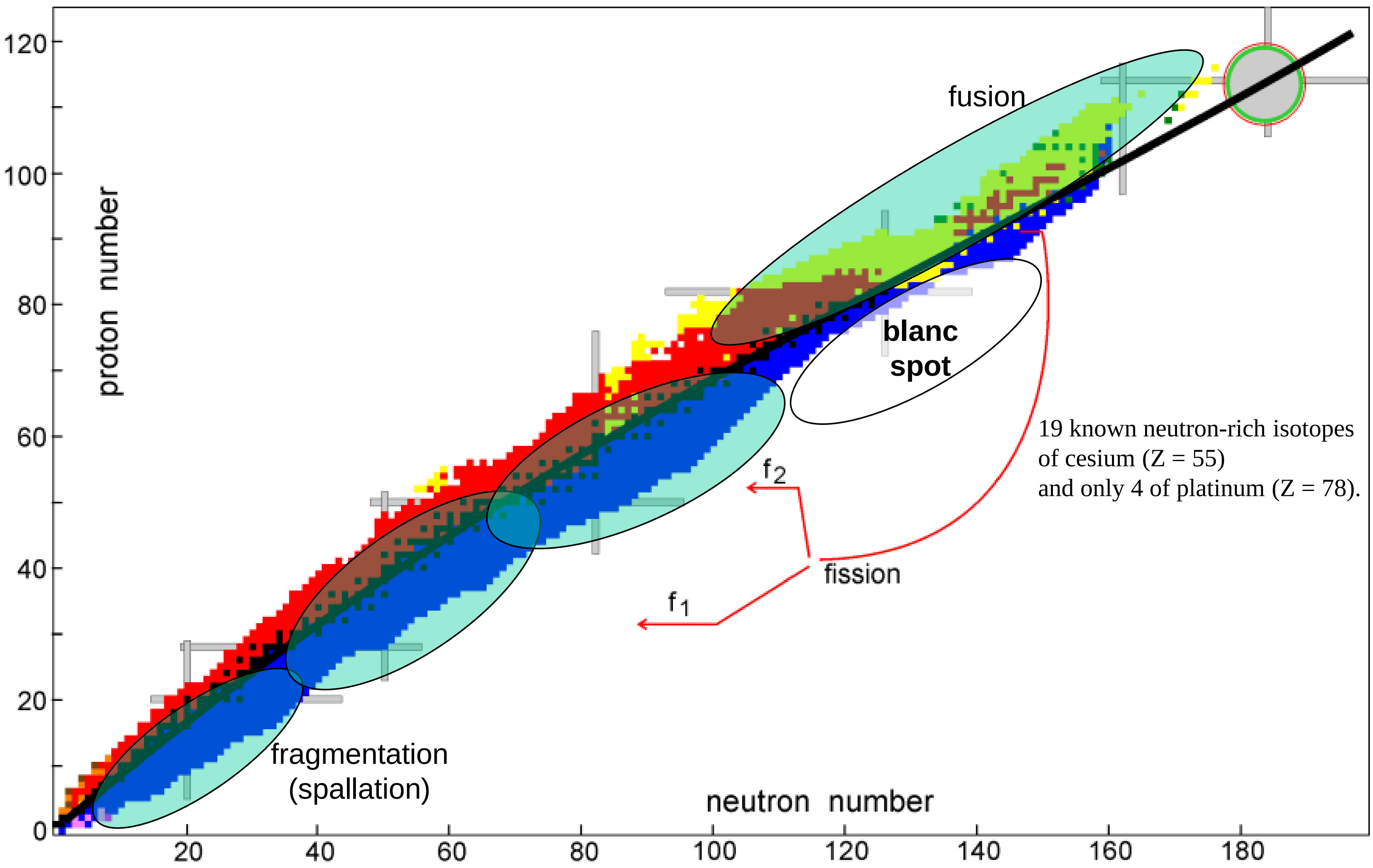
New ideas on the formation of heavy and superheavy neutron rich nuclei

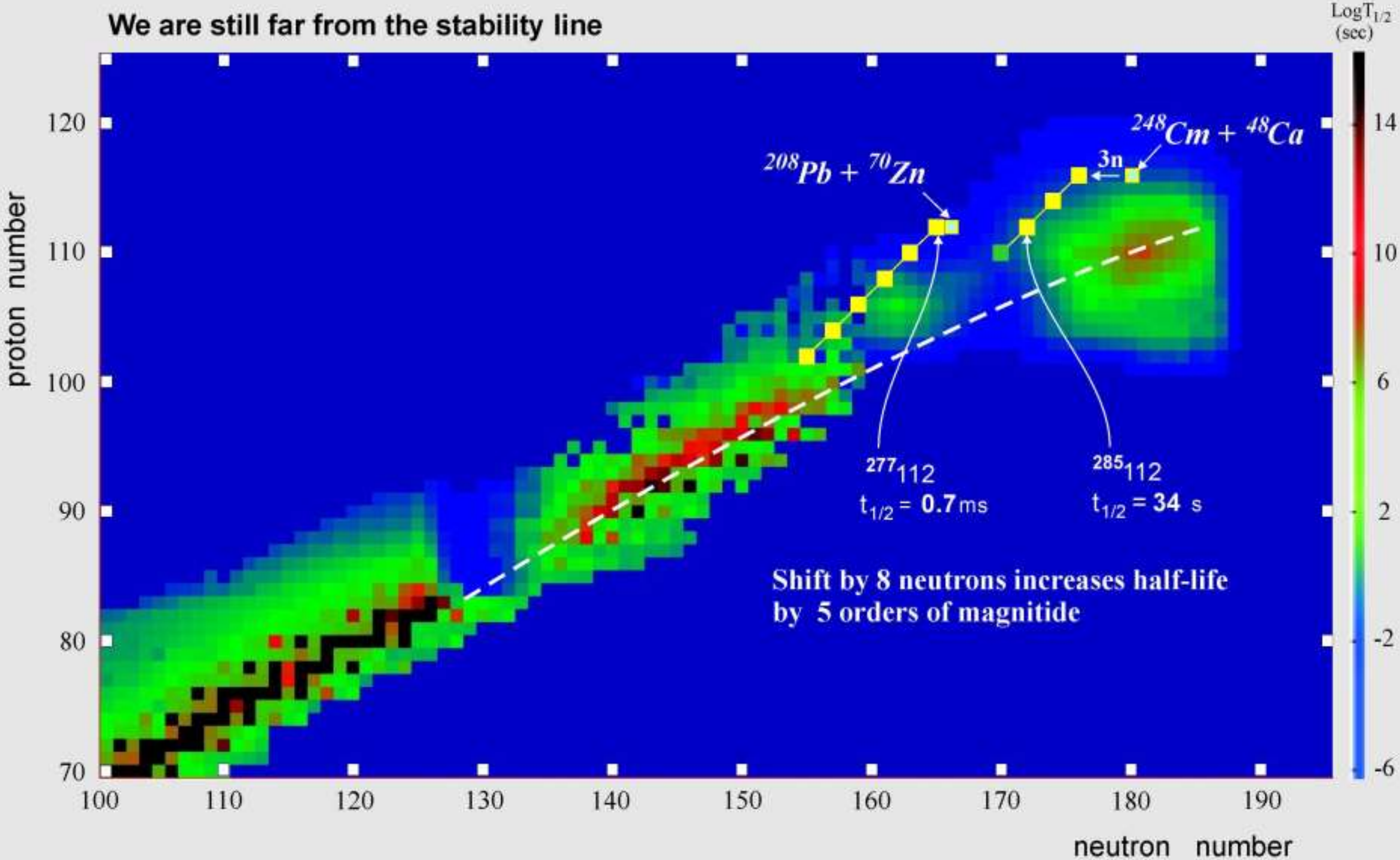
- **Unexplored areas at the “north-east” part of the nuclear map**
- **Use of low-energy multi-nucleon transfer reactions to fill the “blank spots” of the nuclear map**
- **Summary**

Valery Zagrebaev and Walter Greiner for DPG Spring Meeting, Bochum, March 16, 2009

