Low Energy Nuclear Reactions with Transactinides

- Reactions under consideration
- Fusion-fission driving potential and dynamical model
- Fusion dynamics and synthesis of SHE
- Shell effects in damped collisions : New way to superheavies
- Resume

V. Zagrebaev
TAN-2007, Davos, September 24

Studied Reactions

$$\underset{\text{Proj}}{[\mathrm{Ca} \div \mathrm{Ni}]} + \underset{\text{Targ}}{[\mathrm{Th} \div \mathrm{Cf}]}$$

$\xrightarrow{\text{Quasi-Elastic}}$ PLF + TLF

$\xrightarrow{\text{Deep Inelastic}}$ $\mathrm{PLF}^* + \mathrm{TLF}^* \rightarrow \mathrm{PLF} + f_1 + f_2$

$\xrightarrow{\text{Quasi-Fission}}$ $F_1 + F_2$ (Pb - like)

$\xrightarrow{\text{Fusion}}$ $\mathbf{10^{-3}}$ $\mathrm{SHE}^* \rightarrow f_1 + f_2$

$\mathbf{10^{-7}}$ $\searrow$ **EvR** + xn

$$\underset{\text{Proj}}{[\mathrm{Th} \div \mathrm{Cf}]} + \underset{\text{Targ}}{[\mathrm{Th} \div \mathrm{Cf}]}$$

$\xrightarrow{\text{Quasi-Elastic}}$ PLF + TLF

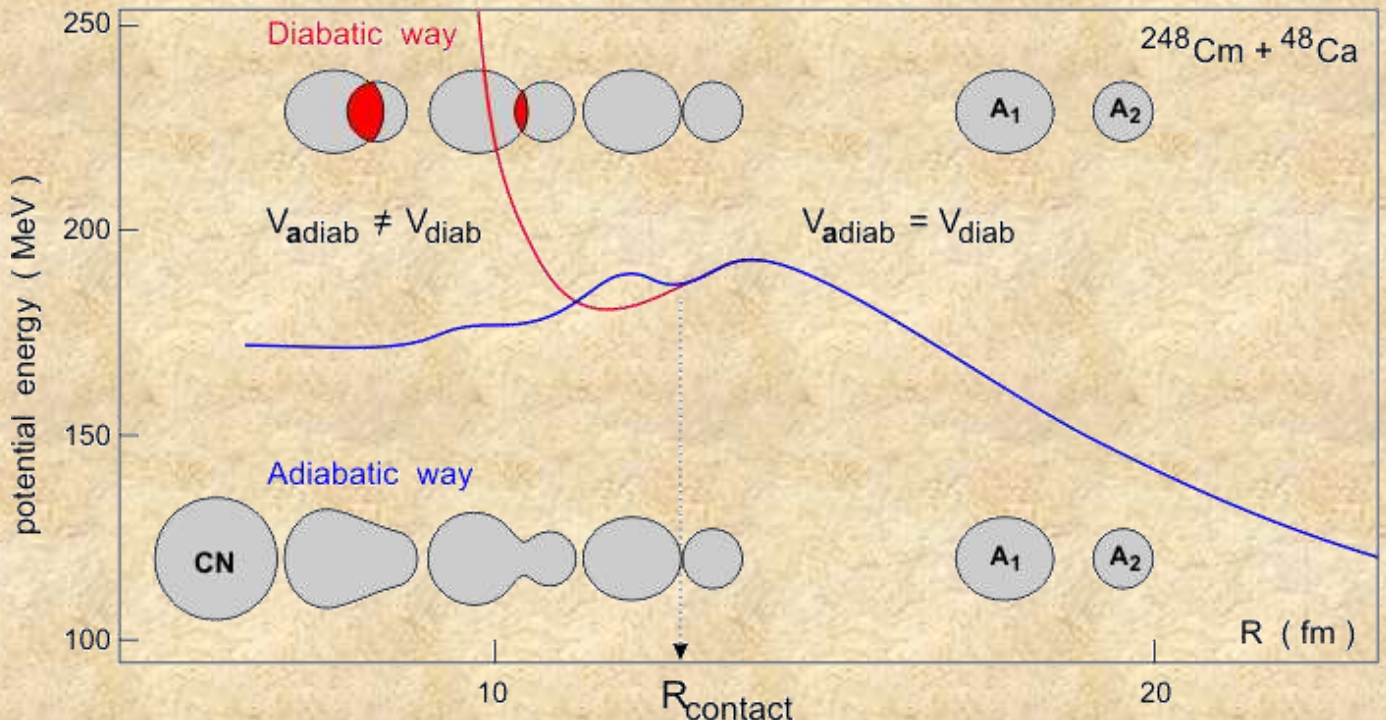
$\xrightarrow{\text{Deep Inelastic}}$ $\mathrm{PLF}^* + \mathrm{TLF}^* \rightarrow f_1 + f_2 + f_3 + f_4$

$\xrightarrow{\text{Shell effects}}$ $\mathrm{Pb}^* + \mathrm{SHE}^* \rightarrow \text{Pb-like} + f_3 + f_4$

$\mathbf{10^{-?}}$ $\searrow$ **EvR** + xn

Diabatic and Adiabatic Potential Energy

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



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

Time - dependent driving potential has to be used

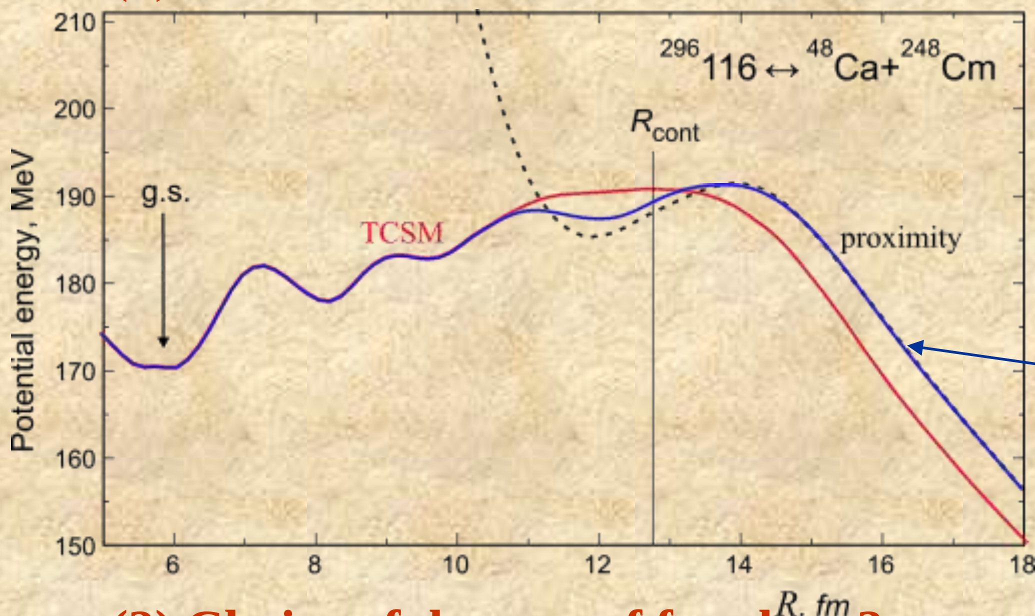
$$V(t) = V_{diab}(\xi)\cdot exp(-\frac{t_{int}}{\tau_{relax}}) + V_{adiab}(\xi)\cdot[1-exp(-\frac{t_{int}}{\tau_{relax}})]$$

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

the same degrees of freedom !

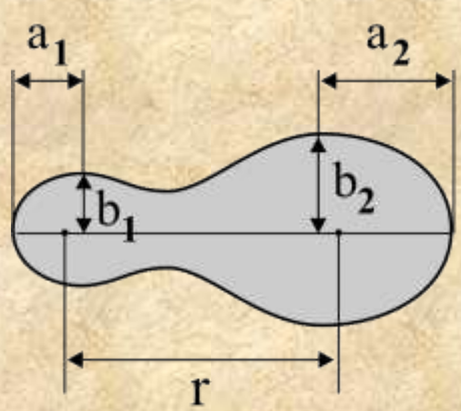
Calculation of multi-dimensional adiabatic potential energy ?

(1) Lack of standard macro-micro 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

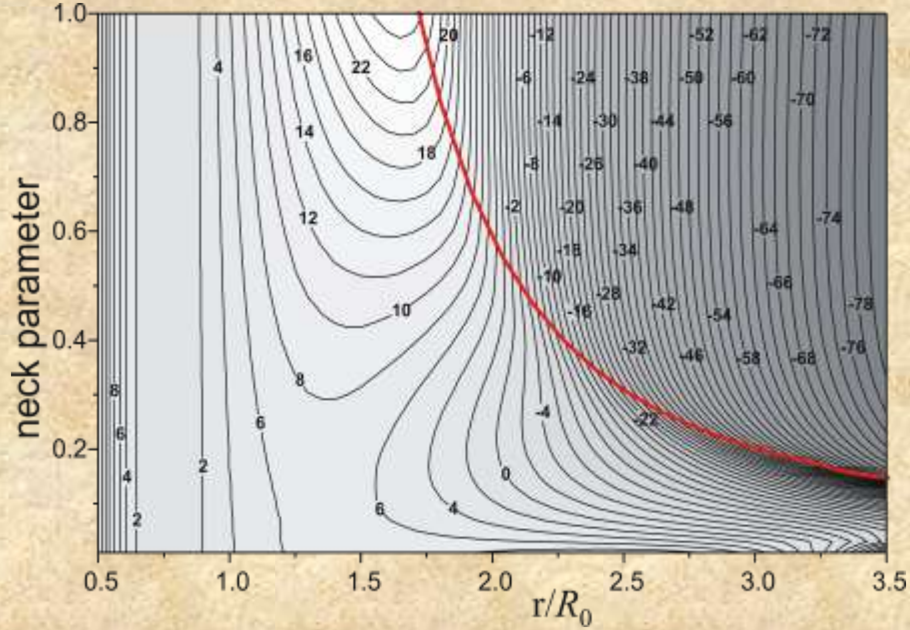
(2) $\delta_1 = 1 - \frac{a_1}{b_1}$

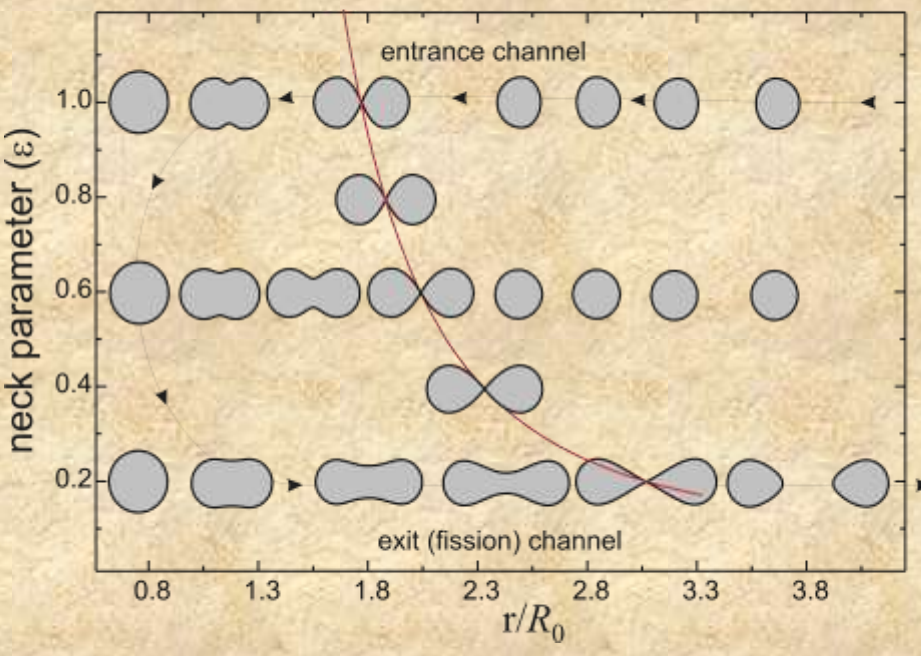
(3) $\delta_2 = 1 - \frac{a_2}{b_2}$

(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

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

entrance channel: **Diabatic potential**

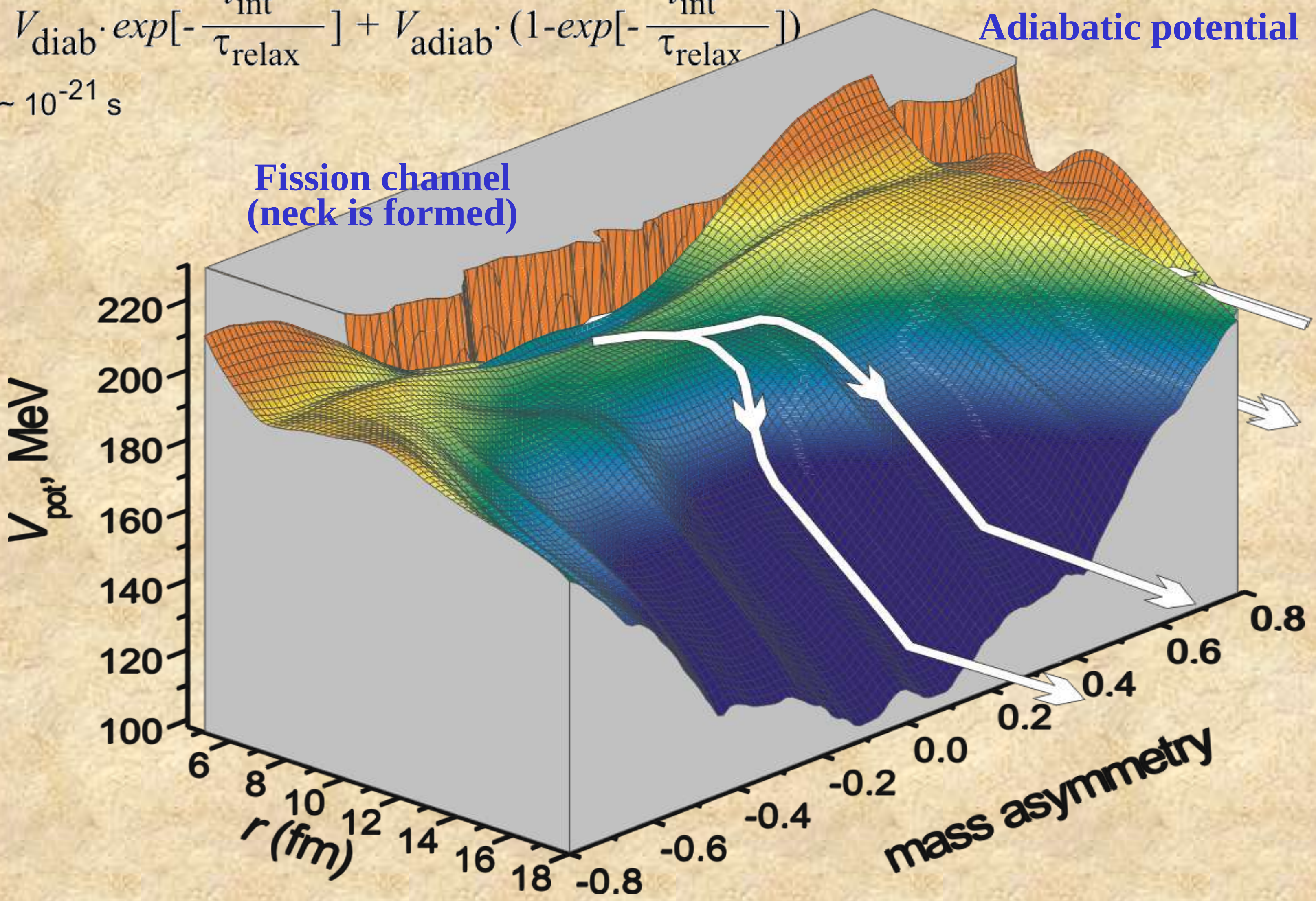
Quasi-Elastic and Deep Inelastic Processes

