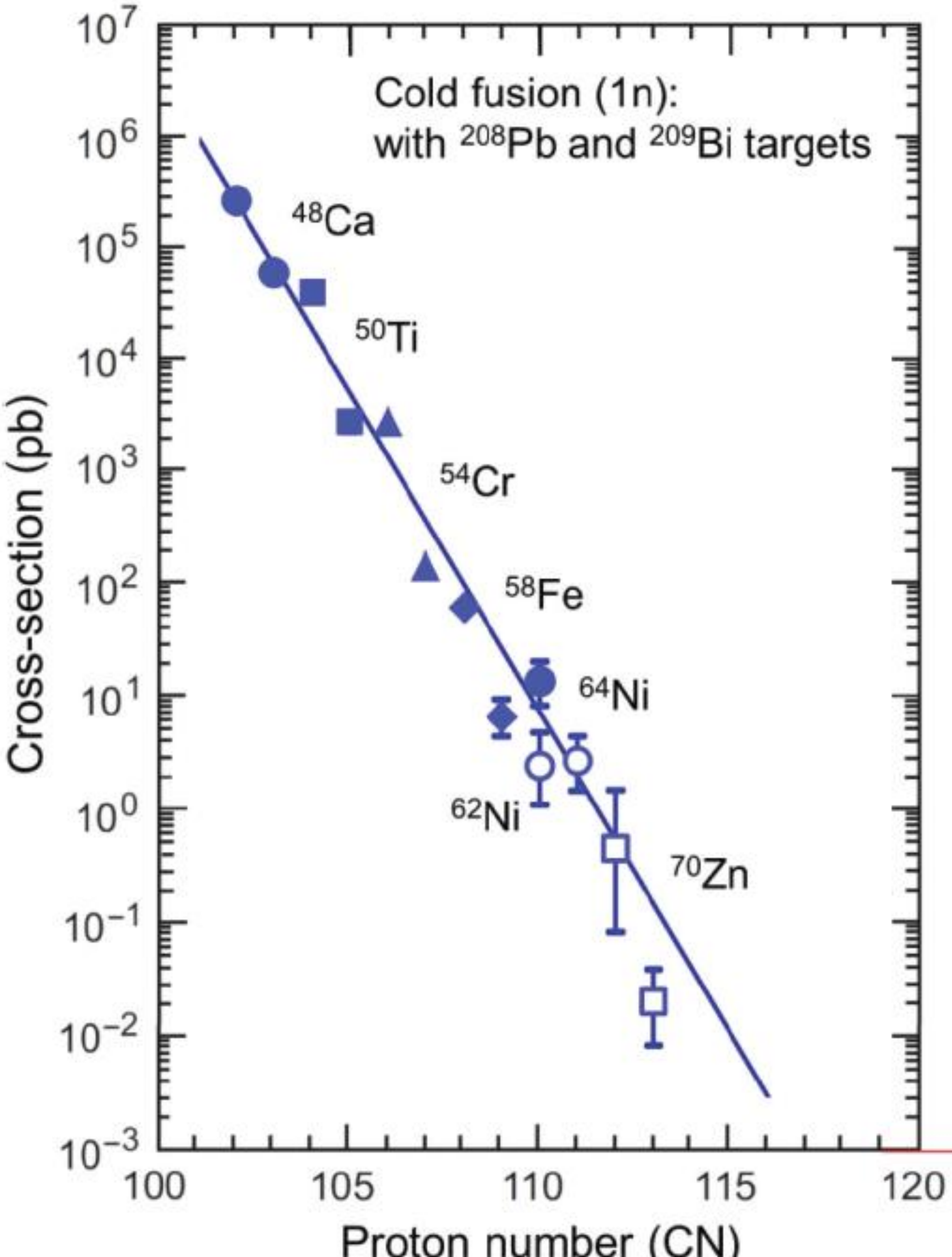
Outline:

- New elements & reaction mechanism
- Capture - deformation & orientation of HI
- Fusion - stochastic nature & centrifugal effect
- Survival - fission barrier & density of states.

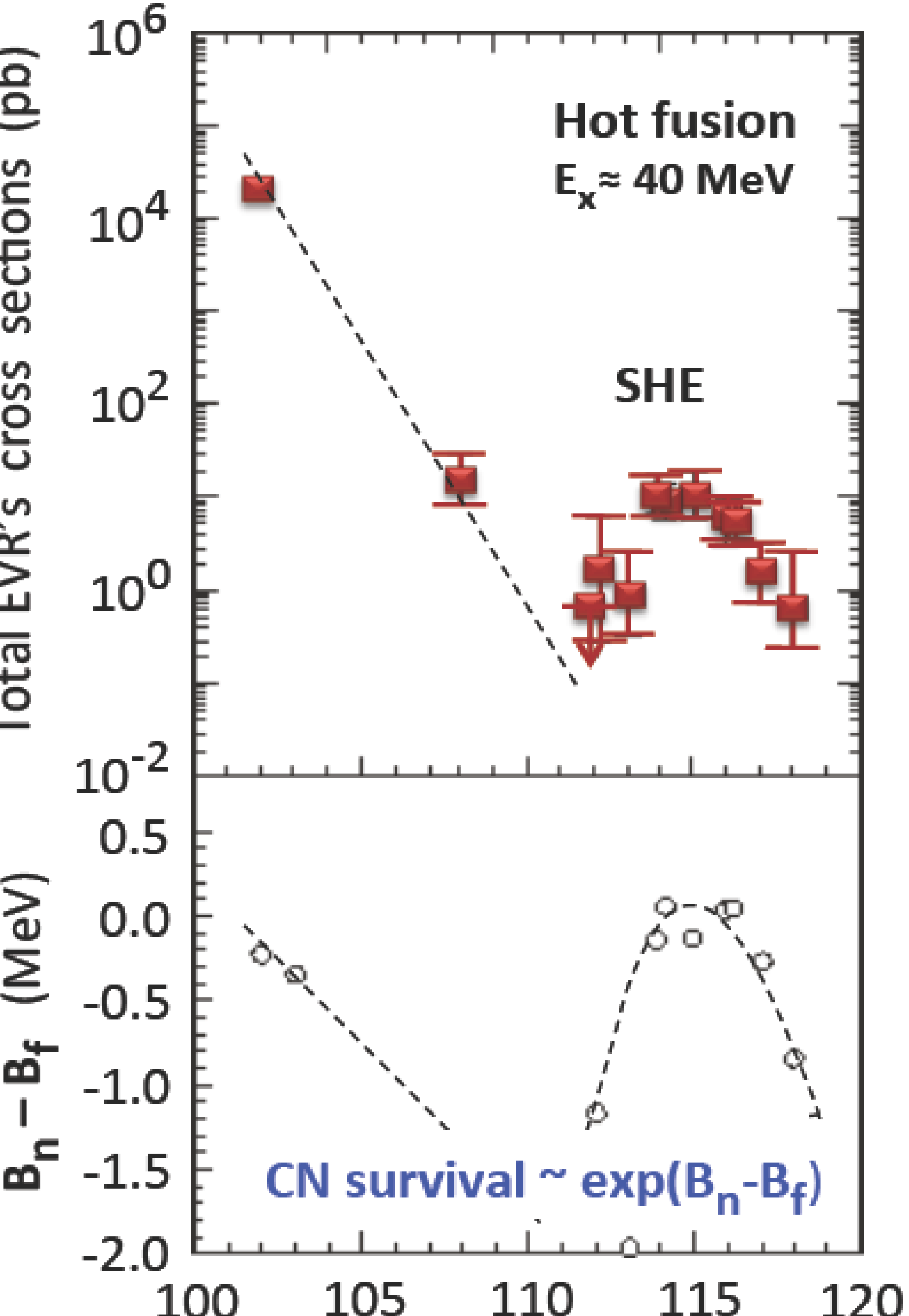
SYNTHESIS SCENARIOS

COLD (102<Z<113)

- the strongly bound target nuclei (208Pb or 209Bi) are bombarded with projectiles ranging from Ca to Zn;
- the excitation energy of the resulting compound nucleus is usually in the range of 10 to 20 MeV;
- as the target-projectile symmetry increases, the compound nucleus production cross section decreases.



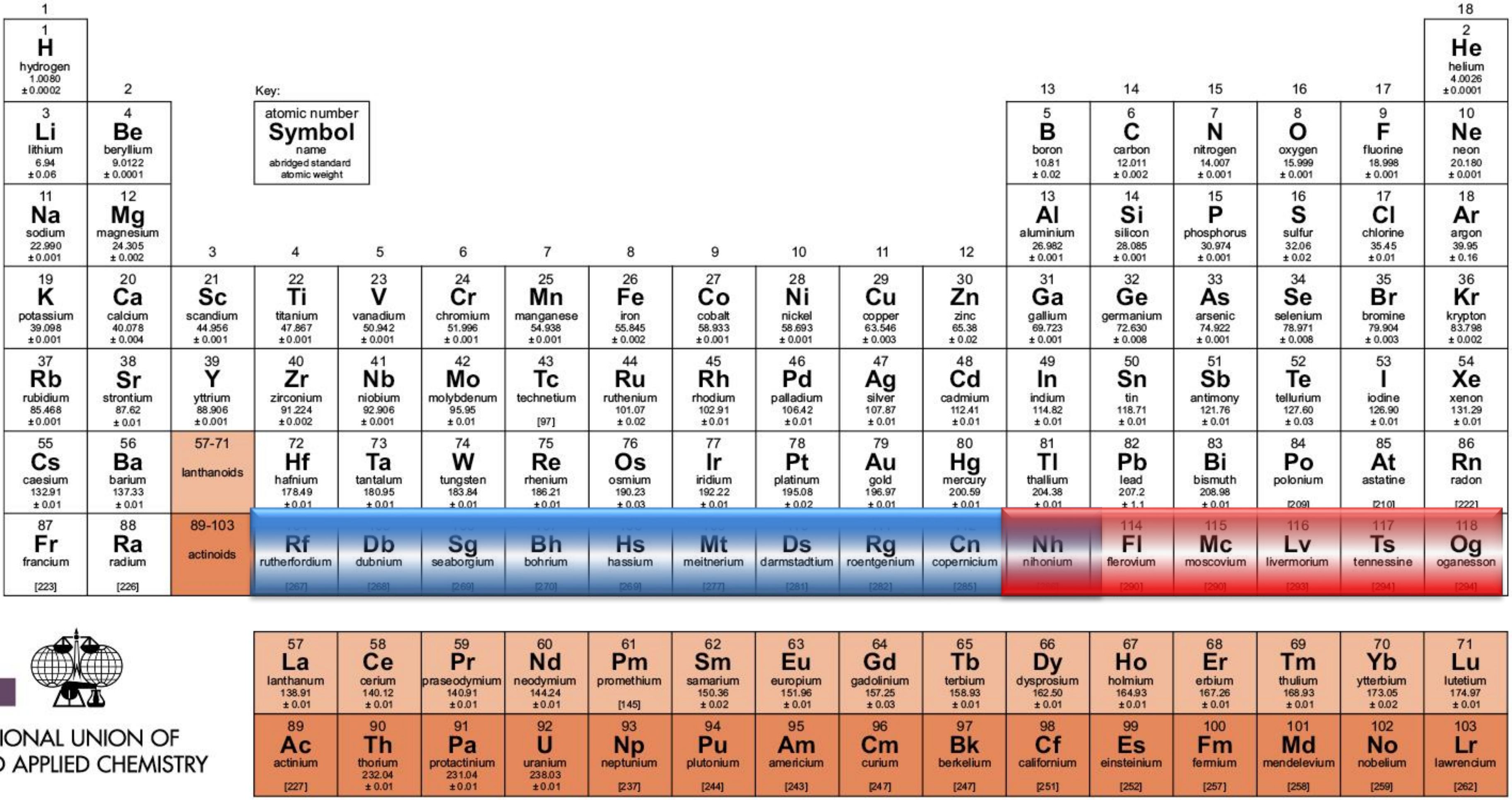
SYNTHESIS SCENARIOS



HOT (112<Z<118)