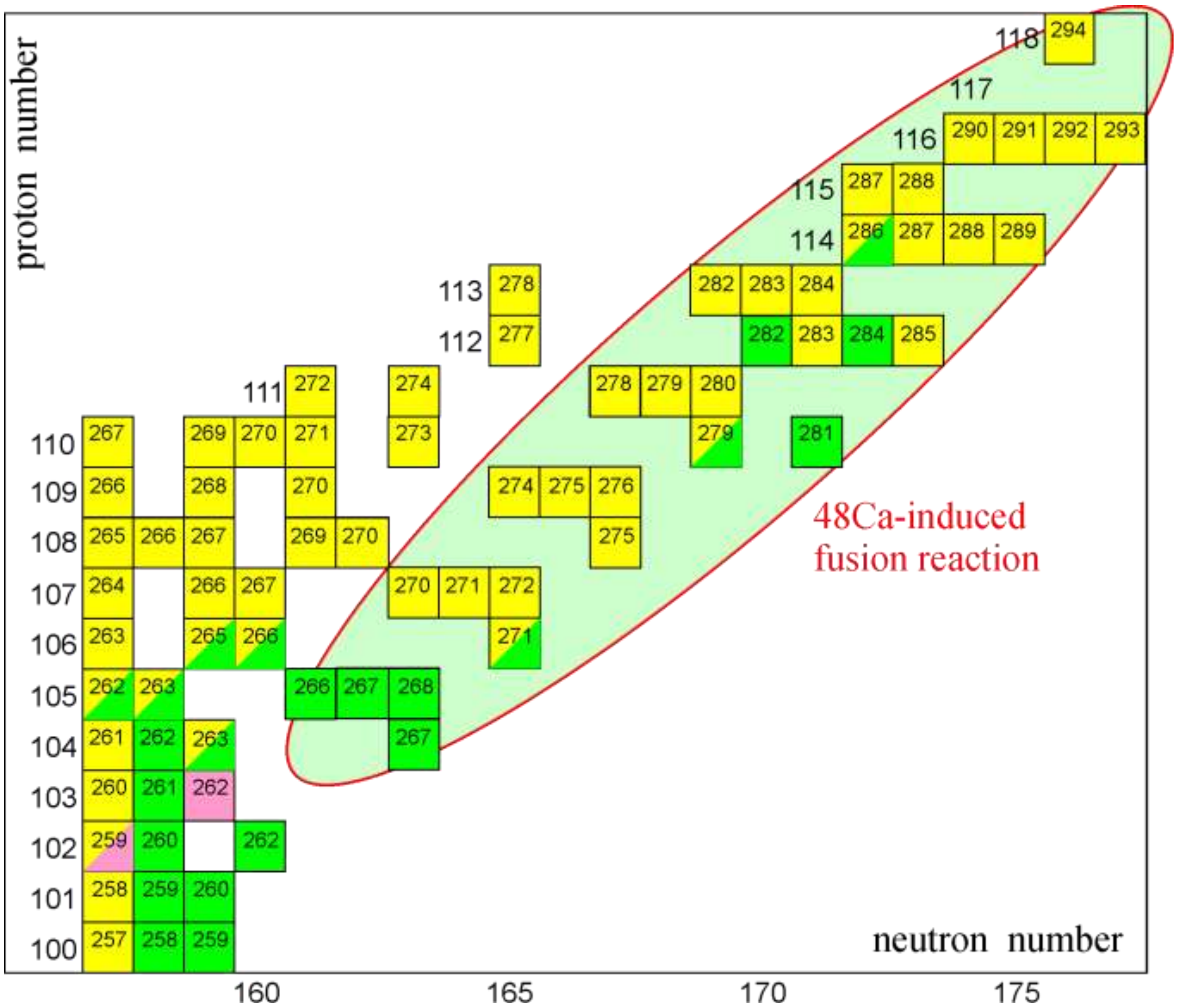
“Blanc Spot” on the Nuclear Map



We are still far from the stability line



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

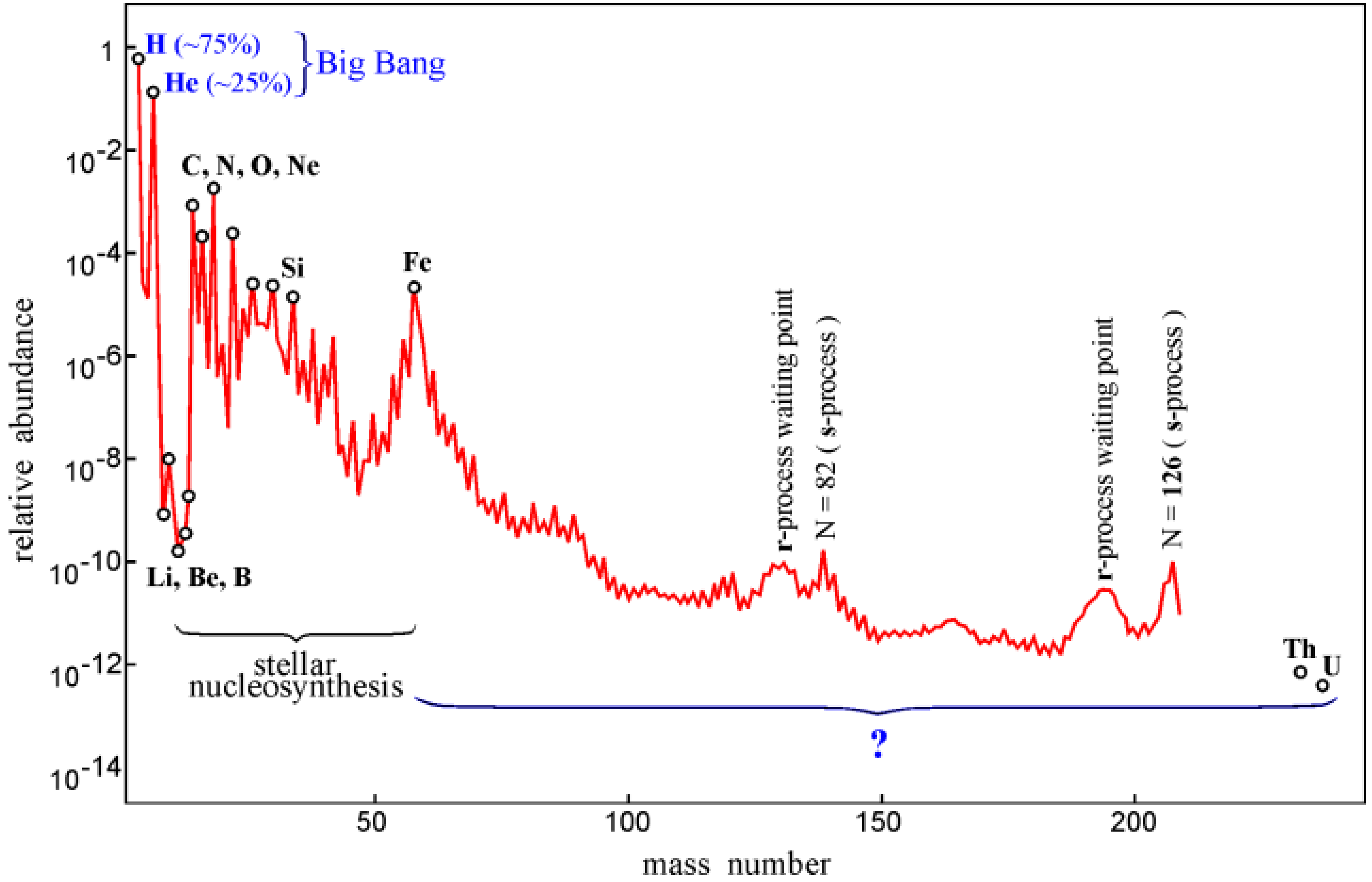


Abundance of elements in the Universe

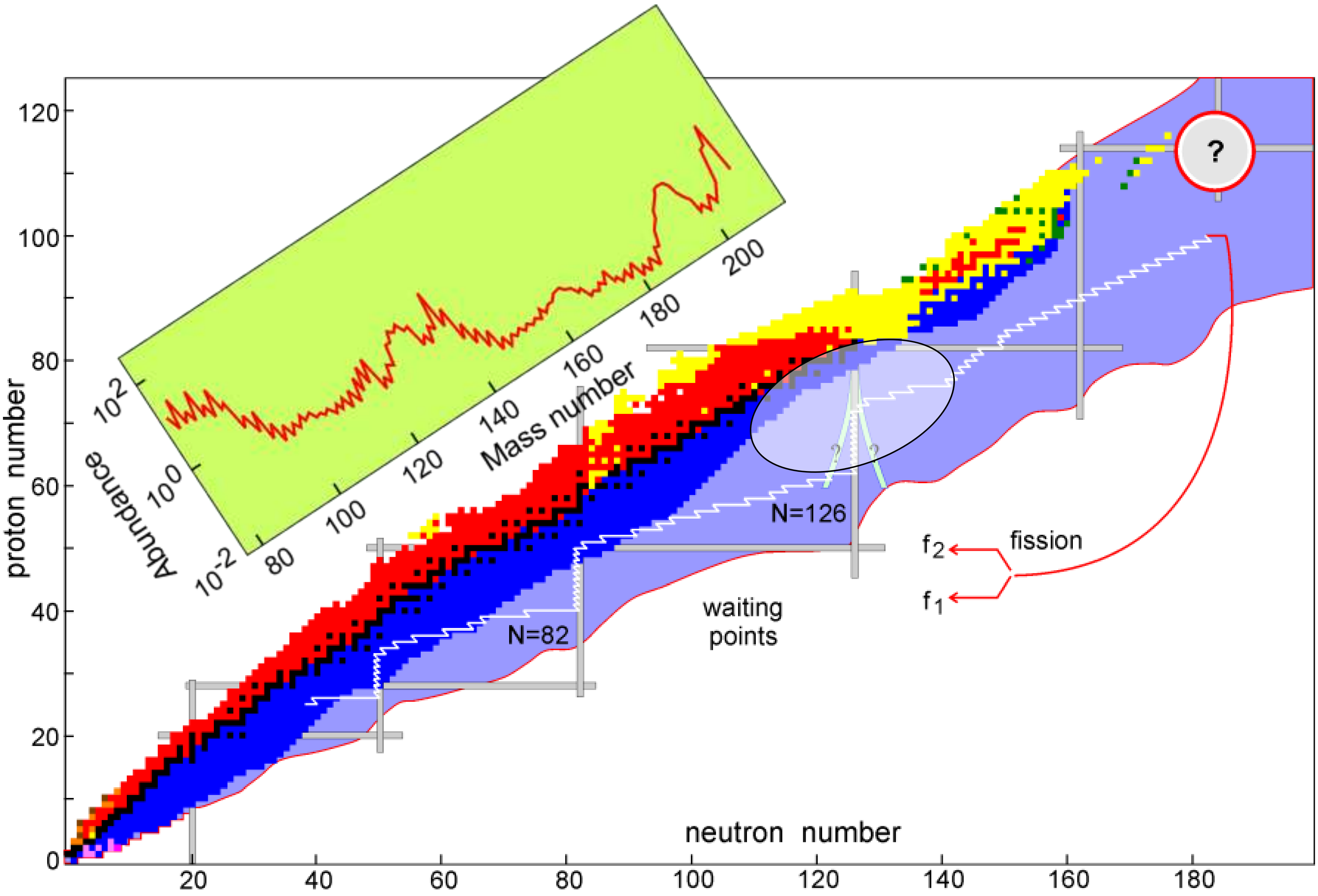
