Fusion and Fission Dynamics of Heavy Nuclear Systems

- **Fusion-fission driving potential**
- **Clustering phenomena in heavy nuclear system**
- **Collision dynamics and synthesis of SHE**
- **New ways to SHE**
- **Resume**

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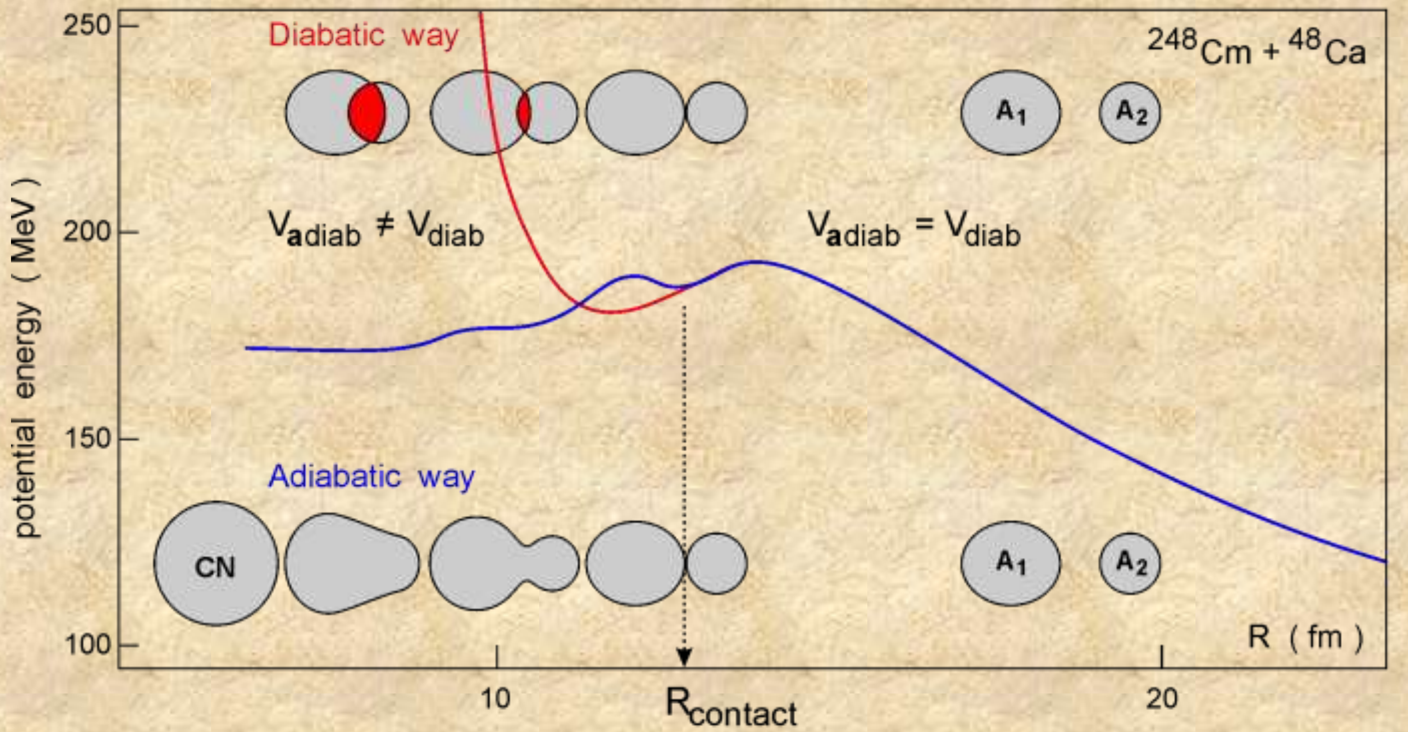
DANF-2006, Smolenice Castle

Diabatic and Adiabatic Potential Energy

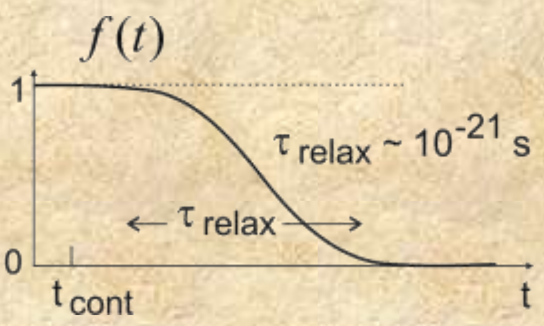
$$V_{diabat}(R,\beta_1,\beta_2,\alpha,\ldots) = V_{12}^{folding}(Z_1,N_1,Z_2,N_2; R, \beta_1,\beta_2,\ldots) + M(A_1) + M(A_2) - M(Proj) - M(Targ)$$



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

At above-barrier energies (≳ 10 MeV / nucleon)
time-dependent driving potential is to be used

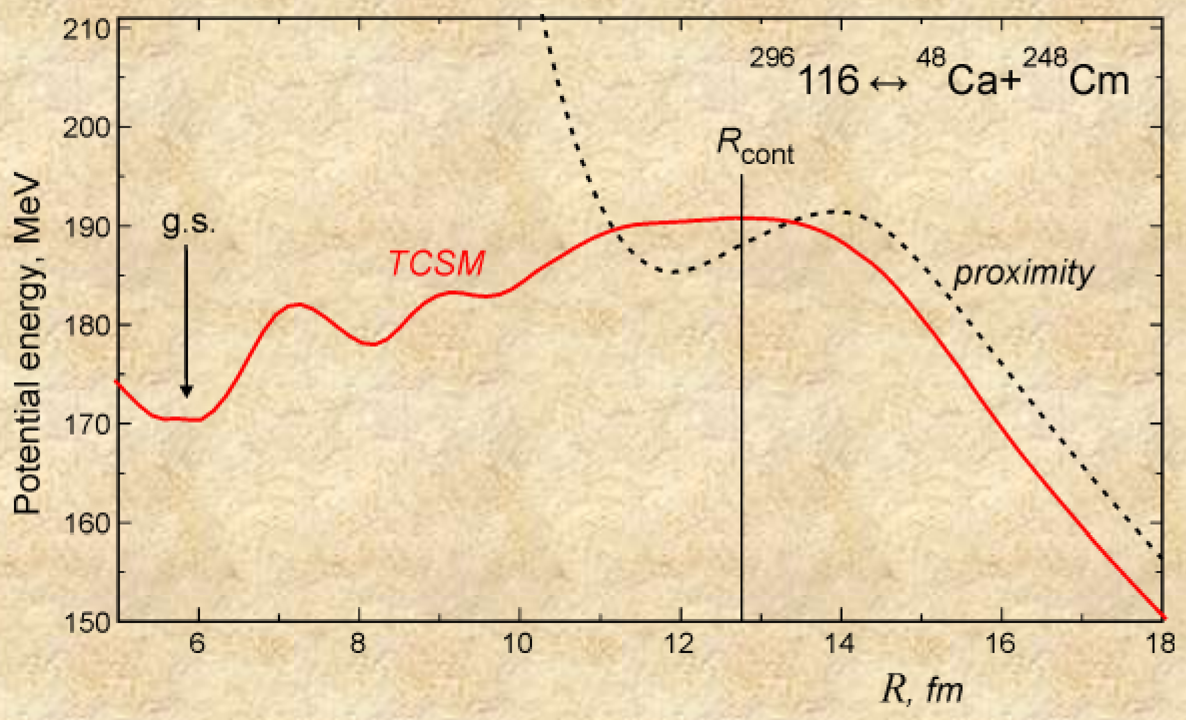
$$V(R,\beta,\alpha;t) = V_{diab}(R,\beta,\alpha)\cdot f(t) + V_{adiab}(R,\beta,\alpha)\cdot[1-f(t)]$$



Calculation of multi-dimensional adiabatic potential energy ?

- Macro – microscopical approaches (LDM + Shell correction)
- Self-consistent mean-field models
- Time-dependent Hartree-Fock ?

