New ideas on the formation of heavy and superheavy neutron rich nuclei

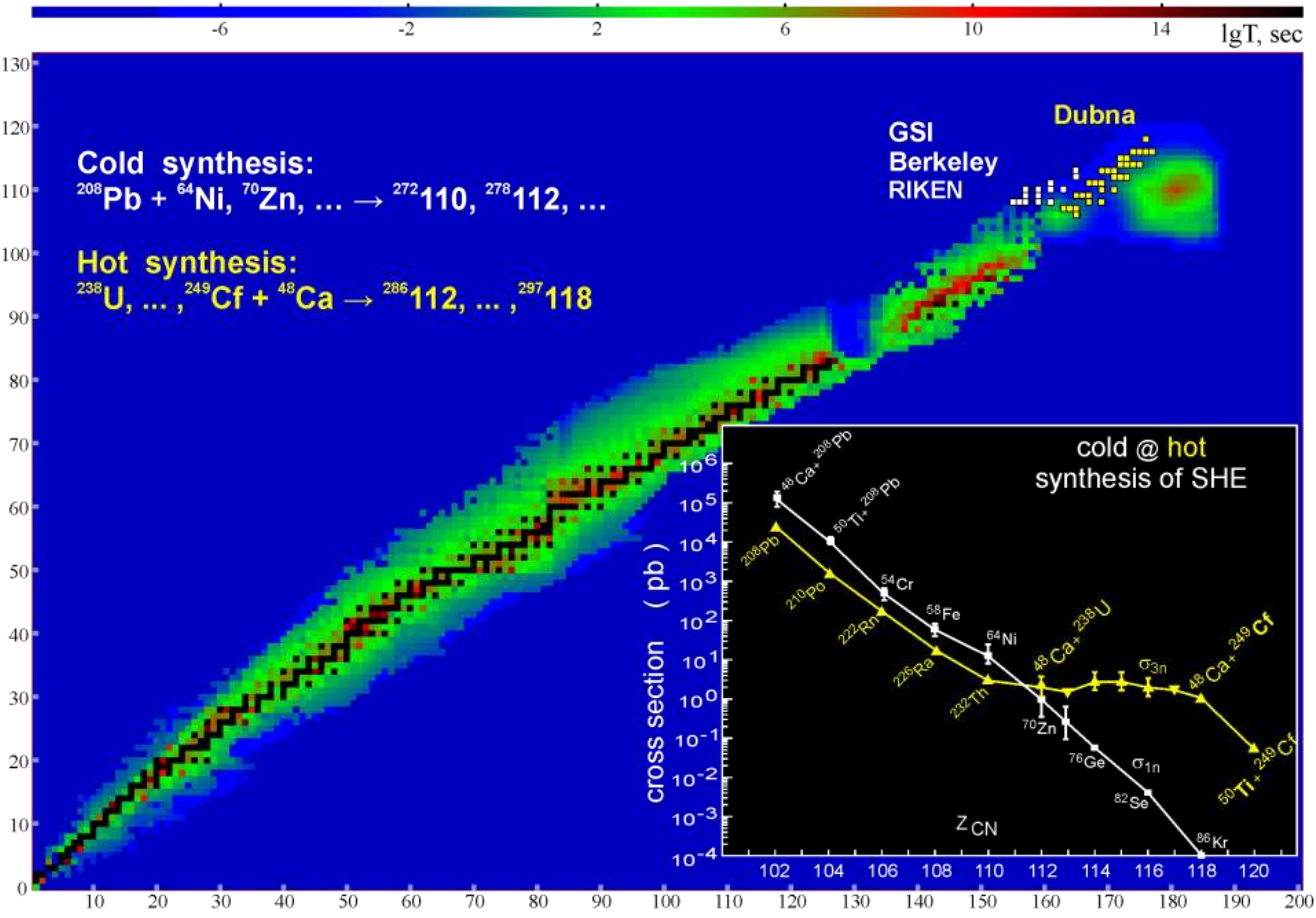
- **Motivation**
- **Unexplored areas at the “north-east” part of the nuclear map**
- **Use of low-energy multi-nucleon transfer reactions to fill the “blank spots” of the nuclear map**
- **Summary**

Valery Zagrebaev and Walter Greiner
for NN-2009, Beijing, August 18, 2009

JINR, Dubna

FIAS, Frankfurt

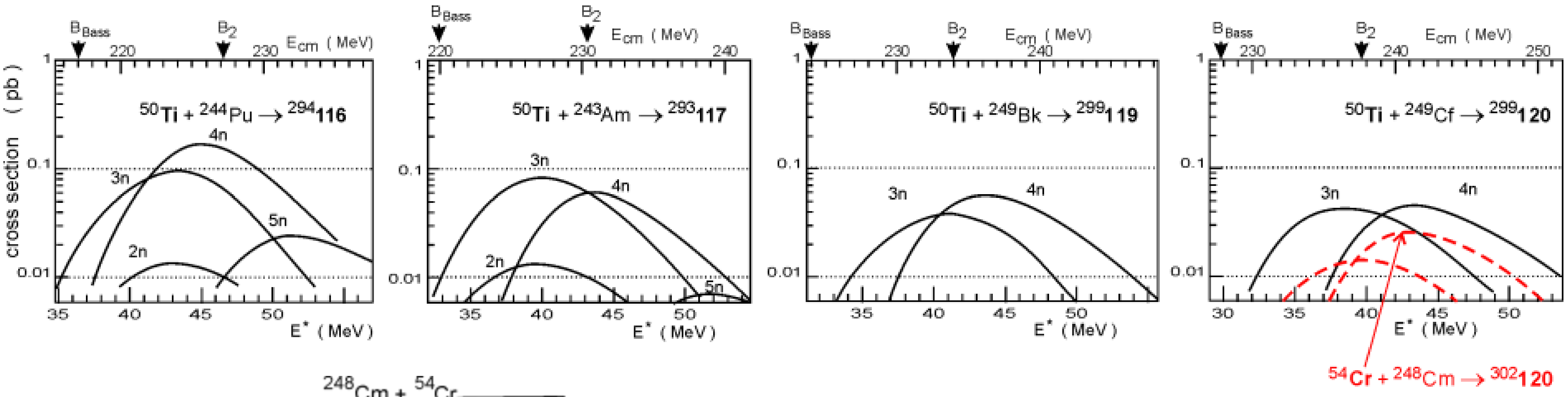
Synthesis of superheavy elements (cold and hot fusion)

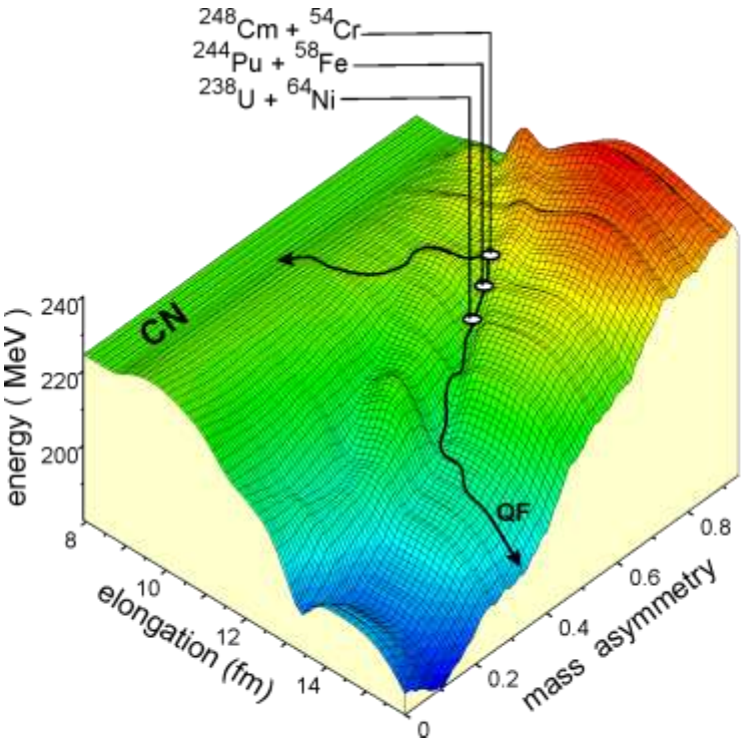


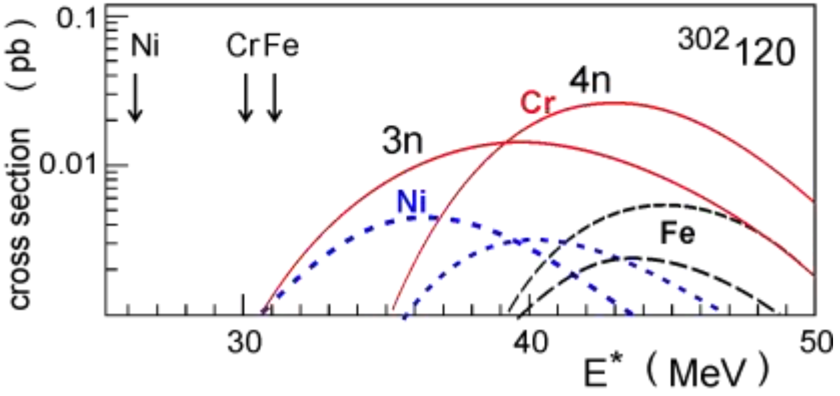
Cold synthesis:
^{208}Pb + ^{64}Ni, ^{70}Zn, ... → ^{272}110, ^{278}112, ...

