Damped Collisions of Heavy Ions.
Second Wind

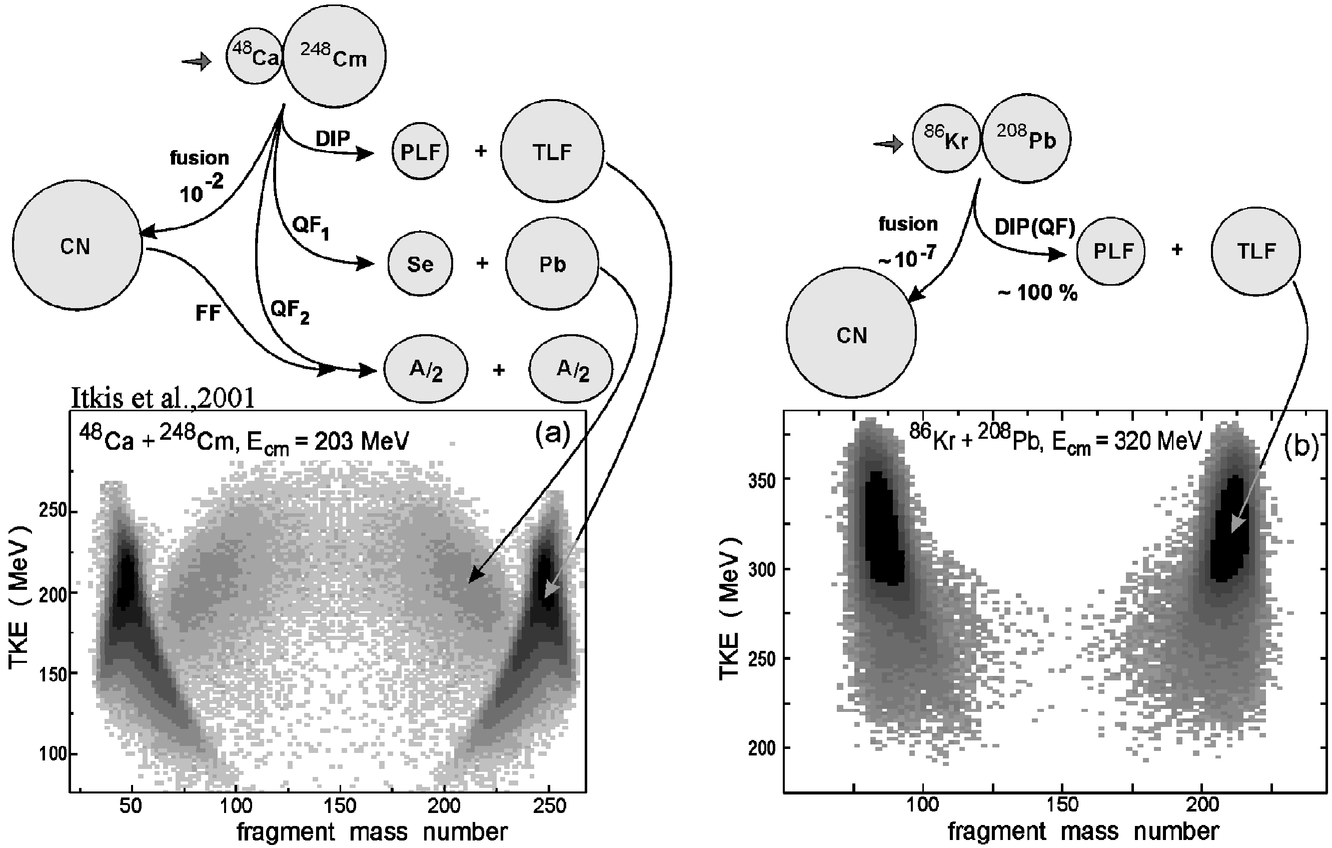
- **Dynamical model (DIC, fusion, fission, quasi-fission)**
- **Good agreement, at last!**
- **Neutron-rich superheavy nuclei**
- **Unexplored area of the nuclear map down the neutron shell N=126**
- **Summary**

JINR, Dubna

Valery Zagrebaev and Walter Greiner
for IRiS-10, Darmstadt, March 1, 2010

FIAS, Frankfurt

Low-energy collisions of HI and “nucleon rearrangement”



DI scattering, quasi-fission, fusion and regular fission are strongly overlapped processes (and very often indistinguishable).
Therefore one needs **simultaneous description** of all these processes.
At near barrier collisions “transfer” of 20, 30 nucleons is in fact “nucleon rearrangement”.

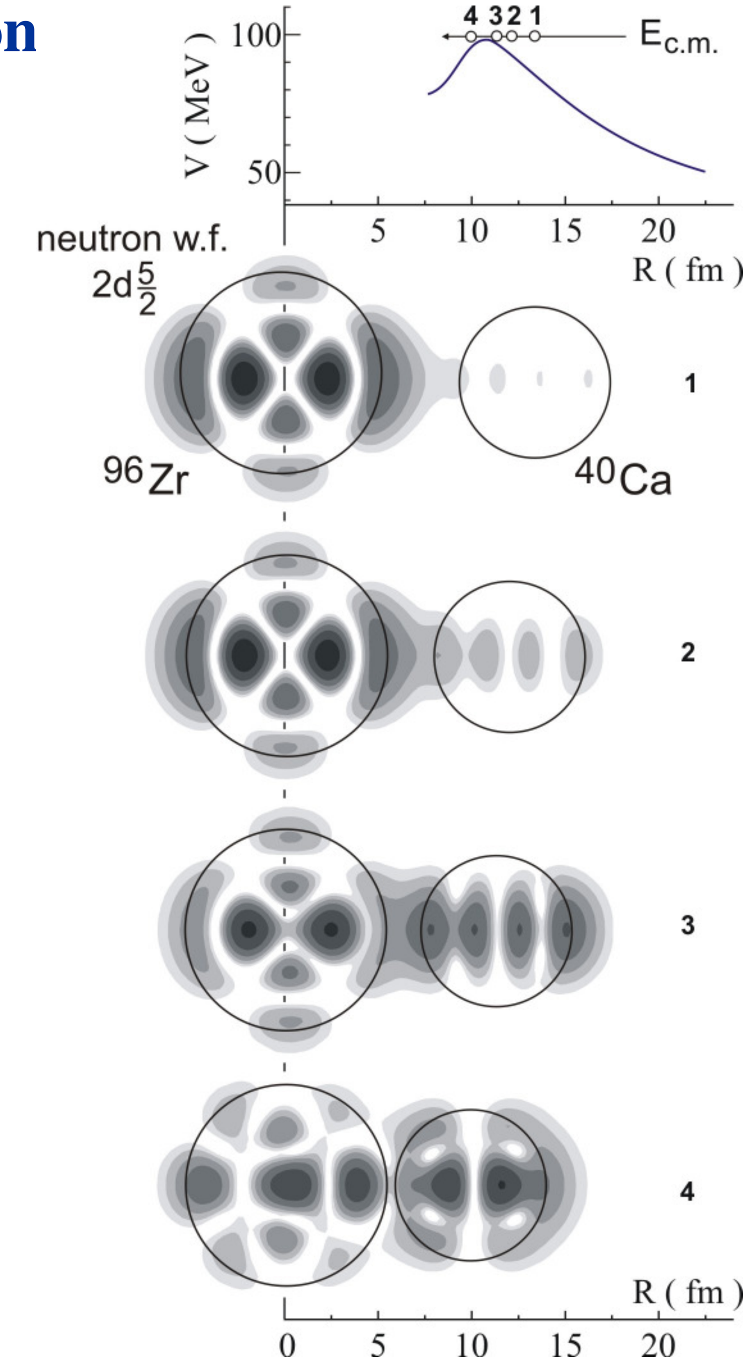
Unified degrees of freedom: R, β_1, β_2, η_Z, η_N.

Unified set of dynamical equations: Langevin type.

What is behavior of valence nucleon at near-barrier collisions of HI ?

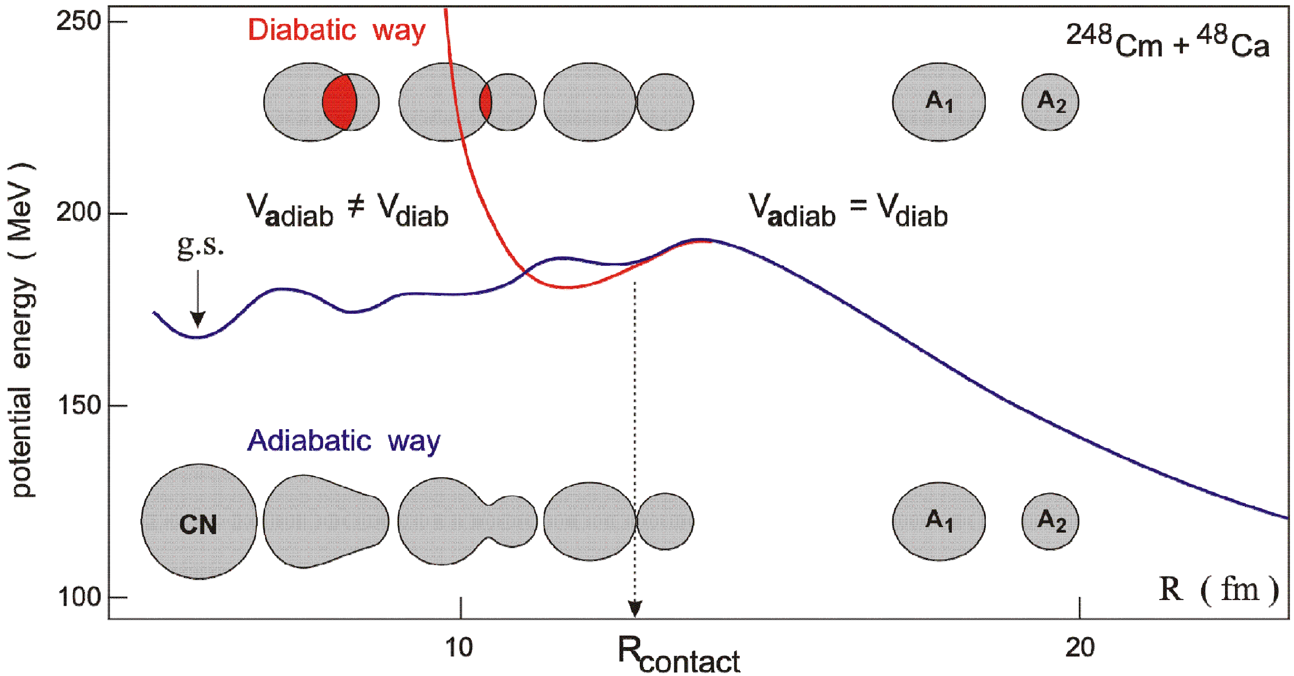
Time-dependent Schrödinger equation shows that at low-energy collisions nucleons do not "jump" from one nucleus to another ~~$(<\psi_i(\mathbf{r}_i)|\psi_k(\mathbf{r}_k)>)$~~.
Wave functions of valence nucleons follow the two-center **molecular states** spreading over both nuclei.

→ **Two-Center Shell Model and Adiabatic Potential Energy Surface are appropriate for description of such processes.**



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

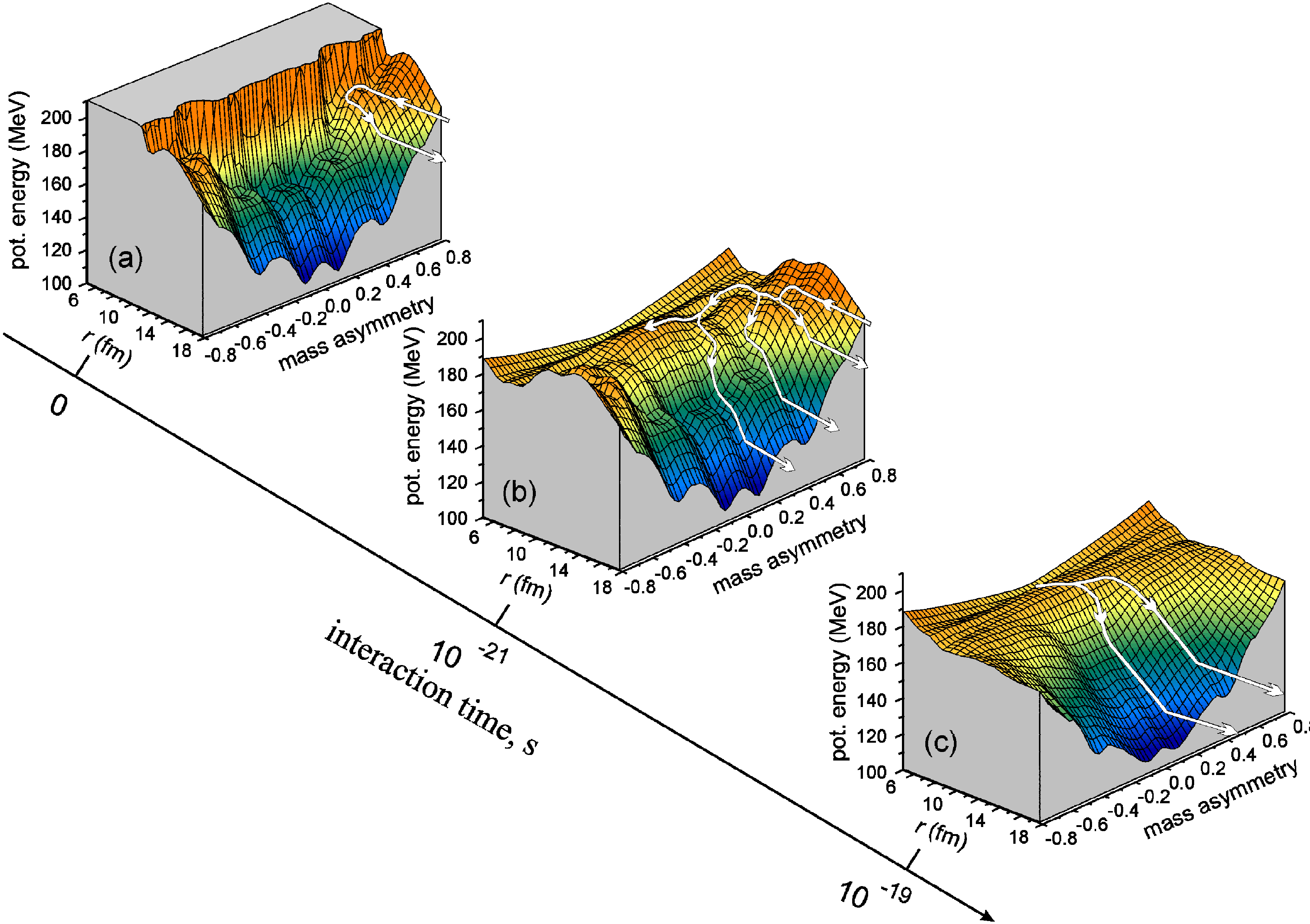
$$V(t) = V_{diab}(\xi)\cdot\exp(-\frac{t_{int}}{\tau_{relax}}) + V_{adiab}(\xi)\cdot[1-\exp(-\frac{t_{int}}{\tau_{relax}})]$$

