Production of New Heavy Nuclei in the North-East Part of the Nuclear Map

- Neutron rich superheavy nuclei
- “Blanc spots” on the nuclear map
- Multi-nucleon transfer
  in low-energy damped collisions of heavy ions
- Summary

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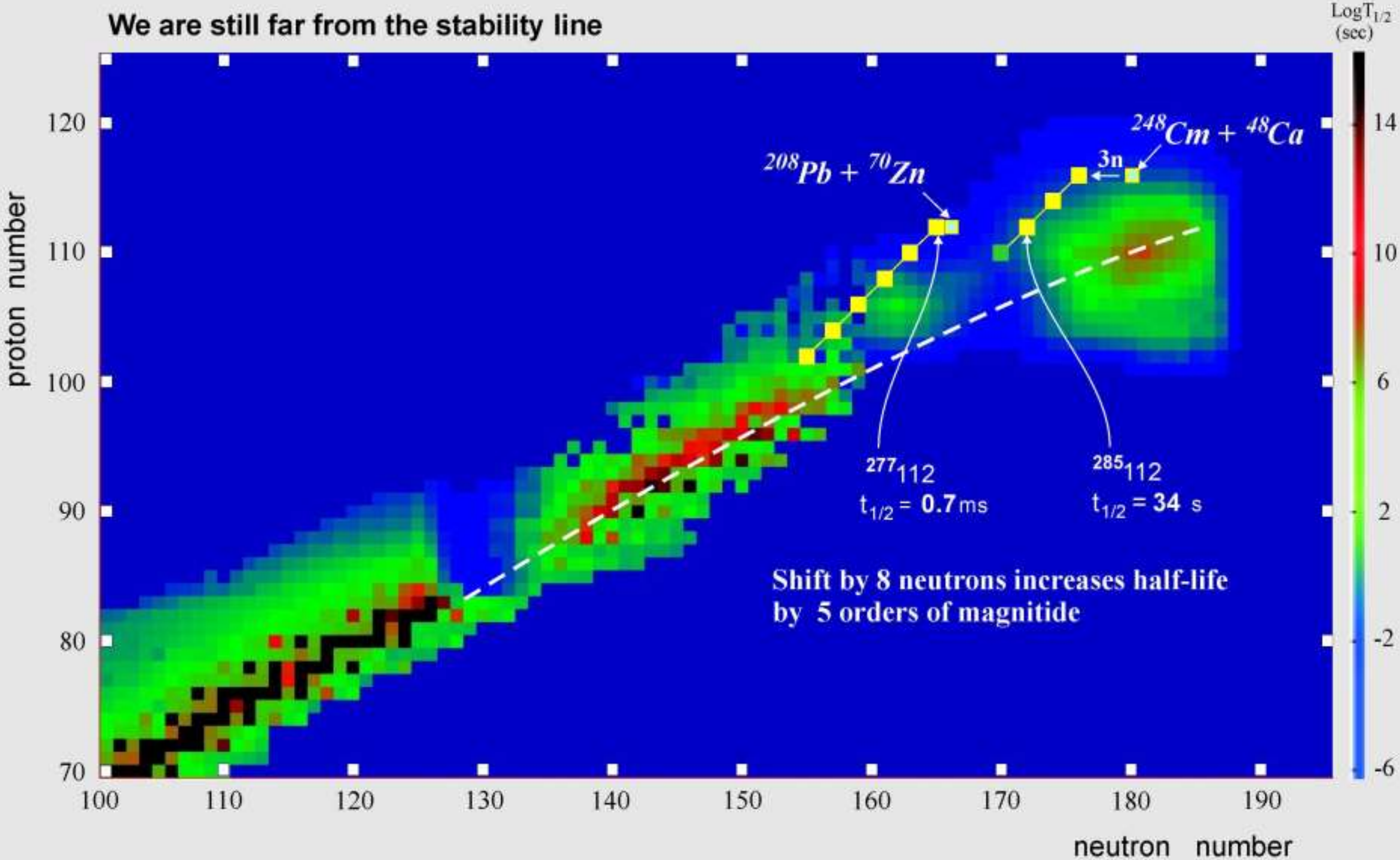
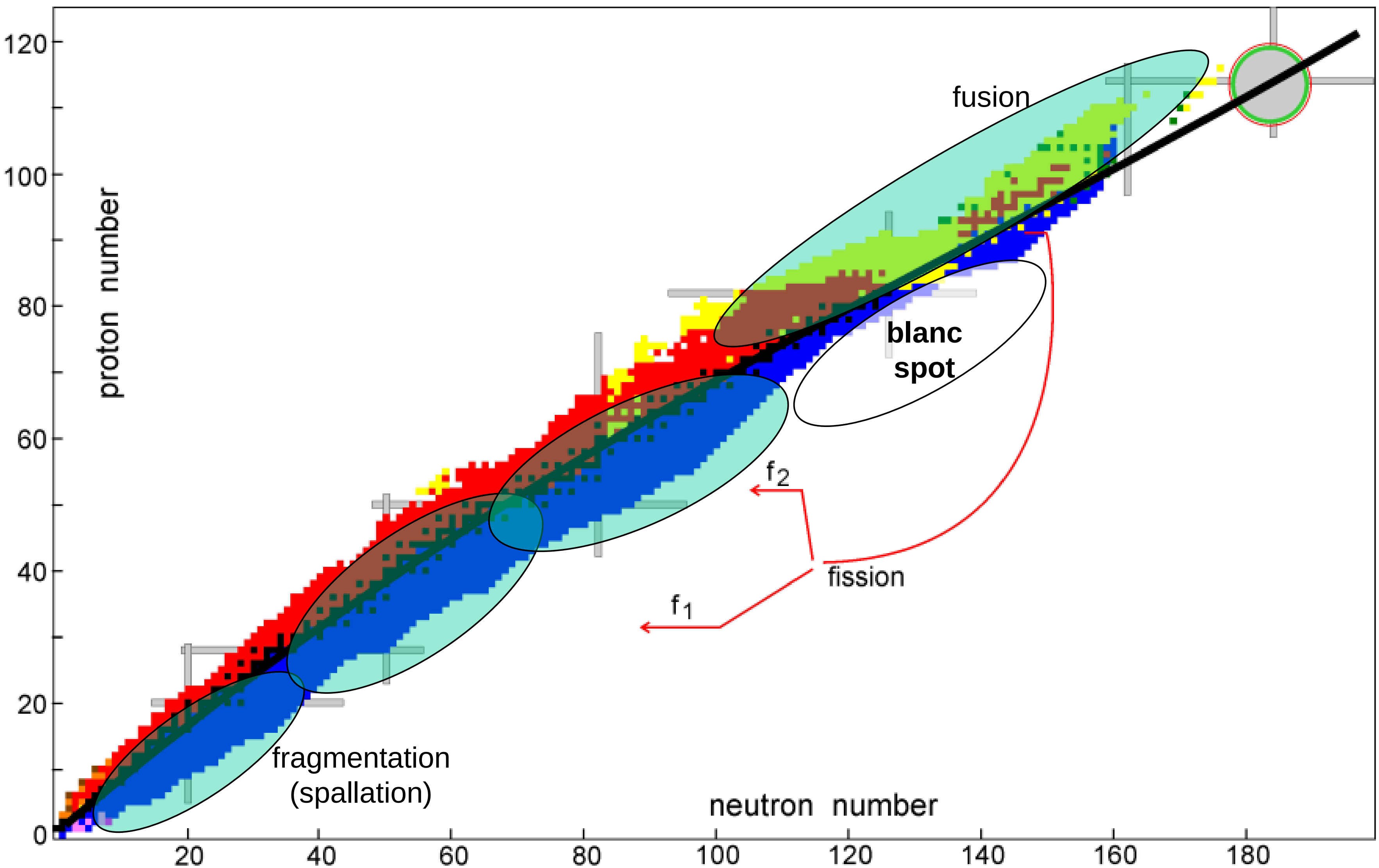
Fusion-08, September 26, 2008, Chicago

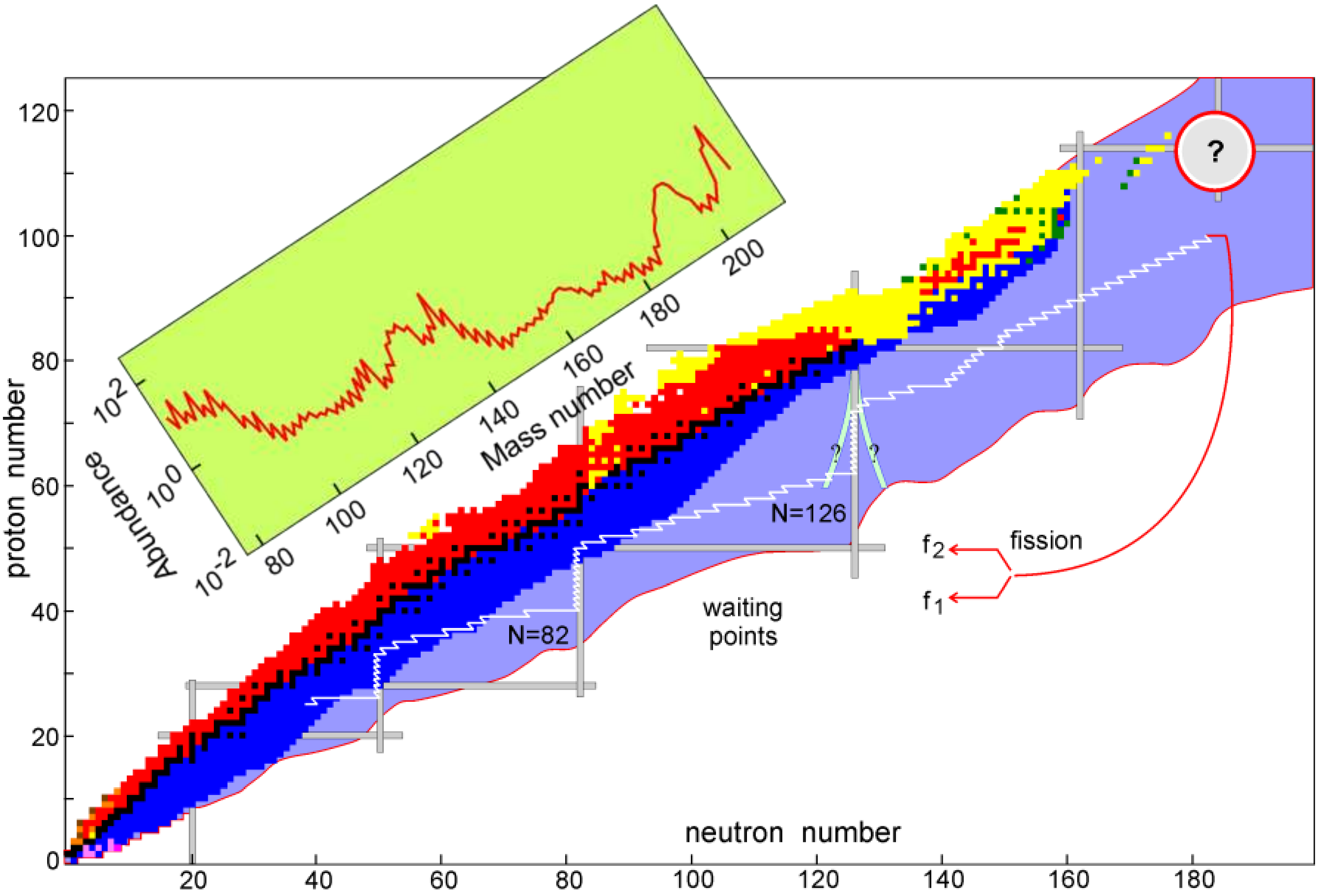
We are still far from the stability line