- the deformed actinide target-nuclei (from U to Cm) are bombarded with a doubly magic 48Ca projectile;
- the excitation energy of the resulting compound nucleus is usually in the range of 30 to 40 MeV, and the dominant evaporation channels are 3n and 4n channels;
- the evaporation residue cross sections do not show any strong dependence on the target-projectile symmetry and are at the picobarn level.

IUPAC Periodic Table of the Elements



Key:

atomic number
Symbol
name
abridged standard atomic weight

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** hydrogen 1.0080 ± 0.0002																	2 **He** helium 4.0026 ± 0.0001
3 **Li** lithium 6.94 ± 0.06	4 **Be** beryllium 9.0122 ± 0.0001											5 **B** boron 10.81 ± 0.02	6 **C** carbon 12.011 ± 0.002	7 **N** nitrogen 14.007 ± 0.001	8 **O** oxygen 15.999 ± 0.001	9 **F** fluorine 18.998 ± 0.001	10 **Ne** neon 20.180 ± 0.001
11 **Na** sodium 22.990 ± 0.001	12 **Mg** magnesium 24.305 ± 0.002											13 **Al** aluminium 26.982 ± 0.001	14 **Si** silicon 28.085 ± 0.001	15 **P** phosphorus 30.974 ± 0.001	16 **S** sulfur 32.06 ± 0.02	17 **Cl** chlorine 35.45 ± 0.01	18 **Ar** argon 39.95 ± 0.16
19 **K** potassium 39.098 ± 0.001	20 **Ca** calcium 40.078 ± 0.004	21 **Sc** scandium 44.956 ± 0.001	22 **Ti** titanium 47.867 ± 0.001	23 **V** vanadium 50.942 ± 0.001	24 **Cr** chromium 51.996 ± 0.001	25 **Mn** manganese 54.938 ± 0.001	26 **Fe** iron 55.845 ± 0.002	27 **Co** cobalt 58.933 ± 0.001	28 **Ni** nickel 58.693 ± 0.001	29 **Cu** copper 63.546 ± 0.003	30 **Zn** zinc 65.38 ± 0.02	31 **Ga** gallium 69.723 ± 0.001	32 **Ge** germanium 72.630 ± 0.008	33 **As** arsenic 74.922 ± 0.001	34 **Se** selenium 78.971 ± 0.008	35 **Br** bromine 79.904 ± 0.003	36 **Kr** krypton 83.798 ± 0.002
37 **Rb** rubidium 85.468 ± 0.001	38 **Sr** strontium 87.62 ± 0.01	39 **Y** yttrium 88.906 ± 0.001	40 **Zr** zirconium 91.224 ± 0.002	41 **Nb** niobium 92.906 ± 0.001	42 **Mo** molybdenum 95.95 ± 0.01	43 **Tc** technetium [97]	44 **Ru** ruthenium 101.07 ± 0.02	45 **Rh** rhodium 102.91 ± 0.01	46 **Pd** palladium 106.42 ± 0.01	47 **Ag** silver 107.87 ± 0.01	48 **Cd** cadmium 112.41 ± 0.01	49 **In** indium 114.82 ± 0.01	50 **Sn** tin 118.71 ± 0.01	51 **Sb** antimony 121.76 ± 0.01	52 **Te** tellurium 127.60 ± 0.03	53 **I** iodine 126.90 ± 0.01	54 **Xe** xenon 131.29 ± 0.01
55 **Cs** caesium 132.91 ± 0.01	56 **Ba** barium 137.33 ± 0.01	57-71 lanthanoids	72 **Hf** hafnium 178.49 ± 0.01	73 **Ta** tantalum 180.95 ± 0.01	74 **W** tungsten 183.84 ± 0.01	75 **Re** rhenium 186.21 ± 0.01	76 **Os** osmium 190.23 ± 0.03	77 **Ir** iridium 192.22 ± 0.01	78 **Pt** platinum 195.08 ± 0.02	79 **Au** gold 196.97 ± 0.01	80 **Hg** mercury 200.59 ± 0.01	81 **Tl** thallium 204.38 ± 0.01	82 **Pb** lead 207.2 ± 1.1	83 **Bi** bismuth 208.98 ± 0.01	84 **Po** polonium [209]	85 **At** astatine [210]	86 **Rn** radon [222]
87 **Fr** francium [223]	88 **Ra** radium [226]	89-103 actinoids	[illegible] **Rf** rutherfordium [267]	[illegible] **Db** dubnium [268]	[illegible] **Sg** seaborgium [269]	[illegible] **Bh** bohrium [270]	[illegible] **Hs** hassium [269]	[illegible] **Mt** meitnerium [277]	[illegible] **Ds** darmstadtium [281]	[illegible] **Rg** roentgenium [282]	[illegible] **Cn** copernicium [285]	[illegible] **Nh** nihonium [illegible]	114 **Fl** flerovium [290]	115 **Mc** moscovium [290]	116 **Lv** livermorium [293]	117 **Ts** tennessine [294]	118 **Og** oganesson [294]

57 **La** lanthanum 138.91 ± 0.01	58 **Ce** cerium 140.12 ± 0.01	59 **Pr** praseodymium 140.91 ± 0.01	60 **Nd** neodymium 144.24 ± 0.01	61 **Pm** promethium [145]	62 **Sm** samarium 150.36 ± 0.02	63 **Eu** europium 151.96 ± 0.01	64 **Gd** gadolinium 157.25 ± 0.03	65 **Tb** terbium 158.93 ± 0.01	66 **Dy** dysprosium 162.50 ± 0.01	67 **Ho** holmium 164.93 ± 0.01	68 **Er** erbium 167.26 ± 0.01	69 **Tm** thulium 168.93 ± 0.01	70 **Yb** ytterbium 173.05 ± 0.02	71 **Lu** lutetium 174.97 ± 0.01
89 **Ac** actinium [227]	90 **Th** thorium 232.04 ± 0.01	91 **Pa** protactinium 231.04 ± 0.01	92 **U** uranium 238.03 ± 0.01	93 **Np** neptunium [237]	94 **Pu** plutonium [244]	95 **Am** americium [243]	96 **Cm** curium [247]	97 **Bk** berkelium [247]	98 **Cf** californium [251]	99 **Es** einsteinium [252]	100 **Fm** fermium [257]	101 **Md** mendelevium [258]	102 **No** nobelium [259]	103 **Lr** lawrencium [262]

ERNATIONAL UNION OF
RE AND APPLIED CHEMISTRY

For notes and updates to this table, see www.iupac.org. This version is dated 4 May 2022.

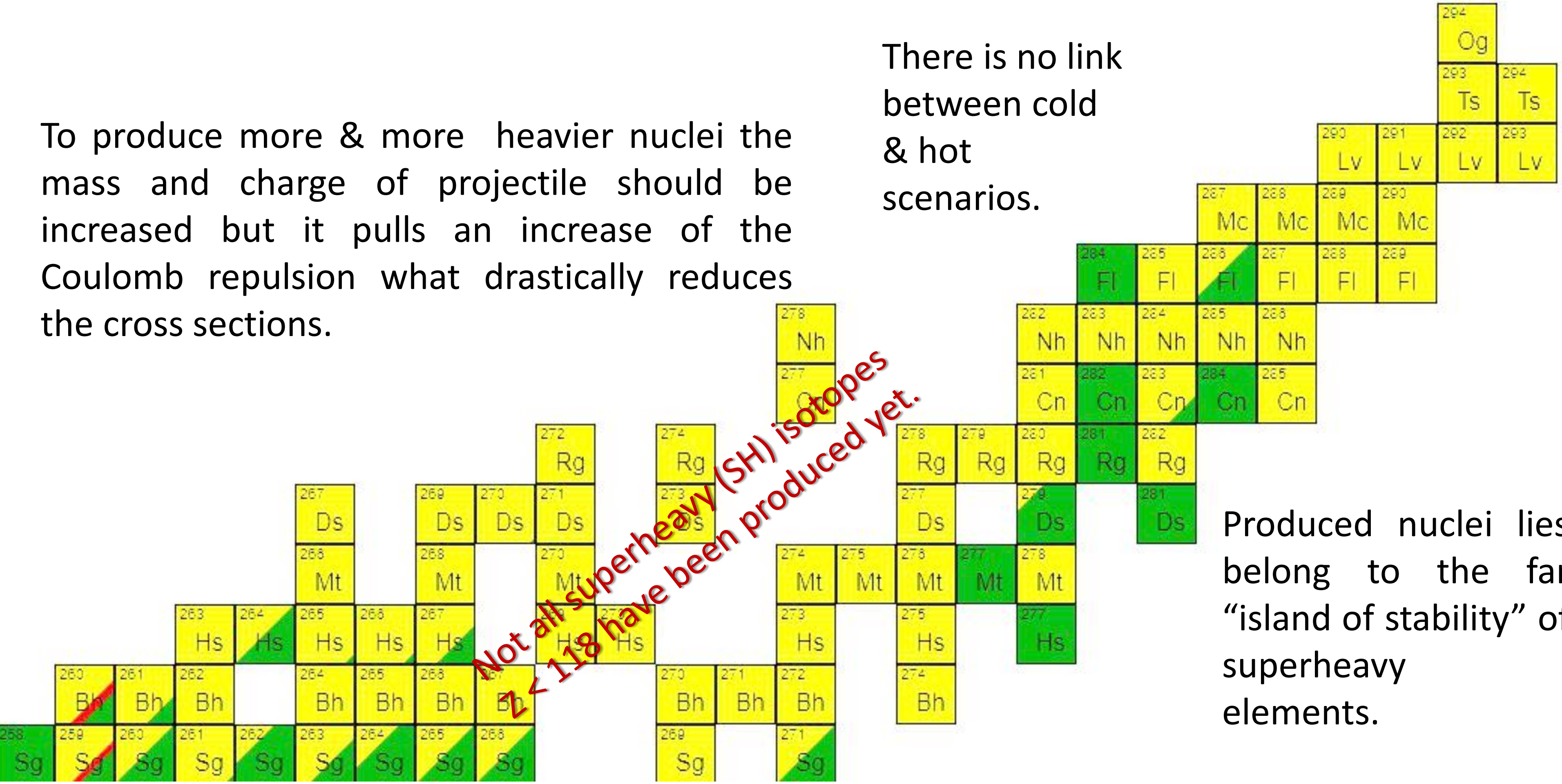
BUT

Attempts of going beyond the reactions Act. + ^{48}Ca by using heavier projectiles like ^{50}Ti, ^{54}Cr, ^{58}Fe, and ^{64}Ni gave no results so far.