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

Adiabatic potential

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

Fission channel (neck is formed)



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:

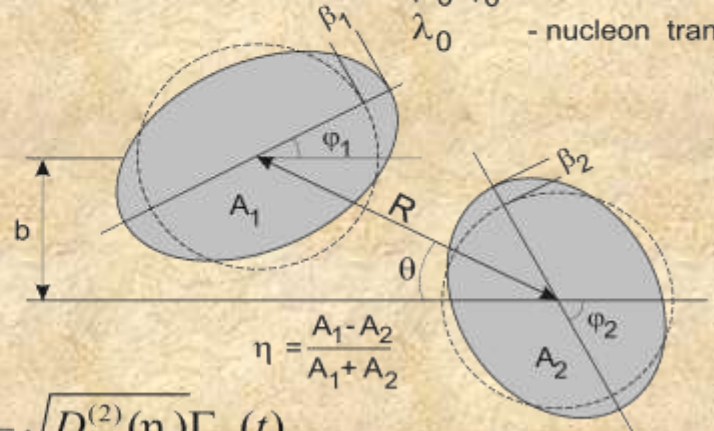
μ_0, γ_0 - nuclear viscosity and friction,

λ_0 - nucleon transfer rate

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

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

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



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

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

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

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

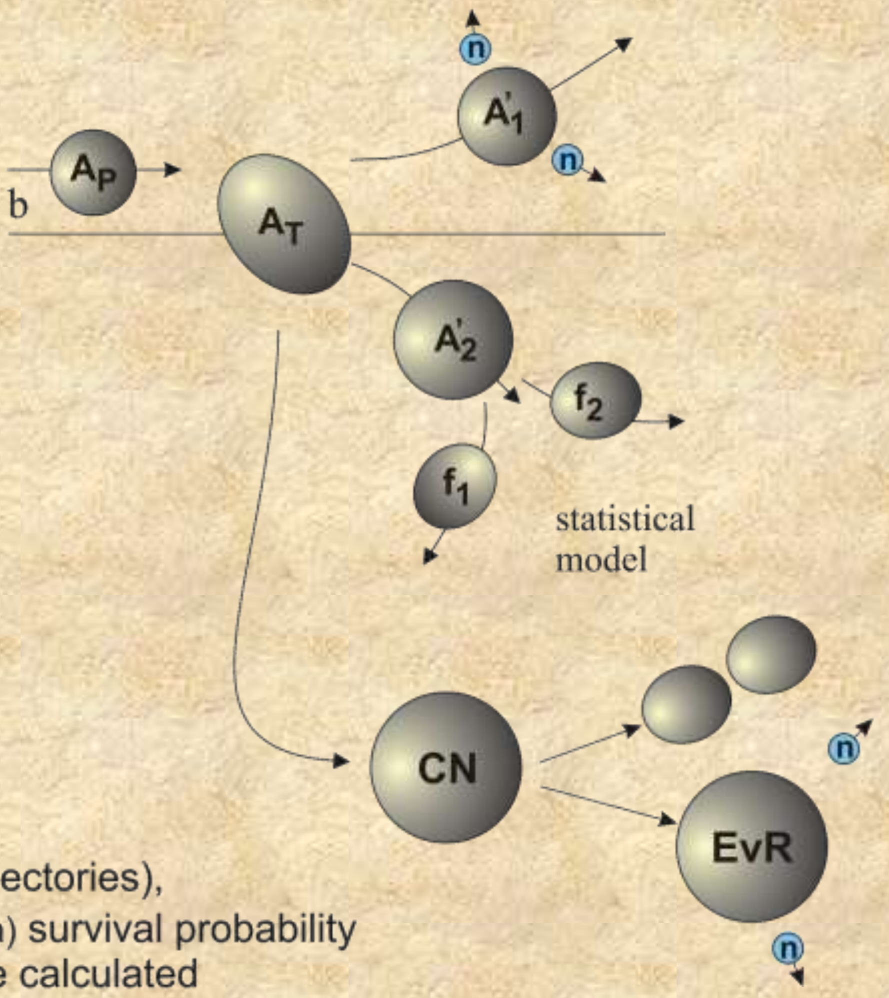
$$\frac{dL_2}{dt} = -\frac{\partial V}{\partial \varphi_2} + \gamma_{\text{tan}}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) a_2 - \frac{a_2}{R}\sqrt{\gamma_{\text{tang}} T}\,\Gamma_{\text{tang}}(t)$$

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

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

Simulation of experiment and cross sections

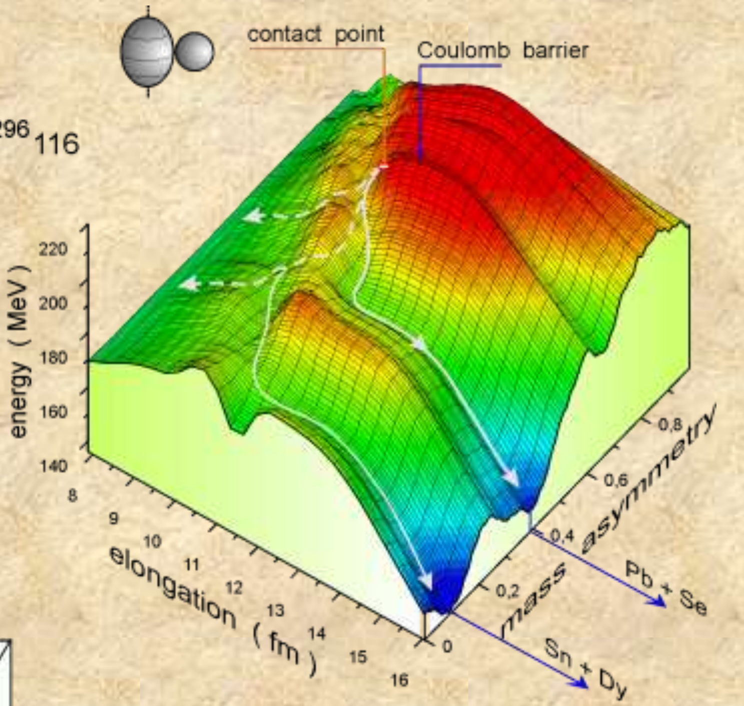
$$\frac{d^2\sigma_\alpha}{d\Omega dE}(E,\theta) = \int_0^\infty bdb \; \frac{\Delta N_\alpha(b,E,\theta)}{N_{tot}(b)} \; \frac{1}{\sin(\theta)\Delta\theta\Delta E}$$

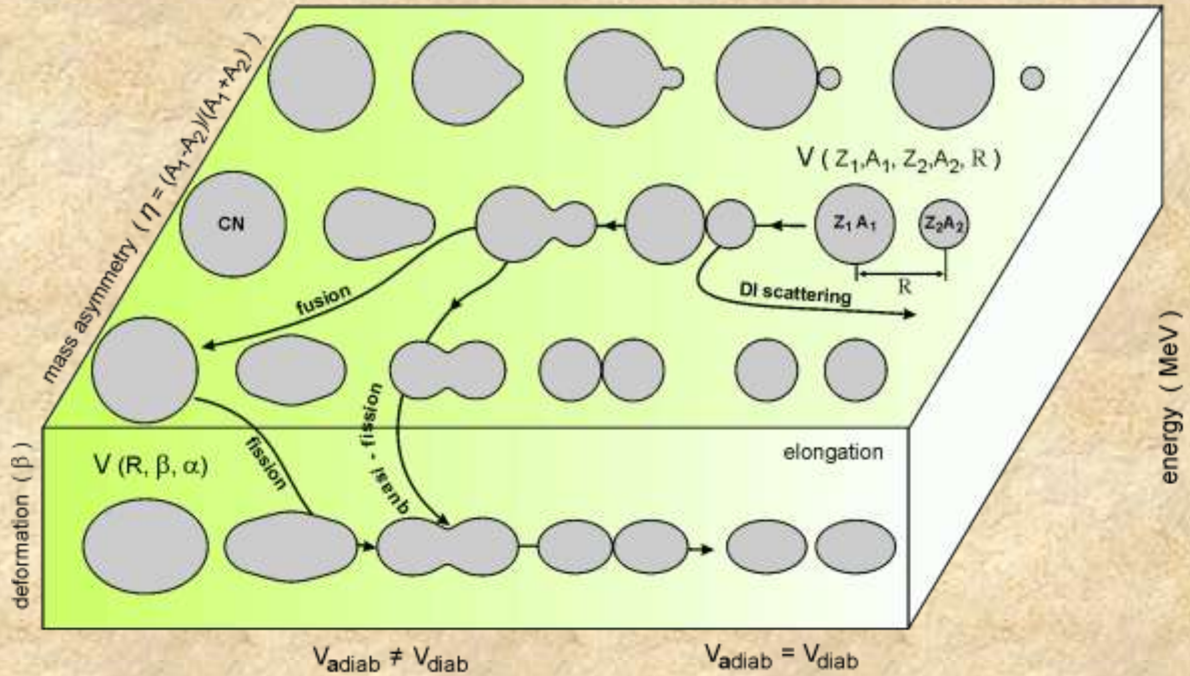


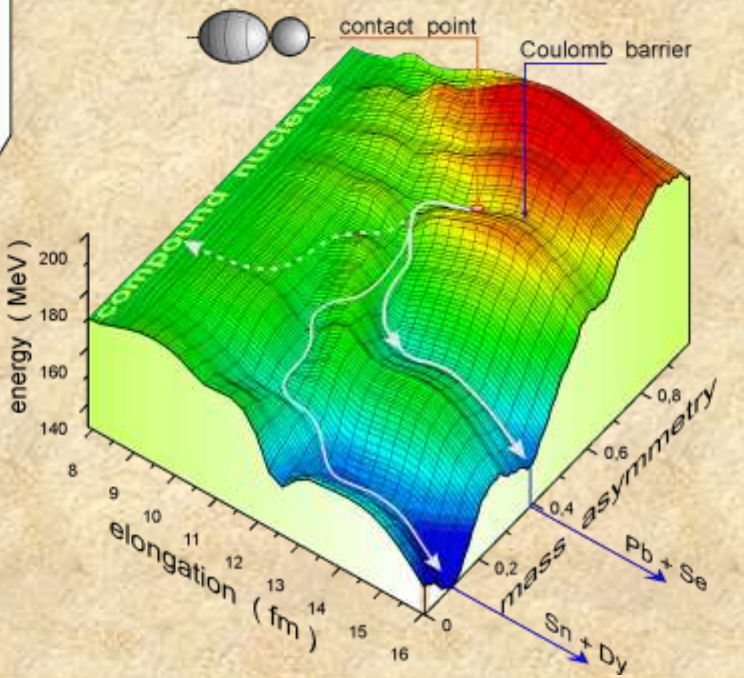
Dynamics: 10^6 tested events (trajectories),
Statistical model: 10^{-6}(3n), 10^{-7}(4n) survival probability
cross sections up to **0.1 pb** can be calculated

Multi-dimensional adiabatic driving potential

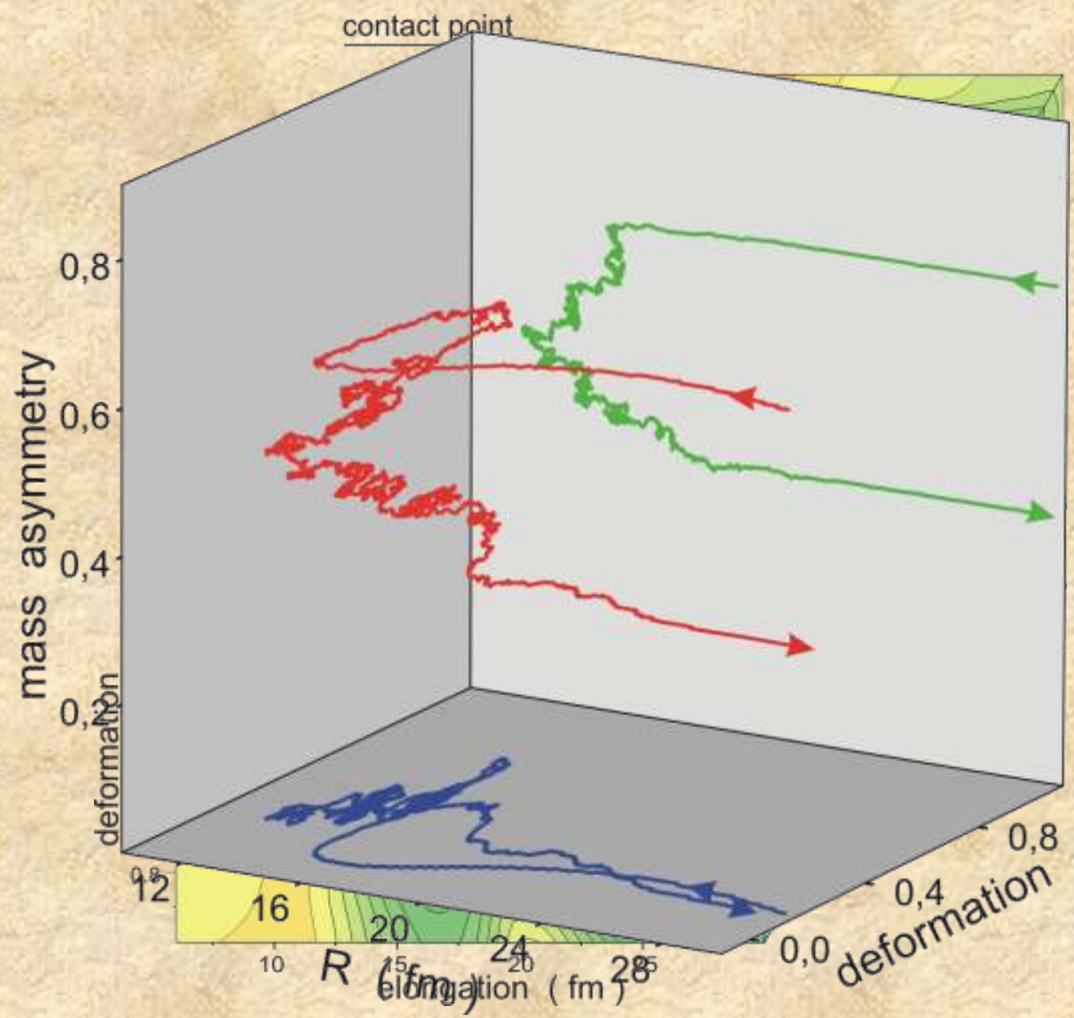
$^{48}Ca + ^{248}Cm \rightarrow ^{296}116$