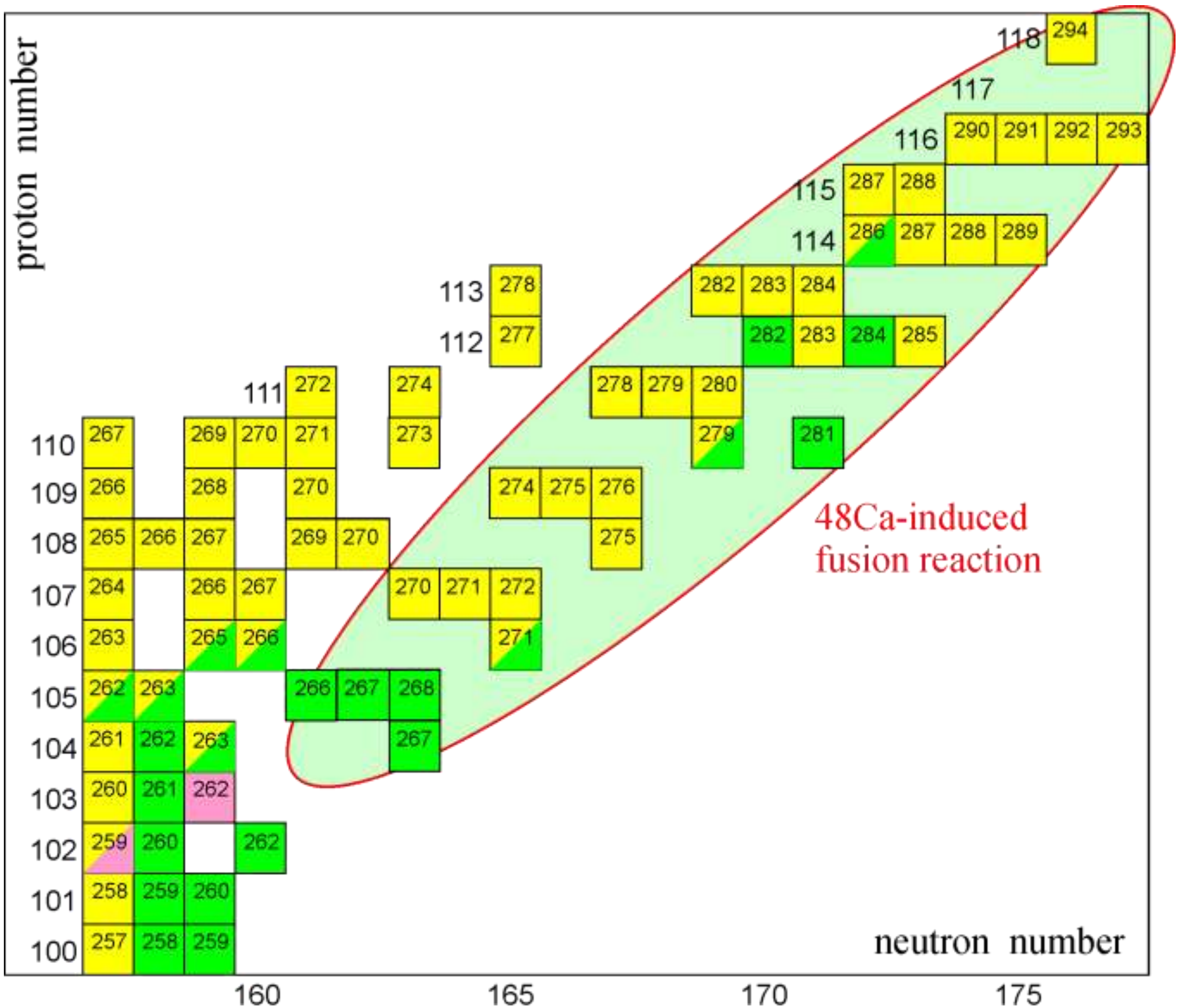
“Blanc Spot” on the Nuclear Map



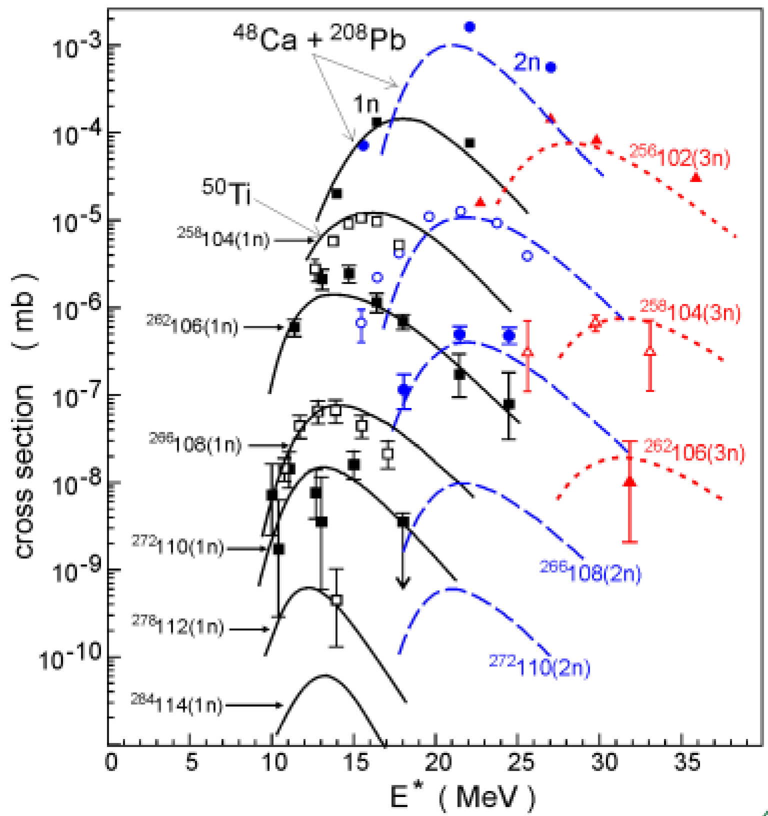
r-process of nucleosynthesis
and the neutron closed shell in the region of N ~ 126

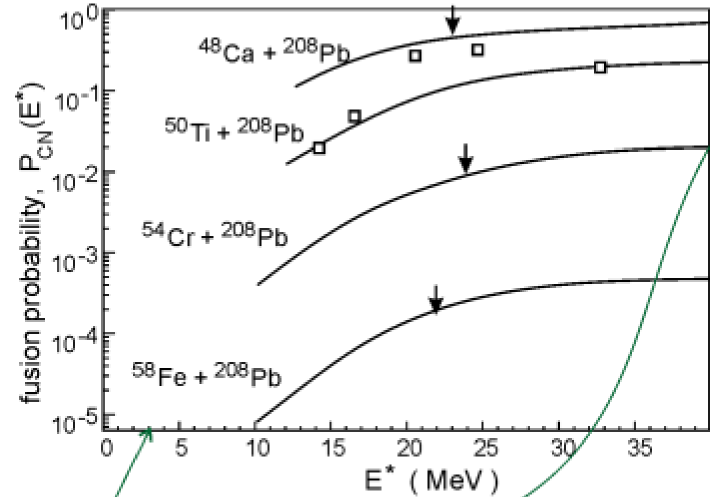


A "gap" in the upper part of the Nuclear Map

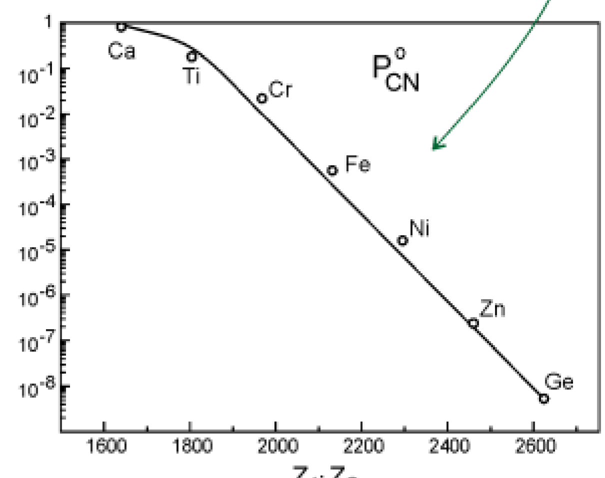


“Cold synthesis” of SHE



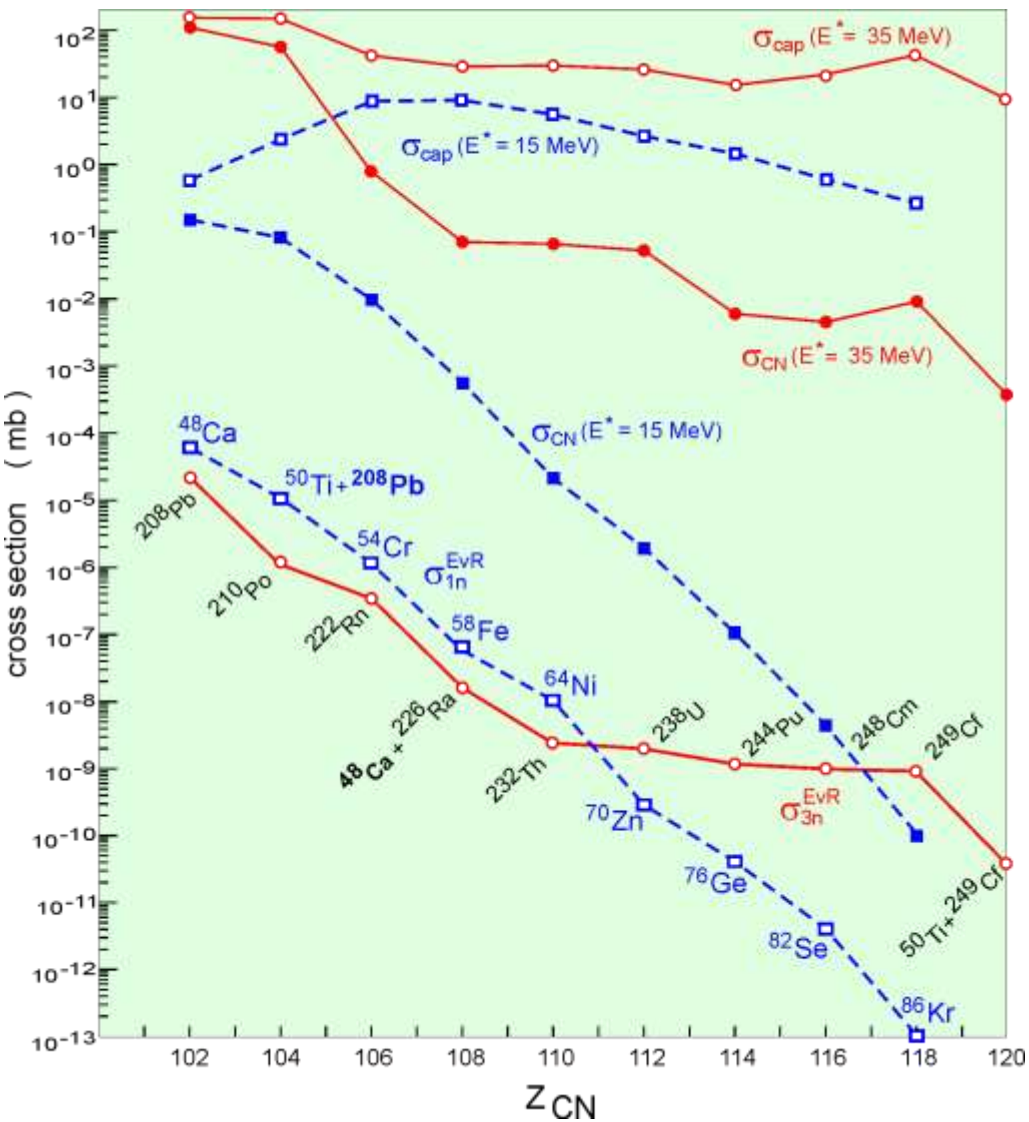


$$P_{CN}(E^*,\ell) = \frac{P^0_{CN}}{1 + \exp\left[\frac{E^*_B - E^*_{int}(\ell)}{\Delta}\right]}$$

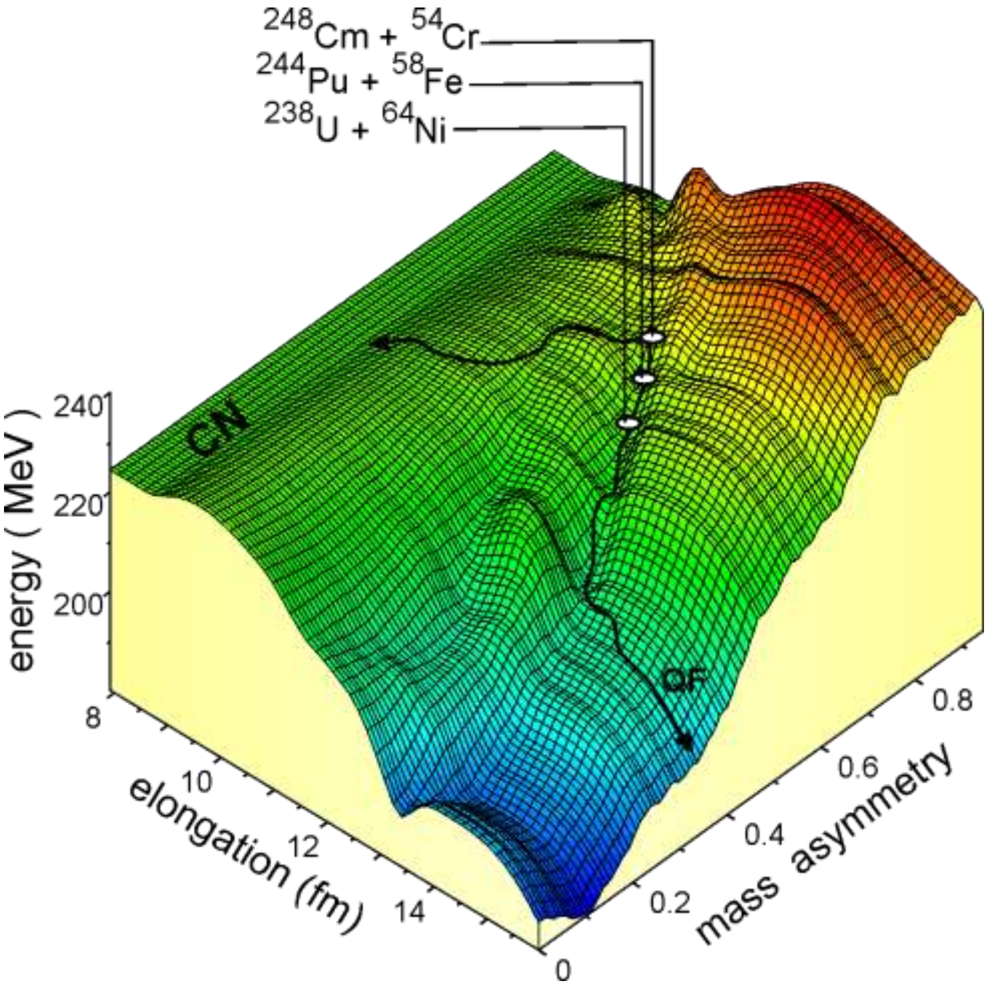


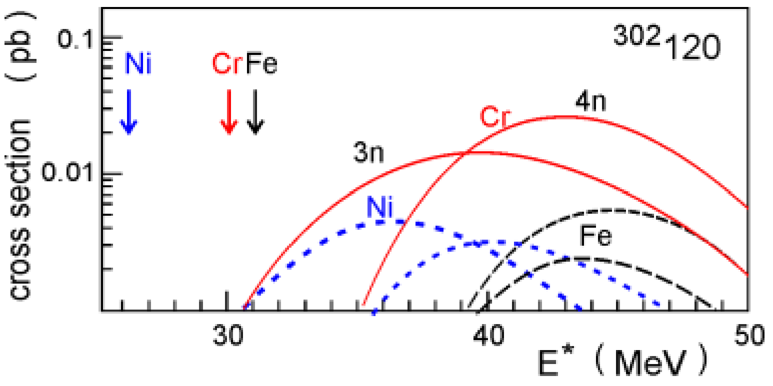
$$\sigma^{xn}_{ER}(E) = \frac{\pi}{k^2}\sum_{\ell=0}^{\infty}(2\ell+1)\cdot P_{cont}(E,\ell)\cdot P_{CN}(E^*,\ell)\cdot P_{xn}(E^*,\ell)$$