Hot synthesis:
^{238}U, ... , ^{249}Cf + ^{48}Ca → ^{286}112, ... , ^{297}118

Beyond ^{48}Ca: ^{50}Ti - induced fusion reactions

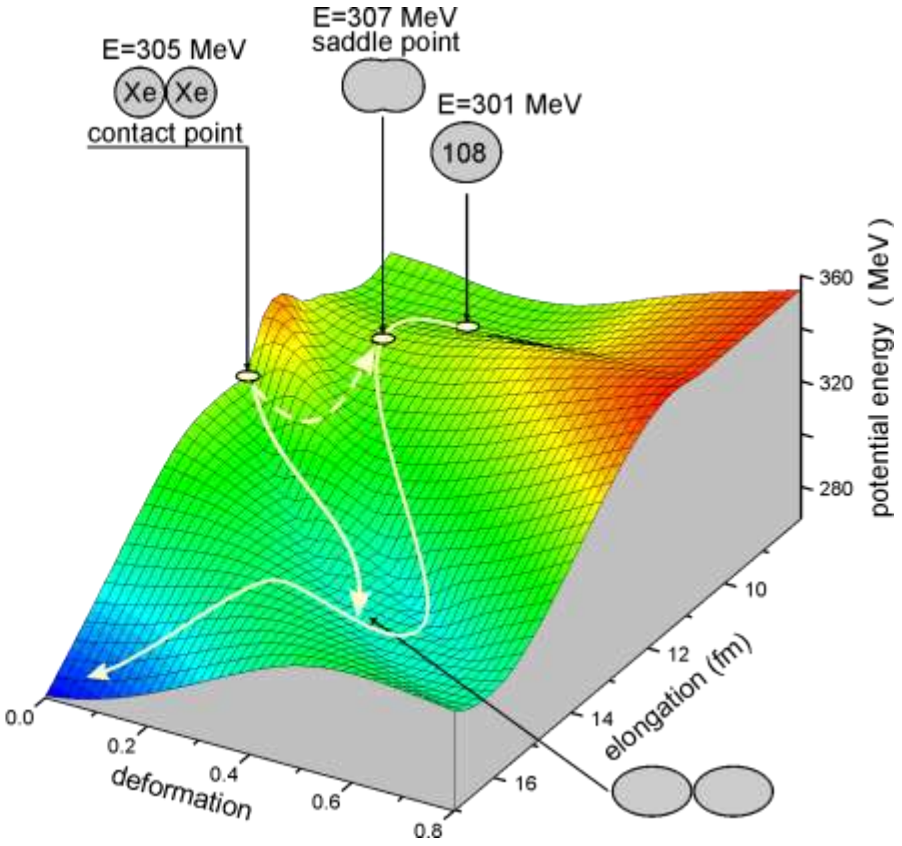


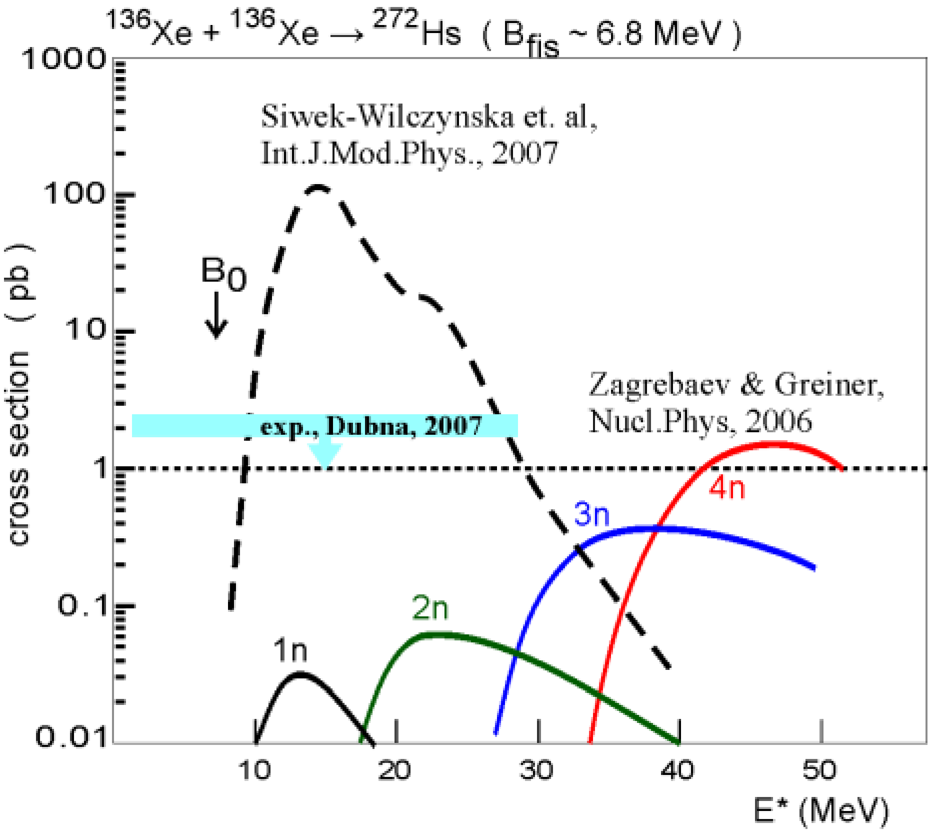




Fusion of “fission fragments”: ^{136}Xe + ^{136}Xe → ^{272}108

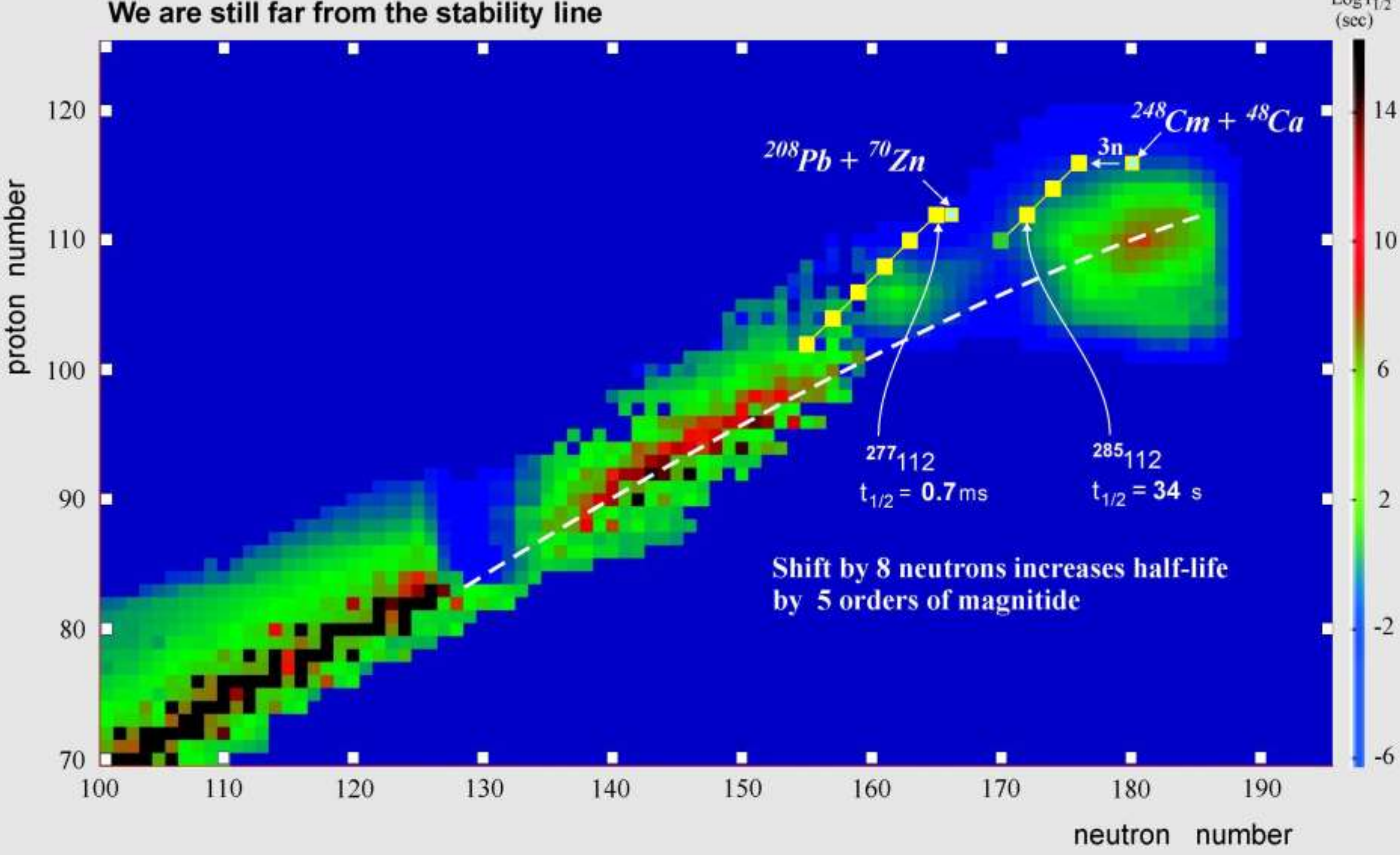
if OK then ^{132}Sn + ^{176}Yb → ^{308}120





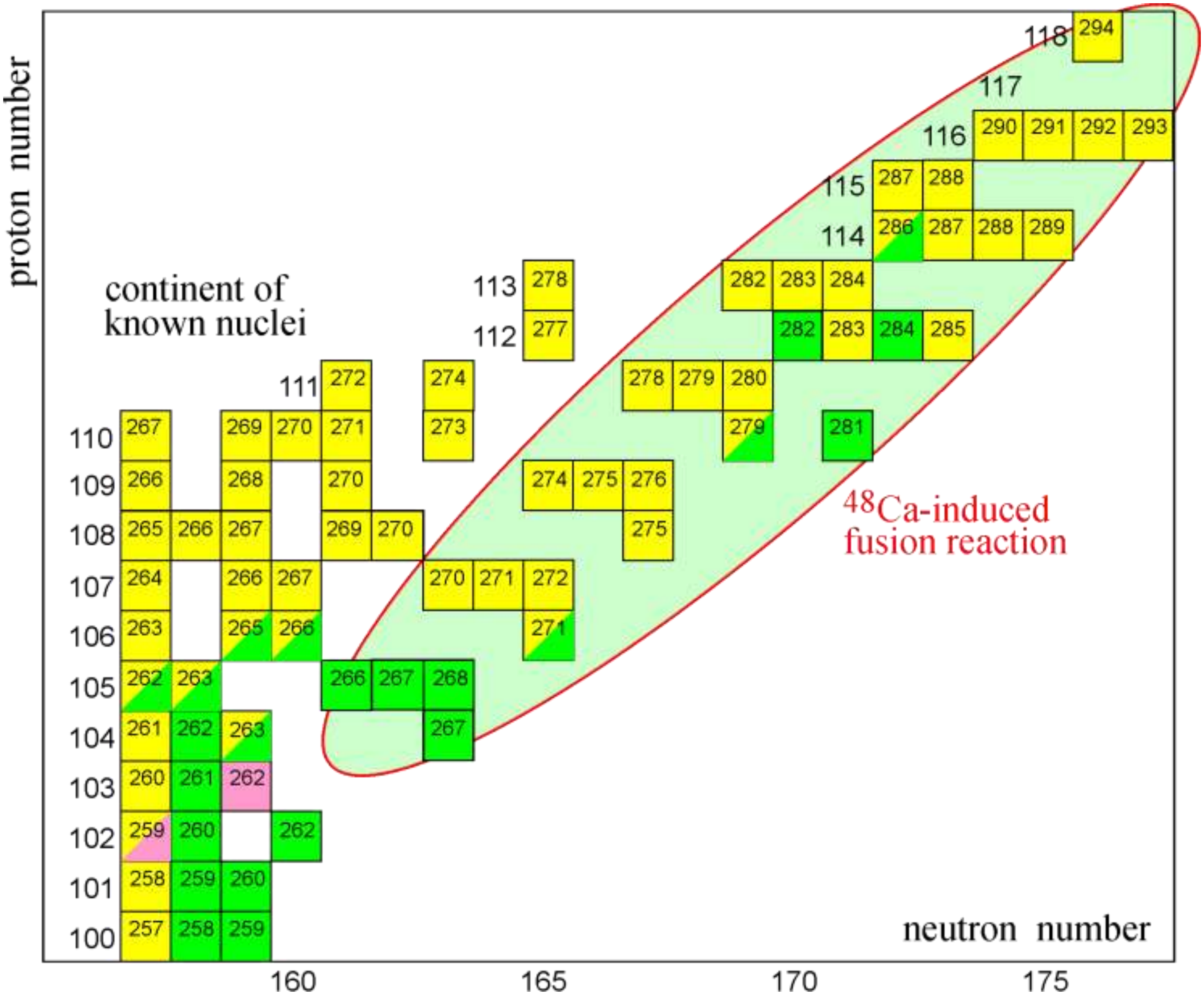
Accelerated fission fragments
hardly may be used
for production of SH nuclei

