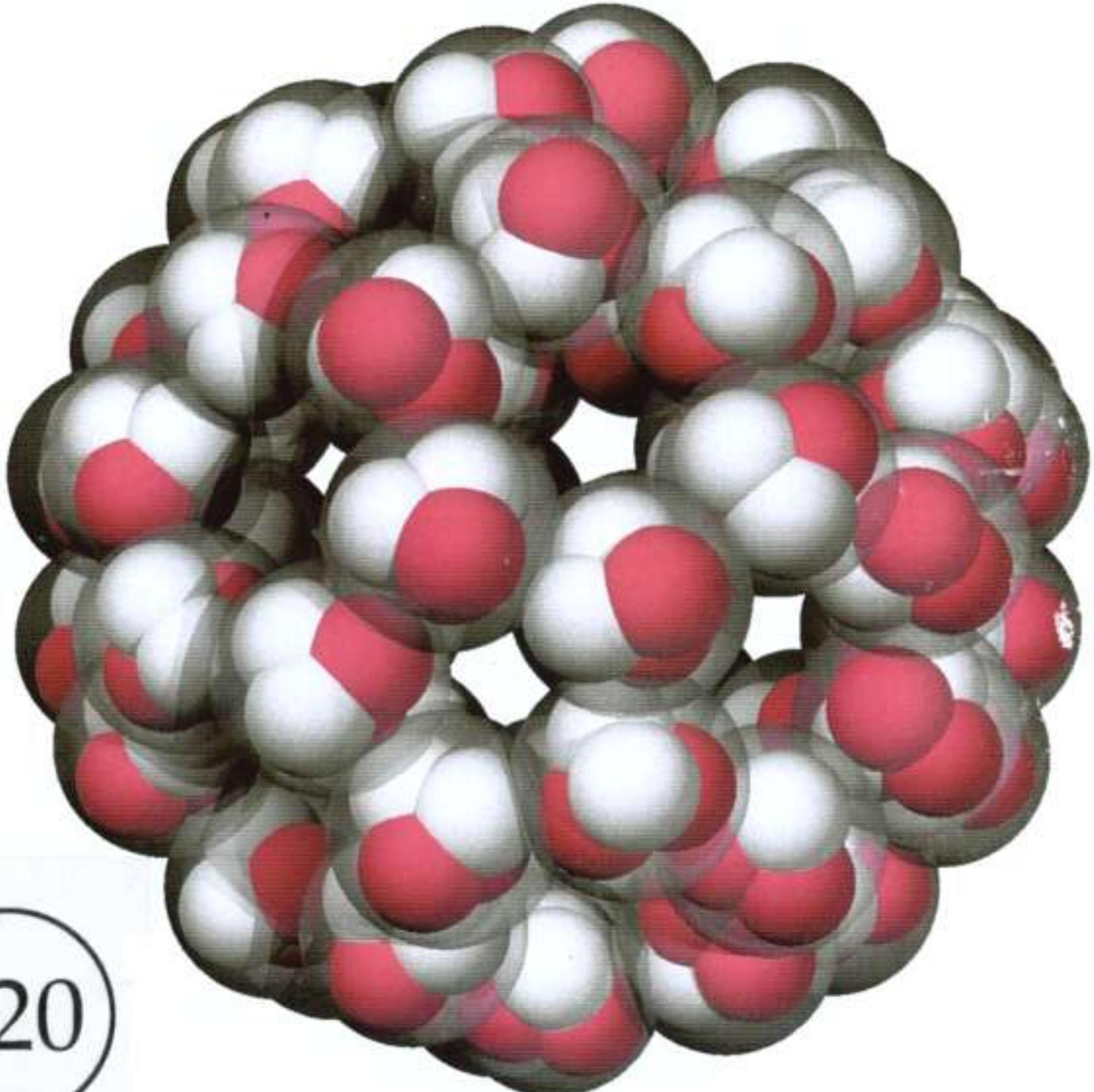
CLUSTERING PHENOMENA IN SUPERHEAVY NUCLEAR SYSTEMS

- **Shell structure of adiabatic potential energy of heavy nuclear system**
- **Clusterization and isomeric states of heavy nuclei**
- **Shell effects in collisions of heavy ions and SHE formation**
- **3-body clusterization in collisions of transactinides**

Valery Zagrebaev and Walter Greiner

Strasbourg, May 15, 2008



304

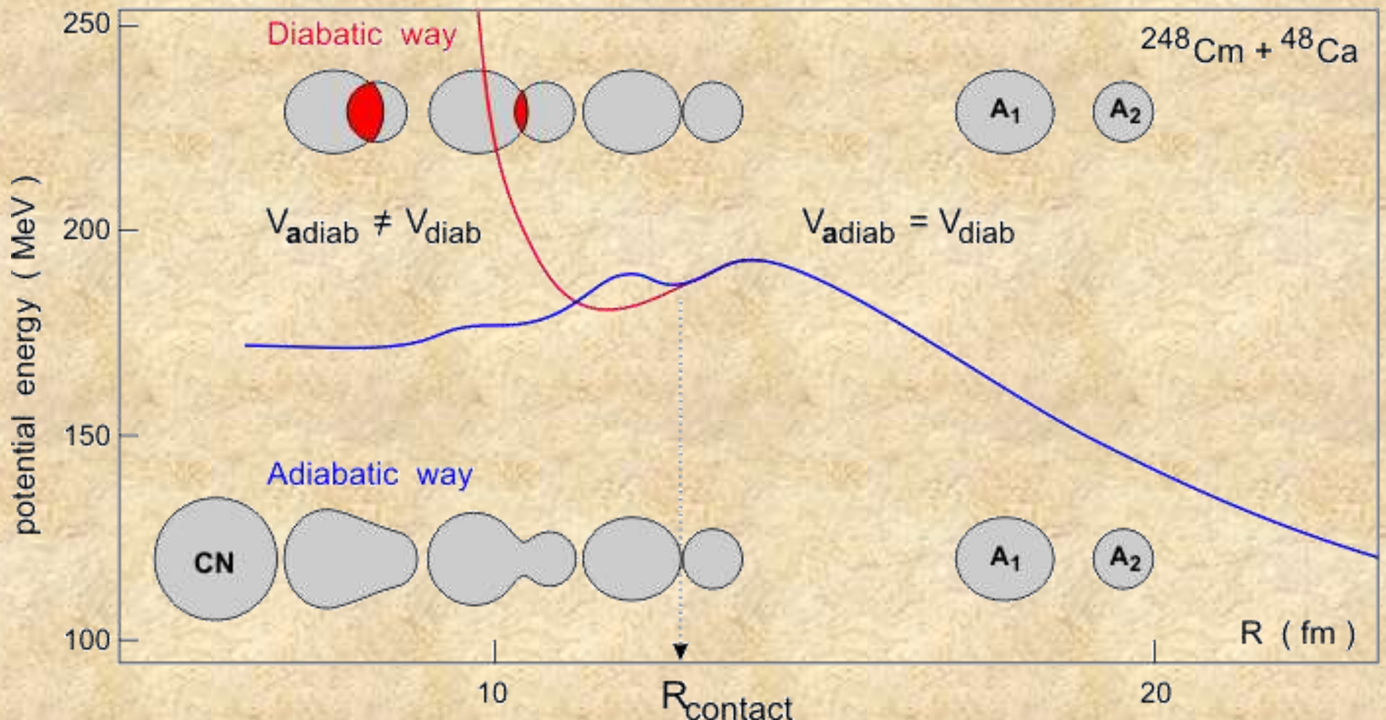
120

184

This is not a subject of my talk

Diabatic and Adiabatic Potential Energy

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



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

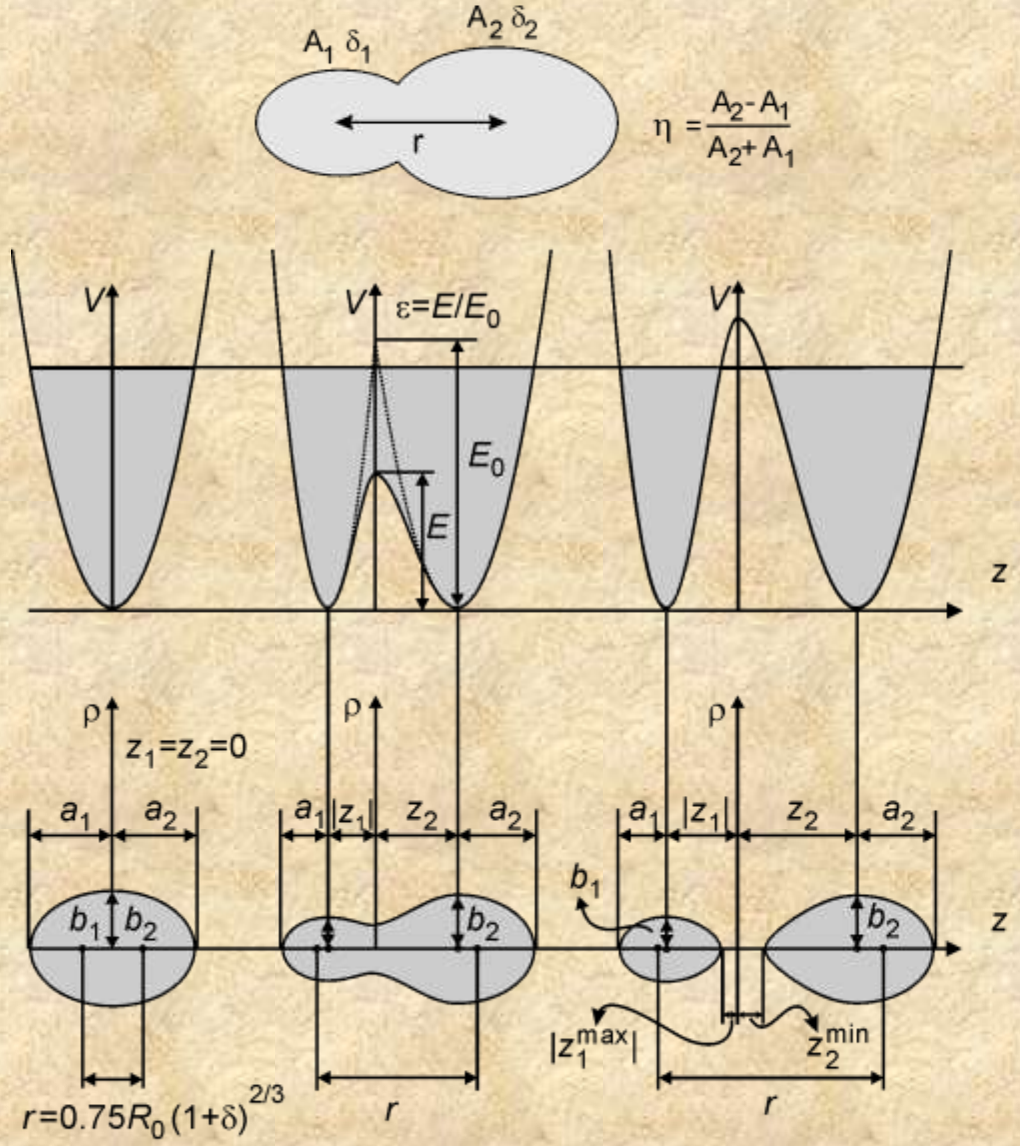
Time-dependent driving potential has to be used

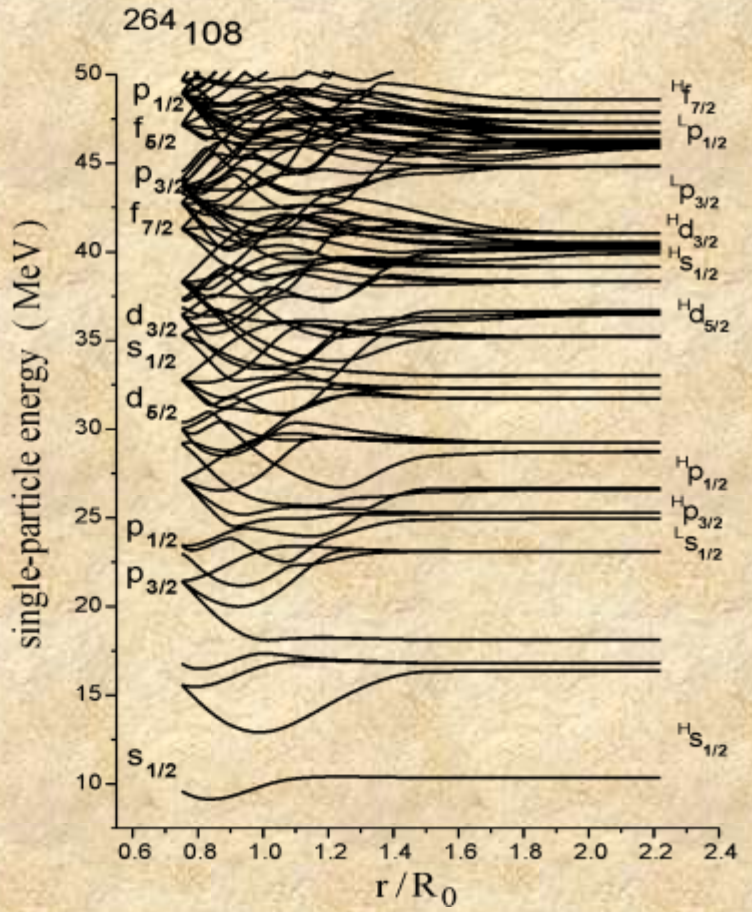
$$V(t) = V_{diab}(\xi)\cdot exp(-\frac{t_{int}}{\tau_{relax}}) + V_{adiab}(\xi)\cdot[1-exp(-\frac{t_{int}}{\tau_{relax}})]$$

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

the same degrees of freedom !

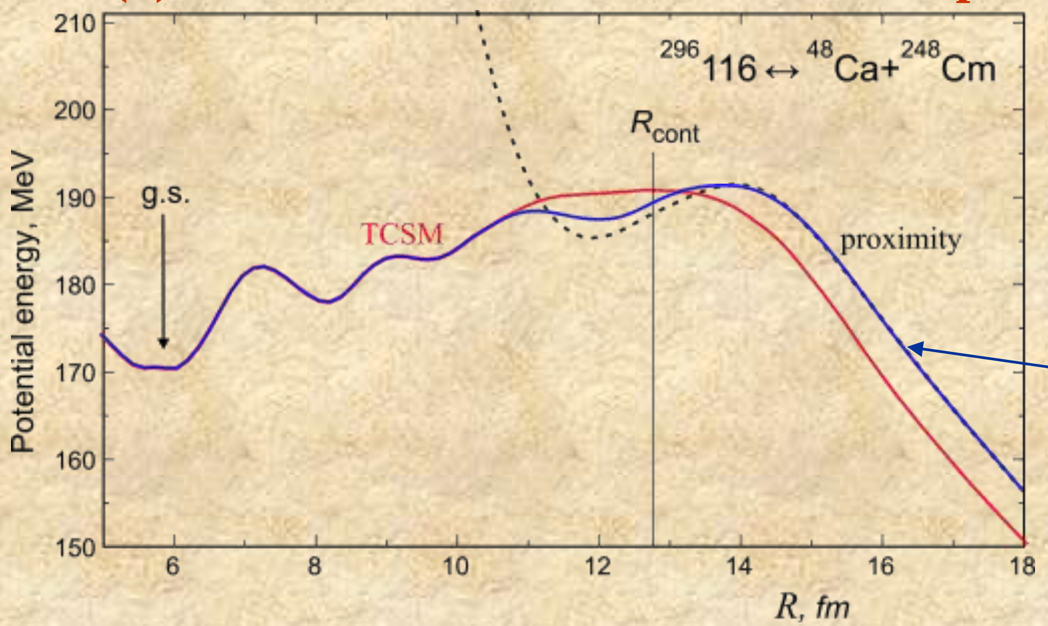
Two-Center Shell Model





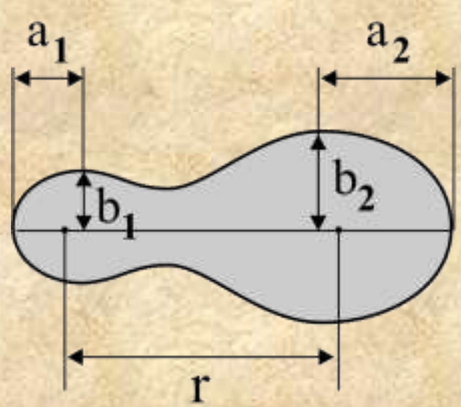
Calculation of multi-dimensional adiabatic potential energy ?