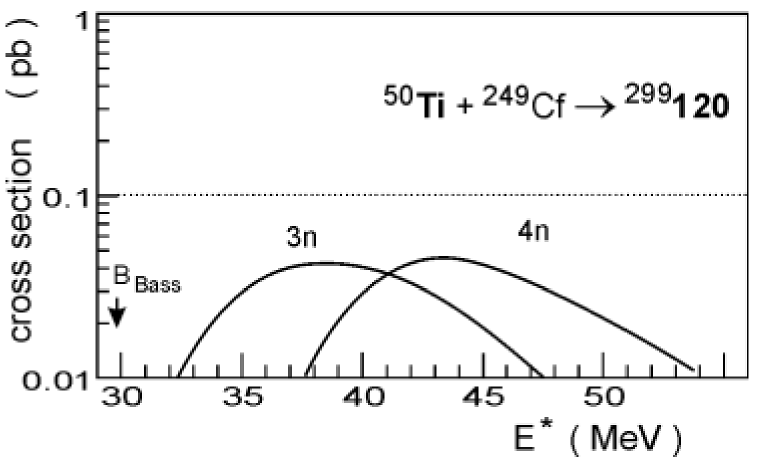
“Cold” and “Hot” synthesis of SHE



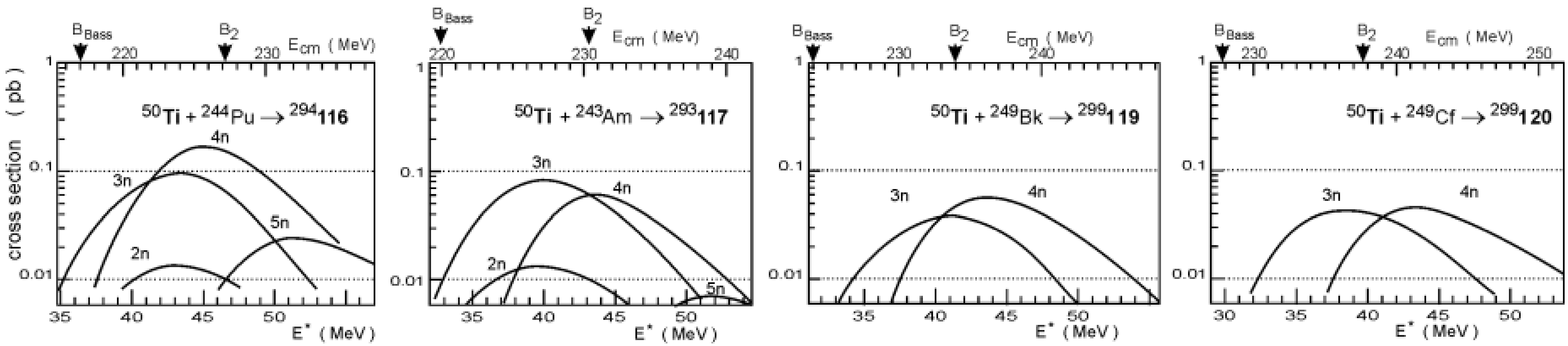
Beyond ^{48}Ca: Synthesis of 120





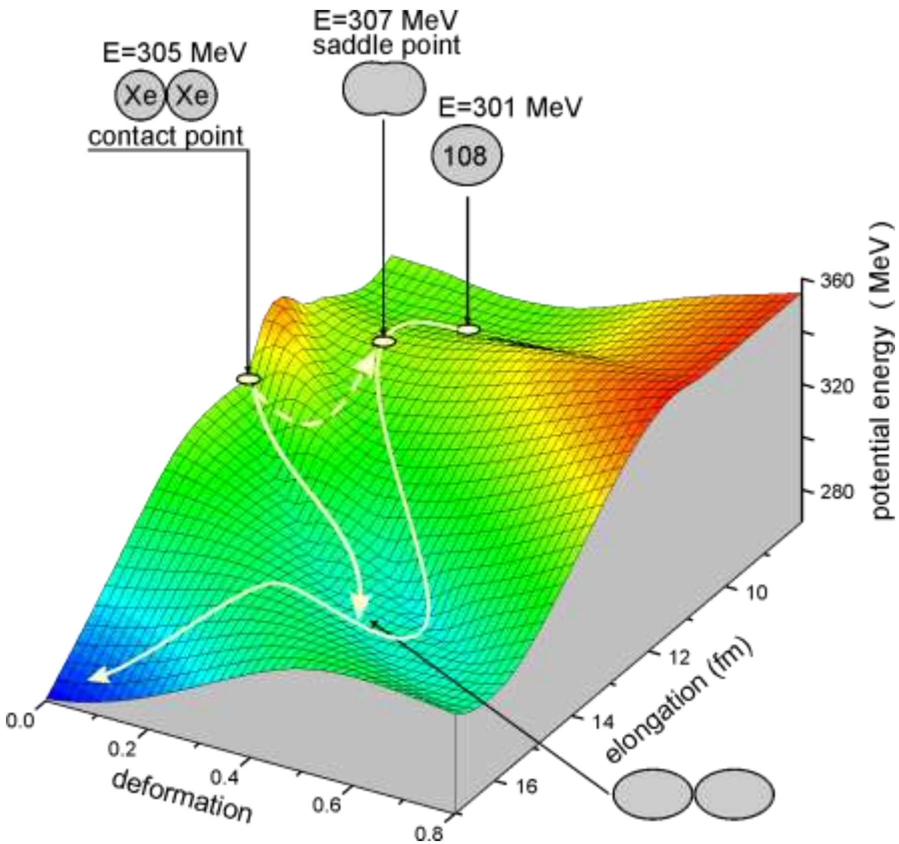


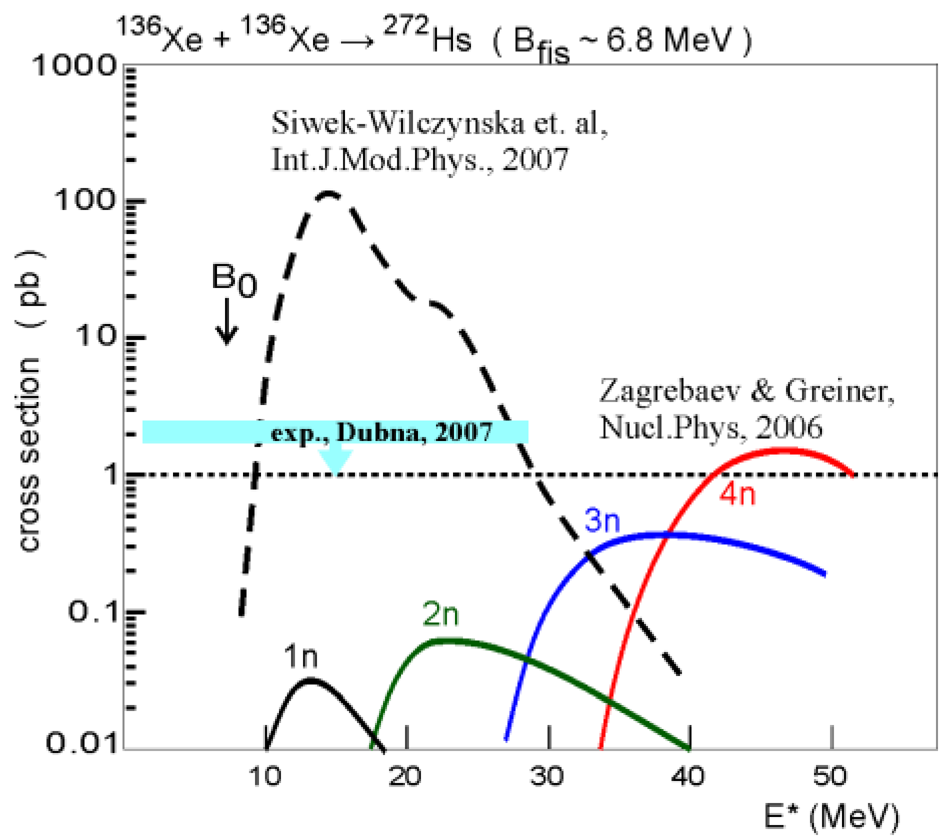
^{50}Ti - induced fusion reactions



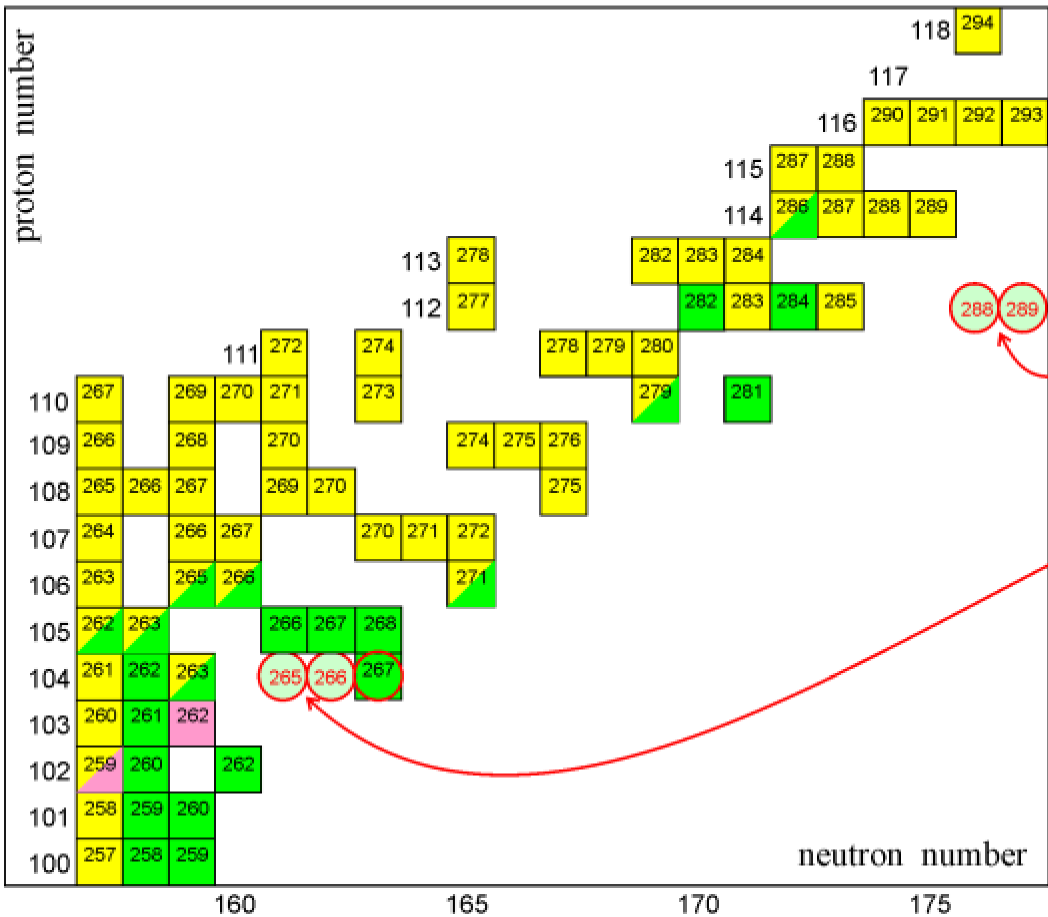
Fusion of “fission fragments”: $^{136}Xe + ^{136}Xe \rightarrow ^{272}108$

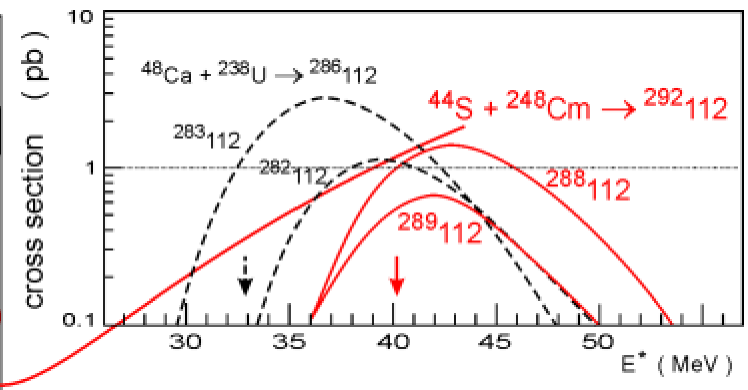
if OK then $^{132}Sn + ^{176}Yb \rightarrow ^{308}120$