We are still far from the stability line

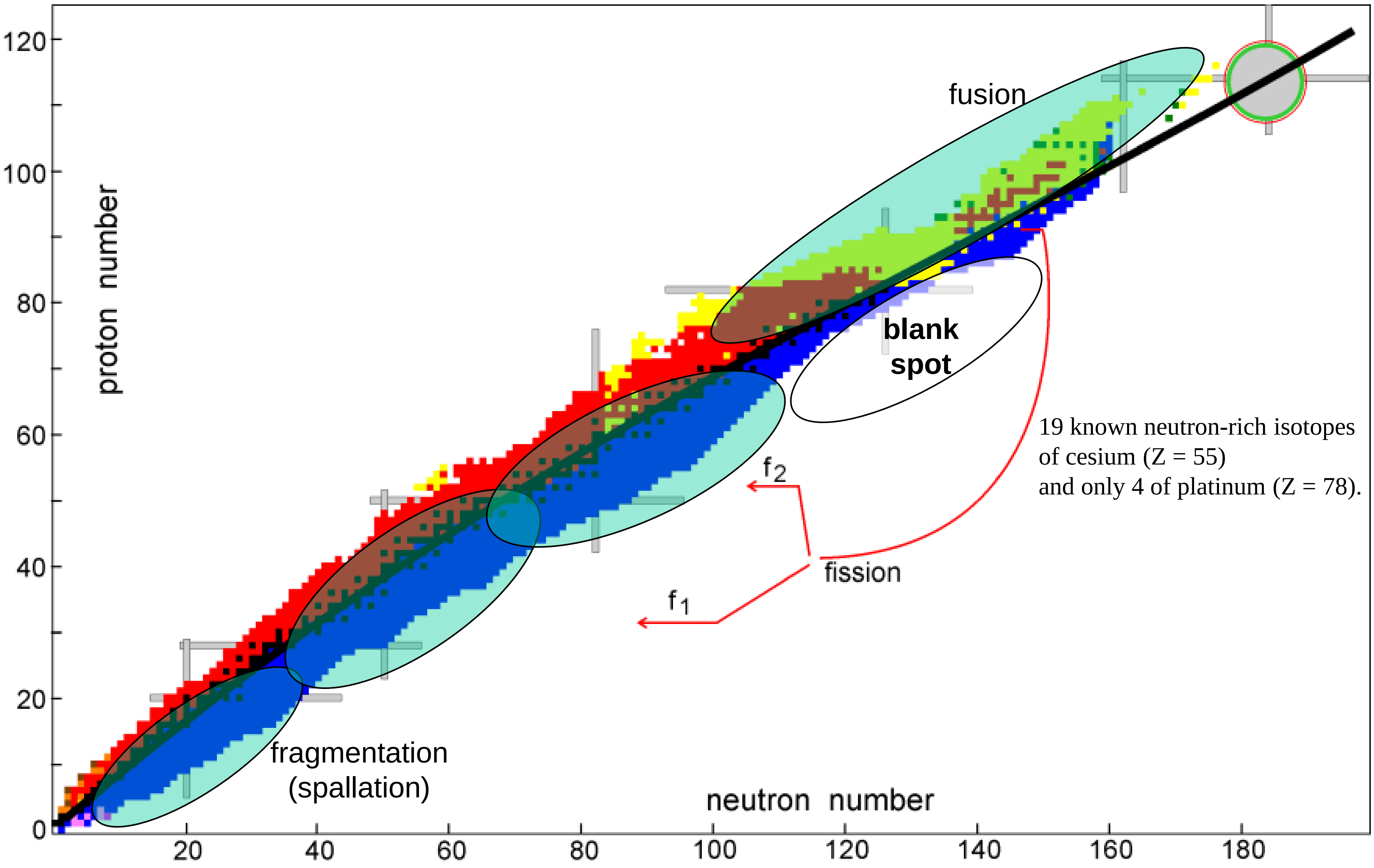


Shift by 8 neutrons increases half-life by 5 orders of magnitide

A “gap” in the upper part of the Nuclear Map



“Blanc Spot” on the Nuclear Map



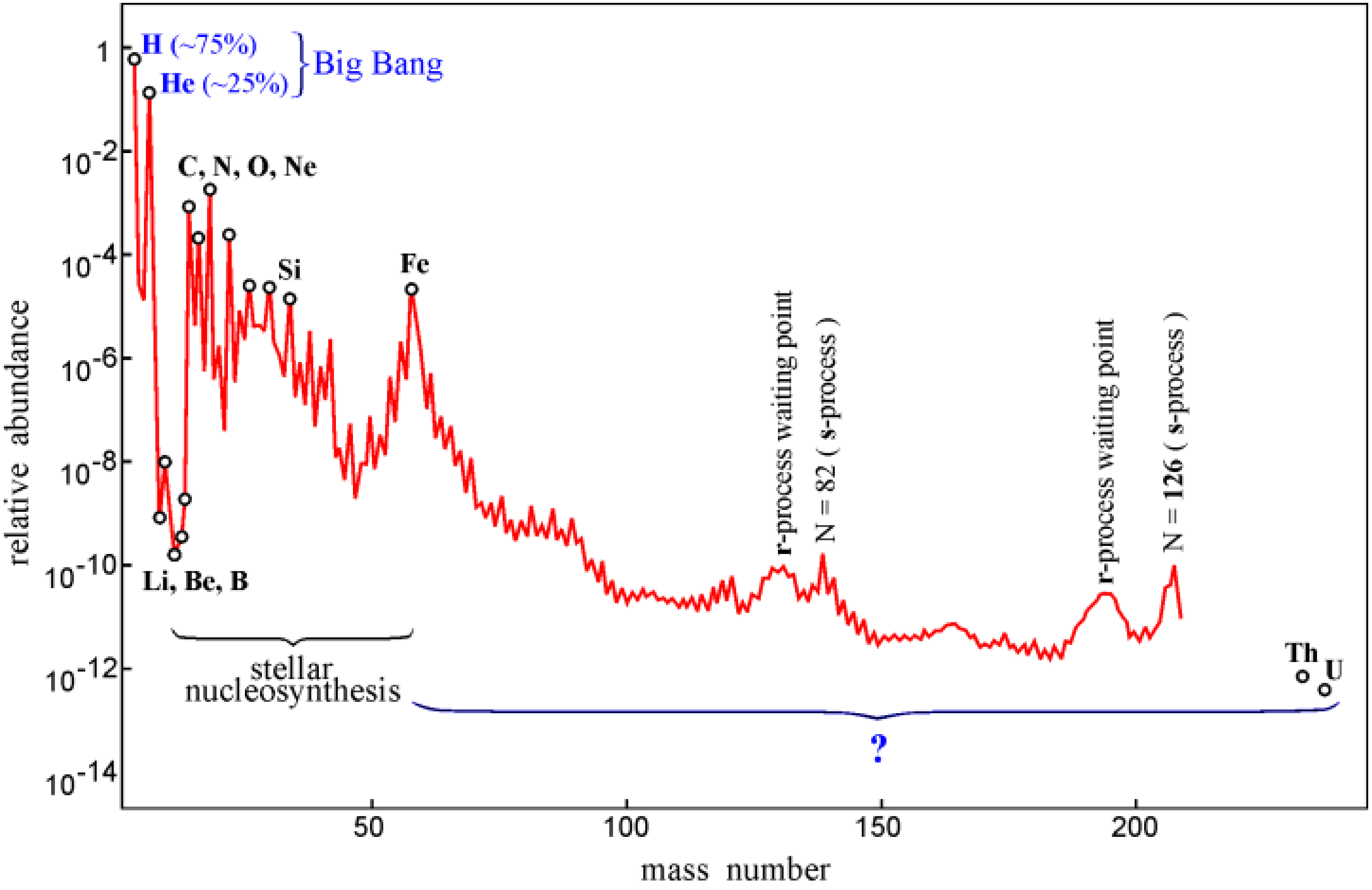
19 known neutron-rich isotopes of cesium (Z = 55) and only 4 of platinum (Z = 78).

Abundance of elements in the Universe

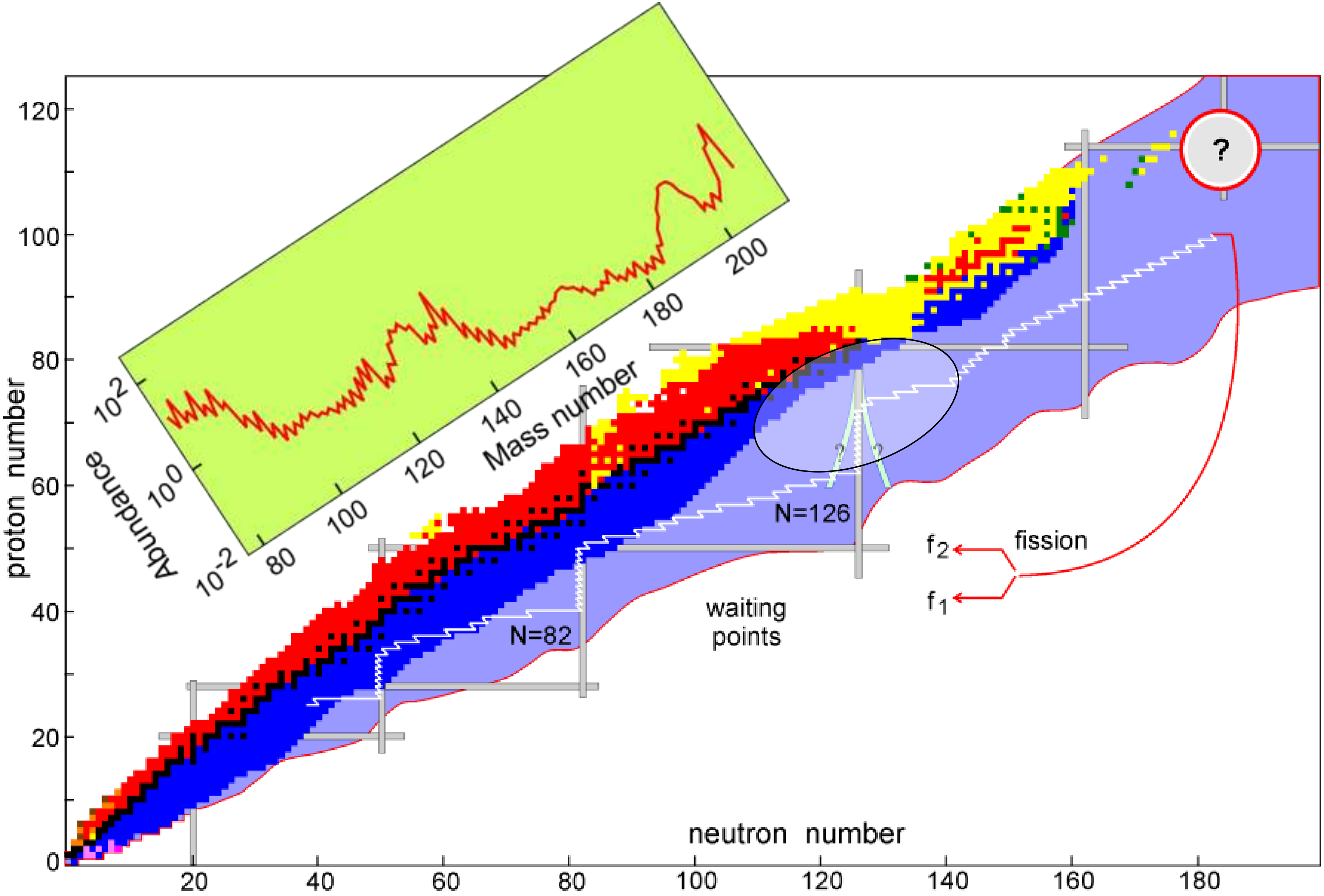
The 11 Greatest Unanswered Questions of Physics
(National Research Council, NAS, USA, 2002):

1. **What is dark matter?**
2. **What is dark energy?**
3. **How were the heavy elements from iron to uranium made?**
4. **Do neutrinos have mass?**

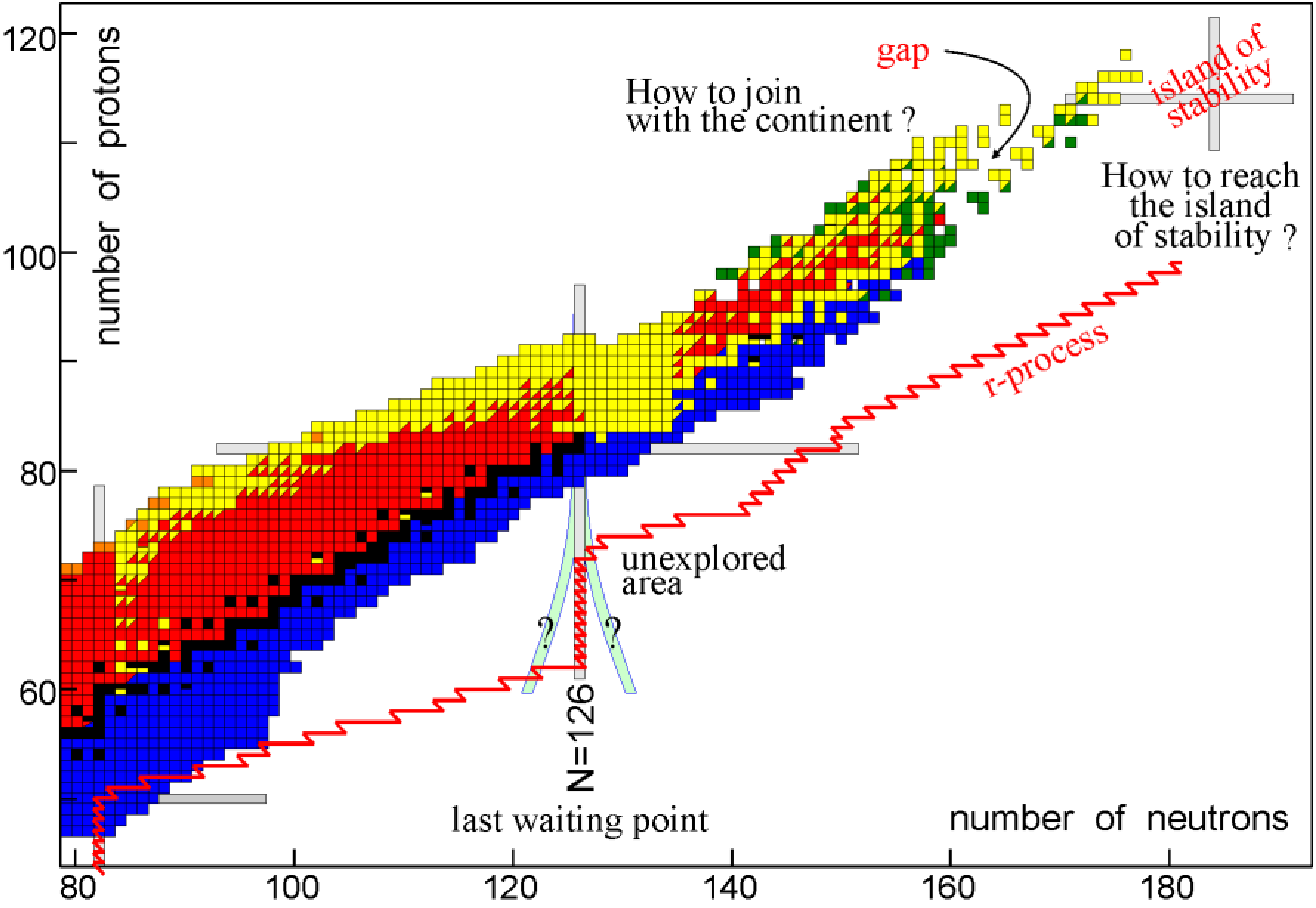
…



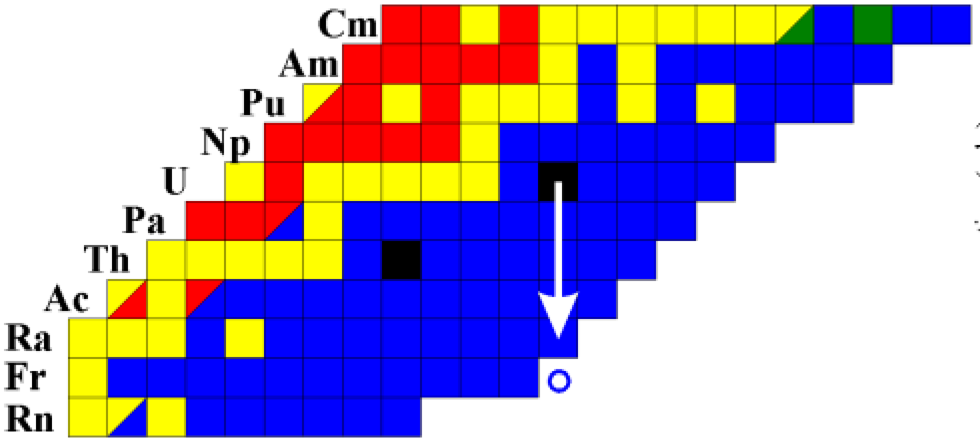
r-process of nucleosynthesis and the neutron closed shell in the region of N ~ 126



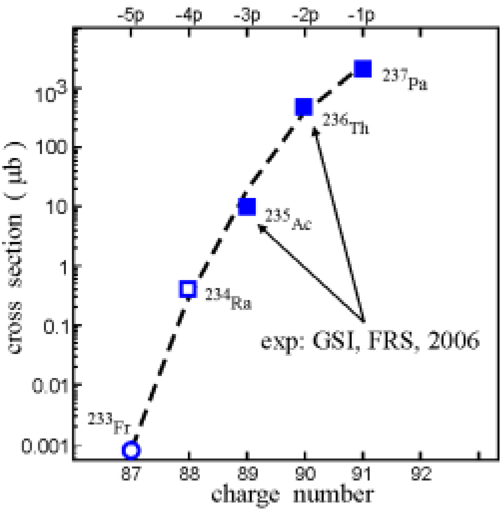
How to explore the north-east part of the nuclear map ?