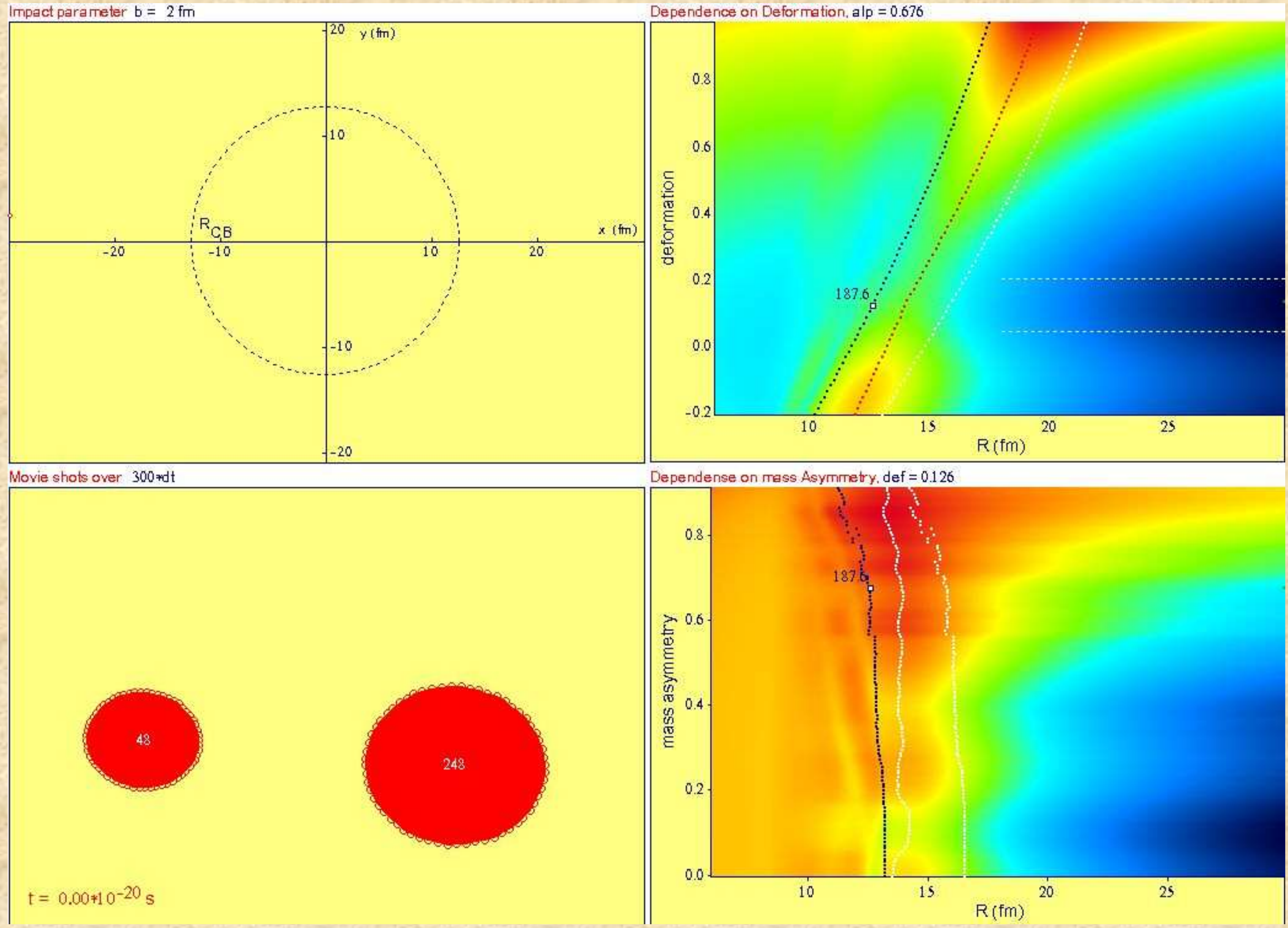




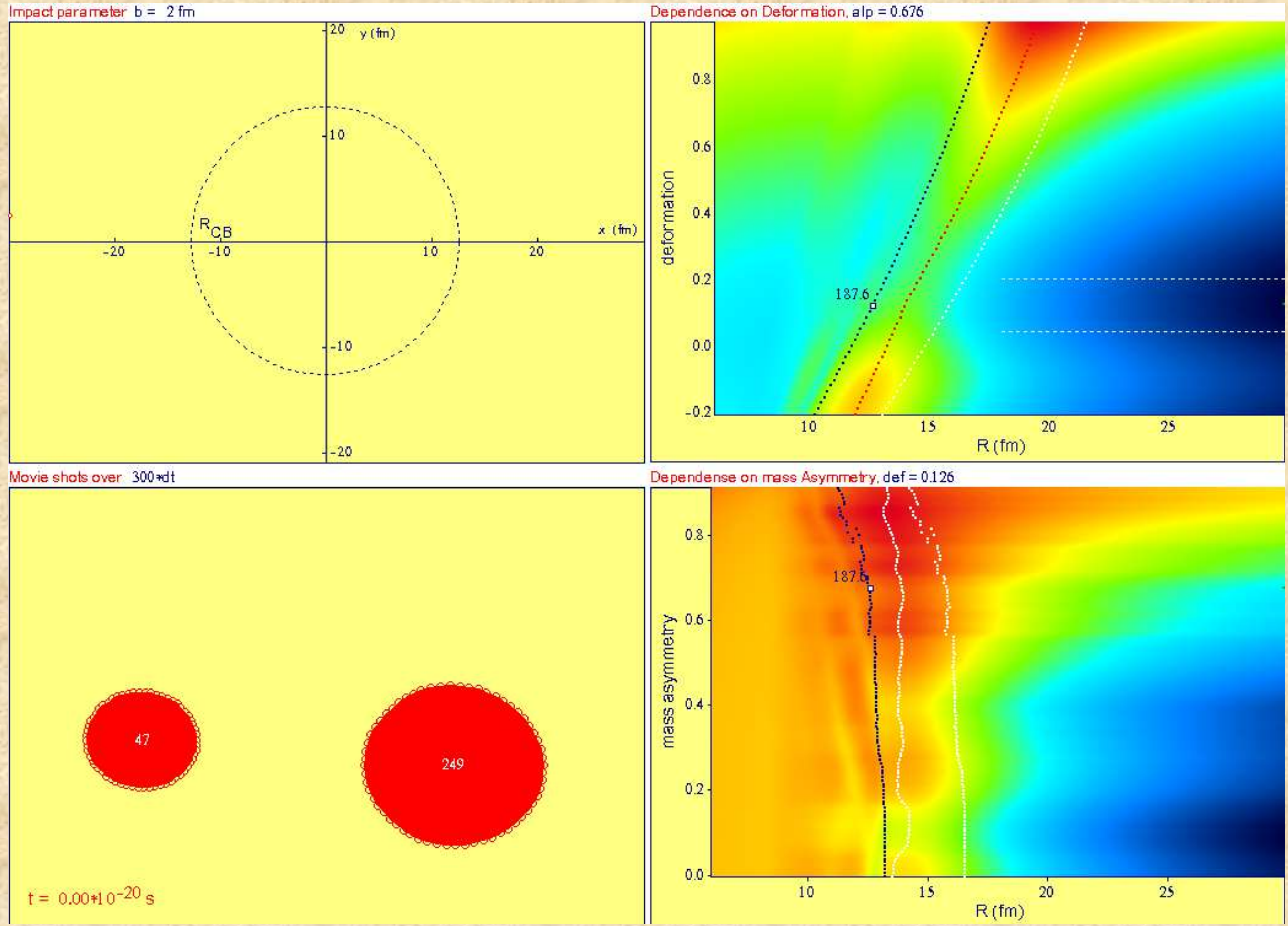
$^{248}Cm + ^{48}Ca \leftrightarrow {}^{296}116$



