New prospects in synthesis and study of superheavy nuclei

- **Superheavy dreams of Walter Greiner**
- **Epoch of “cold” and “hot” fusion reactions (100 < Z <= 118)**
- **Multi-nucleon transfer reactions**
- **Non-accelerative SHE production**
- **Summary**

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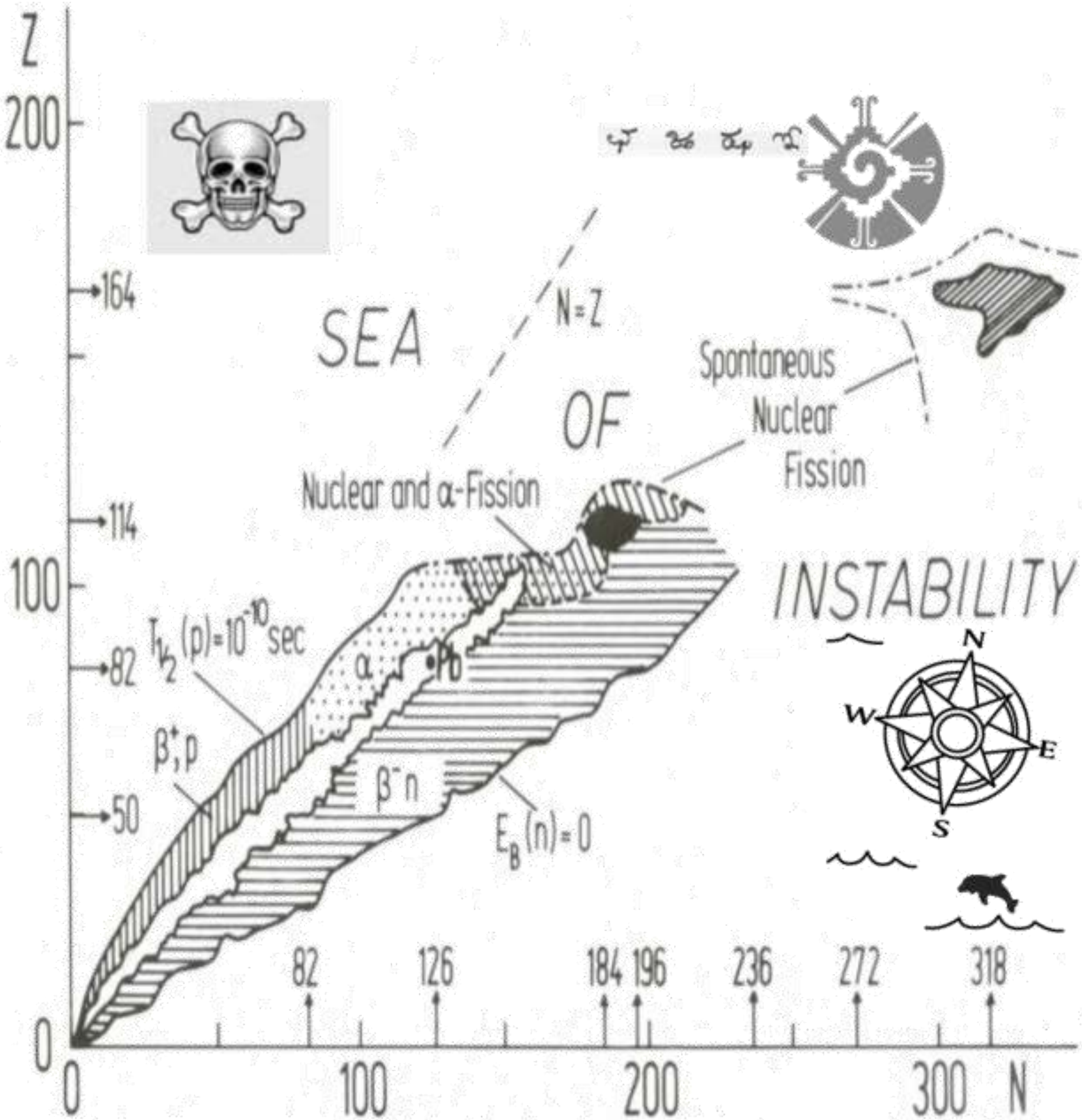
for XIII WONP – VII NURT, *February 08, 2011*, Havana, Cuba

JINR *(Dubna)*

FIAS *(Frankfurt)*

Mendeleev's Table 140 years ago

Ancient Nuclear Map and dreams of Walter Greiner



Mendeleev's Table

период	ряд	группы элементов									
		а I б	а II б	а III б	а IV б	а V б	а VI б	а VII б	а VIII б		
1	I	H 1 $1s^1$ 1,00794 Hydrogen							He 2 $1s^2$ 4,0026 Helium		
2	II	Li 3 $2s^1$ 6,941 Lithium	Be 4 $2s^2$ 9,012182 Beryllium	B 5 $2p^1$ 10,811 Boron	C 6 $2p^2$ 12,011 Carbon	N 7 $2p^3$ 14,00674 Nitrogen	O 8 $2p^4$ 15,9994 Oxygen	F 9 $2p^5$ 18,9984032 Fluorine	Ne 10 $2p^6$ 20,1797 Neon		
3	III	Na 11 $3s^1$ 22,989768 Sodium	Mg 12 $3s^2$ 24,3050 Magnesium	Al 13 $3p^1$ 26,981539 Aluminum	Si 14 $3p^2$ 28,0855 Silicon	P 15 $3p^3$ 30,973762 Phosphorus	S 16 $3p^4$ 32,066 Sulfur	Cl 17 $3p^5$ 35,4527 Chlorine	Ar 18 $3p^6$ 39,948 Argon		
4	IV	K 19 $4s^1$ 39,0983 Potassium	Ca 20 $4s^2$ 40,078 Calcium	21 $3d^14s^2$ Sc 44,955910 Scandium	22 $3d^24s^2$ Ti 47,88 Titanium	23 $3d^34s^2$ V 50,9415 Vanadium	24 $3d^54s^1$ Cr 51,9961 Chromium	25 $3d^54s^2$ Mn 54,93805 Manganese	26 $3d^64s^2$ Fe 55,847 Iron	27 $3d^74s^2$ Co 58,93320 Cobalt	28 $3d^84s^2$ Ni 58,6934 Nickel
	V	29 $3d^{10}4s^1$ Cu 63,546 Copper	30 $3d^{10}4s^2$ Zn 65,39 Zinc	Ga 31 $4p^1$ 69,723 Gallium	Ge 32 $4p^2$ 72,61 Germanium	As 33 $4p^3$ 74,92159 Arsenic	Se 34 $4p^4$ 9,75238 78,96 Selenium	Br 35 $4p^5$ 79,904 Bromine	Kr 36 $4p^6$ 83,80 Krypton		
5	VI	Rb 37 $5s^1$ 85,4678 Rubidium	Sr 38 $5s^2$ 87,62 Strontium	39 $4d^15s^2$ Y 88,90585 Yttrium	40 $4d^25s^2$ Zr 91,224 Zirconium	41 $4d^45s^1$ Nb 92,90638 Niobium	42 $4d^55s^1$ Mo 95,94 Molybdenum	43 $4d^55s^2$ Tc [98] Technetium	44 $4d^75s^1$ Ru 101,07 Ruthenium	45 $4d^85s^1$ Rh 102,90550 Rhodium	46 $4d^{10}$ Pd 106,42 Palladium
	VII	47 $4d^{10}5s^1$ Ag 107,8682 Silver	48 $4d^{10}5s^2$ Cd 112,411 Cadmium	In 49 $5p^1$ 114,818 Indium	Sn 50 $5p^2$ 118,710 Tin	Sb 51 $5p^3$ 121,757 Antimony	Te 52 $5p^4$ 127,60 Tellurium	I 53 $5p^5$ 126,90447 Iodine	Xe 54 $5p^6$ 131,29 Xenon		
6	VIII	Cs 55 $6s^1$ 132,90543 Cesium	Ba 56 $6s^2$ 137,327 Barium	57 $5d^16s^2$ La 138,9055 Lanthanum	72 $5d^26s^2$ Hf 178,49 Hafnium	73 $5d^36s^2$ Ta 180,9479 Tantalum	74 $5d^46s^2$ W 183,84 Tungsten	75 $5d^56s^2$ Re 186,207 Rhenium	76 $5d^66s^2$ Os 190,23 Osmium	77 $5d^76s^2$ Ir 192,22 Iridium	78 $5d^96s^1$ Pt 195,08 Platinum
	IX	79 $5d^{10}6s^1$ Au 196,96654 Gold	80 $5d^{10}6s^2$ Hg 200,59 Mercury	Tl 81 $6p^1$ 204,3833 Thallium	Pb 82 $6p^2$ 207,2 Lead	Bi 83 $6p^3$ 208,98037 Bismuth	Po 84 $6p^4$ [209] Polonium	At 85 $6p^5$ [210] Astatine	Rn 86 $6p^6$ [222] Radon		
7	X	Fr 87 $7s^1$ 4,073 [223] Francium	Ra 88 $7s^2$ 226,025 Radium	89 $6d^17s^2$ Ac [227] Actinium	104 Rf [261] Rutherfordium	105 Db [262] Dubnium	106 Sg [266] Seaborgium	107 Bh [267] Bohrium	108 Hs [269] Hassium	109 Mt [268] Meitnerium	110 Ds [269] Darmstadtium
	XI	111 Rg [269] Roentgenium	112	113	114	115	116	117	118		

атомный номер; символ; атомная масса; электронная конфигурация

s-элементы

p-элементы

d-элементы

f-элементы

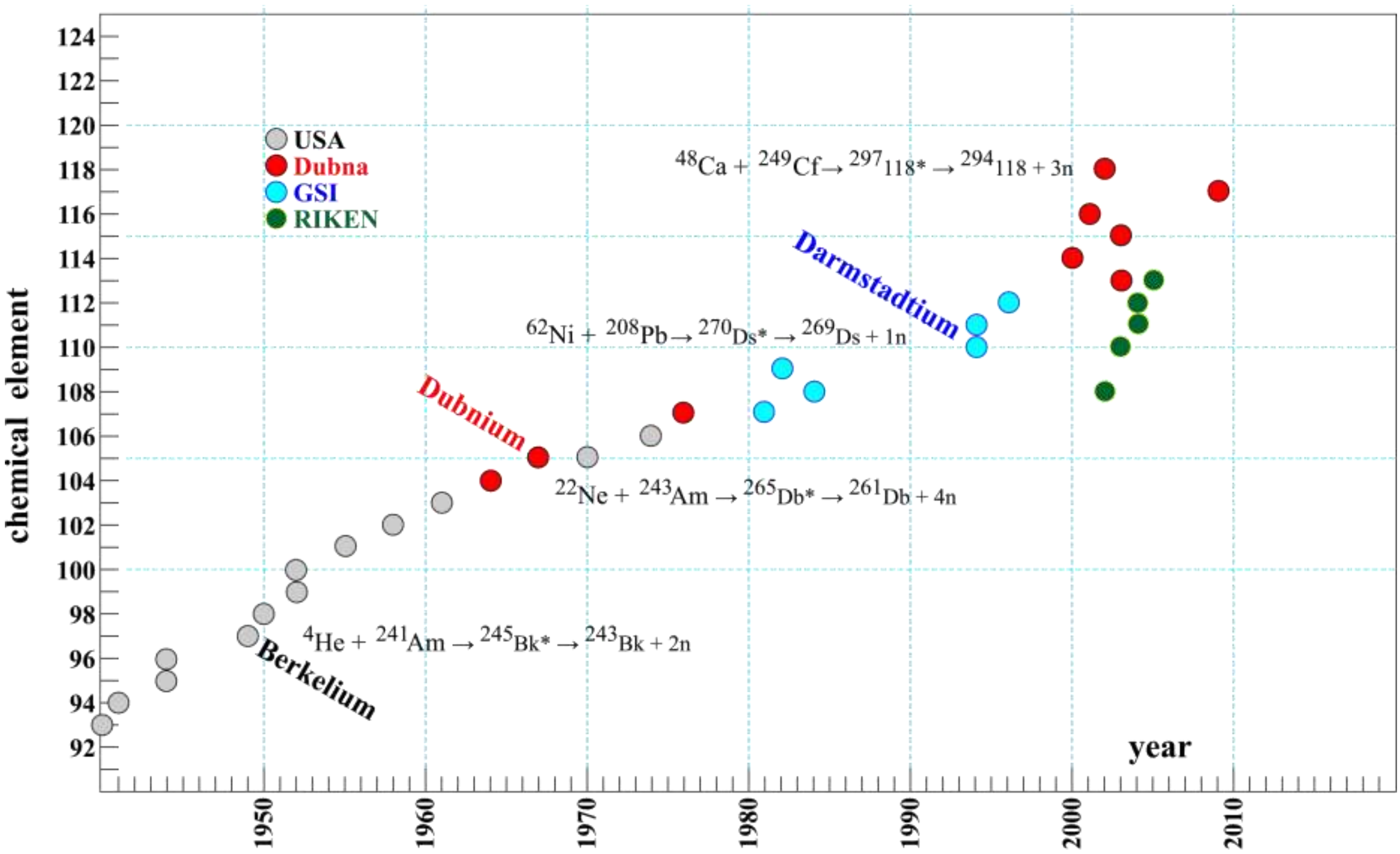
Лантаноиды Lanthanides

Ce $4f^15d^1$ 140,115 Cerium	Pr $4f^3$ 140,90765 Praseodymium	Nd $4f^4$ 144,24 Neodymium	Pm $4f^5$ [145] Promethium	Sm $4f^6$ 150,36 Samarium	Eu $4f^7$ 151,965 Europium	Gd $4f^75d^1$ 157,25 Gadolinium	Tb $4f^9$ 158,92534 Terbium	Dy $4f^{10}$ 162,50 Dysprosium	Ho $4f^{11}$ 164,93032 Holmium	Er $4f^{12}$ 167,26 Erbium	Tm $4f^{13}$ 168,93421 Thulium	Yb $4f^{14}$ 173,04 Ytterbium	Lu $4f^{14}5d^1$ 174,967 Lutetium