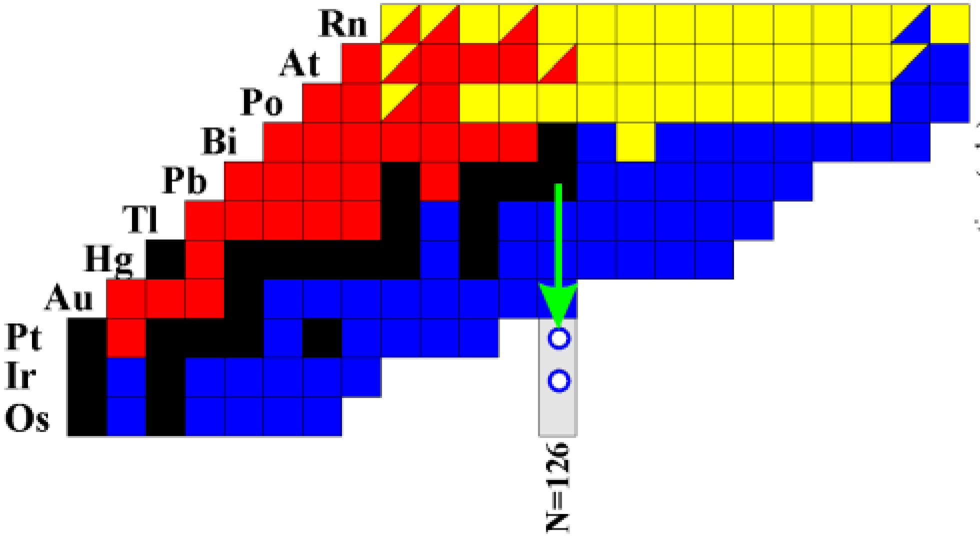


Spallation (break-off) process at high incident energies

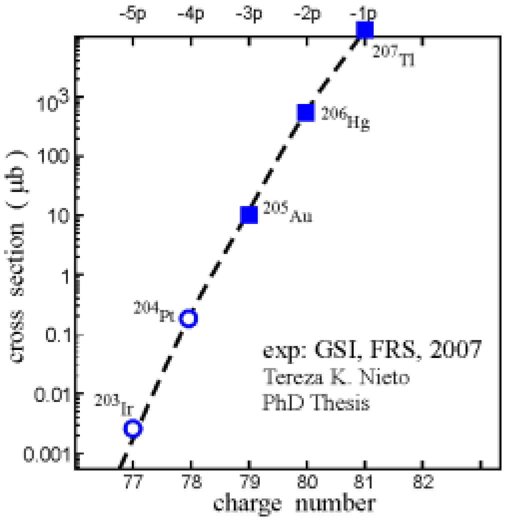


^{238}U(1A GeV) + d





^{208}Pb(1A GeV) + Be

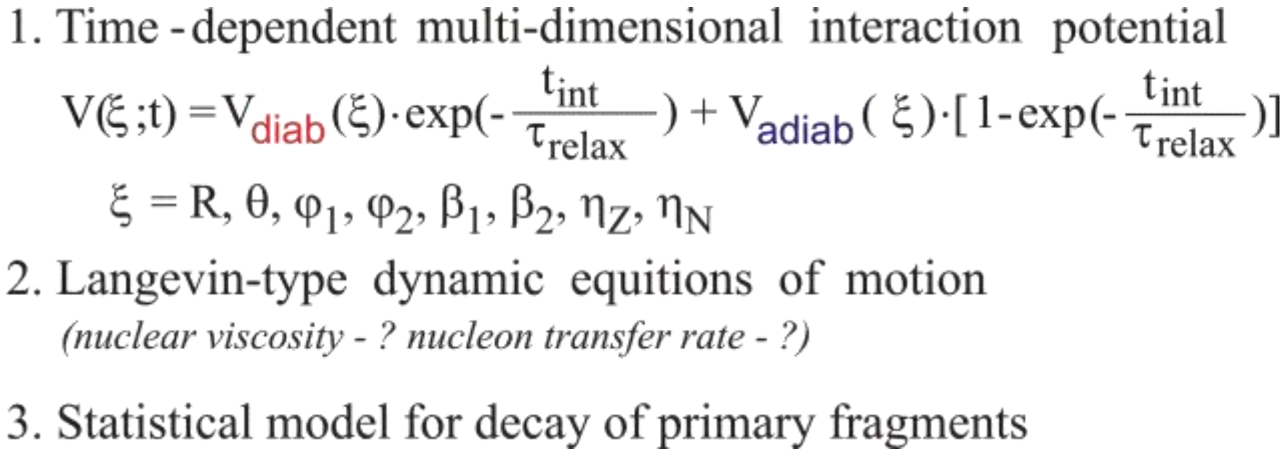


Multi-nucleon transfer reactions in damped collisions of heavy ions for production of heavy neutron rich nuclei

main idea: to get the advantage due to:

(1) Low collision energies

(2) Shell effects



1. Time - dependent multi-dimensional interaction potential

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

$$\xi = R, \theta, \varphi_1, \varphi_2, \beta_1, \beta_2, \eta_Z, \eta_N$$

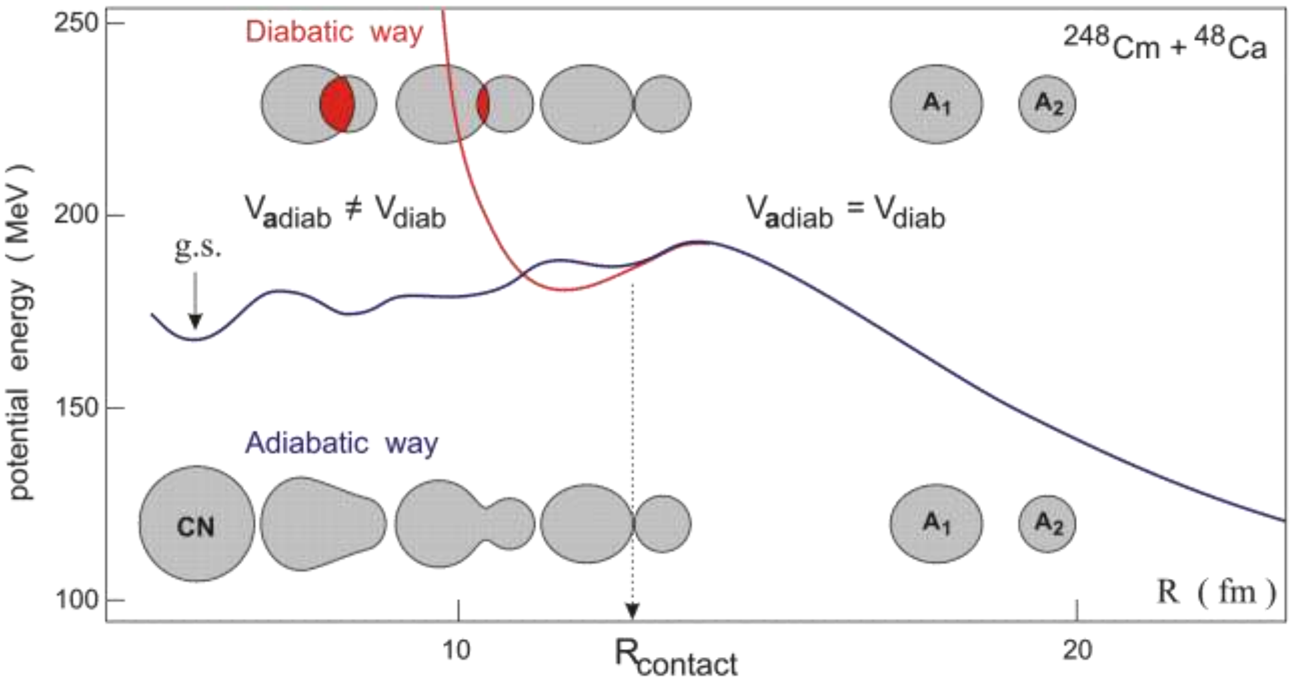
2. Langevin-type dynamic equitions of motion

(nuclear viscosity - ? nucleon transfer rate - ?)

3. Statistical model for decay of primary fragments

Time-dependent Driving Potential

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



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

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*

System of coupled Langevin type Equations of Motion

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

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

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

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

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

$$\frac{d\eta_Z}{dt}=\frac{2}{Z_{\rm CN}}D^{(1)}_{\rm Z}+\frac{2}{Z_{\rm CN}}\sqrt{D^{(2)}_{\rm Z}}\;\Gamma_{\rm Z}(t)$$

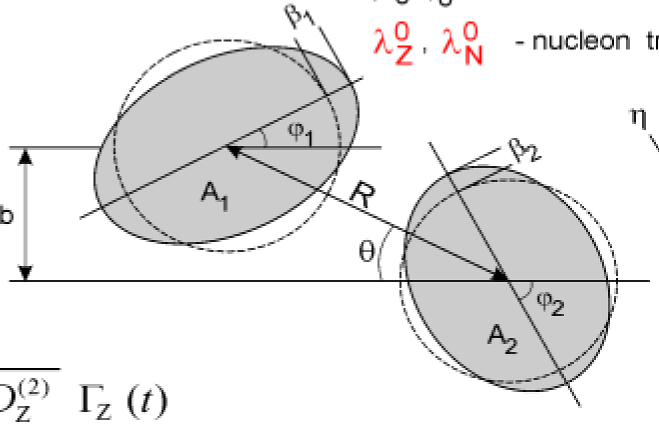
$$\frac{d\eta_N}{dt}=\frac{2}{N_{\rm CN}}D^{(1)}_{\rm N}+\frac{2}{N_{\rm CN}}\sqrt{D^{(2)}_{\rm N}}\;\Gamma_{\rm N}(t)$$