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

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

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

Time-dependent Driving Potential



System of coupled Langevin type Equations of Motion

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

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

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

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

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

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

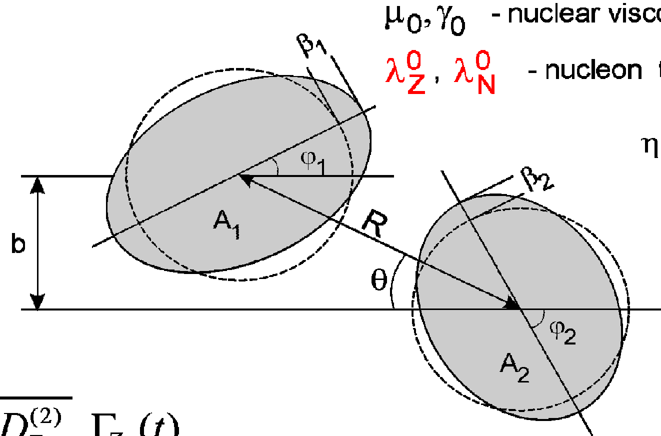
$$\frac{d\eta_N}{dt} = \frac{2}{N_{CN}} D_N^{(1)} + \frac{2}{N_{CN}} \sqrt{D_N^{(2)}}\ \Gamma_N(t)$$

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



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

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

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

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

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

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

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

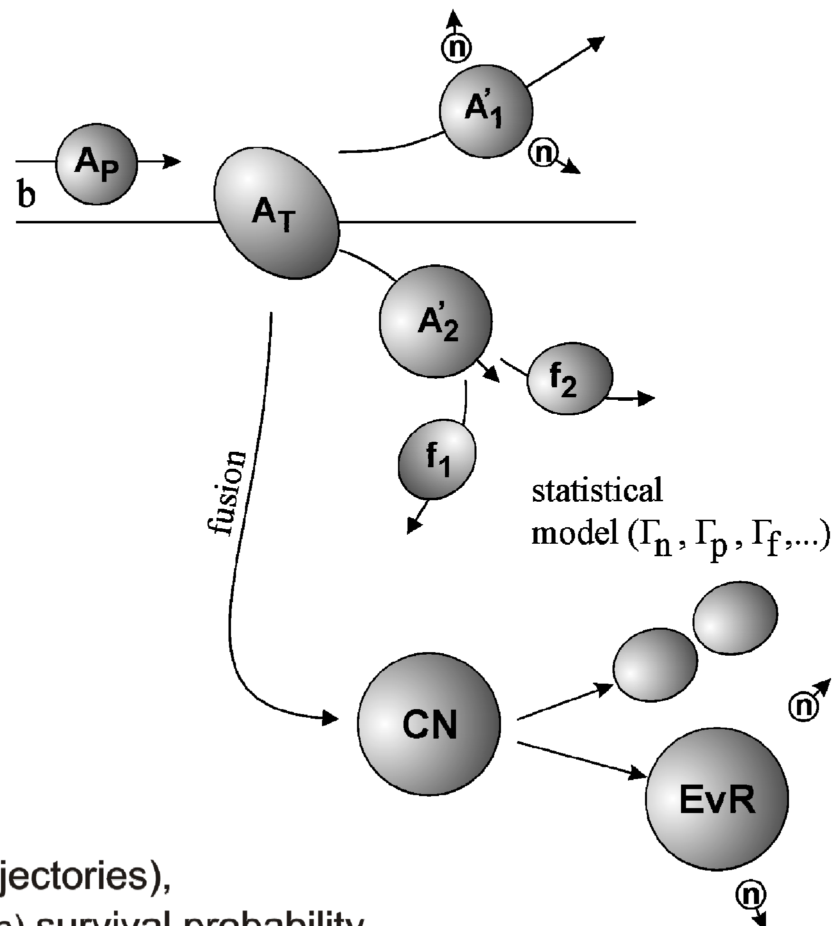
$$\frac{dL_2}{dt} = -\frac{\partial V}{\partial \varphi_2} + \gamma_{\rm tan}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1}a_1 - \frac{L_2}{\Im_2}a_2\right) a_2 - \frac{a_2}{R}\sqrt{\gamma_{\rm tang} T}\,\Gamma_{\rm tang}(t)$$

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

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

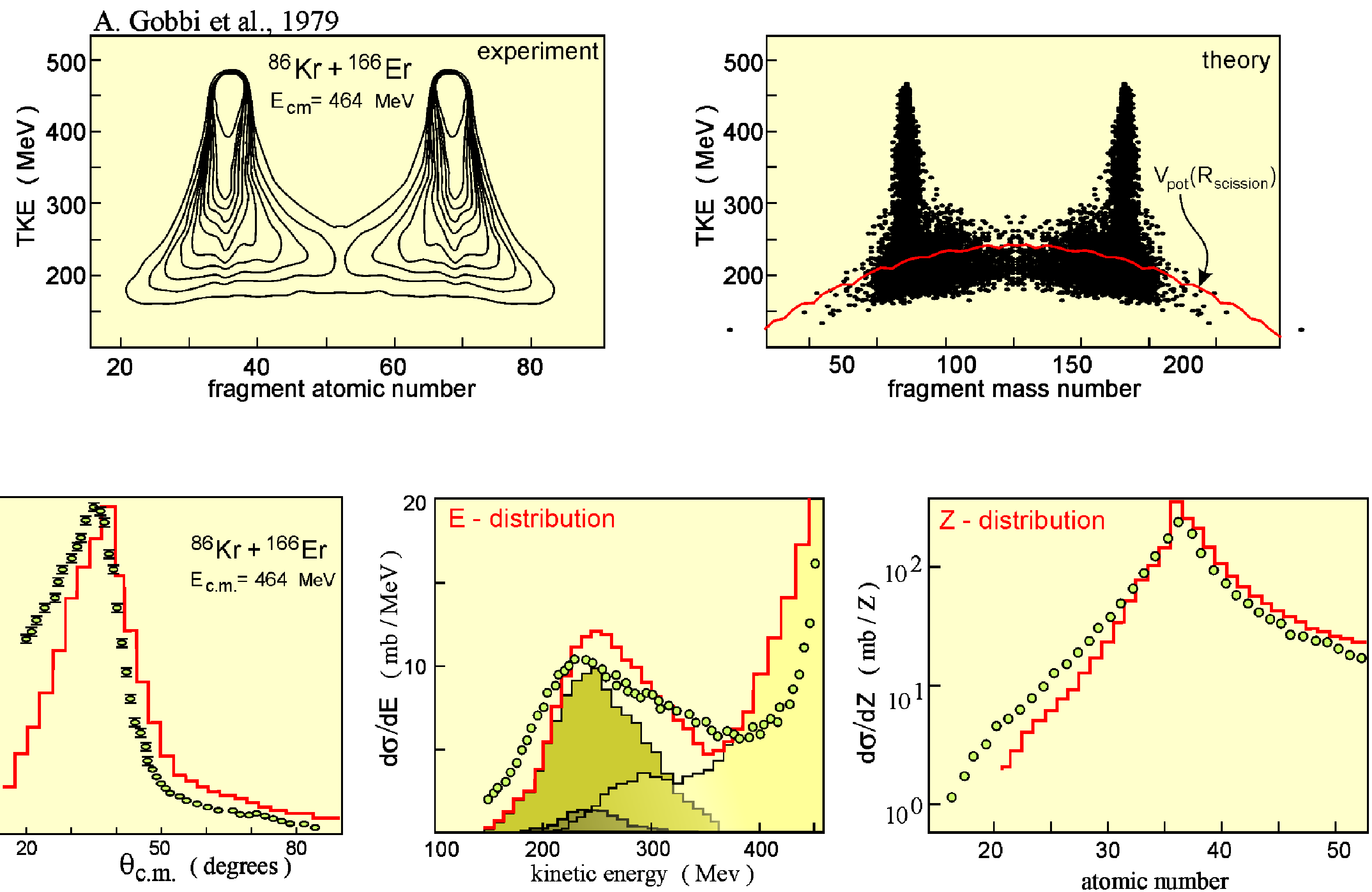
Simulation of experiment and cross sections

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

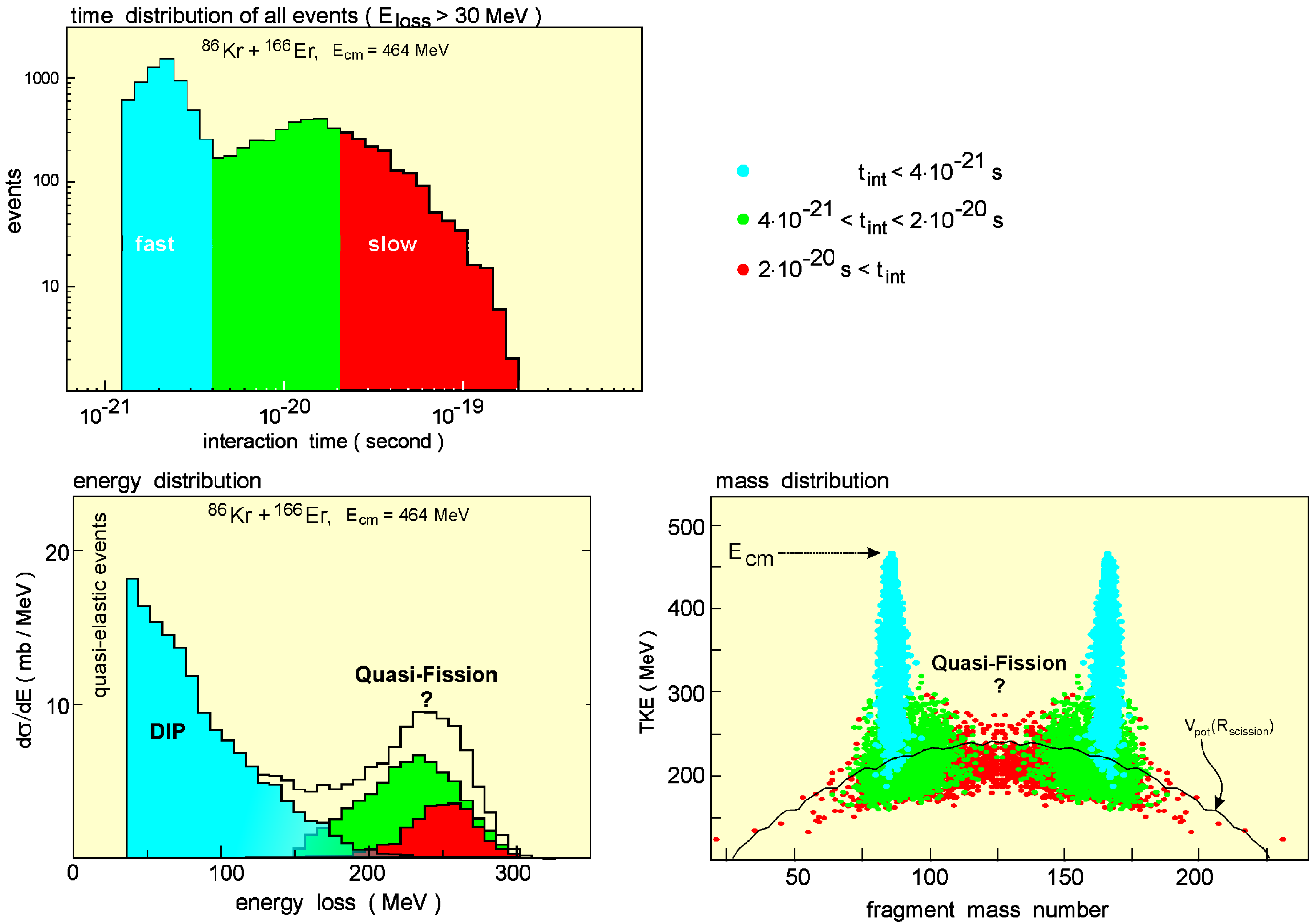


Dynamics: **10^6** tested events (trajectories),
Statistical model: **10^{-6}**(3n), **10^{-7}**(4n) survival probability
cross sections up to **0.1 pb** can be calculated

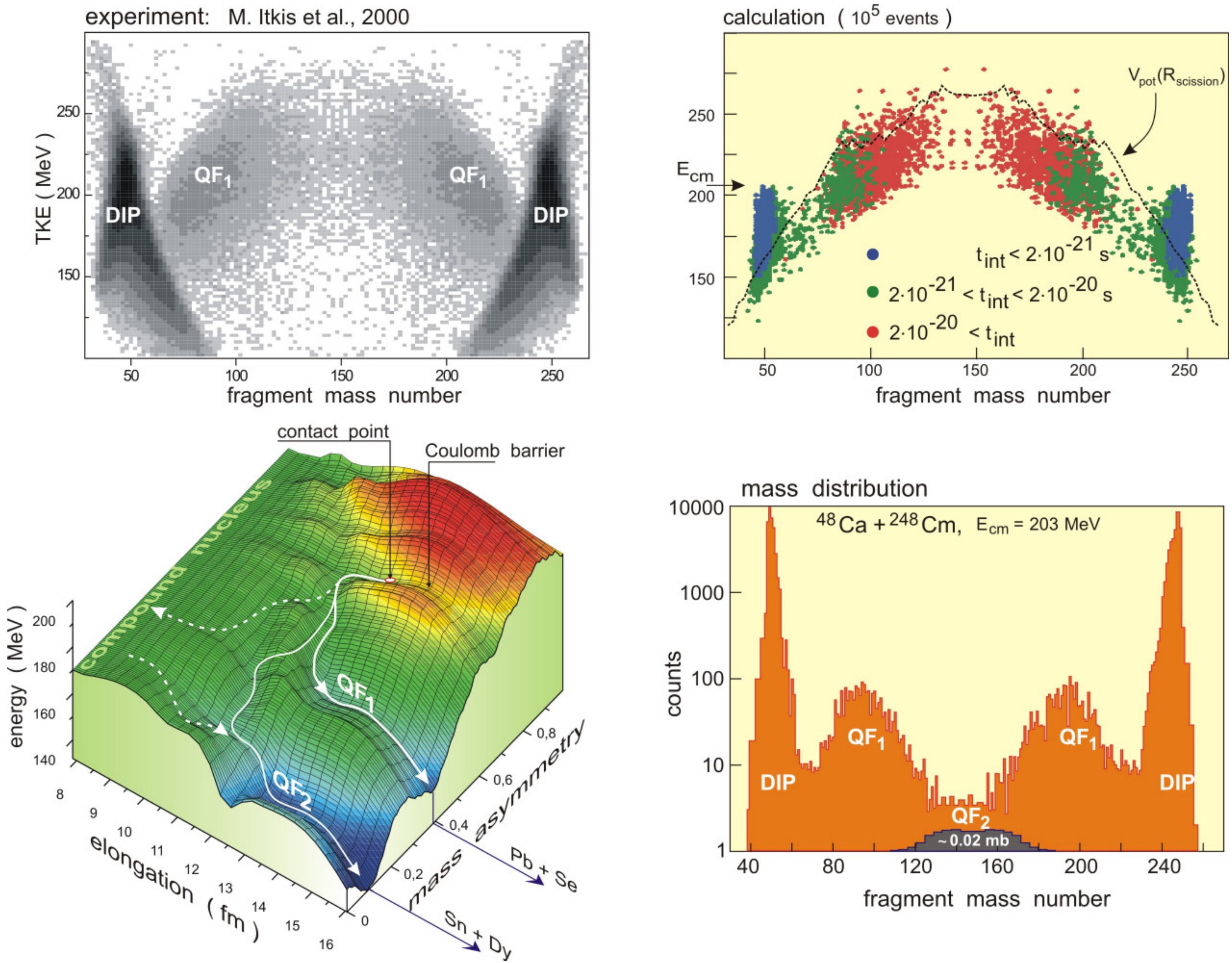
^{86}Kr + ^{166}Er collision at $E_{c.m.}$ = 464 MeV (Coulomb barrier = 260 MeV)