The 11 Greatest Unanswered Questions of Physics
(National Research Council, NAS, USA, 2002):

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?**

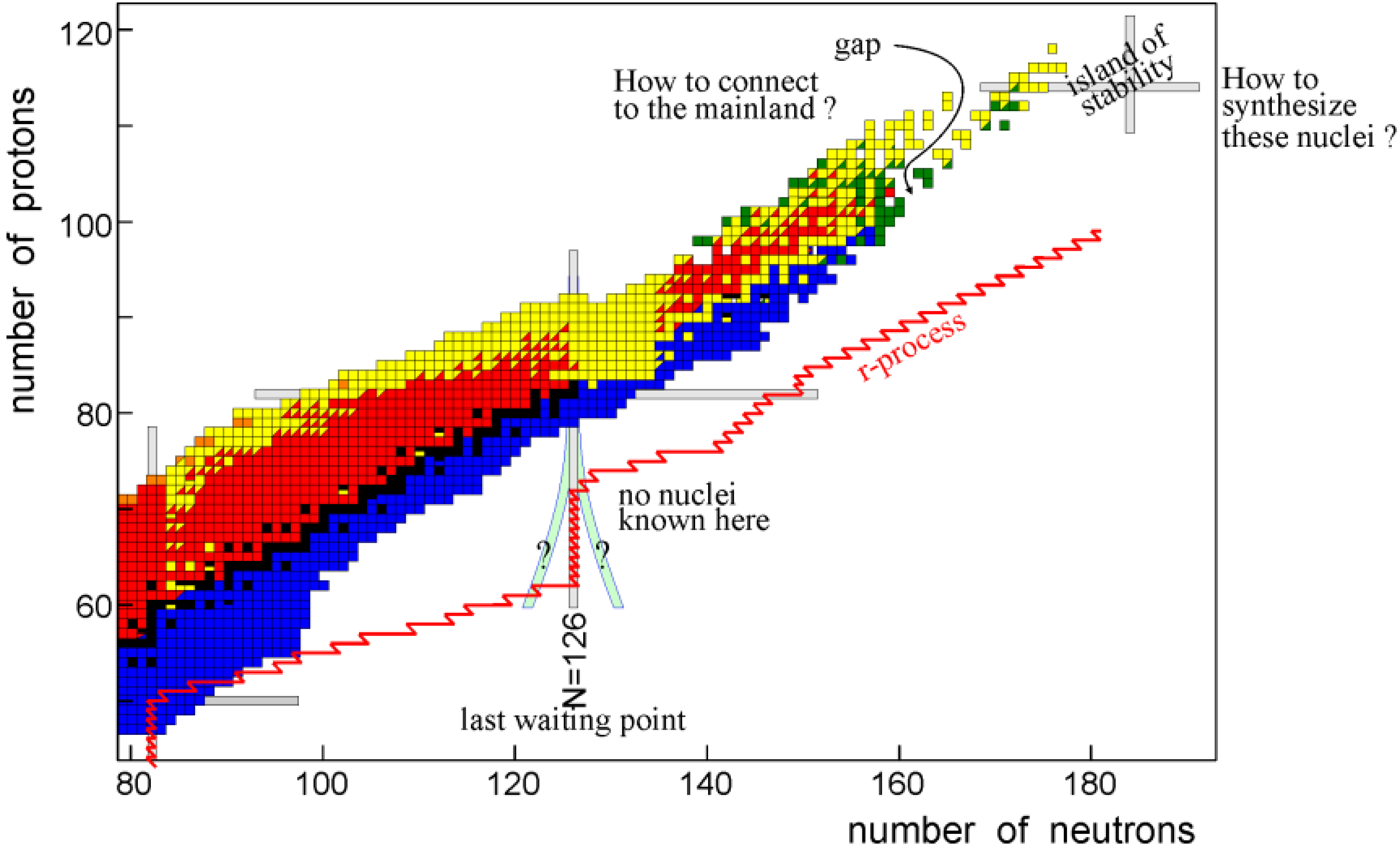
…



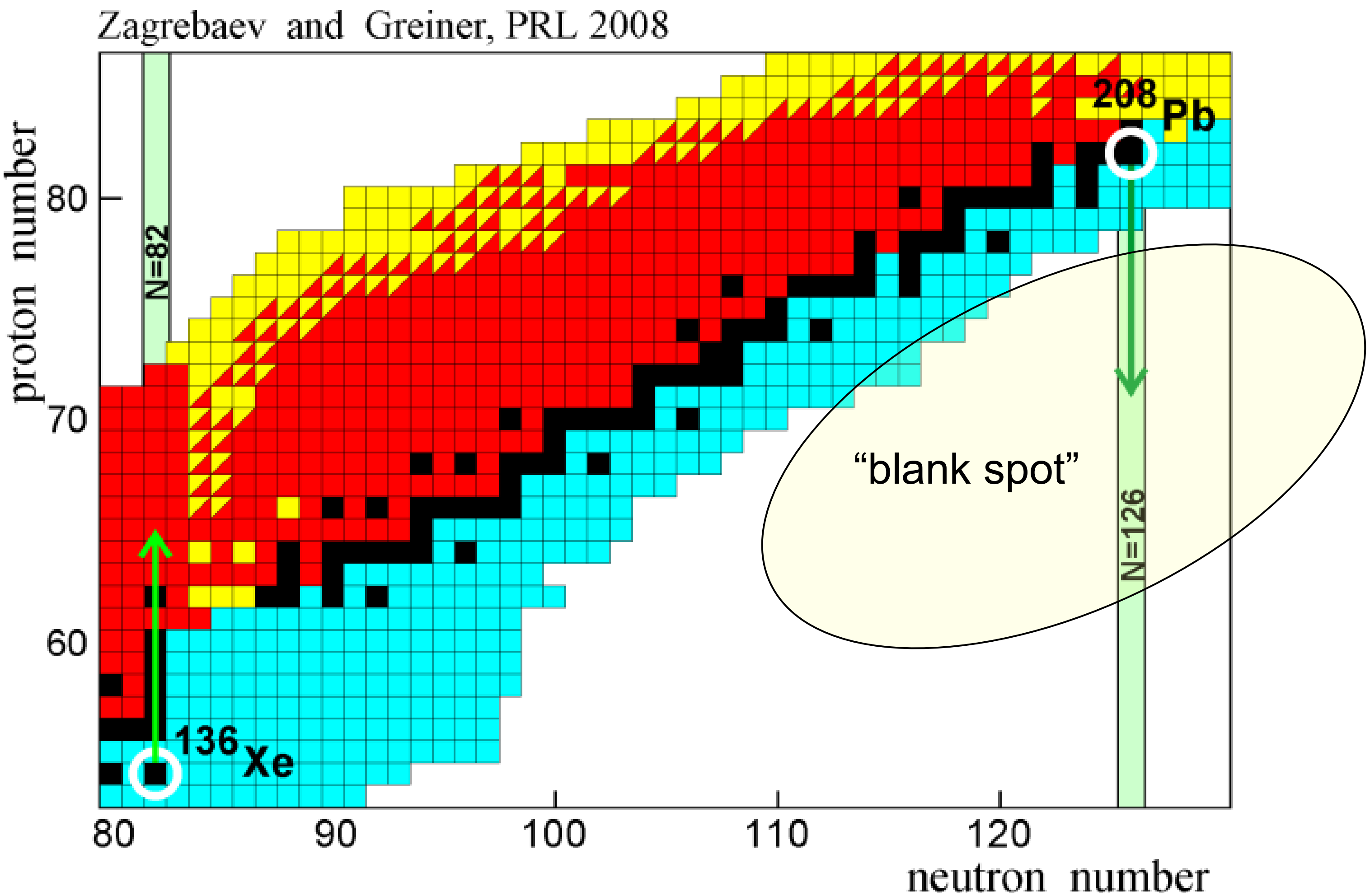
r-process of nucleosynthesis
and the neutron closed shell in the region of N ~ 126