All heavier actinides with Z>98 live to short that one could perform target with them.

To produce more & more heavier nuclei the mass and charge of projectile should be increased but it pulls an increase of the Coulomb repulsion what drastically reduces the cross sections.

There is no link between cold & hot scenarios.



Not all superheavy (SH) isotopes Z < 118 have been produced yet.

Produced nuclei lies belong to the far "island of stability" of superheavy elements.

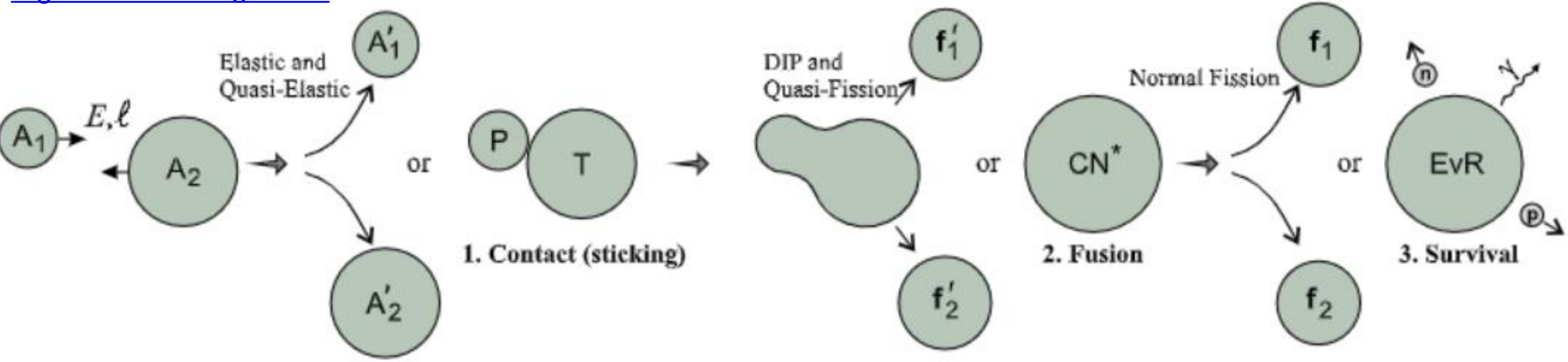
the overarching goal of the models is:

to determine the most appropriate projectile-target combination

to predict the optimal bombardment energy in the entrance channel at which the production cross-section is the most significant

to explain the fusion process in heavy-ion collisions

Fig from Valeri Zagrebaev



$$\sigma(\text{synthesis}) = \pi\lambdabar^{2}\sum_{l=0}^{lmax}(2l+1)T_{l}\times P_{l}(\text{fusion})\times P_{xn}^{\ell}(\text{survive})$$

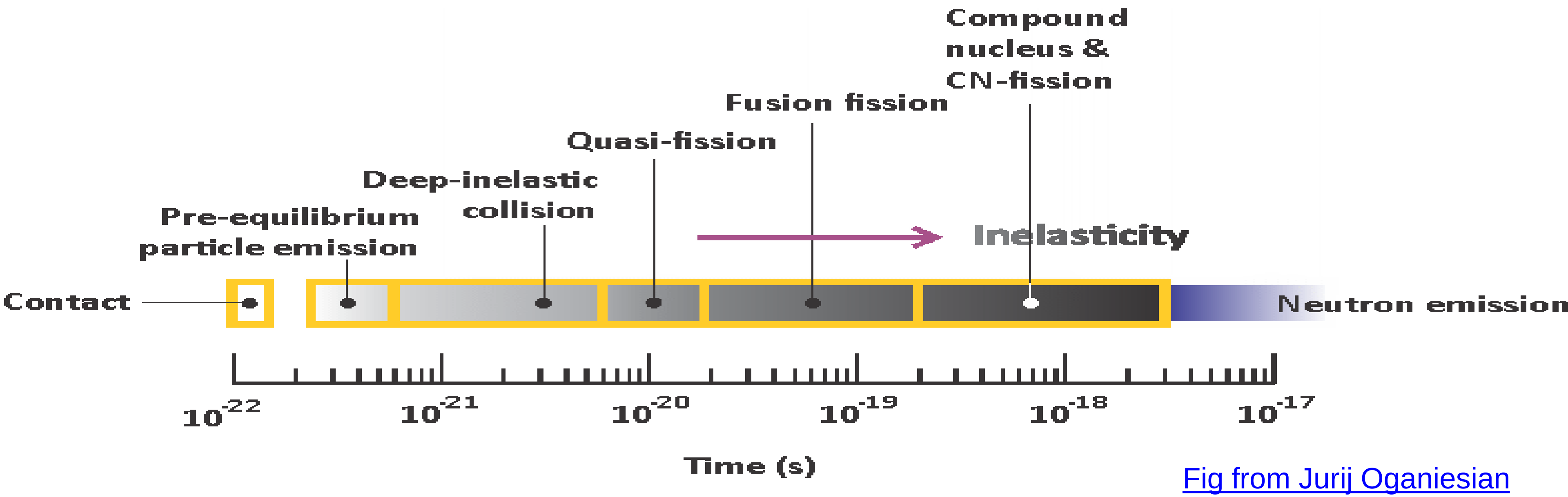
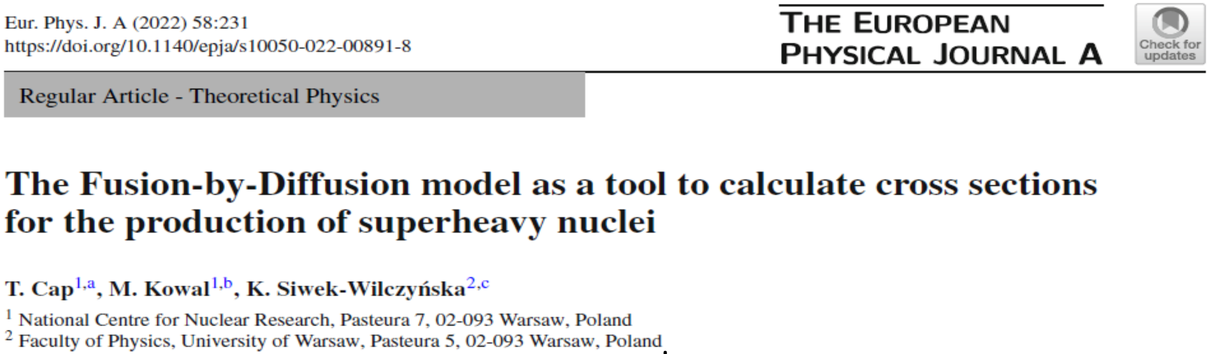


Fig from Jurij Oganiesian

Capture


Eur. Phys. J. A (2022) 58:231
https://doi.org/10.1140/epja/s10050-022-00891-8
THE EUROPEAN PHYSICAL JOURNAL A