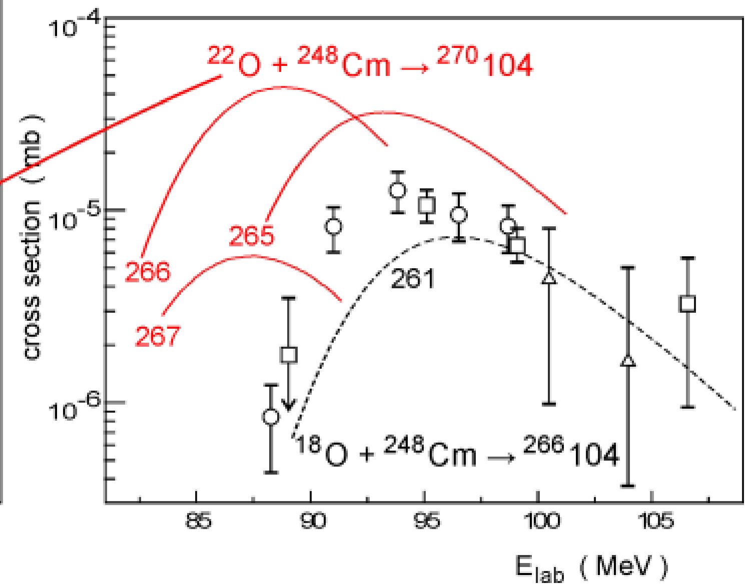




Radioactive Ion Beams for production of neutron rich superheavy nuclei



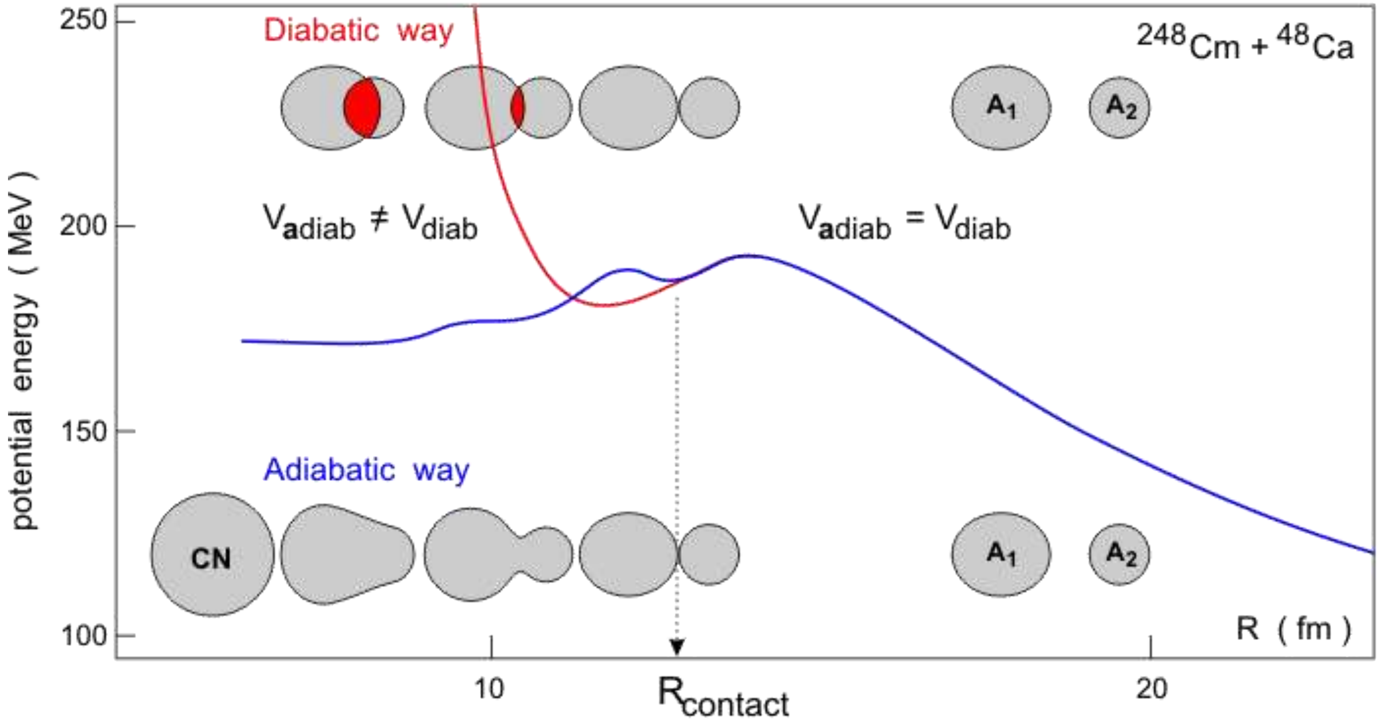




Multi-nucleon transfer reactions in low-energy heavy ion collisions

Time-dependent Driving Potential

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



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

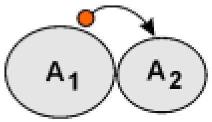
Time-dependent driving potential has to be used

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

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

the same degrees of freedom !

Nucleon Exchange



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

(L. Moretto, 1974)

Distribution function $\varphi(A,t)$ → Master equation $\frac{\partial\varphi}{\partial t} = \sum_{A'=A\pm1} \lambda(A' \to A)\cdot\varphi(A') - \lambda(A \to A')\cdot\varphi(A)$

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

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

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

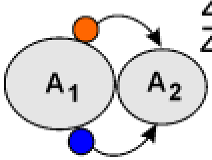
$$\frac{d\eta}{dt} = \frac{2}{A_{\mathrm{CN}}} D_A^{(1)} + \frac{2}{A_{\mathrm{CN}}}\sqrt{D_A^{(2)}}\,\Gamma(t)$$

at $A = A \pm 1$

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

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

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



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

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

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

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

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

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

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

System of coupled Langevin type Equations of Motion

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

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

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

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

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

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

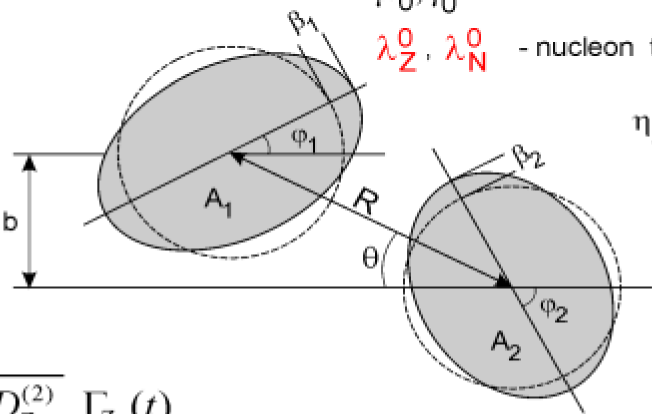
$$\frac{d\eta_Z}{dt} = \frac{2}{Z_{CN}} D_Z^{(1)} + \frac{2}{Z_{CN}} \sqrt{D_Z^{(2)}}\, \Gamma_Z(t)$$

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

Most uncertain parameters:

μ_0, γ_0 - nuclear viscosity and friction,

λ_Z^0, λ_N^0 - nucleon transfer rate



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

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

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

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

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

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

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

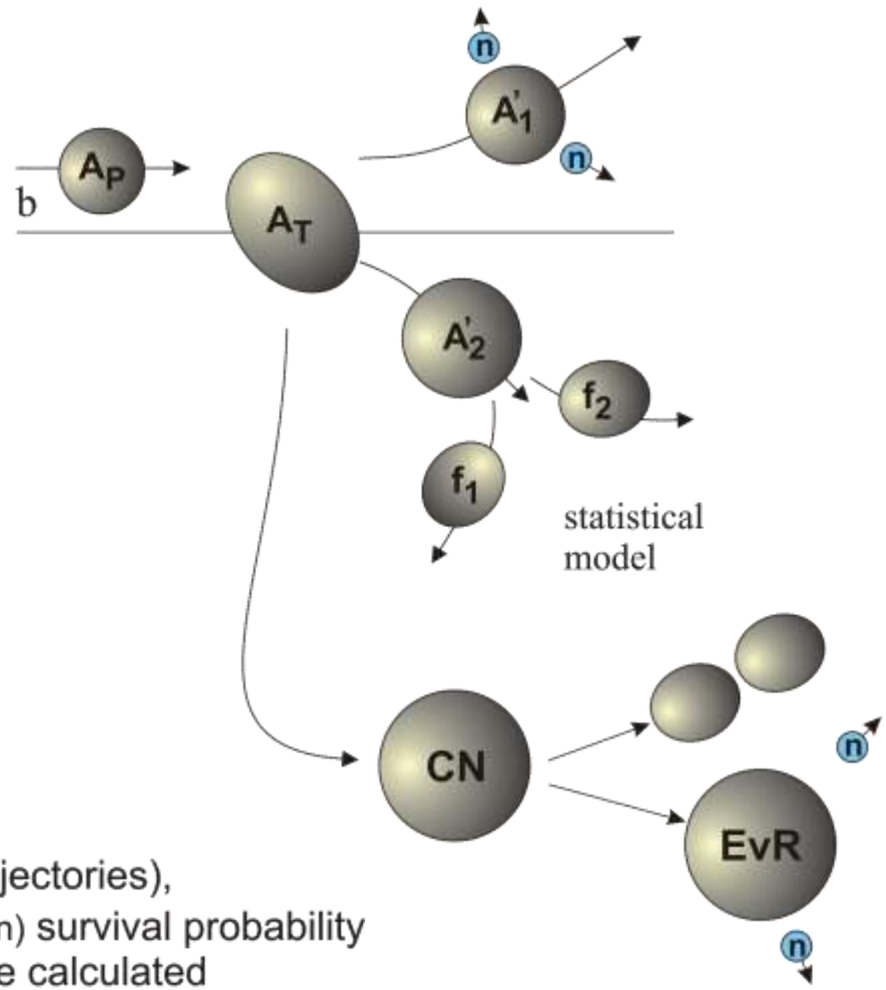
$$\frac{dL_2}{dt} = -\frac{\partial V}{\partial \varphi_2} + \gamma_{tan}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) a_2 - \frac{a_2}{R}\sqrt{\gamma_{tang} T}\,\Gamma_{tang}(t)$$

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

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

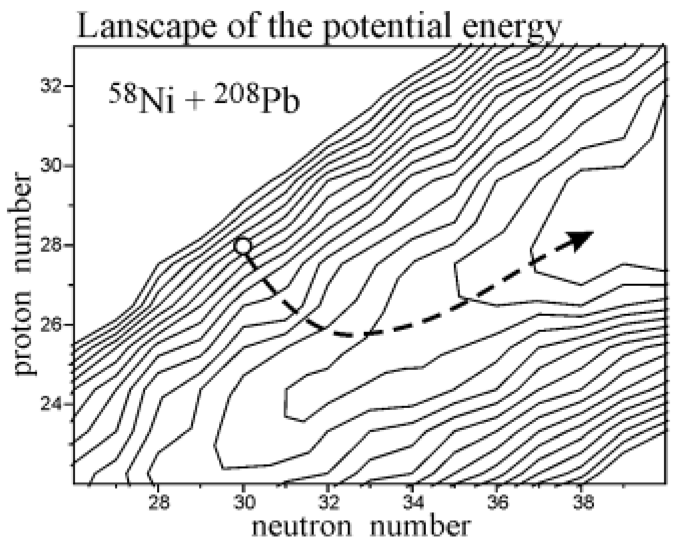
Simulation of experiment and cross sections

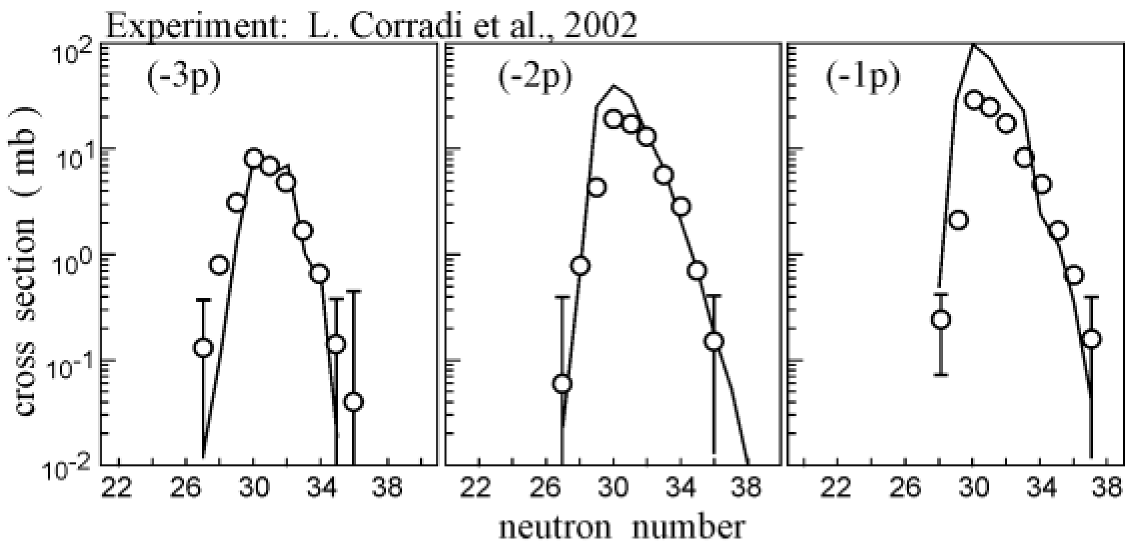
$$\frac{d^2\sigma_\alpha}{d\Omega dE}(E,\theta) = \int_0^\infty bdb \; \frac{\Delta N_\alpha(b,E,\theta)}{N_{tot}(b)} \; \frac{1}{\sin(\theta)\Delta\theta\Delta E}$$