North-east part of the nuclear map



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



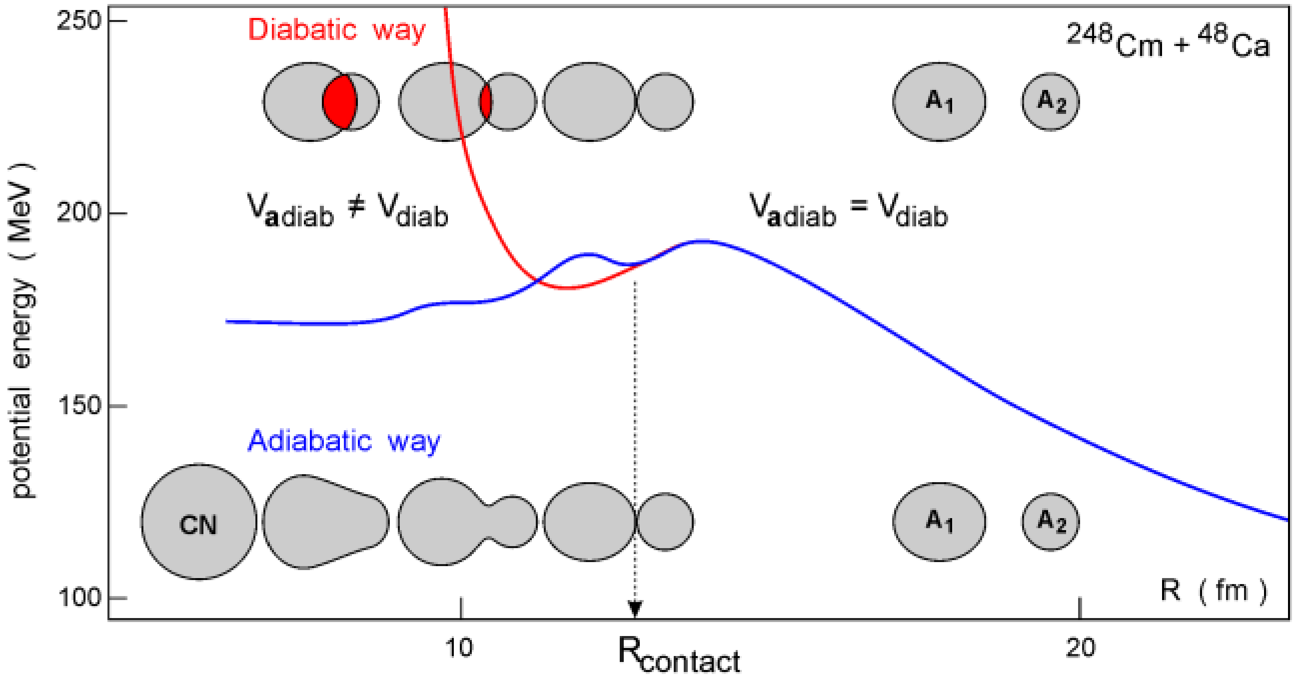
proton transfer along the neutron closed shells:

$$^{136}Xe_{N=82} + {}^{208}Pb_{N=126} \rightarrow {}^{136+\Delta Z}X_{N=82} + {}^{208-\Delta Z}Y_{N=126} + Q \approx 0$$

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

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

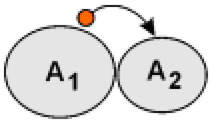
$$V(t) = V_{diab}(\xi)\cdot\exp(-\frac{t_{int}}{\tau_{relax}}) + V_{adiab}(\xi)\cdot[1-\exp(-\frac{t_{int}}{\tau_{relax}})]$$

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

the same degrees of freedom !

All forces, $F_\xi(t) = -\partial V/\partial\xi$, are quite smooth

Nucleon Exchange



$A_1 \to A_1 - 1$
$A_2 \to A_2 + 1$

(L. Moretto, 1974)

Distribution function $\varphi(A_1,t)$ → Master equation

$$\frac{\partial\varphi}{\partial t} = \sum_{A_1'=A_1\pm1} \lambda(A_1' \to A_1)\cdot\varphi(A_1') - \lambda(A_1 \to A_1')\cdot\varphi(A_1)$$

$$\frac{\partial\varphi}{\partial t} = -\frac{\partial}{\partial A_1}\left(D^{(1)}\varphi\right) + \frac{\partial^2}{\partial A_1^2}\left(D^{(2)}\varphi\right)$$

Fokker - Planck
(W. Nörenberg, 1974)

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

Langevin type eq.

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

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

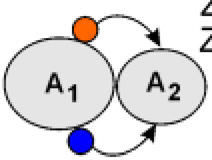
at $A' = A \pm 1$

$$D^{(1)} = \lambda(A_1 \to A_1+1) - \lambda(A_1 \to A_1-1)$$

$$D^{(2)} = \frac{1}{2}[\lambda(A_1 \to A_1+1) + \lambda(A_1 \to A_1-1)]$$

transition probability

$$\lambda^{(\pm)} = \lambda_0\sqrt{\frac{\rho(A\pm1)}{\rho(A)}}P_{tr}(R; A \to A\pm1), \quad \rho \sim exp(2\sqrt{aE^*}), \quad E^* = E_{c.m.} - V(R,\beta_1,\beta_2,\eta)$$



$Z_1 \to Z_1 - 1$
$Z_2 \to Z_2 + 1$

$N_1 \to N_1 - 1$
$N_2 \to N_2 + 1$

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

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

$$D_{N,Z}^{(1)} = \lambda_{N,Z}(A \to A+1) - \lambda_{N,Z}(A \to A-1)$$

$$D_{N,Z}^{(2)} = \frac{1}{2}[\lambda_{N,Z}(A \to A+1) + \lambda_{N,Z}(A \to A-1)]$$

$$\lambda_{N,Z}^{(\pm)} = \lambda_{N,Z}^0\sqrt{\frac{\rho(A\pm1)}{\rho(A)}}P_{tr}(R; A \to A\pm1)$$

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

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

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

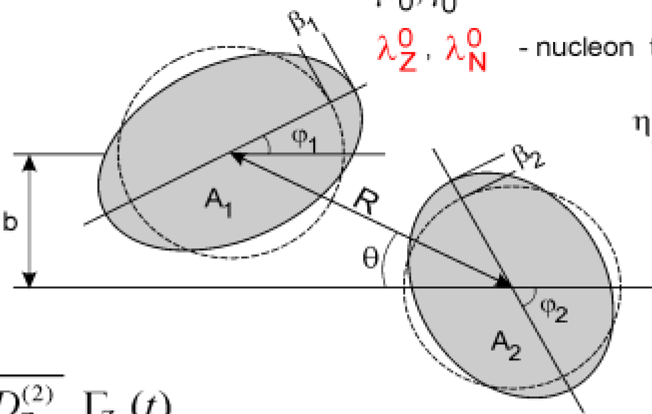
$$\frac{d\varphi_1}{dt} = \frac{L_1}{\Im_1}, \quad \frac{d\varphi_2}{dt} = \frac{L_2}{\Im_2}$$