(1) Lack of standard macro-microscopic adiabatic potential



Extended Two-Center Shell Model,
Zagrebaev, Karpov et al.,
Phys. Part. Nucl., **38**, 2007

(2) Choice of degrees of freedom ?



5 parameters:

(1) r

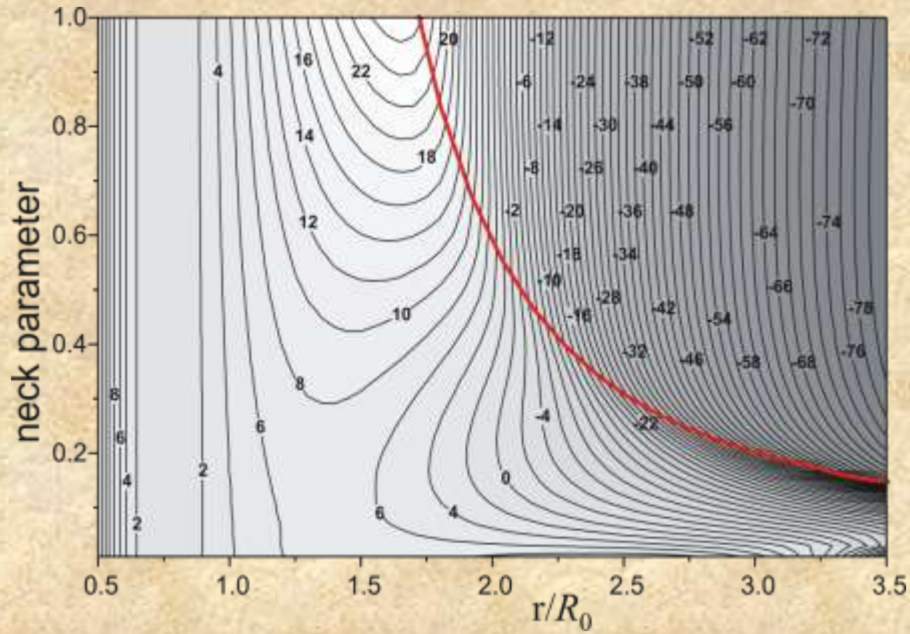
(2) $\delta_1 = 1 - \frac{a_1}{b_1}$

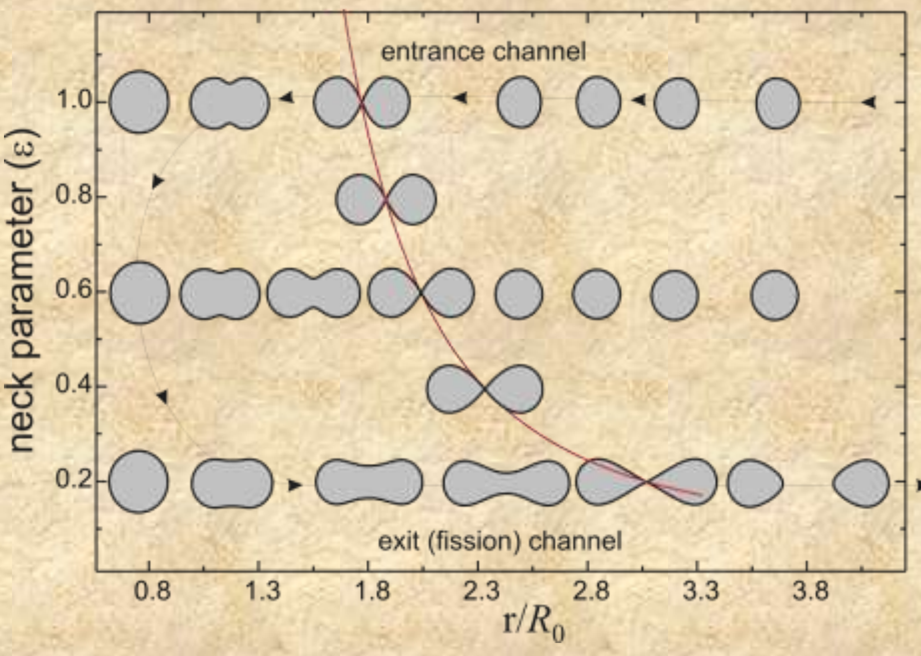
(3) $\delta_2 = 1 - \frac{a_2}{b_2}$

(4) $\eta = \frac{A_2 - A_1}{A_2 + A_1}$

(5) ε – neck parameter

Time dependent adiabatic fusion-fission potential





$$V_{adiab}(r,\delta,\eta,\varepsilon,t) = V_{adiab}(r,\delta,\eta,\varepsilon=1)\cdot exp(-\frac{t}{\tau_\varepsilon}) + V_{adiab}(r,\delta,\eta,\varepsilon=\varepsilon_{out})\cdot[1-exp(-\frac{t}{\tau_\varepsilon})]$$

Time-dependent driving potential

$^{248}Cm + ^{48}Ca \leftrightarrow ^{296}116$

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

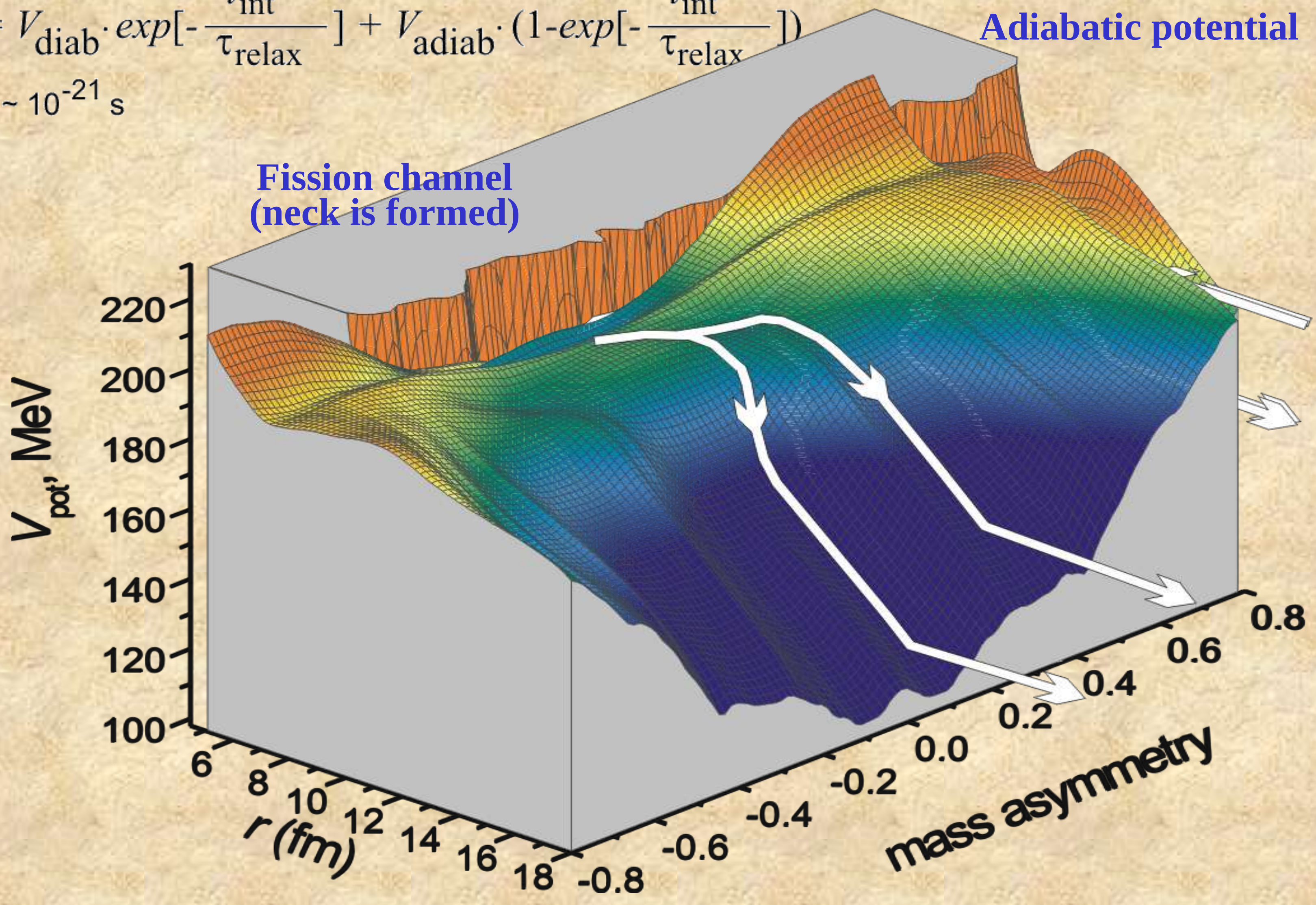
$\tau_{relax} \sim 10^{-21}$ s

entrance channel: **Diabatic potential**

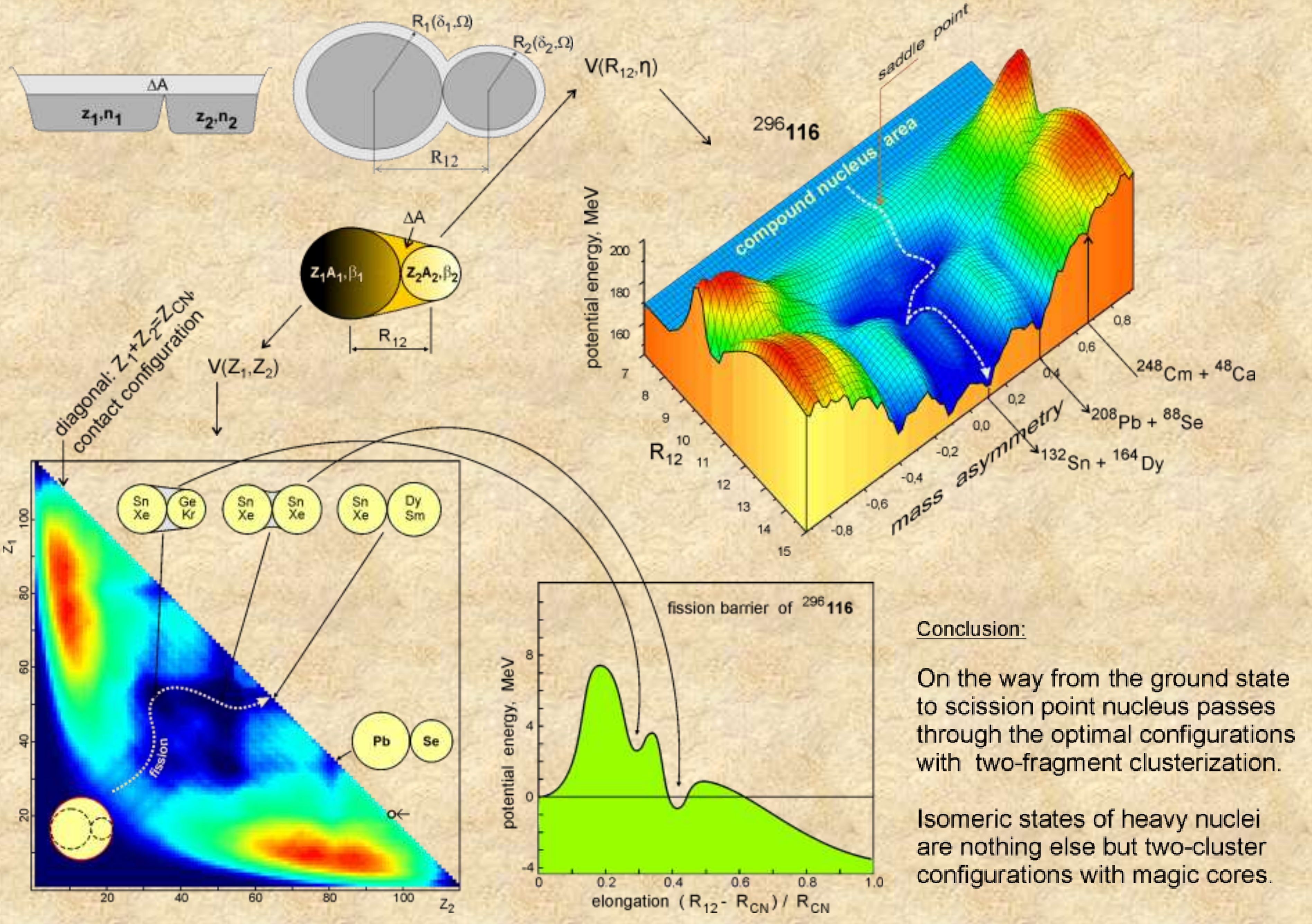
Quasi-Elastic and Deep Inelastic Processes

Adiabatic potential

Fission channel (neck is formed)



Clusterization and Isomeric states of heavy nuclei



Conclusion:

On the way from the ground state to scission point nucleus passes through the optimal configurations with two-fragment clusterization.

Isomeric states of heavy nuclei are nothing else but two-cluster configurations with magic cores.