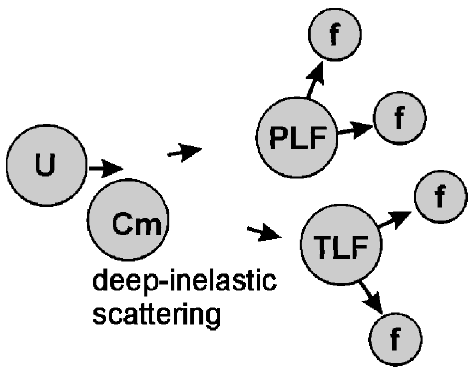
Time analysis

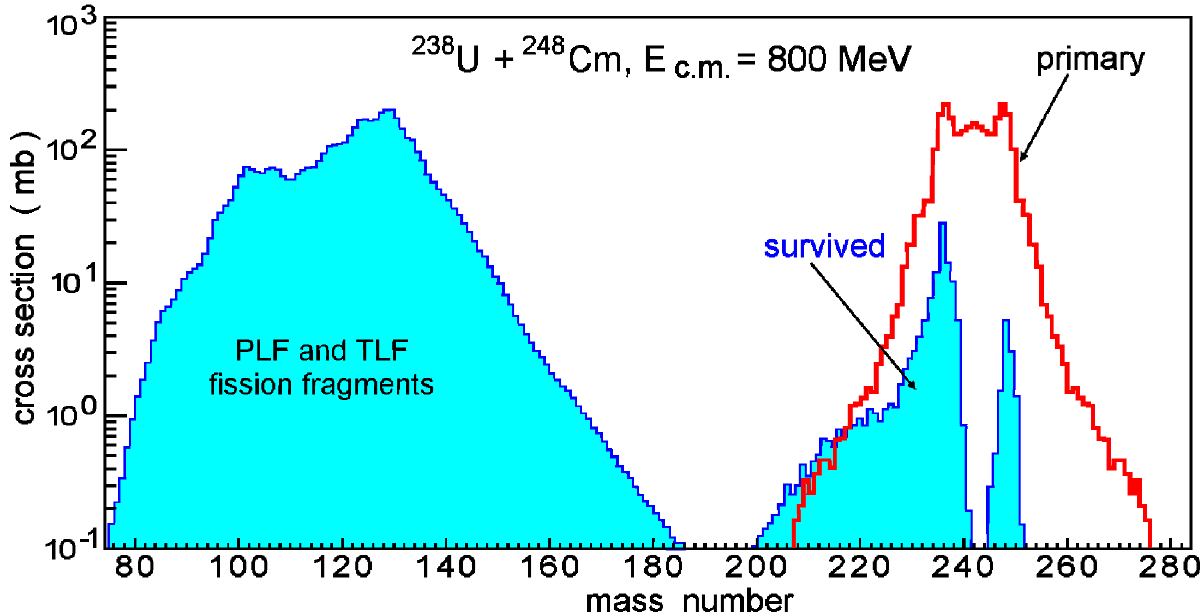


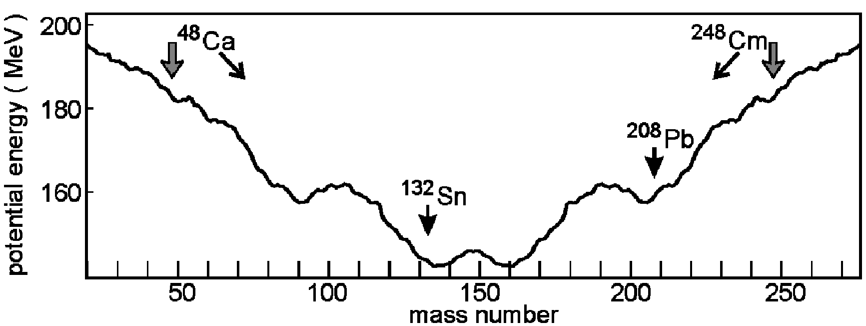
$^{48}Ca + ^{248}Cm$ collisions at E_{cm} = 203 MeV (Shell effects)



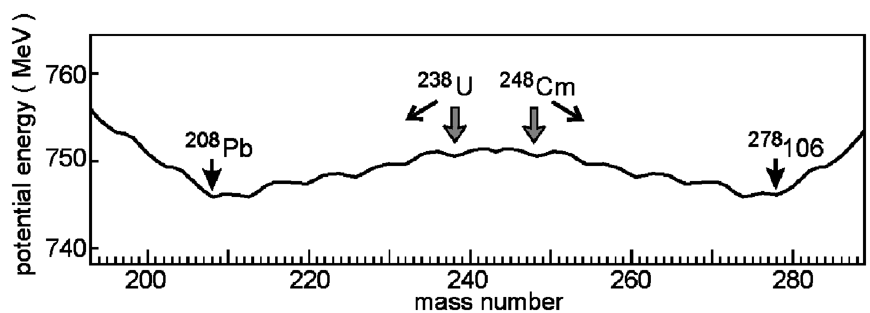
Transfer reactions in damped collision of very heavy nuclei ?





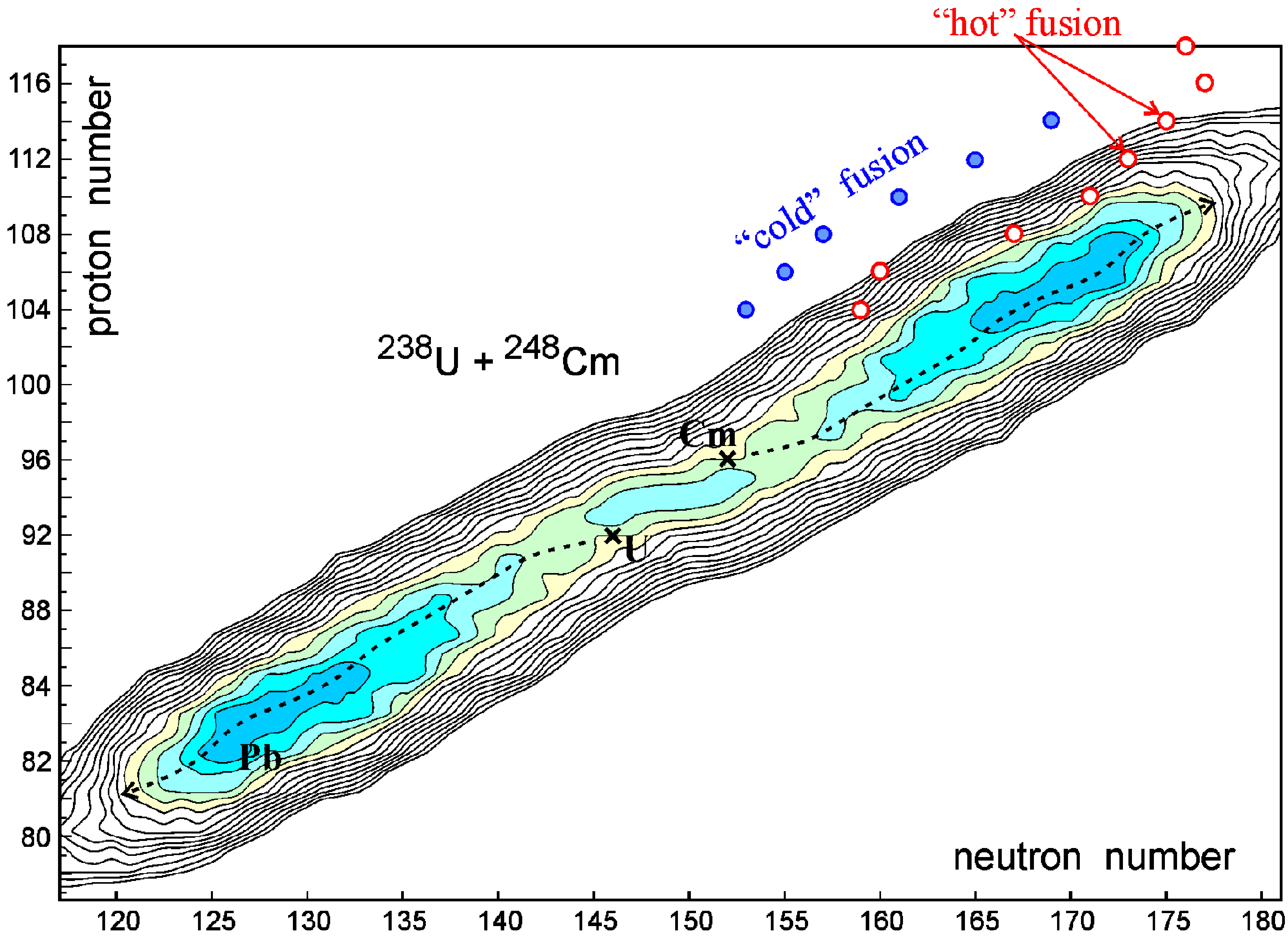


ordinary (symmetrizing) quasi-fission

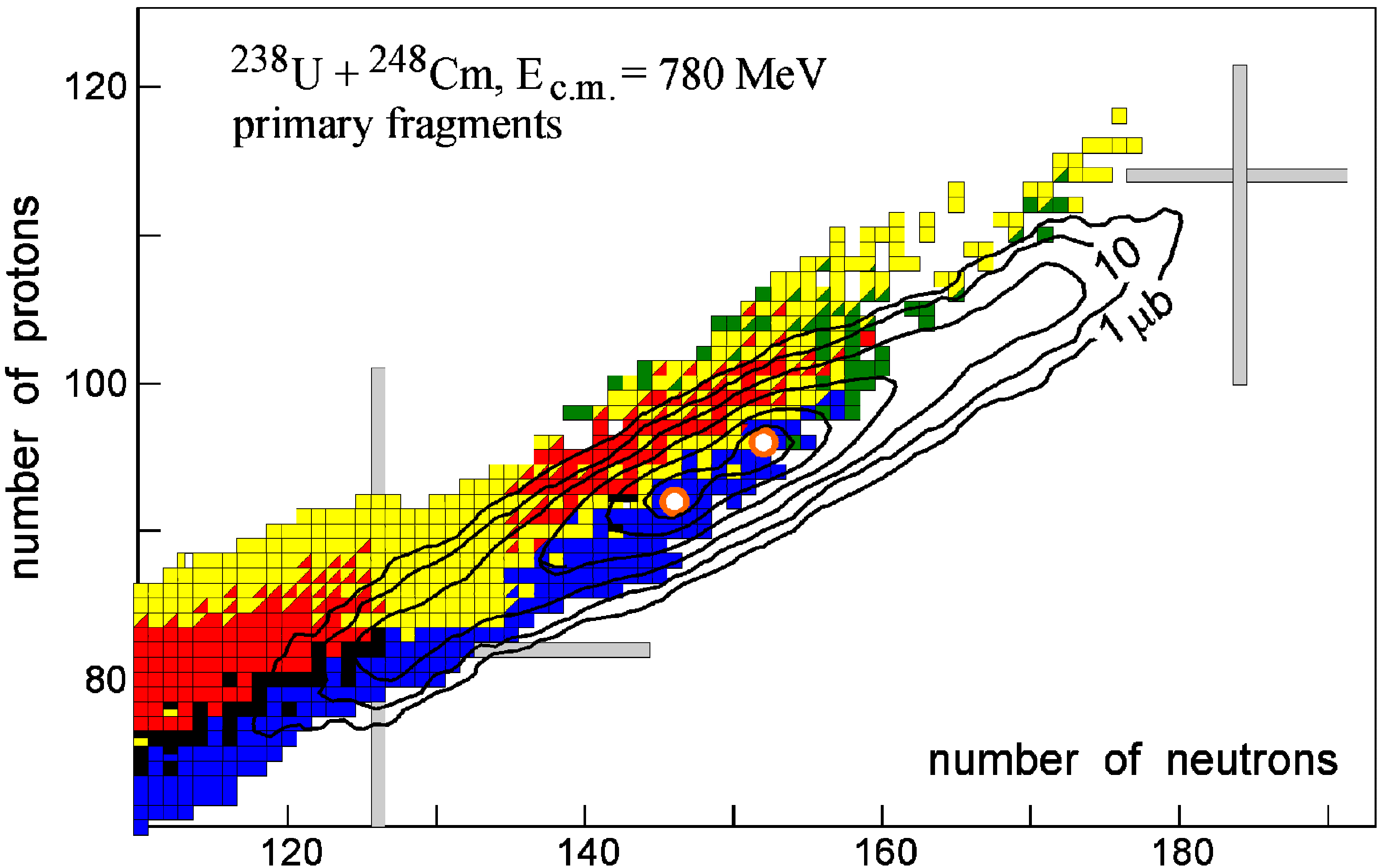


anti-symmetrizing quasi-fission

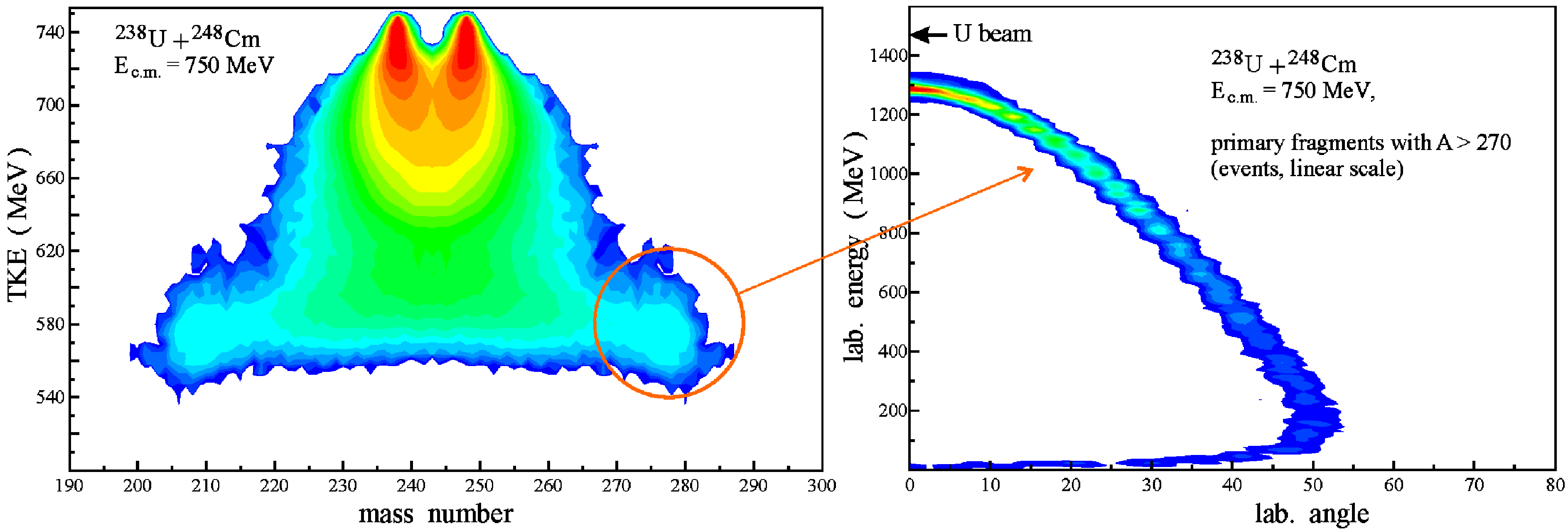
Production of SHE along the stability line in low-energy collisions of actinide nuclei