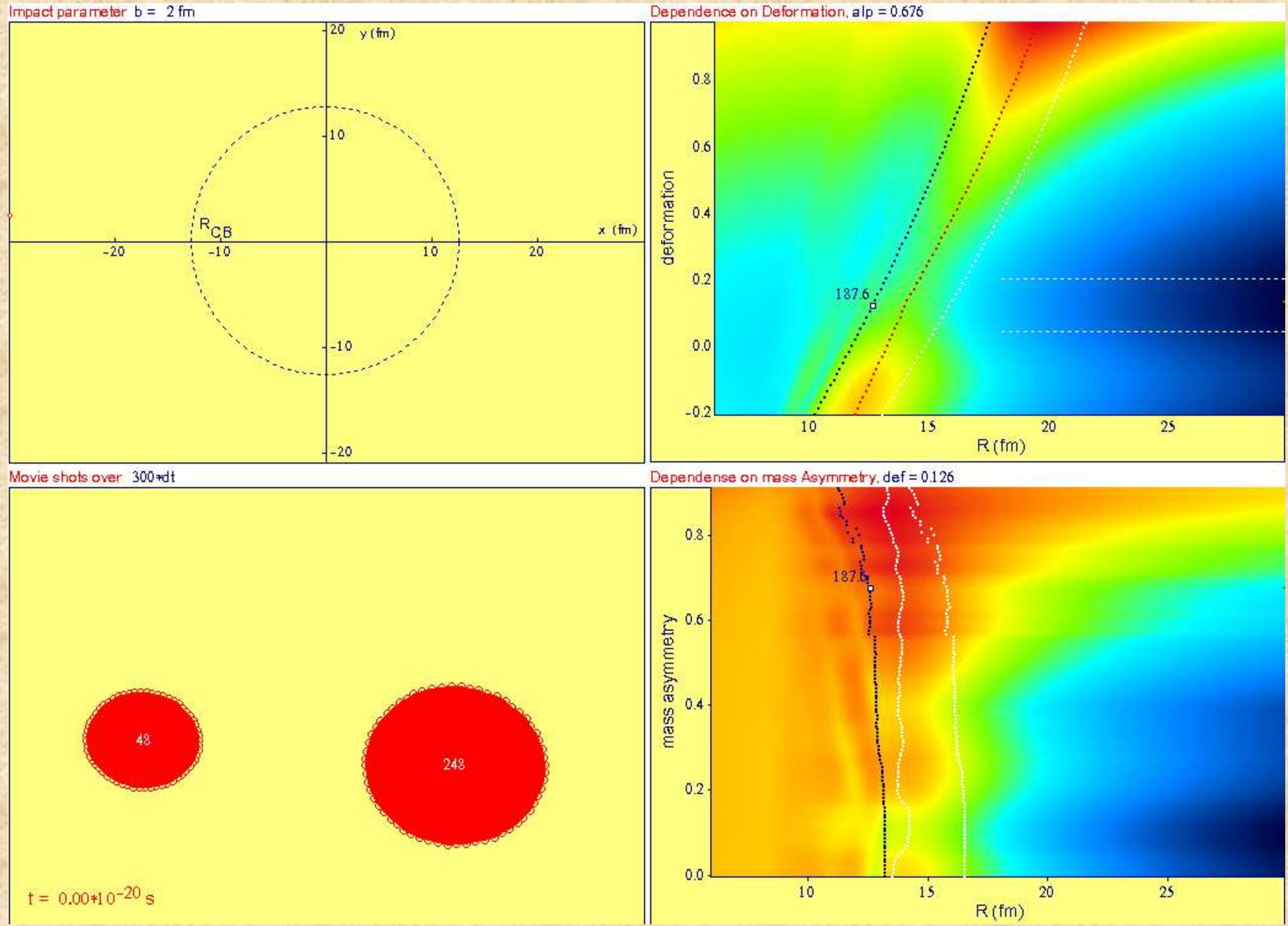
Motion in multi-dimensional space



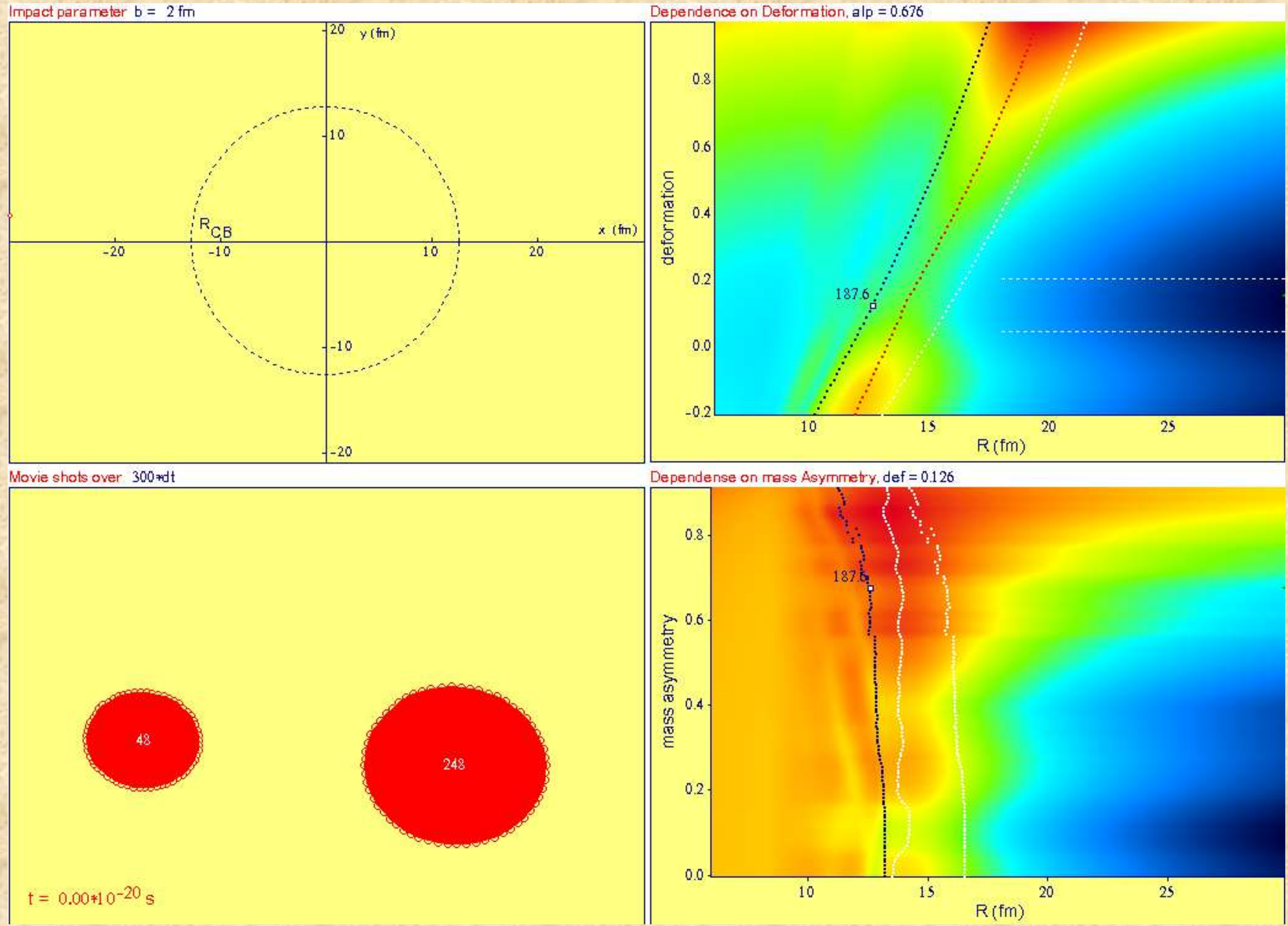
Deep-Inelastic Scattering



Quasi-fission process

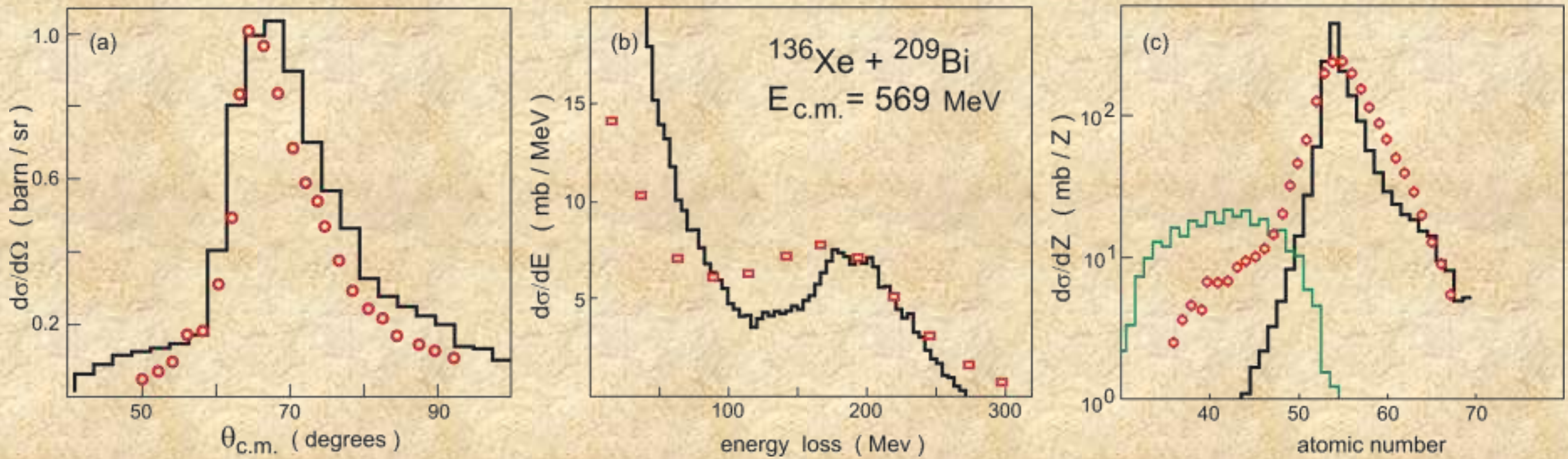


Symmetric quasi-fission

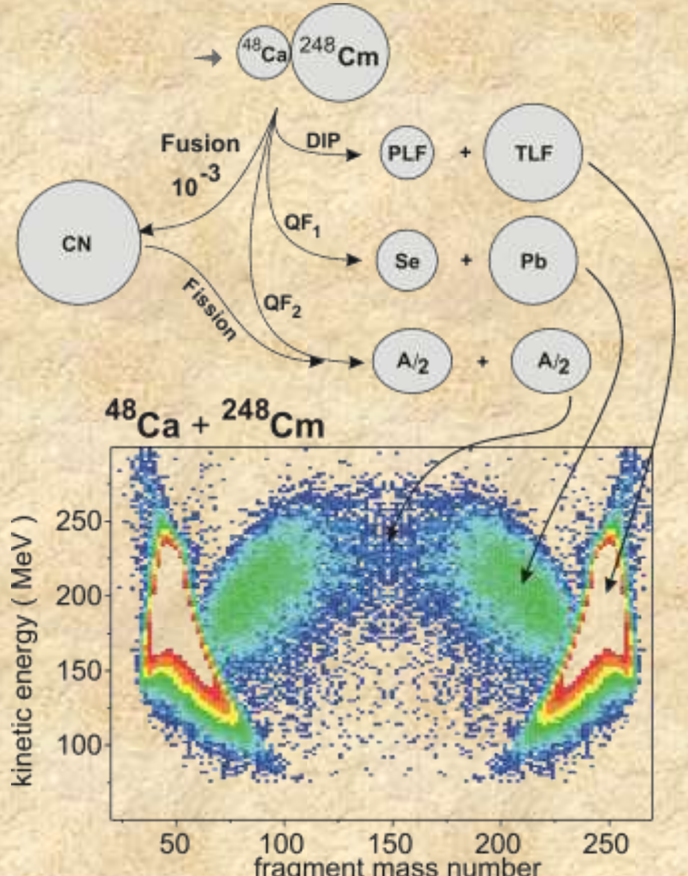


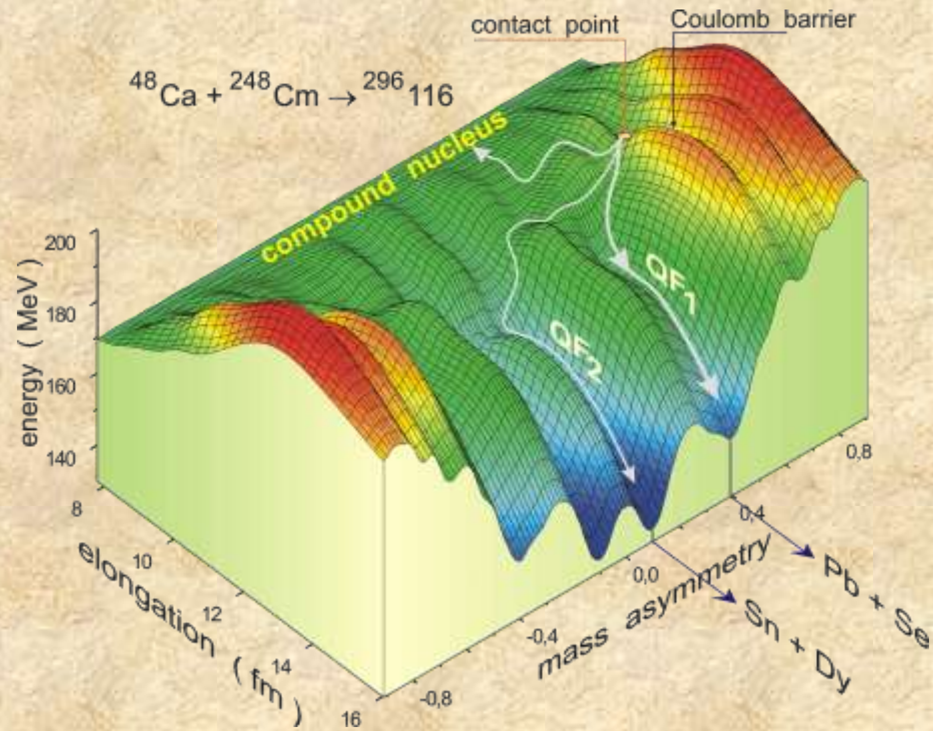
Deep-Inelastic Scattering: $^{136}Xe + {}^{209}Bi$