System of coupled Langevin type Equations of Motion

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

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

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

Most uncertain parameters:

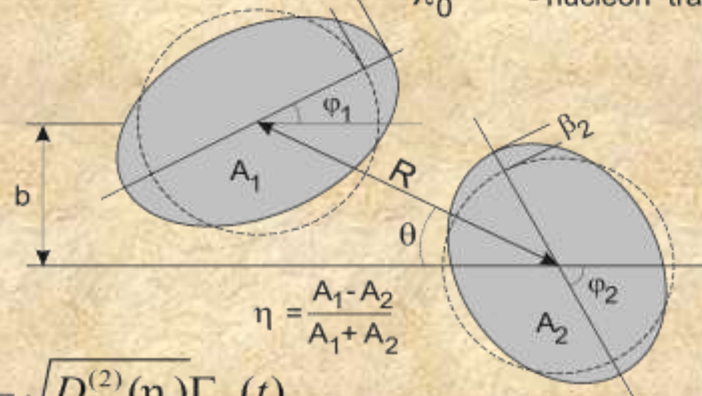
μ_0, γ_0 - nuclear viscosity and friction,

λ_0 - nucleon transfer rate

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

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

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



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

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

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

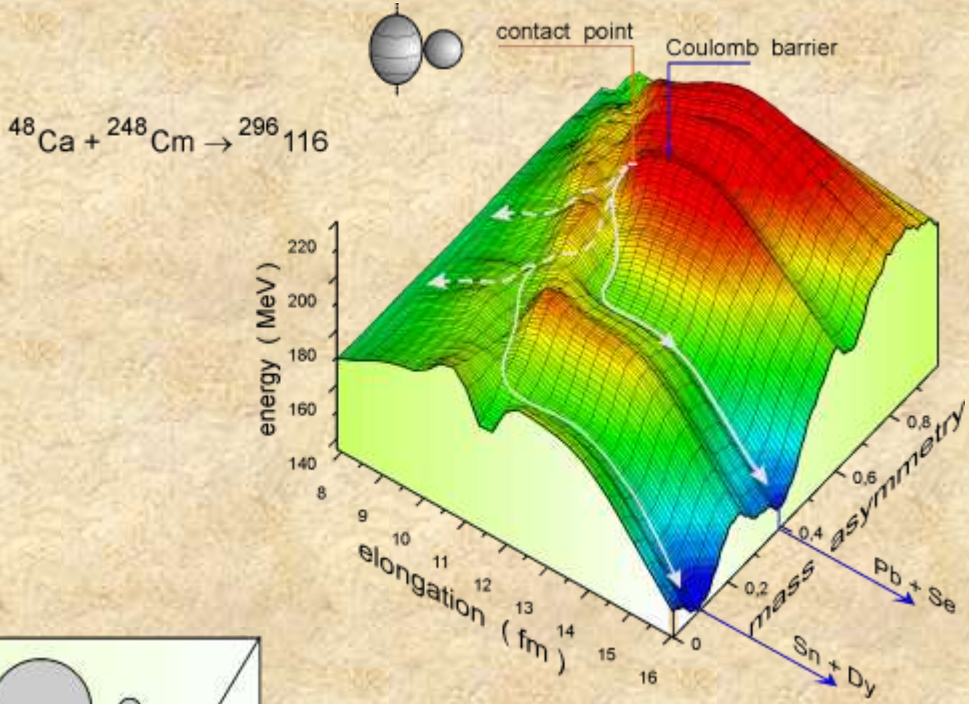
$$\frac{dL_1}{dt}=-\frac{\partial V}{\partial\varphi_1}+\gamma_{\text{tang}}\left(\frac{\ell}{\mu_R R}-\frac{L_1}{\Im_1}a_1-\frac{L_2}{\Im_2}a_2\right)a_1-\frac{a_1}{R}\sqrt{\gamma_{\text{tang}}T}\,\Gamma_{\text{tang}}(t)$$

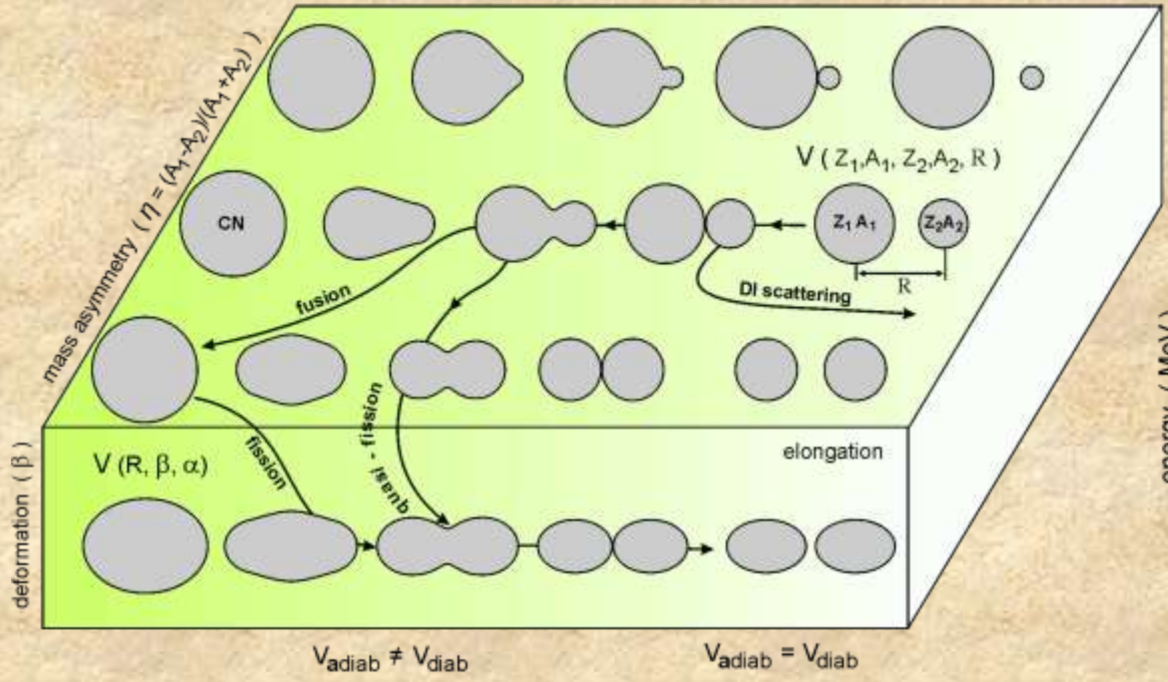
$$\frac{dL_2}{dt}=-\frac{\partial V}{\partial\varphi_2}+\gamma_{\text{tan}}\left(\frac{\ell}{\mu_R R}-\frac{L_1}{\Im_1}a_1-\frac{L_2}{\Im_2}a_2\right)a_2-\frac{a_2}{R}\sqrt{\gamma_{\text{tang}}T}\,\Gamma_{\text{tang}}(t)$$

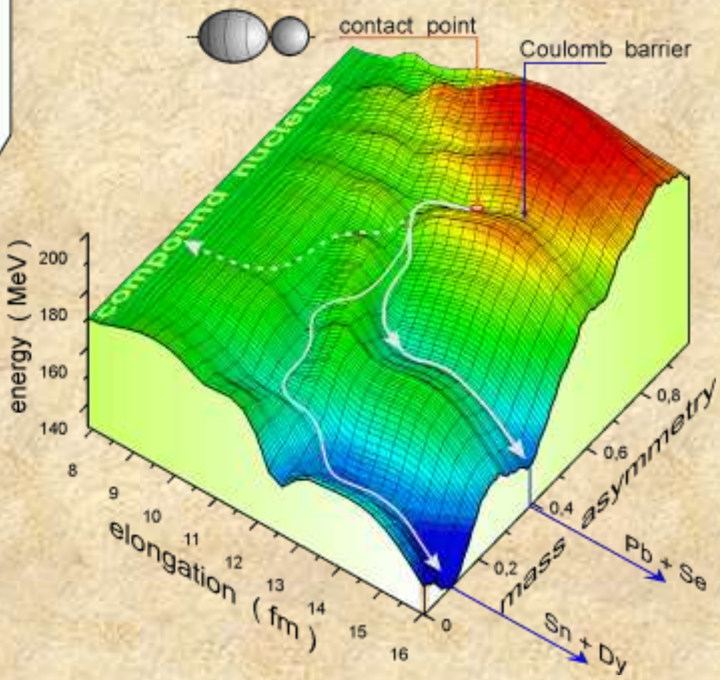
$$\frac{dp_{\beta 1}}{dt}=-\frac{\partial V}{\partial\beta_1}+\frac{p_{\beta 1}^2}{2\mu_{\beta 1}^2}\frac{\partial\mu_{\beta 1}}{\partial\beta_1}+\frac{p_{\beta 2}^2}{2\mu_{\beta 2}^2}\frac{\partial\mu_{\beta 2}}{\partial\beta_1}+\left(\frac{\ell^2}{2\mu_R^2R^2}+\frac{p_R^2}{2\mu_R^2}\right)\frac{\partial\mu_R}{\partial\beta_1}-\gamma_\beta\frac{p_{\beta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

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

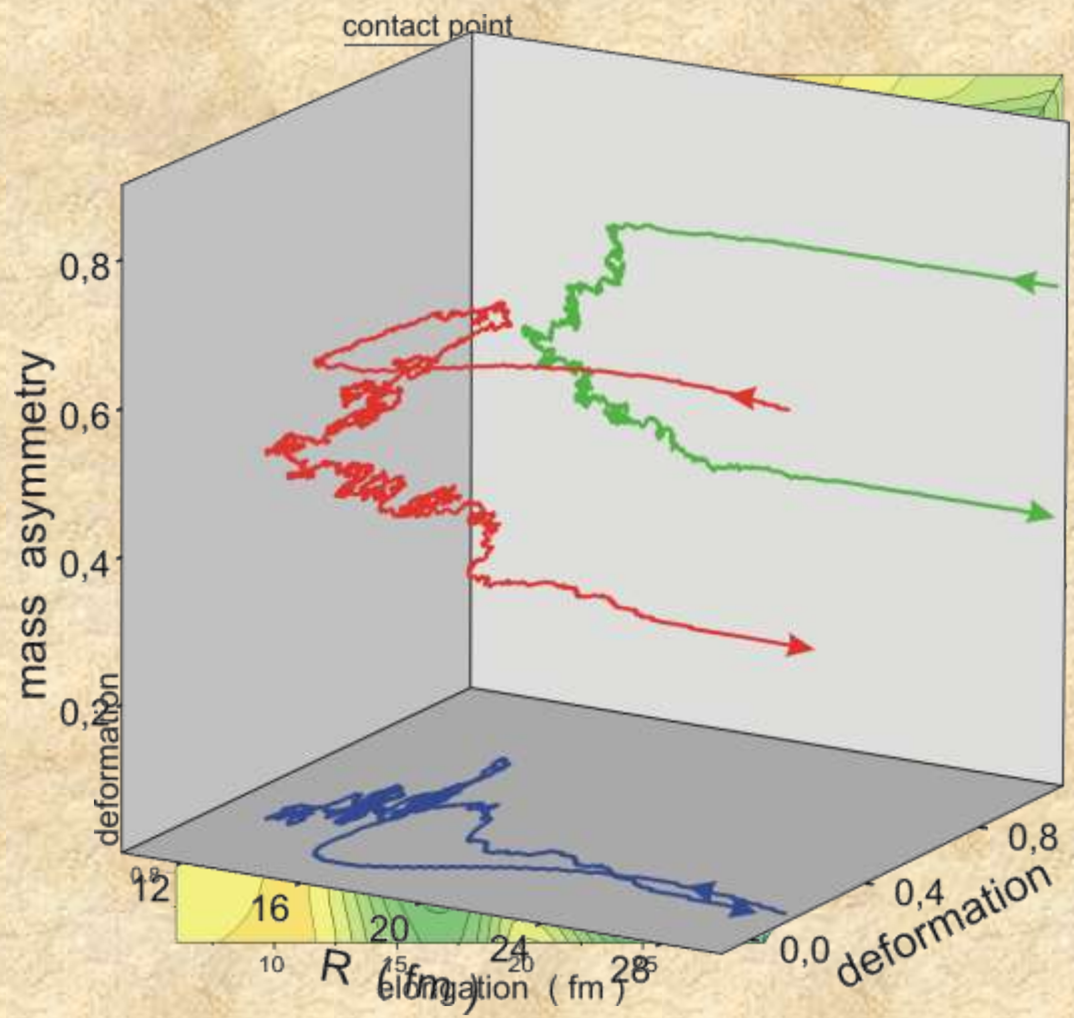
Multi-dimensional adiabatic driving potential