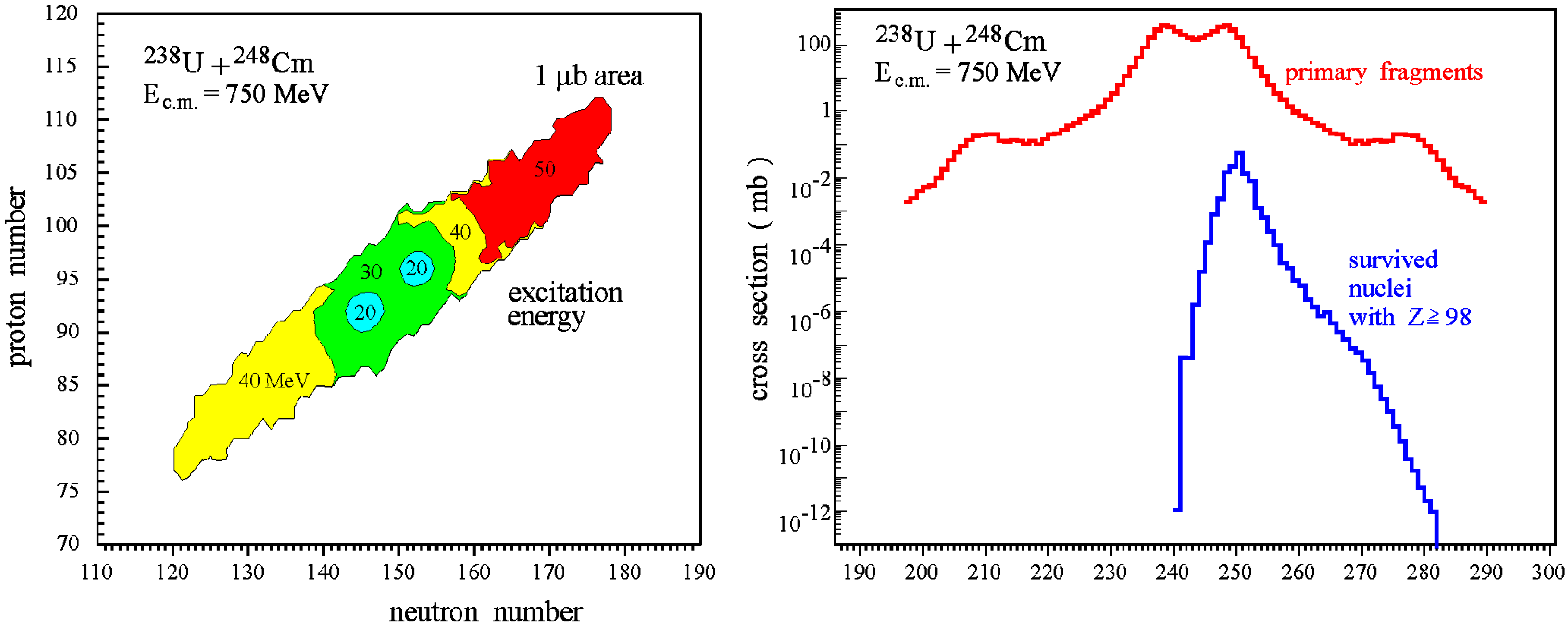
238U + 248Cm. Primary fragments



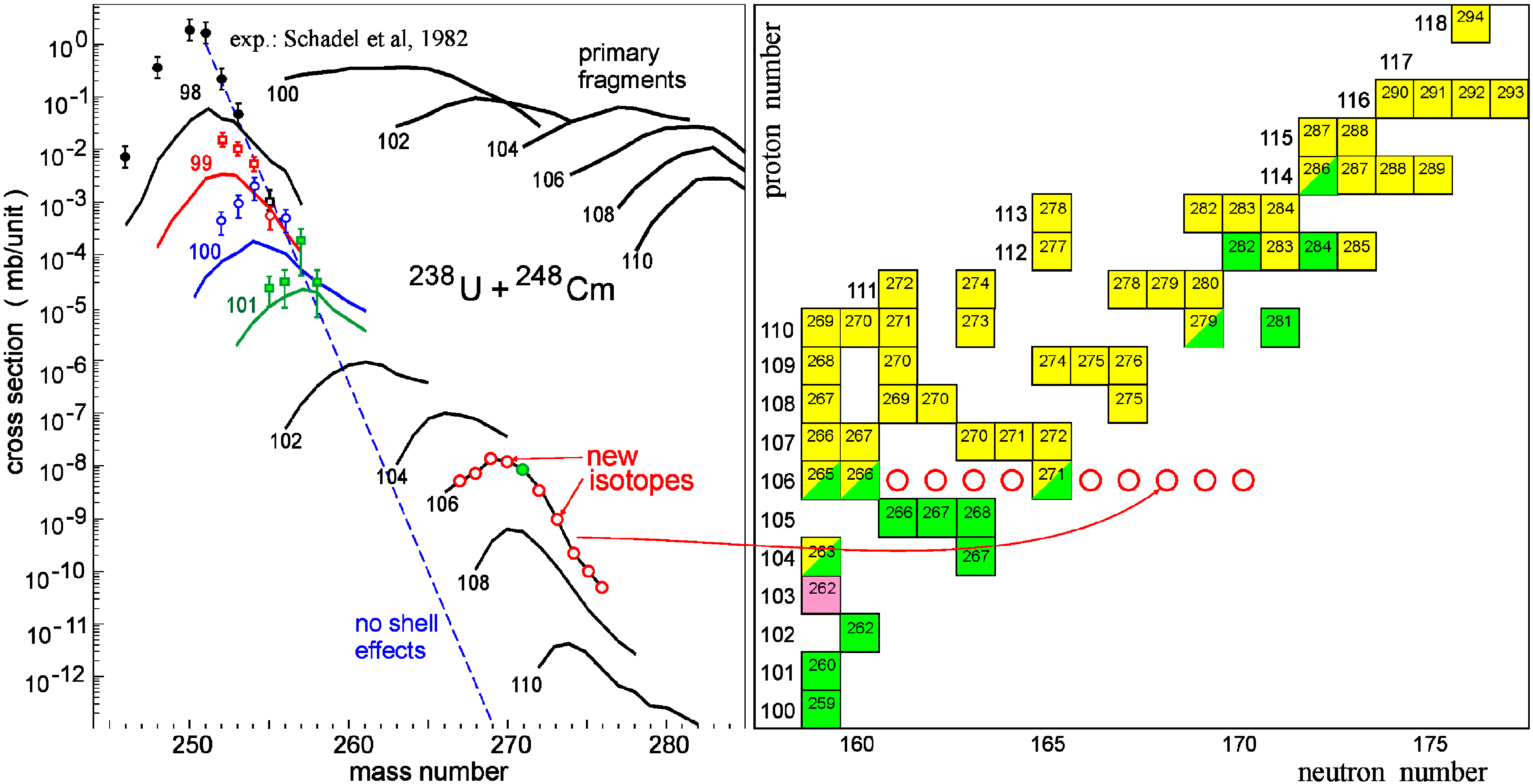
238U + 248Cm. Energy and angular distributions



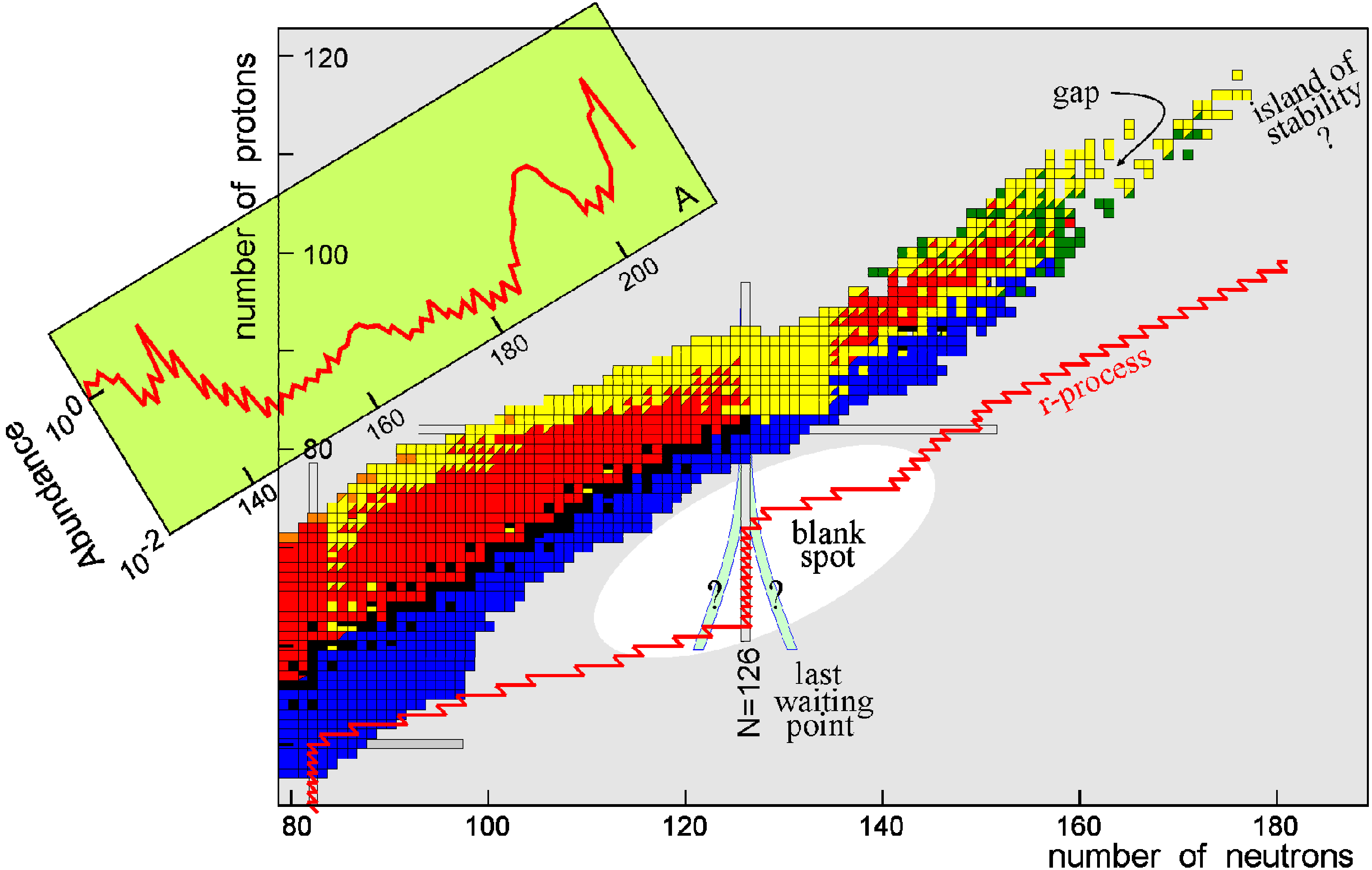
238U + 248Cm. Excitation energies and survival probability



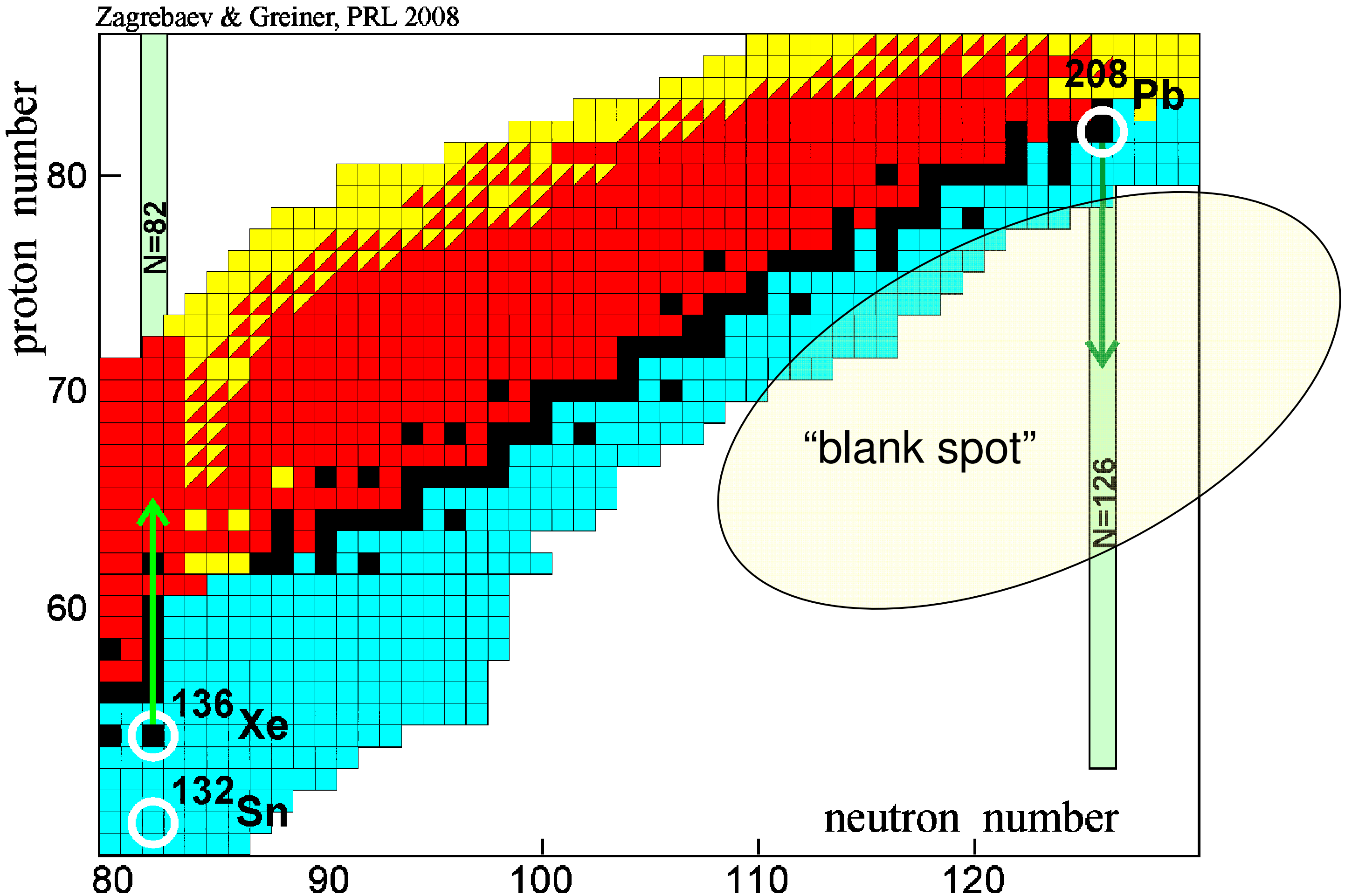
Production of neutron-rich SHE in low-energy collisions of heavy actinide nuclei