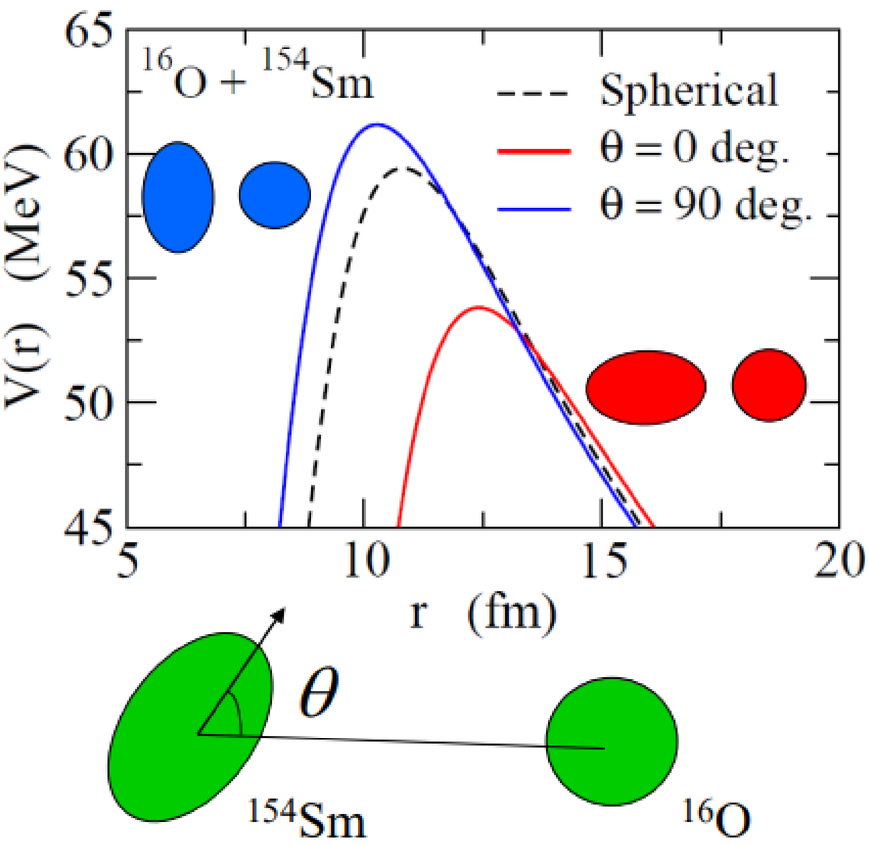
Regular Article - Theoretical Physics

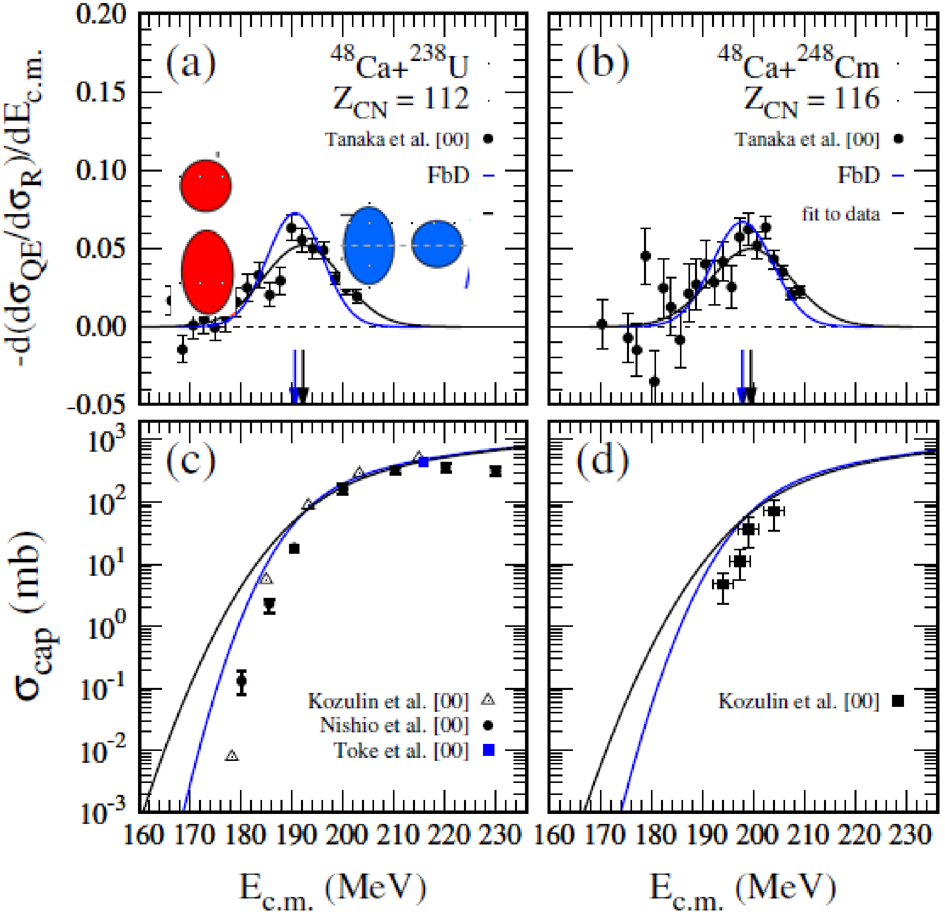
The Fusion-by-Diffusion model as a tool to calculate cross sections for the production of superheavy nuclei

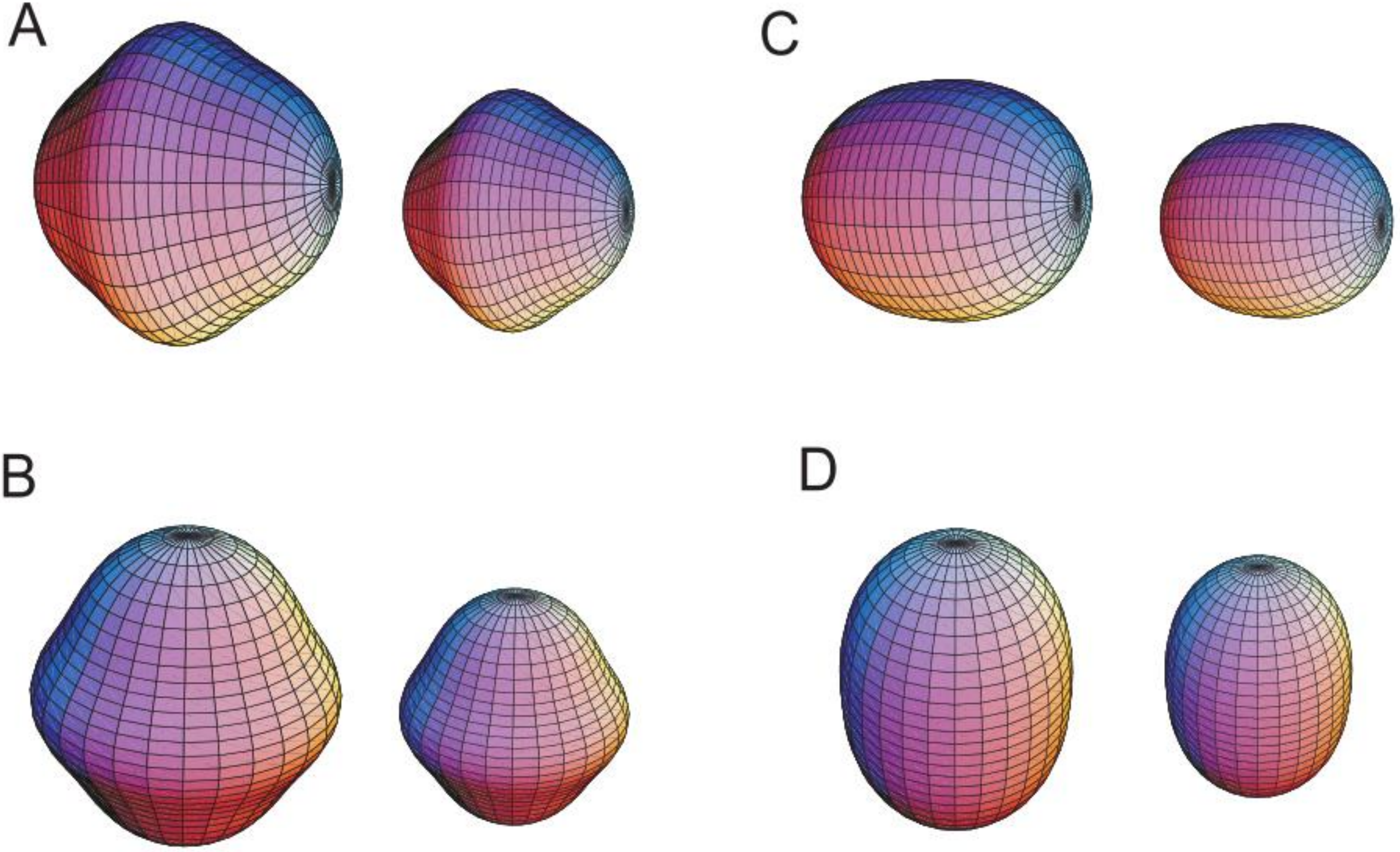
T. Cap[1,a], M. Kowal[1,b], K. Siwek-Wilczyńska[2,c]
[1] National Centre for Nuclear Research, Pasteura 7, 02-093 Warsaw, Poland
[2] Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland

$$V_C = \frac{e^2}{4\pi\varepsilon_0}\frac{Z_a Z_b}{R_a + R_b}$$

$$\sigma(\text{synthesis}) = \pi\lambda\!\!\!^{-}{}^2 \sum_{l=0}^{l\text{max}} \boxed{(2l+1)T_l} \times P_l(\text{fusion}) \times P^{\ell}_{xn}(\text{survive})$$

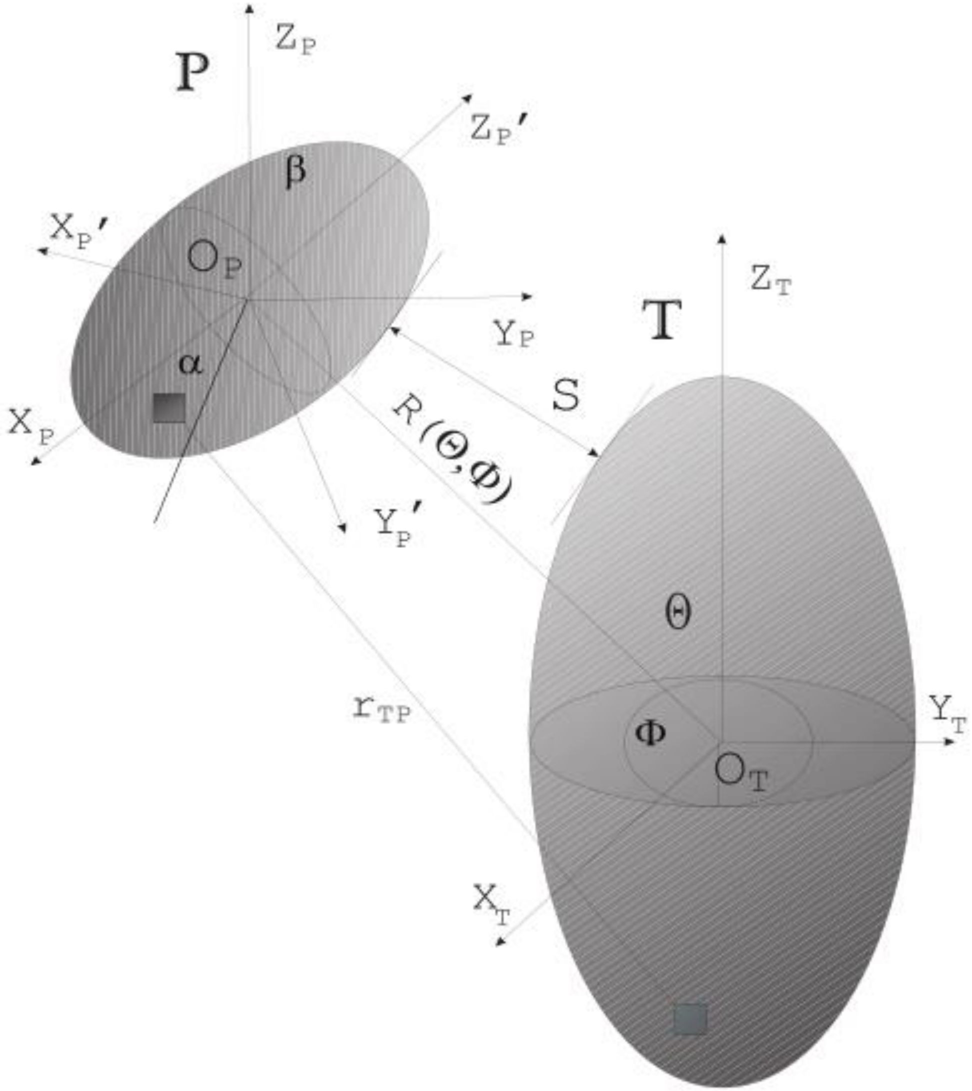





A
C
B
D

$$V_{TOT}(R,\Theta) = V_C(R,\Theta) + V_N(R,\Theta) + V_L(R) \ .$$

$$\vec{R} = \begin{cases} R\,\sin(\Theta)\,\cos(\Phi) \\ R\,\sin(\Theta)\,\sin(\Phi) \\ R\,\cos(\Theta) \end{cases}$$