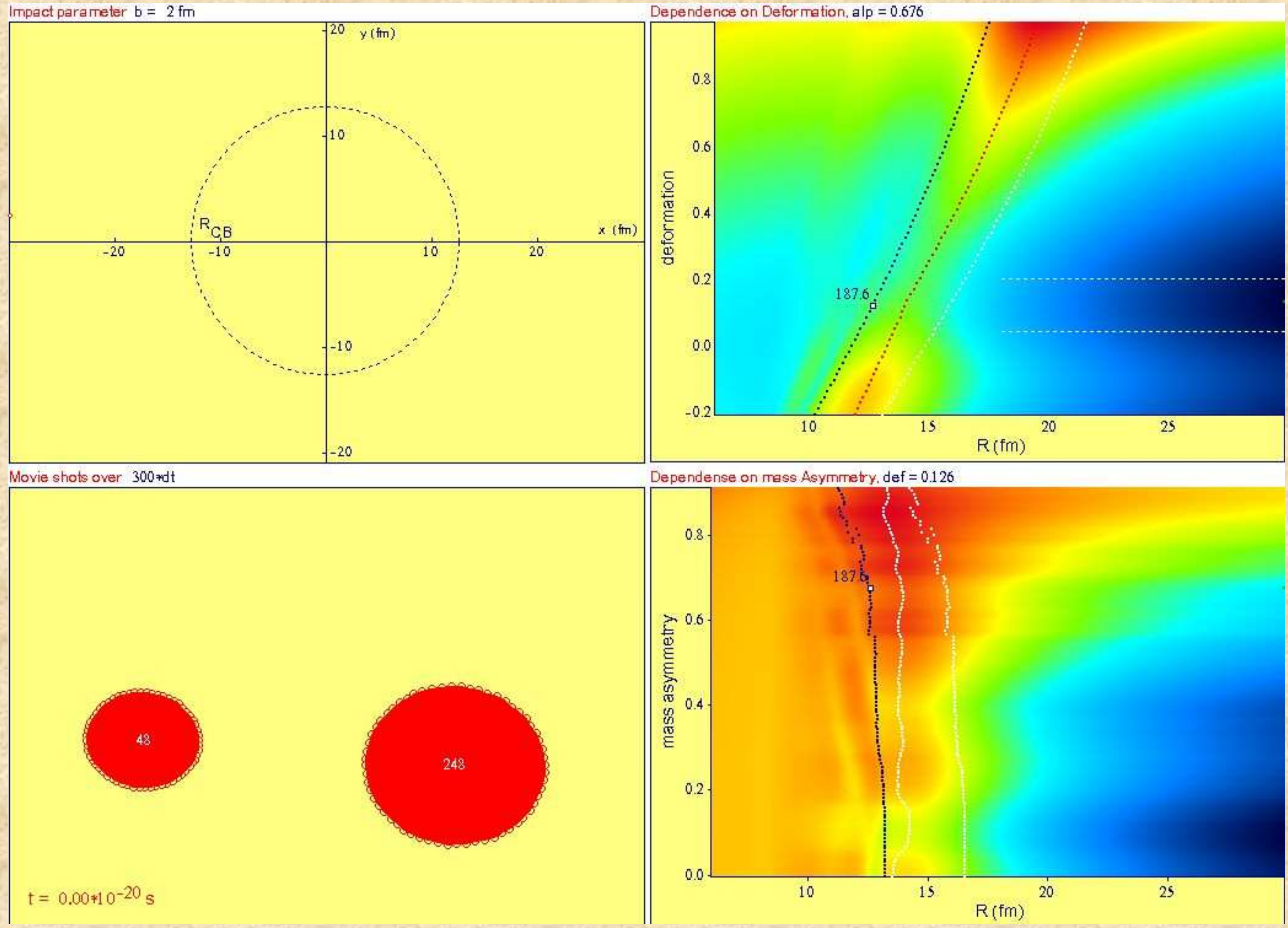




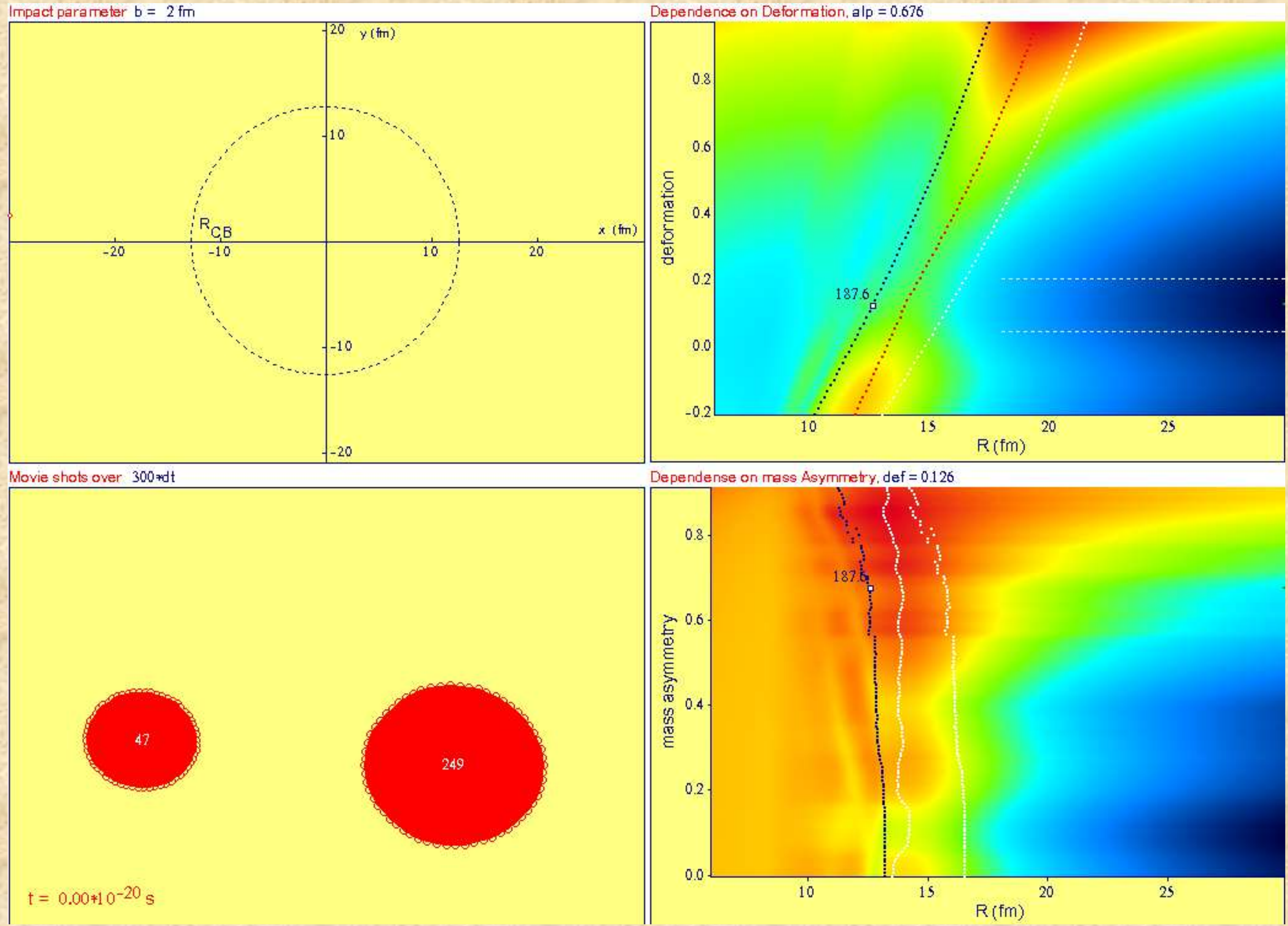
$^{248}Cm + ^{48}Ca \leftrightarrow ^{296}116$



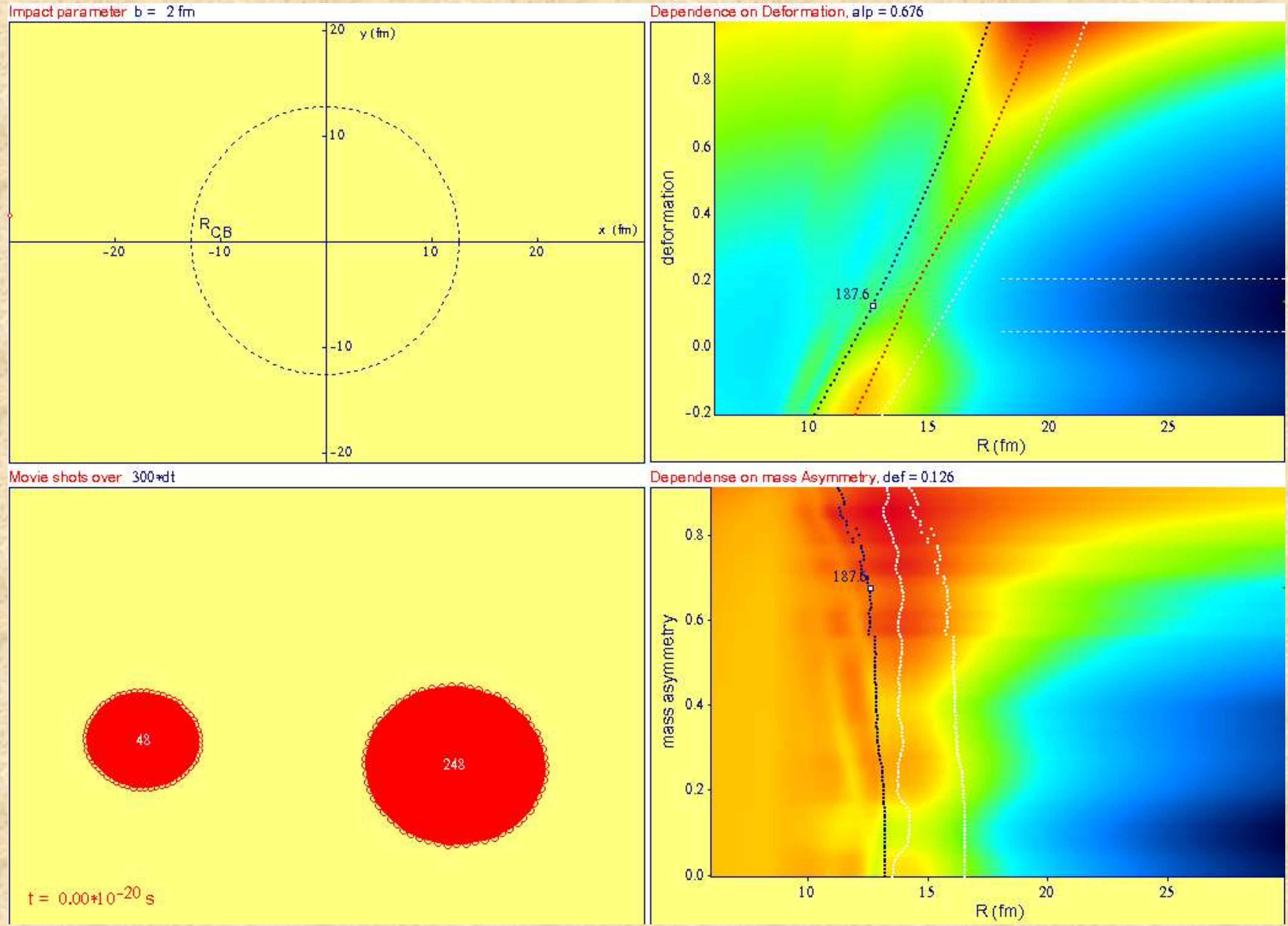
Motion in multi-dimensional space



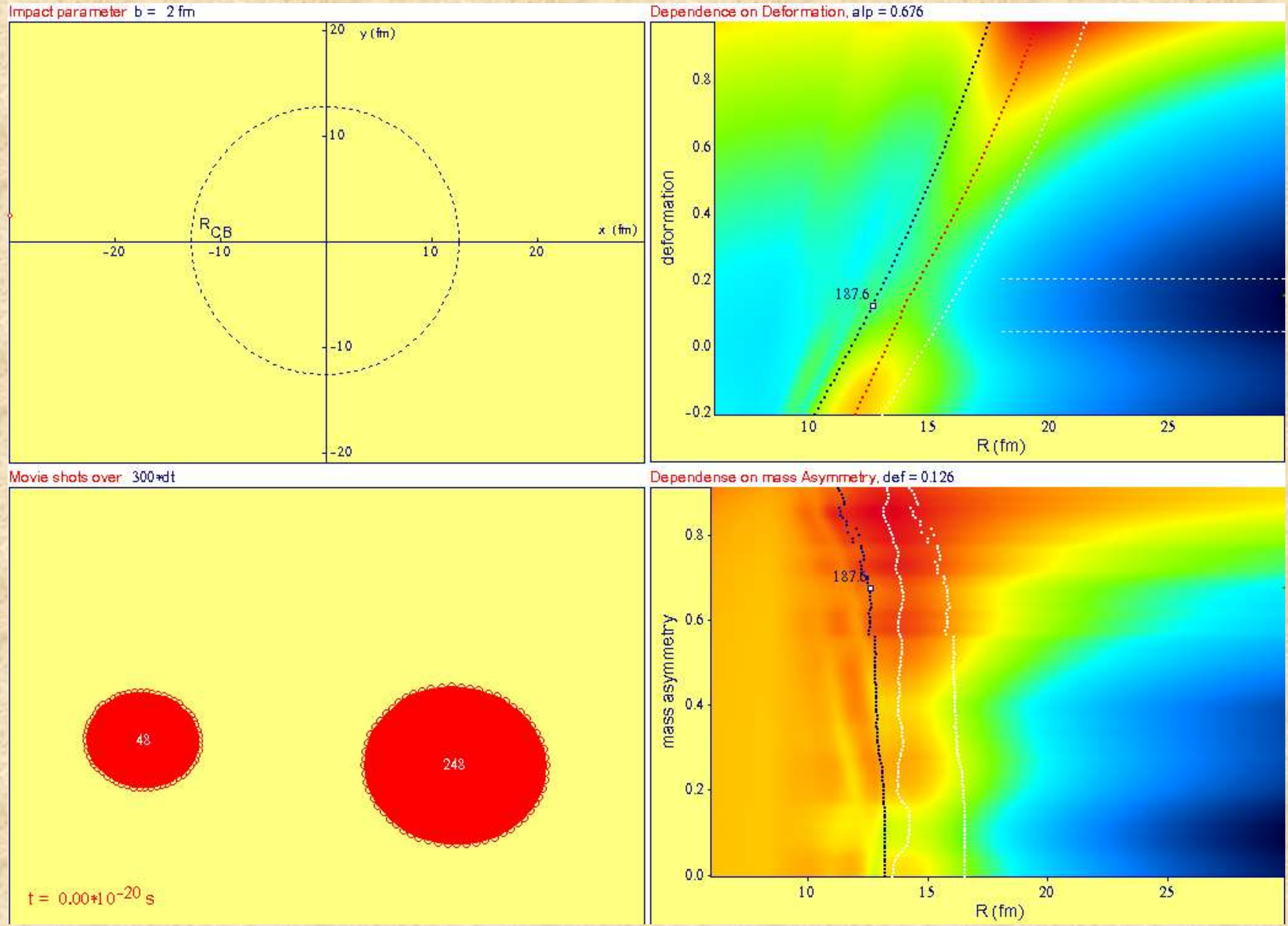
Deep-Inelastic Scattering



Quasi-fission process

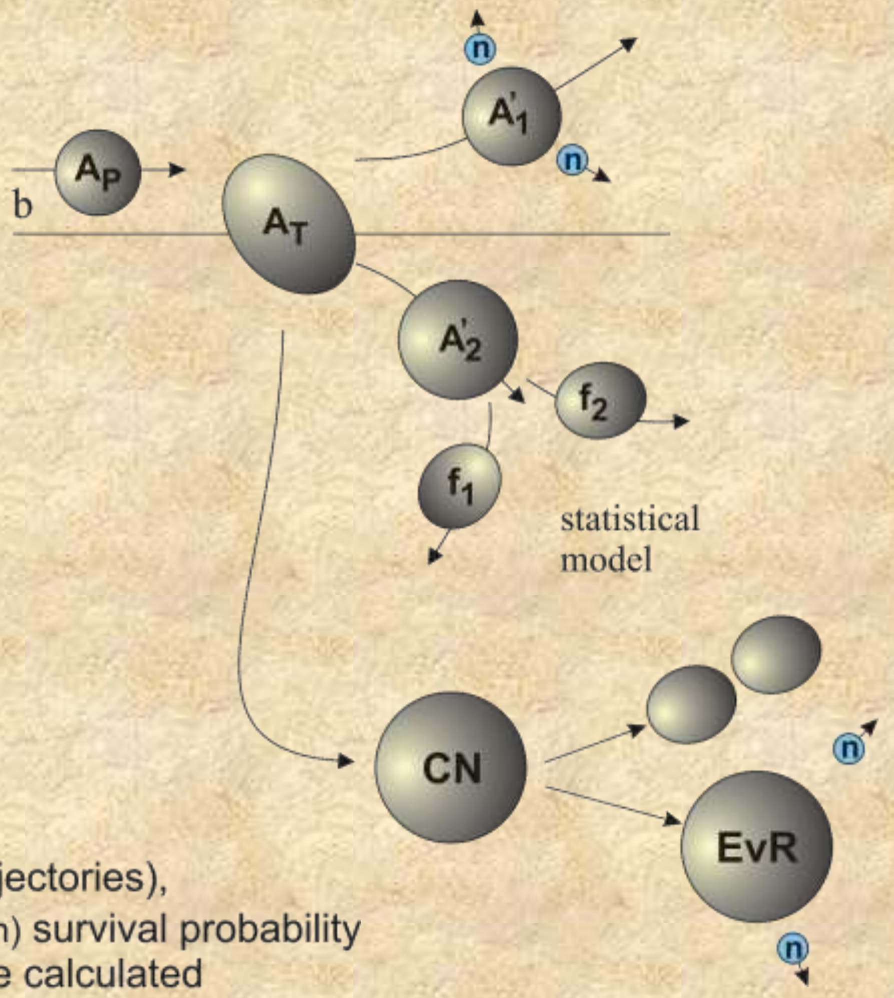


Symmetric quasi-fission



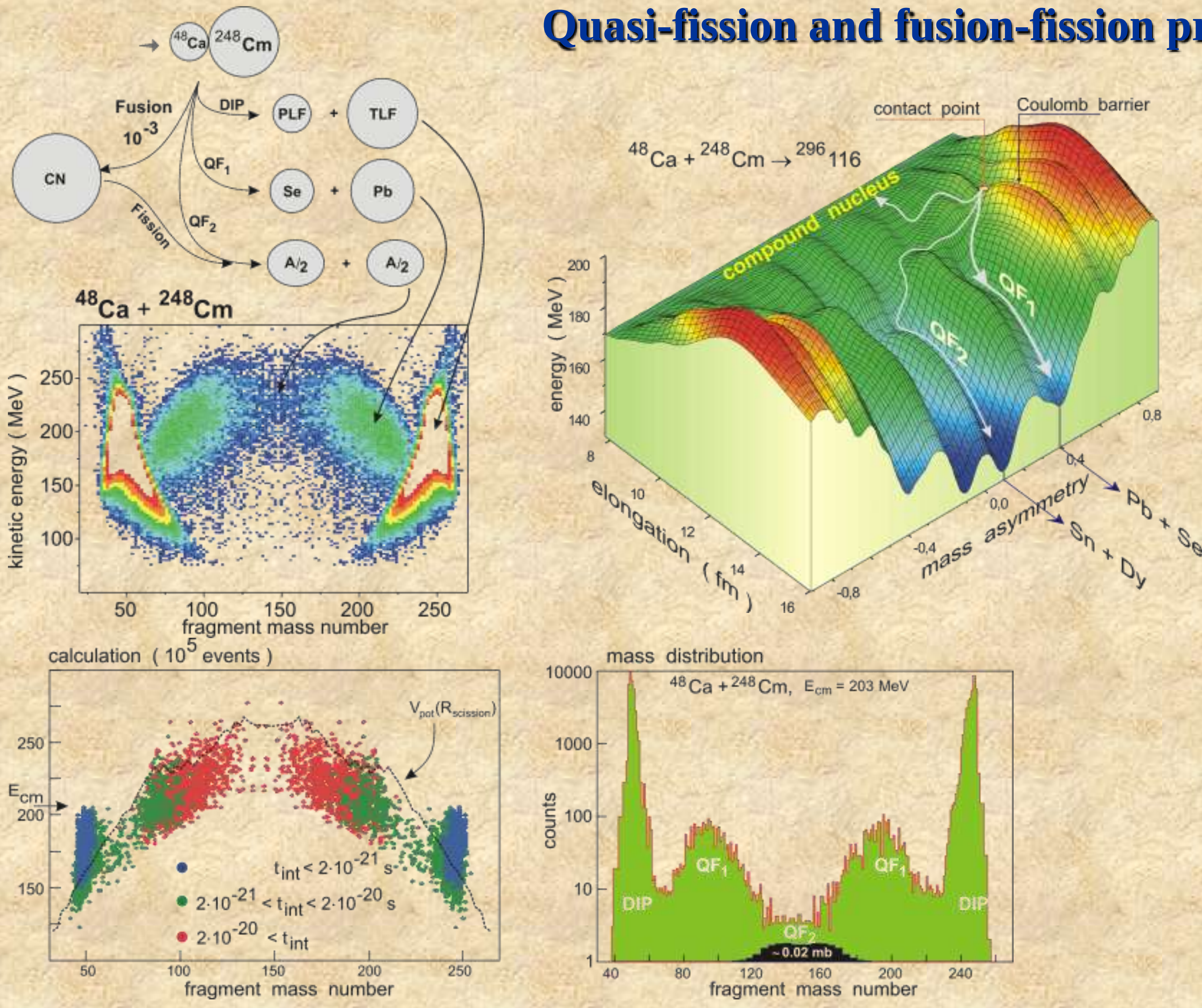
Simulation of experiment and cross sections