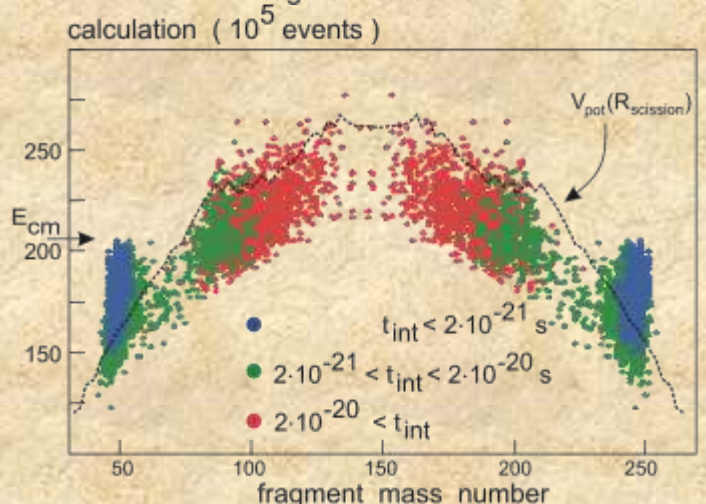
W.W. Wilcke et al., 1980

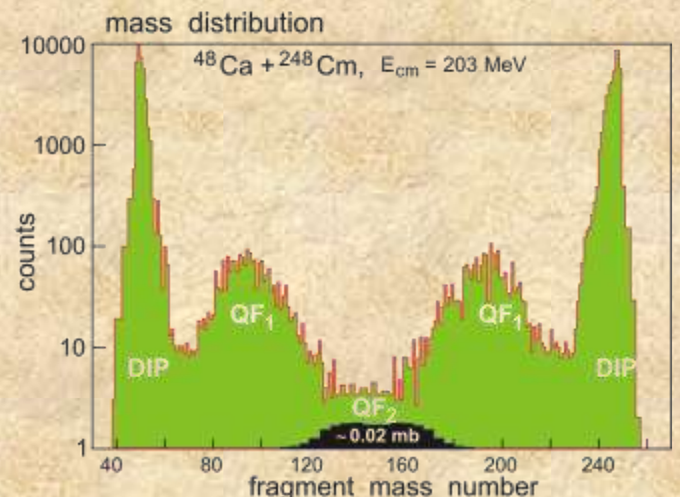


Quasi-fission and fusion-fission processes

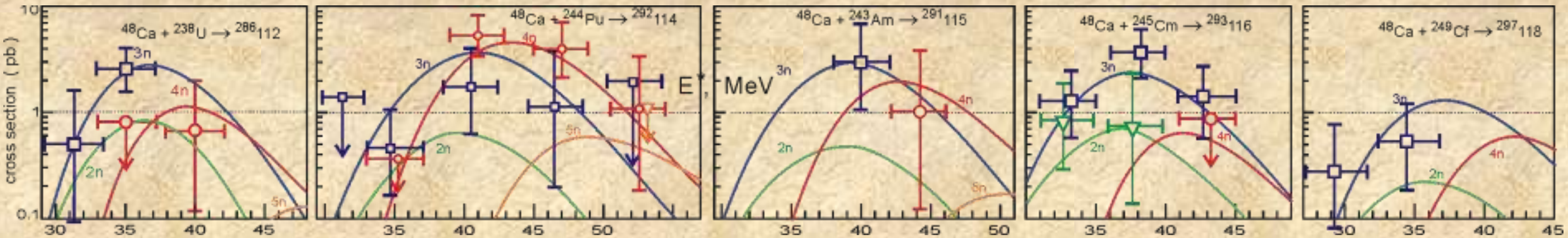


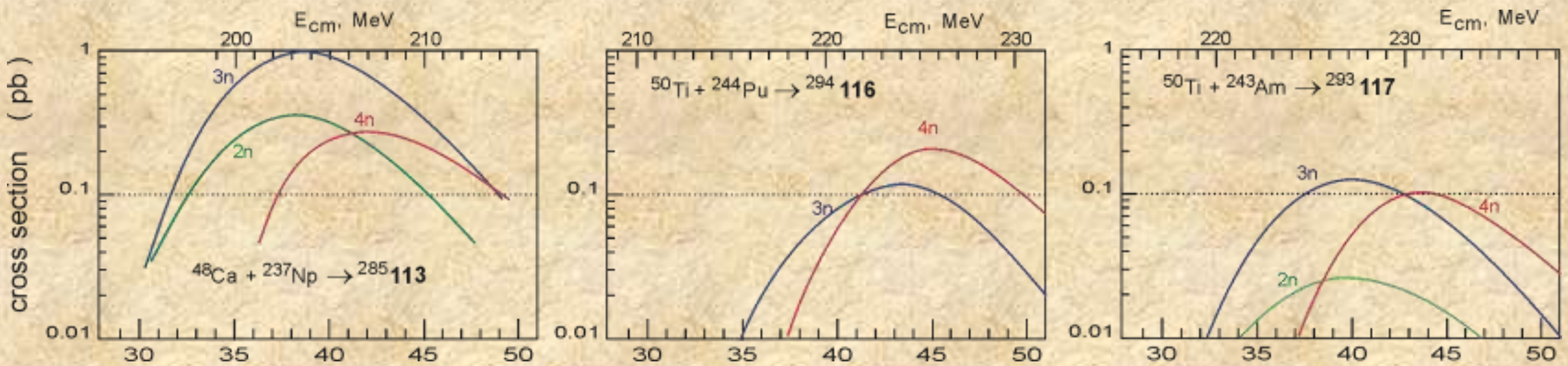




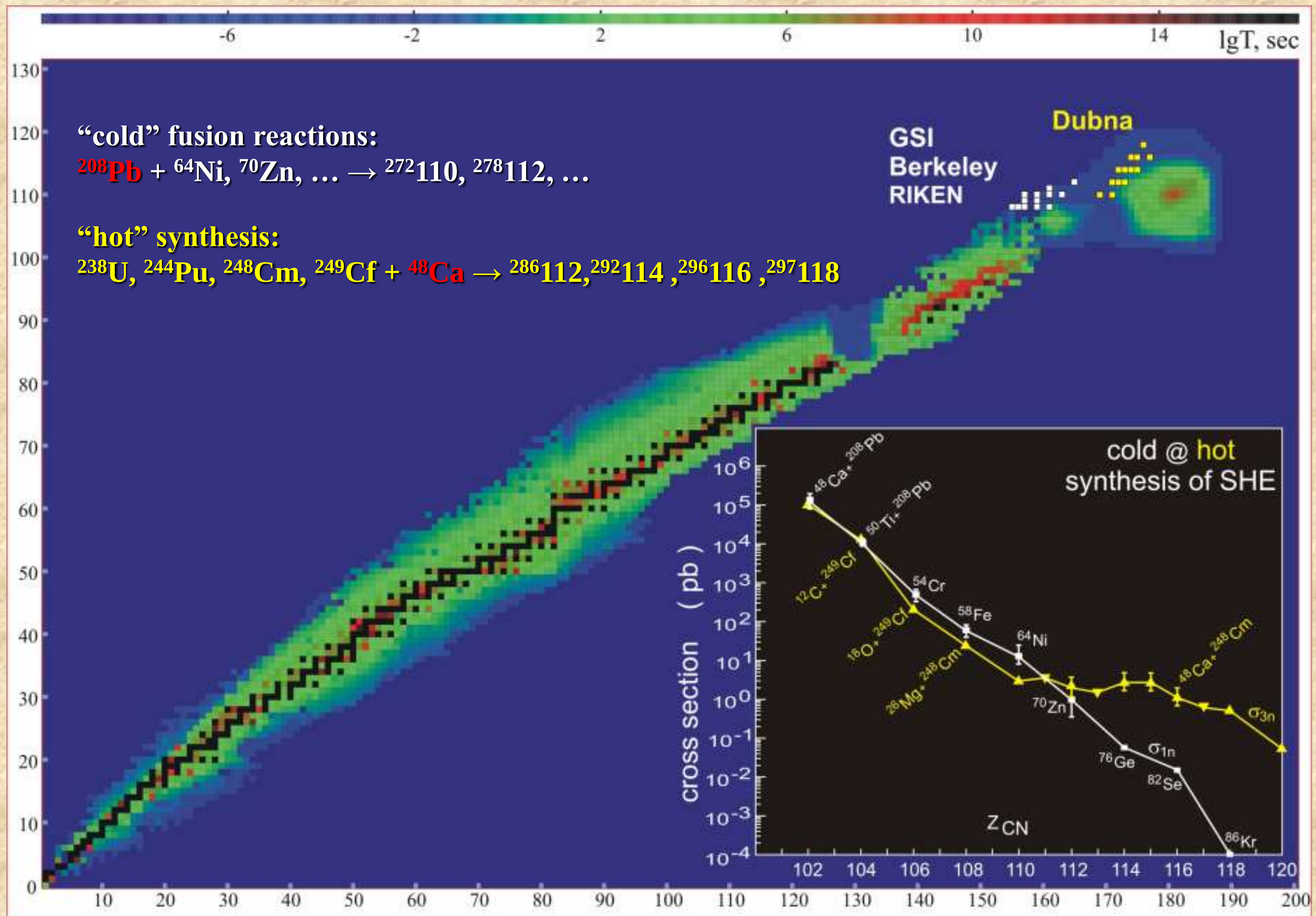


Cross sections for superheavy element production

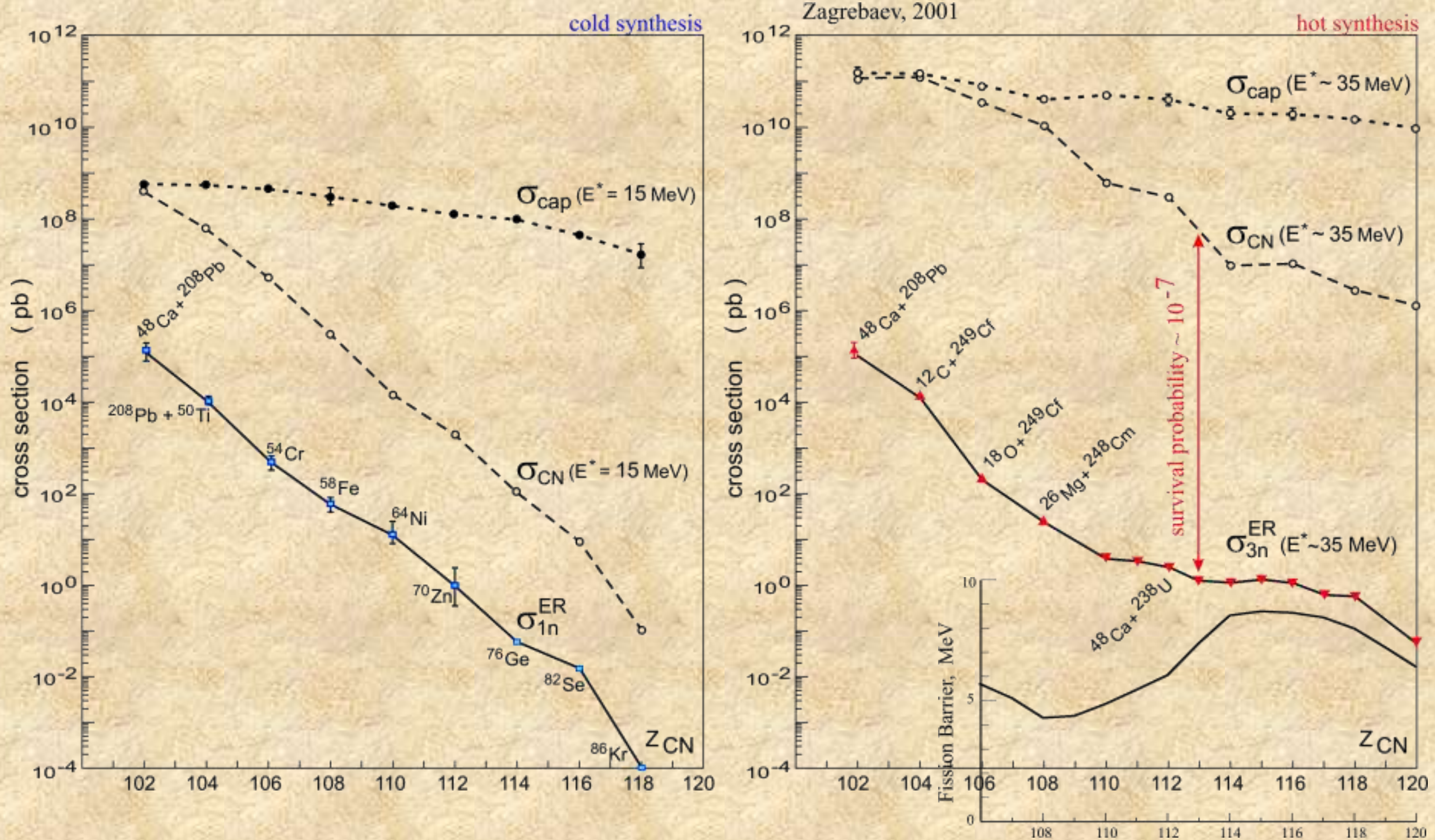




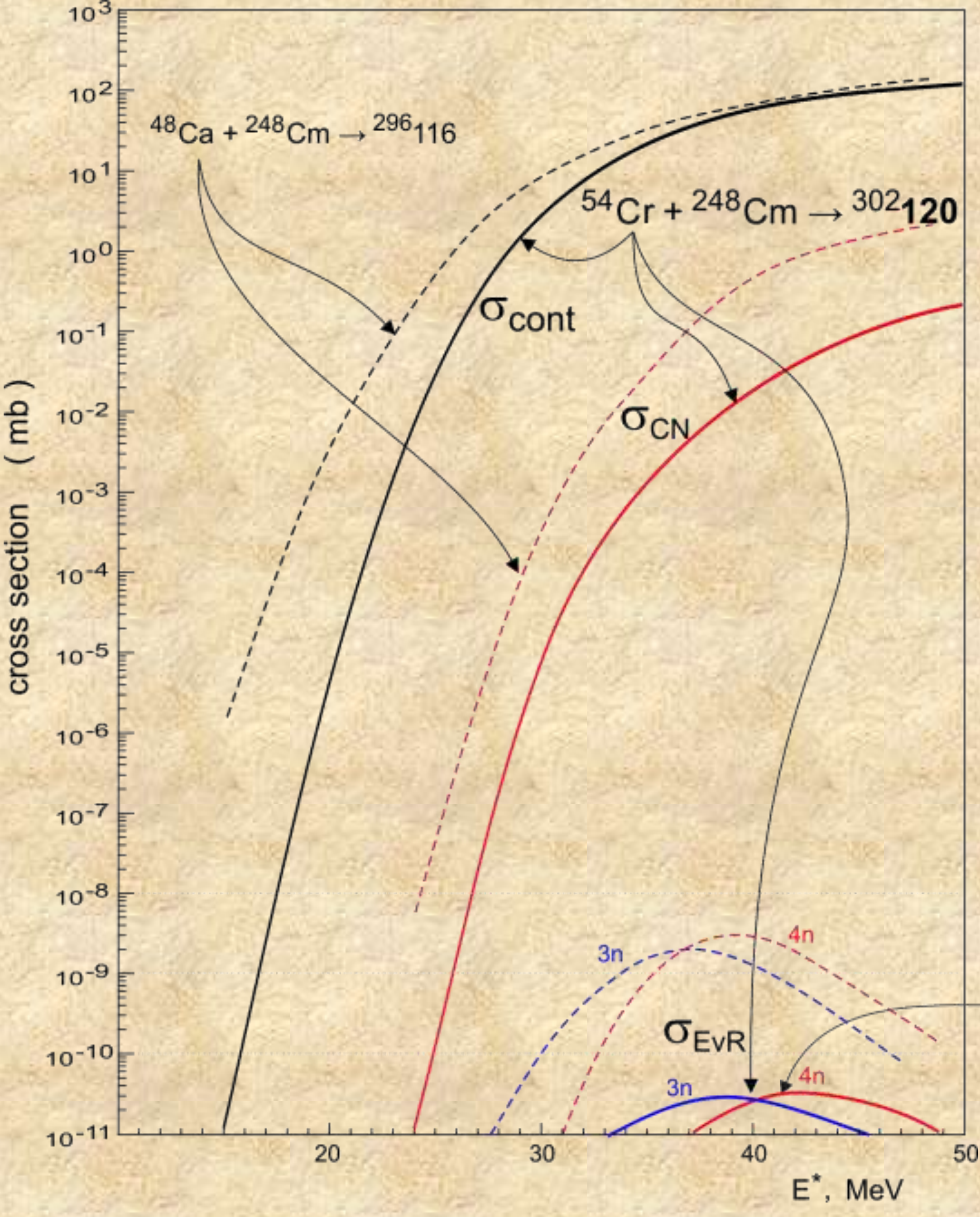
On the way to the first Island of Stability



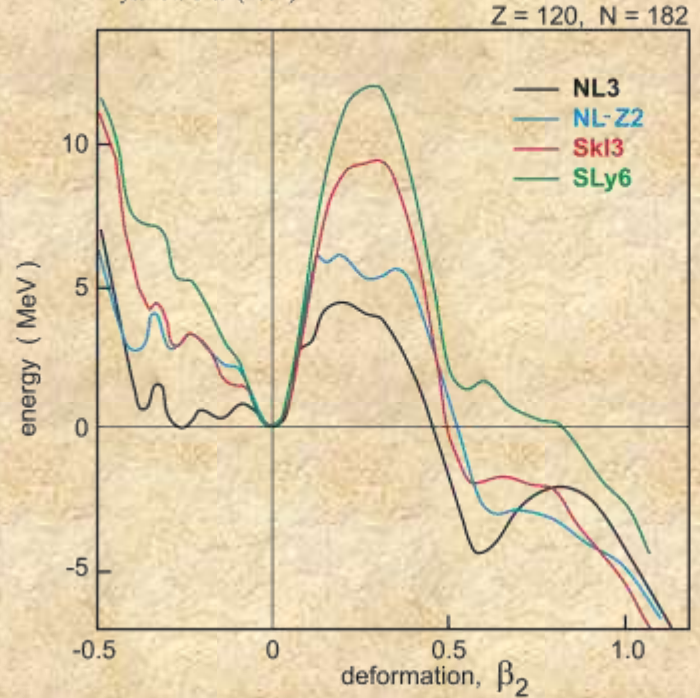
Cross sections for SHE production



Synthesis of 120: $^{54}Cr + ^{248}Cm \rightarrow ^{302}120$ or $^{58}Fe + ^{244}Pu \rightarrow ^{302}120$