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



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

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

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

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

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

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

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

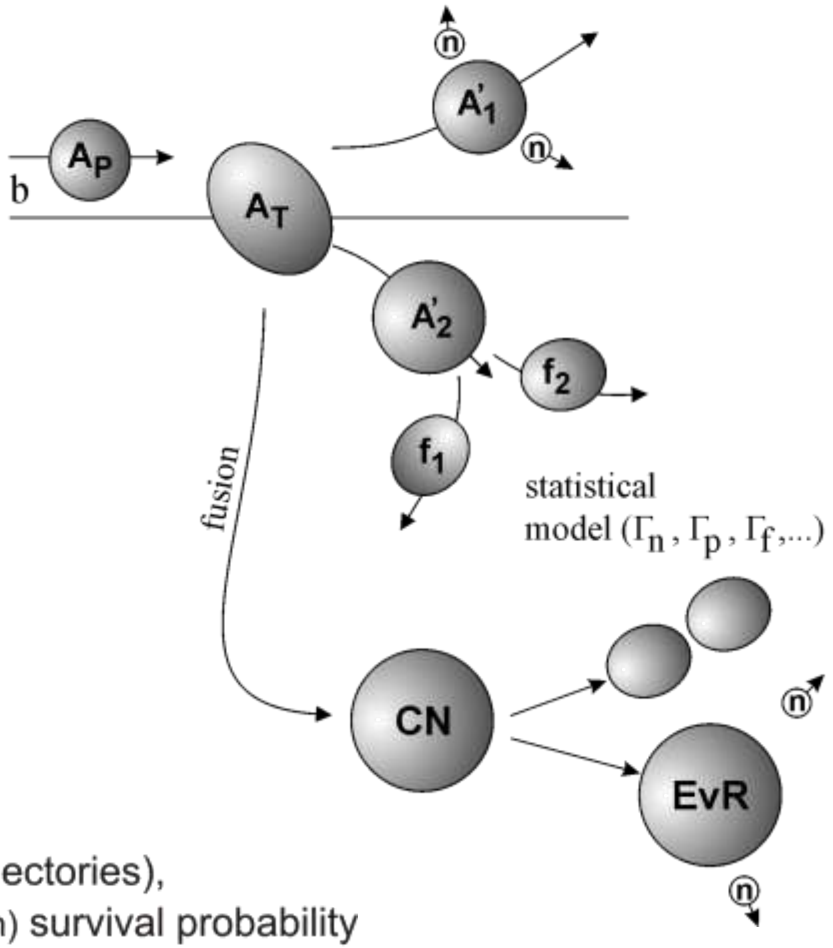
$$\frac{dL_2}{dt}=-\frac{\partial V}{\partial\varphi_2}+\gamma_{\rm tan}\left(\frac{\ell}{\mu_R R}-\frac{L_1}{\Im_1}a_1-\frac{L_2}{\Im_2}a_2\right)a_2-\frac{a_2}{R}\sqrt{\gamma_{\rm tang}T}\,\Gamma_{\rm tang}(t)$$

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

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

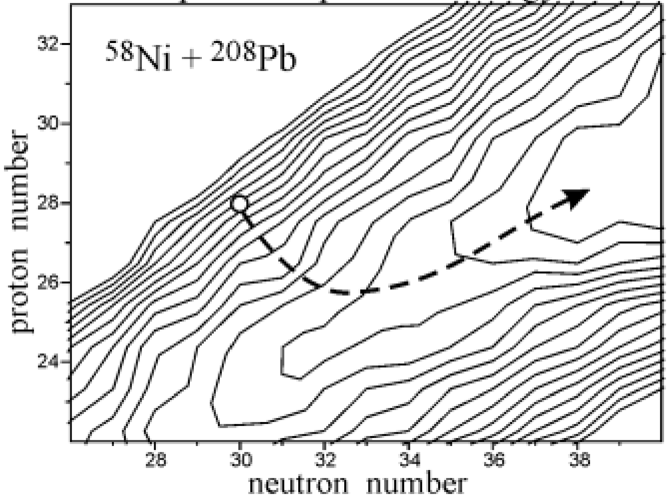
Simulation of experiment and cross sections

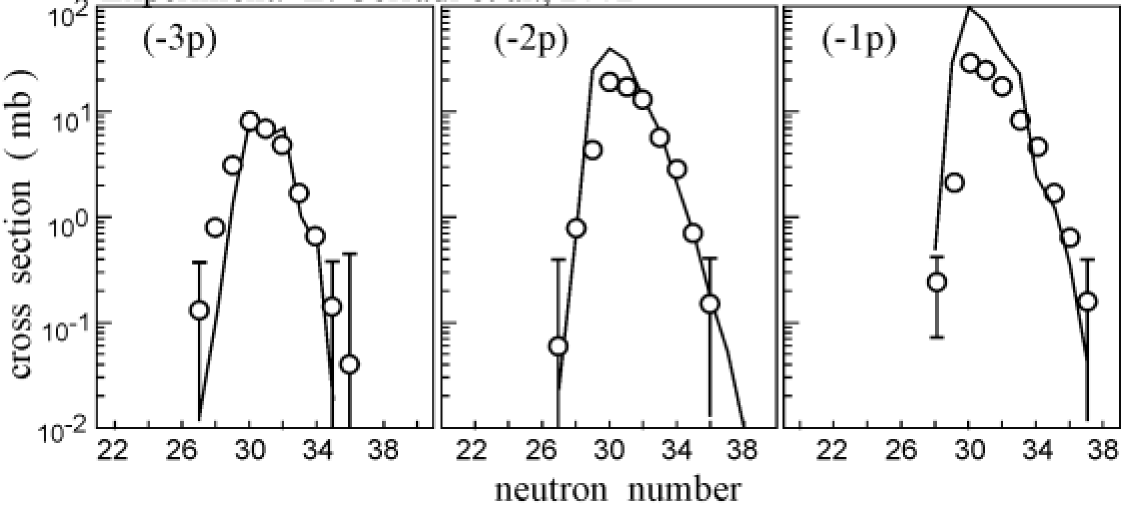
$$\frac{d^2\sigma_{Z,N}}{d\Omega dE}(E,\theta) = \int_0^\infty b\,db \quad \frac{\Delta N_{Z,N}(b,E,\theta)}{N_{tot}(b)} \quad \frac{1}{\sin(\theta)\Delta\theta\Delta E}$$

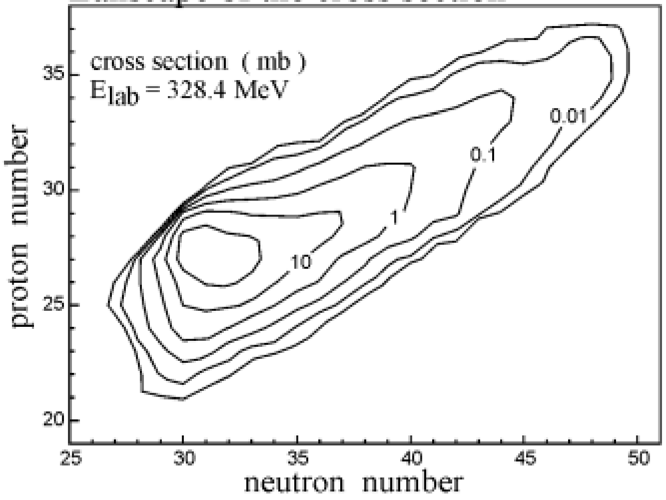


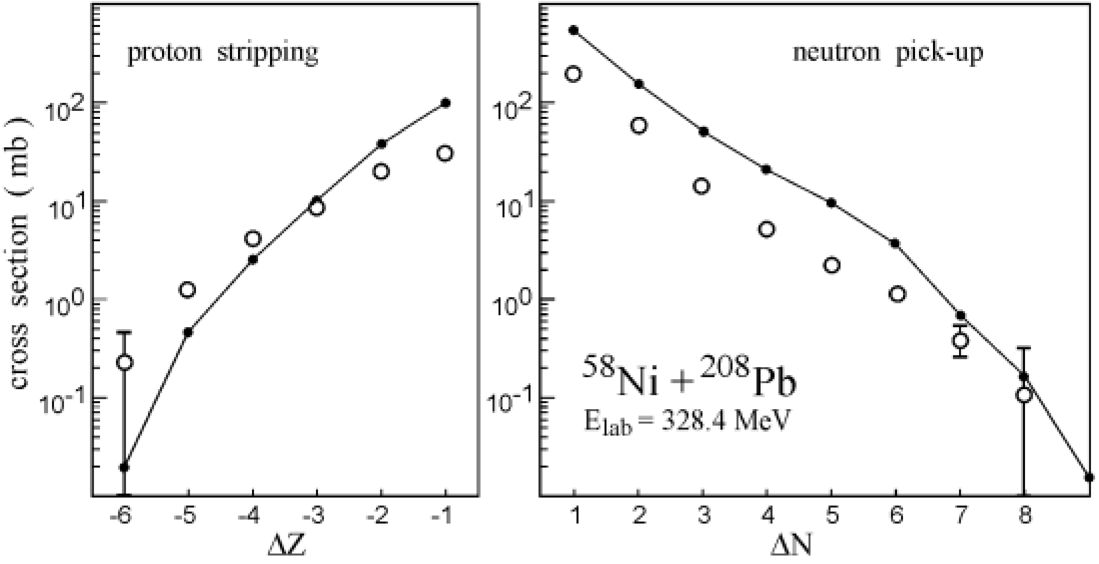
Dynamics: **10^6** tested events (trajectories),
Statistical model: **10^{-6}**(3n), **10^{-7}**(4n) survival probability
cross sections up to **0.1 pb** can be calculated

Comparison with experiment
(few nucleon transfer)


Lanscape of the potential energy

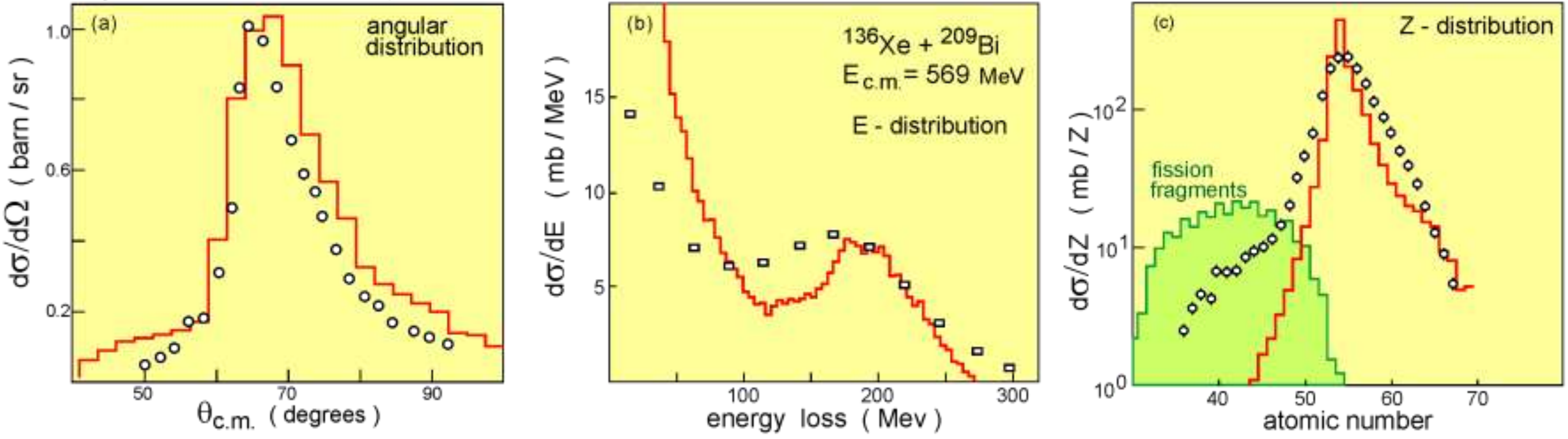

Experiment: L. Corradi et al., 2002

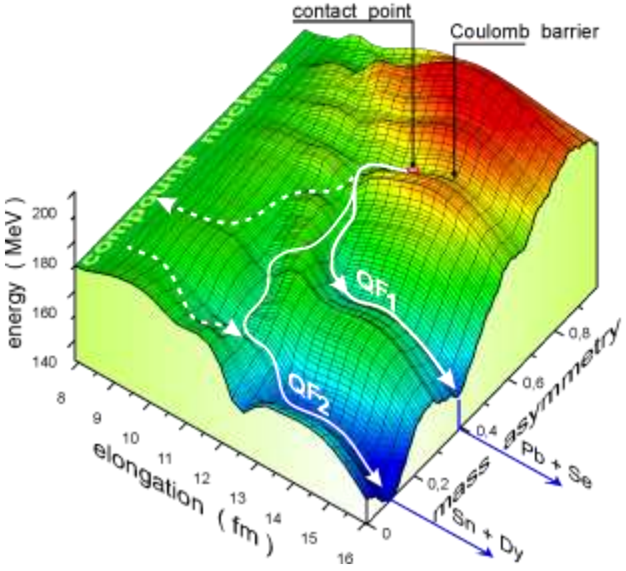

Lanscape of the cross section



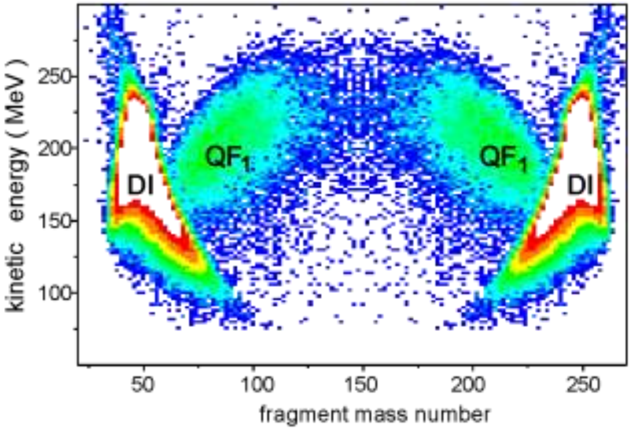
Deep inelastic scattering and quasi-fission phenomena