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

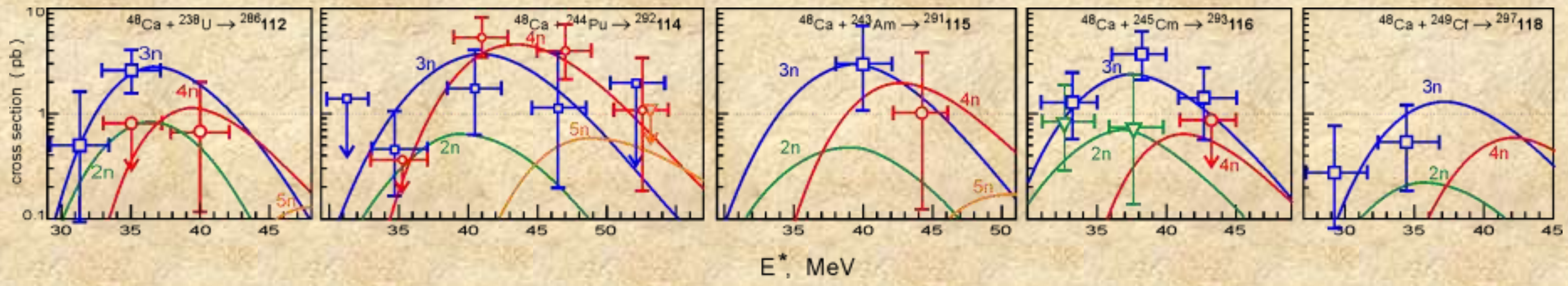


Dynamics: **10^6** tested events (trajectories),
Statistical model: **10^{-6}**(3n), **10^{-7}**(4n) survival probability
cross sections up to **0.1 pb** can be calculated

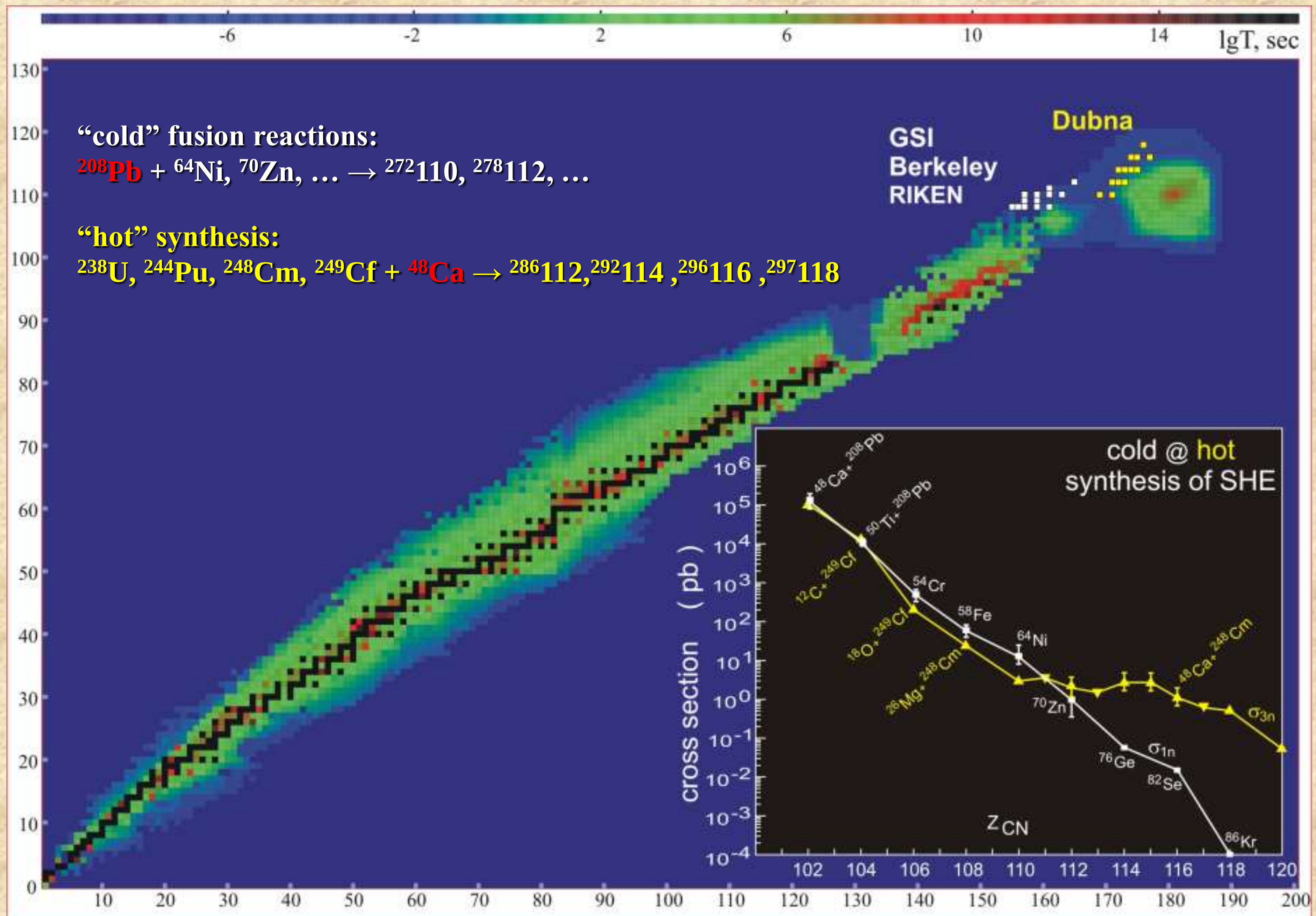
Quasi-fission and fusion-fission processes



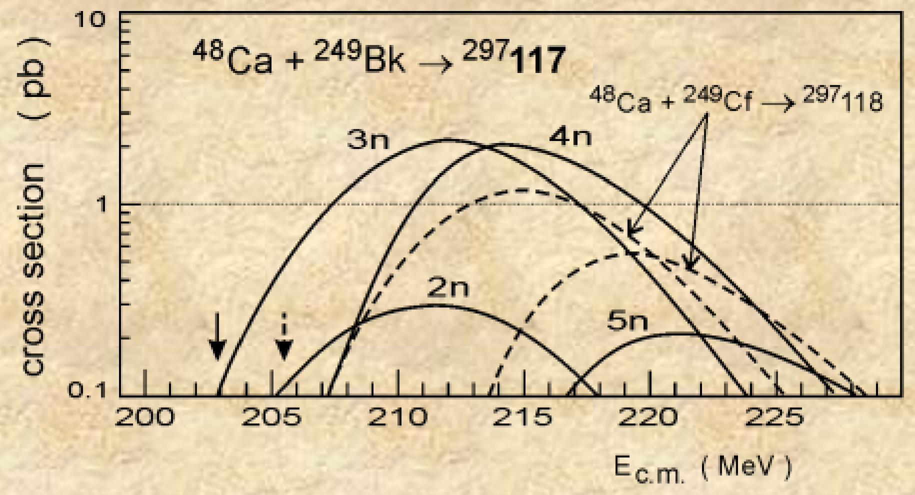
Cross sections for superheavy element production

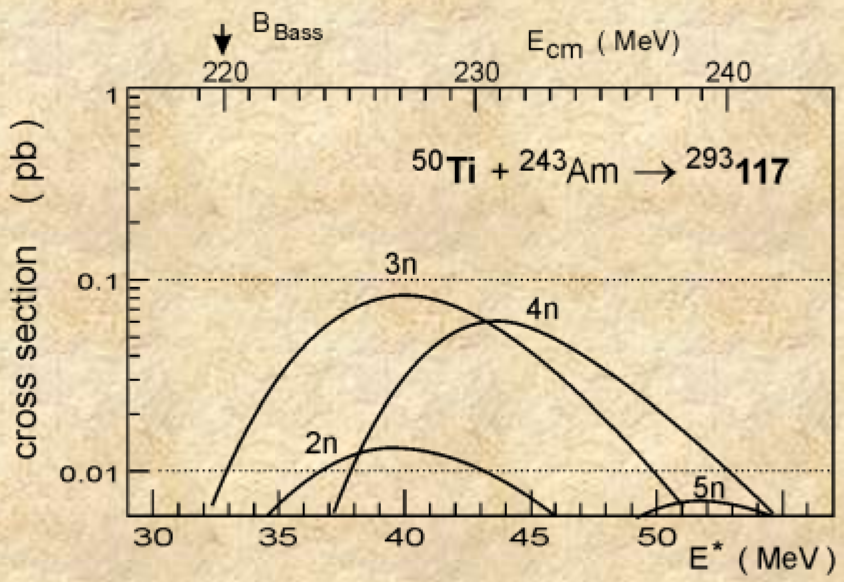


On the way to the first Island of Stability

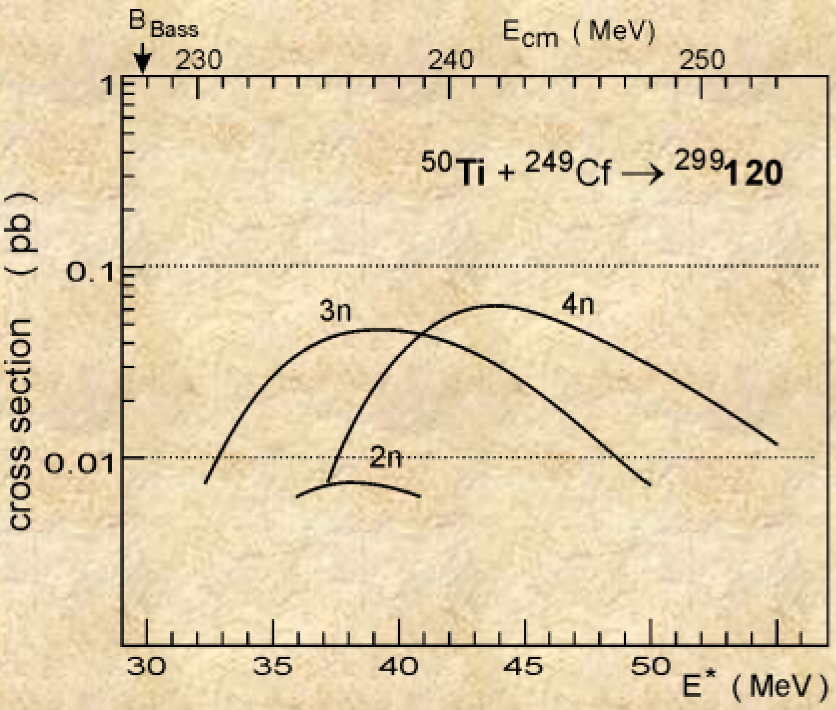


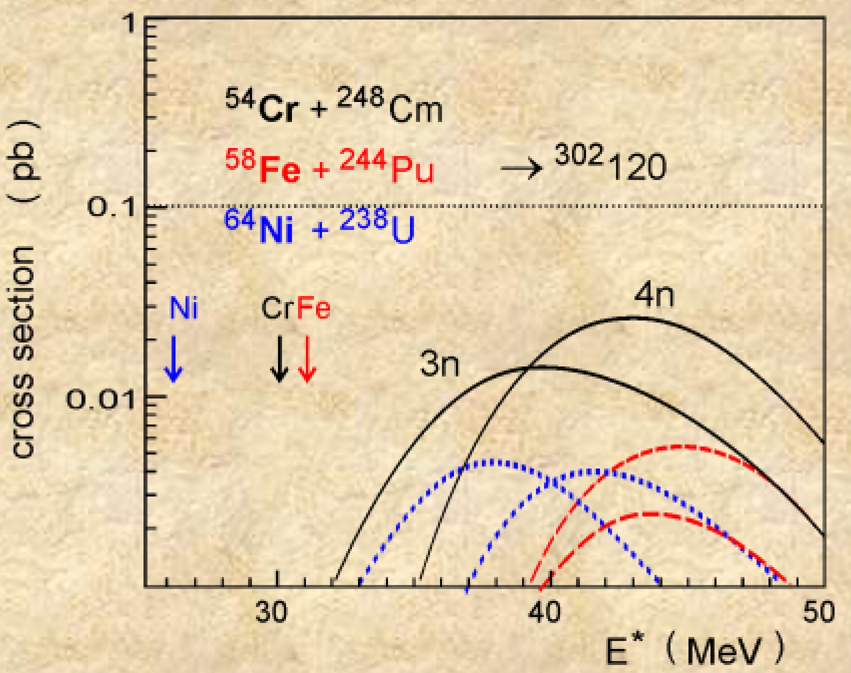
Synthesis of 117: $^{48}Ca + ^{249}Bk \rightarrow ^{297}117$ or $^{50}Ti + ^{243}Am \rightarrow ^{293}117$