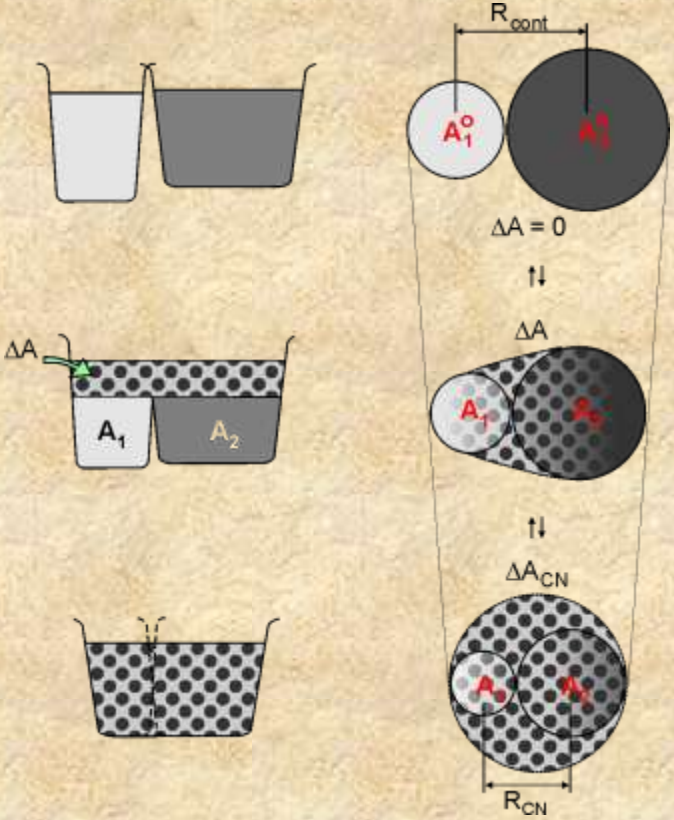
Imperfection of the MM models



Two-Core Model

Total Energy:

$$V_{12} + M_1c^2 + M_2c^2 = V_{12} - B_1 - B_2 \ [\, + (A_1+A_2)m_N c^2 = \text{const} \,]$$



$$= \frac{Z_1^o Z_2^o e^2}{R} + V_{prox}(R)$$

$$V_{12}^o - [\, \beta_1^o \cdot A_1^o + \beta_2^o \cdot A_2^o \,], \quad \text{before contact}$$

$$V_{12} - [\, \tilde{\beta}_1 \cdot A_1 + \tilde{\beta}_2 \cdot A_2 + \frac{\tilde{\beta}_1 + \tilde{\beta}_2}{2} \cdot \Delta A \,], \quad \text{after overlapping}$$

$$\tilde{\beta}_{1,2} = \beta_{1,2}^{exp} \cdot (1 - x) + \beta_{CN} \cdot x$$

$$0 \leqq \frac{\Delta A}{\Delta A_{CN}} \leqq 1$$

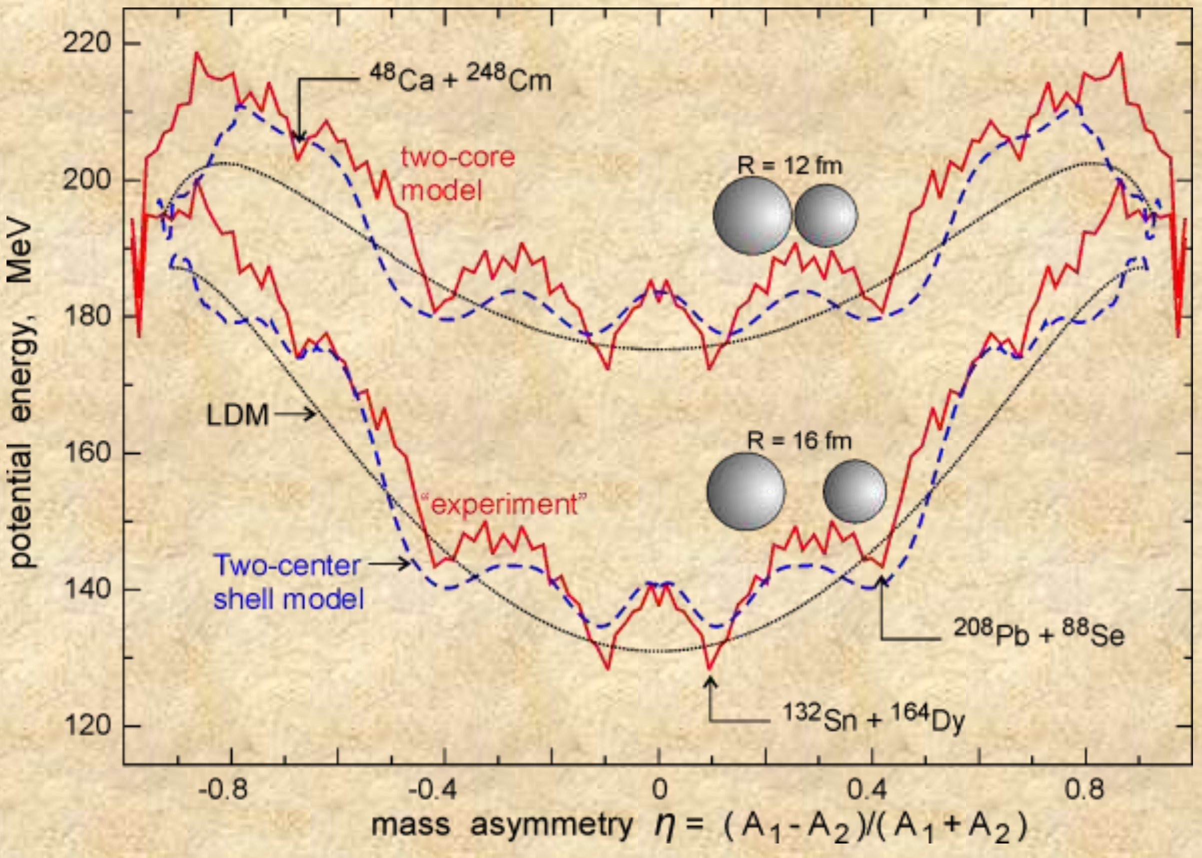
$$V_{12} - [\, \beta_{CN} \cdot A_1 + \beta_{CN} \cdot A_2 + \beta_{CN} \cdot \Delta A \,], \quad \text{g.s. of CN}$$

$V_{12} = 0$; $\beta_{CN} \cdot A_1 + \beta_{CN} \cdot A_2 + \beta_{CN} \cdot \Delta A = B(A_{CN})$

$$V_{fus\text{-}fis}(r, Z_1, N_1, Z_2, N_2, \delta_1, \delta_2) = V_{12} - [\, \tilde{\beta}_1 \cdot A_1 + \tilde{\beta}_2 \cdot A_2 + \tilde{\beta} \cdot \Delta A \,] + B(A_1^o) + B(A_2^o)$$

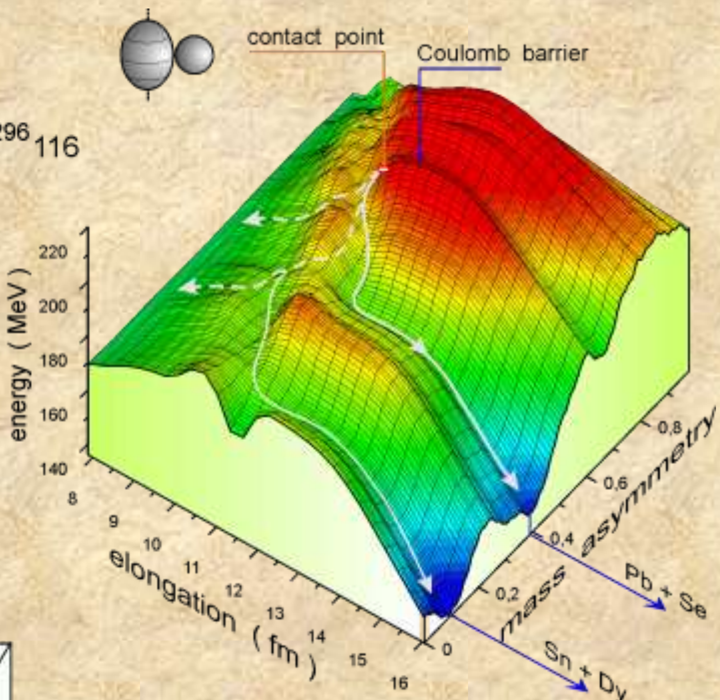
$\tilde{\beta}_1 \cdot A_1 + \tilde{\beta}_2 \cdot A_2 + \tilde{\beta} \cdot \Delta A = B(A_1^o) + B(A_2^o)$ in the entrance channel