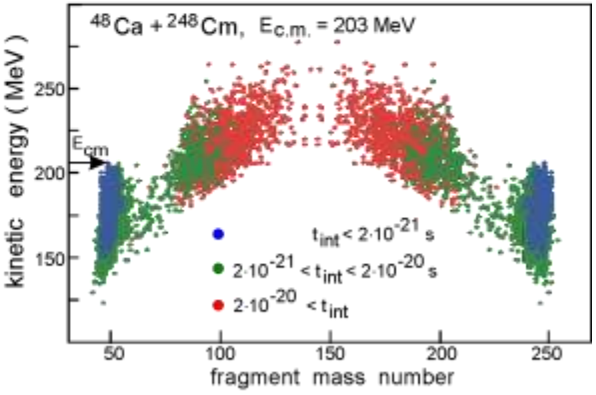
experiment: Wilcke *et al.*, 1980



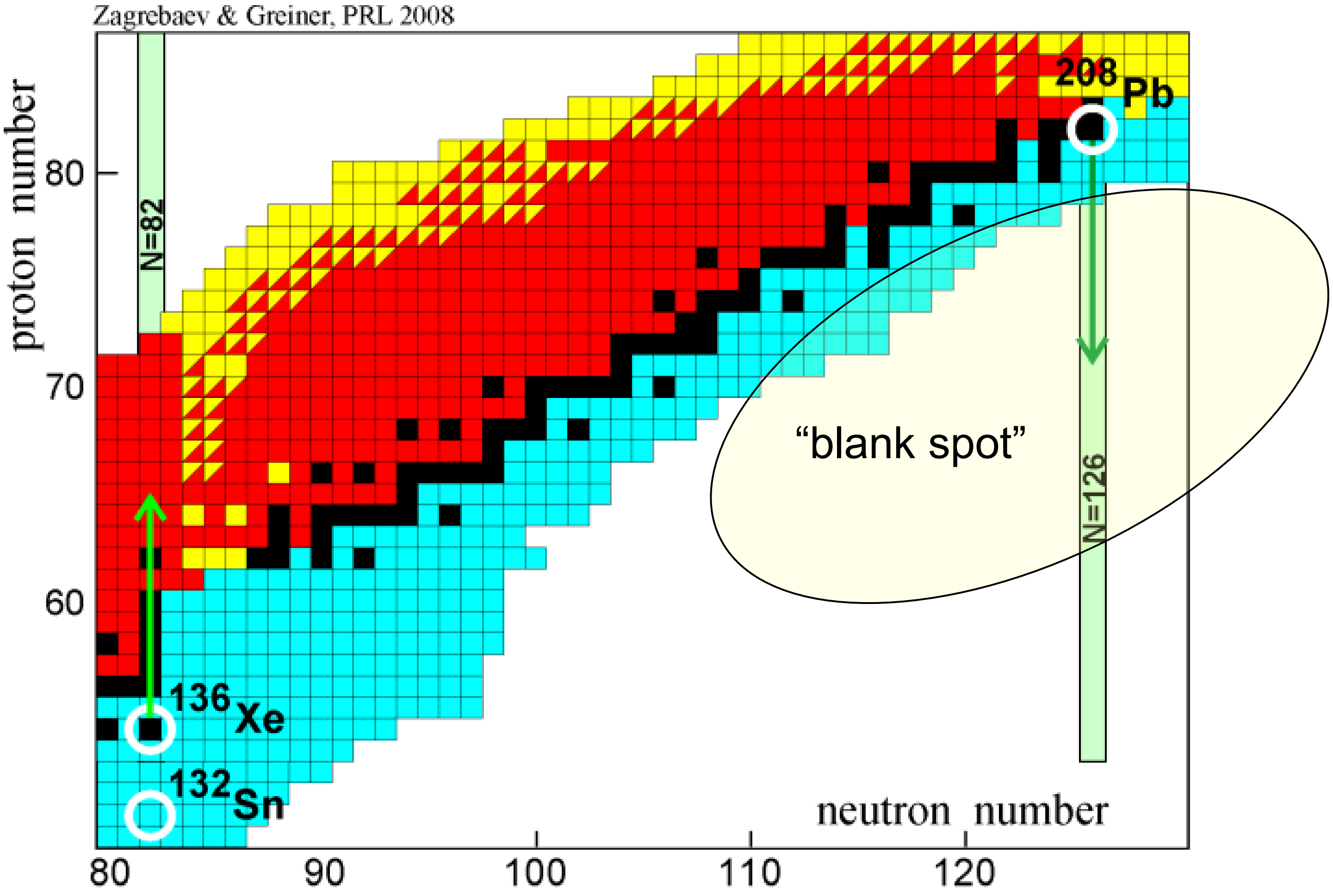


experiment: Itkis *et al.*, 2002





Production on new heavy nuclei in the region of N=126



proton transfer along the neutron closed shells:

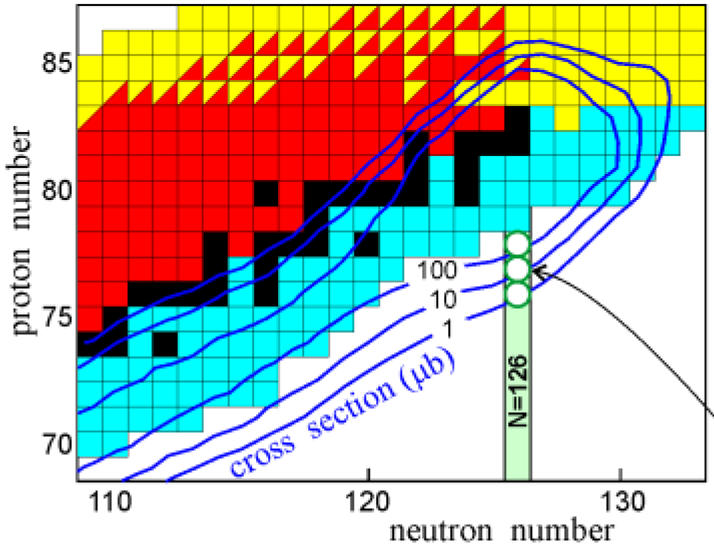
$$^{136}\mathrm{Xe}_{N=82} + {}^{208}\mathrm{Pb}_{N=126} \rightarrow {}^{136+\Delta Z}\mathrm{X}_{N=82} + {}^{208-\Delta Z}\mathrm{Y}_{N=126} + Q \approx 0$$

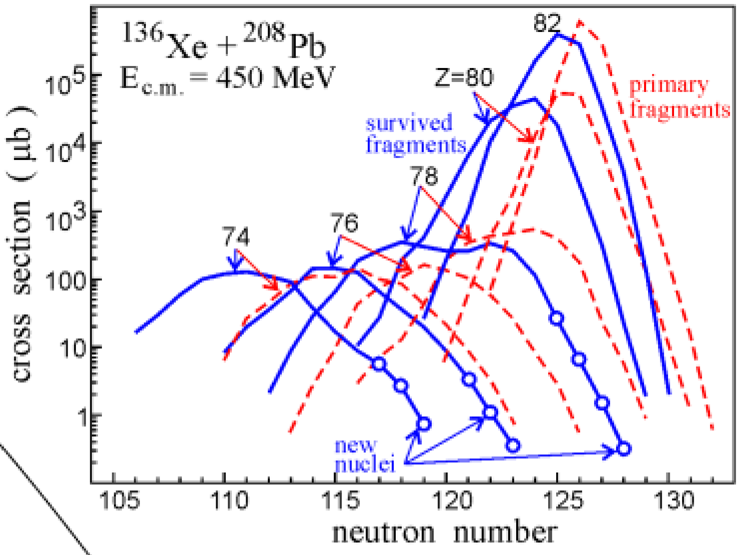
Reactions with $Q \approx 0$ are very favorable for proton transfer

The use of ^{132}Sn is even better !

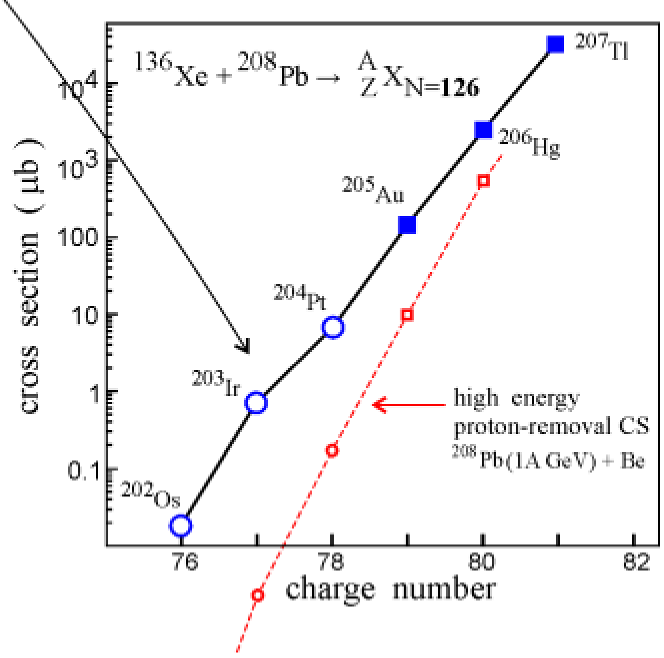
Isotope production
with radioactive beams,
Dasso, Pollarolo, Winther,
PRL 1994

Production on new heavy nuclei in the region of N=126 in the Xe + Pb collisions

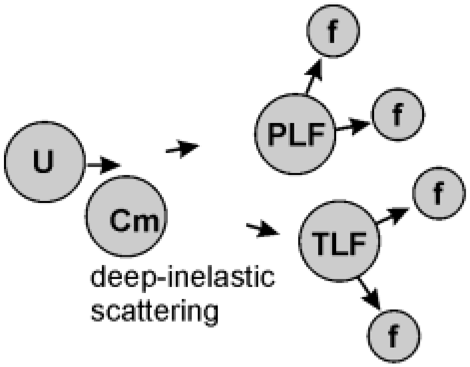


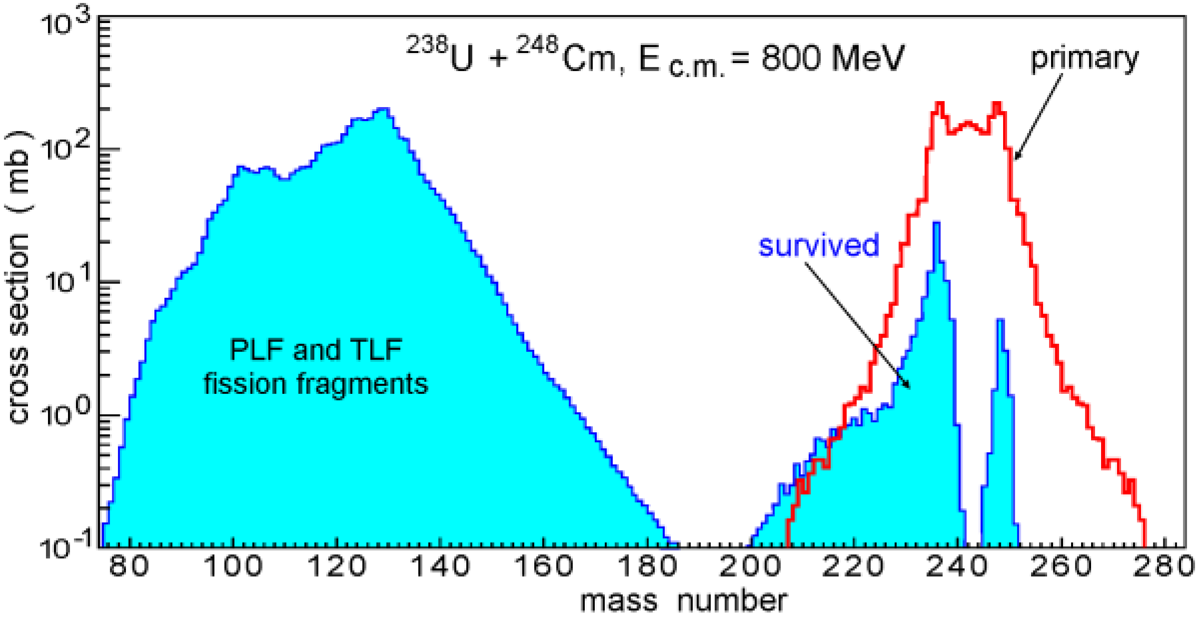


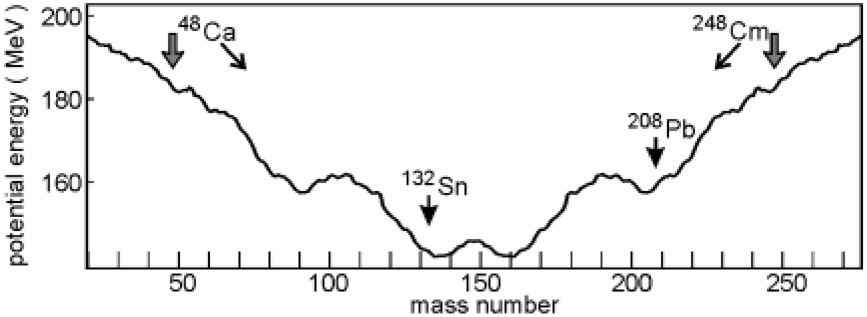
Several tens of new neutron-rich nuclides can be produced with cross section higher than one microbarn in the near-barrier collision of 136Xe with 208Pb



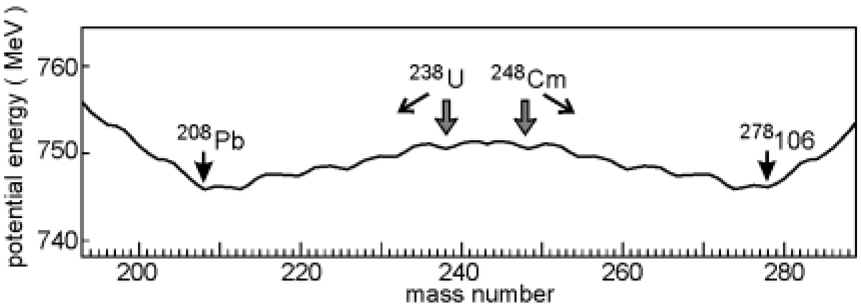
Transfer reactions in damped collision of very heavy nuclei ?