Актиноиды Actinides

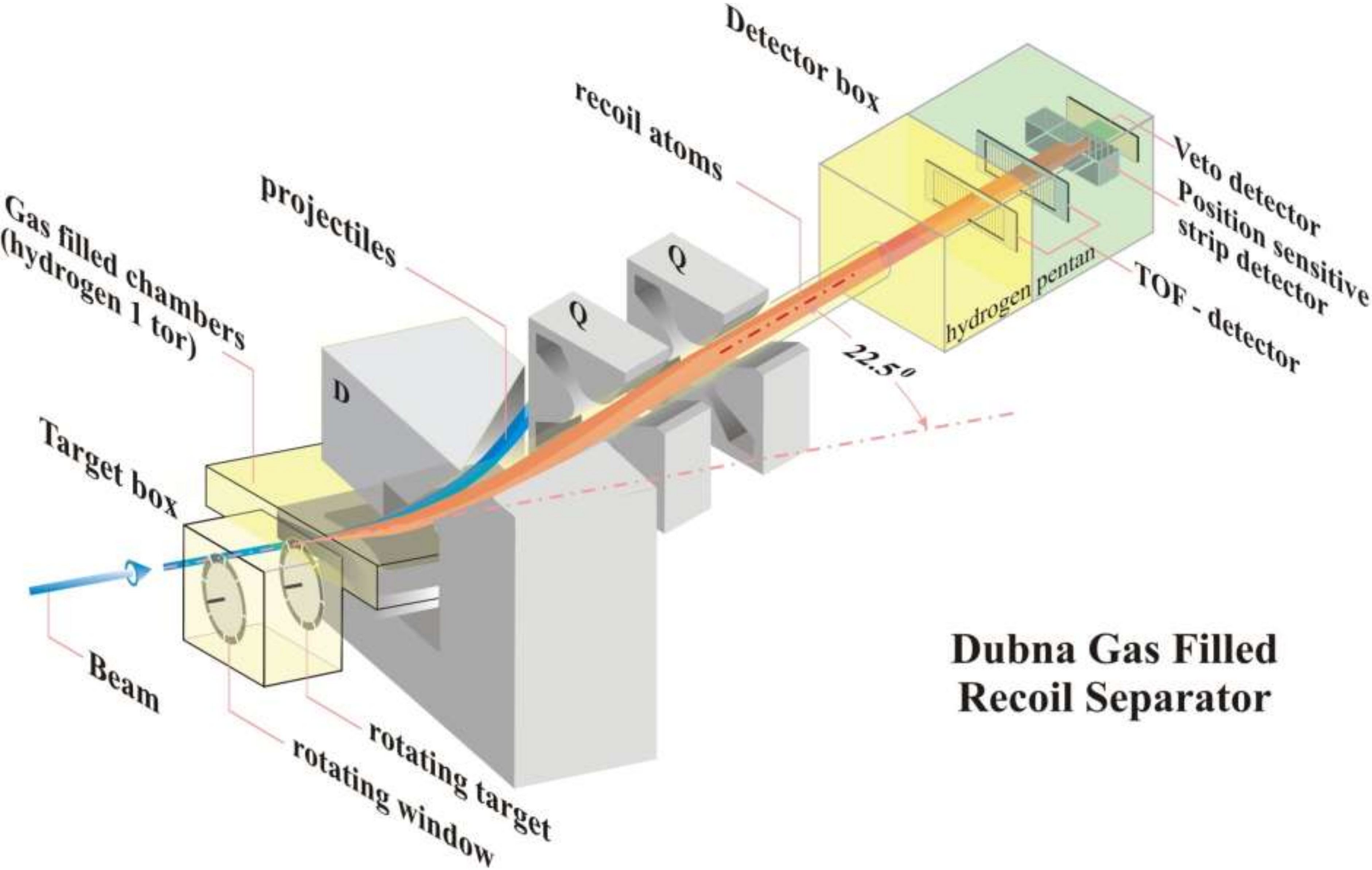
Th $7s^26d^2$ 232,0381 Thorium	Pa $5f^26d^1$ 231,03588 Protactinium	U $5f^36d^1$ 238,0289 Uranium	Np $5f^46d^1$ [237] Neptunium	Pu $5f^6$ [244] Plutonium	Am $5f^7$ [243] Americium	Cm $5f^76d^1$ [247] Curium	Bk $5f^9$ [247] Berkelium	Cf $5f^{10}$ [251] Californium	Es $5f^{11}$ [252] Einsteinium	Fm $5f^{12}$ [257] Fermium	Md $5f^{13}$ [258] Mendelevium	No $5f^{14}$ [259] Nobelium	Lr $5f^{14}6d^1$ [262] Lawrencium

Synthesis of new elements (history)



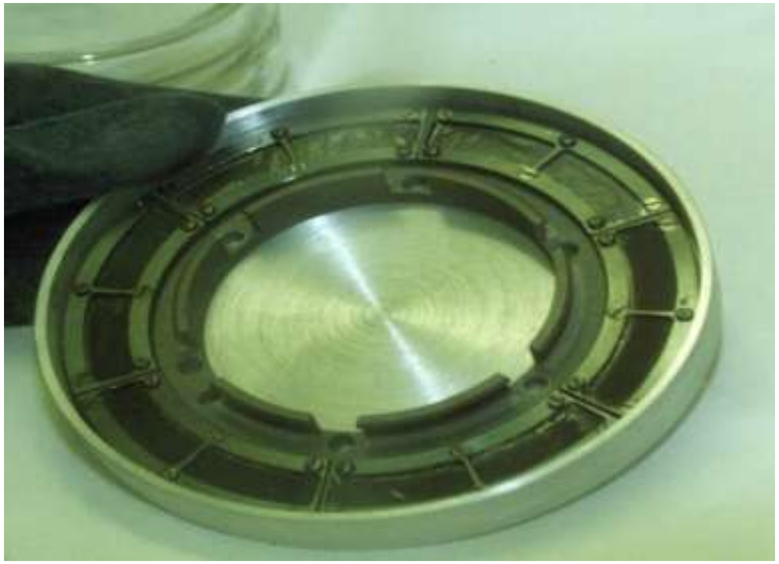
Synthesis of superheavy elements (experiment)

Synthesis of superheavy elements (experiment)

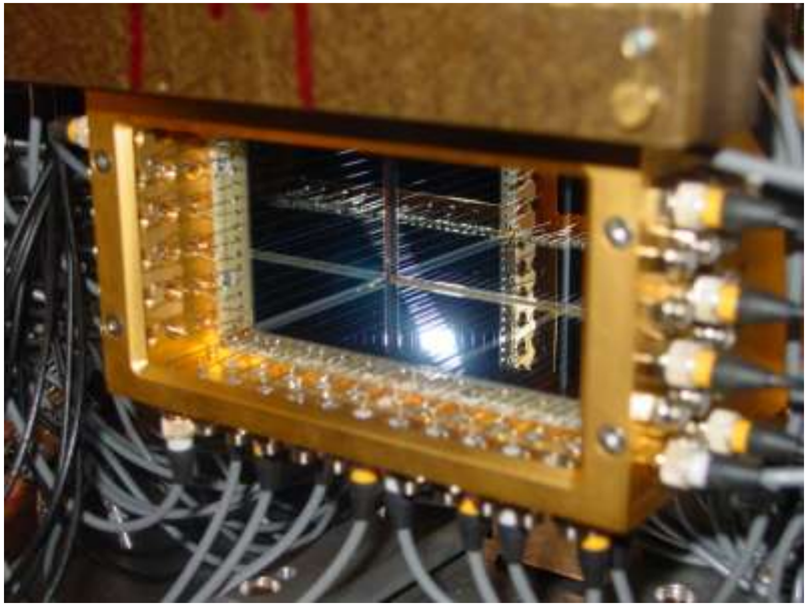


Dubna Gas Filled Recoil Separator

Target made of ^{249}Cf (half-life is 350 years)



Detectors for SH nucleus recoil and products of its decay



Significance of Theory

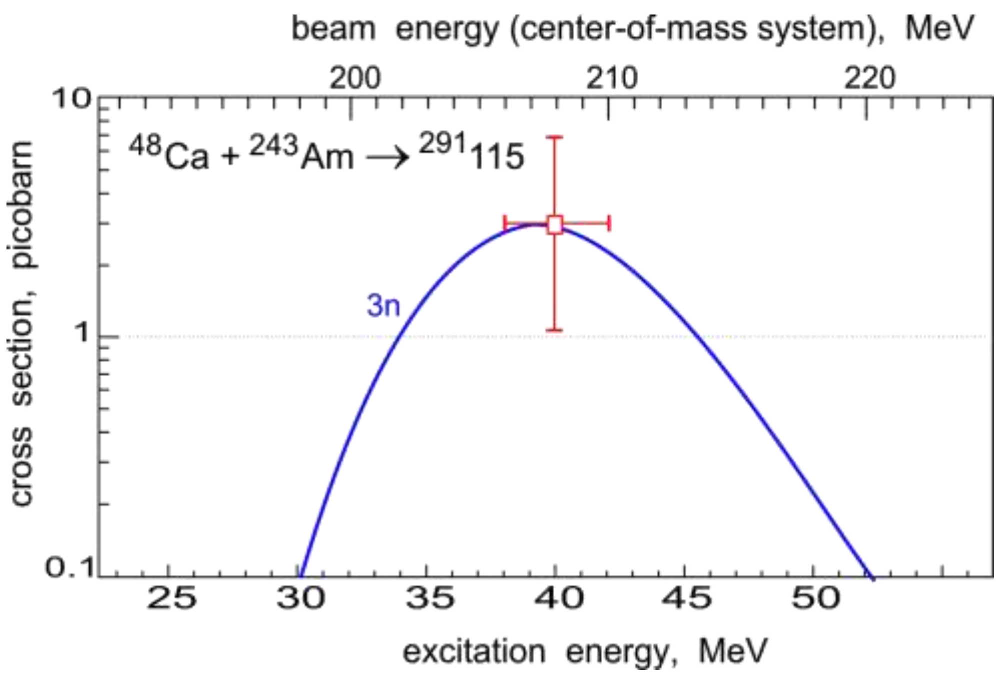
Which nuclei are to be fused ?

«cold» synthesis: ^{208}Pb + ^{64}Ni, ^{70}Zn, … → $^{272}110$, $^{278}112$, … (GSI, Germany)

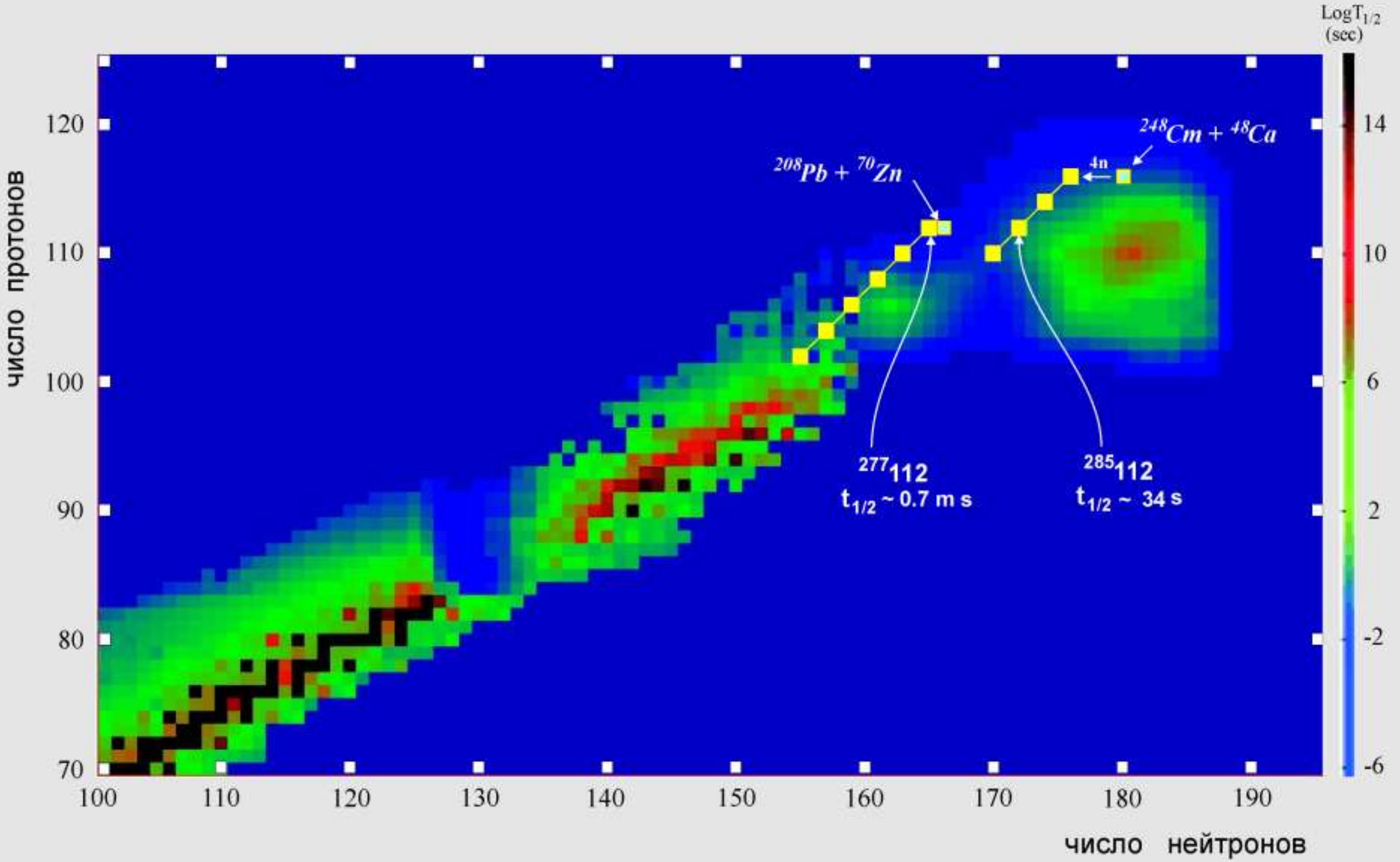
«hot» synthesis: ^{238}U, ^{244}Pu, ^{248}Cm, ^{249}Cf + ^{48}Ca → $^{286}112$, $^{292}114$, $^{296}116$, $^{297}118$ (Dubna)

Symmetric combinations: ^{148}Nd + ^{154}Sm → $^{302}122$? Radioactive beams of ^{132}Sn, etc. ?