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

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

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

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



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

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

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

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

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

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

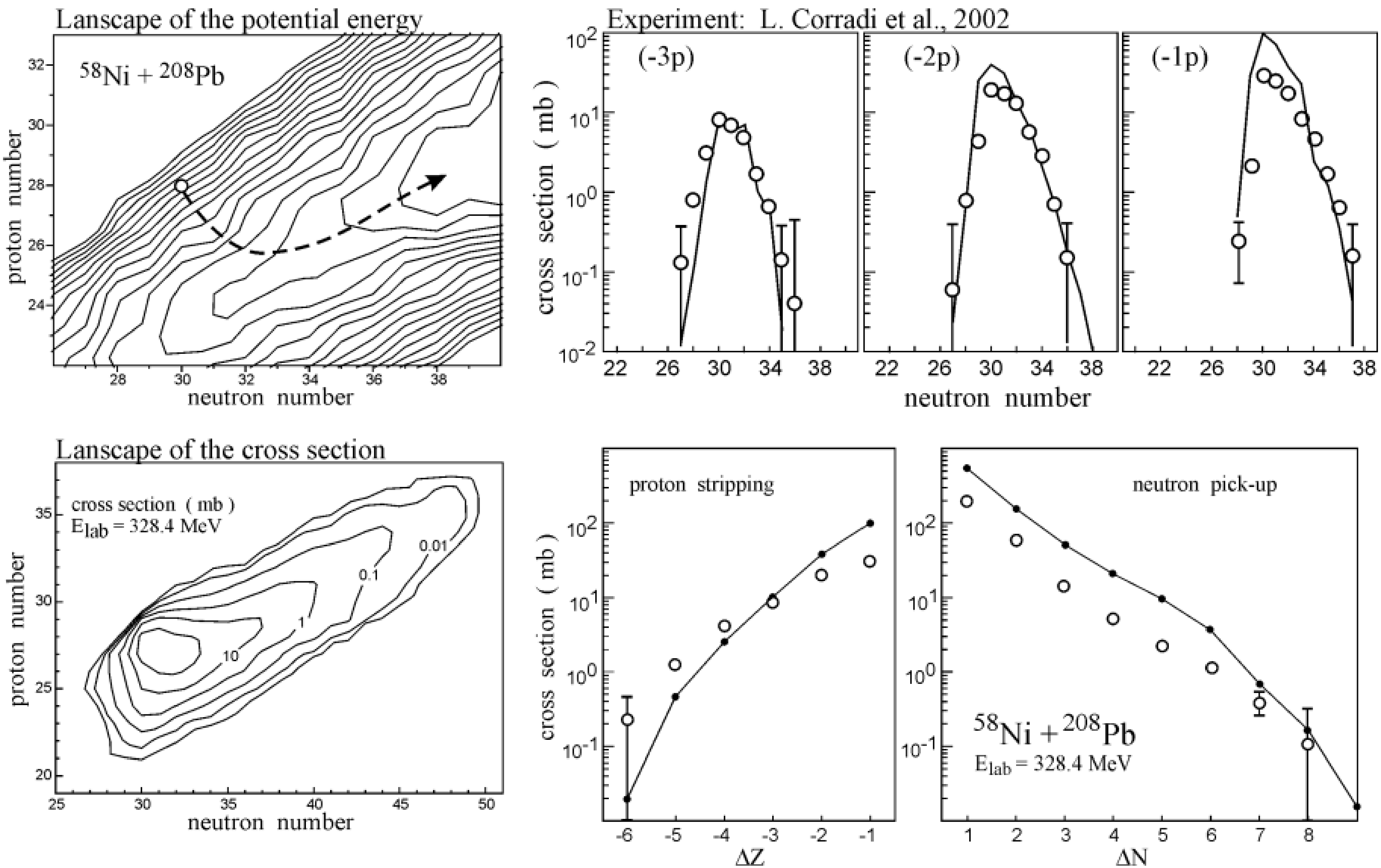
$$\frac{dL_1}{dt} = -\frac{\partial V}{\partial \varphi_1} + \gamma_{\text{tang}}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) a_1 - \frac{a_1}{R}\sqrt{\gamma_{\text{tang}} T}\,\Gamma_{\text{tang}}(t)$$

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

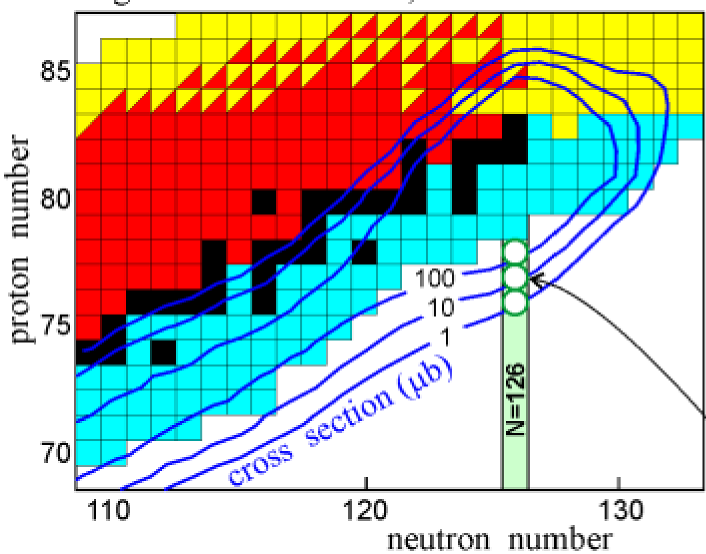
$$\frac{dp_{\beta 1}}{dt} = -\frac{\partial V}{\partial \beta_1} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial \beta_1} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial \beta_1} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial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

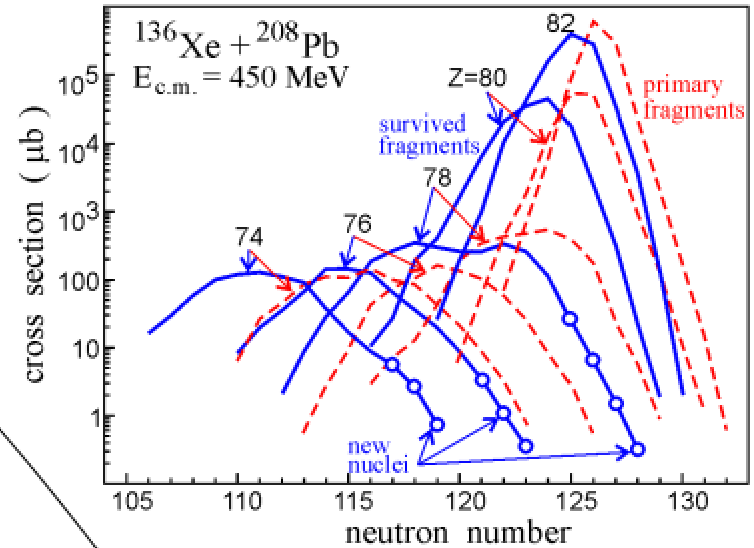
$$\frac{dp_{\beta 2}}{dt} = -\frac{\partial V}{\partial \beta_2} + \frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial \mu_{\beta 1}}{\partial \beta_2} + \frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial \mu_{\beta 2}}{\partial \beta_2} + \left(\frac{\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial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