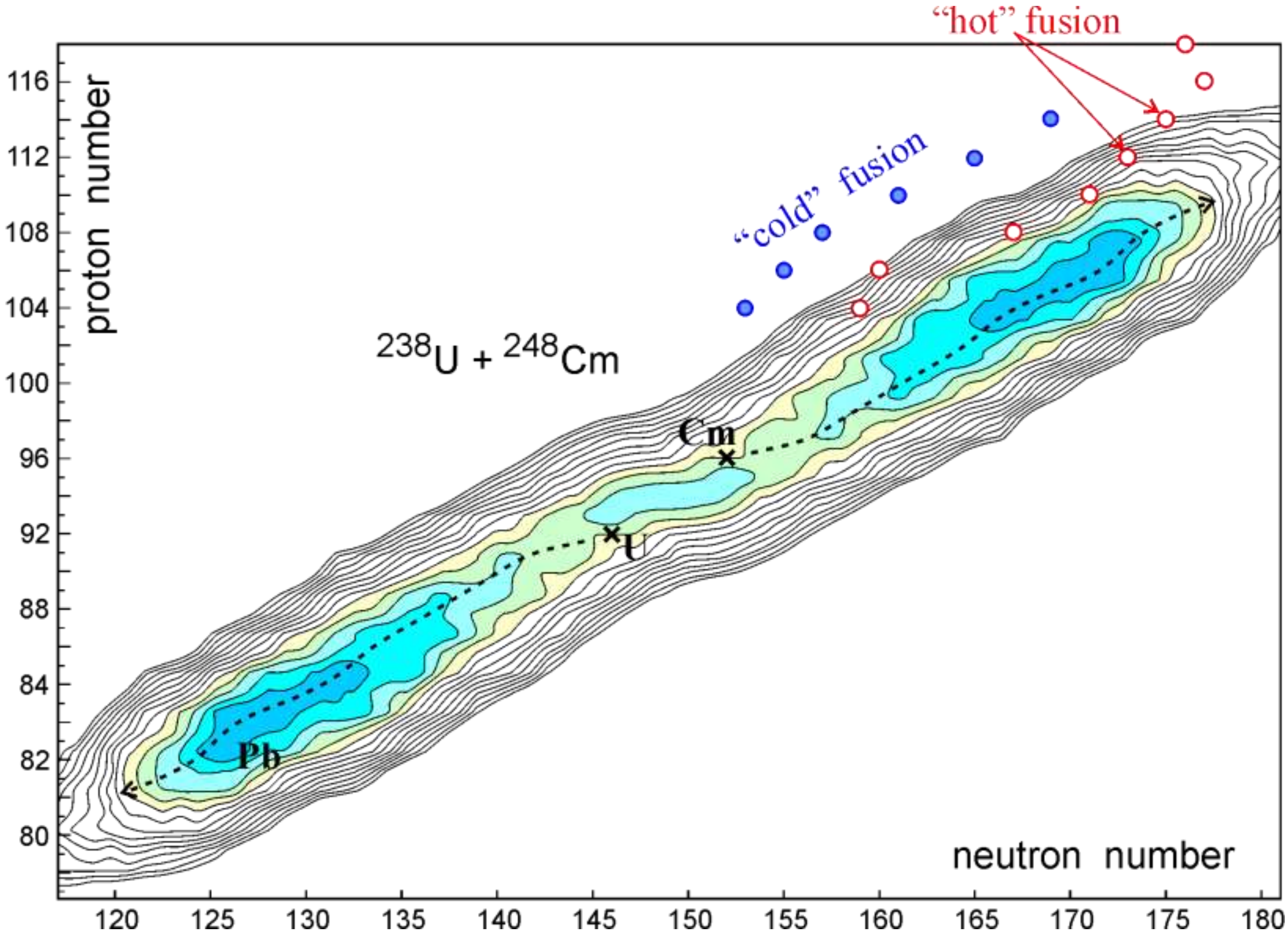


ordinary (symmetrizing) quasi-fission

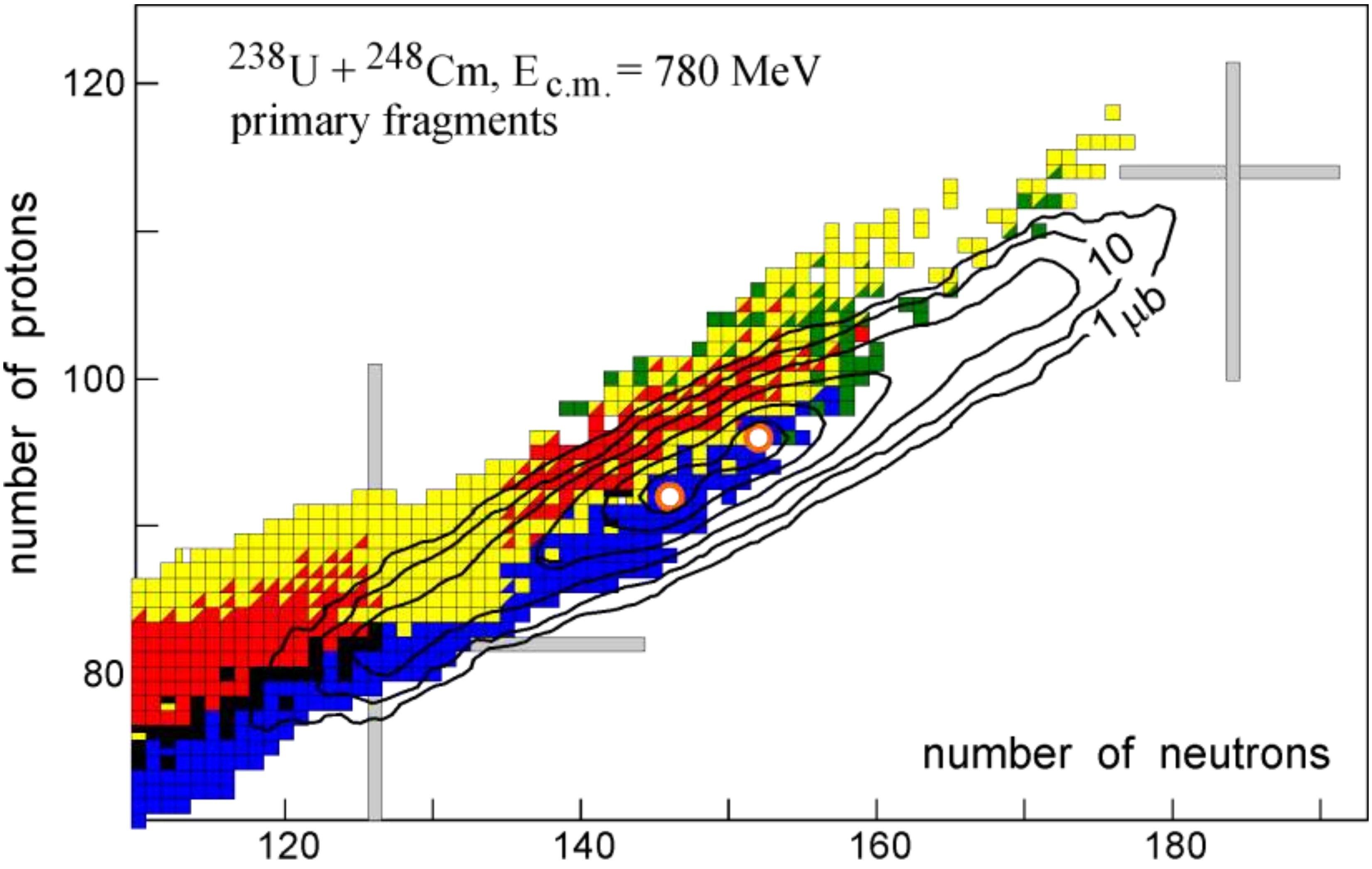


anti-symmetrizing quasi-fission

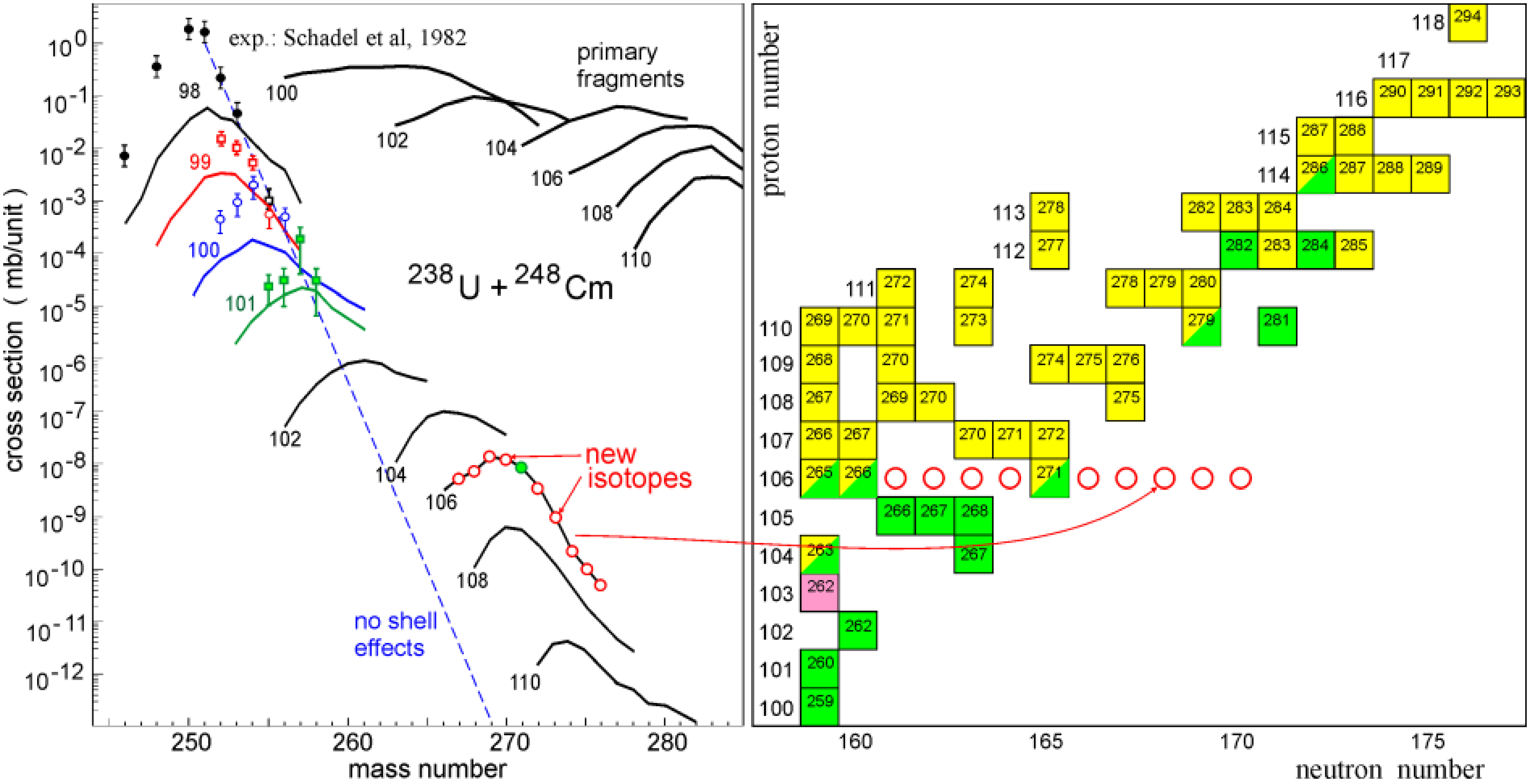
Production of SHE along the stability line in low-energy collisions of actinide nuclei