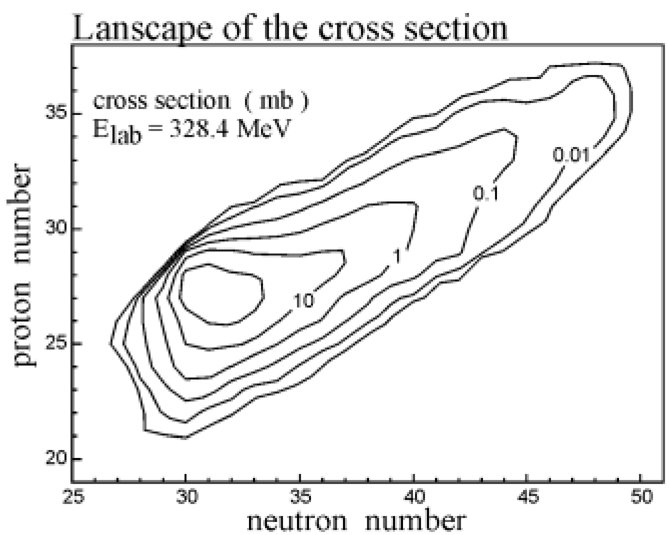


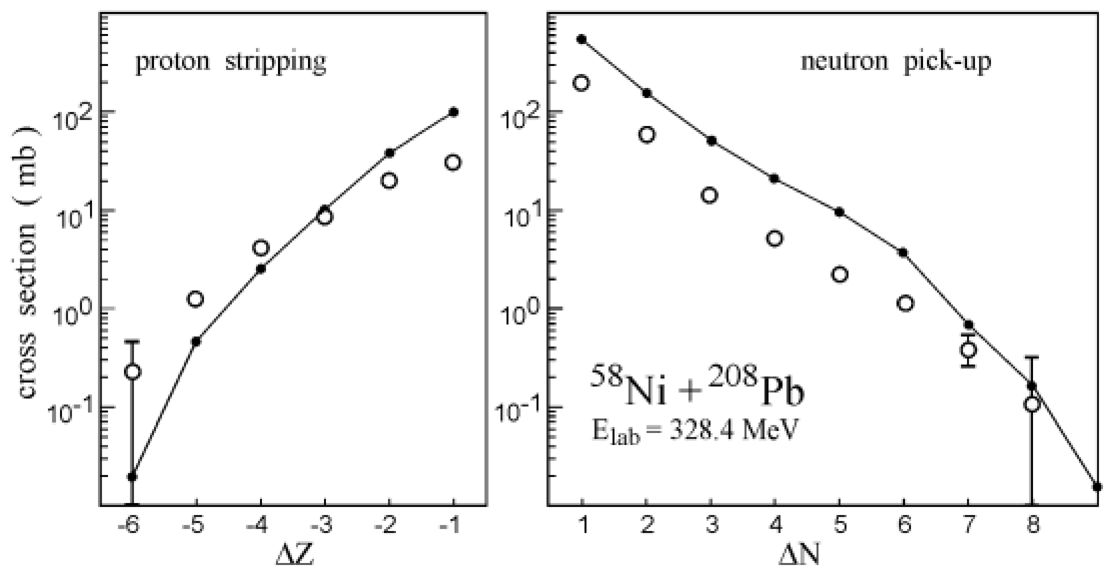
Dynamics: **10^6** tested events (trajectories),
Statistical model: **10^{-6}**(3n), **10^{-7}**(4n) survival probability
cross sections up to **0.1 pb** can be calculated

Comparison with experiment on multi-nucleon transfer



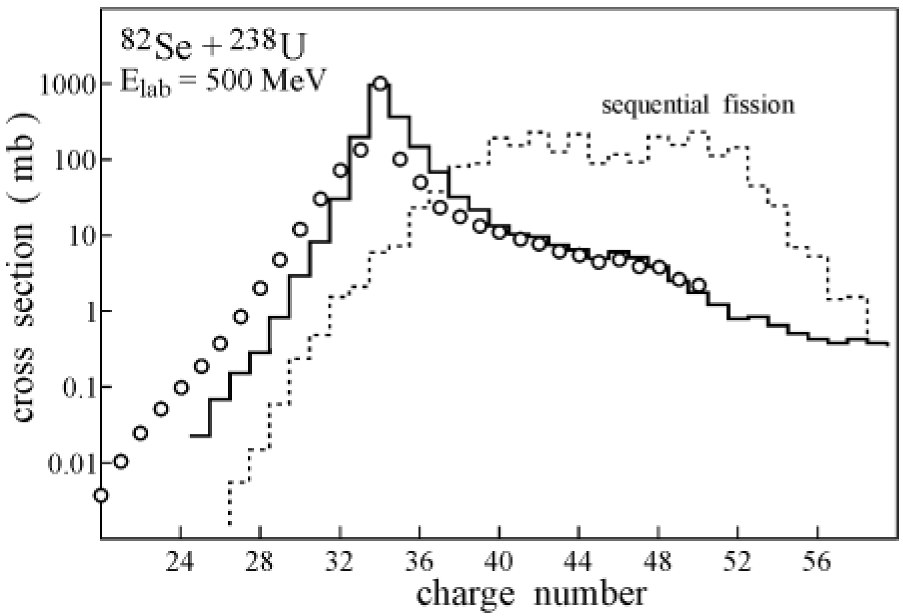


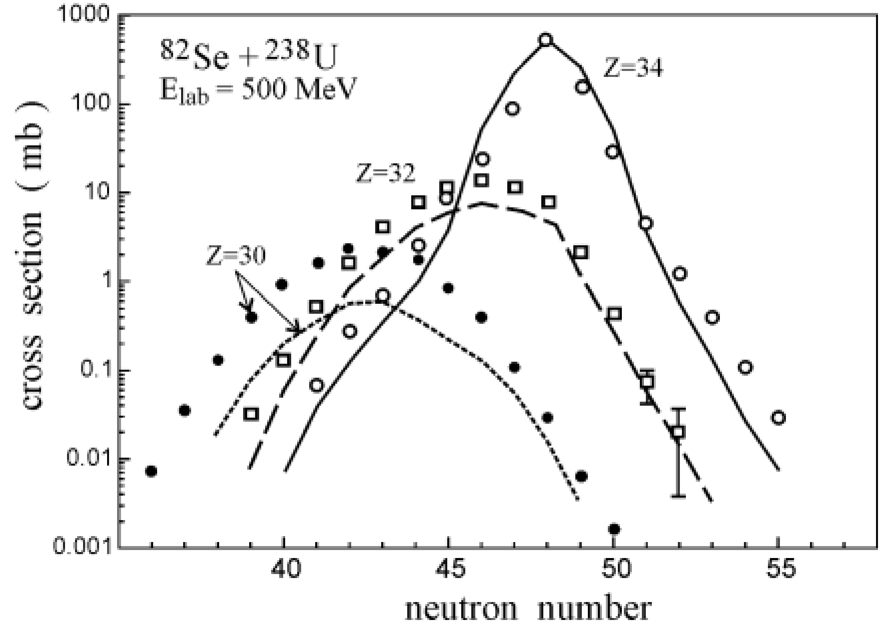




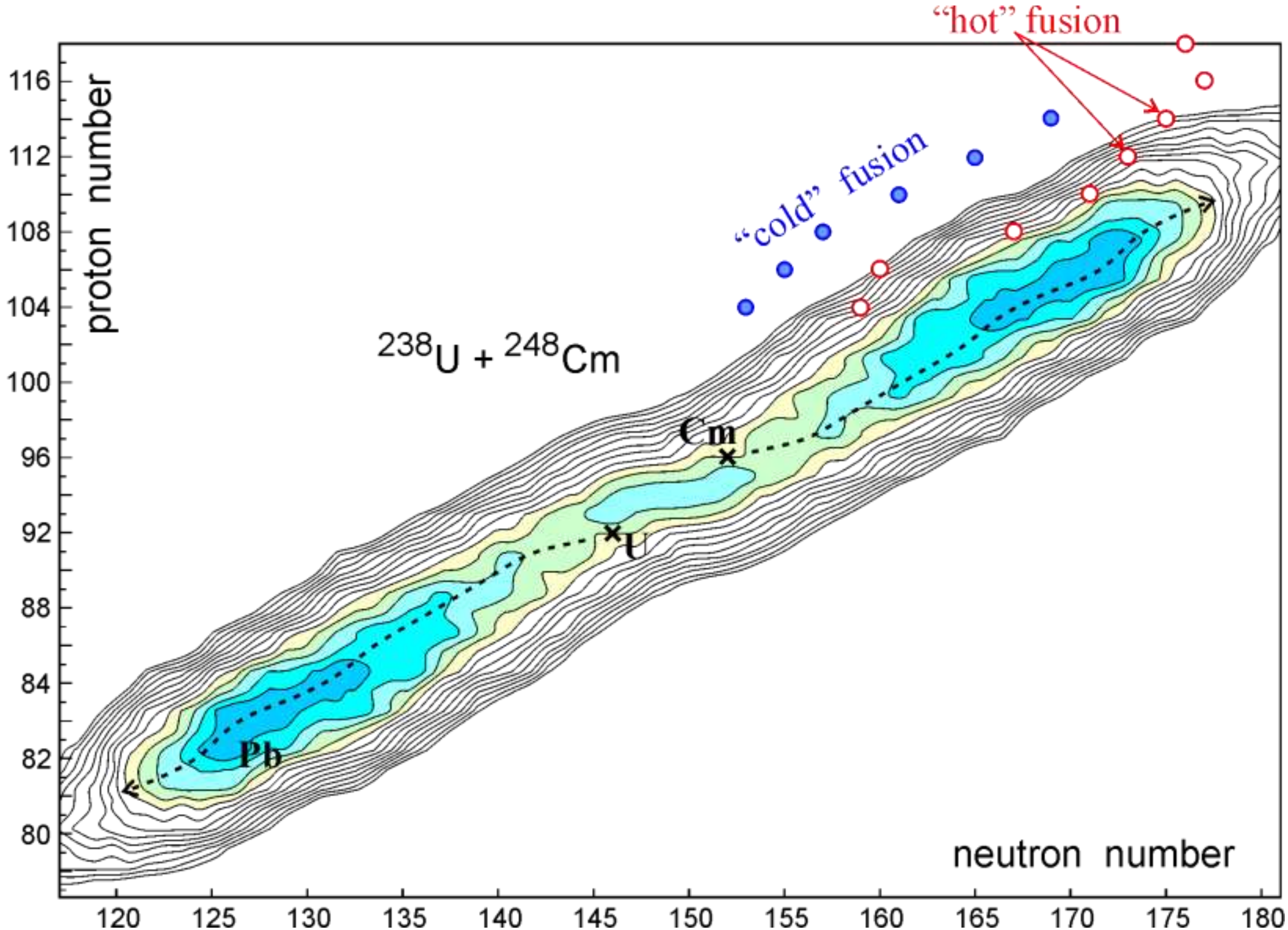
Comparison with experiment on multi-nucleon transfer