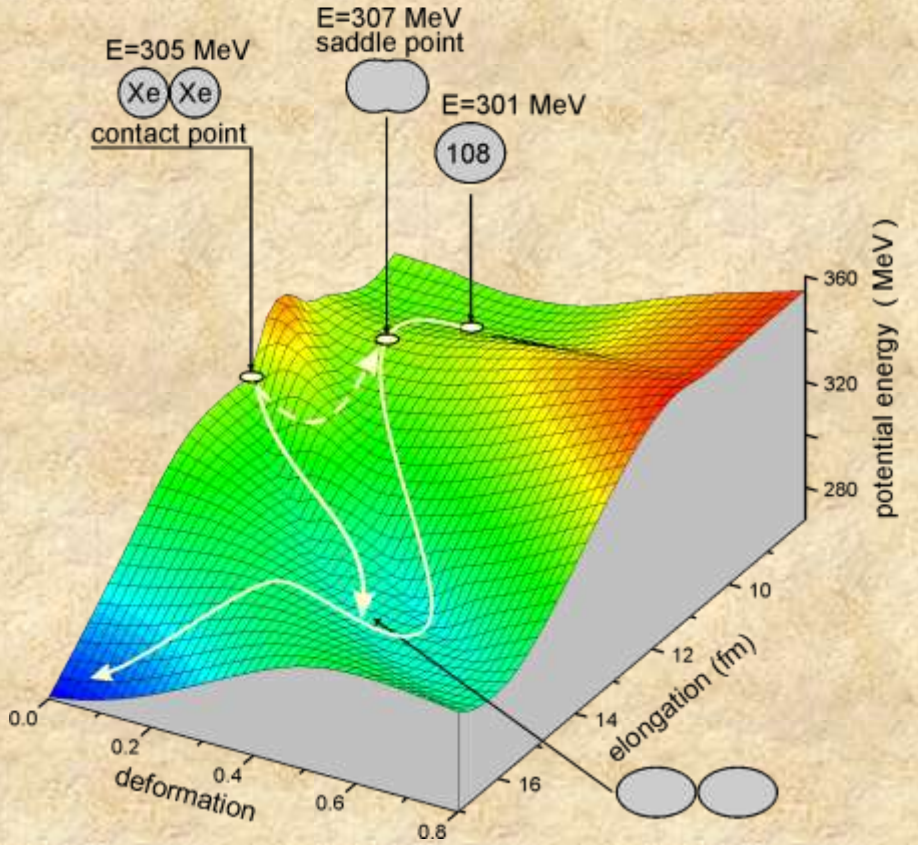
Synthesis of 120

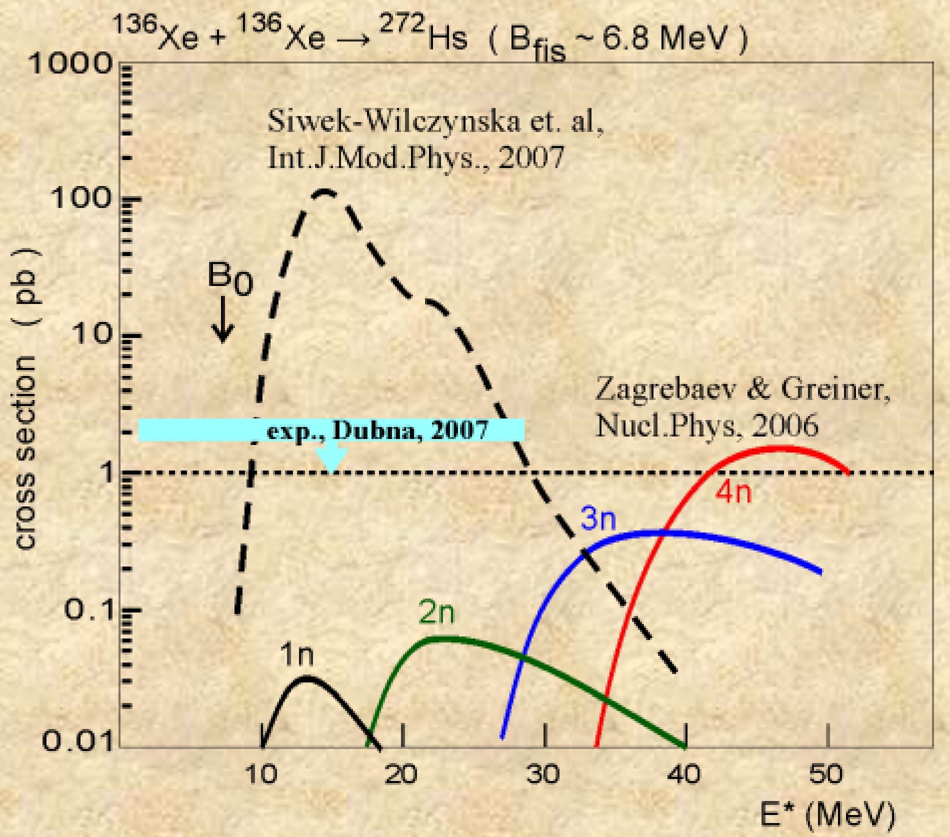




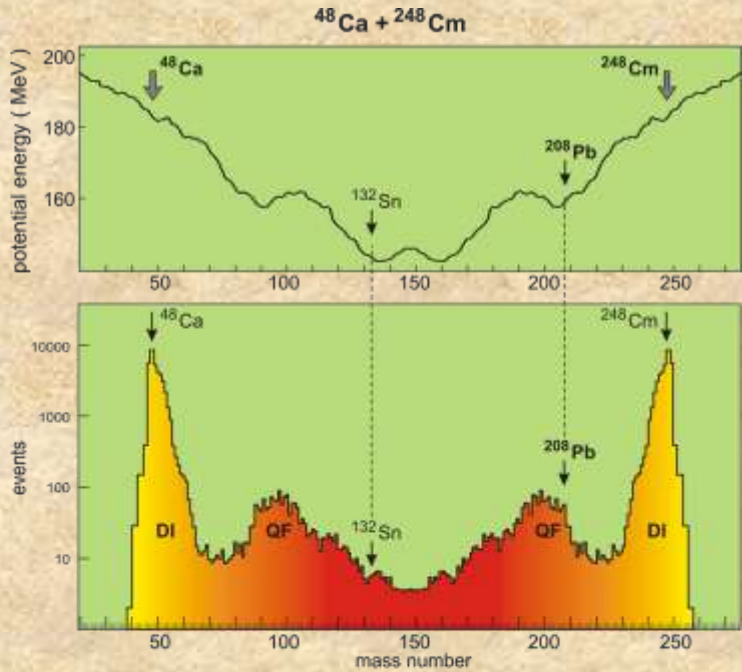
Fusion of "fission fragments": $^{136}Xe + ^{136}Xe \rightarrow {}^{272}108$

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

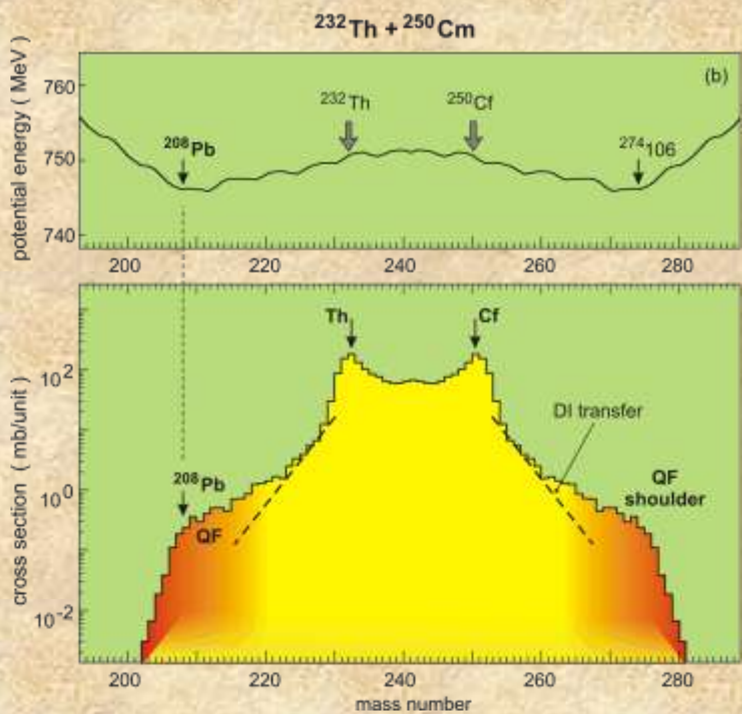




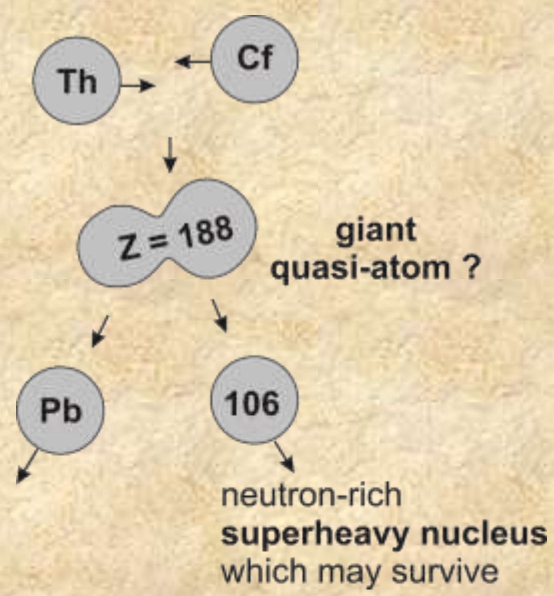
Inverse (antisymmetrizing) qasi-fission process



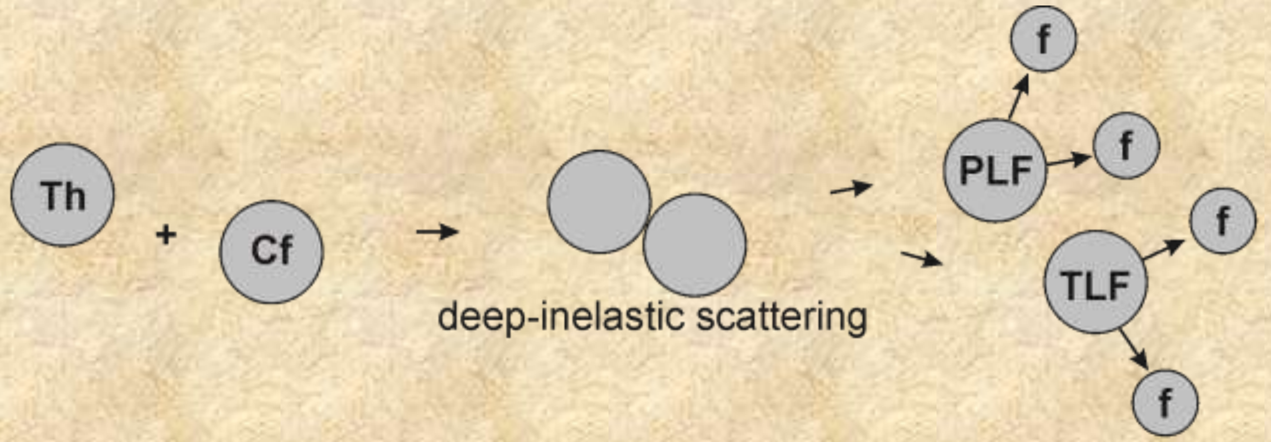
normal
(symmetrizing)
quasi-fission

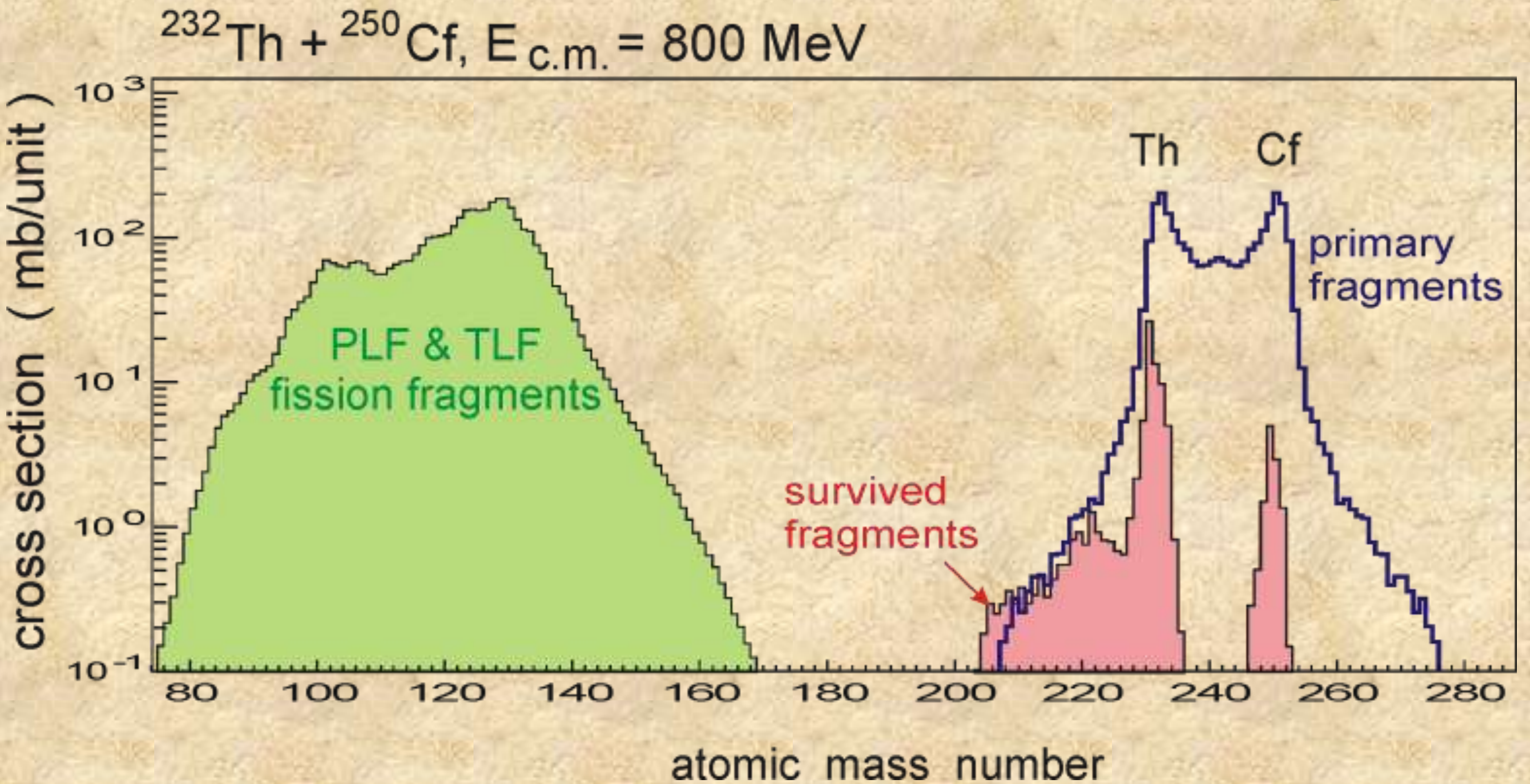


"inverse"
(antisymmetrizing)
quasi-fission

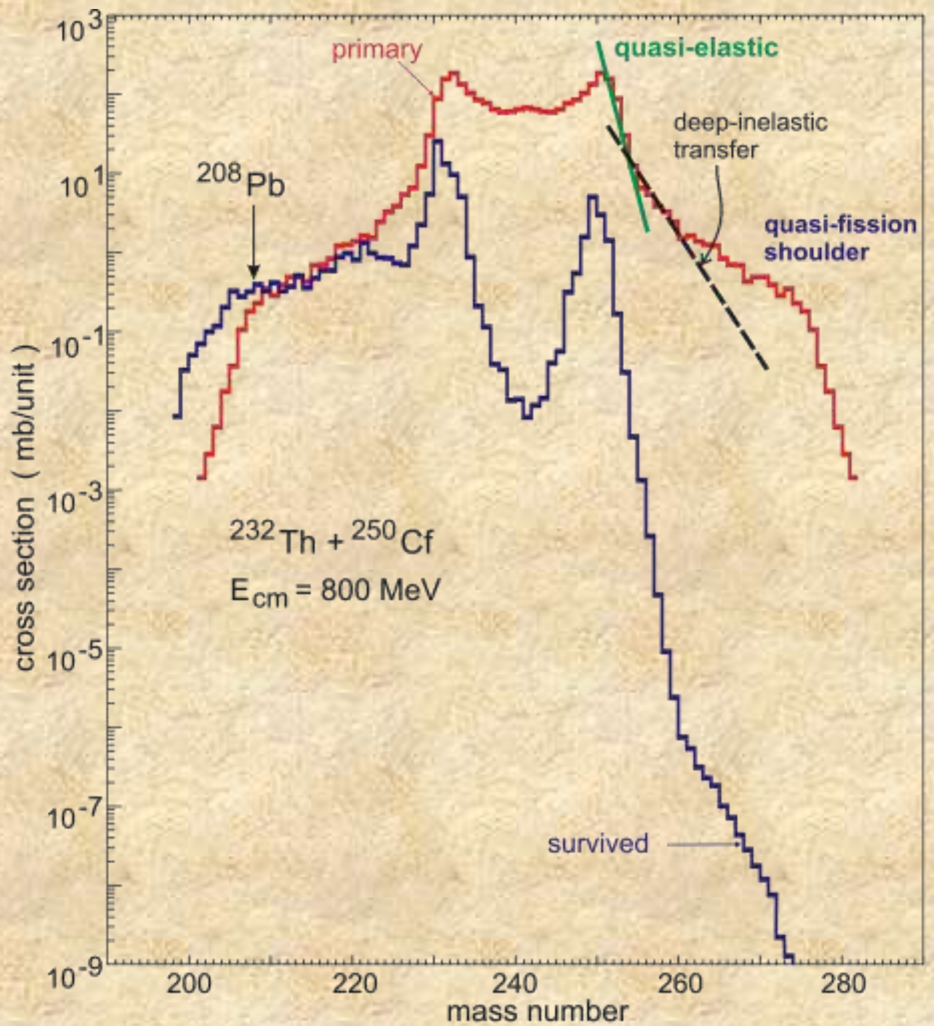


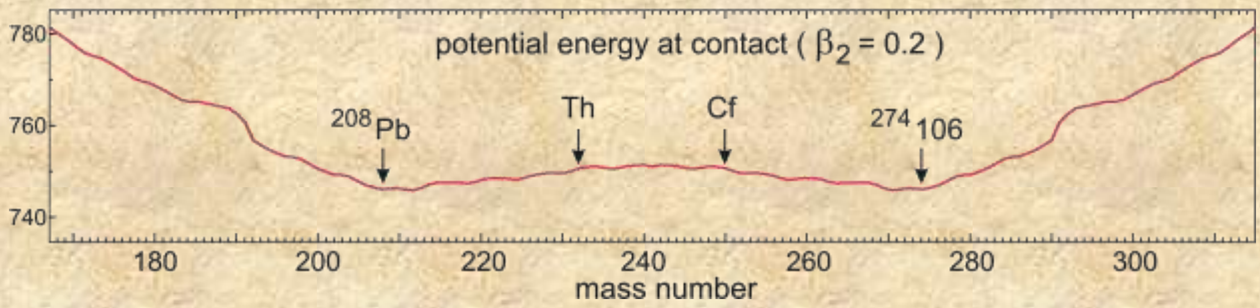
Collision of very heavy (transactinide) nuclei ?