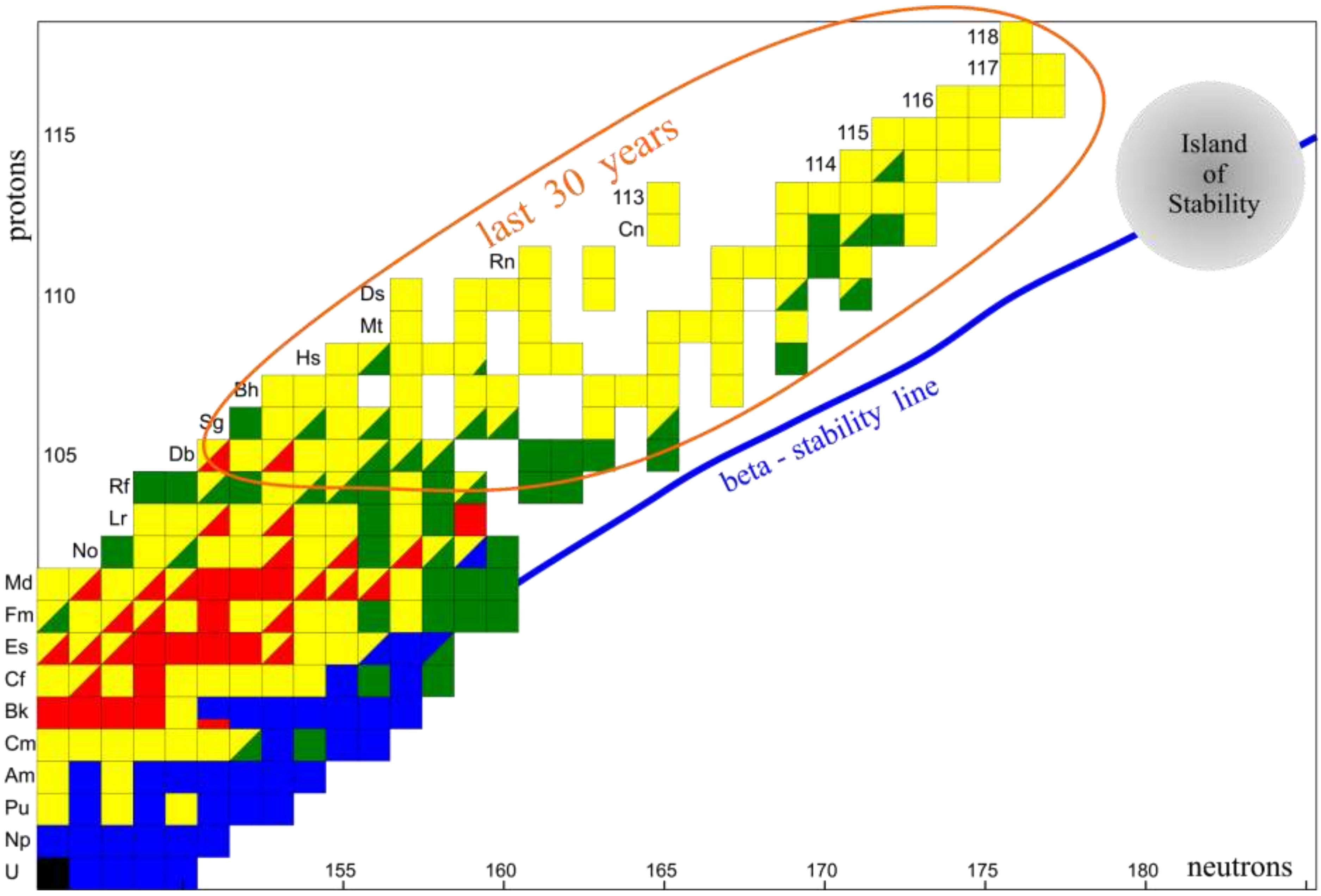
How to choose colliding energy ?



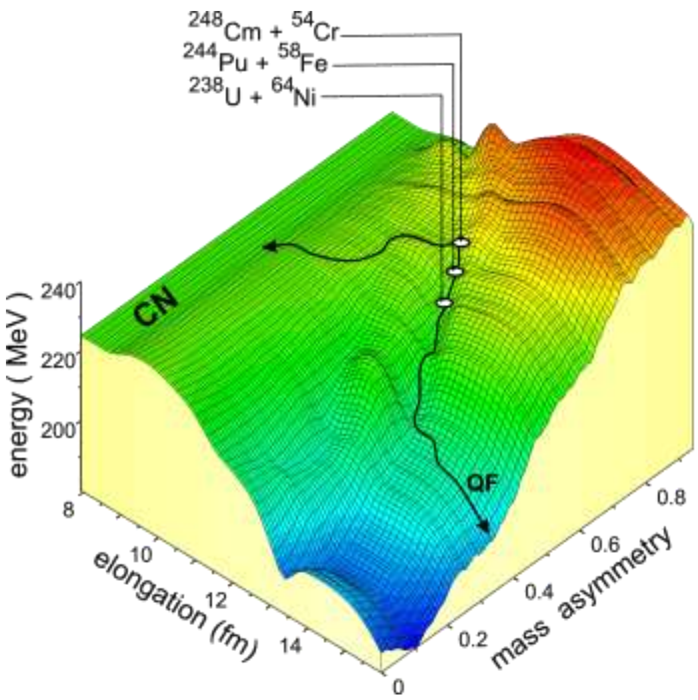
Superheavy Elements (Island of Stability)

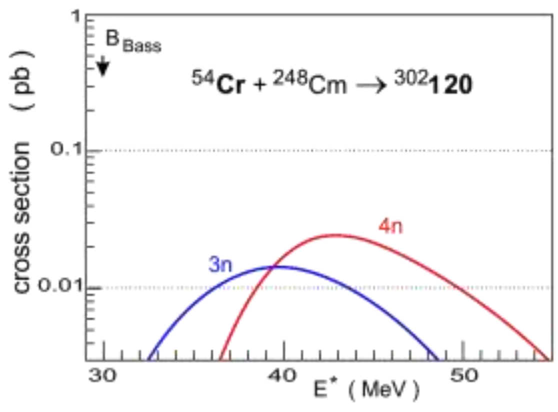


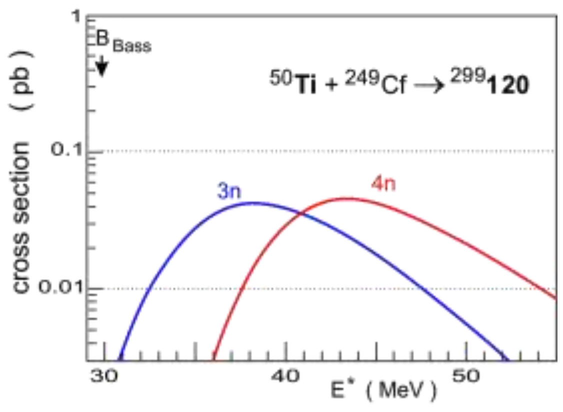
Great progress in synthesis of superheavy nuclei



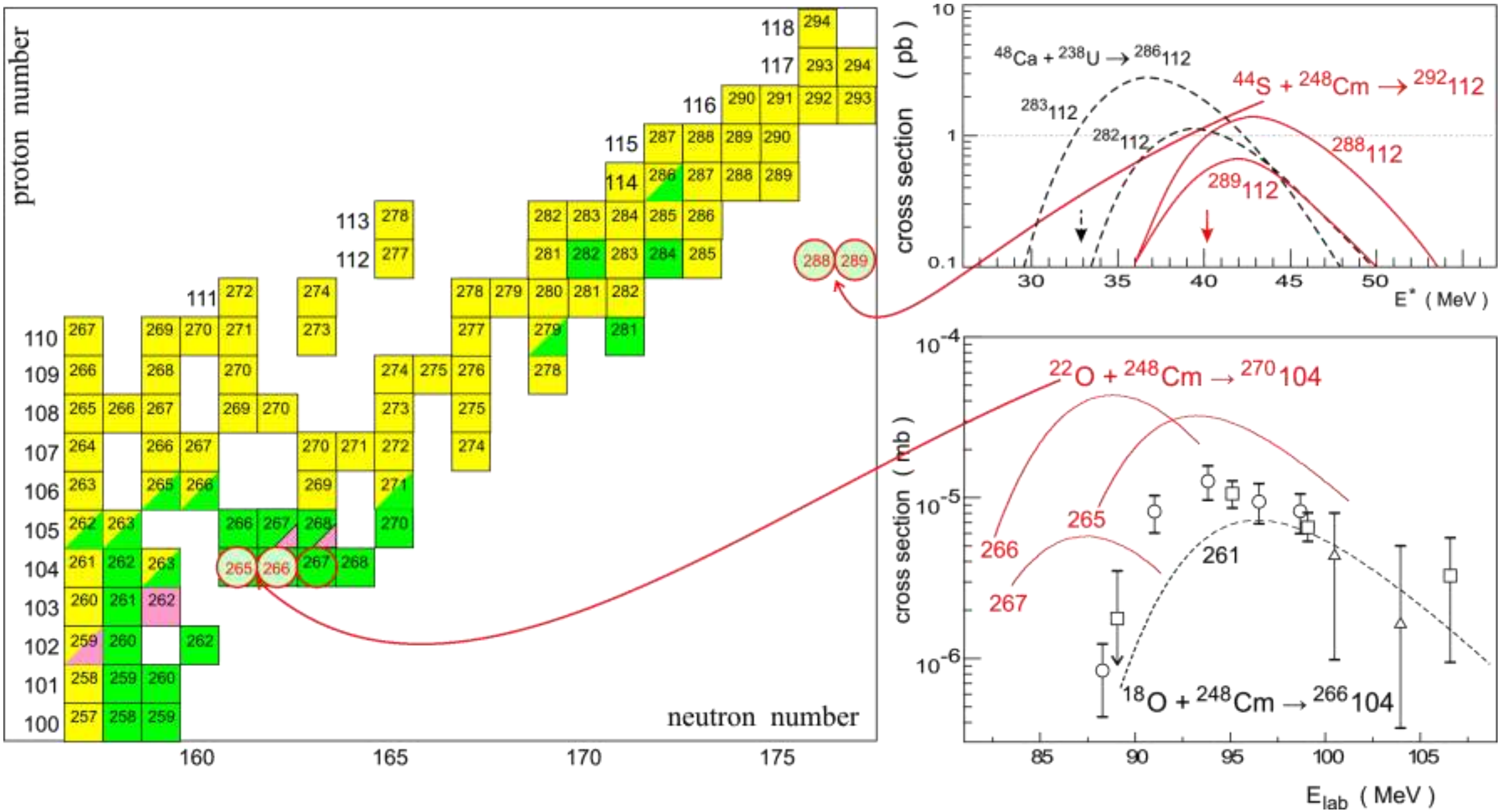
Beyond ^{48}Ca: Pursuit of 120







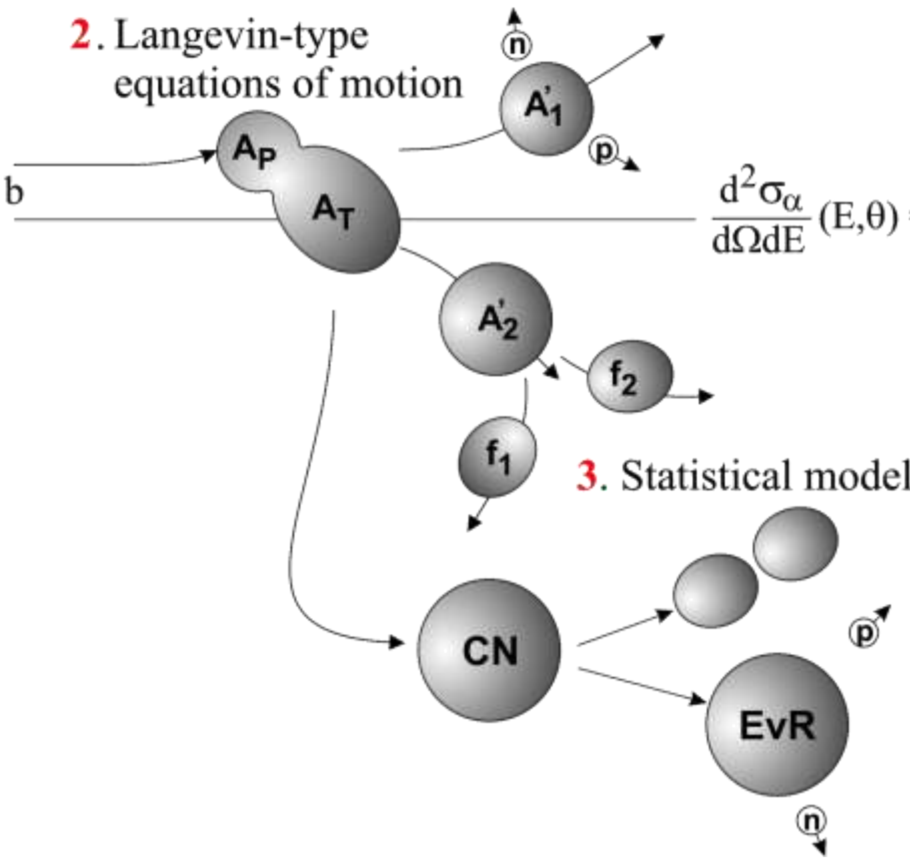
Radioactive Ion Beams for production of neutron rich superheavy nuclei ?