How to explore the 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:

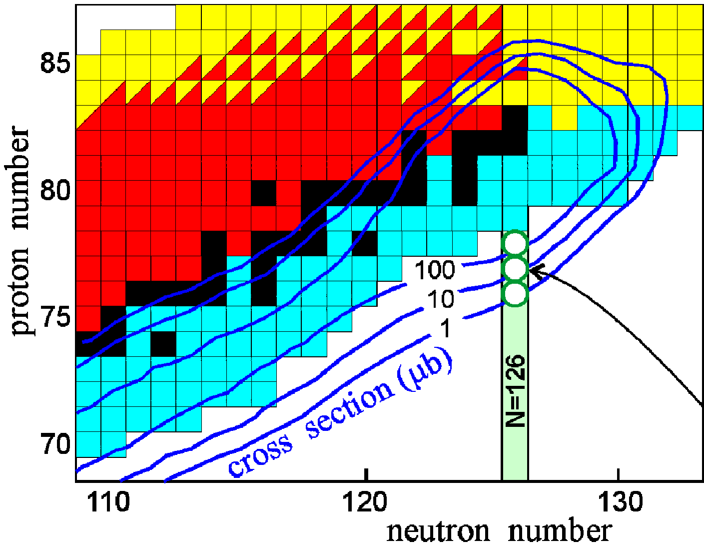
$$^{136}Xe_{N=82} + {}^{208}Pb_{N=126} \rightarrow {}^{136+\Delta Z}X_{N=82} + {}^{208-\Delta Z}Y_{N=126} + Q \approx 0$$

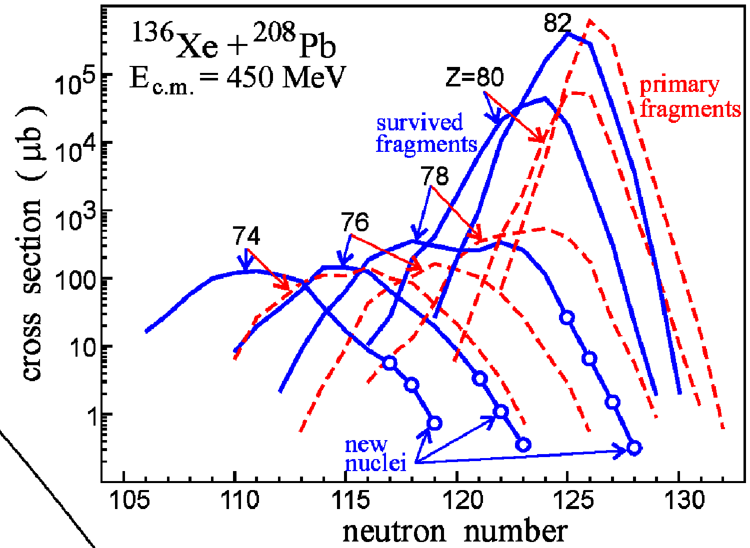
Reactions with $Q \approx 0$ are very favorable for proton transfer

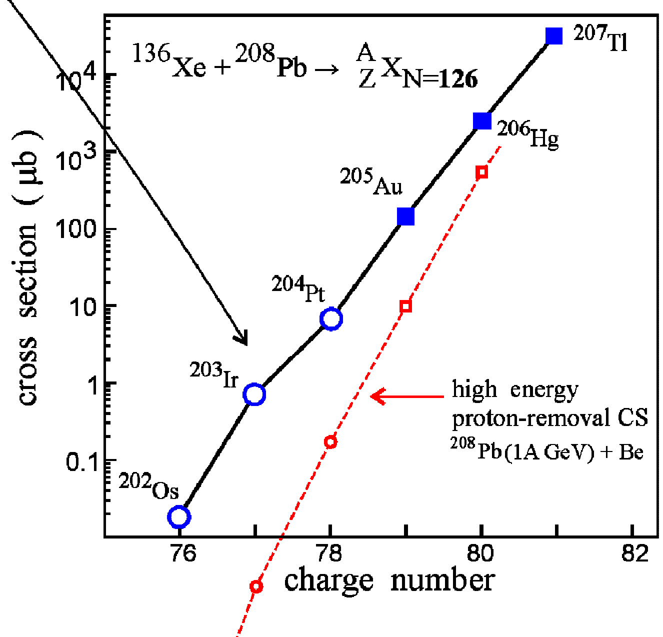
The use of ^{132}Sn is even better !

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

Summary

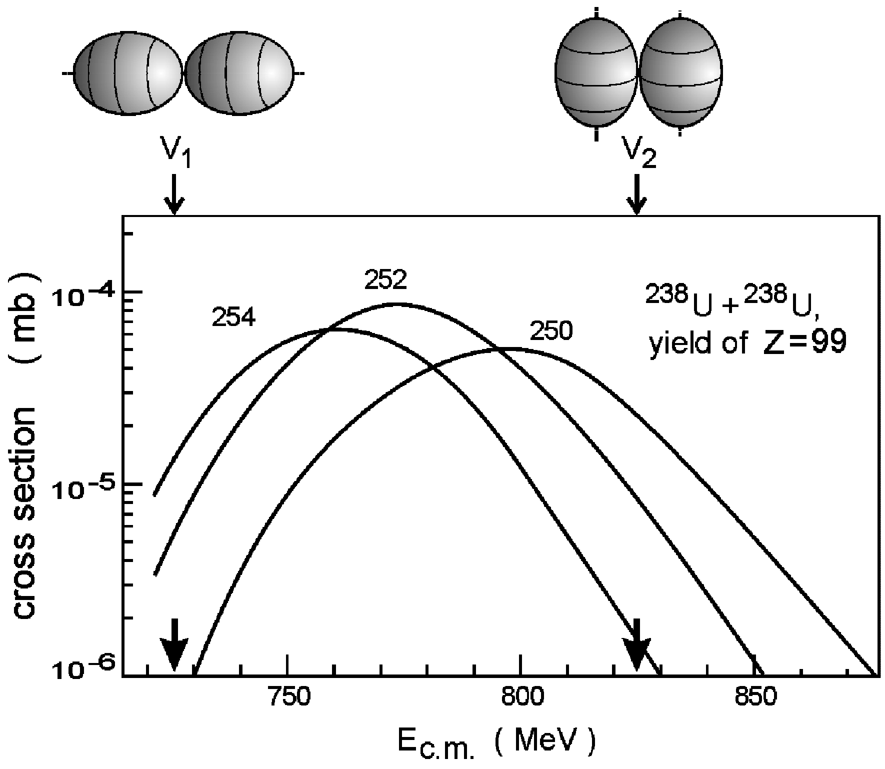
- **Transport dynamical model based on Langevin-type equations of motion and time-dependent driving potential (8 degrees of freedom) seems to be appropriate for description of low-energy heavy ion collisions (including those with large mass and charge rearrangement).**

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

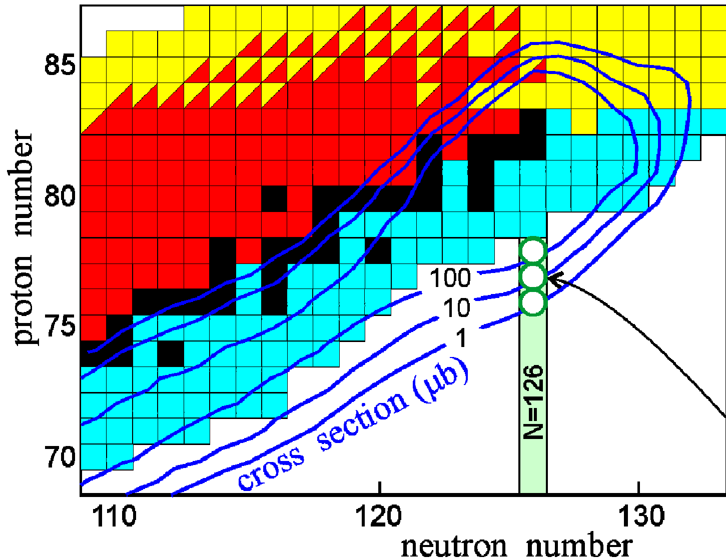
- **Near-barrier collisions of heavy ions (Xe+Pb like) allow us to fill and explore also the north-east area of the nuclear map (important for astrophysical investigations).**

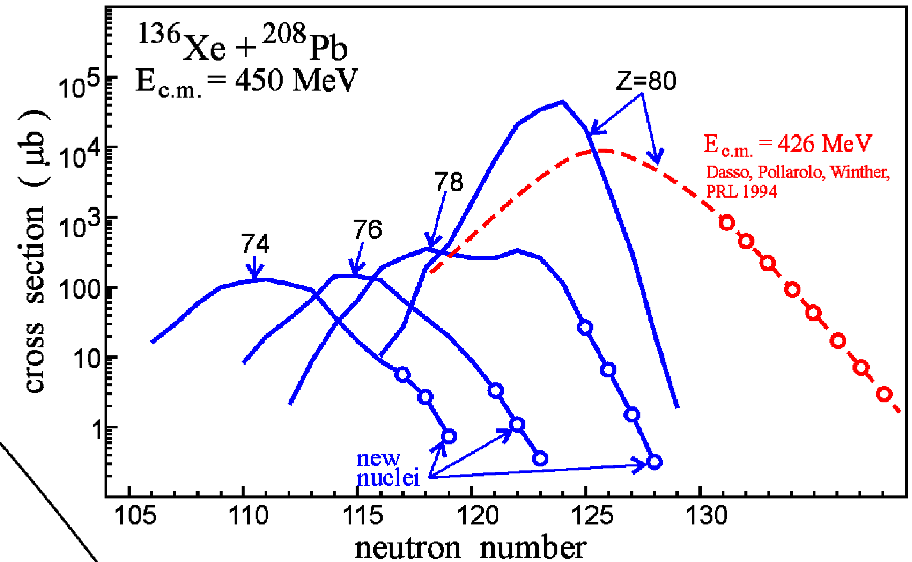
- **New kind of separators (and/or new experimental methods) are needed to perform such experiments.**

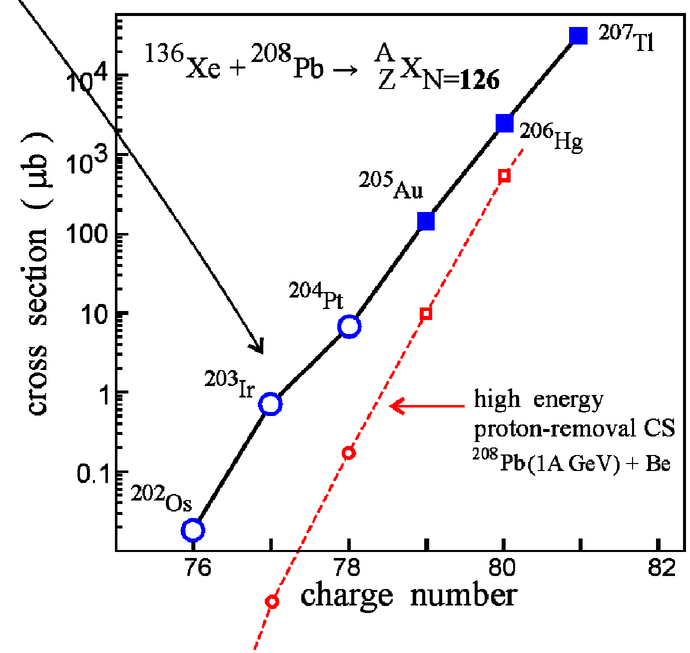
Excitation functions for production of SHE in collisions of actinides