Experiment: L. Corradi et al., 2006

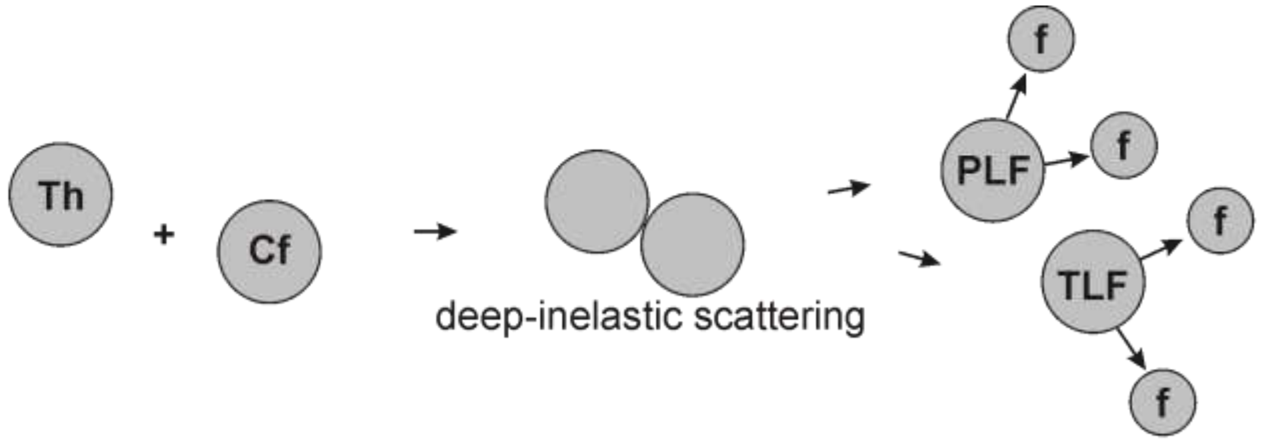


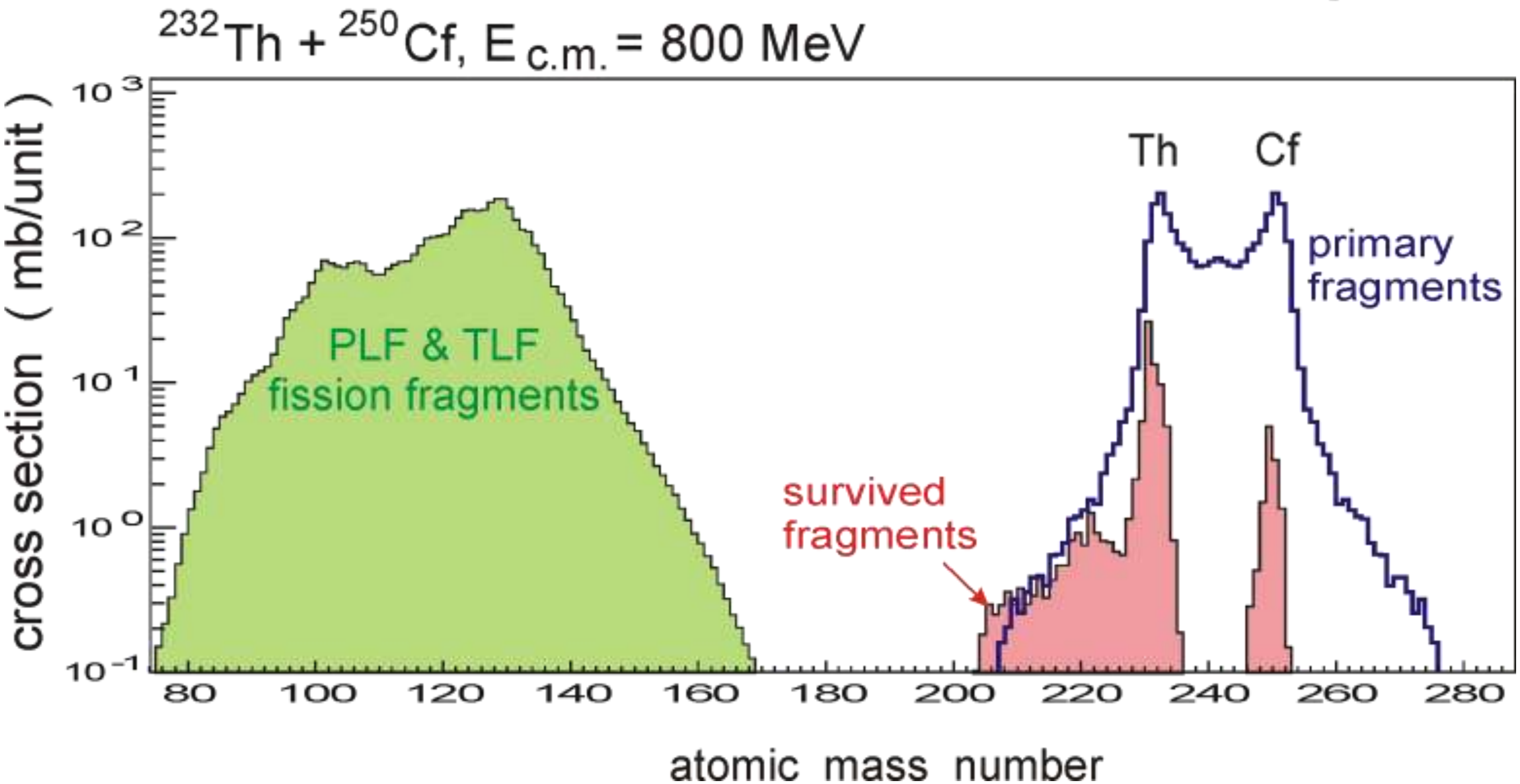


Most probable way of evolution of the giant nuclear system

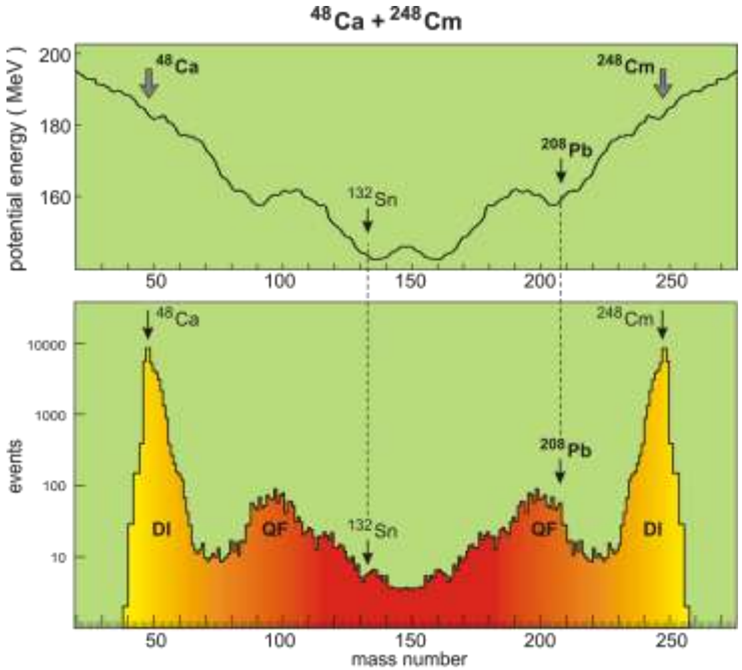


Transfer reactions in damped collision of very heavy nuclei ?

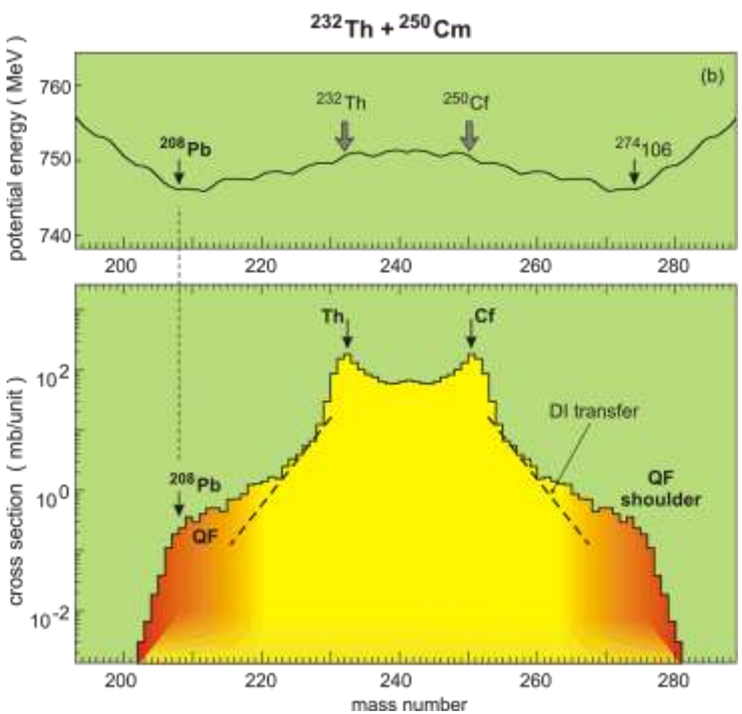




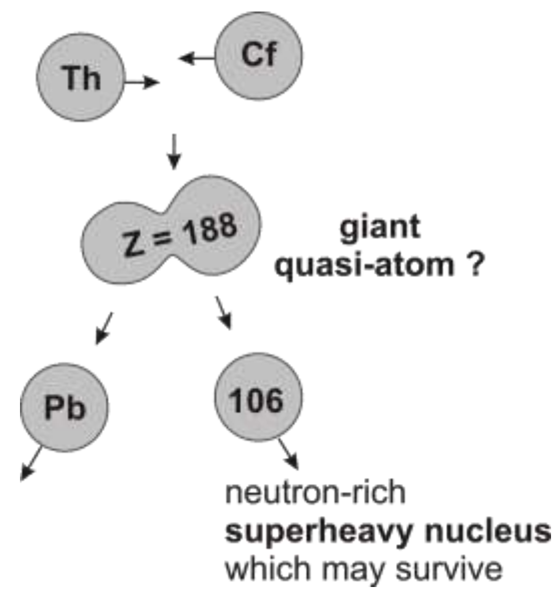
Inverse (antisymmetrizing) quasi-fission process



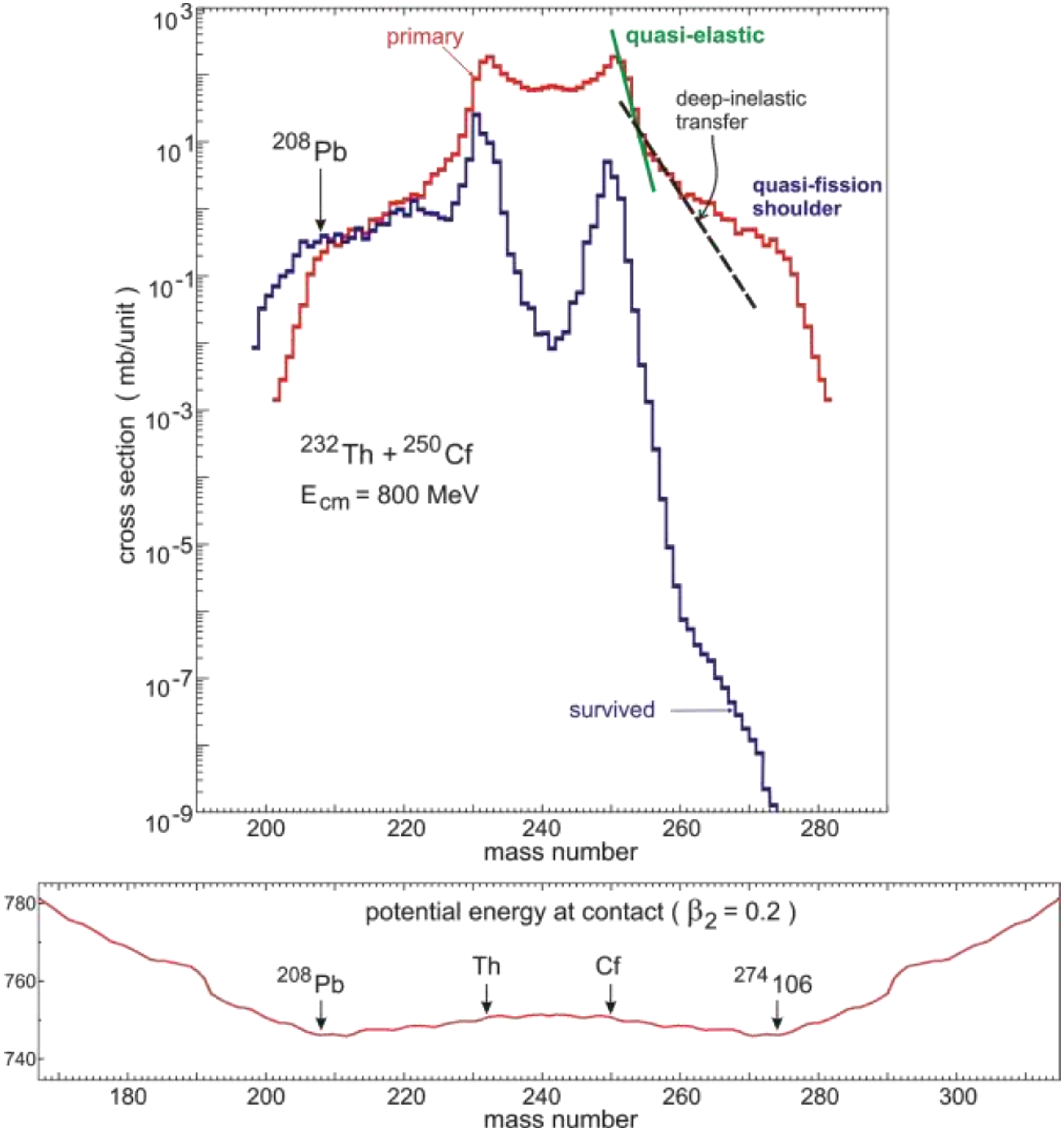
normal (symmetrizing) quasi-fission



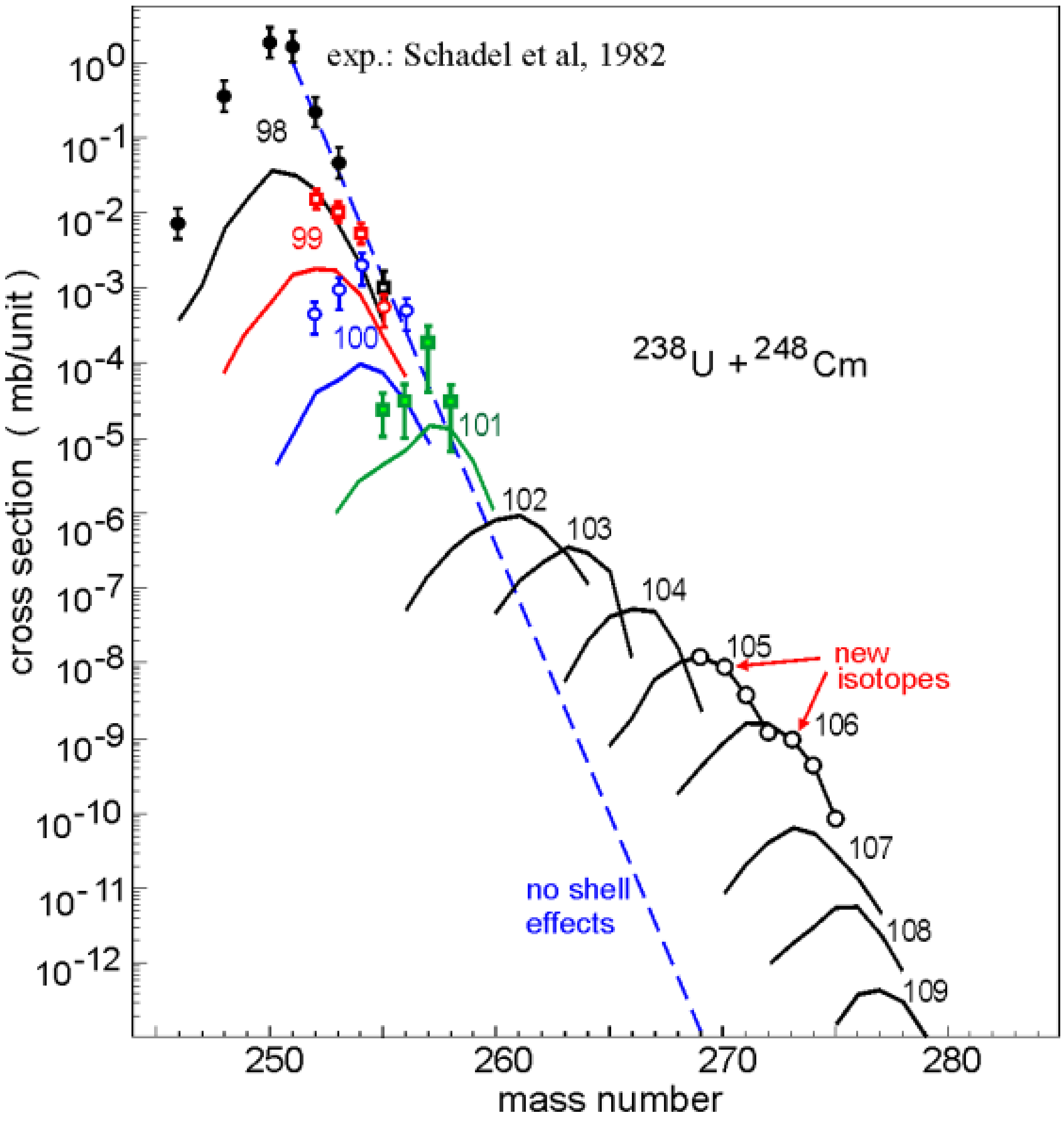
“inverse” (antisymmetrizing) quasi-fission