Multi-nucleon transfer reactions in low-energy heavy ion collisions

Simulation of experiment and cross sections

1. Time-dependent driving potential $V(r,\xi;t)$:
Folding → Adiabatic Two-Center Shell Model

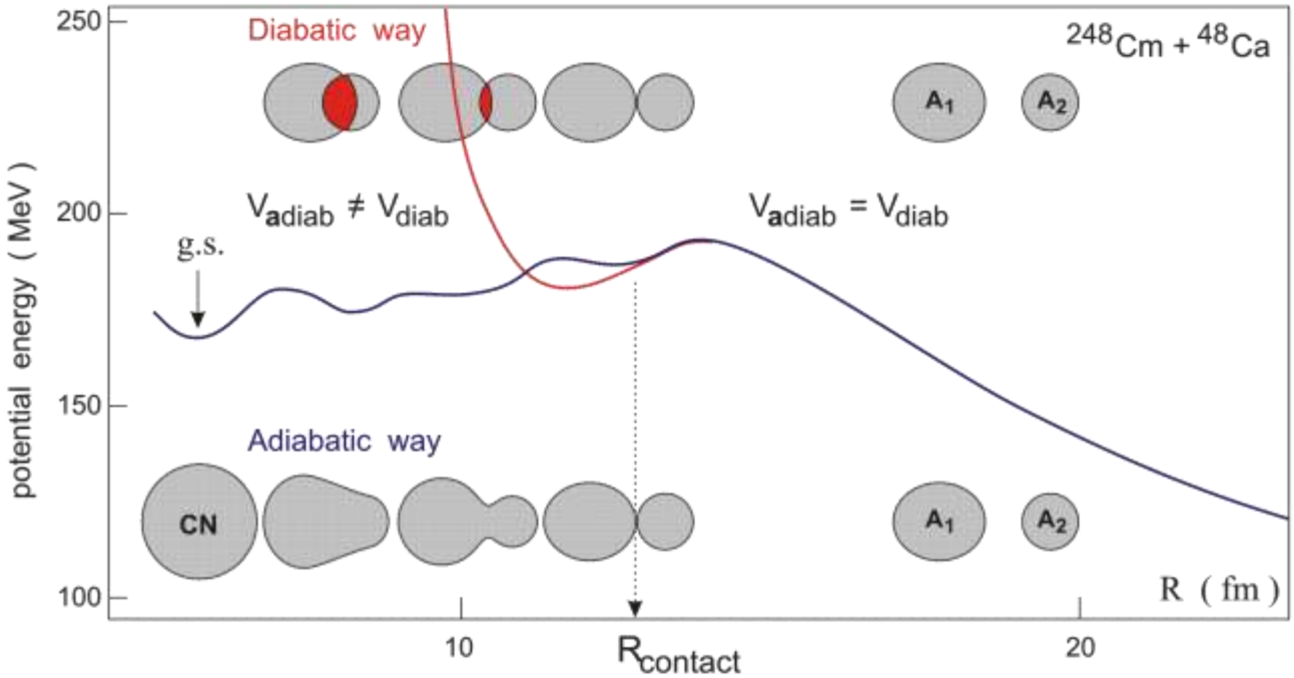


$$\frac{d^2\sigma_\alpha}{d\Omega dE}(E,\theta) = \int_0^\infty b db \; \frac{\Delta N_\alpha(b,E,\theta)}{N_{tot}(b)} \; \frac{1}{\sin(\theta)\Delta\theta\Delta E}$$

Dynamics: **10^6** tested events (trajectories),
Statistical model: **10^{-6}**(3n), **10^{-7}**(4n) survival probability
cross sections up to **0.1 pb** can be calculated

Time-dependent Driving Potential

$$V_{diabat}(R,\beta_1,\beta_2,\alpha,...) = V_{12}^{folding}(Z_1,N_1,Z_2,N_2;R,\beta_1,\beta_2,...) + M(A_1) + M(A_2) - M(Proj) - M(Targ)$$



$$V_{adiabat}(R,\beta_1,\beta_2,\eta,...) = M_{TCSM}(R,\beta_1,\beta_2,\eta,...) - M(Proj) - M(Targ)$$

Time-dependent driving potential has to be used

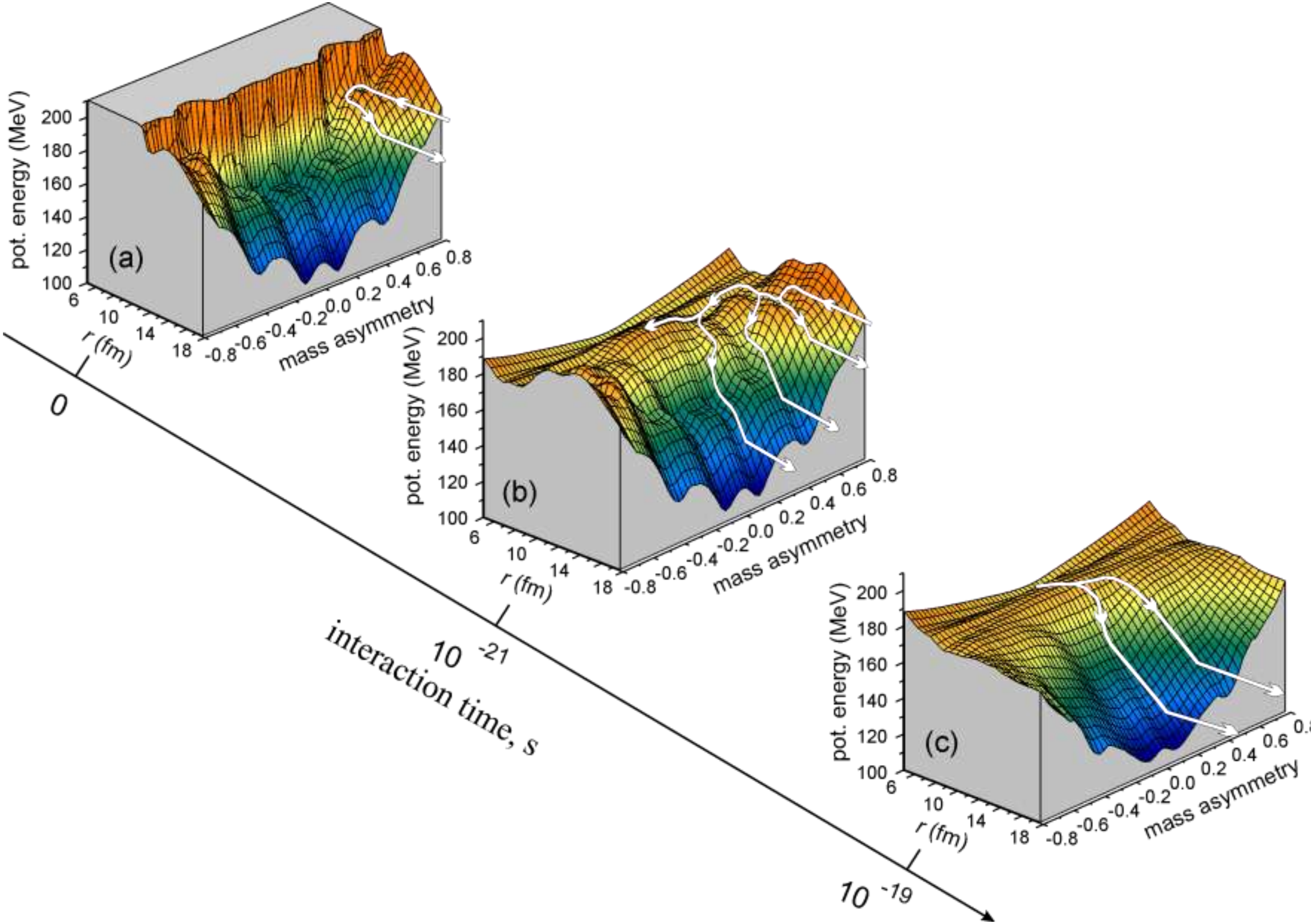
$$V(t) = V_{diab}(\xi)\cdot\exp\left(-\frac{t_{int}}{\tau_{relax}}\right) + V_{adiab}(\xi)\cdot\left[1-\exp\left(-\frac{t_{int}}{\tau_{relax}}\right)\right]$$

$\tau_{relax} \sim 10^{-21}$ s

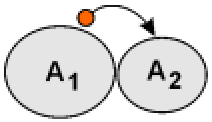
the same degrees of freedom ($\xi = R, \theta, \varphi_1, \varphi_2, \beta_1, \beta_2, \eta_Z, \eta_N$) *!*

All forces, $F_i(t) = -\partial V/\partial\xi_i$, *are quite smooth*

Time-dependent Driving Potential



Nucleon Exchange



$A_1 \rightarrow A_1 - 1$
$A_2 \rightarrow A_2 + 1$

(L. Moretto, 1974)

Distribution function $\varphi(A_1, t)$ → Master equation
$$\frac{\partial \varphi}{\partial t} = \sum_{A_1' = A_1 \pm 1} \lambda(A_1' \rightarrow A_1) \cdot \varphi(A_1') - \lambda(A_1 \rightarrow A_1') \cdot \varphi(A_1)$$

$$\frac{\partial \varphi}{\partial t} = -\frac{\partial}{\partial A_1}\left(D^{(1)} \varphi\right) + \frac{\partial^2}{\partial A_1^2}\left(D^{(2)} \varphi\right)$$
Fokker - Planck
(W. Nörenberg, 1974)

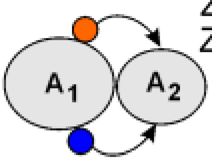
$$\frac{dA_1}{dt} = D^{(1)} + \sqrt{D^{(2)}}\,\Gamma(t)$$
Langevin type eq.

$$\eta = \frac{A_1 - A_2}{A_{CN}} = \frac{A_1 - (A_{CN} - A_1)}{A_{CN}} = \frac{2A_1 - A_{CN}}{A_{CN}}$$

$$\frac{d\eta}{dt} = \frac{2}{A_{CN}} D_A^{(1)} + \frac{2}{A_{CN}} \sqrt{D_A^{(2)}}\,\Gamma(t)$$

at $A' = A \pm 1$
$$D^{(1)} = \lambda(A_1 \rightarrow A_1 + 1) - \lambda(A_1 \rightarrow A_1 - 1)$$
$$D^{(2)} = \frac{1}{2}[\lambda(A_1 \rightarrow A_1 + 1) + \lambda(A_1 \rightarrow A_1 - 1)]$$

transition probability
$$\lambda^{(\pm)} = \lambda_0 \sqrt{\frac{\rho(A \pm 1)}{\rho(A)}} P_{tr}(R; A \rightarrow A \pm 1), \quad \rho \sim exp(2\sqrt{aE^*}), \quad E^* = E_{c.m.} - V(R, \beta_1, \beta_2, \eta)$$



$Z_1 \rightarrow Z_1 - 1$
$Z_2 \rightarrow Z_2 + 1$

$N_1 \rightarrow N_1 - 1$
$N_2 \rightarrow N_2 + 1$

$$\eta_Z = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$
$$\eta_N = \frac{N_1 - N_2}{N_1 + N_2}$$

$$D_{N,Z}^{(1)} = \lambda_{N,Z}(A \rightarrow A + 1) - \lambda_{N,Z}(A \rightarrow A - 1)$$
$$D_{N,Z}^{(2)} = \frac{1}{2}[\lambda_{N,Z}(A \rightarrow A + 1) + \lambda_{N,Z}(A \rightarrow A - 1)]$$
$$\lambda_{N,Z}^{(\pm)} = \lambda_{N,Z}^{0} \sqrt{\frac{\rho(A \pm 1)}{\rho(A)}} P_{tr}(R; A \rightarrow A \pm 1)$$

System of coupled Langevin type Equations of Motion

Variables: $\{R, \theta, \varphi_1, \varphi_2, \beta_1, \beta_2, \eta_Z, \eta_N\}$

Most uncertain parameters:

μ_0, γ_0 - nuclear viscosity and friction,

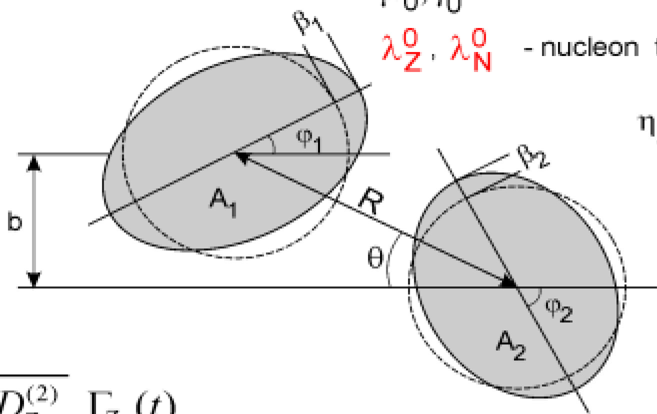
λ_Z^0, λ_N^0 - nucleon transfer rate

$$\eta = \frac{A_1 - A_2}{A_1 + A_2}$$

$$\eta_Z = \frac{Z_1 - Z_2}{Z_1 + Z_2}$$

$$\eta_N = \frac{N_1 - N_2}{N_1 + N_2}$$

$$\lambda_Z^0 = \lambda_N^0 = \frac{\lambda^0}{2}$$



$$\frac{dR}{dt} = \frac{p_R}{\mu_R}$$

$$\frac{d\vartheta}{dt} = \frac{\ell}{\mu_R R^2}$$

$$\frac{d\varphi_1}{dt} = \frac{L_1}{\Im_1}, \quad \frac{d\varphi_2}{dt} = \frac{L_2}{\Im_2}$$

$$\frac{d\beta_1}{dt} = \frac{p_{\beta 1}}{\mu_{\beta 1}}$$

$$\frac{d\beta_2}{dt} = \frac{p_{\beta 2}}{\mu_{\beta 2}}$$

$$\frac{d\eta_Z}{dt} = \frac{2}{Z_{CN}} D_Z^{(1)} + \frac{2}{Z_{CN}} \sqrt{D_Z^{(2)}}\, \Gamma_Z(t)$$

$$\frac{d\eta_N}{dt} = \frac{2}{N_{CN}} D_N^{(1)} + \frac{2}{N_{CN}} \sqrt{D_N^{(2)}}\, \Gamma_N(t)$$

$$\frac{dp_R}{dt} = -\frac{\partial V}{\partial R} + \frac{\ell^2}{\mu_R R^3} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial R} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial R} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial R} - \gamma_R \frac{p_R}{\mu_R} + \sqrt{\gamma_R T}\,\Gamma_R(t)$$

$$\frac{d\ell}{dt} = -\frac{\partial V}{\partial \vartheta} - \gamma_{tang}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) R + \sqrt{\gamma_{tang} T}\,\Gamma_{tang}(t)$$