Comparison with experiment on multi-nucleon transfer

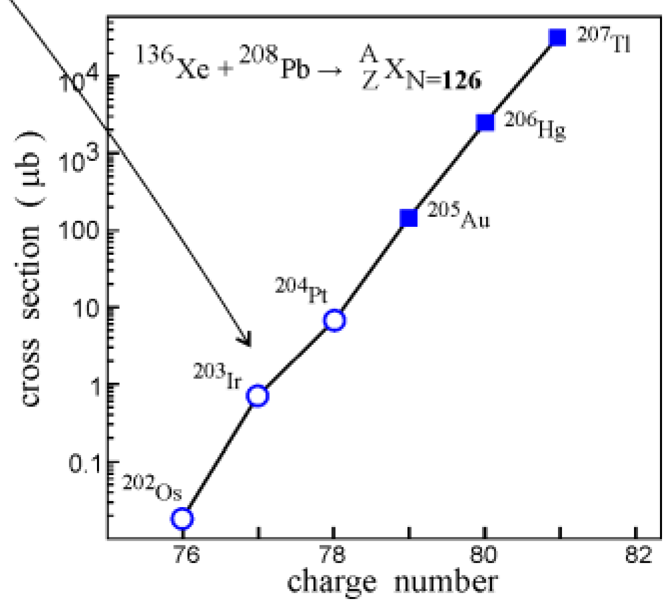


Production on new heavy nuclei in the region of N=126 in the Xe + Pb collisions

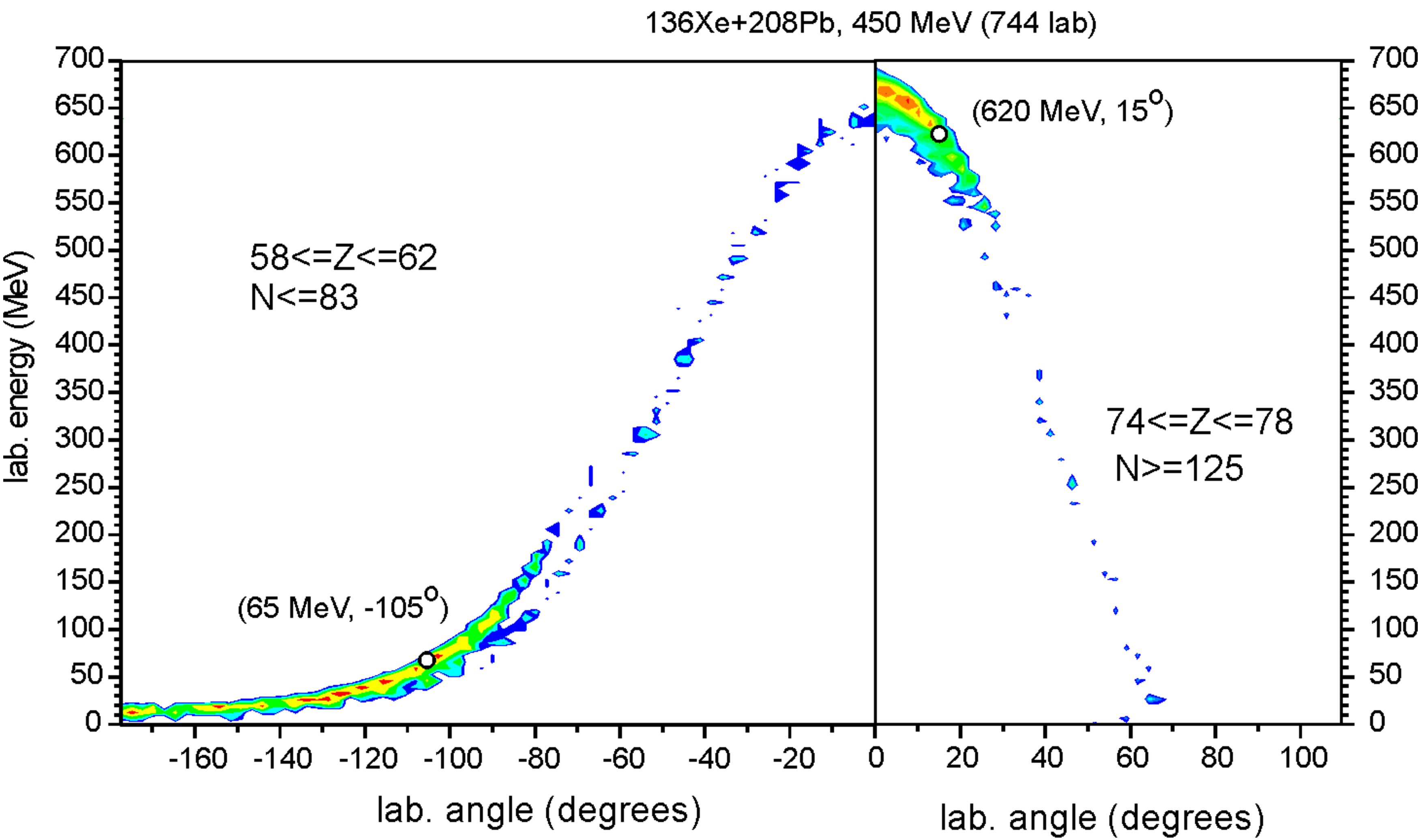




Several tens of new neutron-rich nuclides can be produced with cross section higher than one microbarn in the near-barrier collision of 136Xe with 208Pb