Electrostatic Interaction

$$V_C = \int_{V_P} \int_{V_T} \frac{\rho_T(\vec{r}_T)\rho_P(\vec{r}_P)}{r_{TP}} d^3 r_T \, d^3 r_P$$

$$\frac{1}{r_{TP}} = \sum_{l_T}^{\infty} \sum_{l_P}^{\infty} \frac{(-1)^{l_P} r_T^{l_T} r_P^{l_P}}{R^{l_T+l_P+1}} \sum_{m_T=-l_T}^{l_T} \sum_{m_P=-l_P}^{l_P} C_{l_T,l_P}^{m_T,m_P} \; Y_{l_T+l_P}^{-(m_T+m_P)}(\Theta,\Phi) \\ \times Y_{l_T}^{m_T}(\vartheta_T,\varphi_T) \; Y_{l_P}^{m_P}(\vartheta_P,\varphi_P) \; ,$$

$$Q_{l_{T(P)}}^{m_{T(P)}}(\vartheta_{T(P)},\varphi_{T(P)}) = \int_{V_{T(P)}} \rho_{T(P)}(r_{T(P)}) r_{T(P)}^{l_{T(P)}} Y_{l_{T(P)}}^{m_{T(P)}}(\vartheta_{T(P)},\varphi_{T(P)}) d\tau_{T(P)}$$

$$V_C = \sum_{l_T}^{\infty} \sum_{l_P}^{\infty} \frac{(-1)^{l_P}}{R^{l_T+l_P+1}} \sum_{m_T=-l_T}^{l_T} \sum_{m_P=-l_P}^{l_P} \sum_{m'_P=-l_P}^{l_P} C_{l_T,l_P}^{m_T,m_P} \; Y_{l_T+l_P}^{-(m_T+m_P)}(\Theta,\Phi) \\ \times Q_{l_T}^{m_T}(\vartheta_T,\varphi_T) \; D_{m'_P,m_P}^{l_P}(\alpha,\beta,\gamma) \; Q_{l_P}^{m'_P}(\vartheta'_P,\varphi'_P) \; .$$

Nuclear Interaction

$$V_N = \ 4\ \pi\gamma\ K\ \psi(s)$$

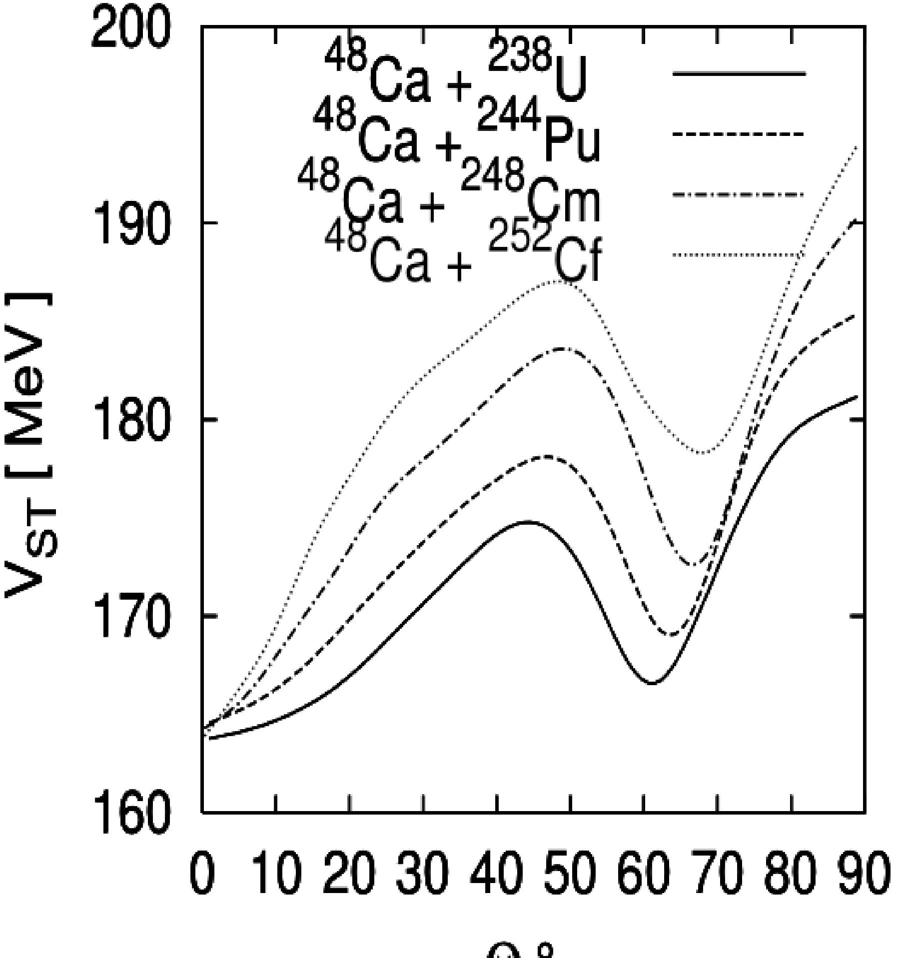
$$\frac{1}{K^2} = \frac{1}{R_{1T}R_{1P}} + \frac{1}{R_{2T}R_{2P}} + \frac{1}{R_{1T}R_{2P}} + \frac{1}{R_{2T}R_{1P}}$$

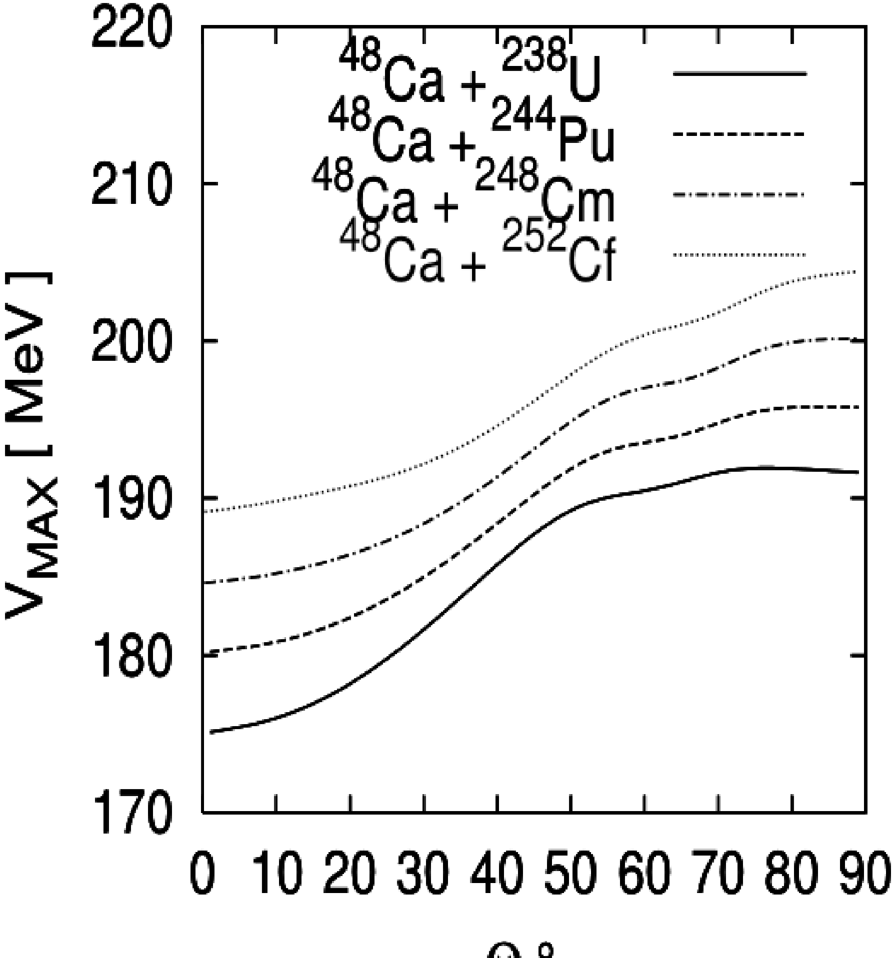
$$\begin{aligned} s = min[\,&(R\sin(\vartheta)\cos(\varphi) + R_P(\vartheta_P,\varphi_P)\sin(\vartheta_P)\cos(\varphi_P) - R_T(\vartheta_T,\varphi_T)\sin(\vartheta_T)\cos(\varphi_T))^2 \\ &+(R\sin(\vartheta)\sin(\varphi) + R_P(\vartheta_P,\varphi_P)\sin(\vartheta_P)\sin(\varphi_P) - R_T(\vartheta_T,\varphi_T)\sin(\vartheta_T)\sin(\varphi_T))^2 \\ &+(R\cos(\vartheta) + R_P(\vartheta_P,\varphi_P)\cos(\vartheta_P) - R_T(\vartheta_T,\varphi_T)\cos(\vartheta_T))^2\,]^{\frac{1}{2}} \qquad (4.24 \end{aligned}$$

$$\psi(s) = -0.1333 + \sum_n^5 \frac{c_n}{n+1}(2.5-s)^{n+1}\,, \qquad 0 < s < 2.5$$