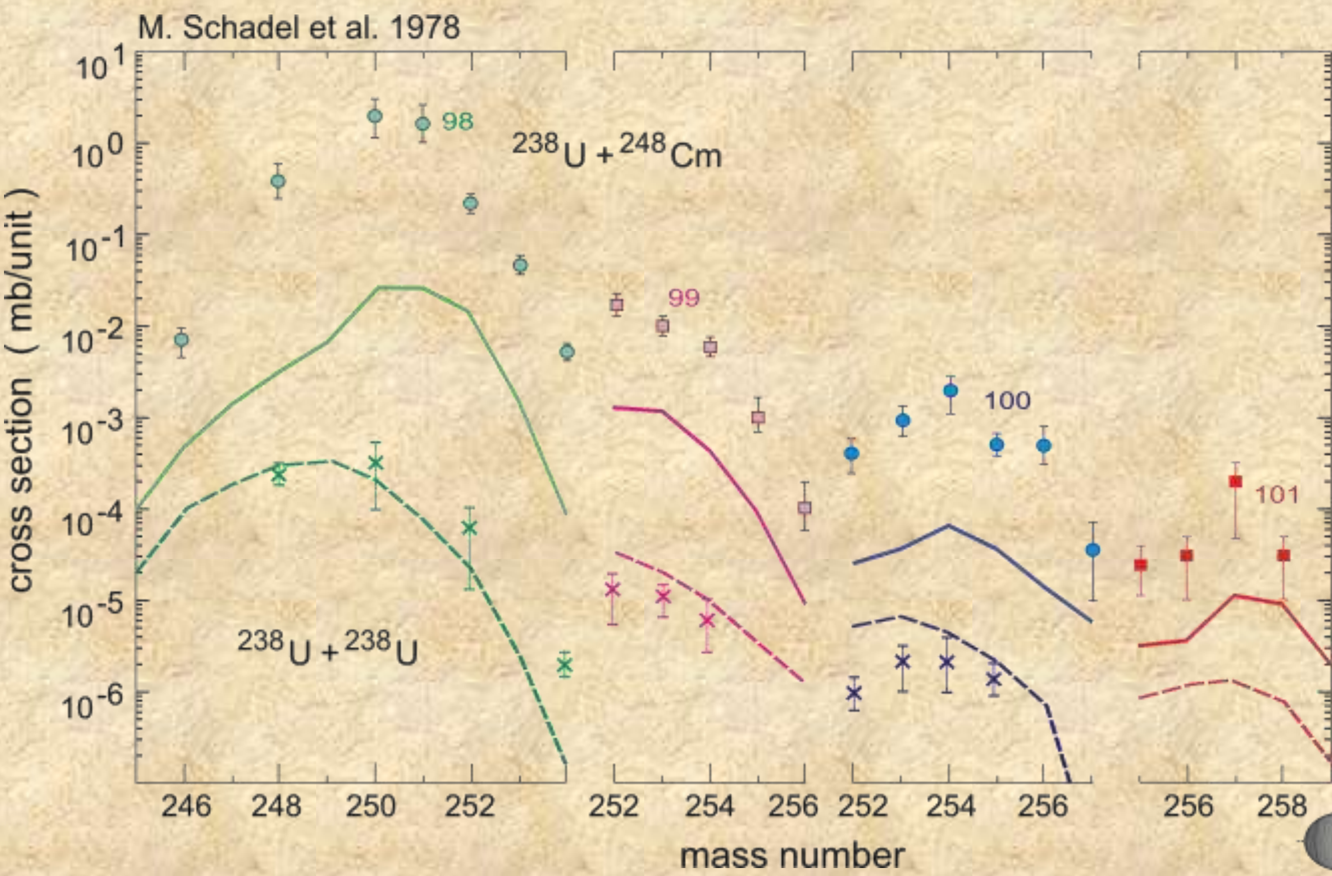


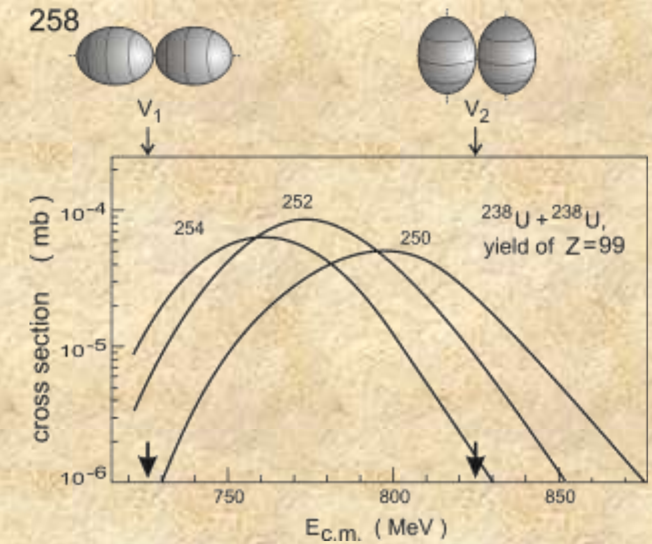
Shell effects in damped collisions of transactinides. New way to superheavies



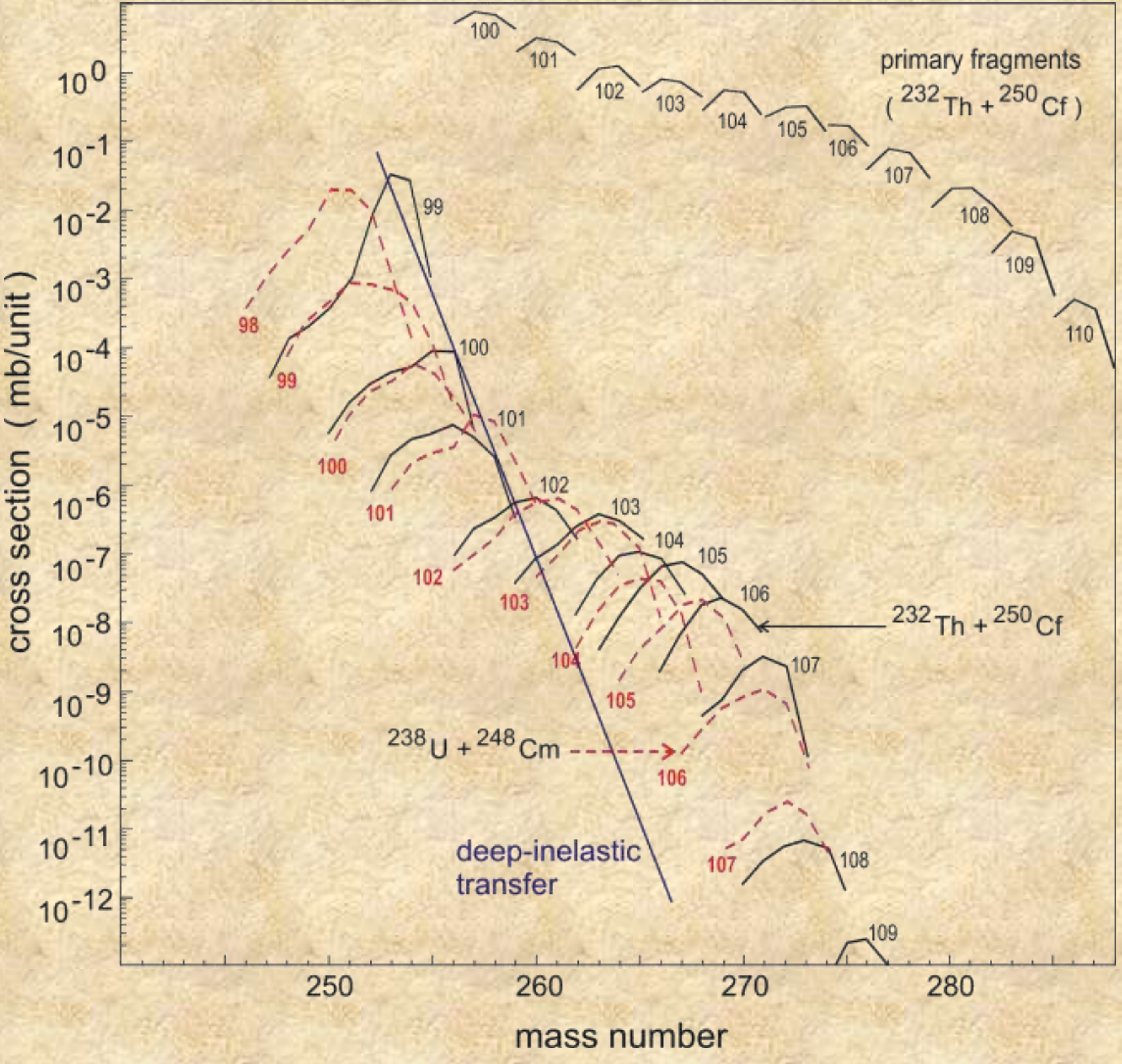


Comparison with available experimental data



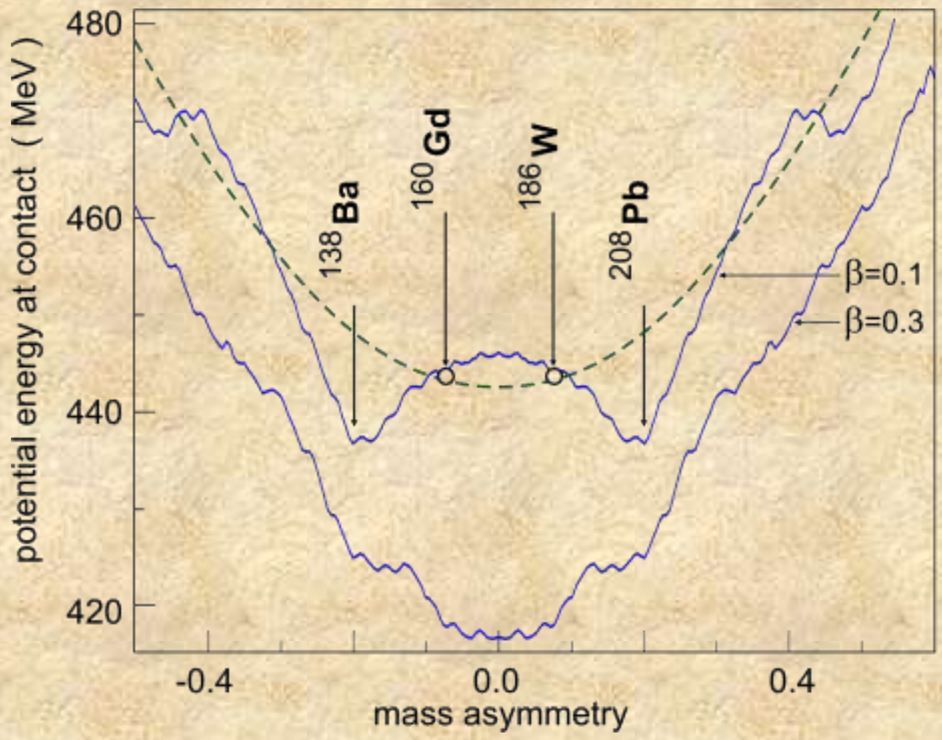


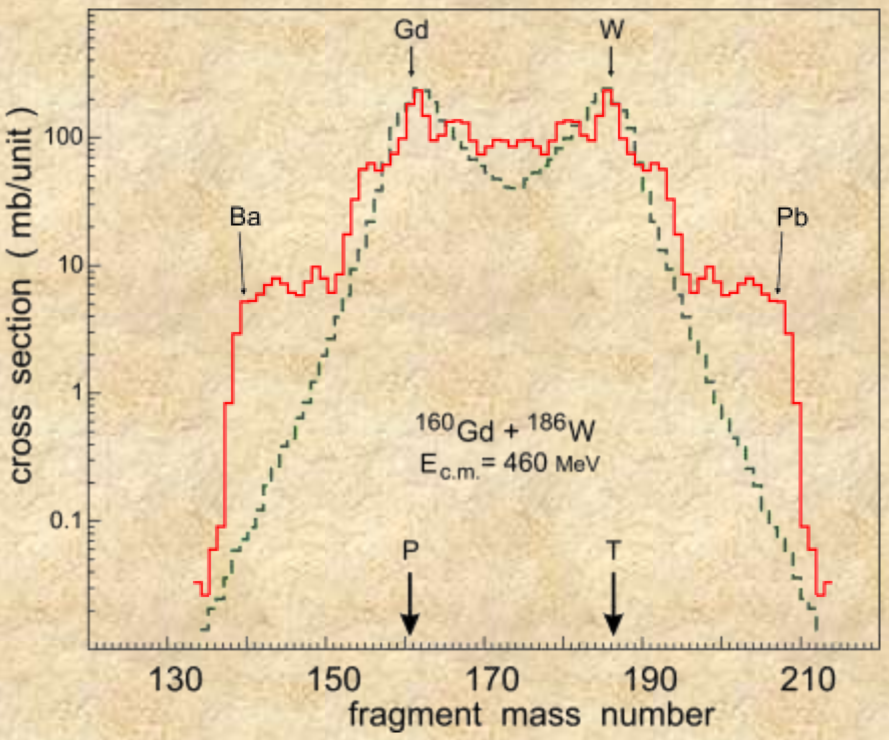
Isotopic yield of SHE in collisions of transactinides