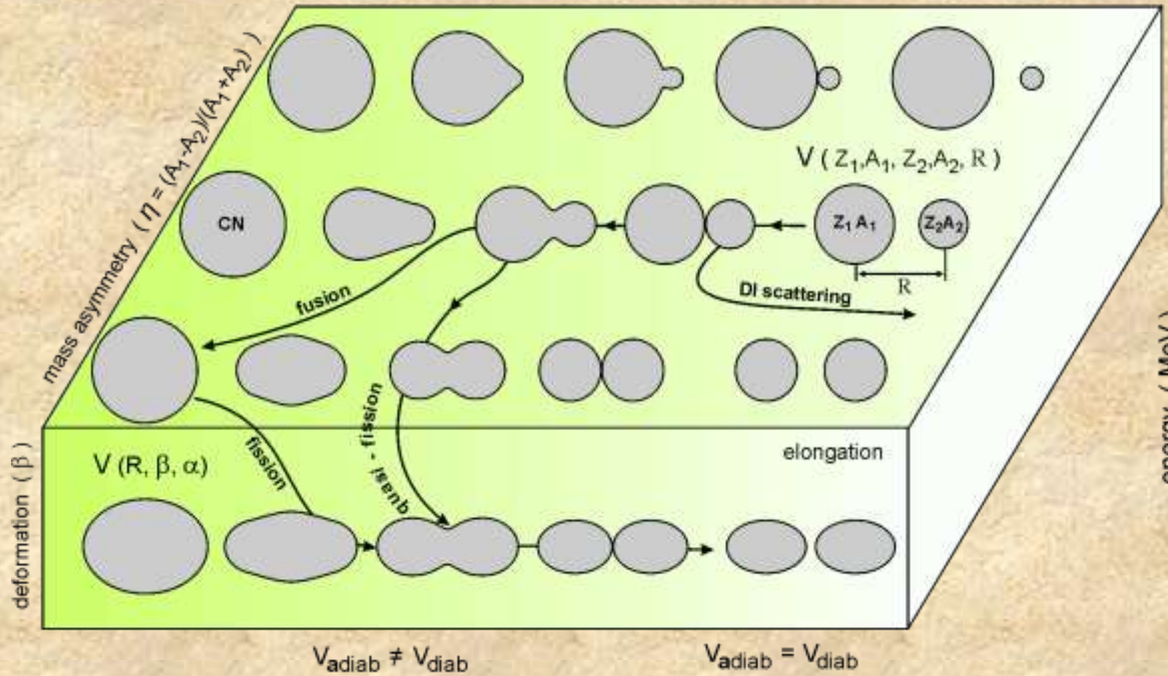
Consistency of TCSM and Two-Core Model

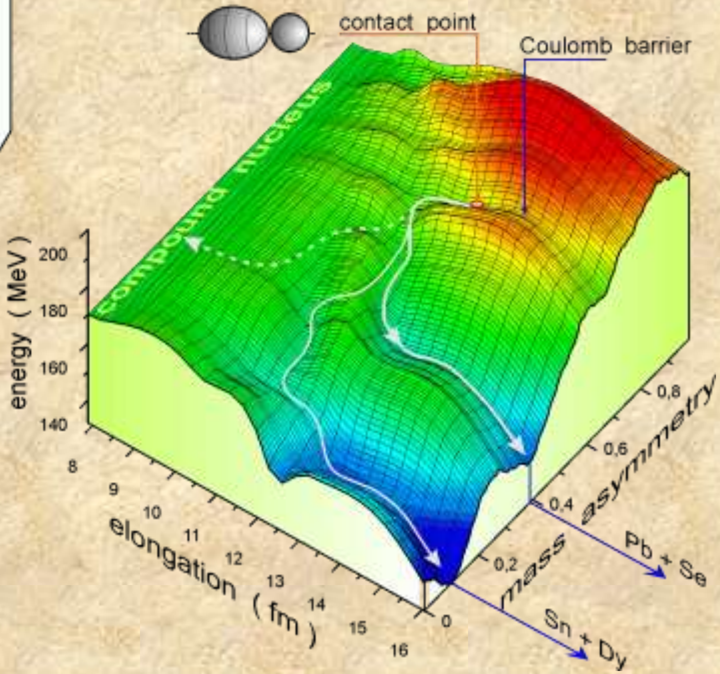


Multi-dimensional adiabatic driving potential

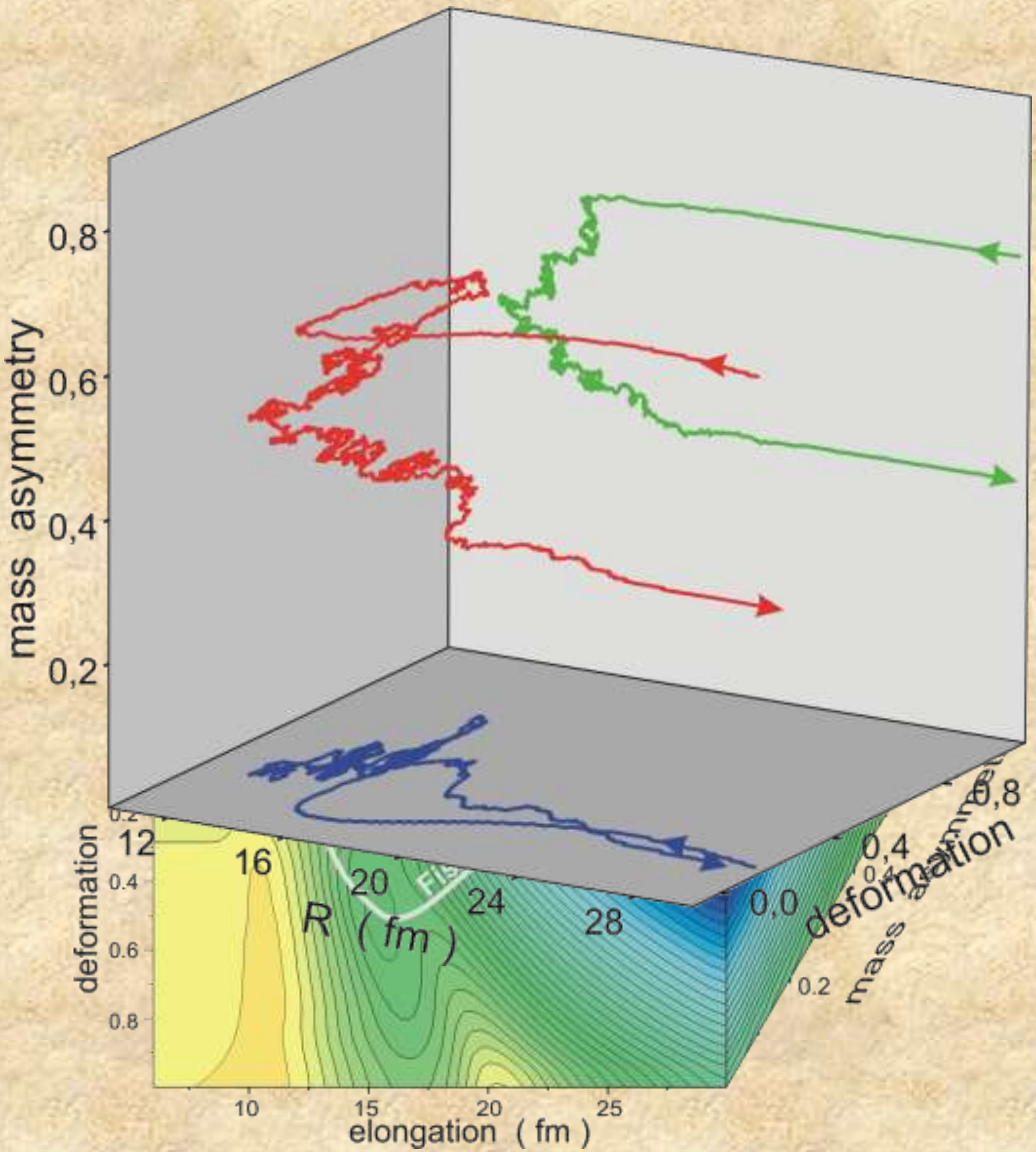
$^{48}Ca + ^{248}Cm \rightarrow ^{296}116$