Shell effects in damped collisions of transactinides. New way to superheavies

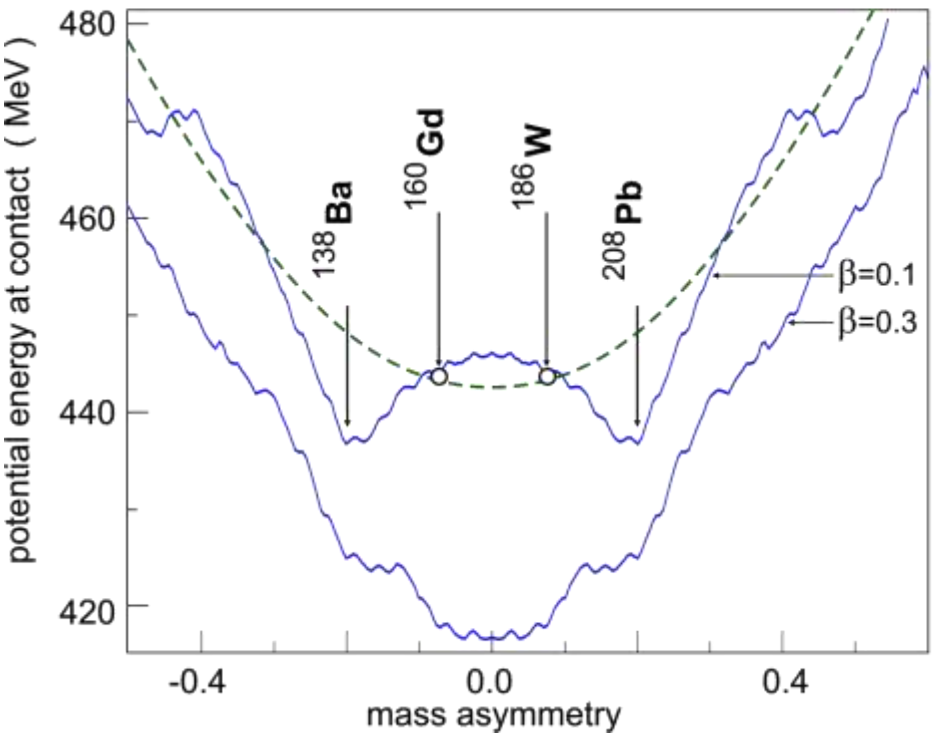


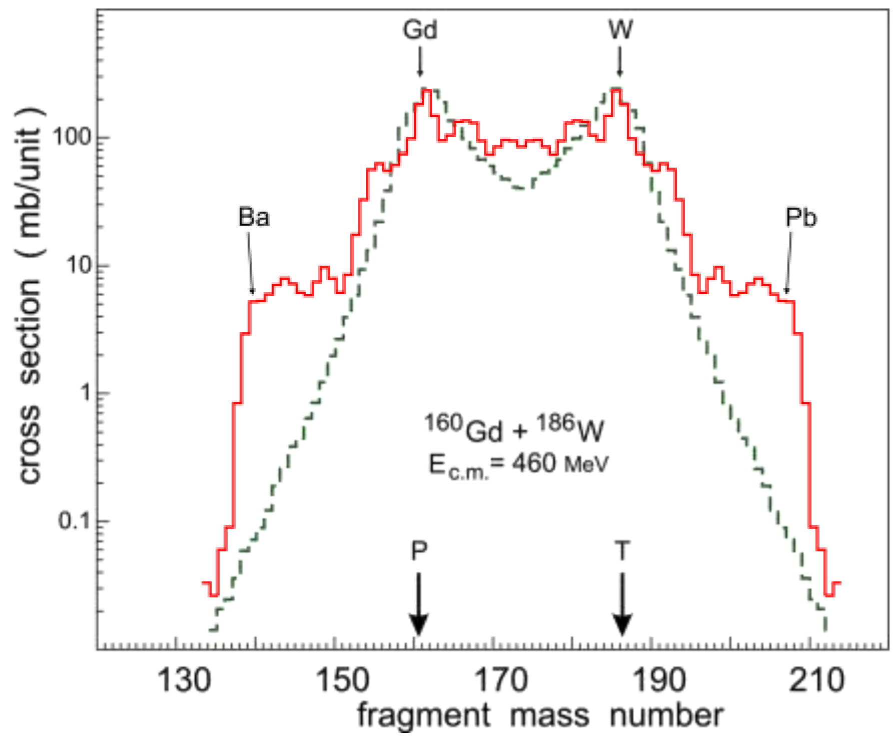
Isotopic yield of SHE in collisions of transactinides



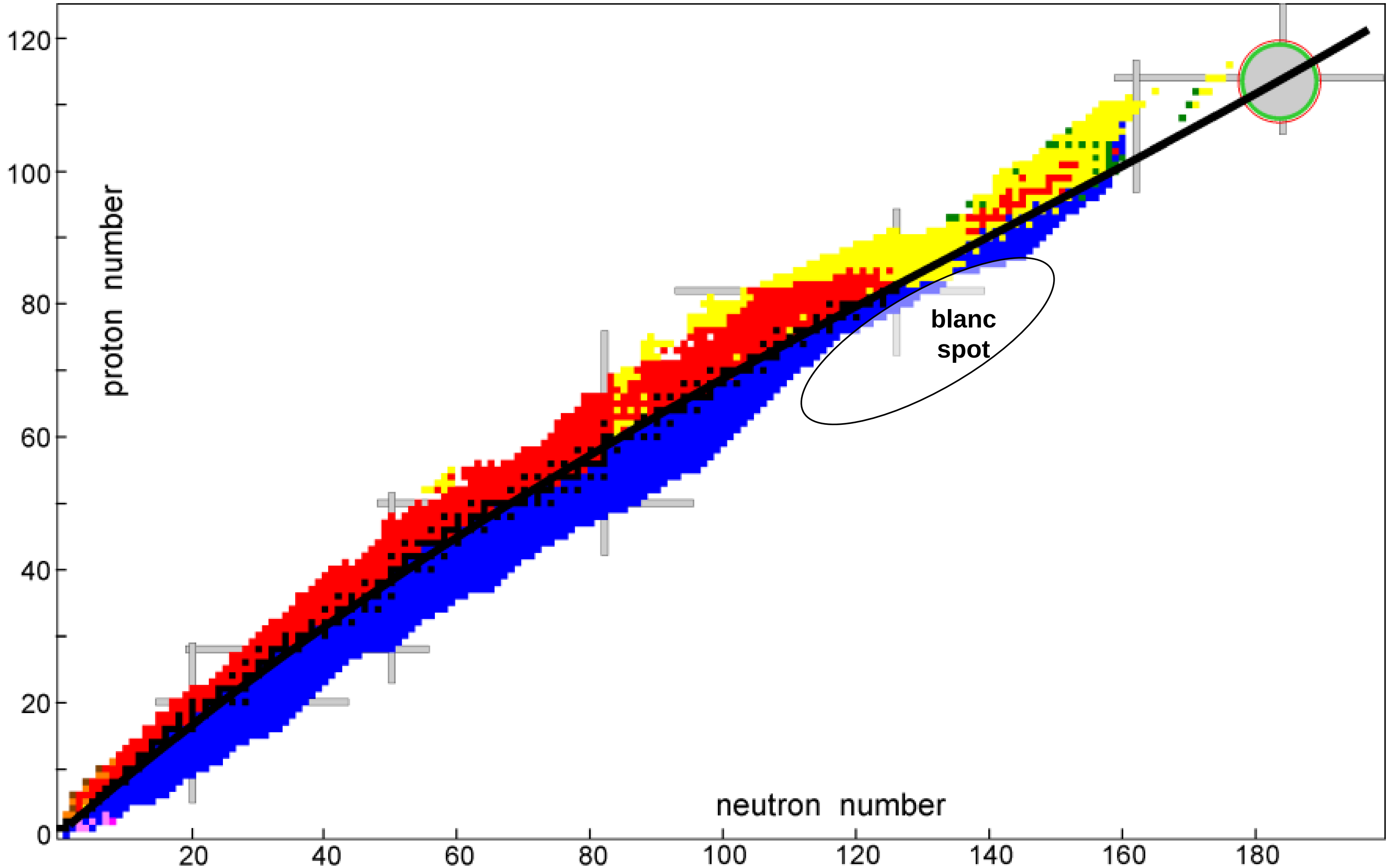
Shell effects in damped collisions
$^{160}Gd + ^{186}W$

(proposal for a new experiment)