Production on new heavy nuclei in the Xe + Pb collisions







Several tens of new neutron-rich nuclides
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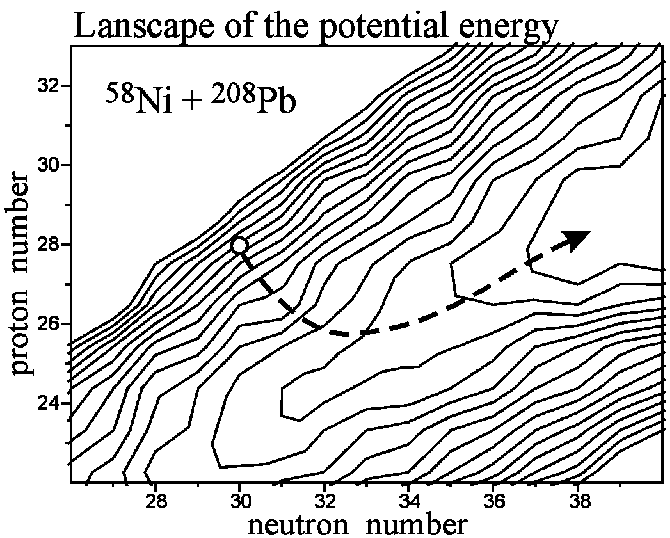
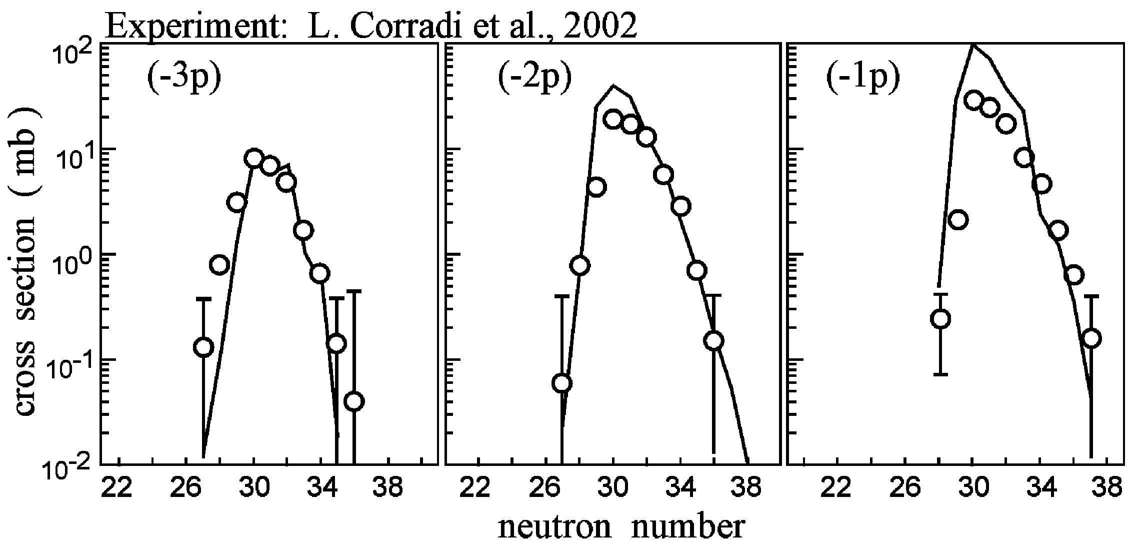
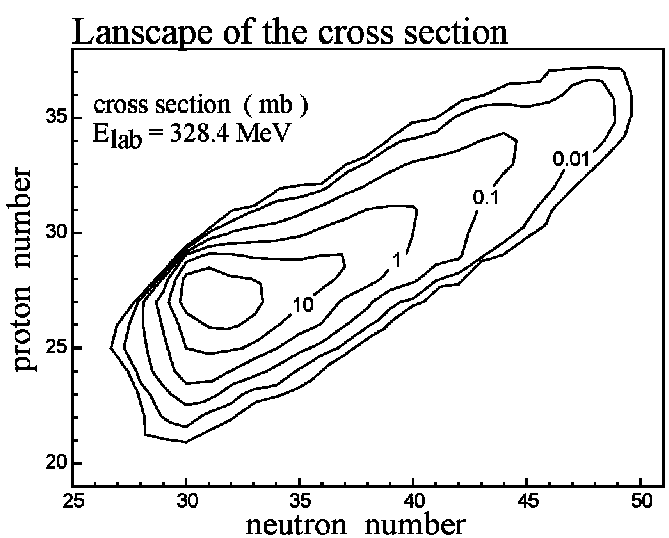
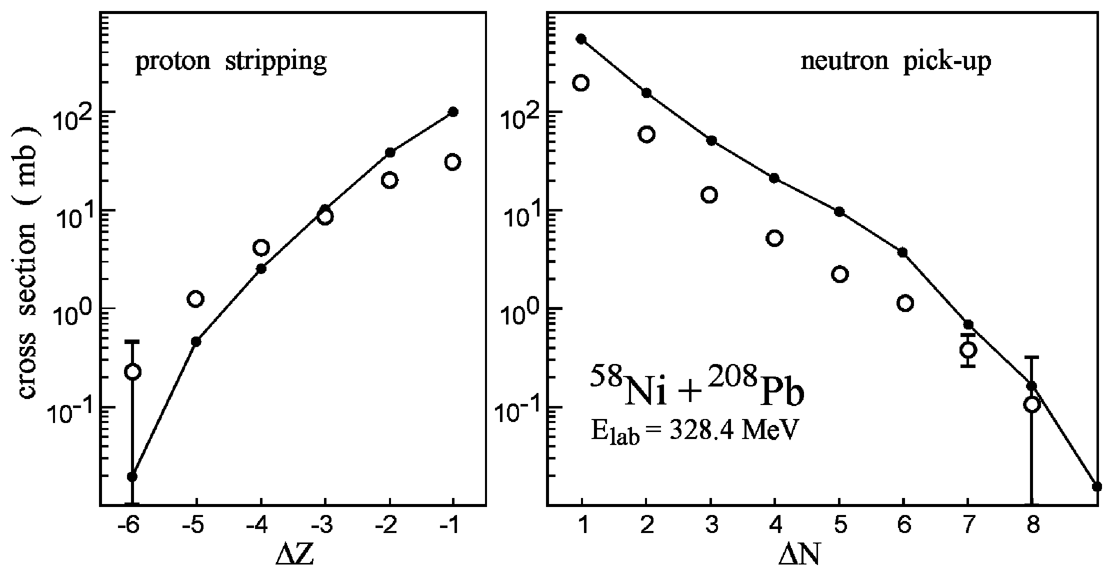
near-barrier collision of 136Xe with 208Pb

Comparison with experiment on multi-nucleon transfer



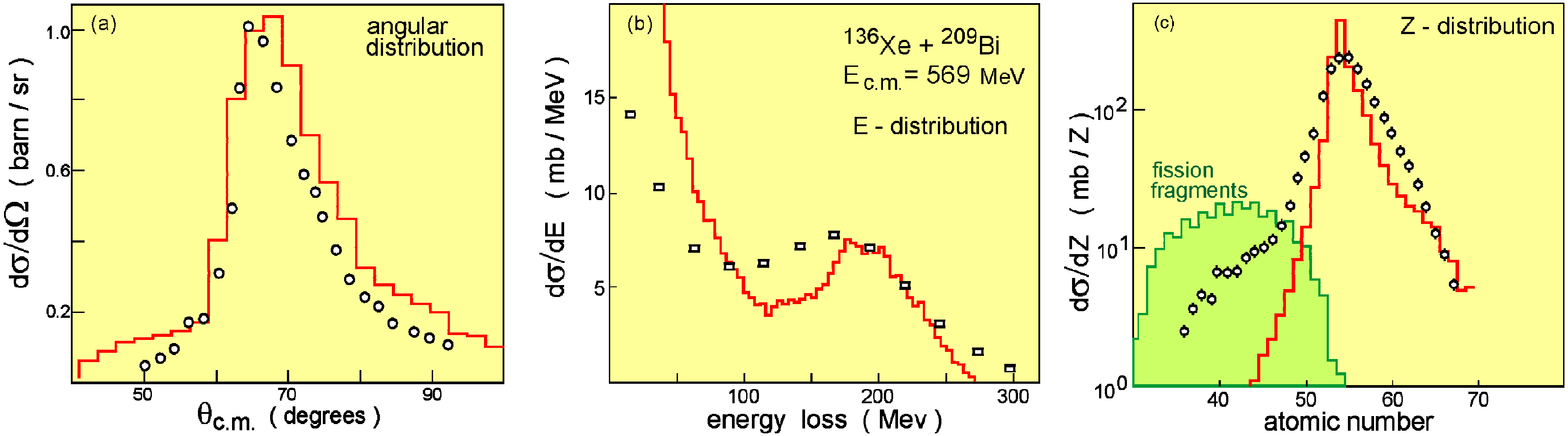


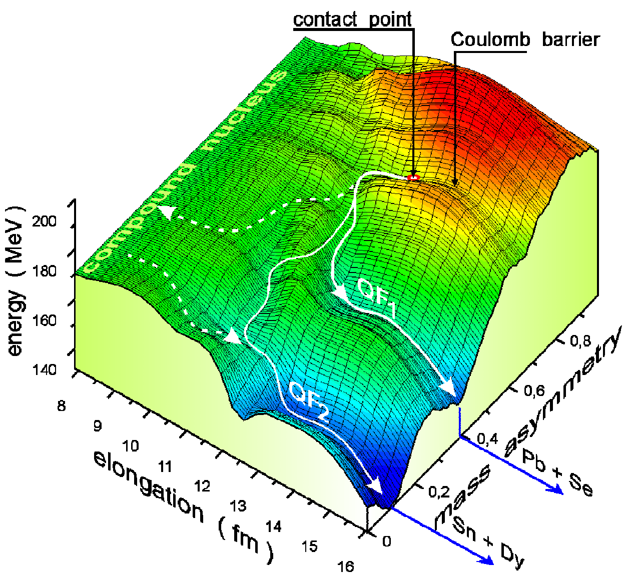




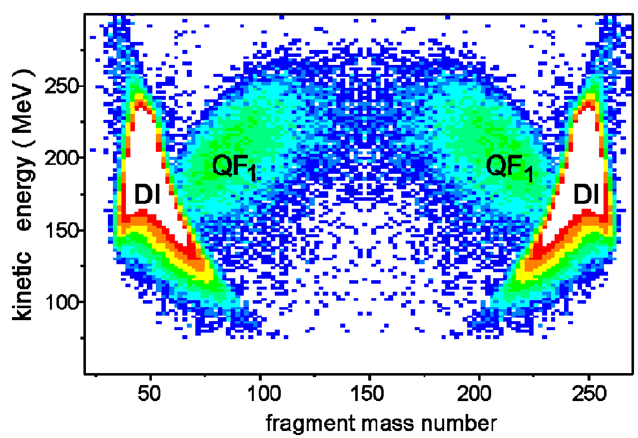
Deep inelastic scattering and quasi-fission phenomena