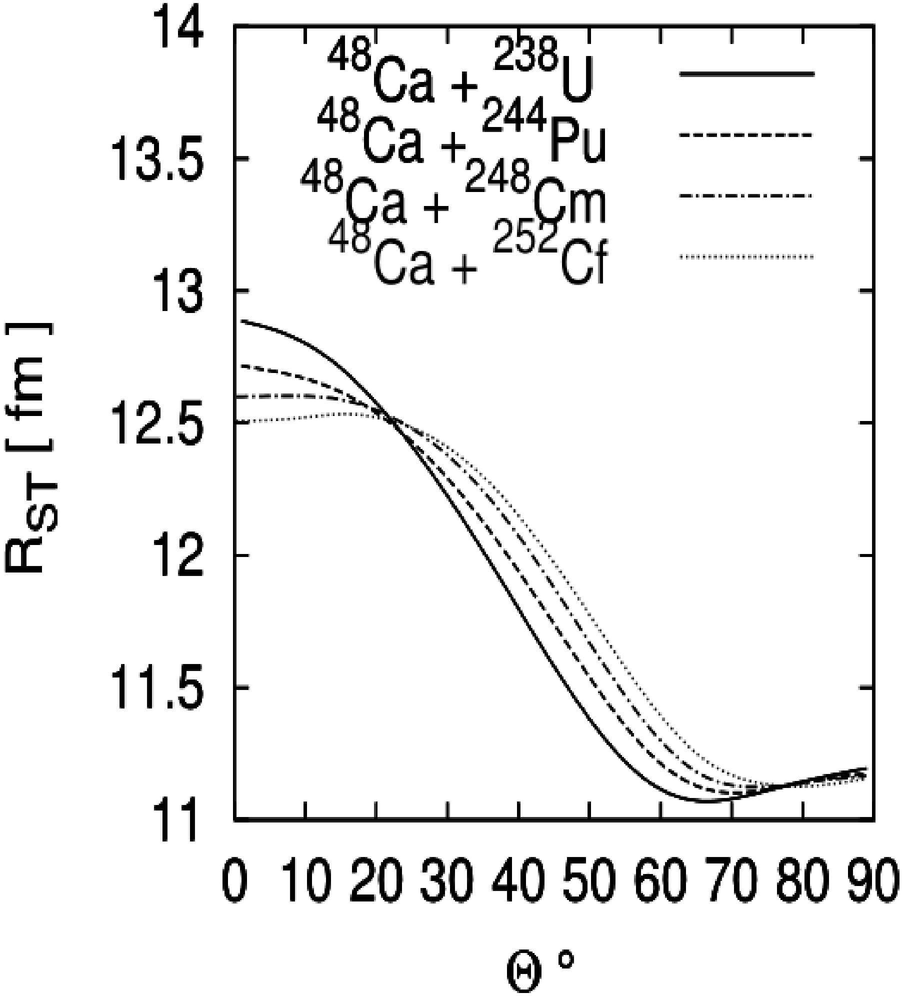
$$\psi(s) = -0.09551 \cdot exp[\frac{(2.75-s)}{0.7176}]\,, \qquad s > 2.5$$

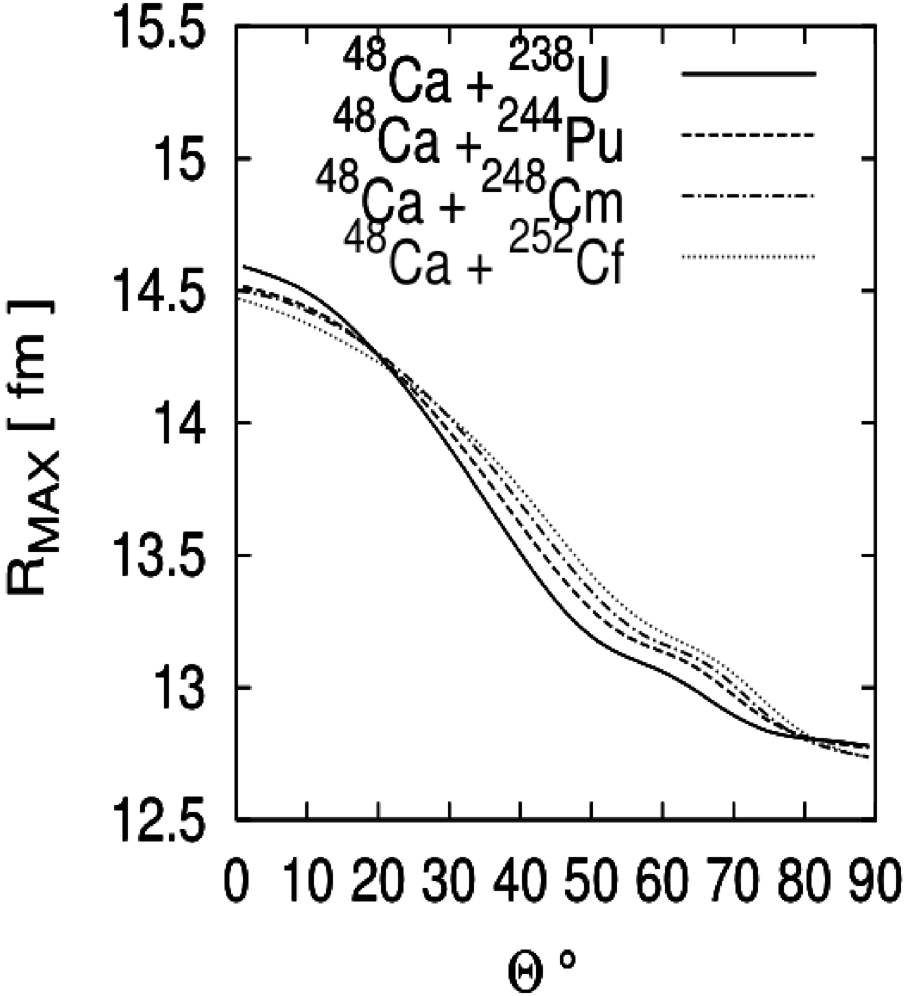
Entrance barrier parameters





Entrance barrier parameters





$$\sigma(\text{synthesis}) = \pi\bar{\lambda}^2 \sum_{l=0}^{lmax}(2l+1)T_l \times \boxed{P_l(\text{fusion})} \times P_{xn}^{\ell}(\text{survive})$$

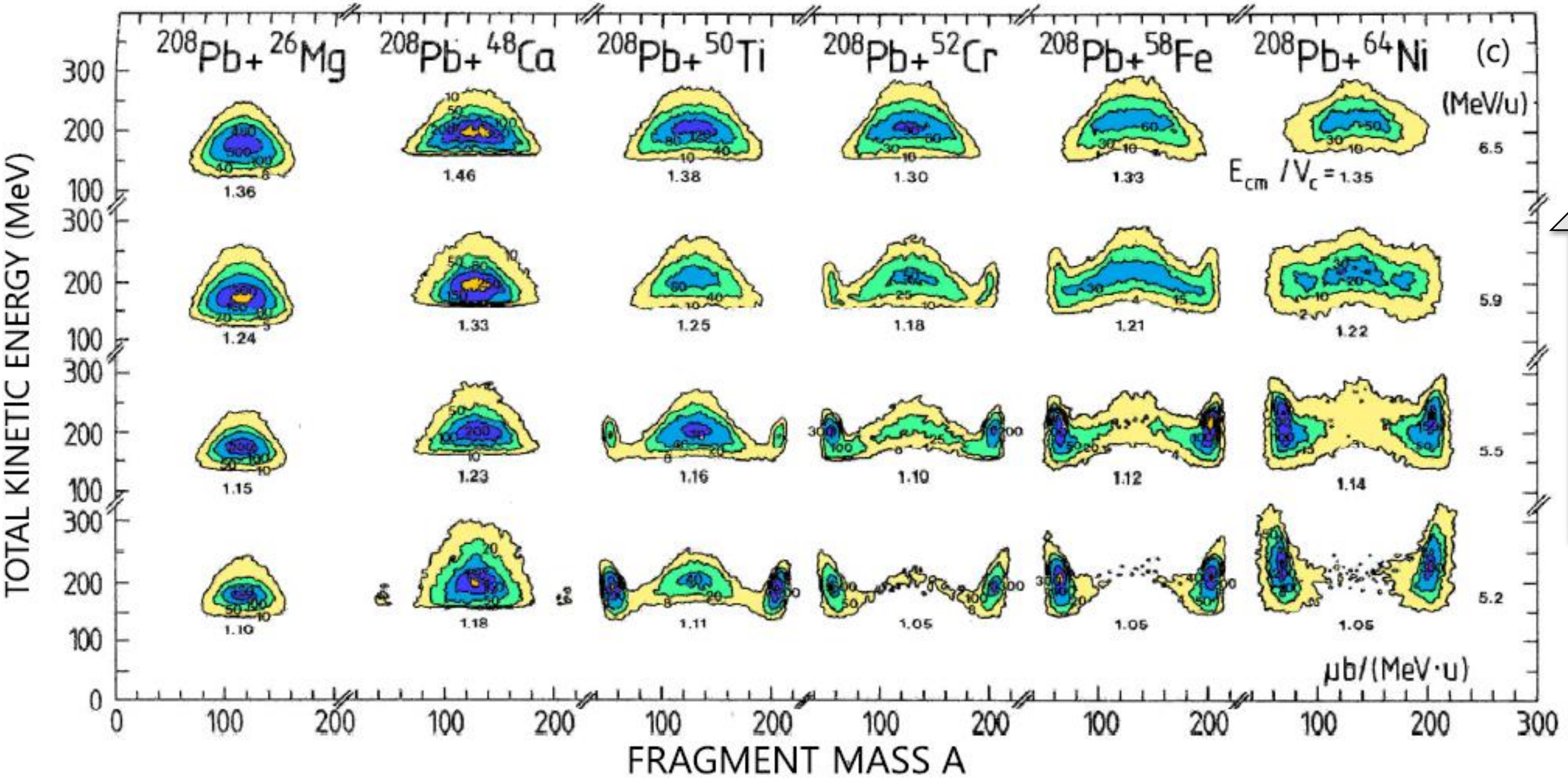
Basic assumptions:

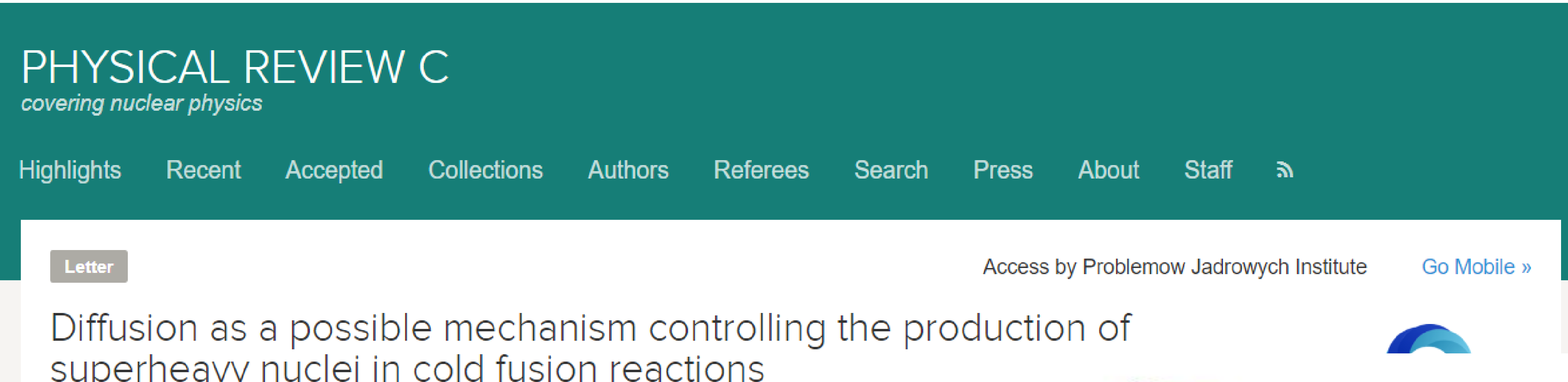
- After the capture stage, the internal mass asymmetrical conditional saddle point - the fusion barrier - must be overcome by the system.
- The stochastic nature of the fusion process is accompanied by dissipation of energy and angular momentum.
- All nucleons are transformed from projectile to the target by a diffusion process.