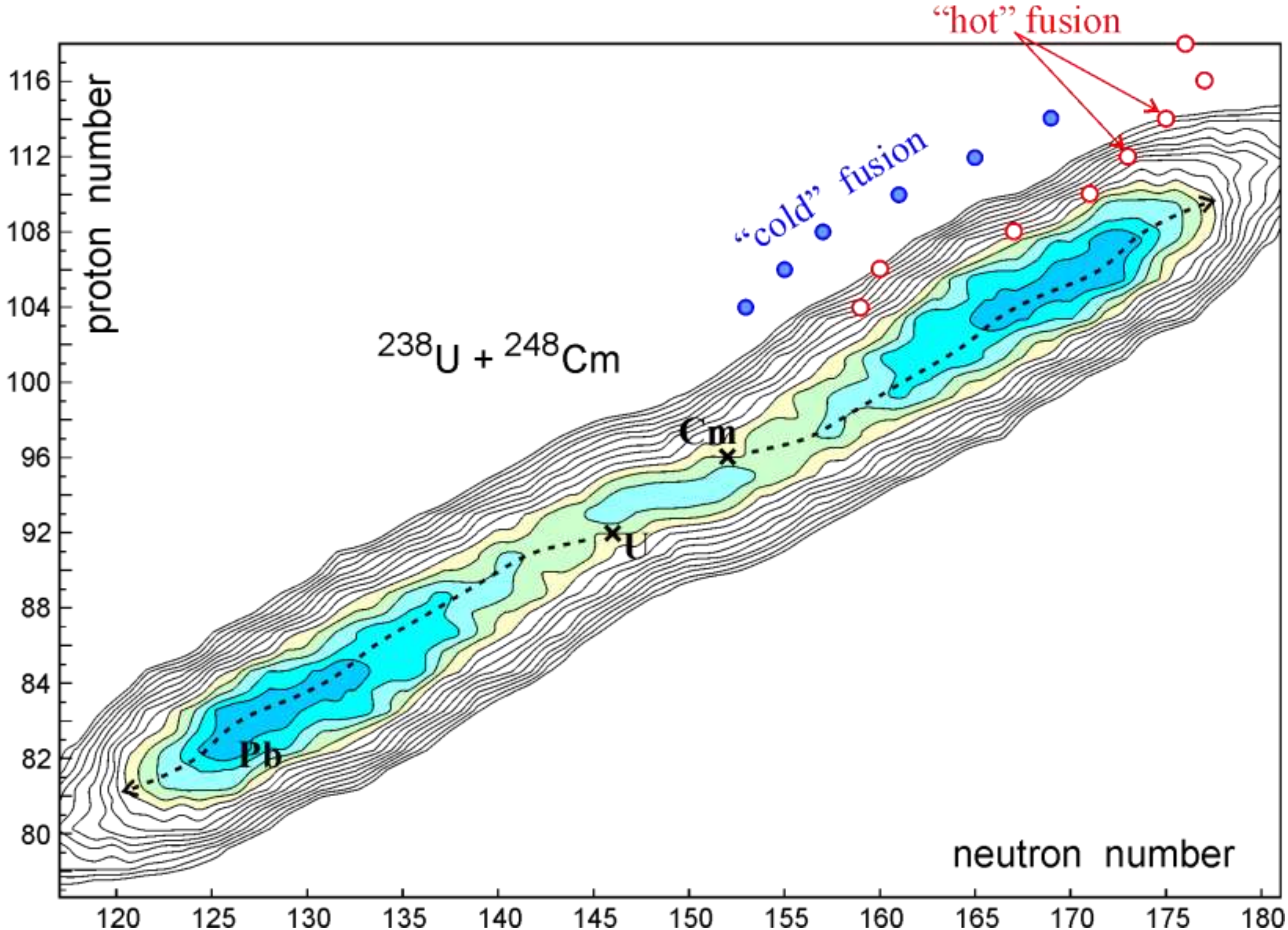


Angular and energy distribution

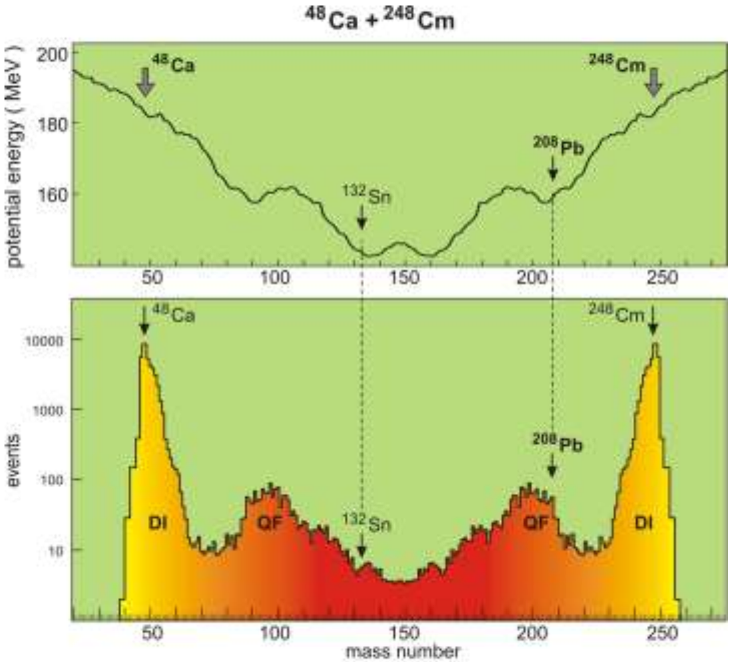


Problem of identification of heavy neutron rich nuclei !?

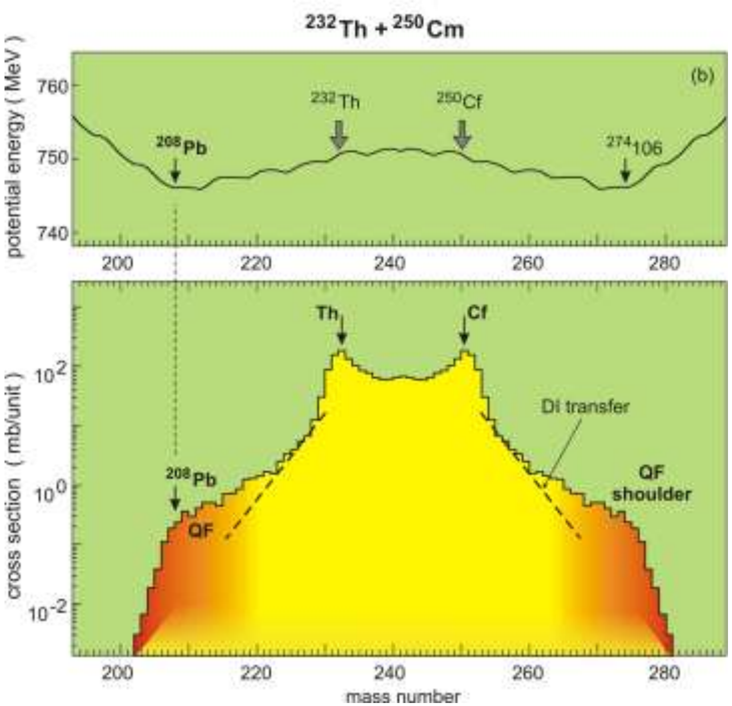
How may we produce SHE at the stability line ?



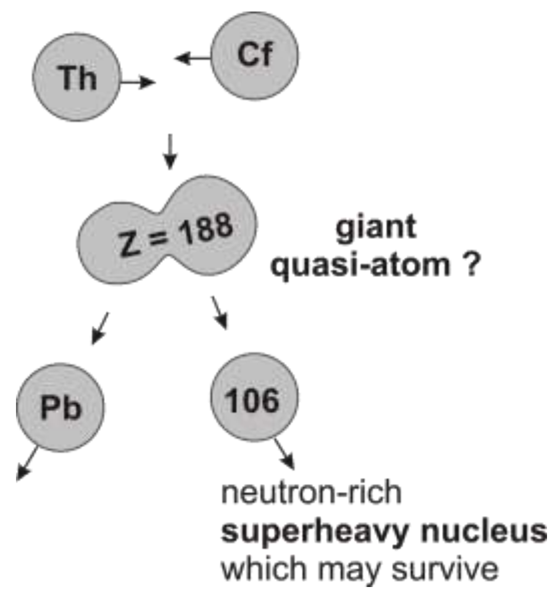
Shell effects in low-energy collisions of heavy nulei