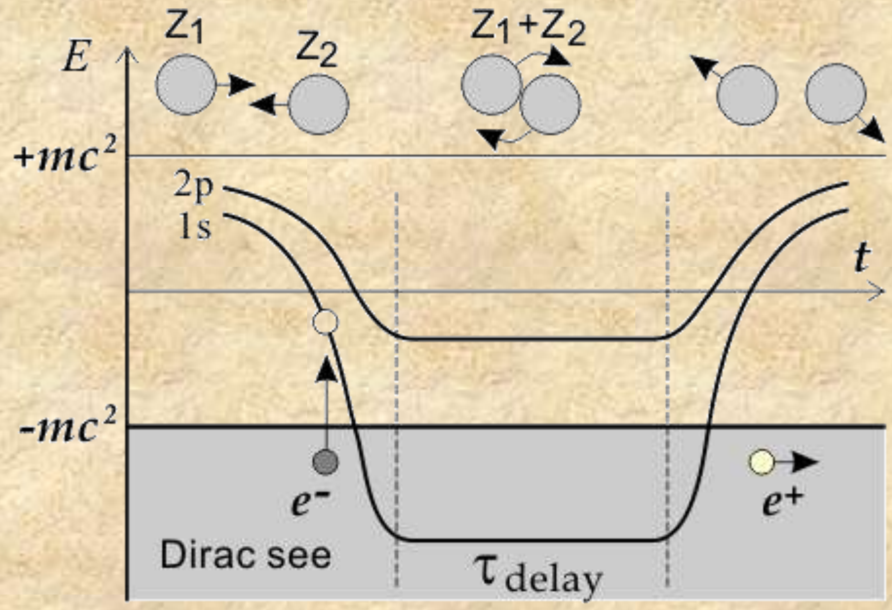
Shell effects in damped collisions
^{160}Gd + ^{186}W

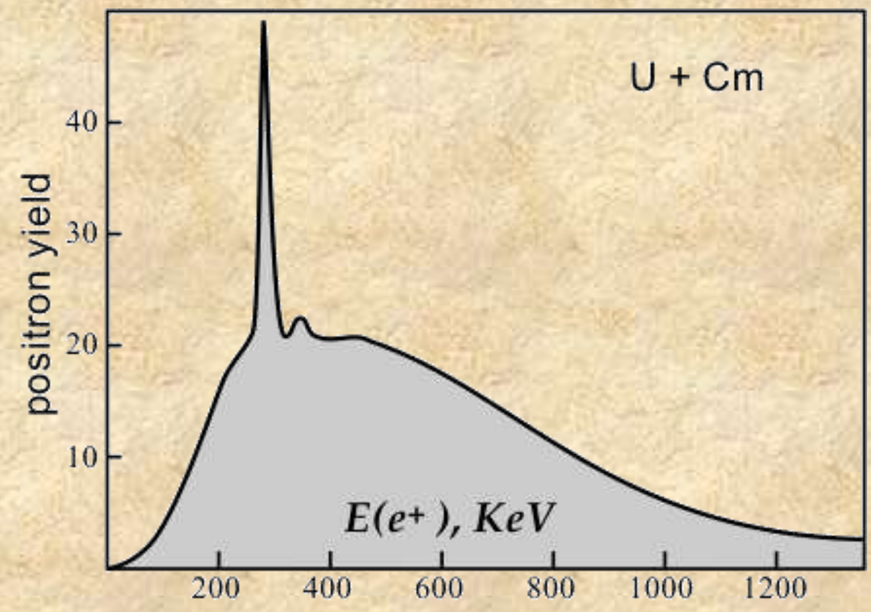
(proposal for a new experiment)





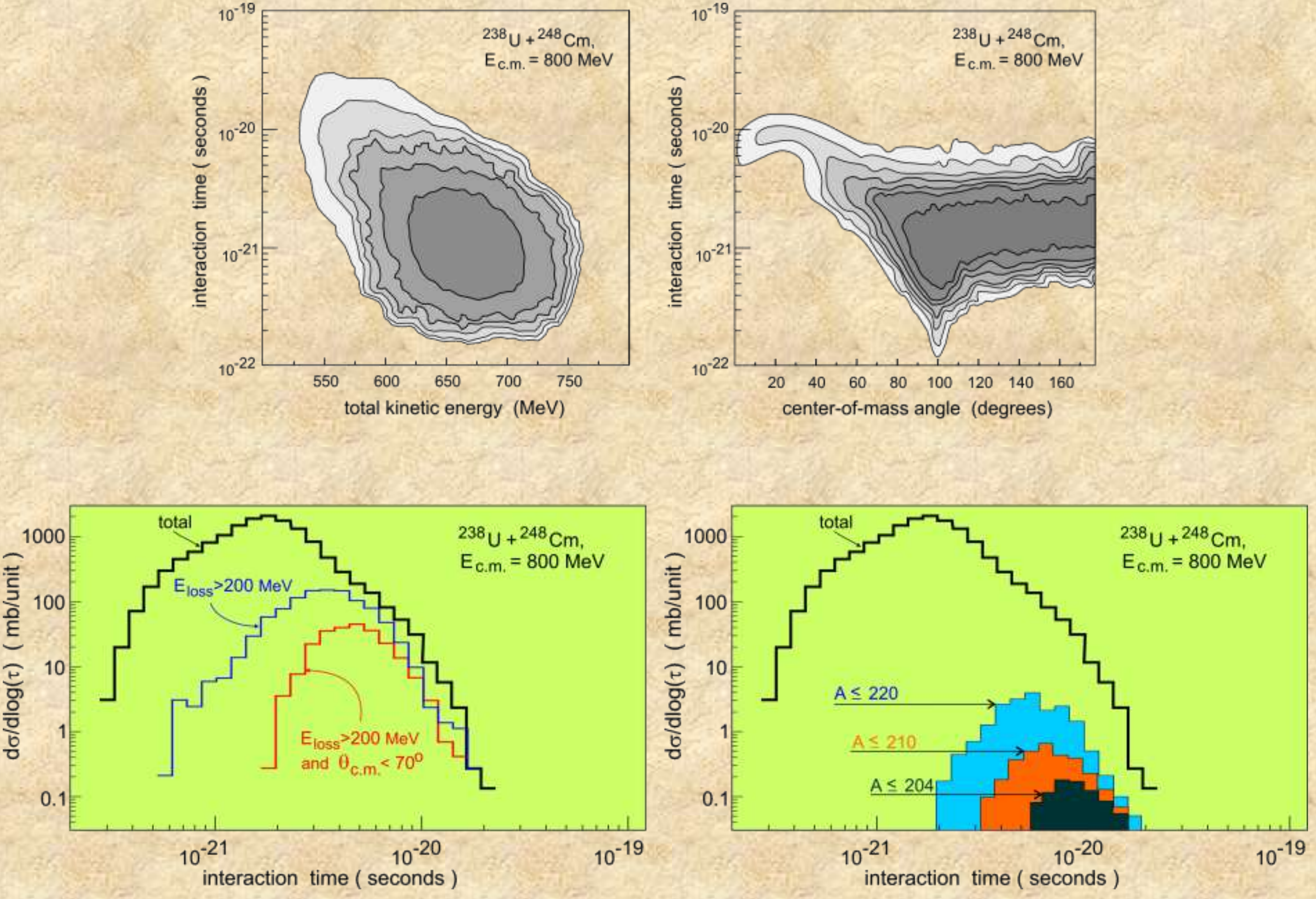
Spontaneous positron emission in super-strong electric field



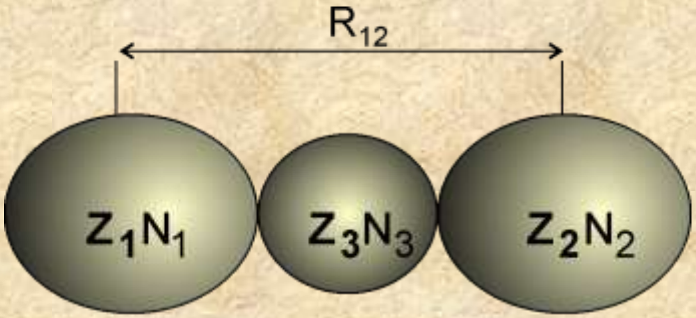


W. Greiner, J.Reinhard, 1981

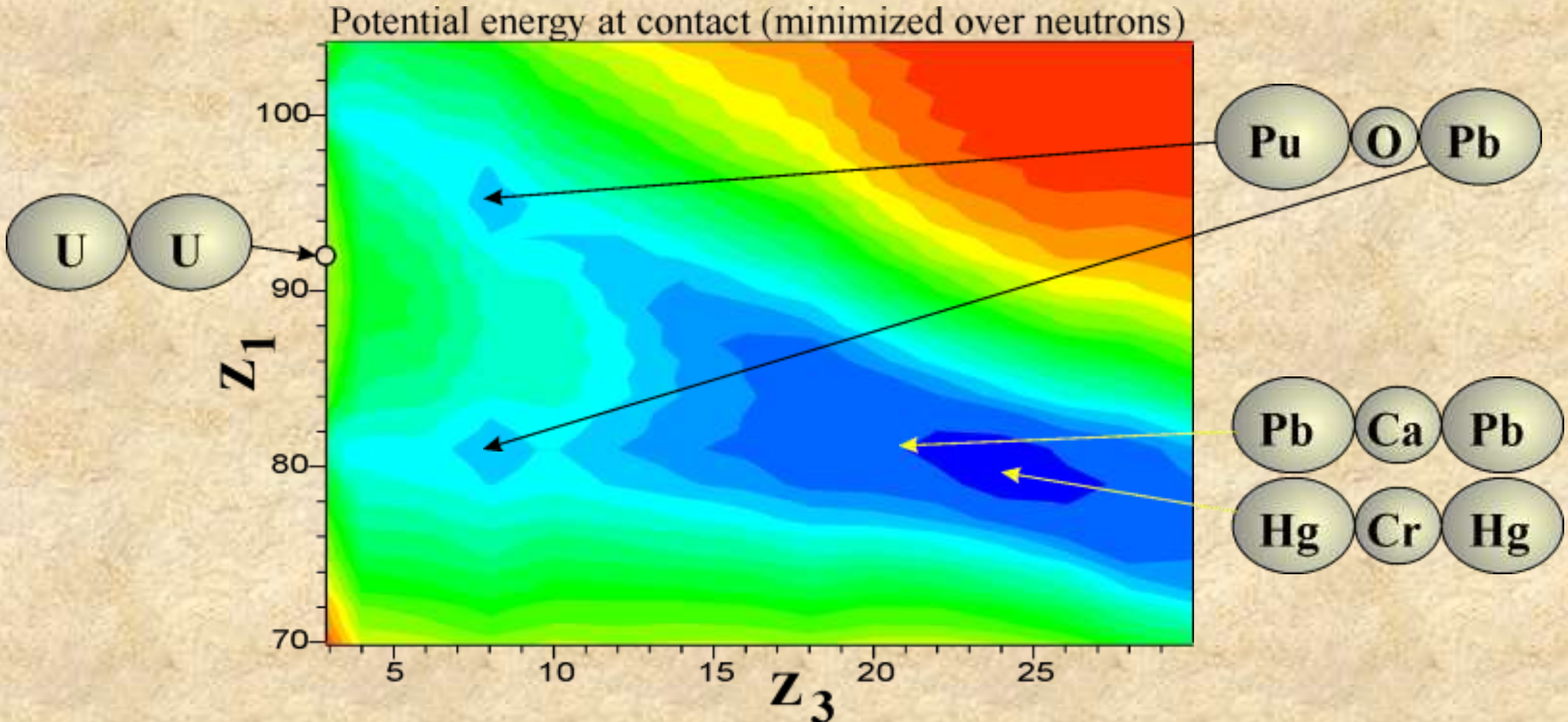
What are the triggers for a long reaction time ?



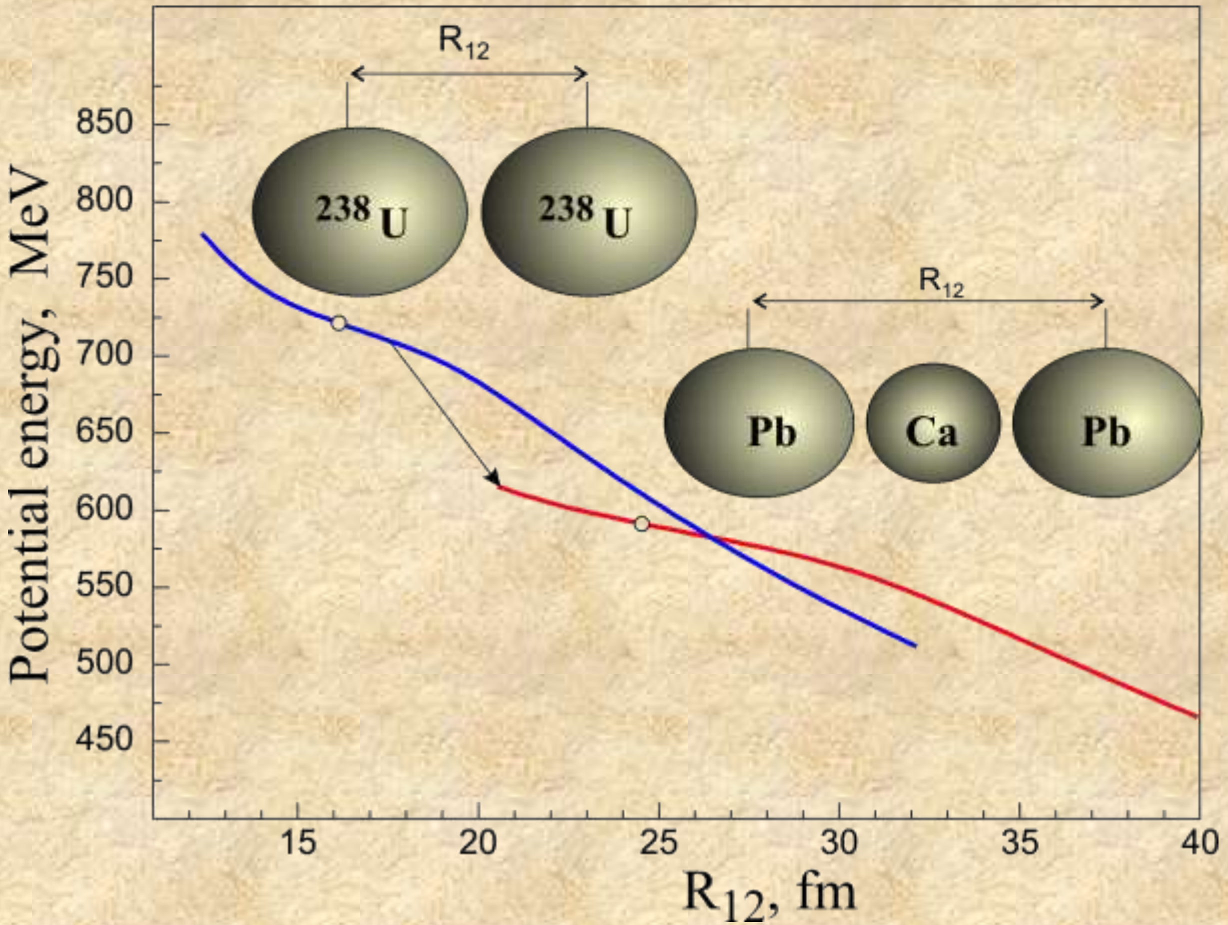
3 - Cluster Configurations ?



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



Clusterization in collisions of transactinides



Summary

- The **Shell effects** play an important role both in structure of heavy nuclei and in low-energy reactions (decay, fusion, fission, transfer, etc.).
- Multi-dimensional fusion-fission driving potential reveals local minima of the **shape isomeric states**, which are nothing else but **two-cluster configurations with magic cores**.
- Shell effects in low-energy **damped collisions of transuranium** nuclei may lead to a noticeable yield of **long-lived neutron-rich SHE** due to a large mass and charge rearrangement in the "inverse quasi-fission" process caused by the Z=82 and N=126 nuclear shells.
- Giant nuclear system formed in U+U-like collisions may live rather long (**positron formation**) and break to a **3-cluster configuration** with two magic nuclei in the region of lead.
- There are several very promising possibilities for synthesis on new SH elements and isotopes. With **titanium beam** (instead of 48Ca) and actinide targets we may move upward to 120 element.
- Cross sections of SHE formation in **symmetric fusion reactions** (including neutron rich fission fragments) are estimated to be **less than 1 pb**.

Valery Zagrebaev and Walter Greiner