Fusion - By - Diffusion - Smoluchowski equation
W. J. Świątecki, K. Siwek-Wilczyńska, and J. Wilczyński
Phys. Rev. C **71**, 014602 (2005).

Di - Nuclear - System - master equation
G.G. Adamian, N.V. Antonenko, Eur. Phys. J. A (2022).

Experimental studies of the competition between fusion and quasifission in the formation of heavy and superheavy nuclei, D.J. Hinde, M. Dasgupta, E.C. Simpson, Progress in Particle and Nuclear Physics, Volume 118, May 2021, 103856.





PHYSICAL REVIEW C
covering nuclear physics

Highlights Recent Accepted Collections Authors Referees Search Press About Staff

Letter

Access by Problemow Jadrowych Institute

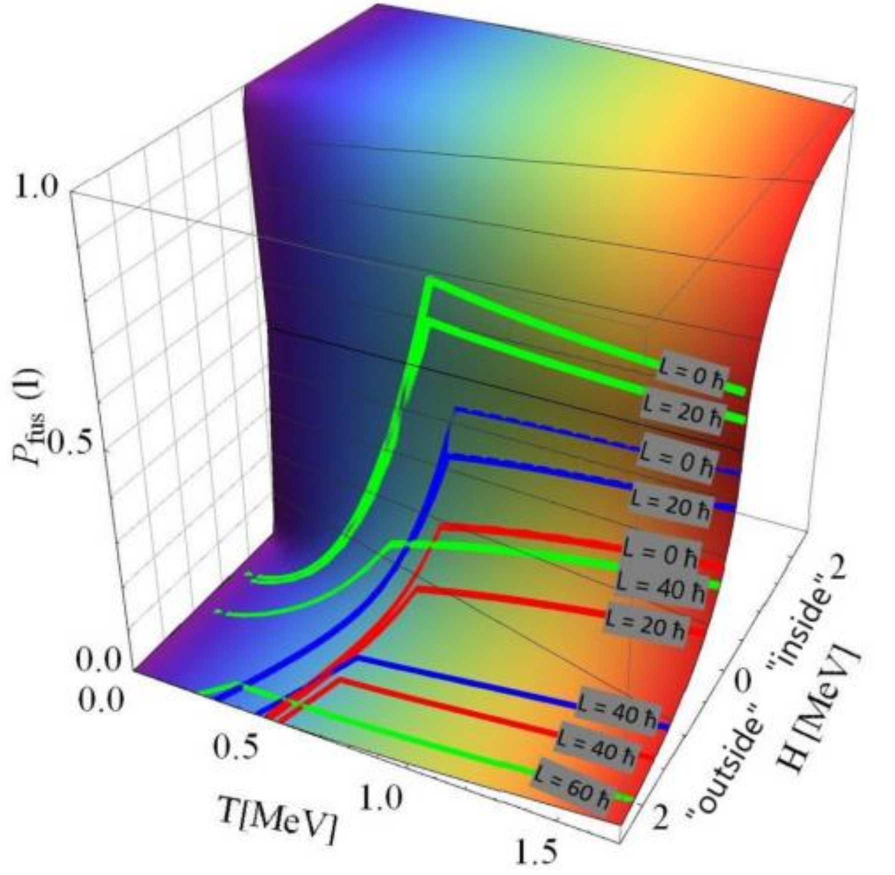
Go Mobile »

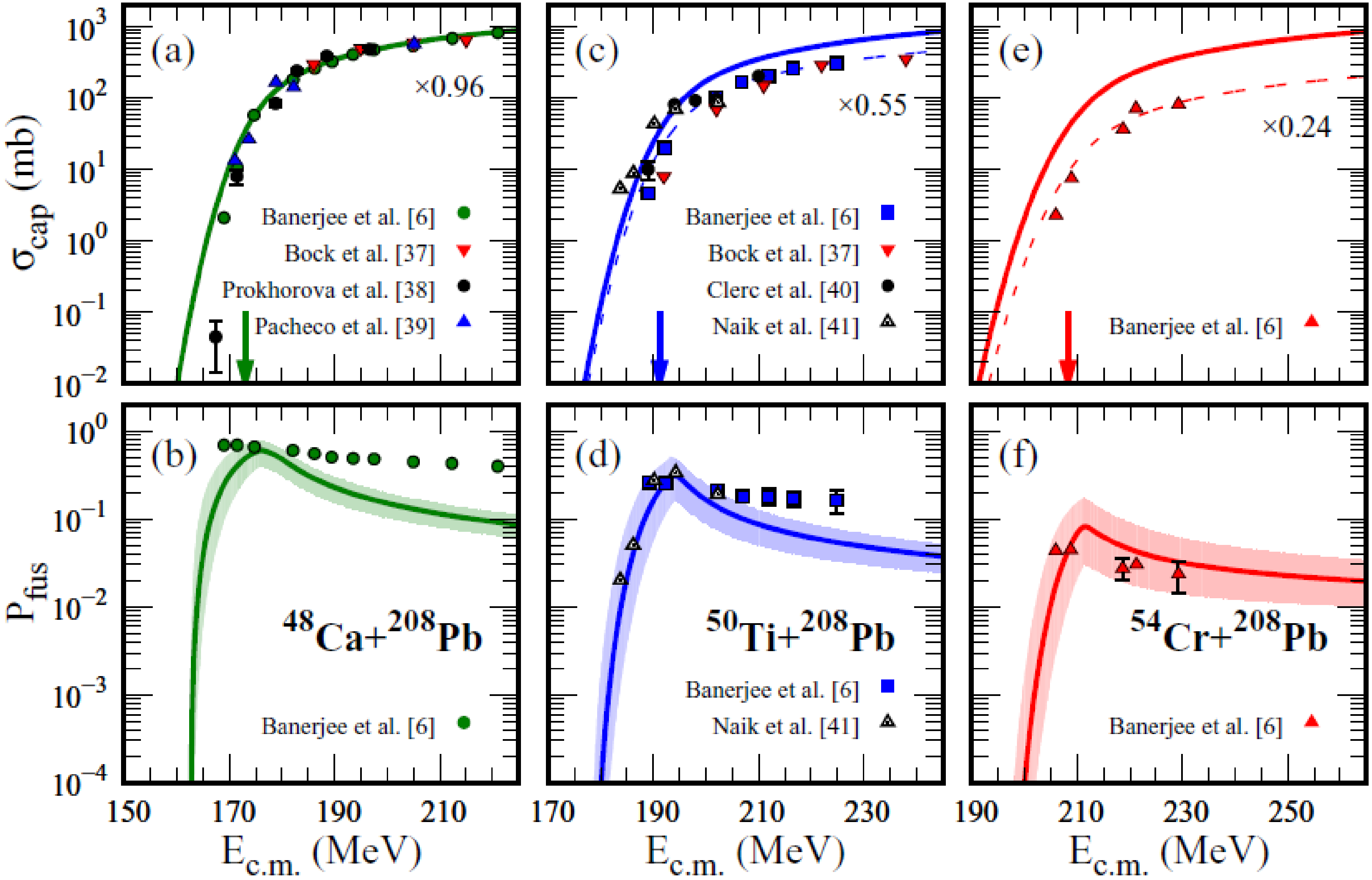
Diffusion as a possible mechanism controlling the production of superheavy nuclei in cold fusion reactions

T. Cap, M. Kowal, and K. Siwek-Wilczyńska
Phys. Rev. C **105**, L051601 – Published 16 May 2022

Langevin in the overdamped limit:

$$\boxed{P_{\mathrm{CN}}(E)=\frac{1}{2}\left[1-\mathrm{erf}\left(\frac{\Delta V}{T}\right)\right]}$$

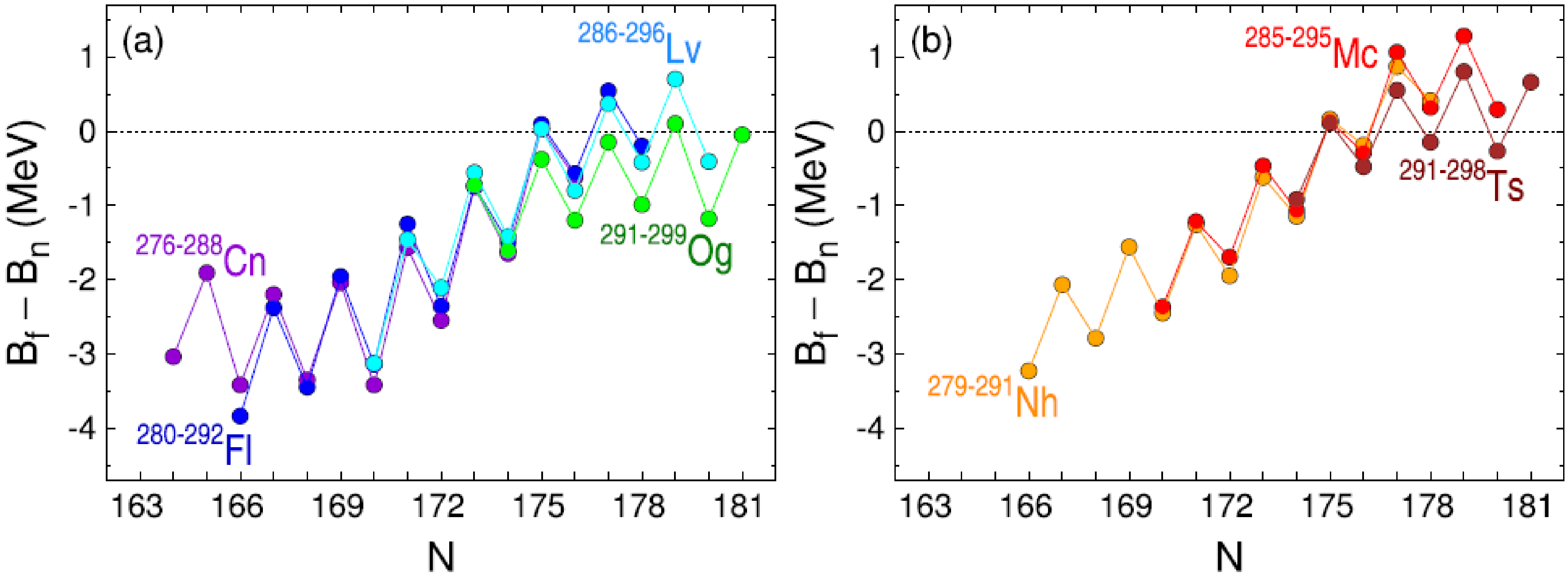




$$P_{\mathrm{fus}} = \frac{1}{(l_{\mathrm{max}}+1)^2}\sum_{l=0}^{l_{\mathrm{max}}}(2l+1)P_{\mathrm{fus}}(l),$$