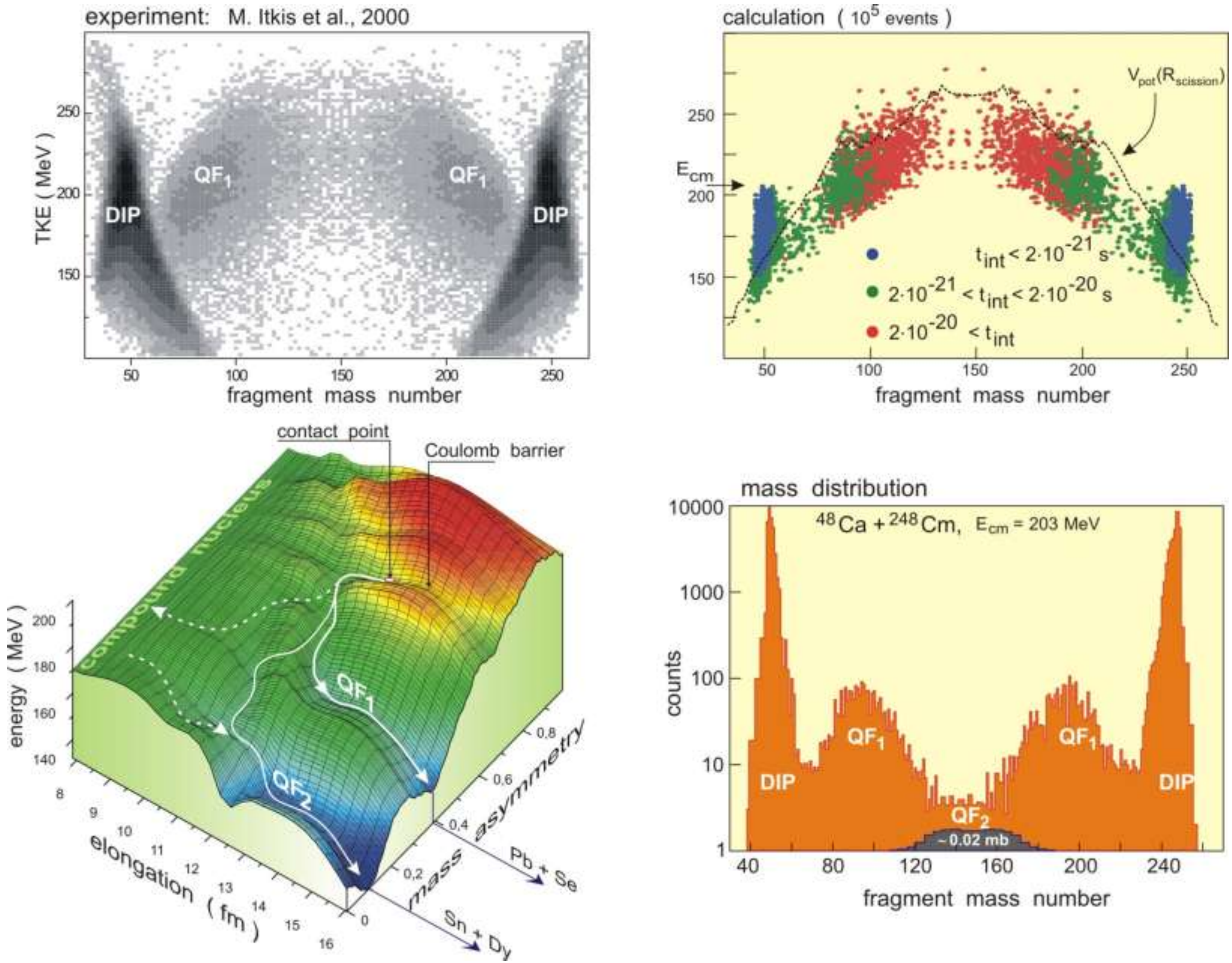
$$\frac{dL_1}{dt} = -\frac{\partial V}{\partial \varphi_1} + \gamma_{tang}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) a_1 - \frac{a_1}{R}\sqrt{\gamma_{tang} T}\,\Gamma_{tang}(t)$$

$$\frac{dL_2}{dt} = -\frac{\partial V}{\partial \varphi_2} + \gamma_{tan}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) a_2 - \frac{a_2}{R}\sqrt{\gamma_{tang} T}\,\Gamma_{tang}(t)$$

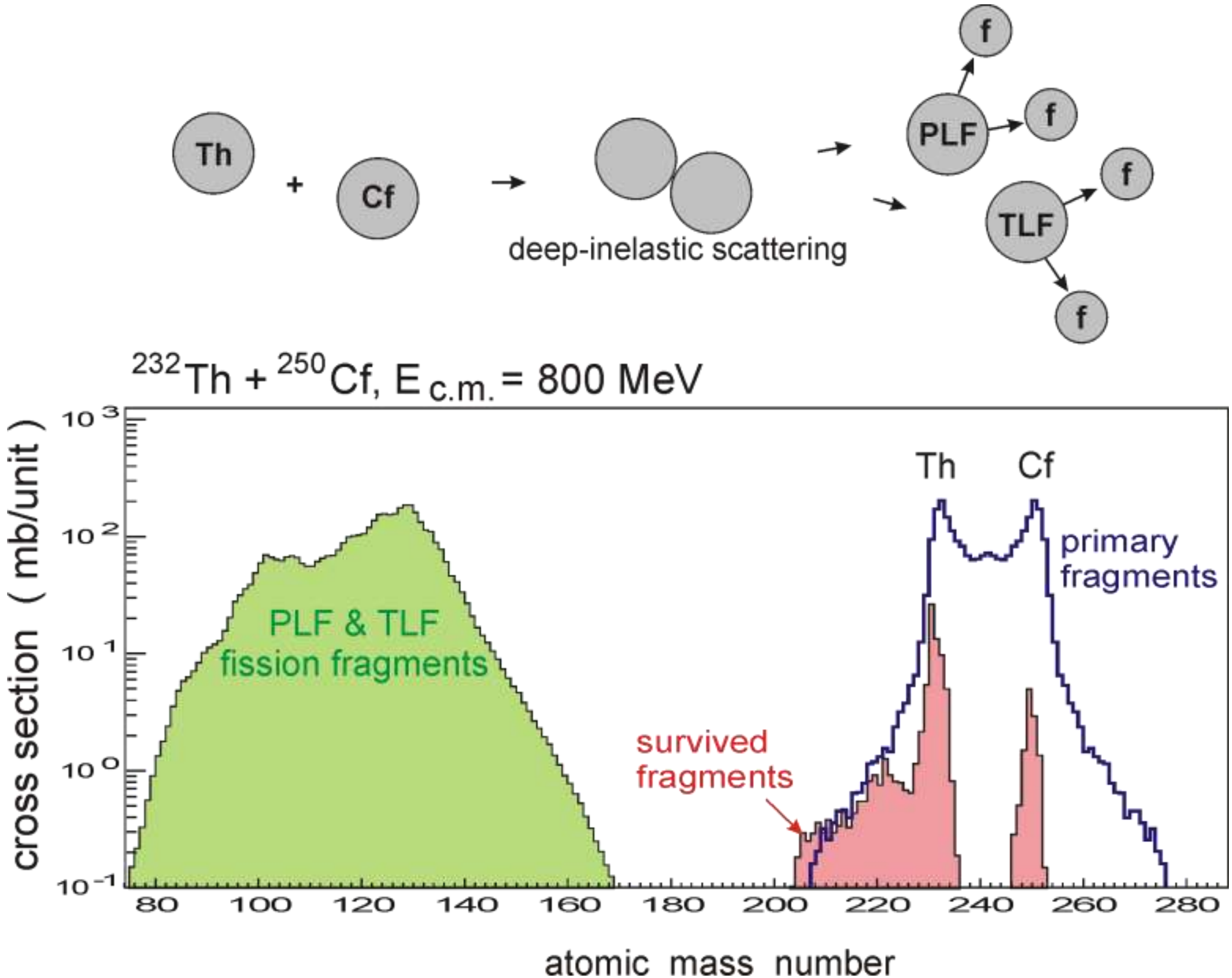
$$\frac{dp_{\beta 1}}{dt} = -\frac{\partial V}{\partial \beta_1} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial \beta_1} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial \beta_1} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial \beta_1} - \gamma_\beta \frac{p_{\beta 1}}{\mu_{\beta 1}} + \sqrt{\gamma_{\beta 1} T}\,\Gamma_{\beta 1}(t)$$

$$\frac{dp_{\beta 2}}{dt} = -\frac{\partial V}{\partial \beta_2} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial \beta_2} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial \beta_2} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial \beta_2} - \gamma_\beta \frac{p_{\beta 2}}{\mu_{\beta 2}} + \sqrt{\gamma_{\beta 2} T}\,\Gamma_{\beta 2}(t)$$

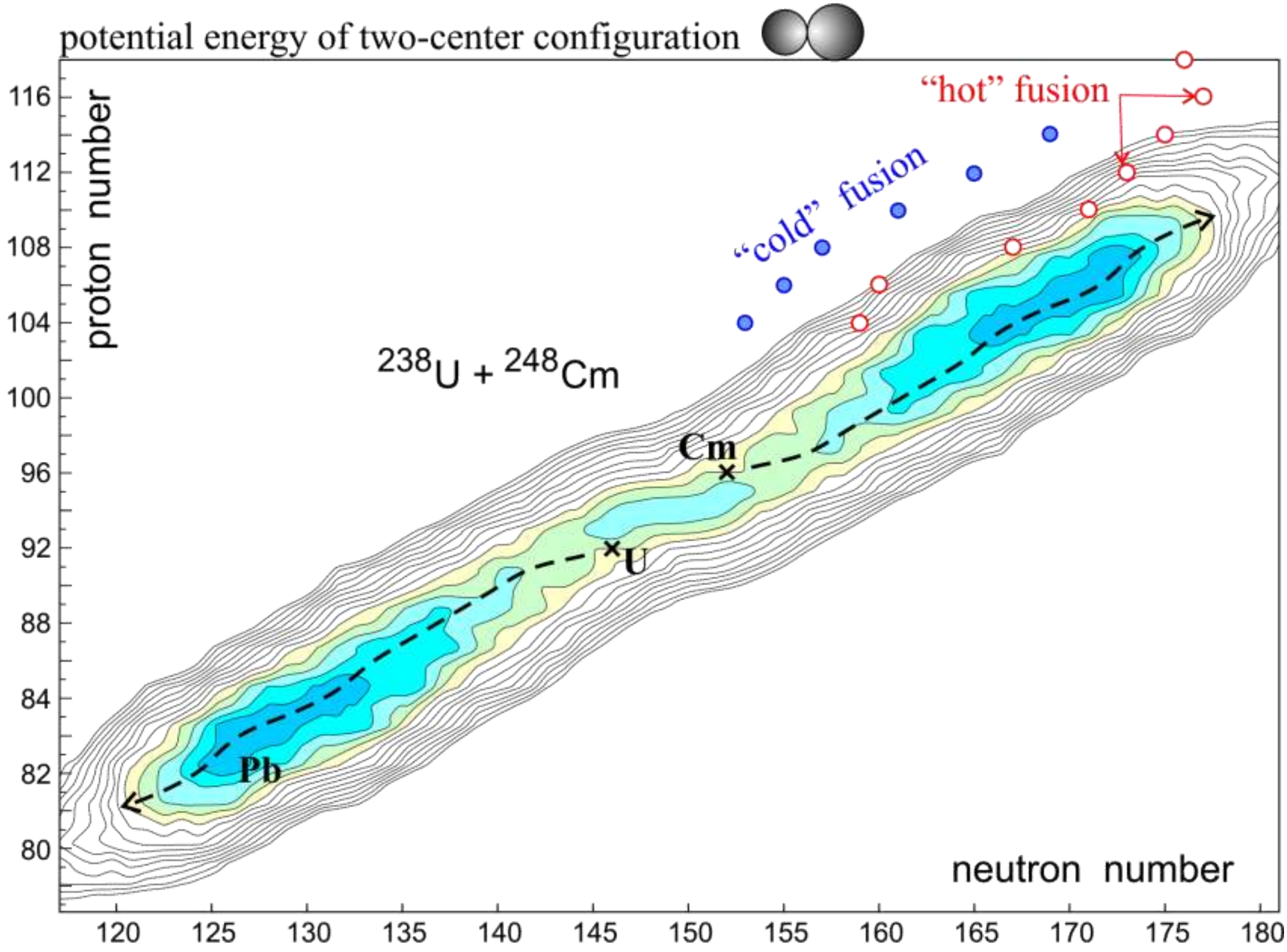
Good agreement with experiment: e.g. $^{48}Ca + ^{248}Cm$