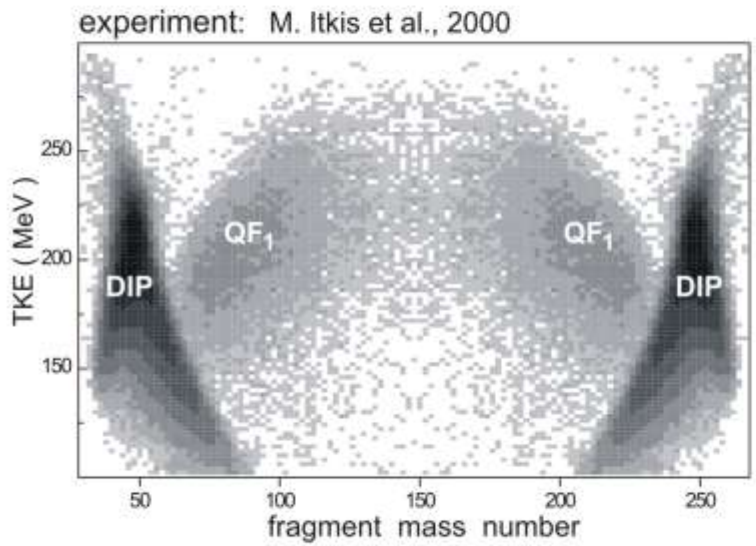


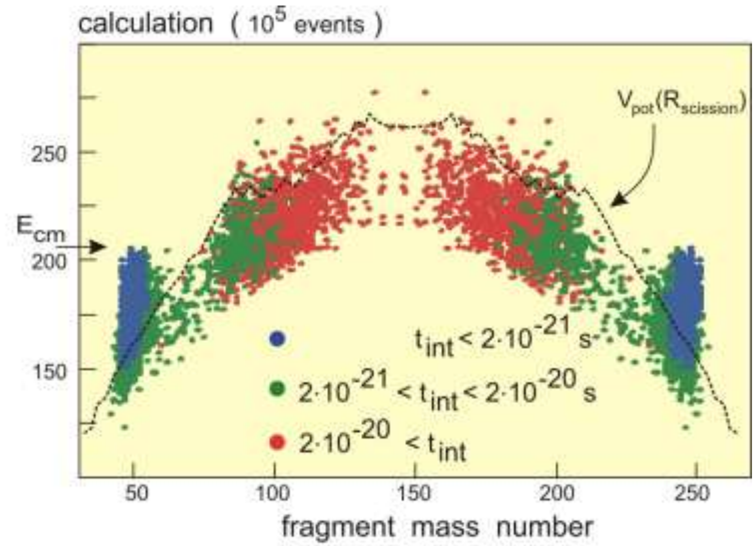


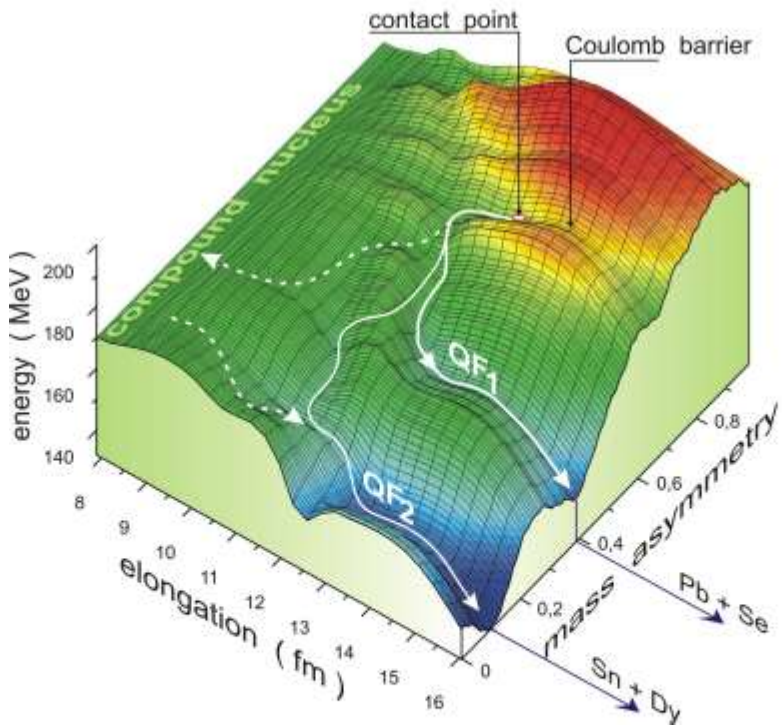
"Blanc Spot" on the Nuclear Map

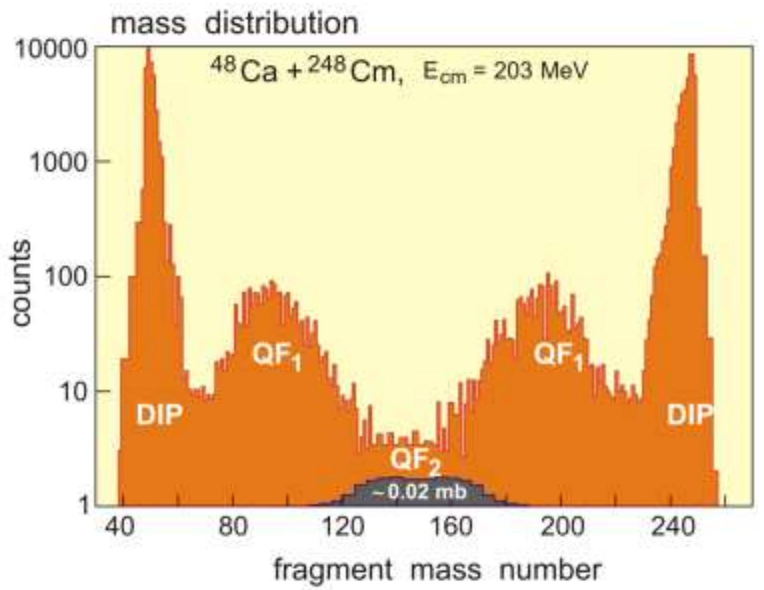


Quasi-Fission process: e.g. $^{48}Ca + ^{248}Cm$

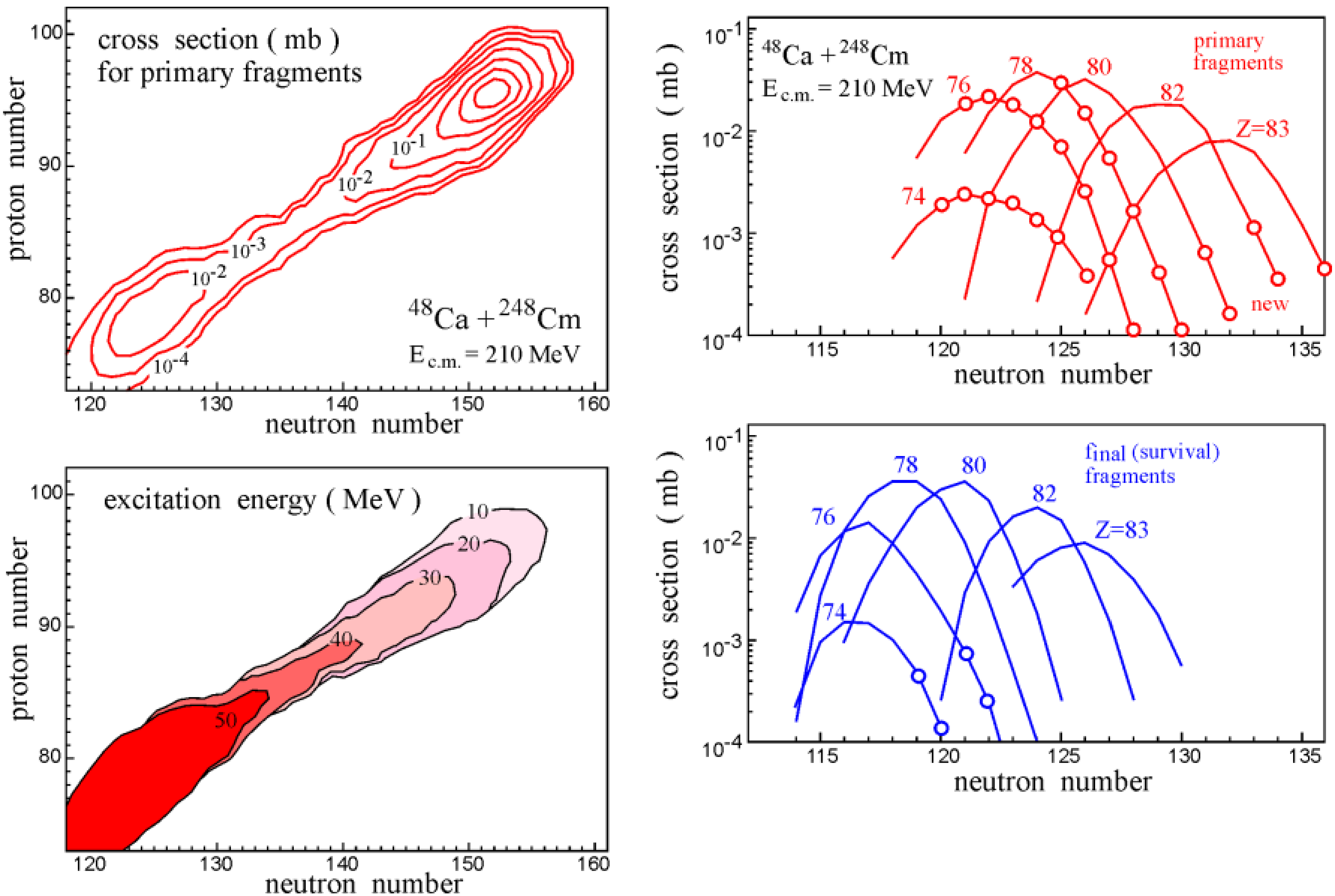






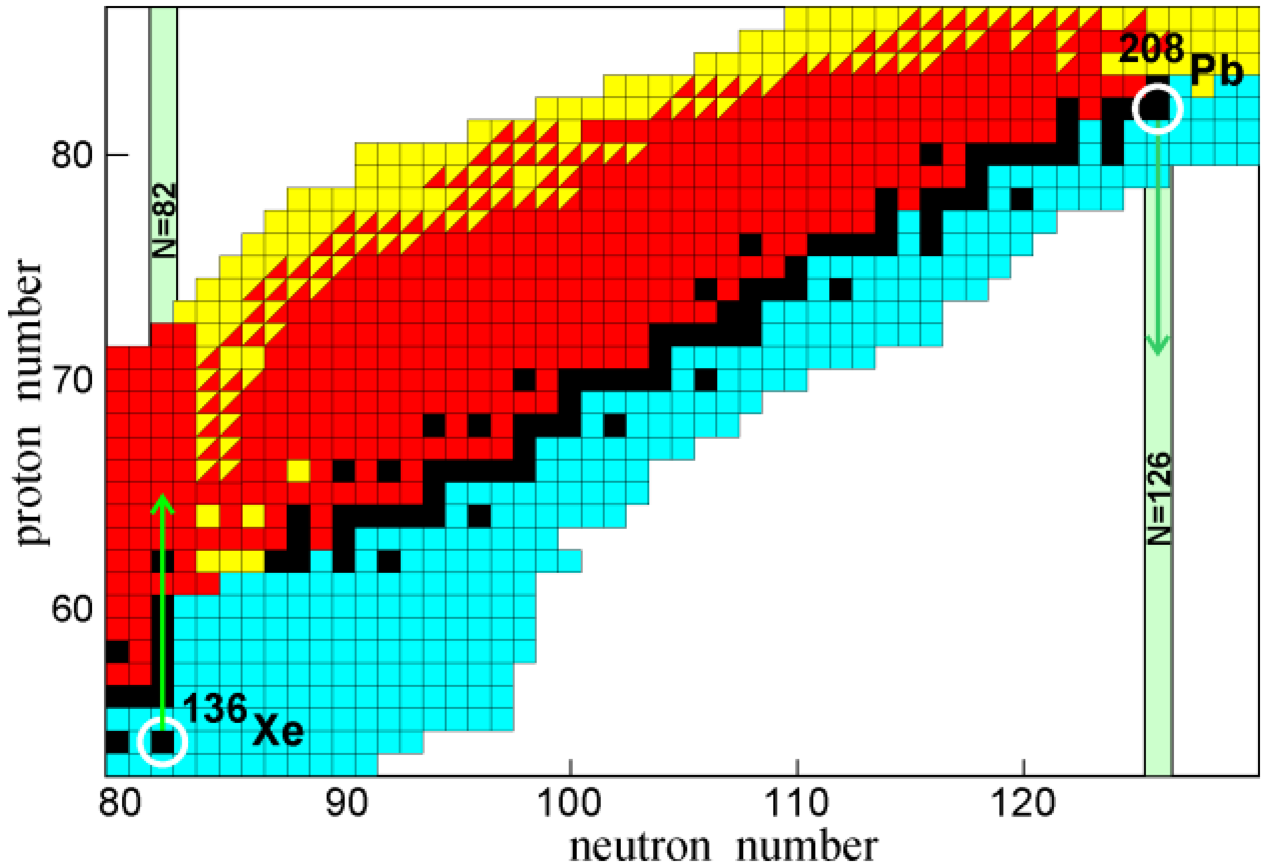


Production on new heavy nuclei in the quasi-fission process

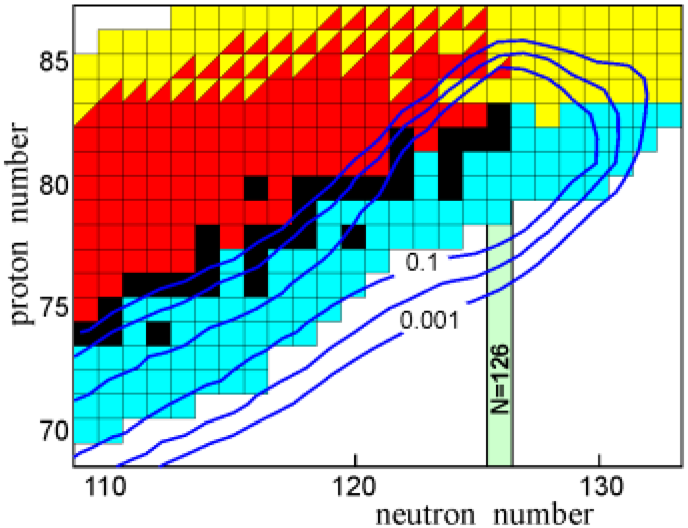


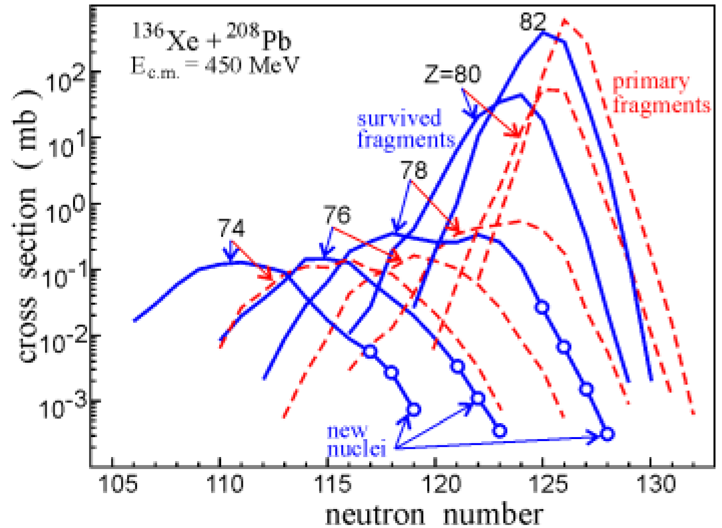
Production on new heavy nuclei in the region of N=126

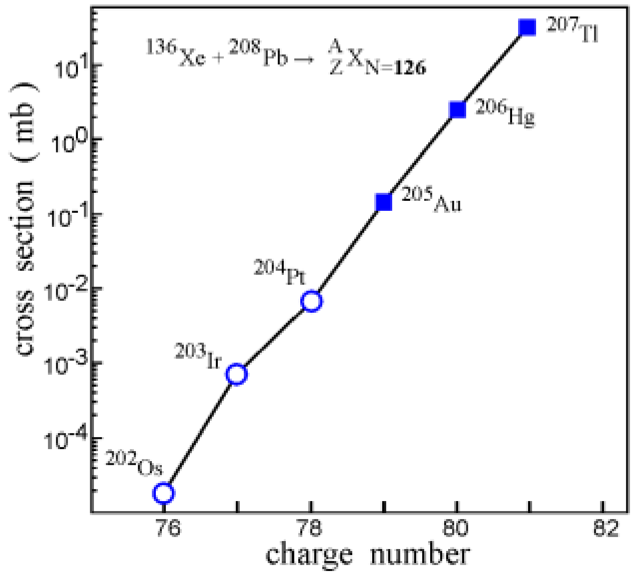
(Phys. Rev. Letters, 2008)



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







Summary

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

- **This "blank spot" of the nuclear map can be filled neither in fission reactions nor in fragmentation processes.**

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

- **Several tens of new 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.**