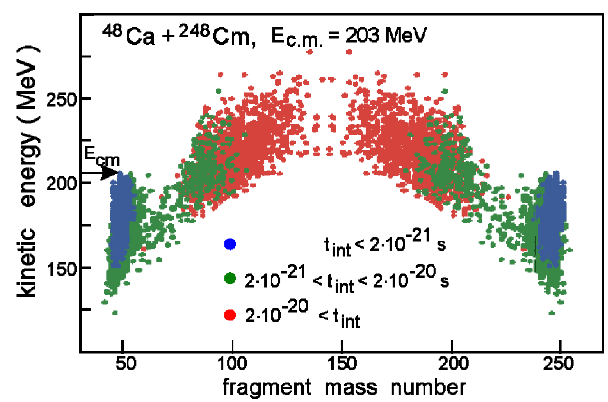
experiment: Wilcke *et al.*, 1980



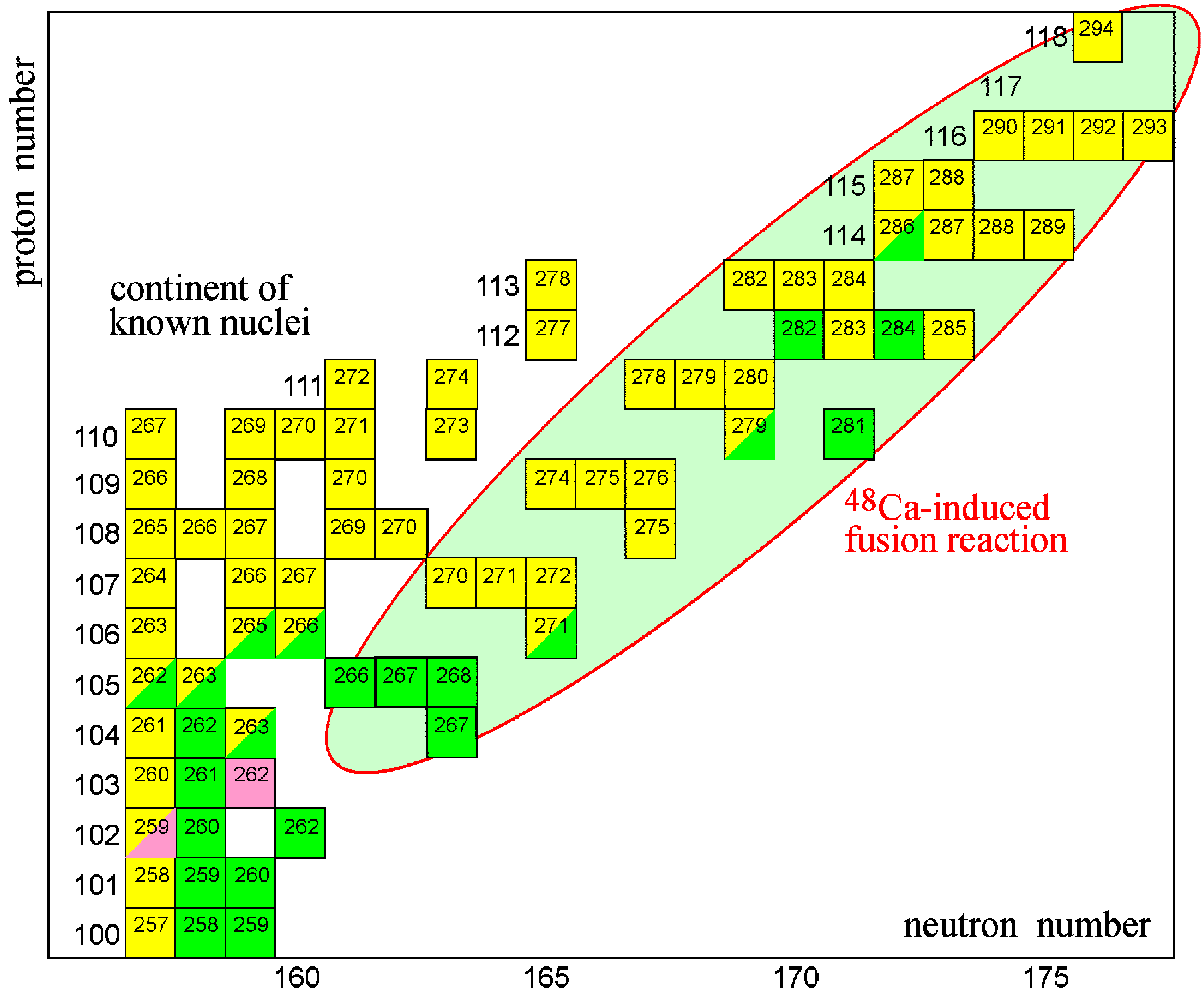


experiment: Itkis *et al.*, 2002

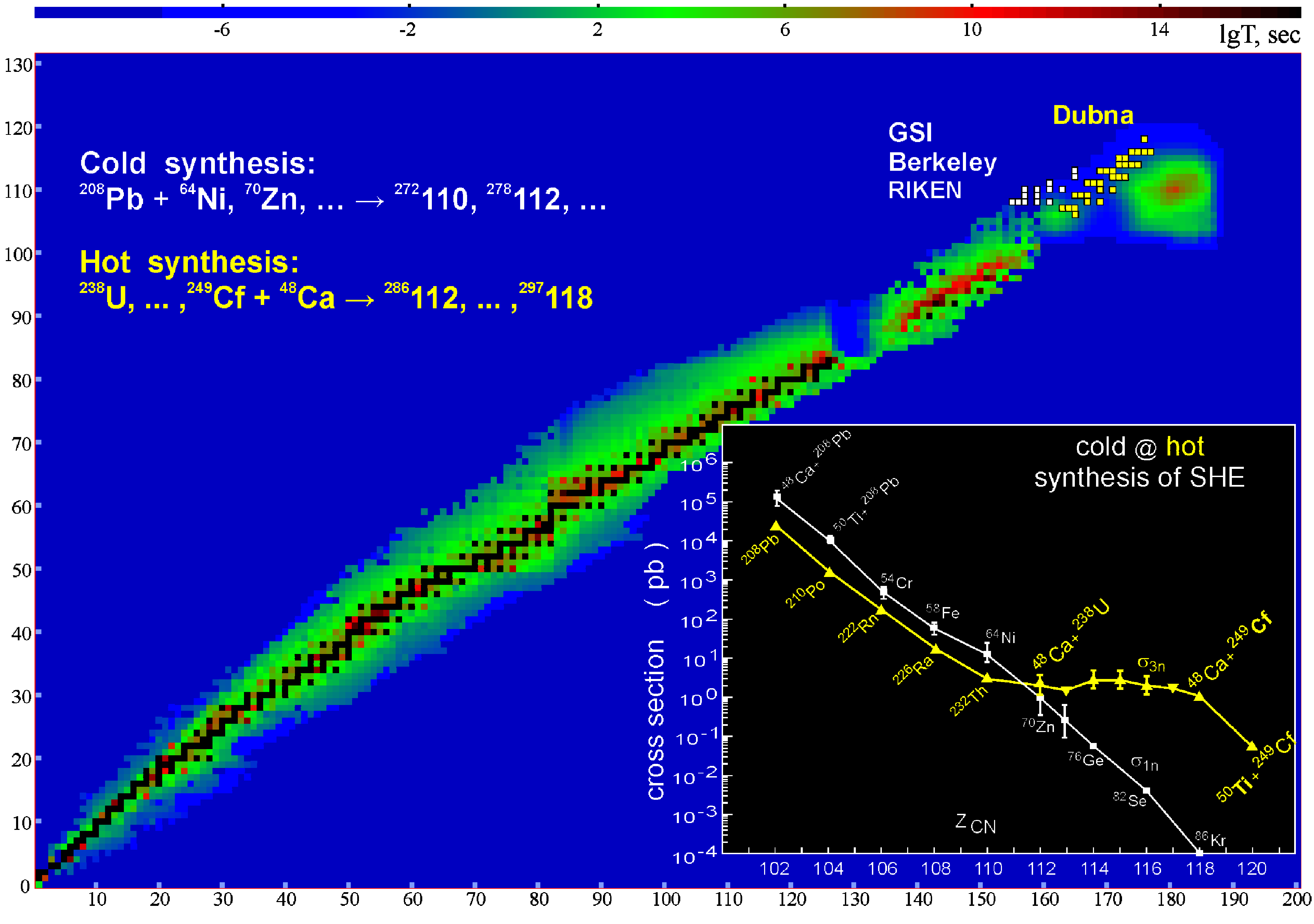




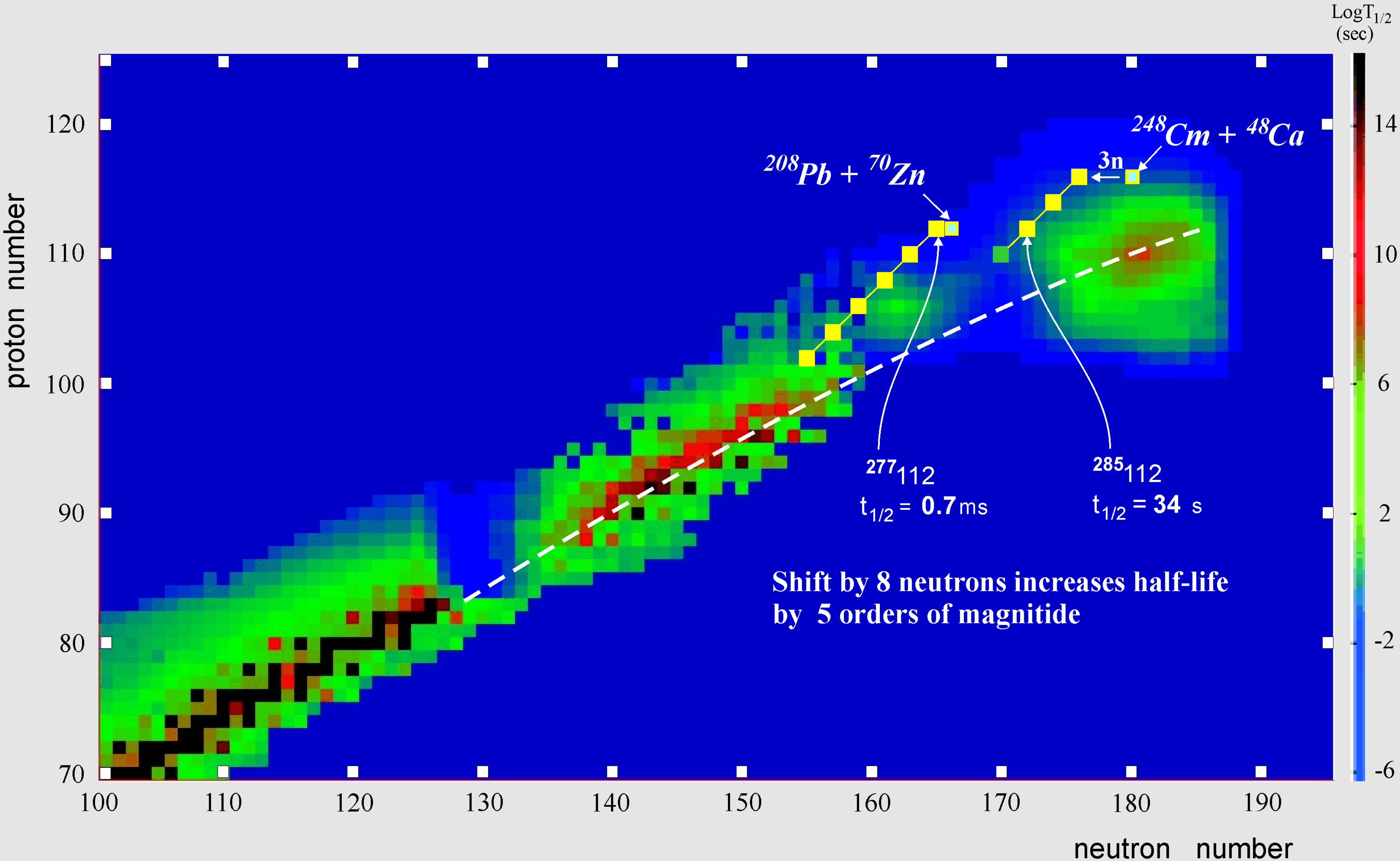
A "gap" in the upper part of the Nuclear Map



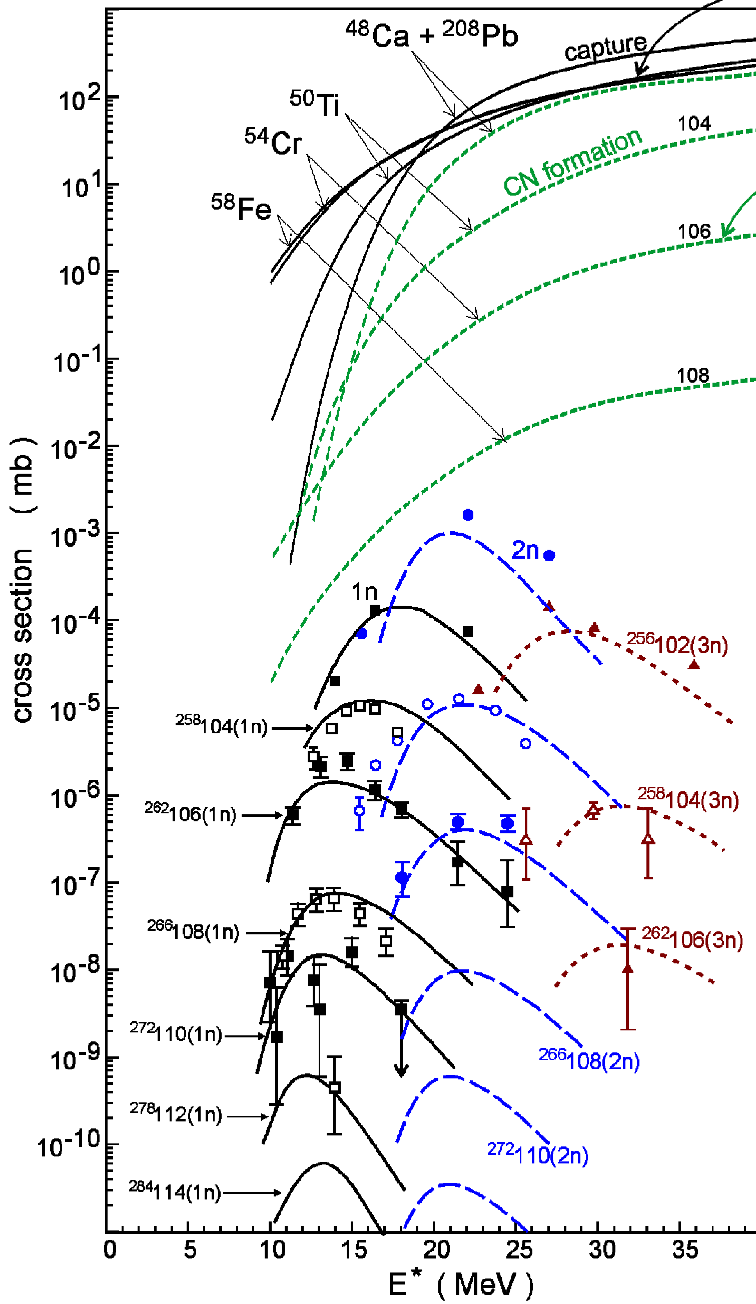
Synthesis of superheavy elements (cold and hot fusion)



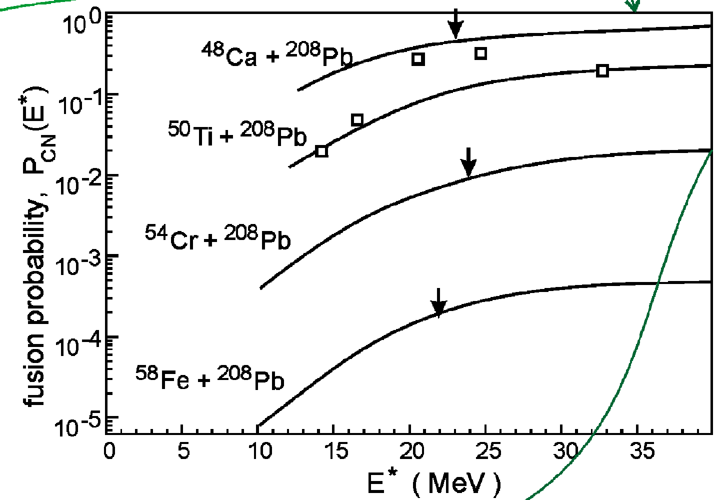
We are still far from the line of stability



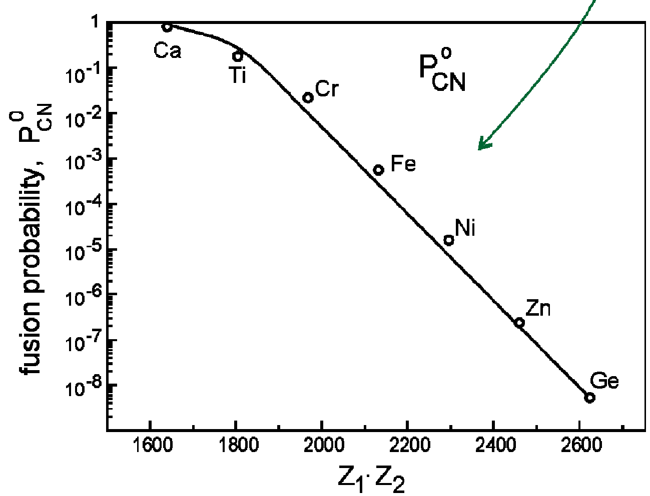
"Cold" synthesis of SHE



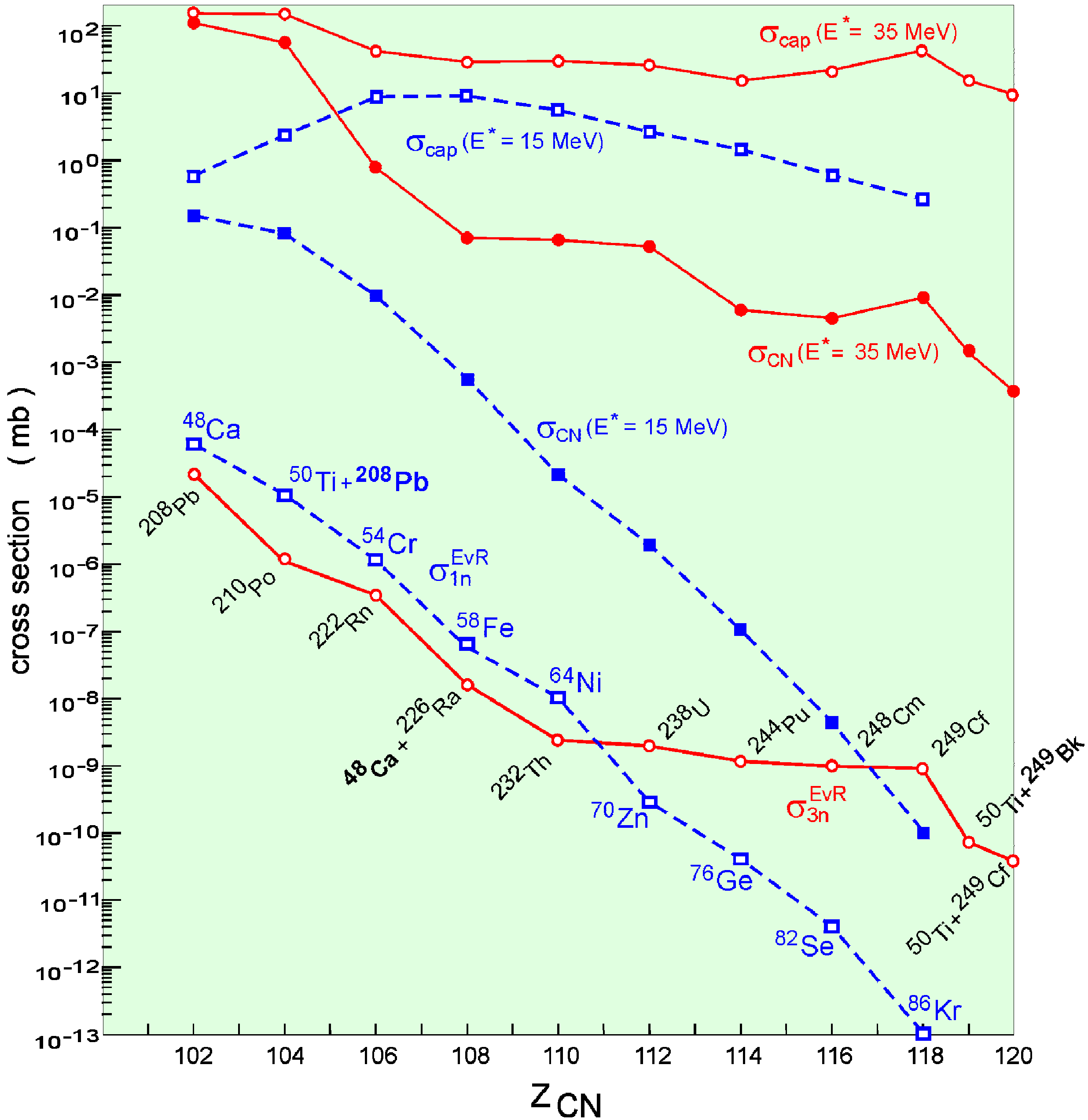
$$\sigma_{ER}^{xn}(E) = \frac{\pi}{k^2}\sum_{\ell=0}^{\infty}(2\ell+1)\cdot P_{cont}(E,\ell)\cdot P_{CN}(E^*,\ell)\cdot P_{xn}(E^*,\ell)$$