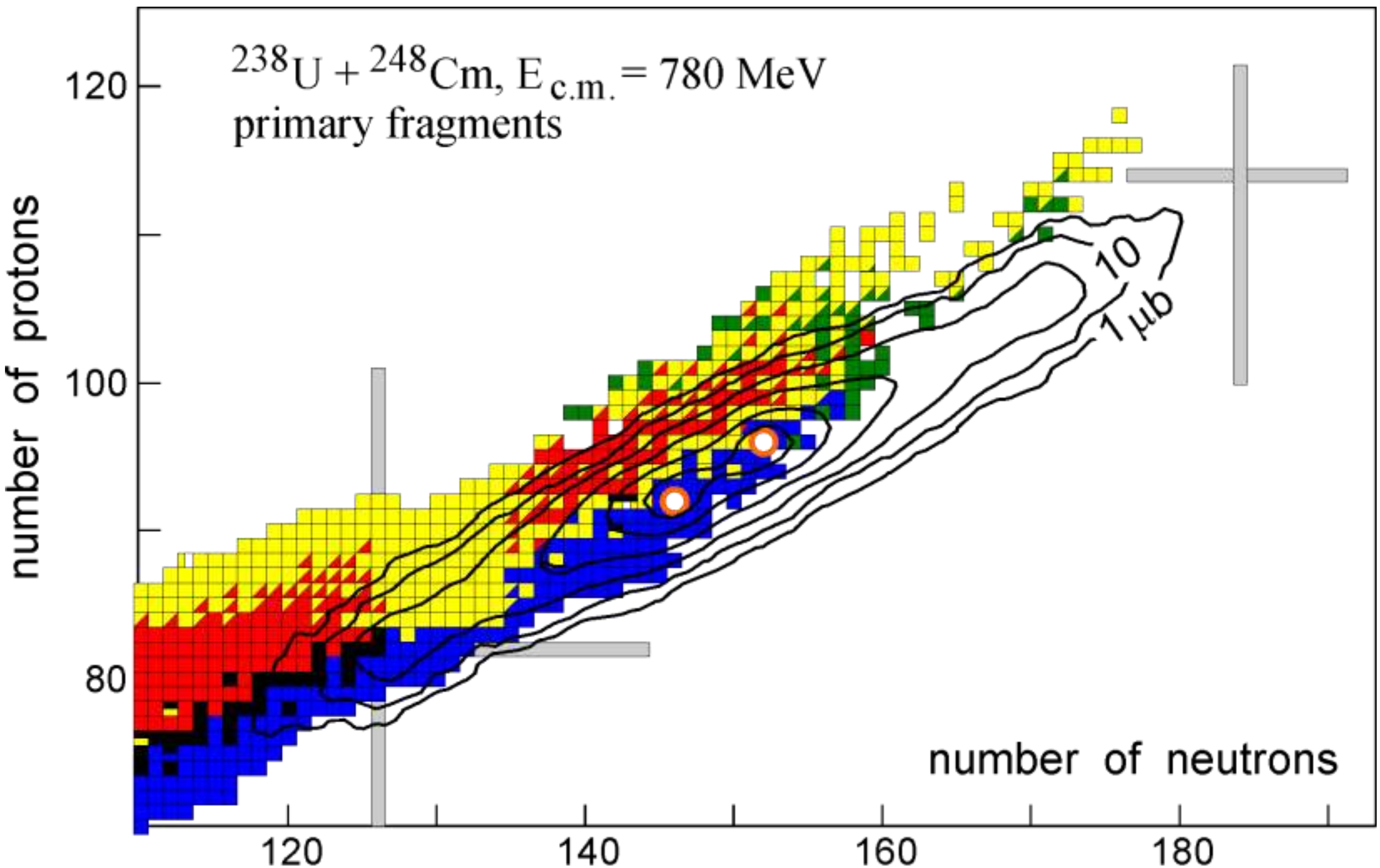
Transfer reactions in damped collision of very heavy nuclei ?



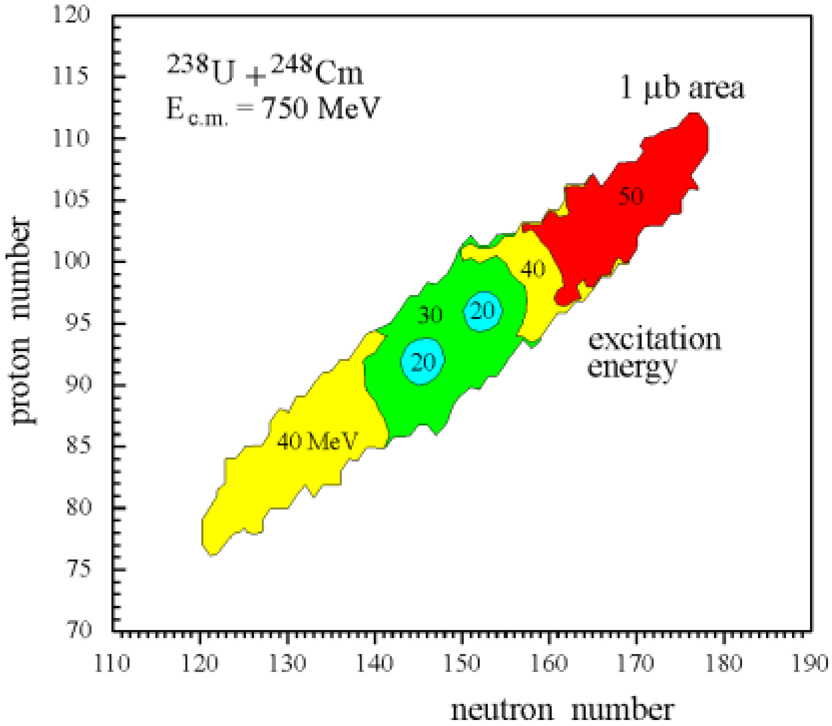
Most probable way of evolution of the giant nuclear system

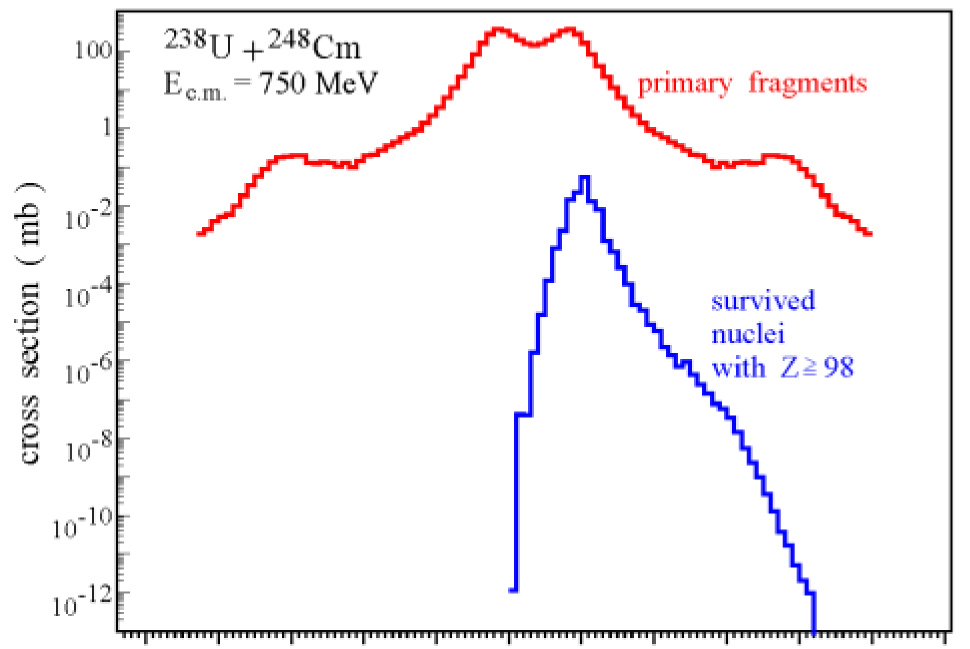


238U + 248Cm. Primary fragments

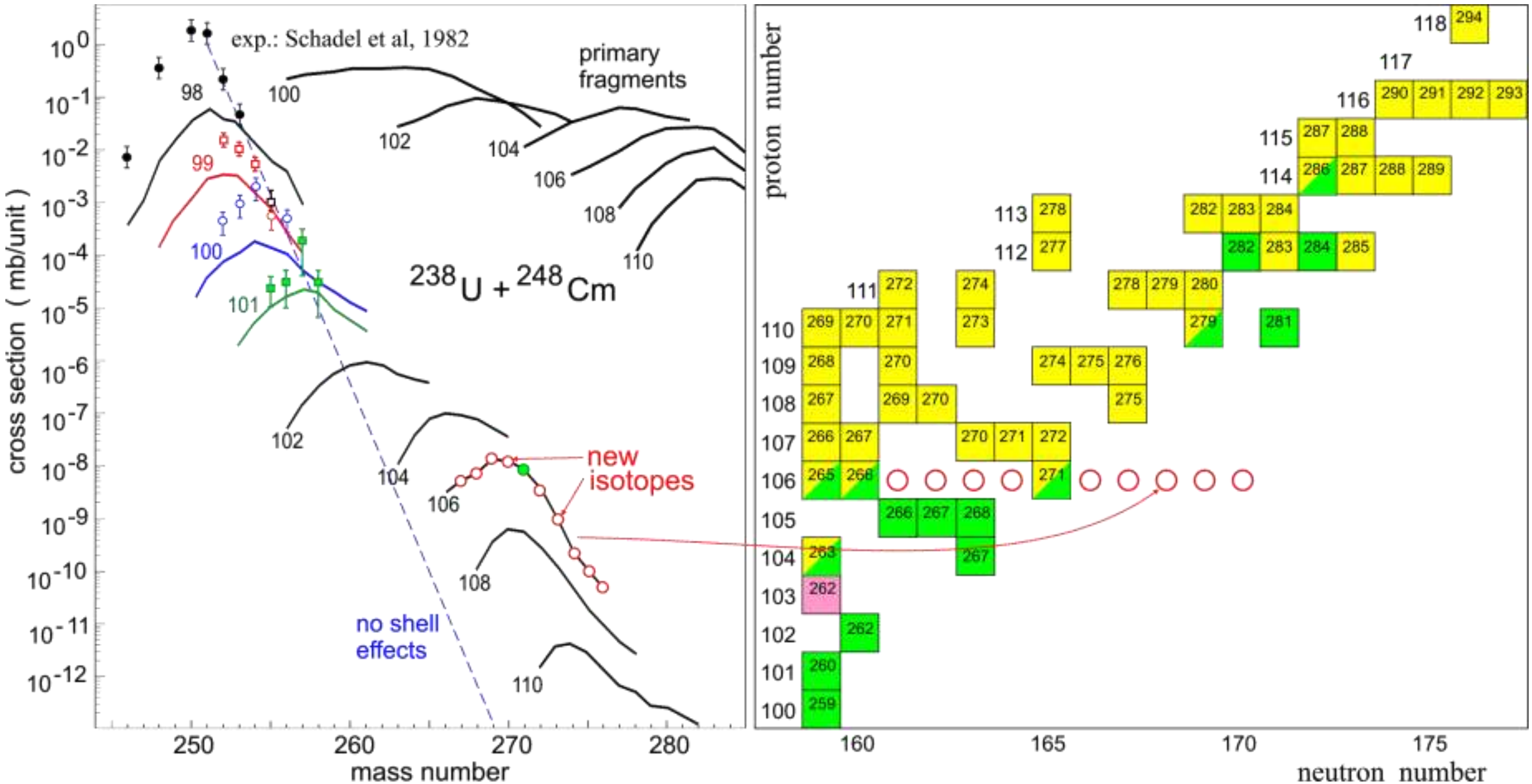


238U + 248Cm. Excitation energies and survival probability





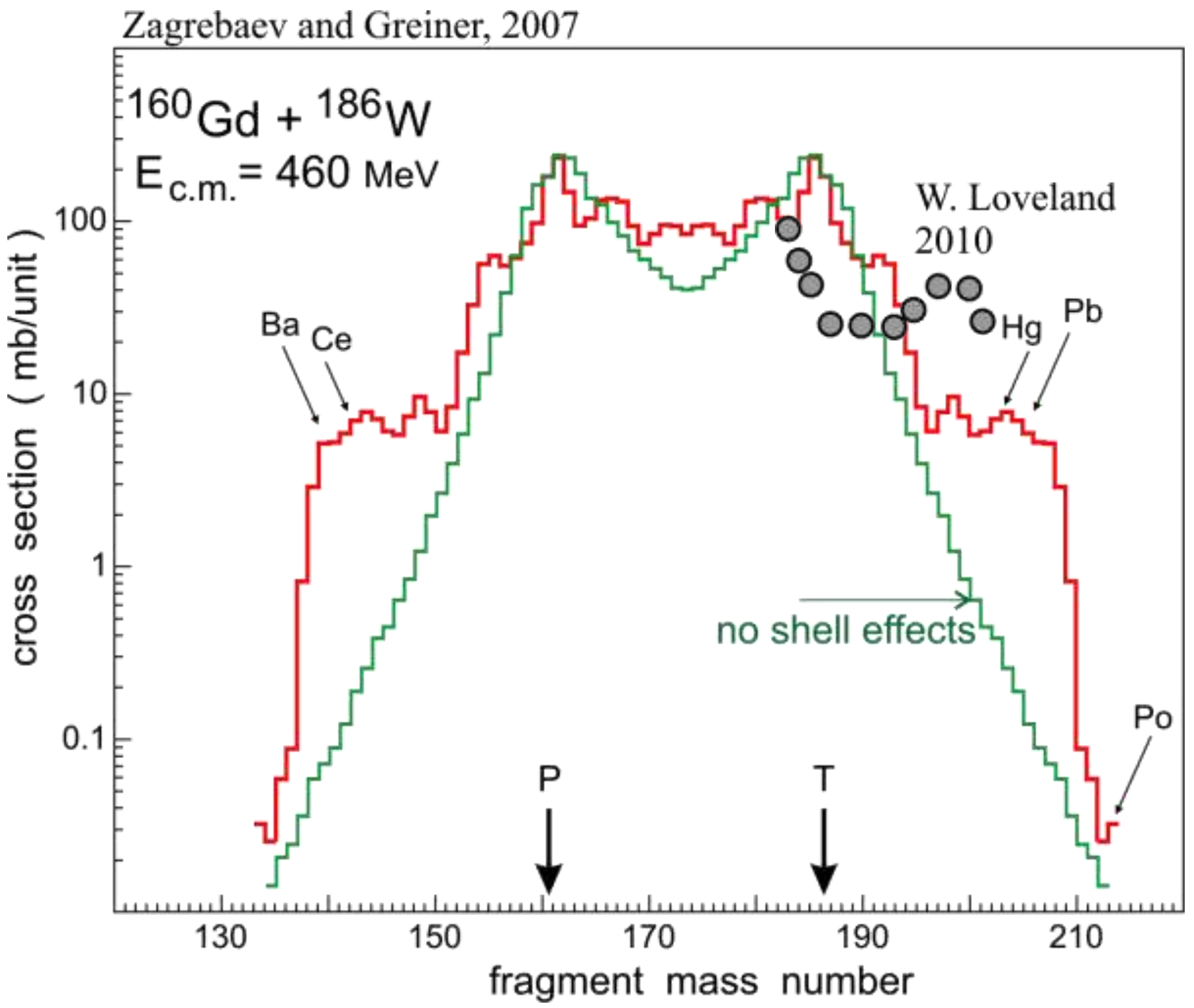
Isotopic yield of SHE in collisions of heavy actinide nuclei



How much is a role of the shell effects in damped collisions ?