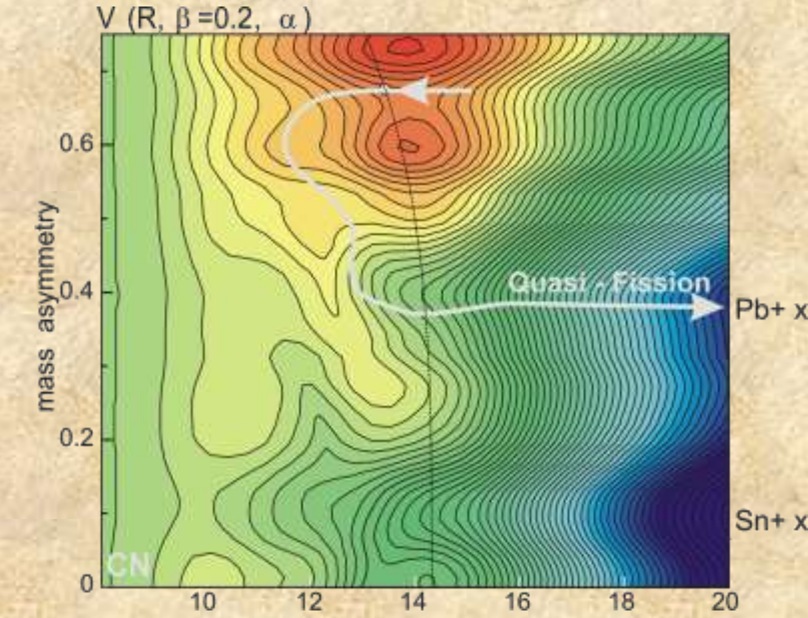


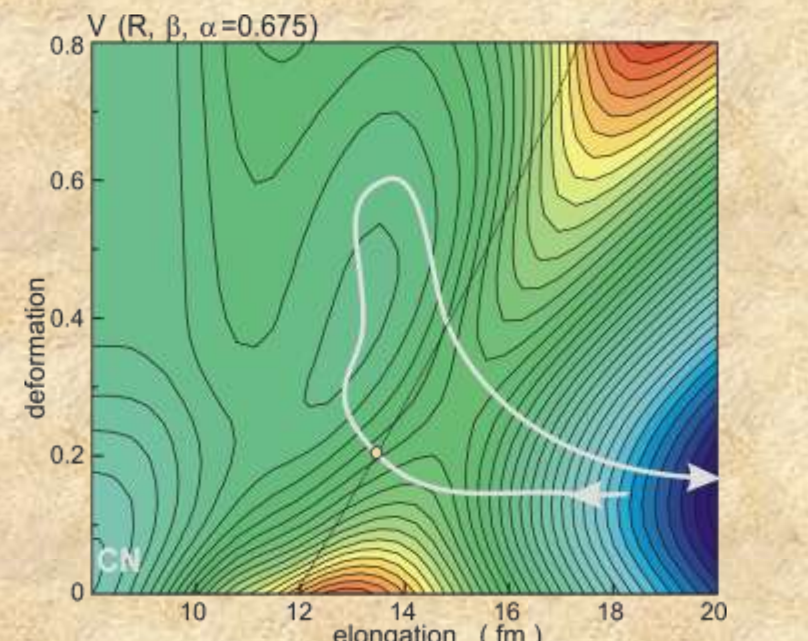




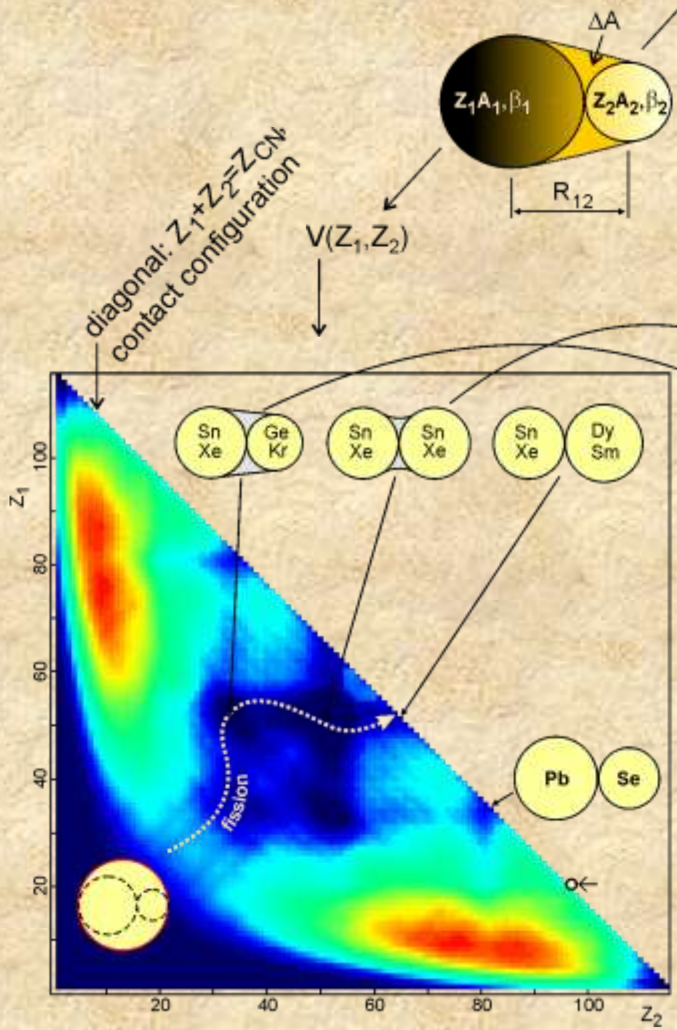
$^{248}Cm + ^{48}Ca \leftrightarrow ^{296}116$