238U + 248Cm. Primary fragments



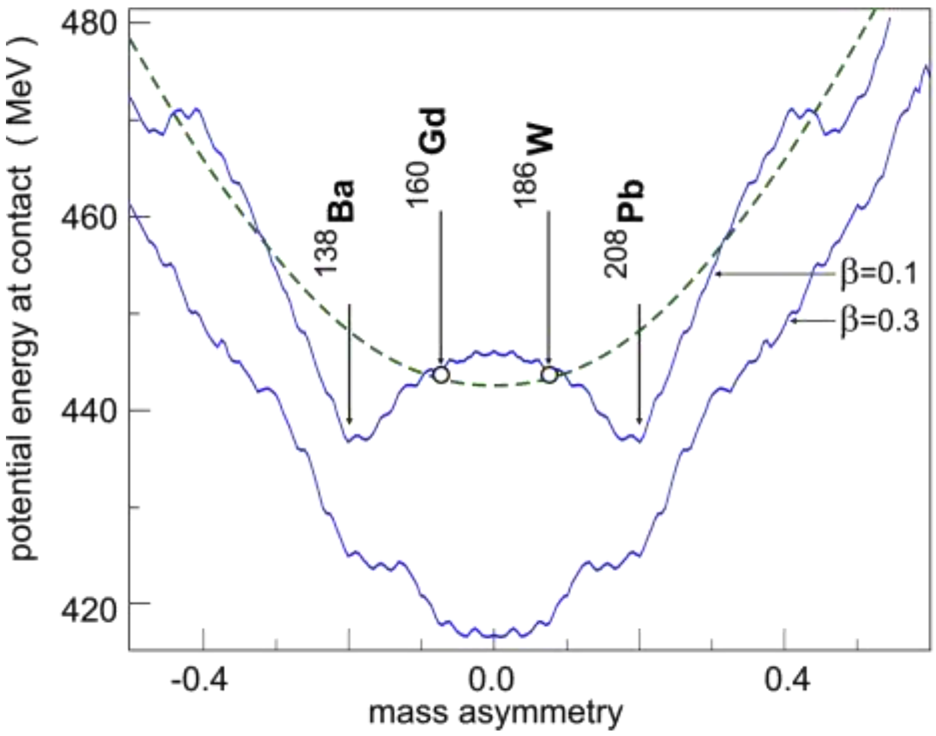
Production of neutron-rich SHE
in low-energy collisions of heavy actinide nuclei

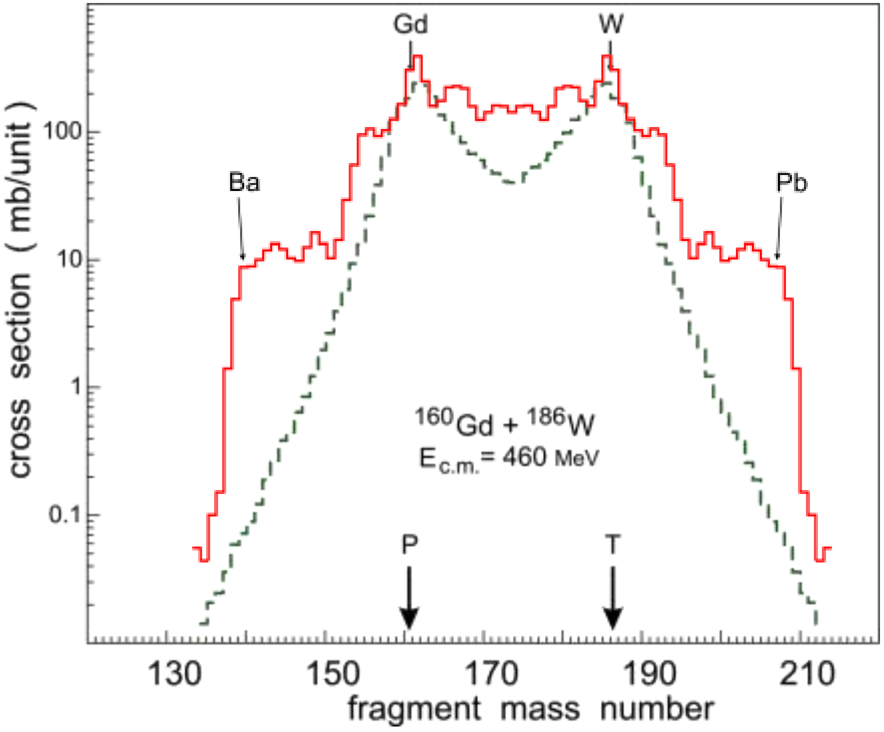


Shell effects in damped collisions

^{160}Gd + ^{186}W

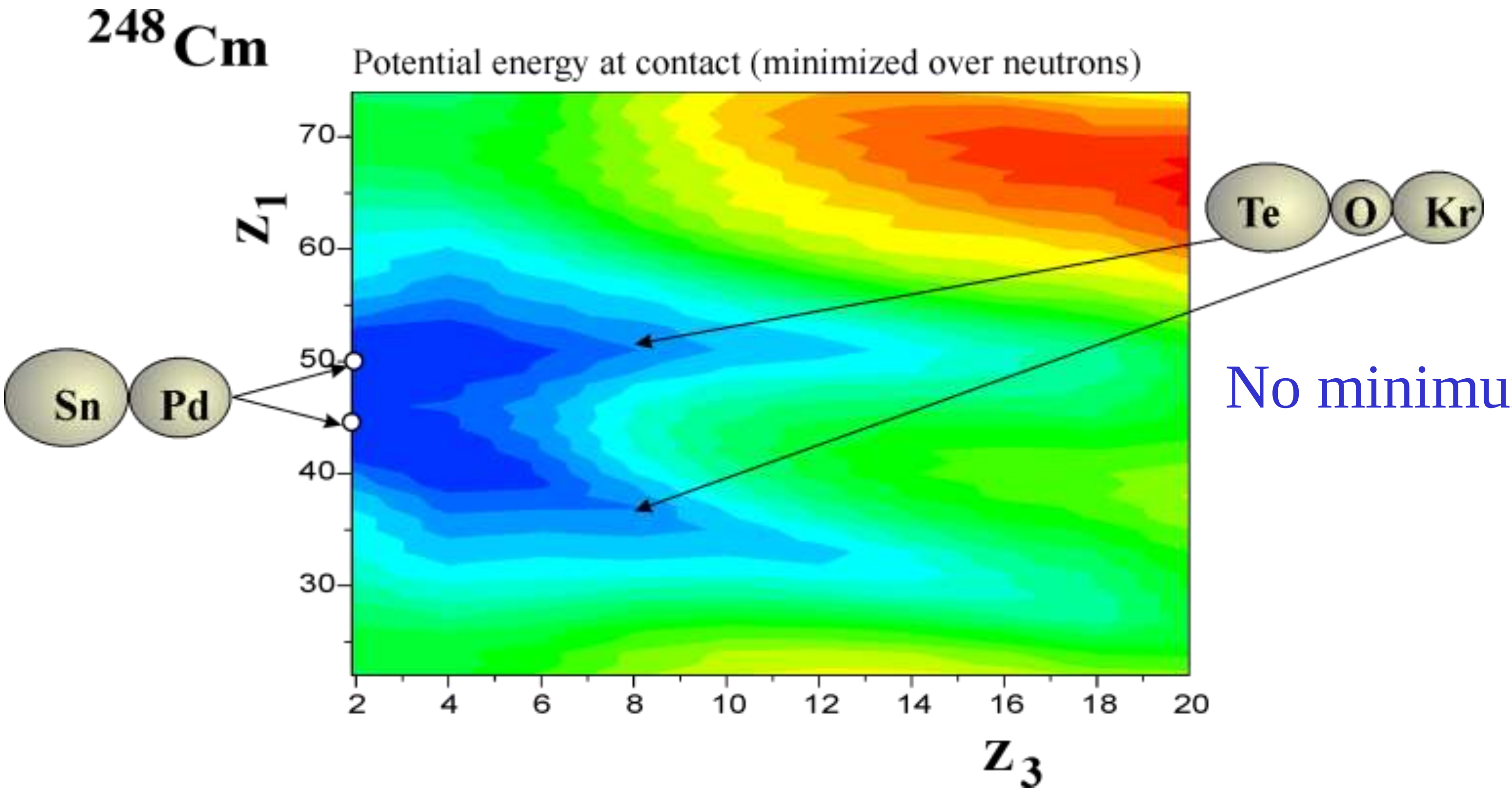
(proposal for test experiment)





3-cluster configurations?

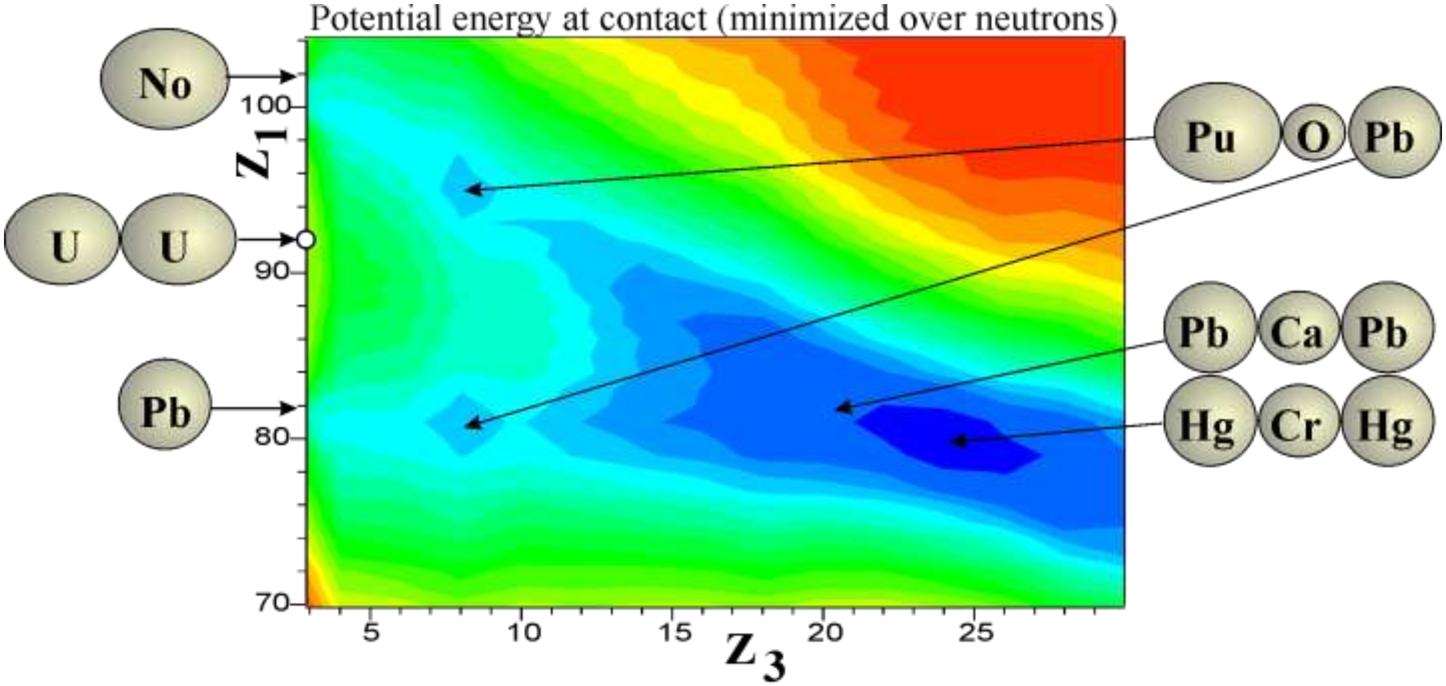
$V(Z_1,Z_2,Z_3;R_{12},R_{13}, \beta_1,\beta_2,\beta_3) = ?$



No minimum

3-cluster configurations and ternary fission of a giant nuclear molecule

$V(Z_1,Z_2,Z_3;R_{12},R_{13},\beta_1,\beta_2,\beta_3) = ?$



proposal for a new experiment
(three-body quasi-fission):

$^{238}U + {}^{238}U \rightarrow Pb + Pb + Ca$

Summary

- **The low-energy multi-nucleon transfer reactions can be used for the production of heavy and superheavy neutron-rich nuclei located at the unexplored "north-east" area of the nuclear map.**

- **Several tens of new neutron-rich isotopes of the elements with $Z = 70 - 80$ (also those located along the closed neutron shell $N = 126$) can be produced in the collision of ^{136}Xe with ^{208}Pb with cross sections higher than one microbarn.**

- **Superheavy neutron-rich nuclei close to the island of stability can be produced in low-energy damped collisions of actinide nuclei (U +Cm).**

- **Three-body clusterization and ternary fission (U+U → Pb+Ca+Pb) might be also discovered in such collisions.**