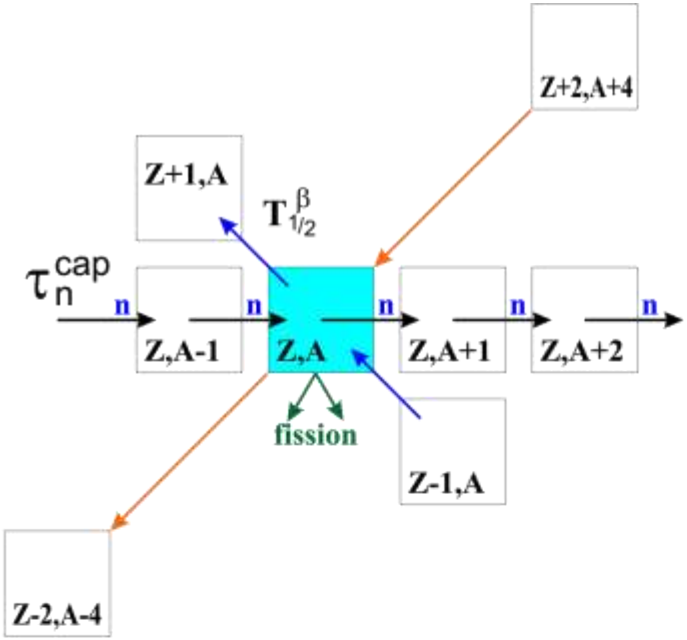
$^{160}Gd + ^{186}W$

(proposal for a new experiment)



Non-accelerative production of superheavy nuclei

Nucleogenesis under the influence of neutron flux



$$\frac{dN_{ZA}}{dt} = N_{ZA\text{-}1}\, n_0\, \sigma^{n\gamma}_{ZA\text{-}1} - N_{ZA}\, n_0\, \sigma^{n\gamma}_{ZA} - N_{ZA}\frac{\ln 2}{T^{\beta}_{ZA}} - N_{ZA}\frac{\ln 2}{T^{\alpha}_{ZA}} - N_{ZA}\frac{\ln 2}{T^{fis}_{ZA}} + N_{Z\text{-}1A}\frac{\ln 2}{T^{\beta}_{Z\text{-}1A}} + N_{Z+2A+4}\frac{\ln 2}{T^{\alpha}_{Z+2A+4}}$$

time of neutron capture

$$\tau_n^{cap} = \frac{1}{n_0 \times \sigma(n,\gamma)}$$

n_0 is the neutron flux ($\frac{1}{cm^2 \cdot sec}$),

$\sigma(n,\gamma)$ is the n-capture cross section (~ 1 barn = 10^{-24} cm^2, E_n= 0.5 MeV)

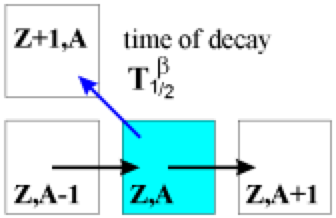
the shift to the right stops

when $\mathbf{T}_{1/2}\,(\mathbf{Z,A}) < \tau_n^{cap}$

n_0 (reactor) < $10^{19}\,\frac{1}{cm^2 \cdot sec}$, $\tau_n^{cap} > 10^5$ sec (1 day)

n_0 (explosion) ~ $10^{30}\,\frac{1}{cm^2 \cdot sec}$, τ_n^{cap} ~ 1 μs

Nucleogenesis in reactors and in nuclear explosion



time of neutron capture

$$\tau_n^{cap} = \frac{1}{n_0 \times \sigma(n,\gamma)}$$

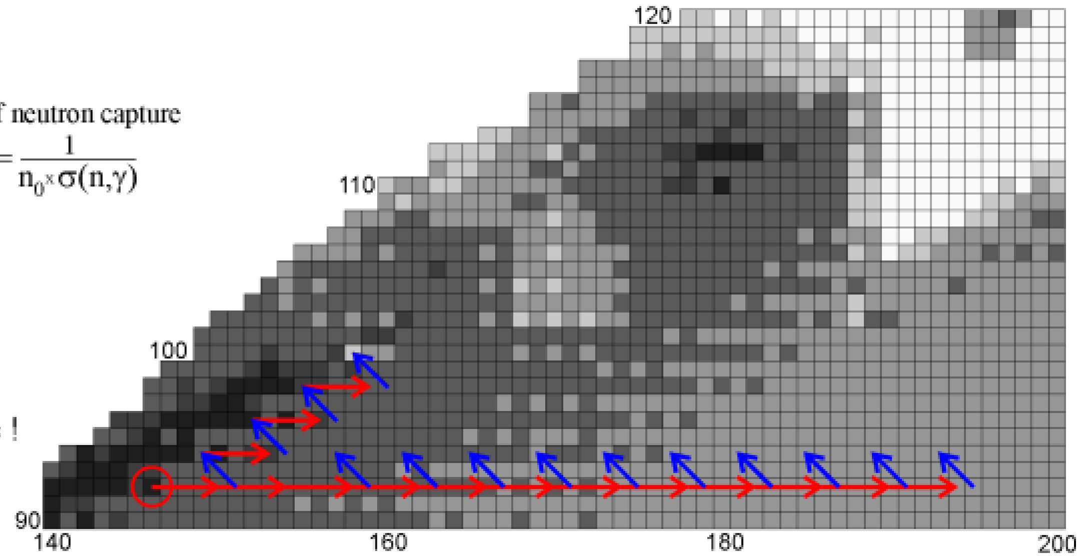
neutron capture stops

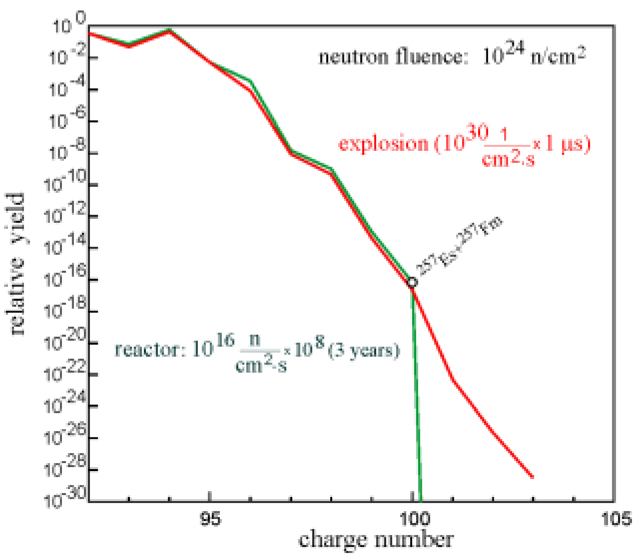
when $T^{\beta}_{1/2}(Z,A) < \tau_n^{cap}$

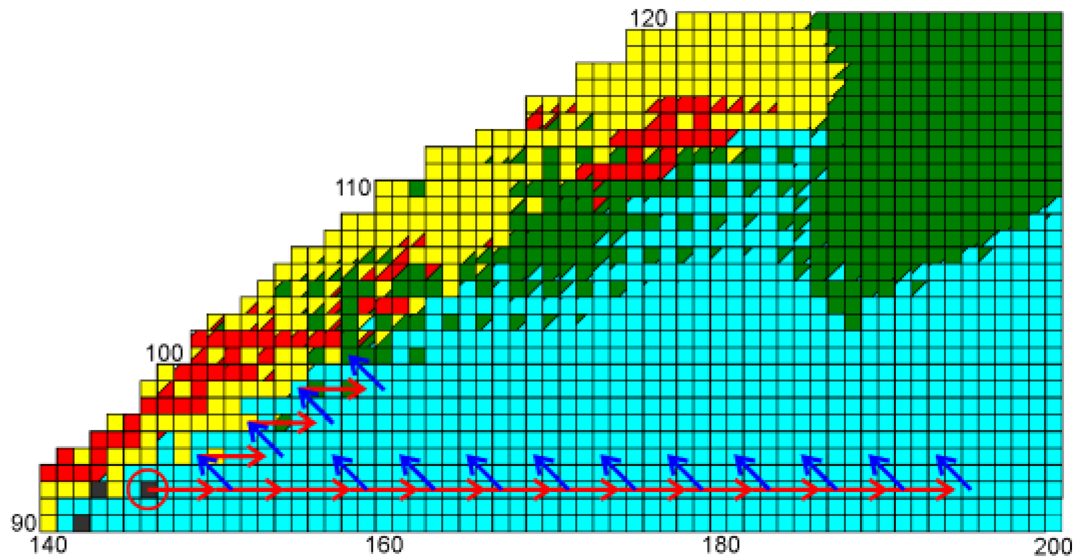
n_0 (reactor) $< 10^{19} \frac{1}{cm^2 \cdot sec}$, $\tau_n^{cap} > 10^5$ sec (1 day),

but $T^{fis}_{1/2}$ ($^{258\text{-}260}$Fm) <= 1 sec !

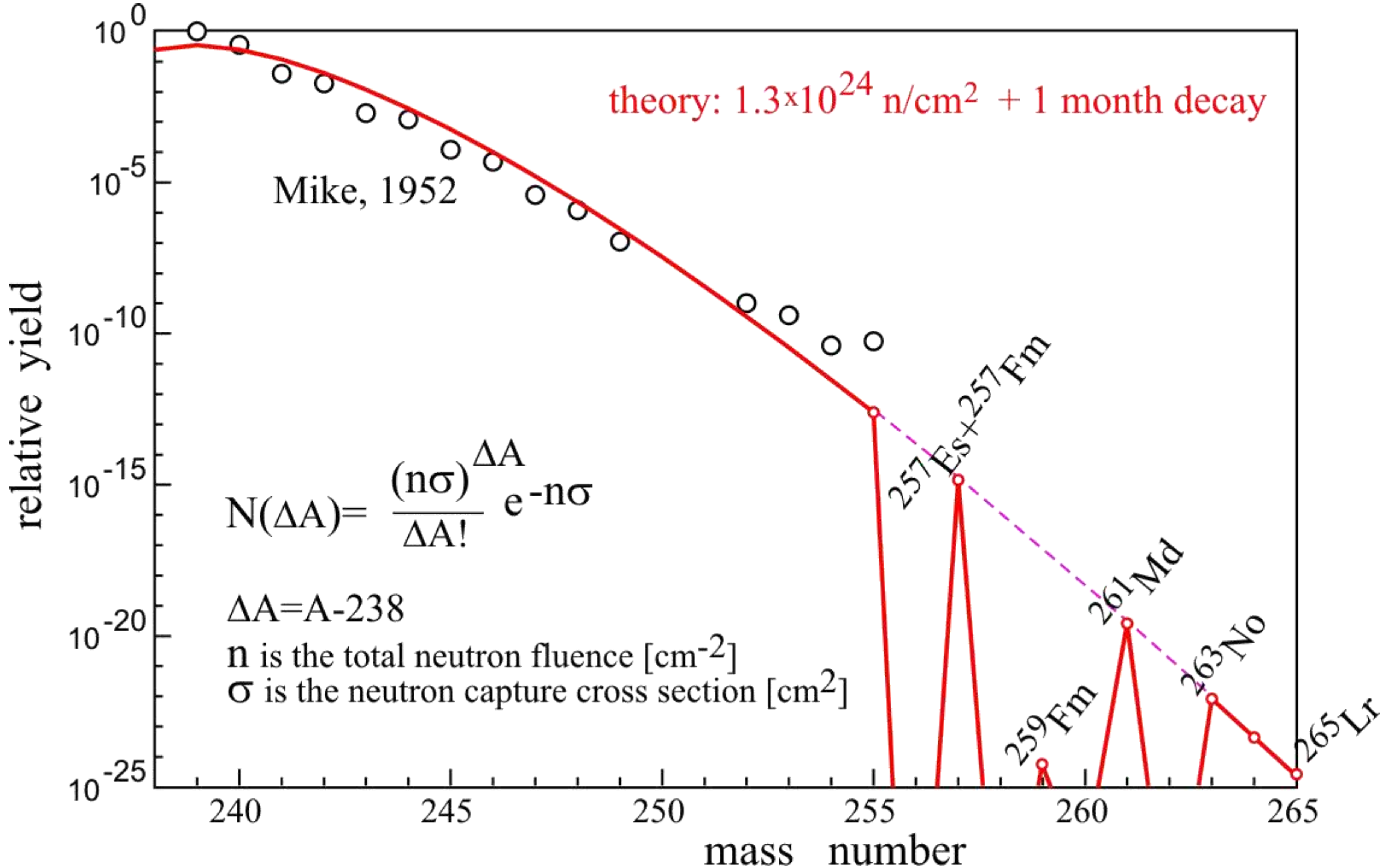
n_0 (explosion) $\sim 10^{30} \frac{1}{cm^2 \cdot sec}$, $\tau_n^{cap} \sim 1\ \mu s$