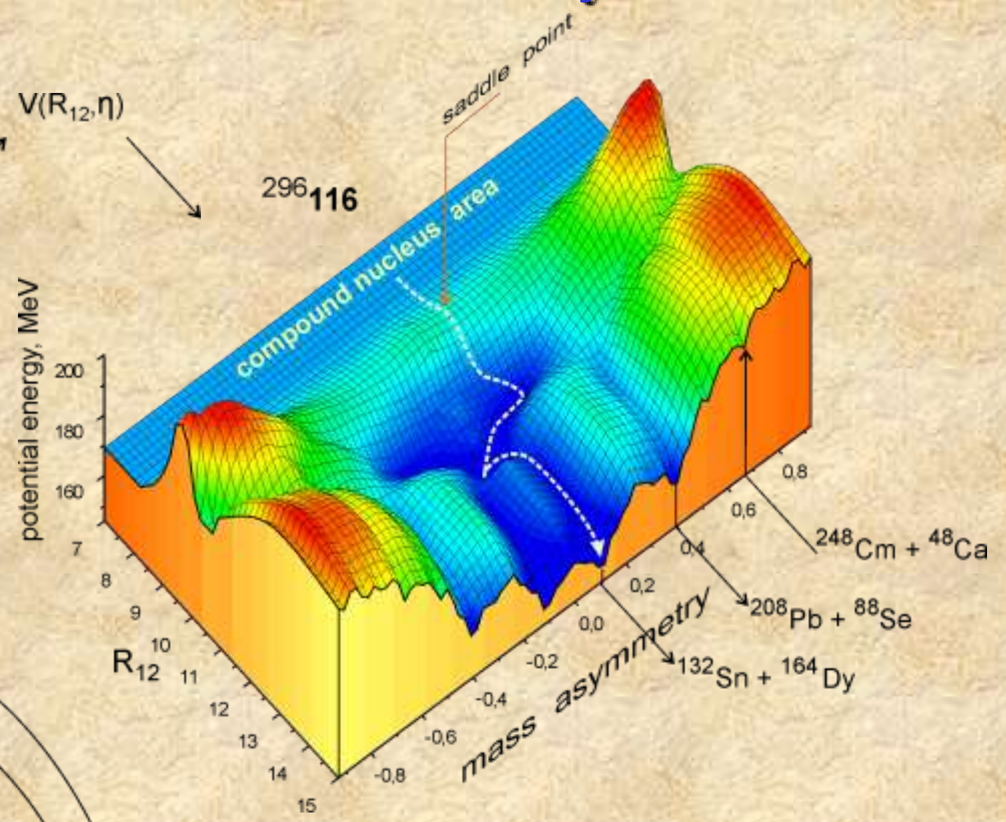


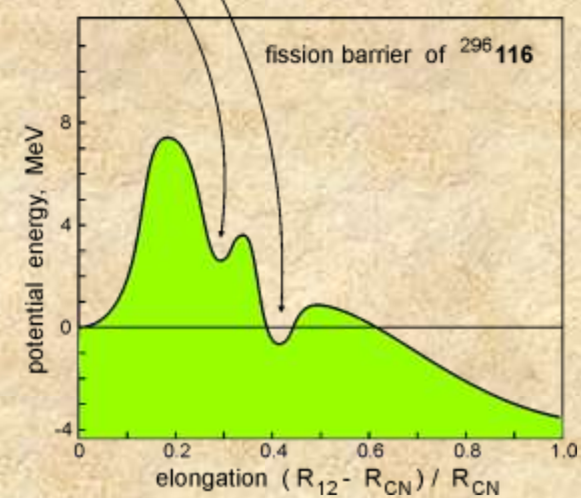




Clusterization and Isomeric states of heavy nuclei





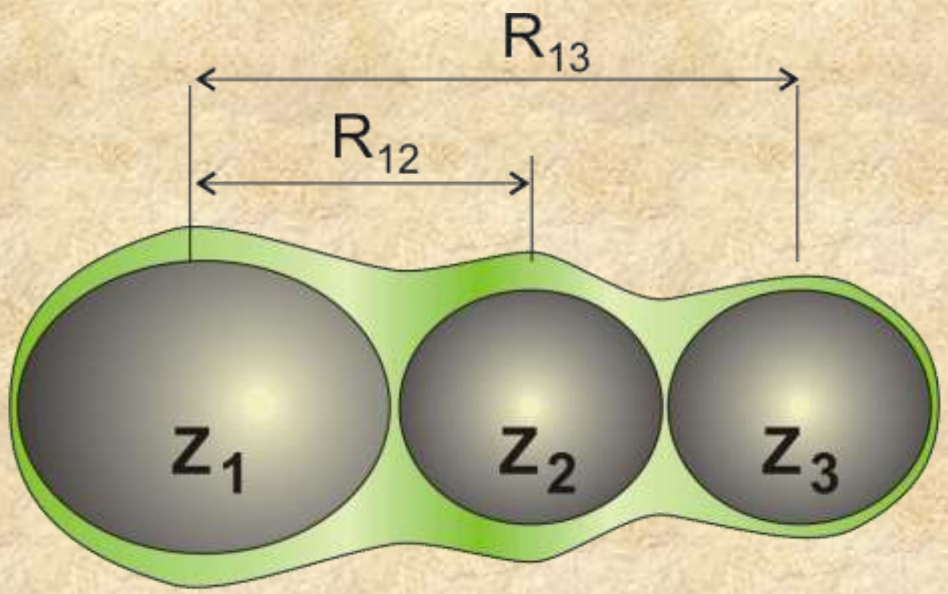


Conclusion:

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.

3 - Cluster Isomeric States ?



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

$$V(Z_1, Z_2, Z_3; \beta_1, \beta_2, \beta_3) = ?$$

System of coupled Langevin type Equations of Motion

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

Most uncertain parameters:

μ_0, γ_0 - nuclear viscosity and friction,

λ_0 - nucleon transfer rate

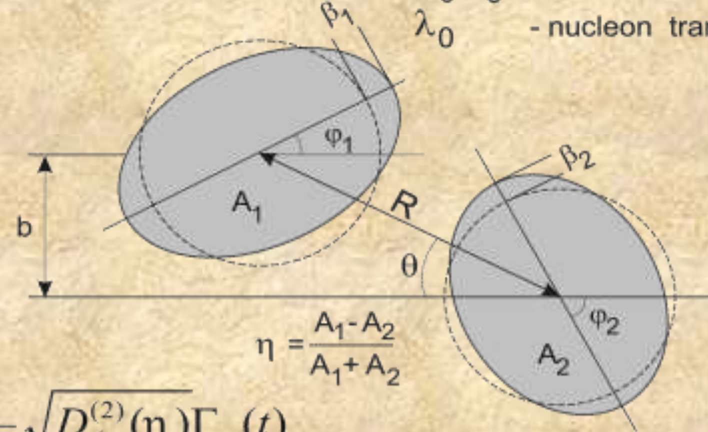
$$\frac{dR}{dt} = \frac{p_R}{\mu_R}$$

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

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

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

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



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

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

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

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

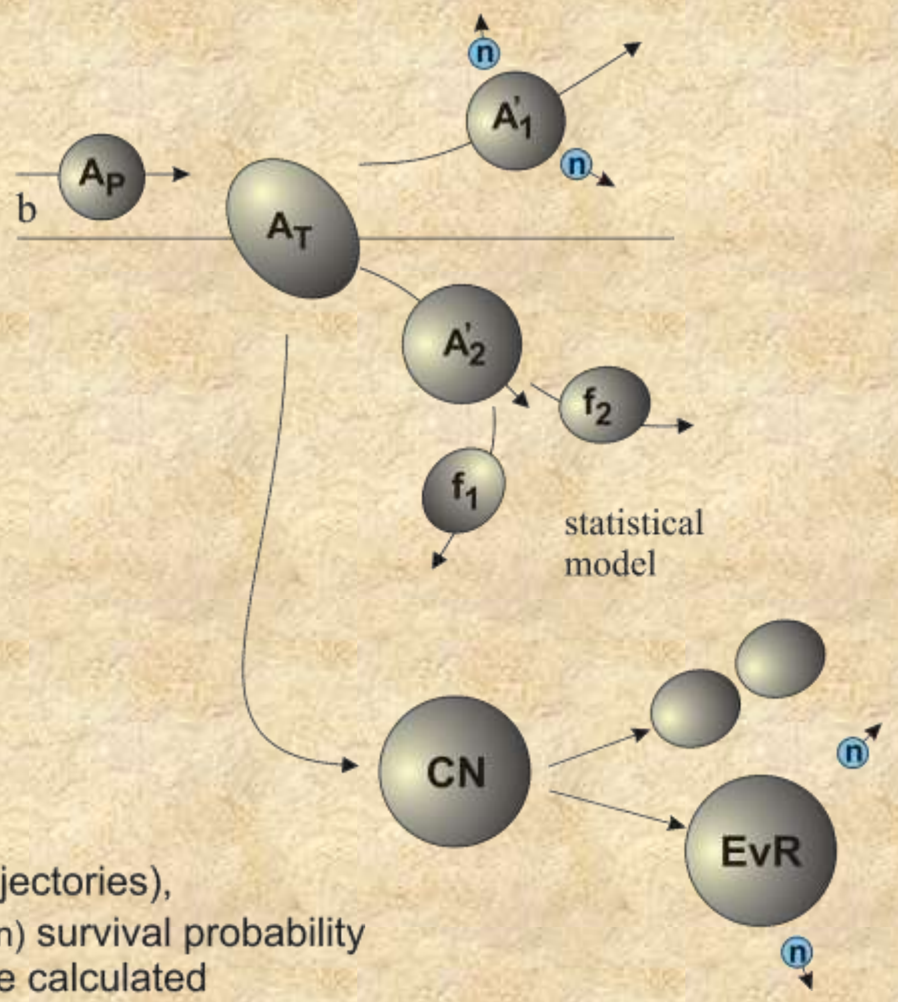
$$\frac{dL_2}{dt} = -\frac{\partial V}{\partial \varphi_2} + \gamma_{\text{tan}}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1} a_1 - \frac{L_2}{\Im_2} a_2\right) a_2 - \frac{a_2}{R}\sqrt{\gamma_{\text{tang}} T}\,\Gamma_{\text{tang}}(t)$$