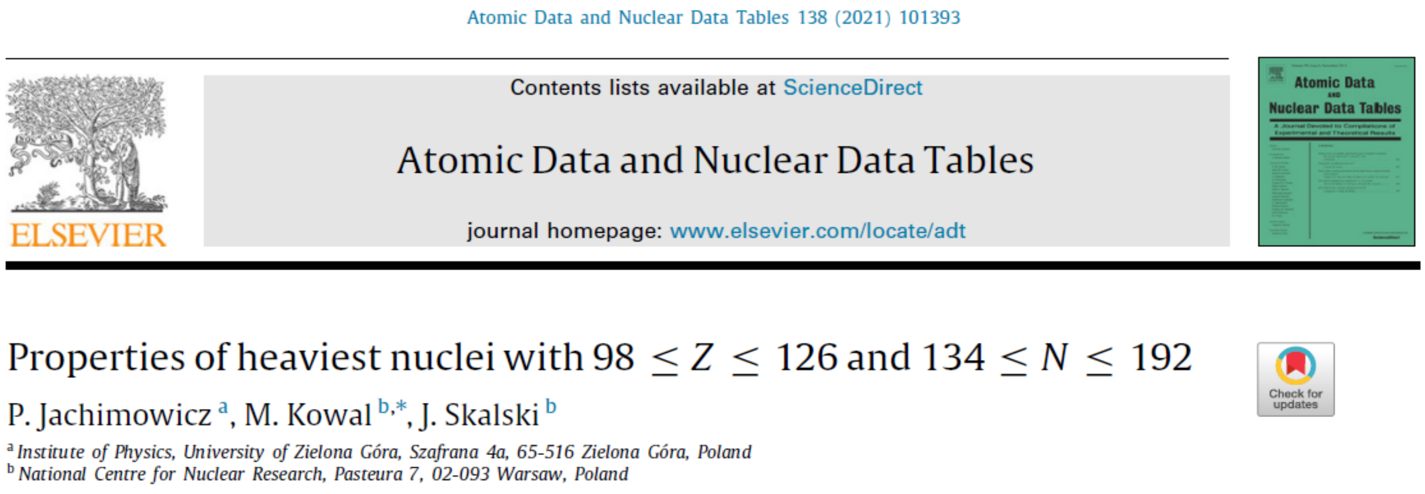
$$\sigma(\text{synthesis}) = \pi\lambda\!\!\!^{-}{}^2 \sum_{l=0}^{l\text{max}} (2l+1)T_l \times P_l(\text{fusion}) \times \boxed{P^{\ell}_{xn}(\text{survive})}$$

$$\frac{\Gamma_n}{\Gamma_f} = \frac{gA^{2/3}}{K_0} \frac{\int_0^{U-B_n} \varepsilon \rho_{\text{GS}}(U - B_n - \varepsilon)d\varepsilon}{\int_0^{U-B_f} \rho_{\text{SP}}(U - B_f - \varepsilon)d\varepsilon}, \xrightarrow{U>Bn>Bf>T} \frac{\Gamma_n}{\Gamma_f} = \frac{4mR_0^2}{\hbar^2} \exp\left(-\frac{B_n - B_f}{T}\right).$$



Microscopic-macroscopic method

application of ADNT2021 tables to estimate the chances of producing new elements



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

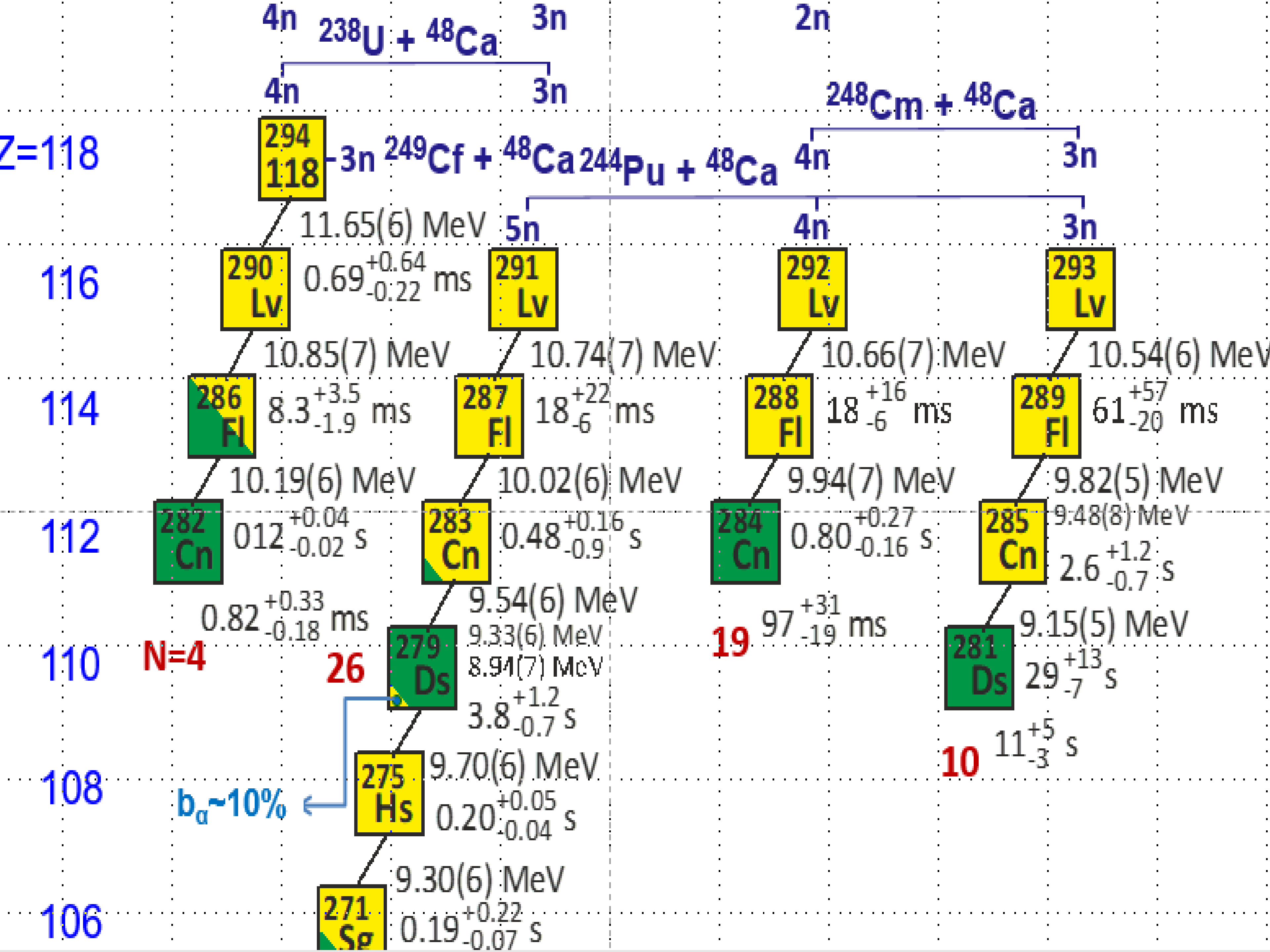
$$E_{tot}(\beta_{\lambda\mu}) = E_{macro}(\beta_{\lambda\mu}) + E_{micro}(\beta_{\lambda\mu})$$

$$E_{macro}(\beta_{\lambda\mu}) = \mathrm{Yukawa} + \mathrm{exponential}$$

$$E_{micro}(\beta_{\lambda\mu}) = \mathrm{Woods\text{-}Saxon} + \mathrm{pairing\ BCS}$$

$$R(\theta,\phi) = cR_0\left\{1 + \sum_{\lambda=1}^{\infty} \sum_{\mu=-\lambda}^{+\lambda} \beta_{\lambda\mu} Y_{\lambda\mu}(\theta,\phi)\right\}$$

I. Muntian, Z. Patyk and A. Sobiczewski, Acta Phys. Pol. B 32, 691 (2001).
H. J. Krappe, J. R. Nix and A. J. Sierk, Phys. Rev. C20, 992 (1979).
S. Cwiok, J. Dudek, W. Nazarewicz, J. Skalski and T. Werner, Comput. Phys. Commun. 46, 379 (1987).


4n
^{238}U + ^{48}Ca
3n
2n
4n
3n
^{248}Cm + ^{48}Ca
Z=118
294 118
3n
^{249}Cf + ^{48}Ca
^{244}Pu + ^{48}Ca
4n
3n
11.65(6) MeV
5n
4n
3n
116
290 Lv
$0.69^{+0.64}_{-0.22}$ ms
291 Lv
292 Lv
293 Lv
10.85(7) MeV
10.74(7) MeV
10.66(7) MeV
10.54(6) MeV
114
286 Fl
$8.3^{+3.5}_{-1.9}$ ms
287 Fl
18^{+22}_{-6} ms
288 Fl
18^{+16}_{-6} ms
289 Fl
61^{+57}_{-20} ms
10.19(6) MeV
10.02(6) MeV
9.94(7) MeV
9.82(5) MeV
112
282 Cn
$012^{+0.04}_{-0.02}$ s
283 Cn
$0.48^{+0.16}_{-0.9}$ s
284 Cn
$0.80^{+0.27}_{-0.16}$ s
285 Cn
9.48(8) MeV
$2.6^{+1.2}_{-0.7}$ s
$0.82^{+0.33}_{-0.18}$ ms
9.54(6) MeV
97^{+31}_{-19} ms
9.15(5) MeV
110
N=4
26
279 Ds
9.33(6) MeV
8.94(7) MeV
$3.8^{+1.2}_{-0.7}$ s
19
281 Ds
29^{+13}_{-7} s
11^{+5}_{-3} s
10
108
b_{α}~10%
275 Hs
9.70(6) MeV
$0.20^{+0.05}_{-0.04}$ s
9.30(6) MeV
106
271 Sg
$0.19^{+0.22}_{-0.07}$ s