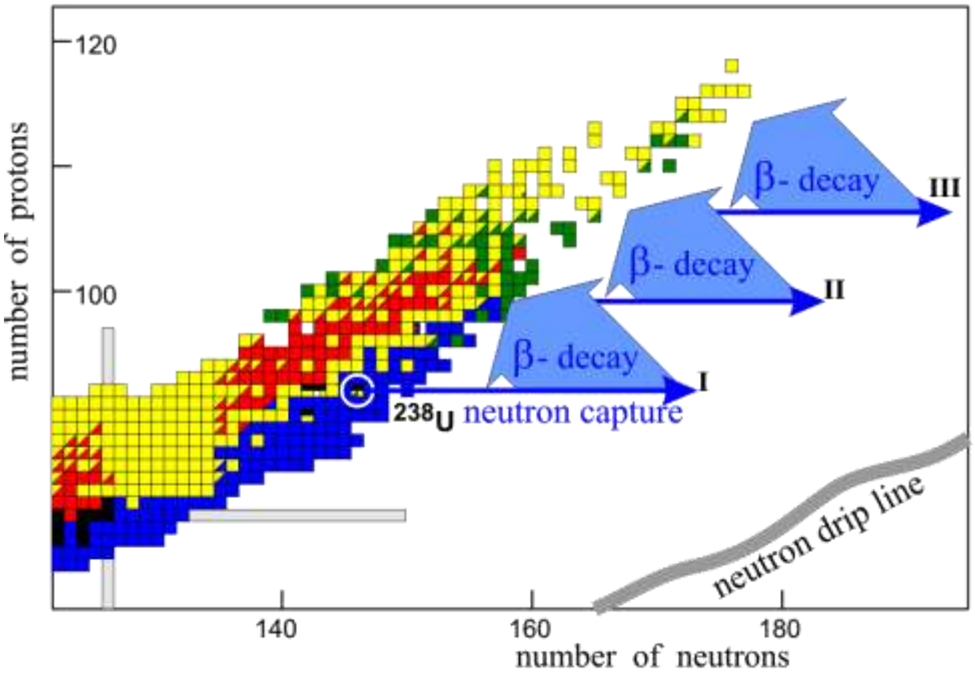


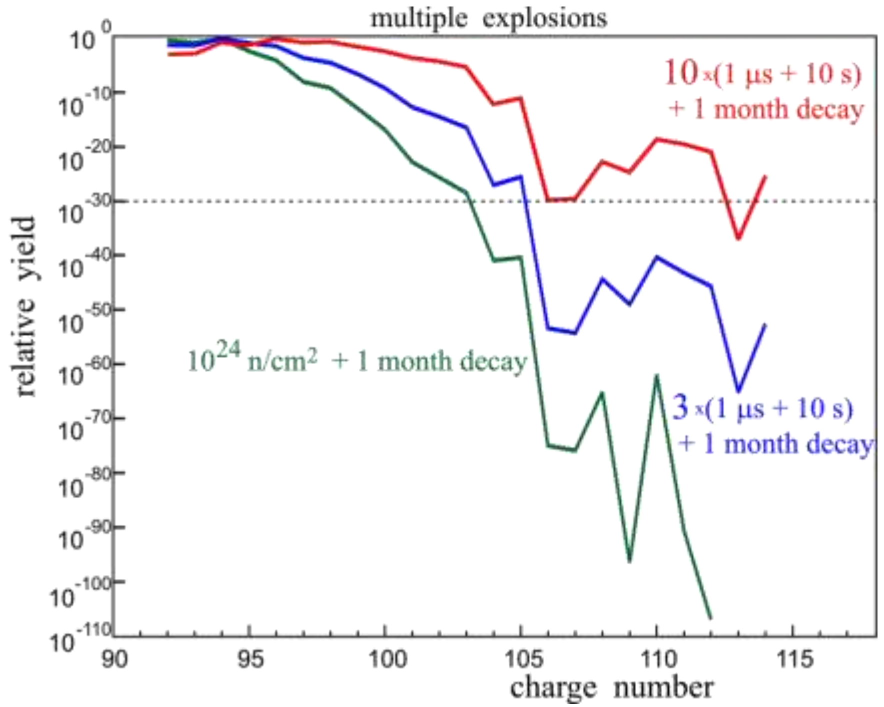


Rapid neutron capture in nuclear explosion

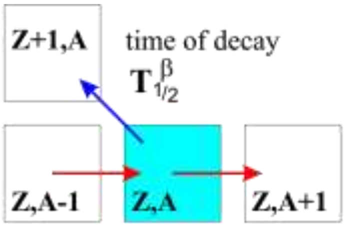


Multiple nuclear explosions





Pulsed reactors: Bypassing the gaps of instability



neutron capture stops

when $T^{\beta}_{1/2}(Z,A) < \tau_n^{cap}$

time of neutron capture

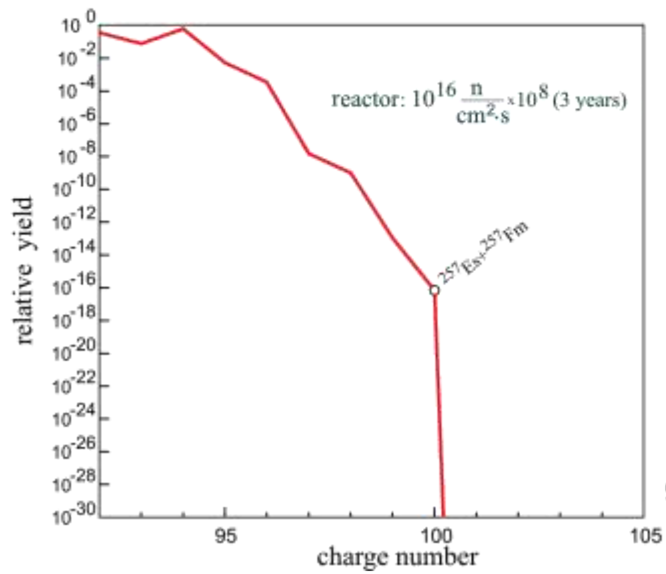
$\tau_n^{cap} = \frac{1}{n_0 \times \sigma(n,\gamma)}$

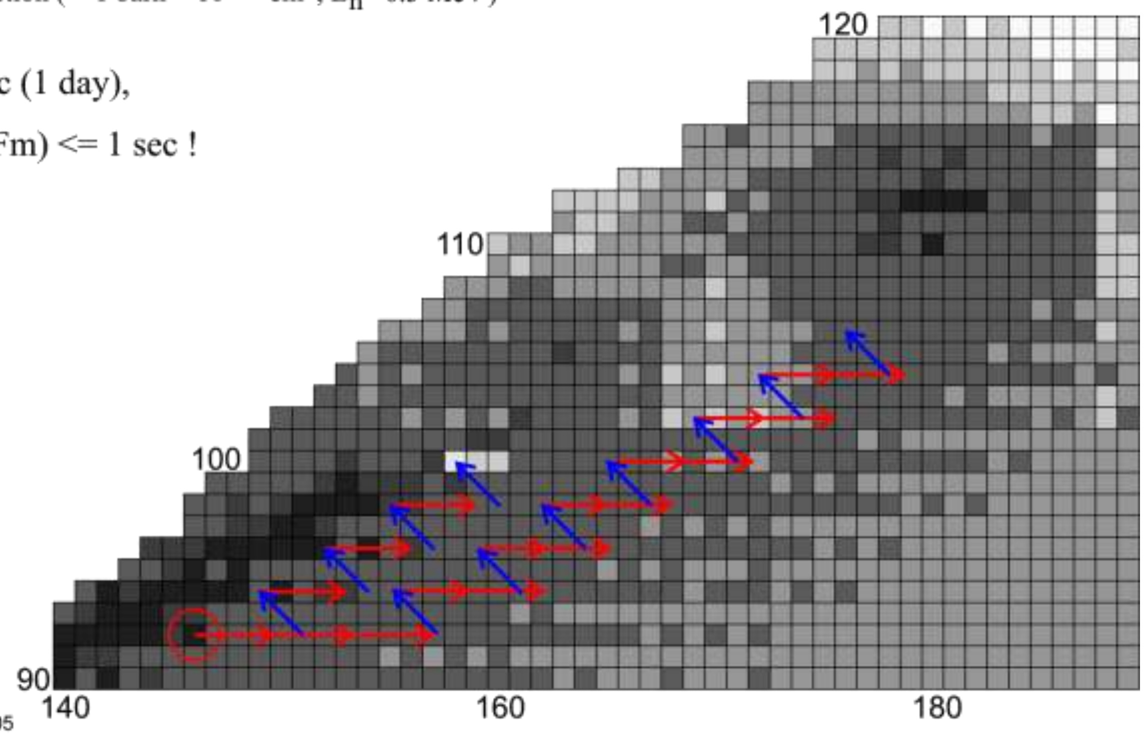
n_0 is the neutron flux ($\frac{1}{cm^2 \cdot sec}$),

$\sigma(n,\gamma)$ is the n-capture cross section (~ 1 barn = 10^{-24} cm^2, E_n= 0.5 MeV)

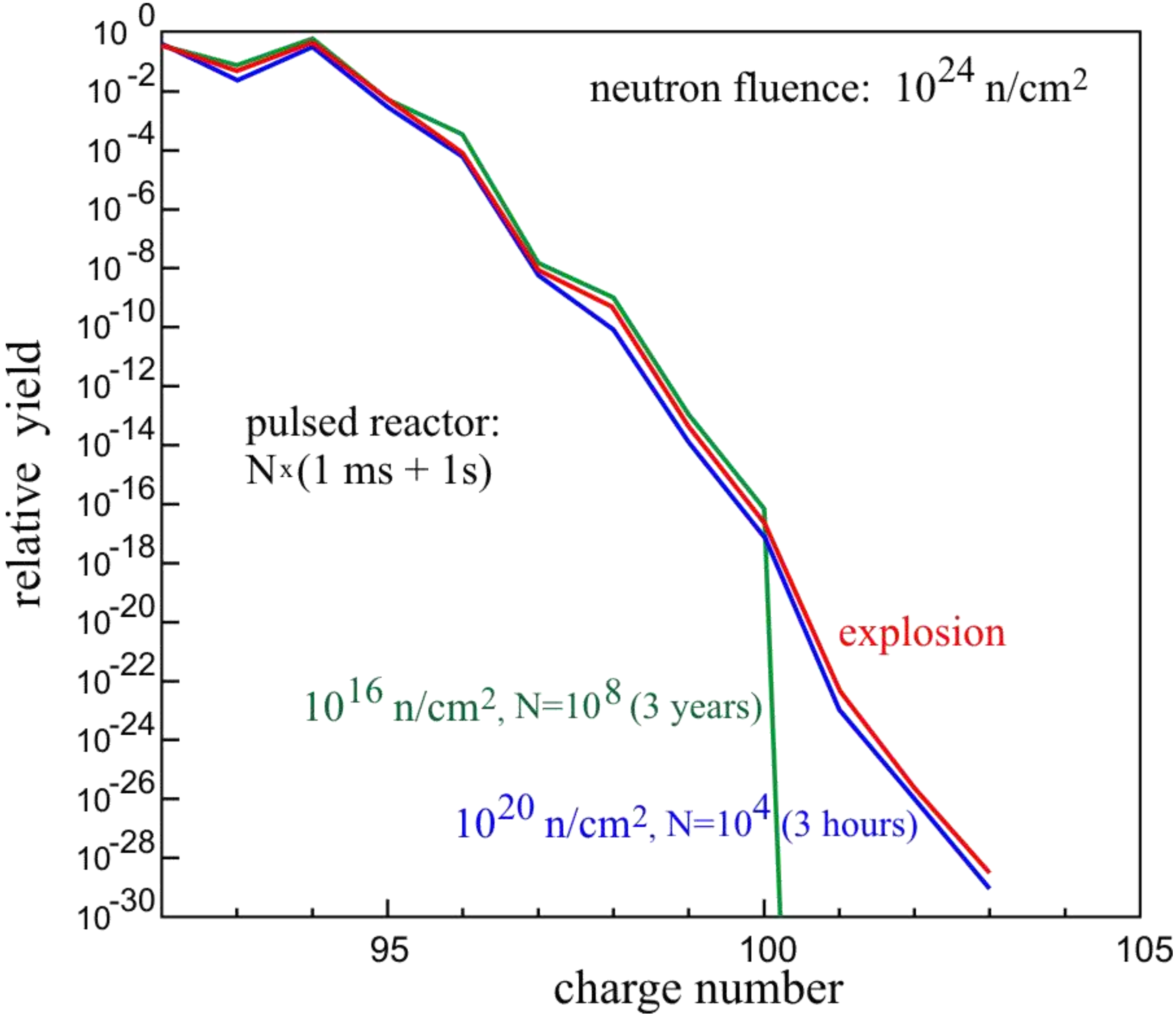
n_0 (reactor) < $10^{19} \frac{1}{cm^2 \cdot sec}$, $\tau_n^{cap} > 10^5$ sec (1 day),

but $T^{fis}_{1/2}$ ($^{258\text{-}260}$Fm) <= 1 sec !





New generation of Pulsed Reactors ?



Summary

- Element 120 is reachable in the Ti and/or Cr fusion reactions at the level of 0.02 pb
- Multi-nucleon transfer reactions are to be used for synthesis of neutron rich long living SH nuclei
- A macroscopic amount of the long-living SH nuclei located at the island of stability may be really produced in the multiple (rather "soft") nuclear explosions
- This goal could be also reached by using the pulsed nuclear reactors of next generation

Problems

- Where is the island of stability ?
  What is the most stable SH element to find it in Nature ?
- How much is the shell-effect enhancement in transfer reactions?
- How extensive is the Fm gap ? What is the nearest "blue" (beta-decayed) Fm isotope ?
  How deep (short-living) is the gap in the region of Z~108, A~270 ?
- Is it possible to construct desired pulsed reactor to overcome the both gaps ?
  Or "soft" multiple explosions are still cheaper?