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

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

Simulation of experiment and cross sections

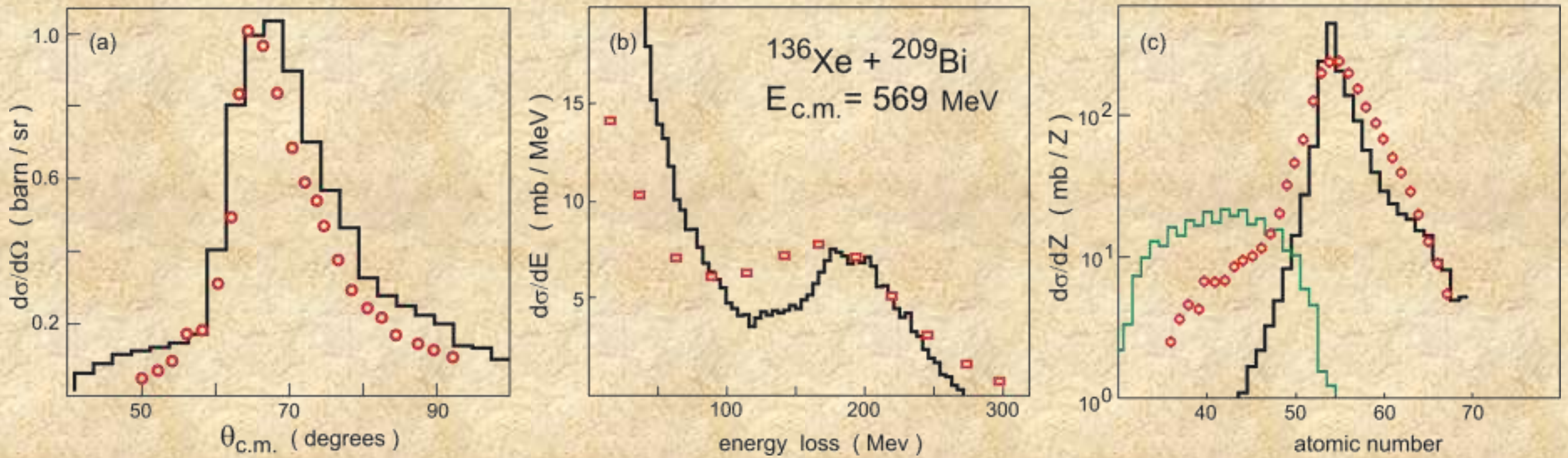
$$\frac{d^2\sigma_\alpha}{d\Omega dE}(E,\theta) = \int_0^\infty bdb \; \frac{\Delta N_\alpha(b,E,\theta)}{N_{tot}(b)} \; \frac{1}{\sin(\theta)\Delta\theta\Delta E}$$



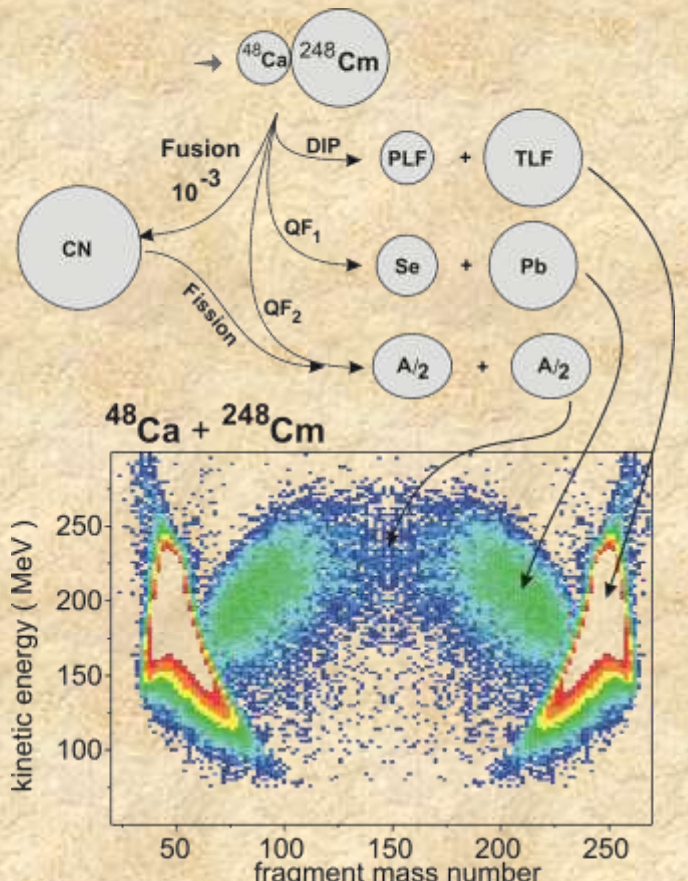
Dynamics: **10^6** tested events (trajectories),
Statistical model: **10^{-6}**(3n), **10^{-7}**(4n) survival probability
cross sections up to **0.1 pb** can be calculated

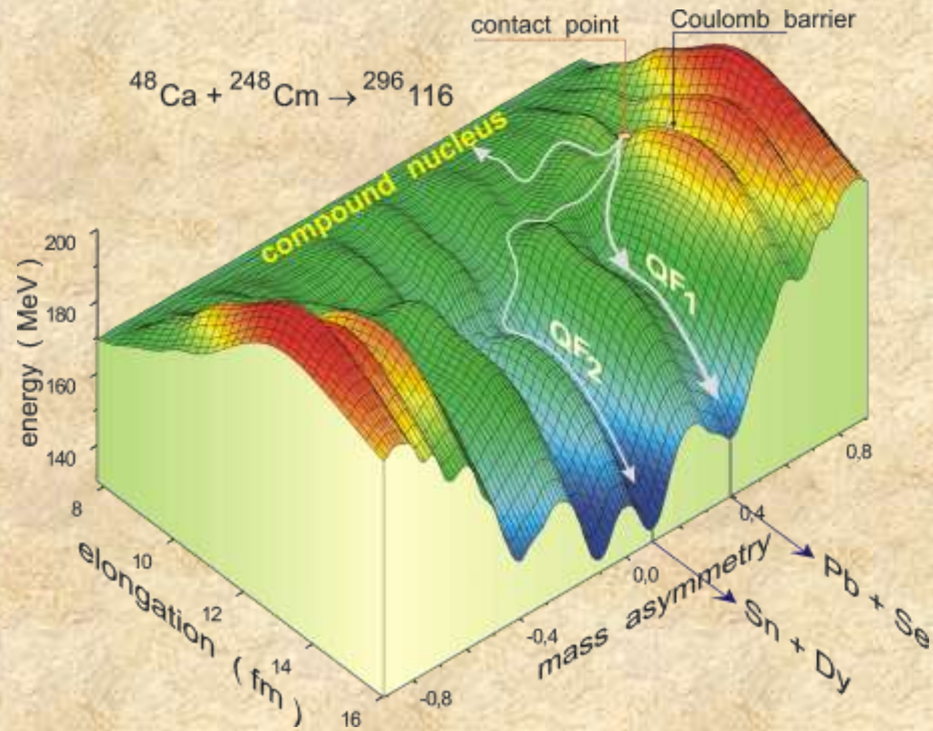
Deep-Inelastic Scattering: $^{136}Xe + ^{209}Bi$