T. Bürvenich, M. Bender, A. Maruhn, and P.-G. Reinhard, Phys.Rev. C **69** (2004)

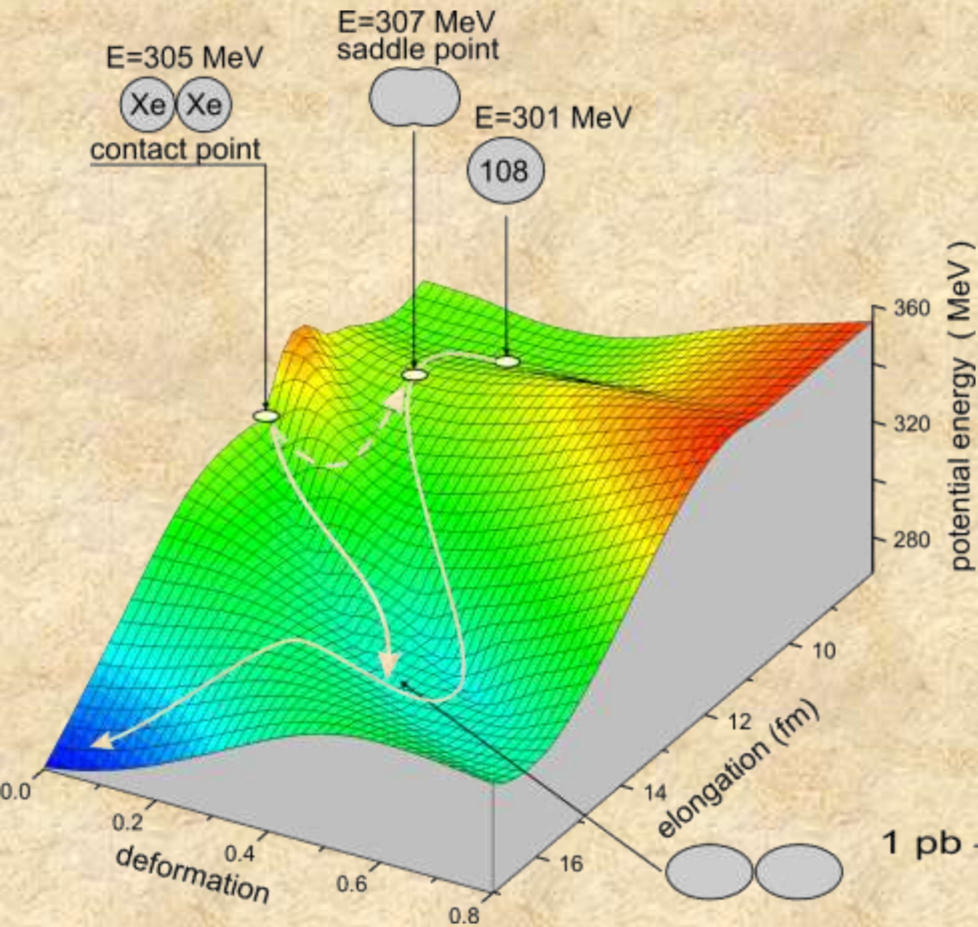


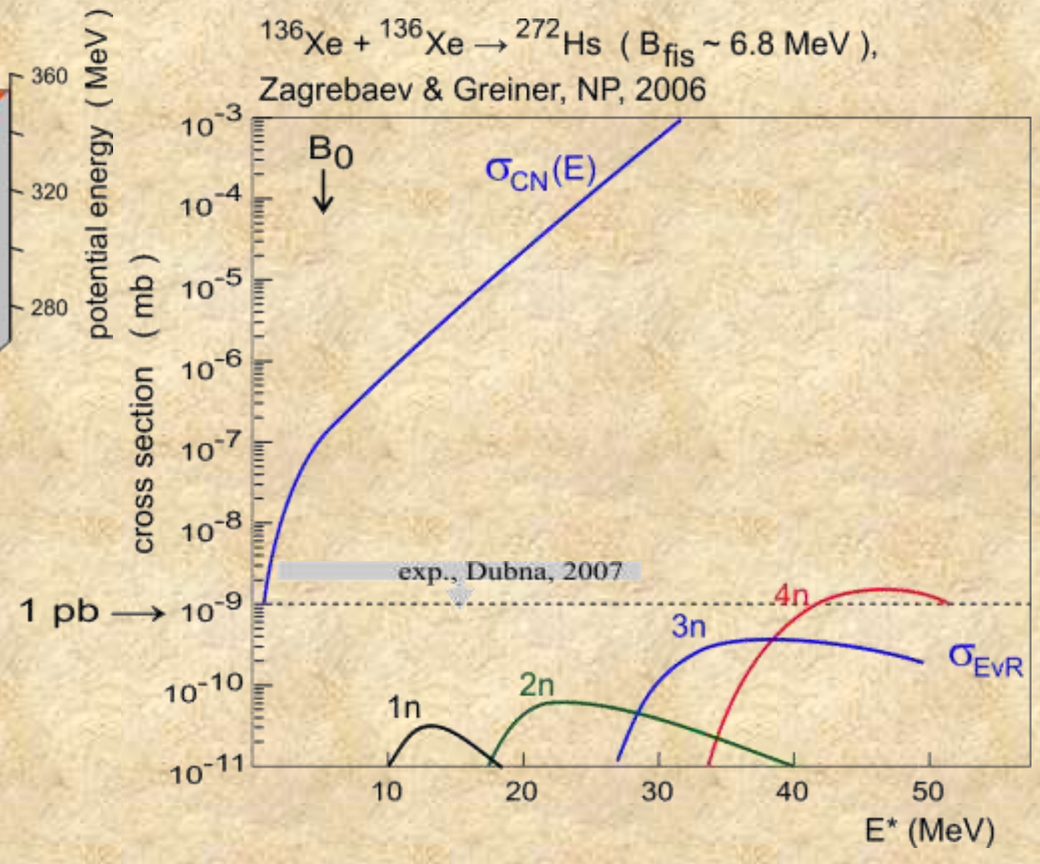
Fission barriers of ^{302}**120**

B_{fis}, MeV	Model
~ 6	A. Sobiscewski
~ 7	P. Möller et al.
~ 6	RMF
~ 11	SkHF

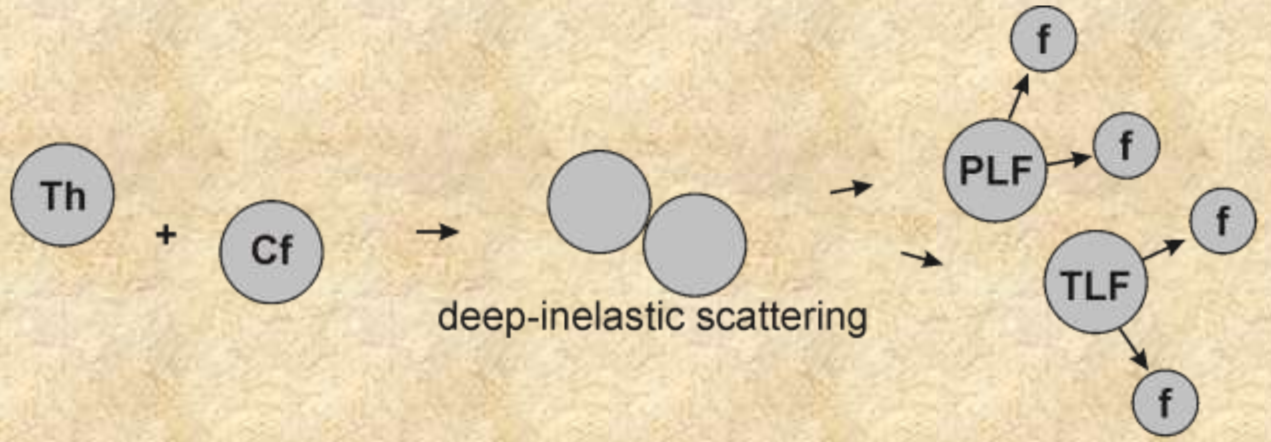
Fusion of "fission fragments": $^{136}Xe + ^{136}Xe \rightarrow ^{272}108$

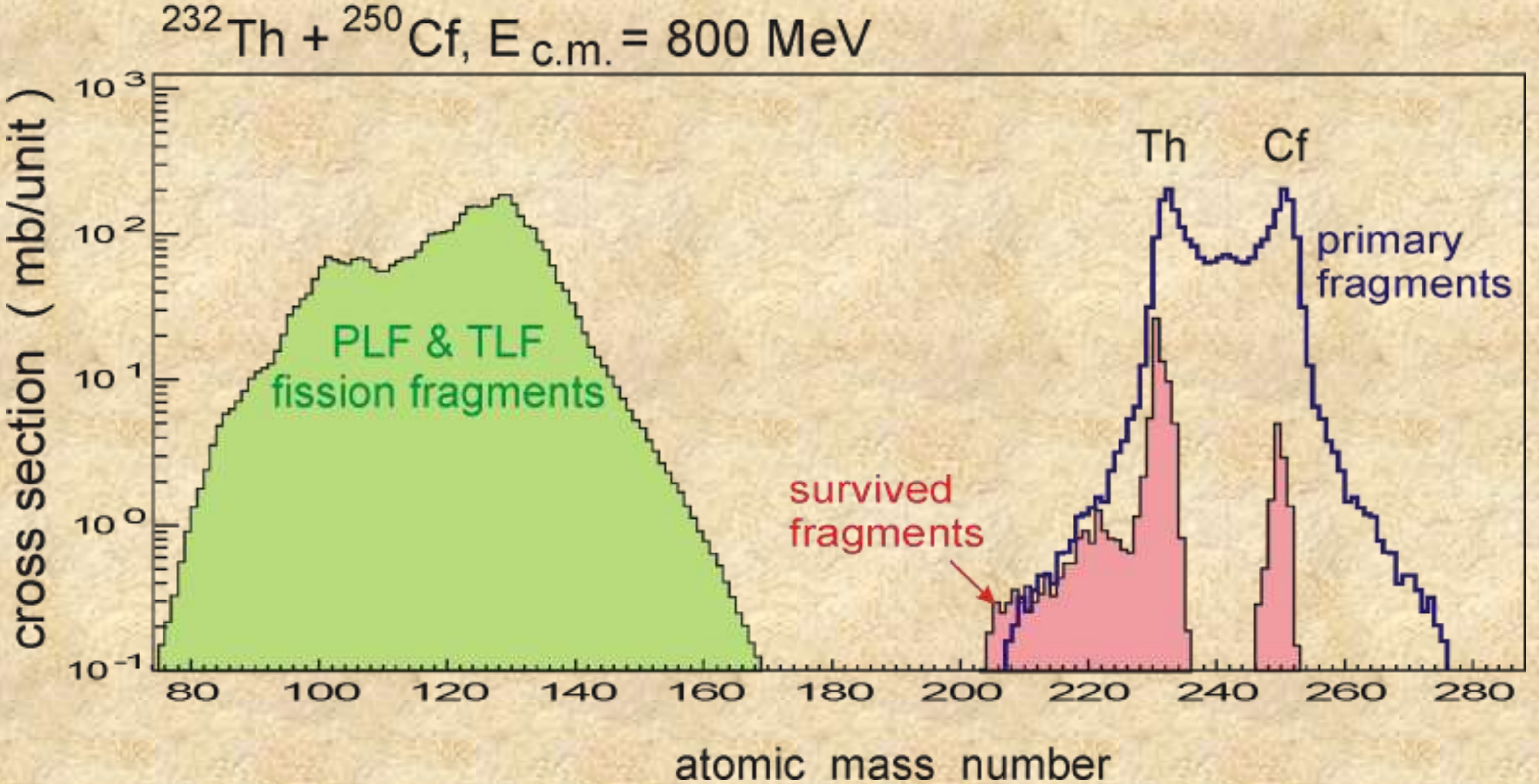
if OK then $^{132}Sn + ^{176}Yb \rightarrow ^{308}120$



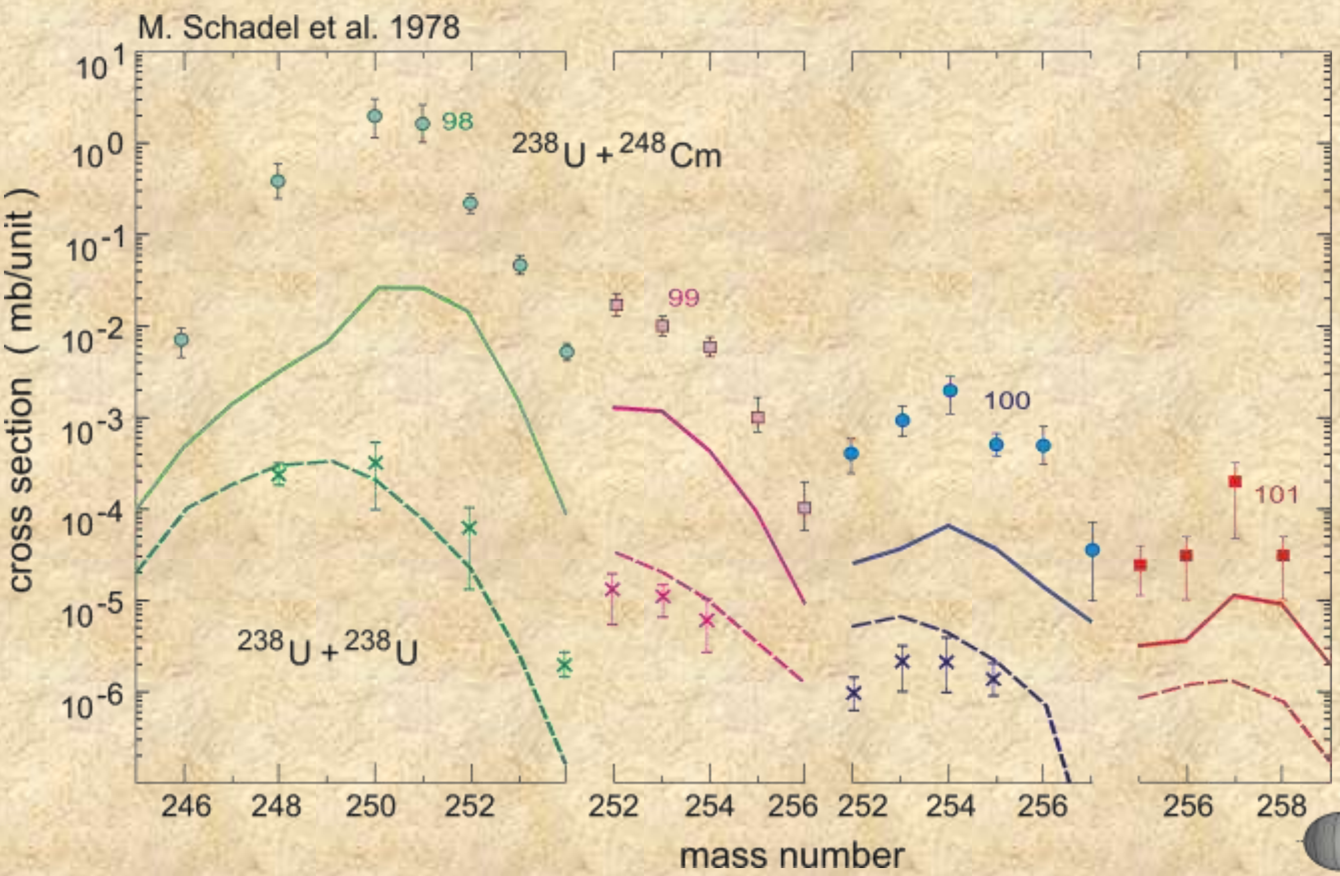


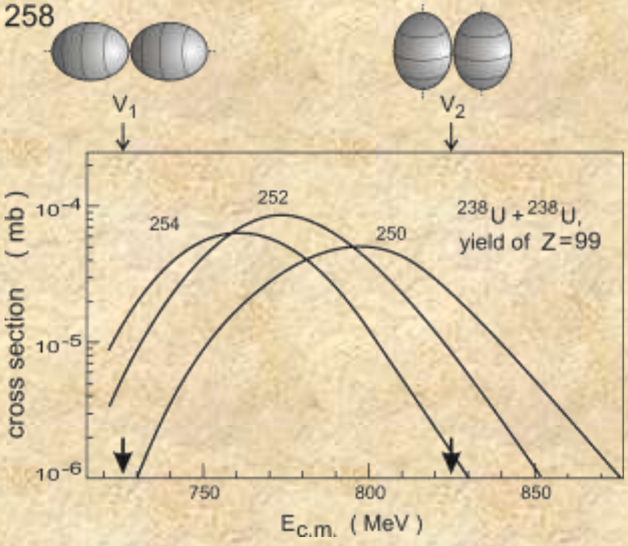
Collision of very heavy (transactinide) nuclei ?



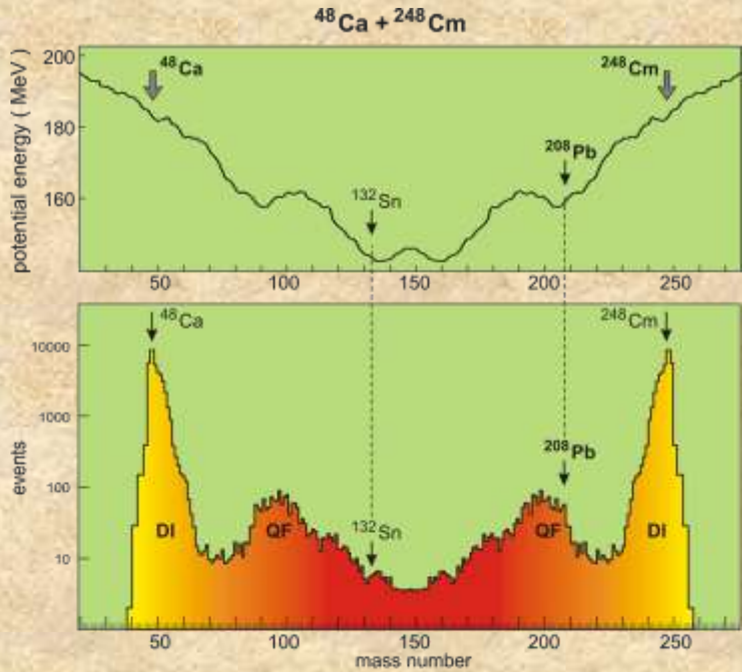


Comparison with available experimental data

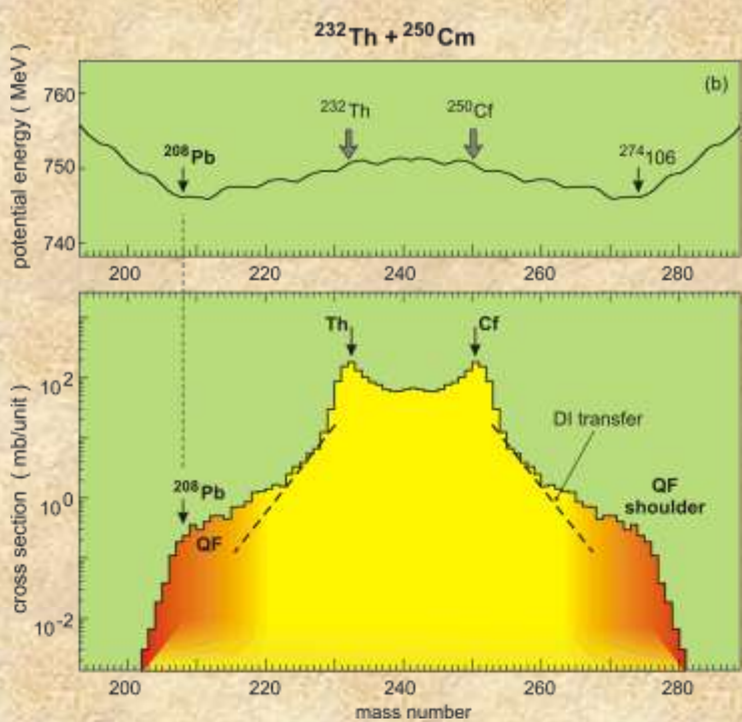




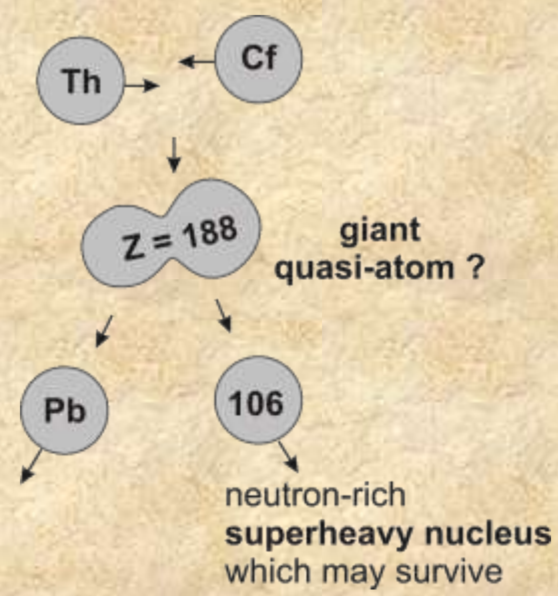
Inverse (antisymmetrizing) quasi-fission process