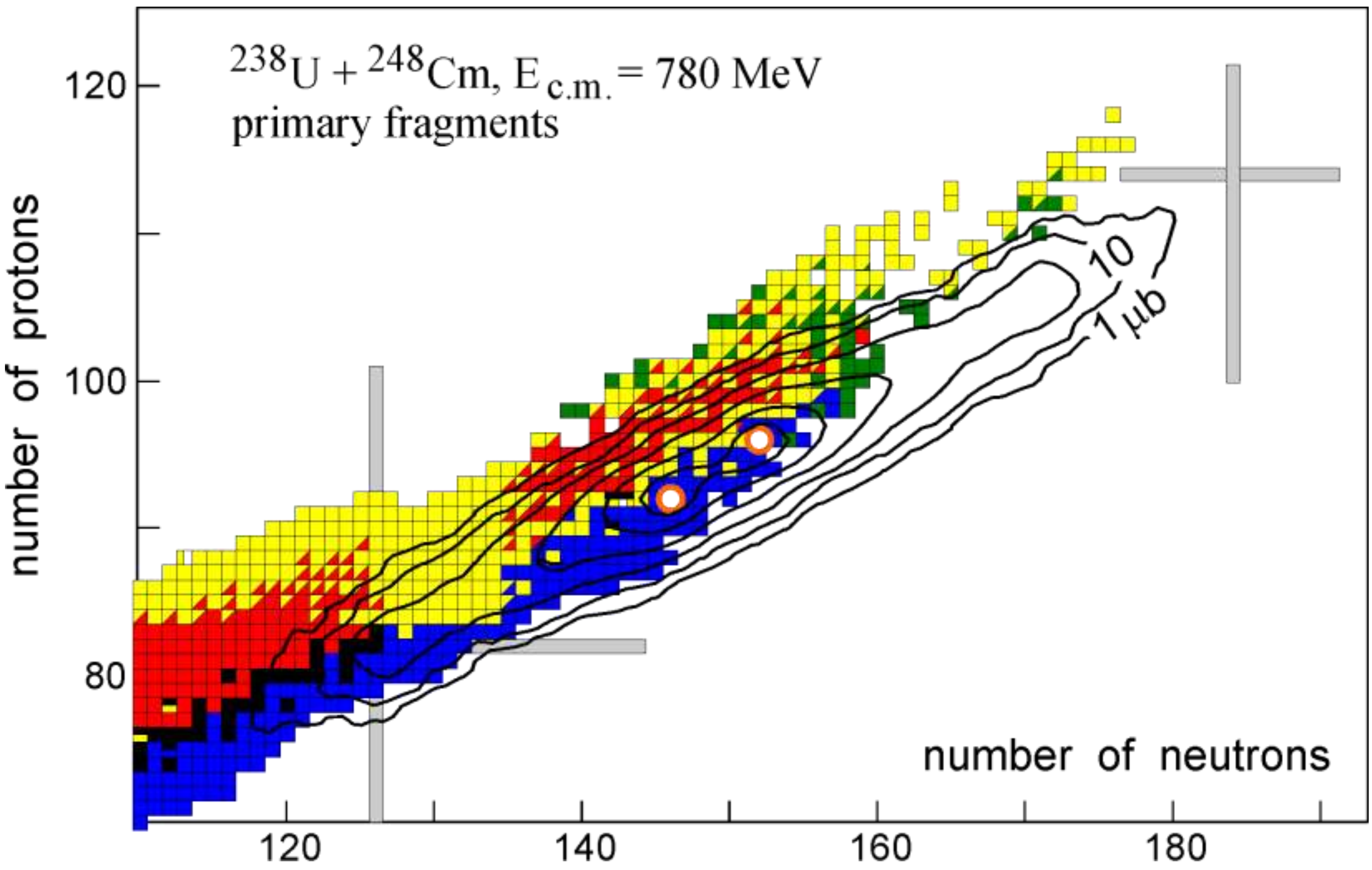
normal (symmetrizing) quasi-fission



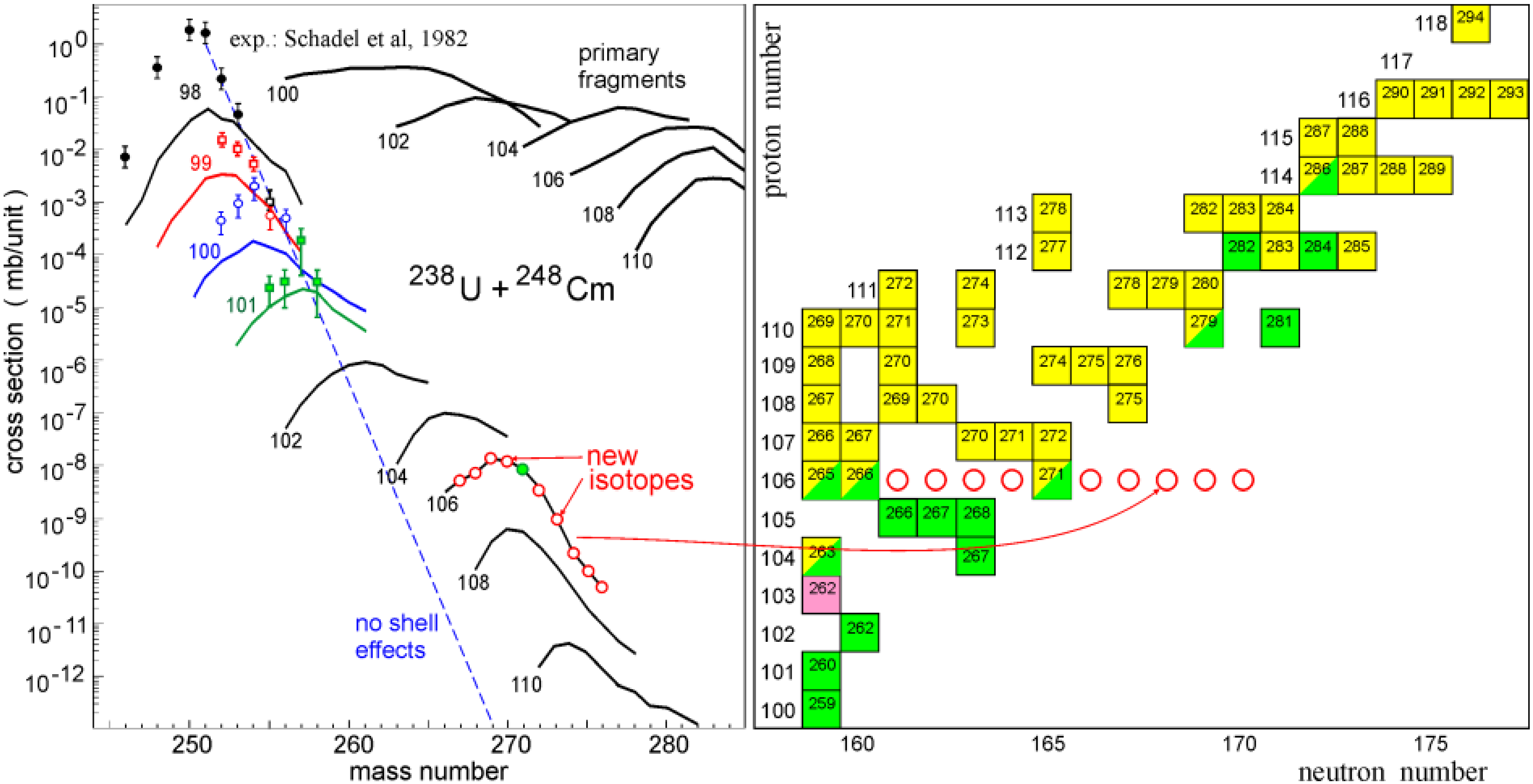
"inverse" (antisymmetrizing) quasi-fission



238U + 248Cm. Primary fragments



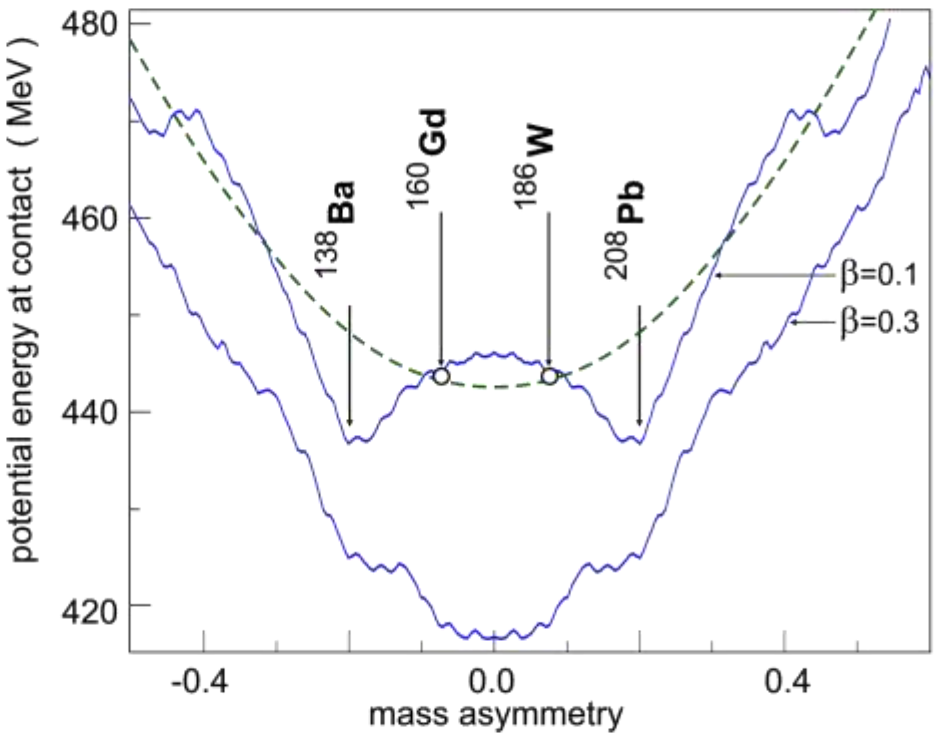
Production of neutron-rich SHE in low-energy collisions of heavy actinide nuclei

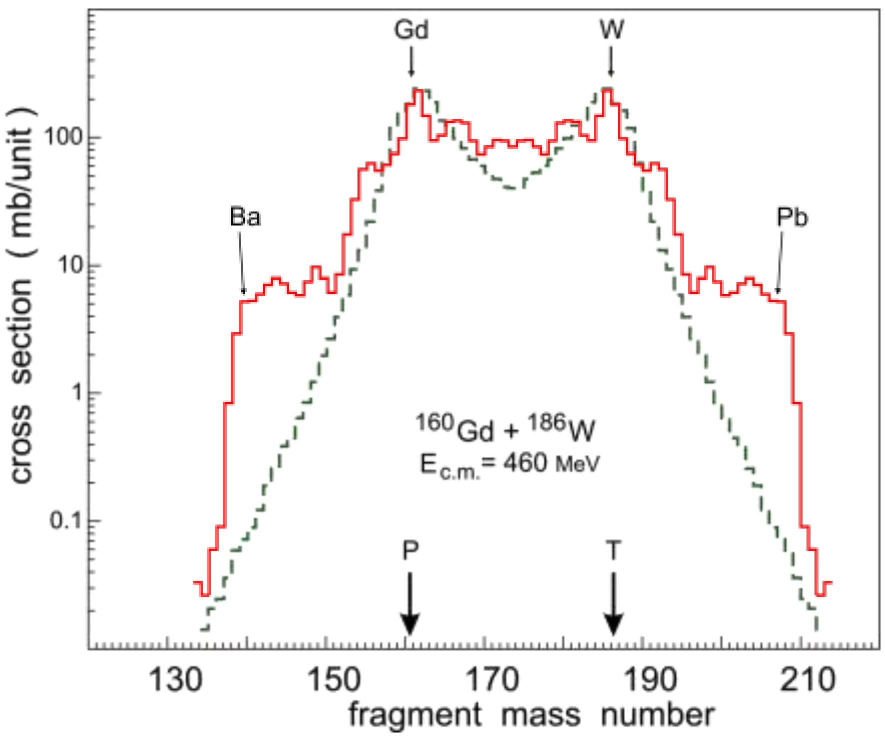


Shell effects in damped collisions

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

(proposal for a new experiment)





Summary

- **A new method is proposed for synthesis of unknown heavy neutron-rich nuclei located at the "north-east" part of the nuclear map.**

- **This unexplored area of the nuclear map can be filled neither in fusion-fission reactions nor in fragmentation processes.**

- **The low-energy multi-nucleon transfer reactions can be used for the production of heavy and superheavy neutron-rich nuclei.**

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