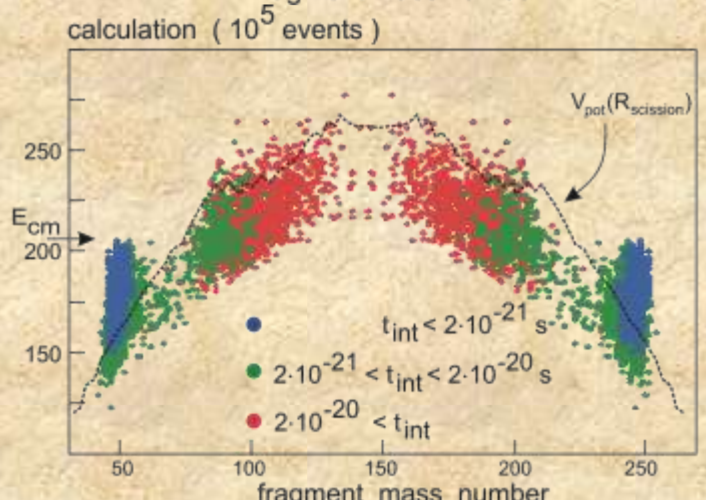
W.W. Wilcke et al., 1980

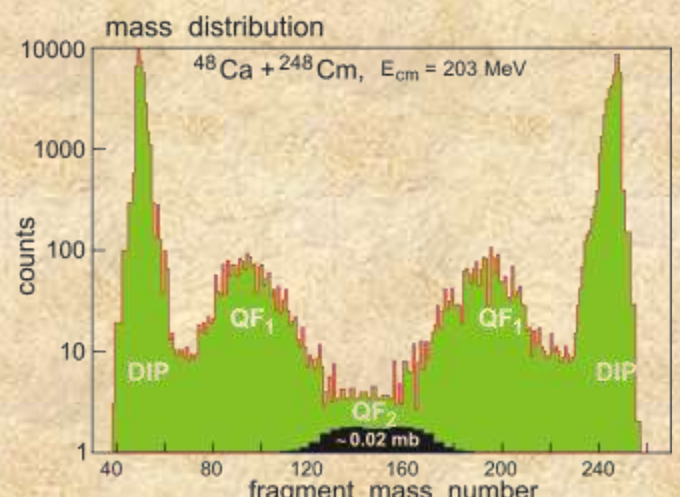


Quasi-fission and fusion-fission processes

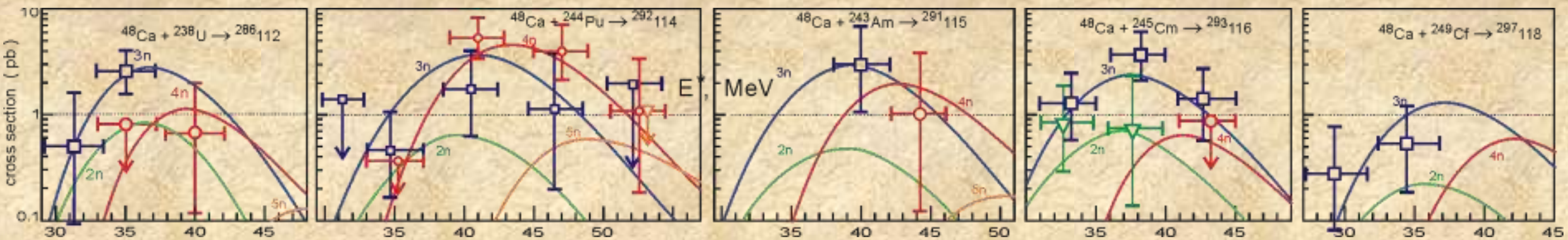


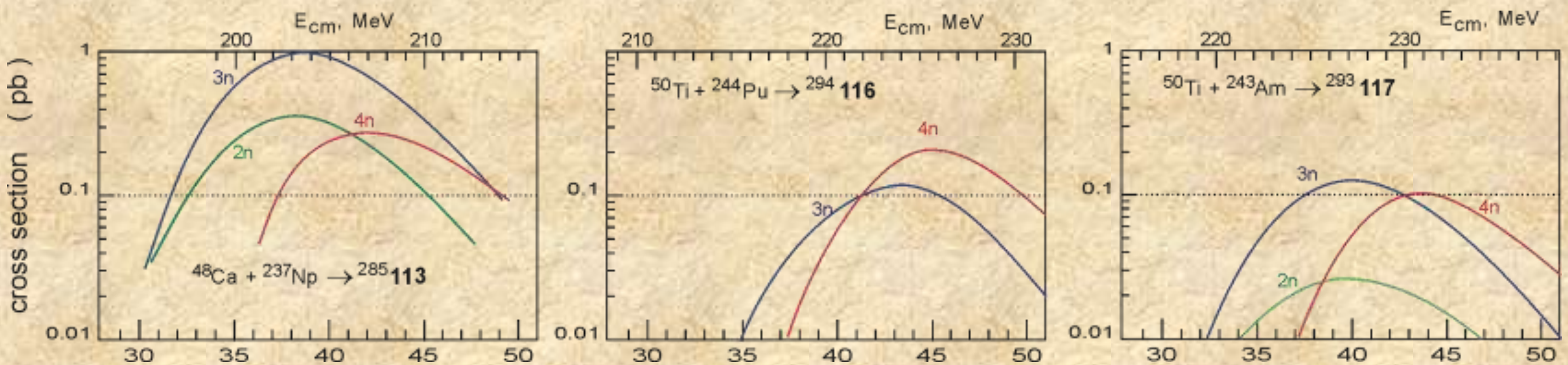