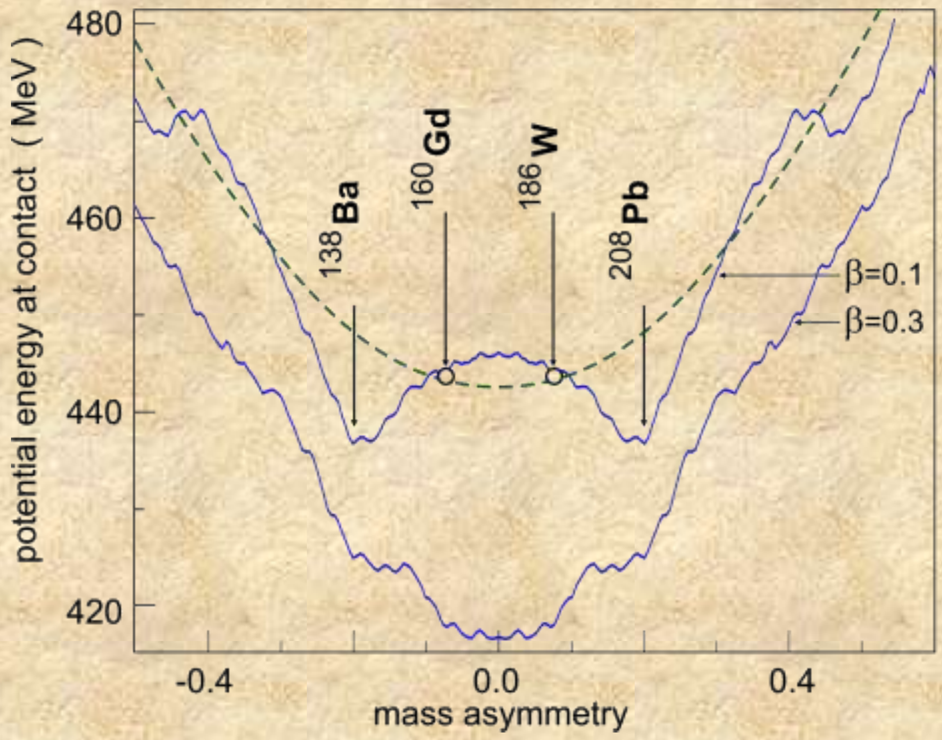
normal (symmetrizing) quasi-fission

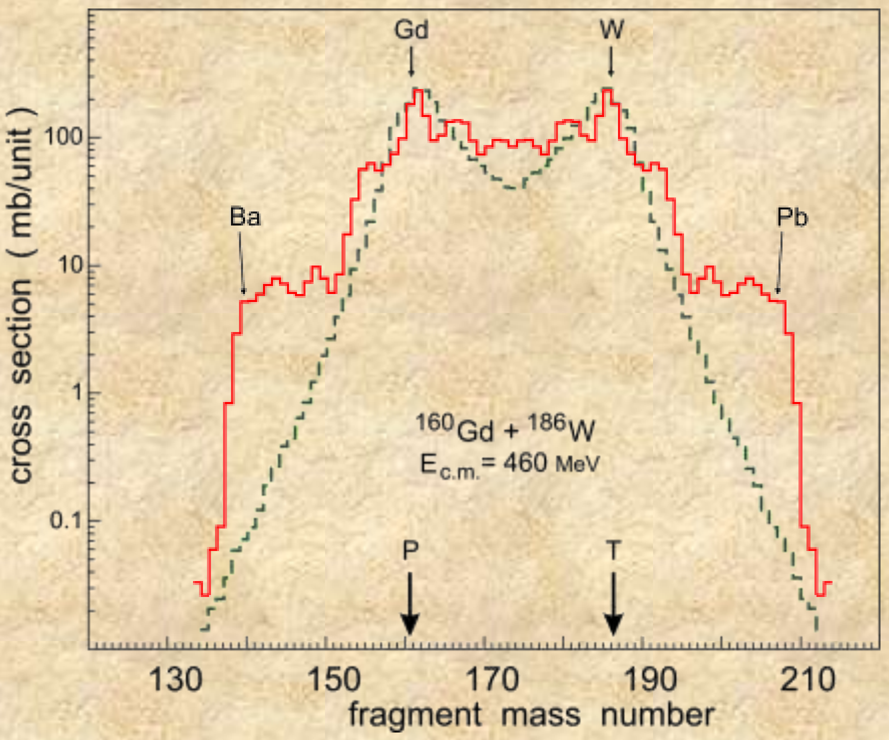


“inverse” (antisymmetrizing) quasi-fission

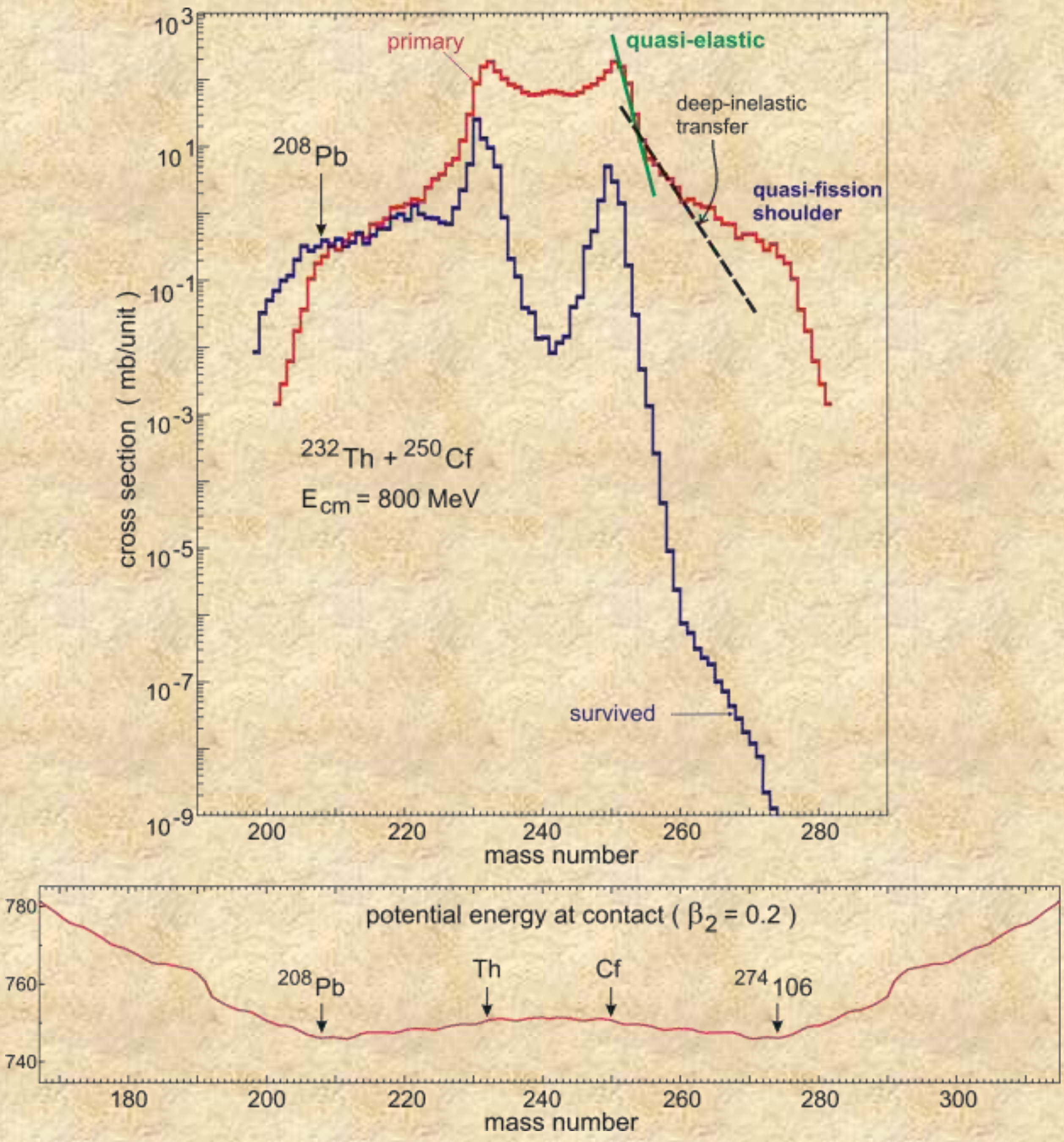


Shell effects in damped collisions
^{160}Gd + ^{186}W
(proposal for a new experiment)

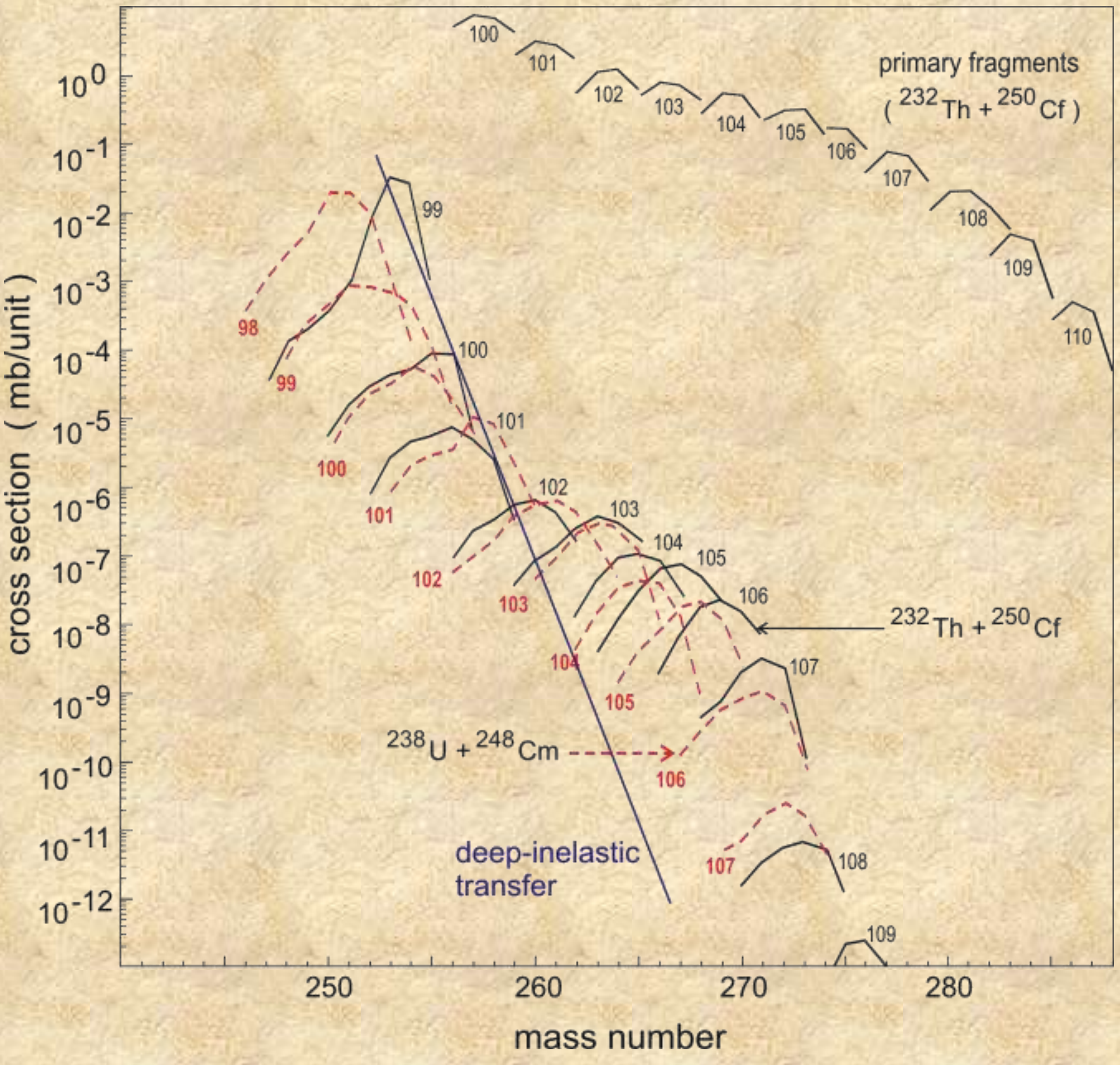




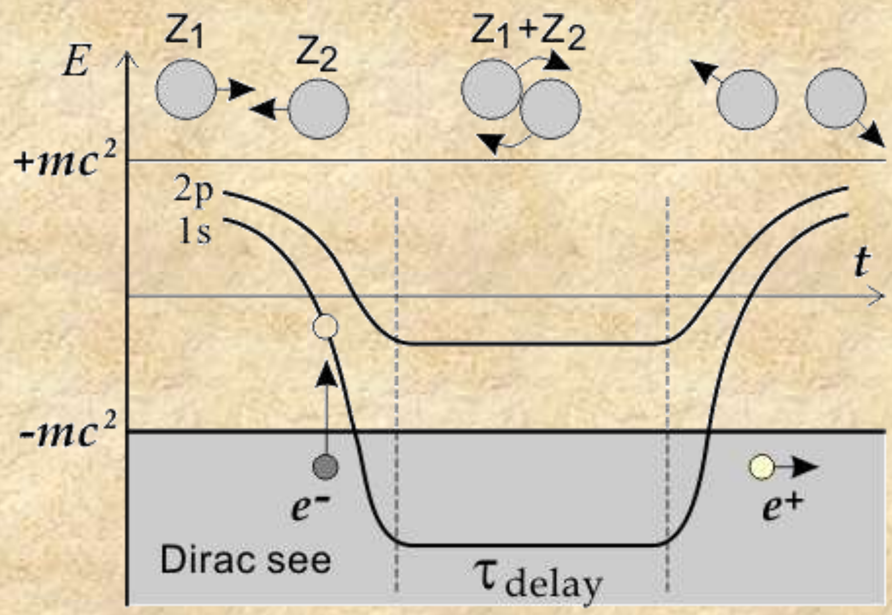
Shell effects in damped collisions of transactinides. New way to superheavies