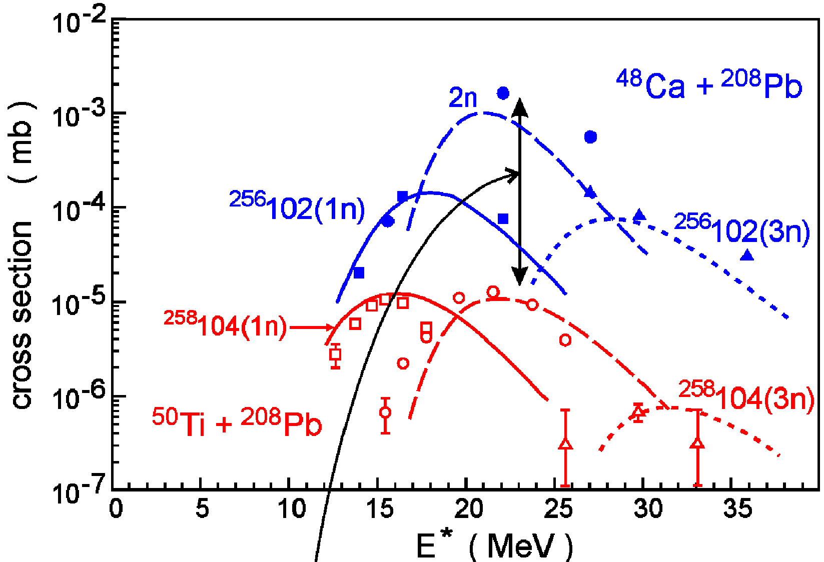
$$P_{CN}(E^*,\ell) = \frac{P_{CN}^0}{1 + \exp\left[\frac{E_B^* - E_{int}^*(\ell)}{\Delta}\right]}$$

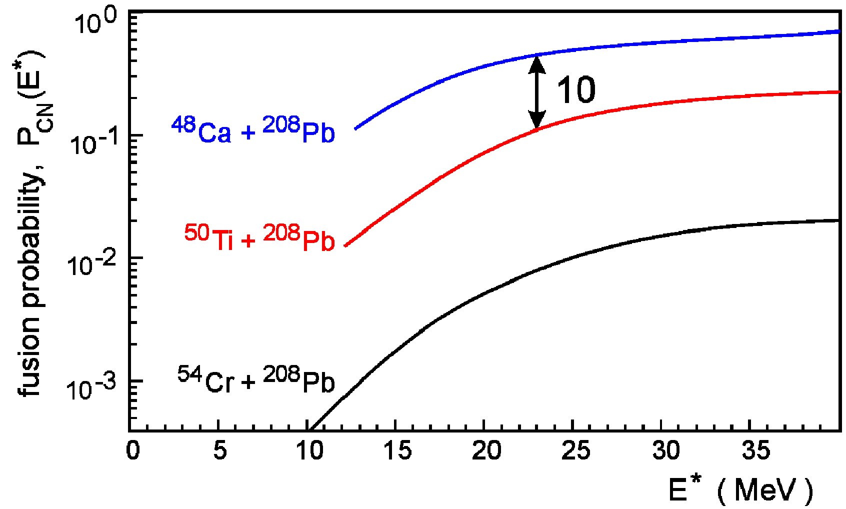


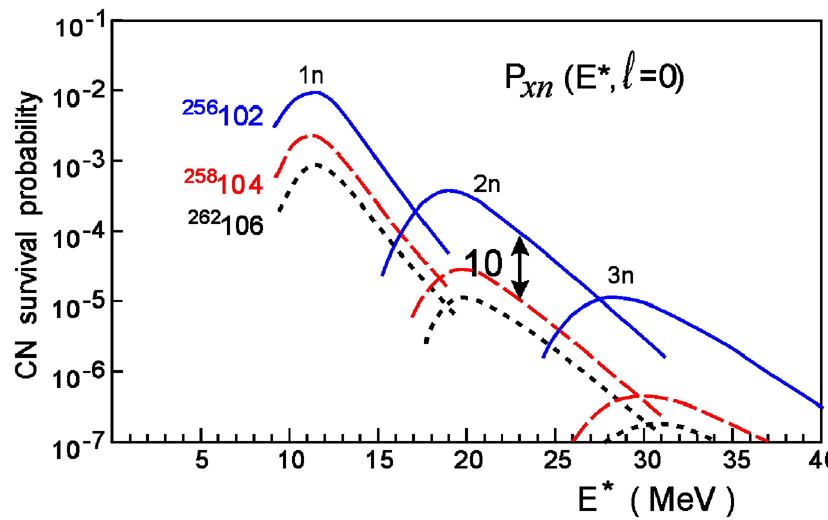
“Cold” and “Hot” synthesis of SHE



Beyond ^{48}Ca: How much ^{50}Ti is worse ?



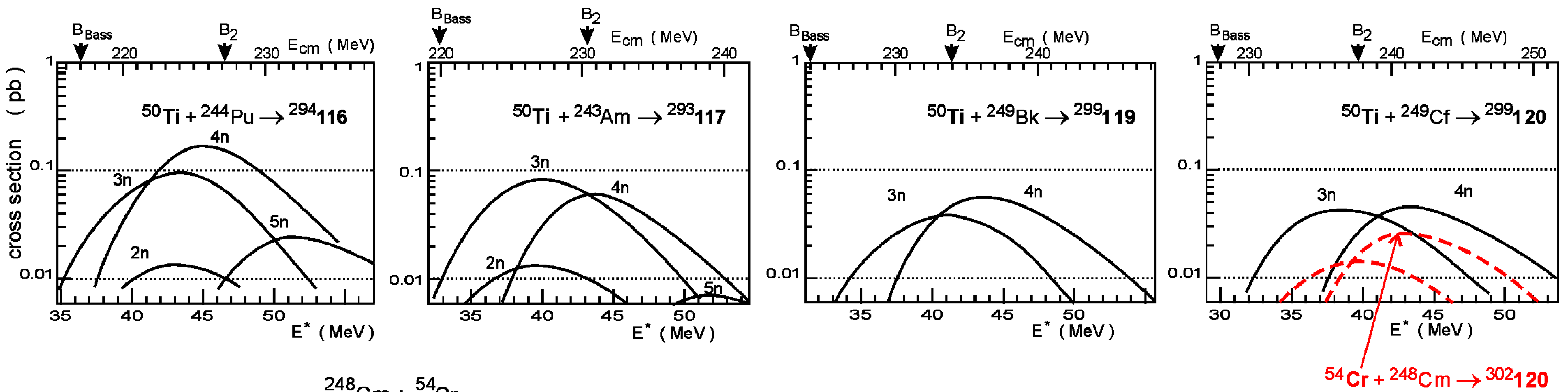


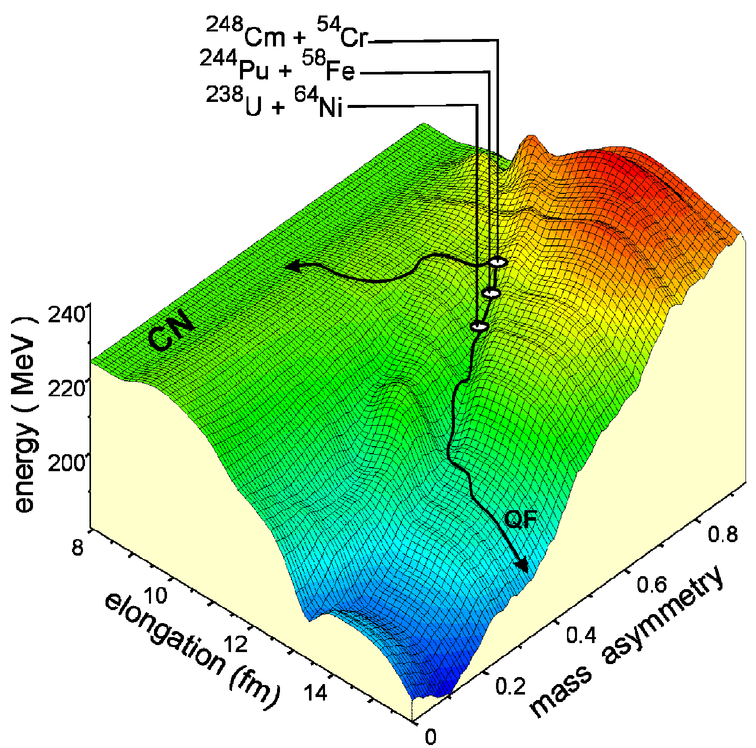


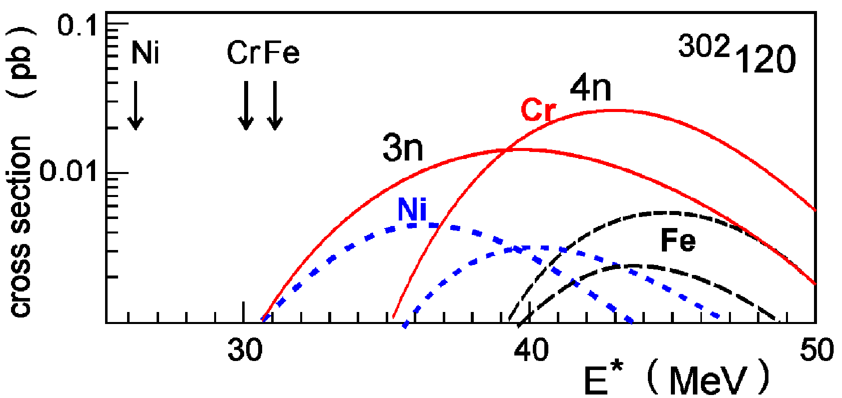
$$\frac{\sigma(^{48}\mathrm{Ca})}{\sigma(^{50}\mathrm{Ti})}$$ two orders of magnitude

	B_{LD}	δW	B_f	E_n
^{256}102	1.26	4.48	**5.7**	**7.1**
^{258}104	0.77	4.49	**5.3**	**7.6**

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

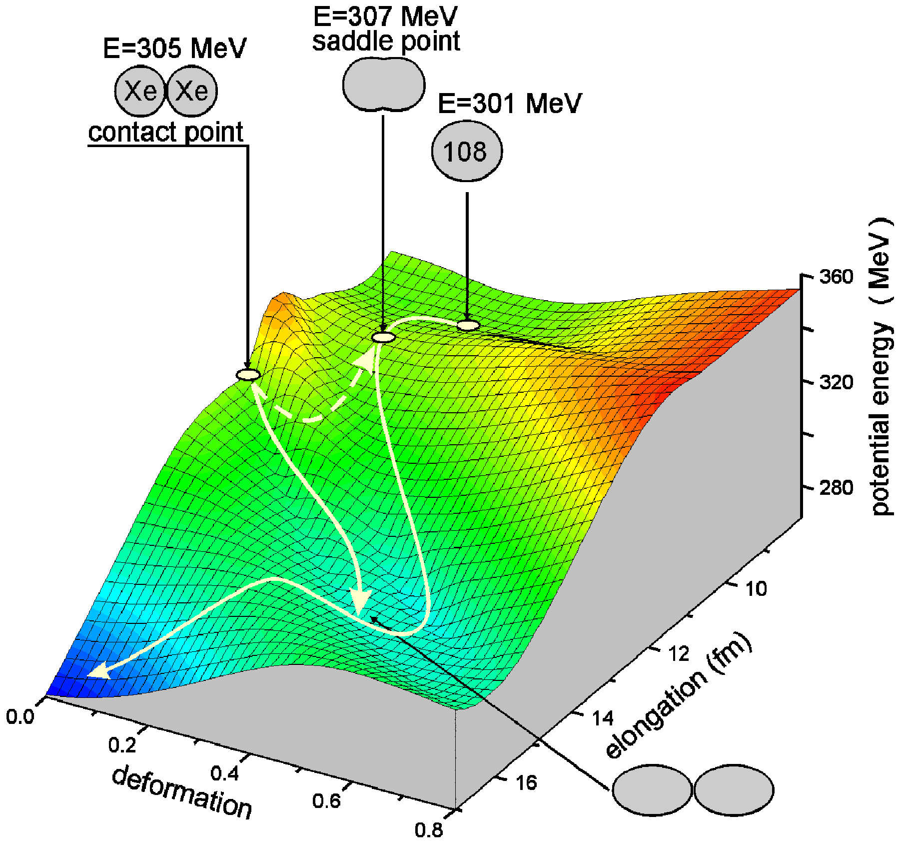


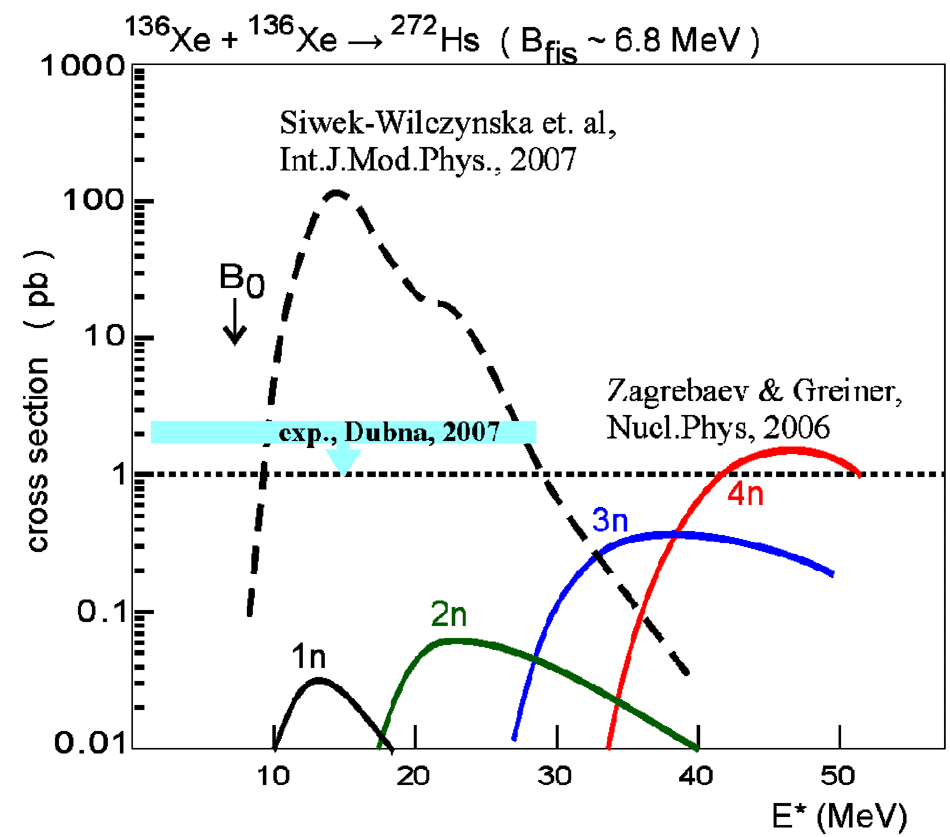




Fusion of "fission fragments": $^{136}Xe + ^{136}Xe \rightarrow ^{272}108$

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





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

Radioactive Ion Beams
for the production of neutron rich superheavy nuclei