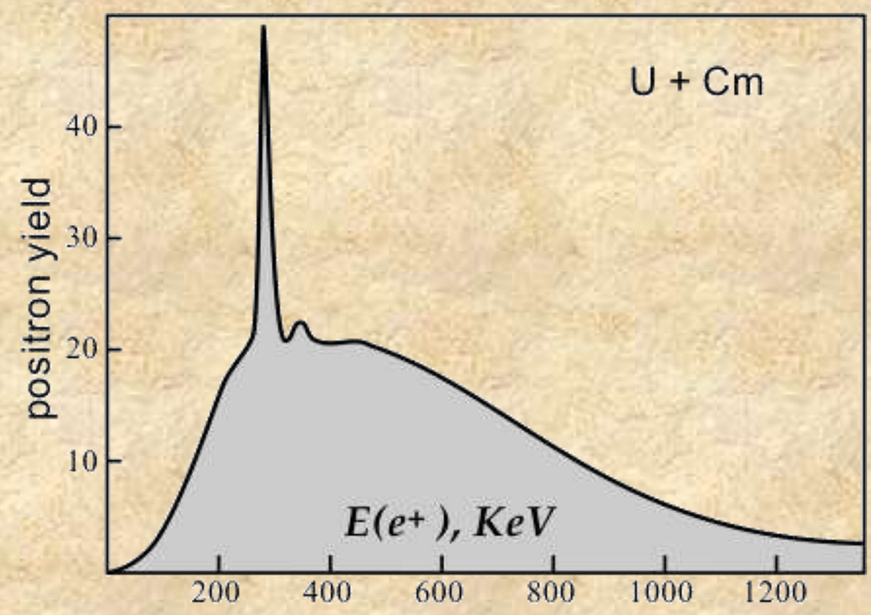


Isotopic yield of SHE in collisions of transactinides



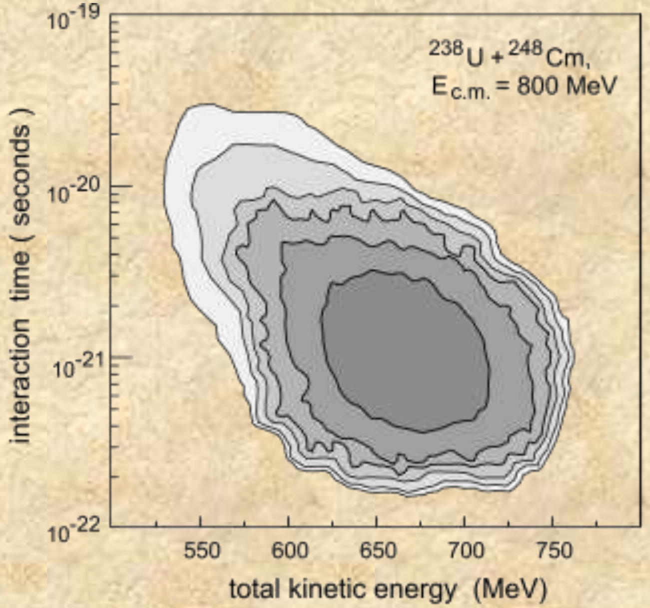
Spontaneous positron emission in super-strong electric field

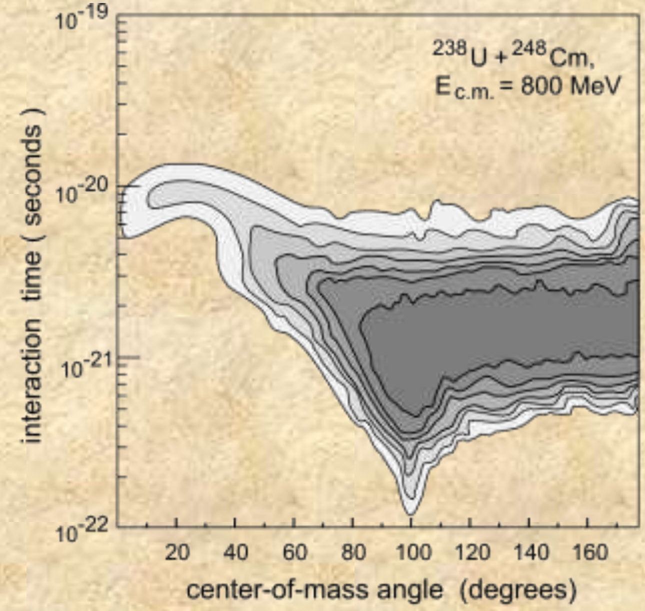


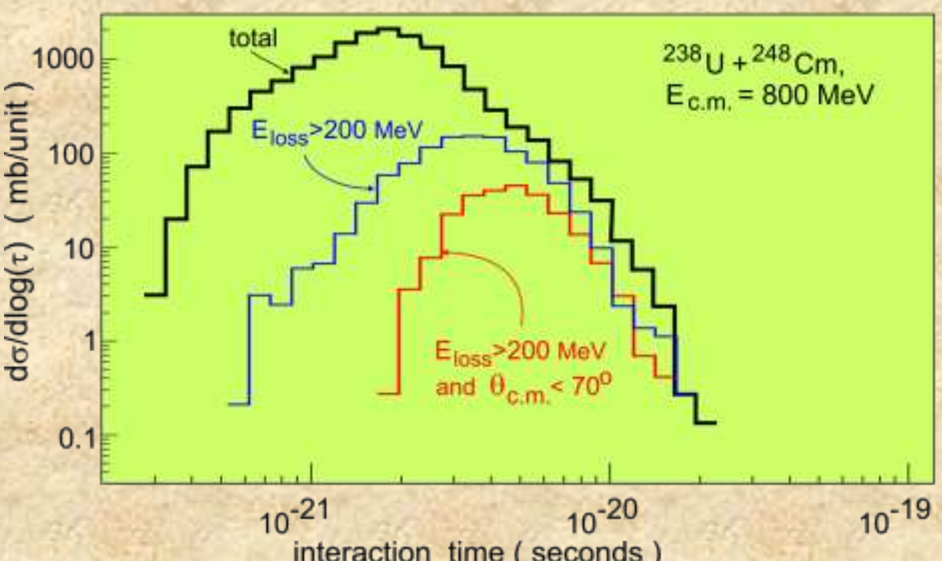


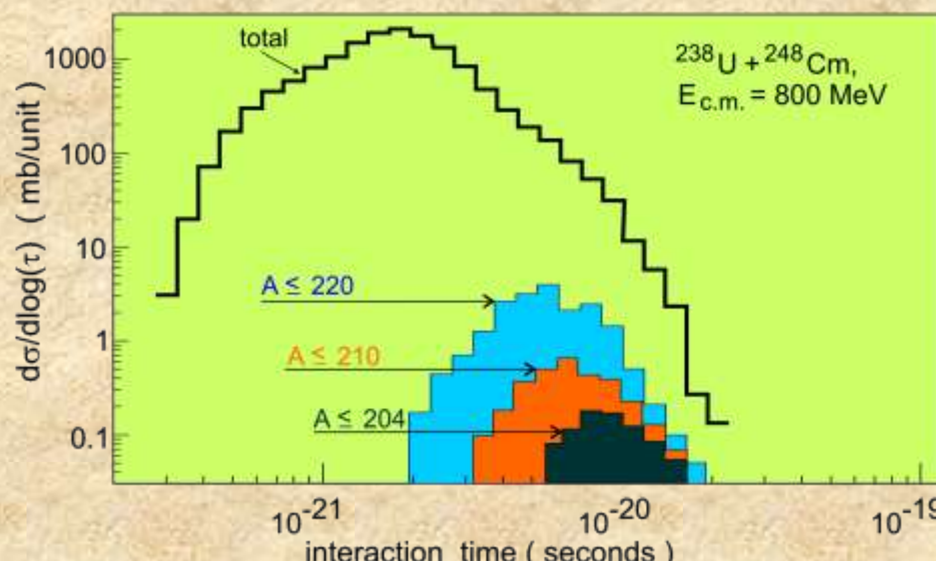
W. Greiner, J.Reinhard, 1981

What are the triggers for a long reaction time ?

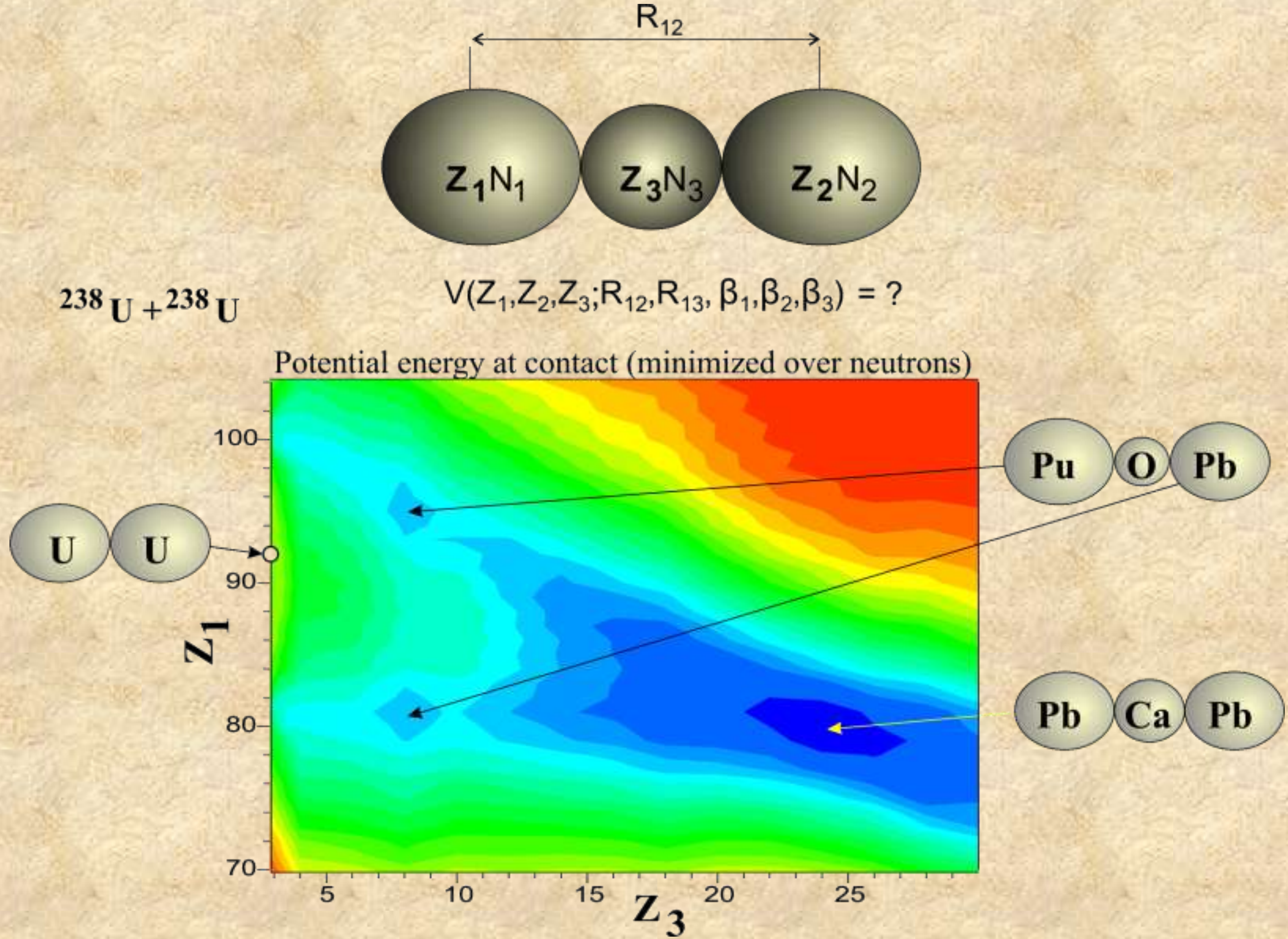




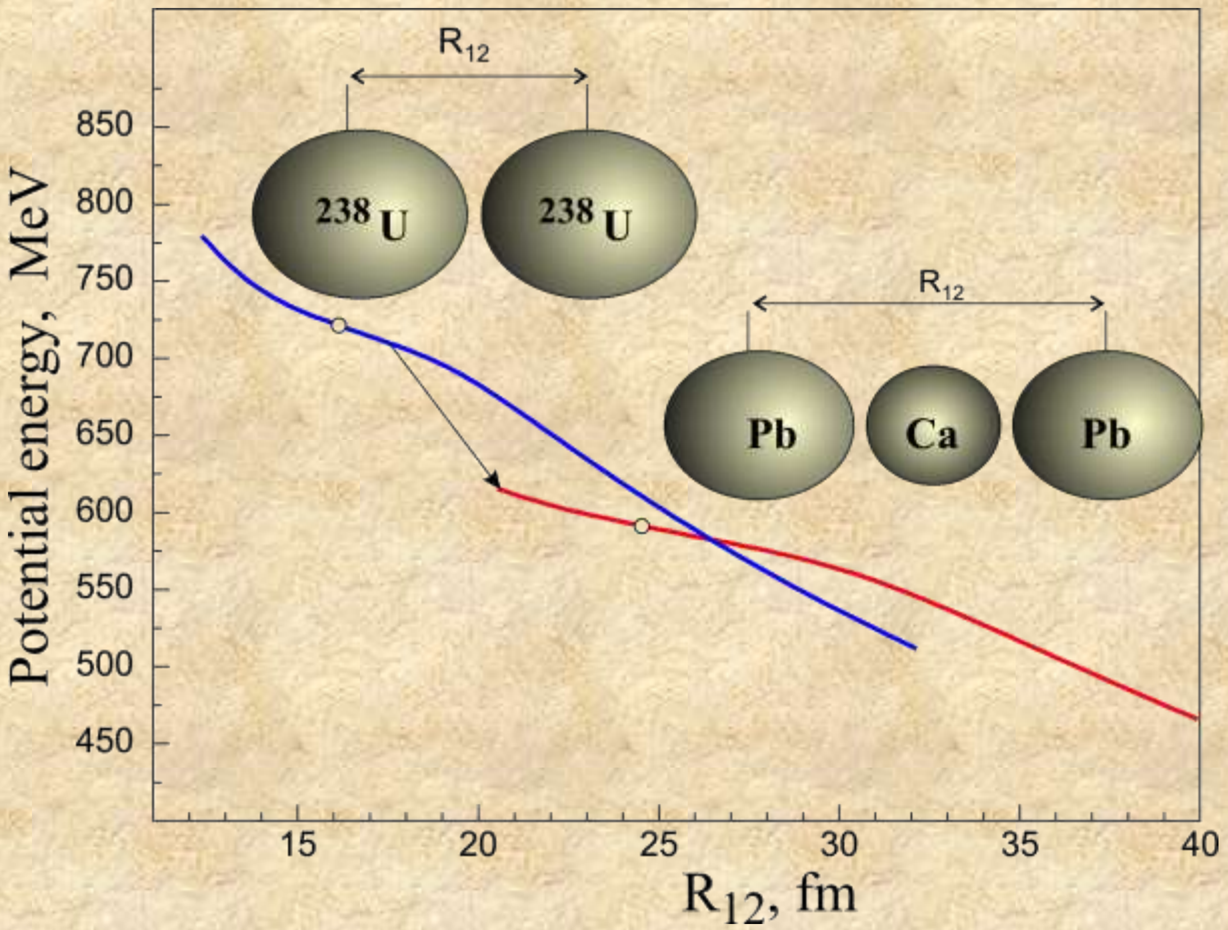




3-body clusterization in collisions of transactinides



Clusterization and time-delay



Summary

- For the first time **a new model** is developed for the simultaneous description of all strongly coupled channels: Deep-Inelastic scattering, Quasi-Fission, Fusion and regular Fission. The whole evolution of the heavy nuclear system can be traced starting from the infinite distance and ending in DI, QF, and/or Fusion-Fission channels.

- Cross sections of SHE formation in **fusion reactions of ^{50}Ti, ^{54}Cr, ^{58}Fe,… with transactinide targets** are significantly lower as compared with ^{48}Ca induced reactions. Only extraordinary shell effects at Z>=120 may change the situation.

- Cross sections of SHE formation in **symmetric fusion reactions** (including neutron rich fission fragments) are estimated at the level of 0.1 pb. Such reactions may be used only for synthesis of rather stable (well survivable) superheavies at above-barrier beam energies (4n, 5n, … evaporation channels).

- Shell effects in low-energy **damped collisions of transactinides** 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.