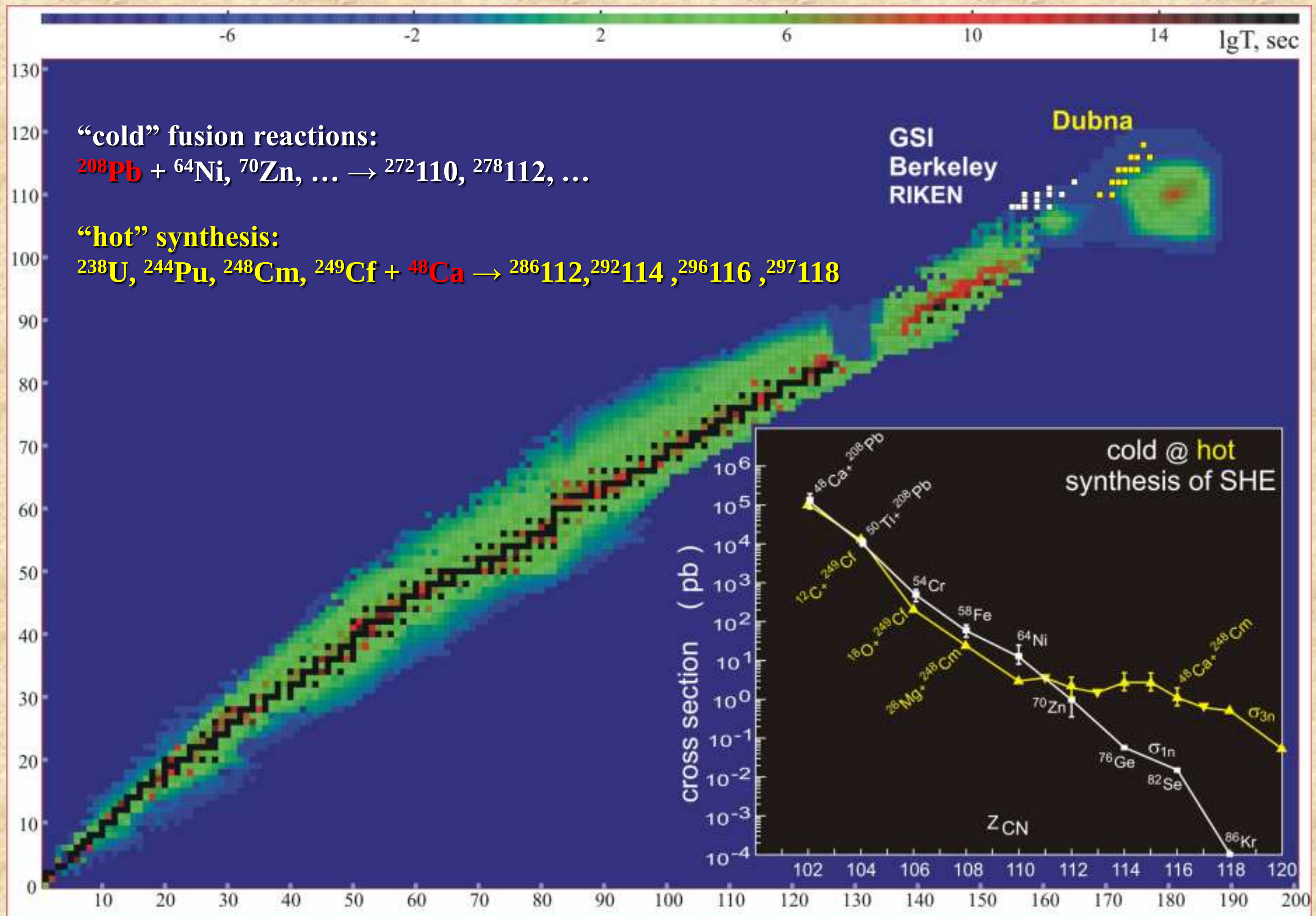


Cross sections for superheavy element production

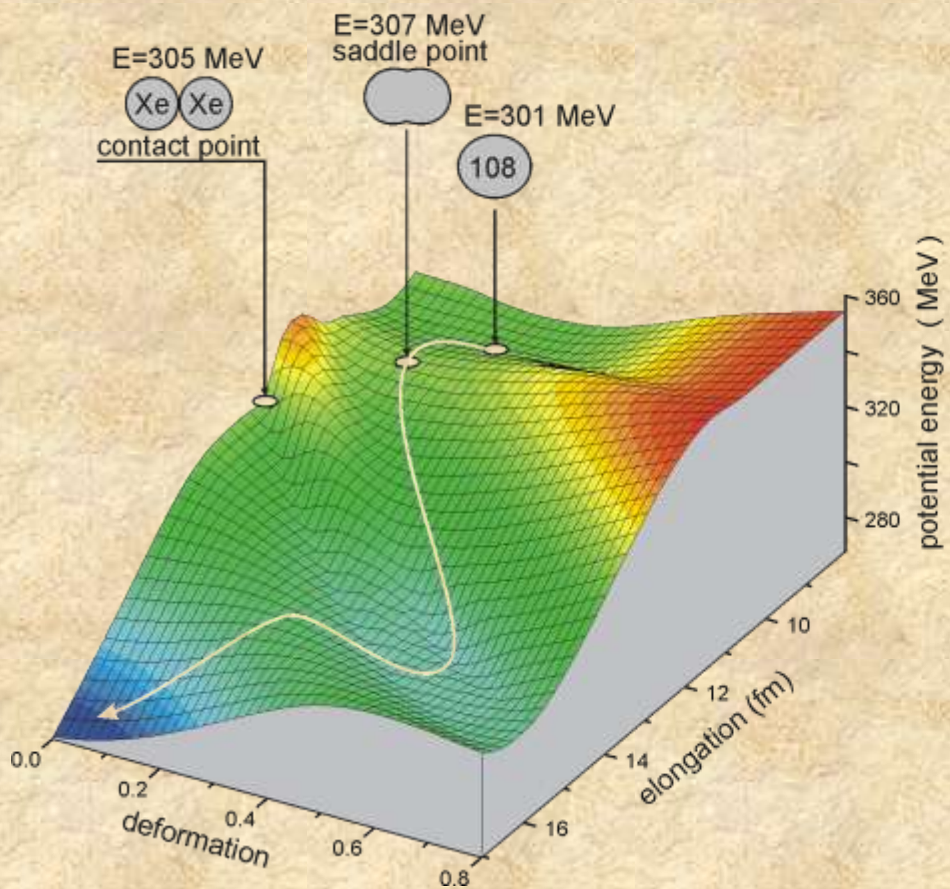


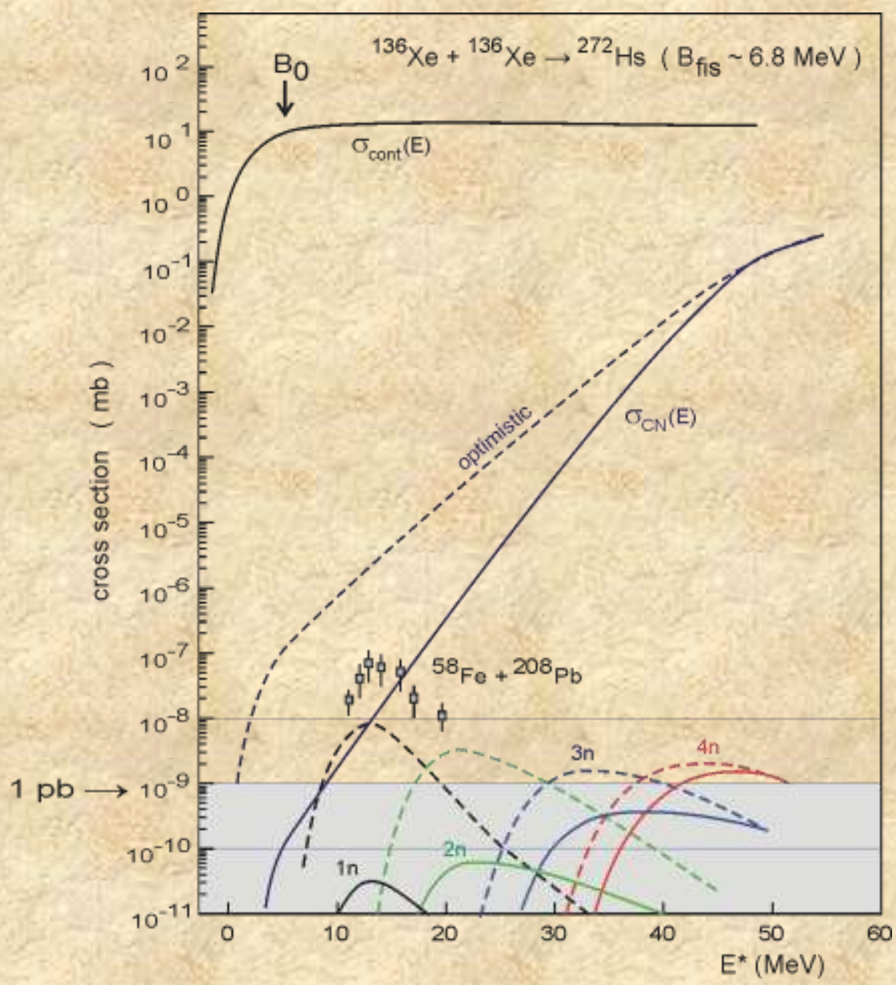


On the way to the first Island of Stability



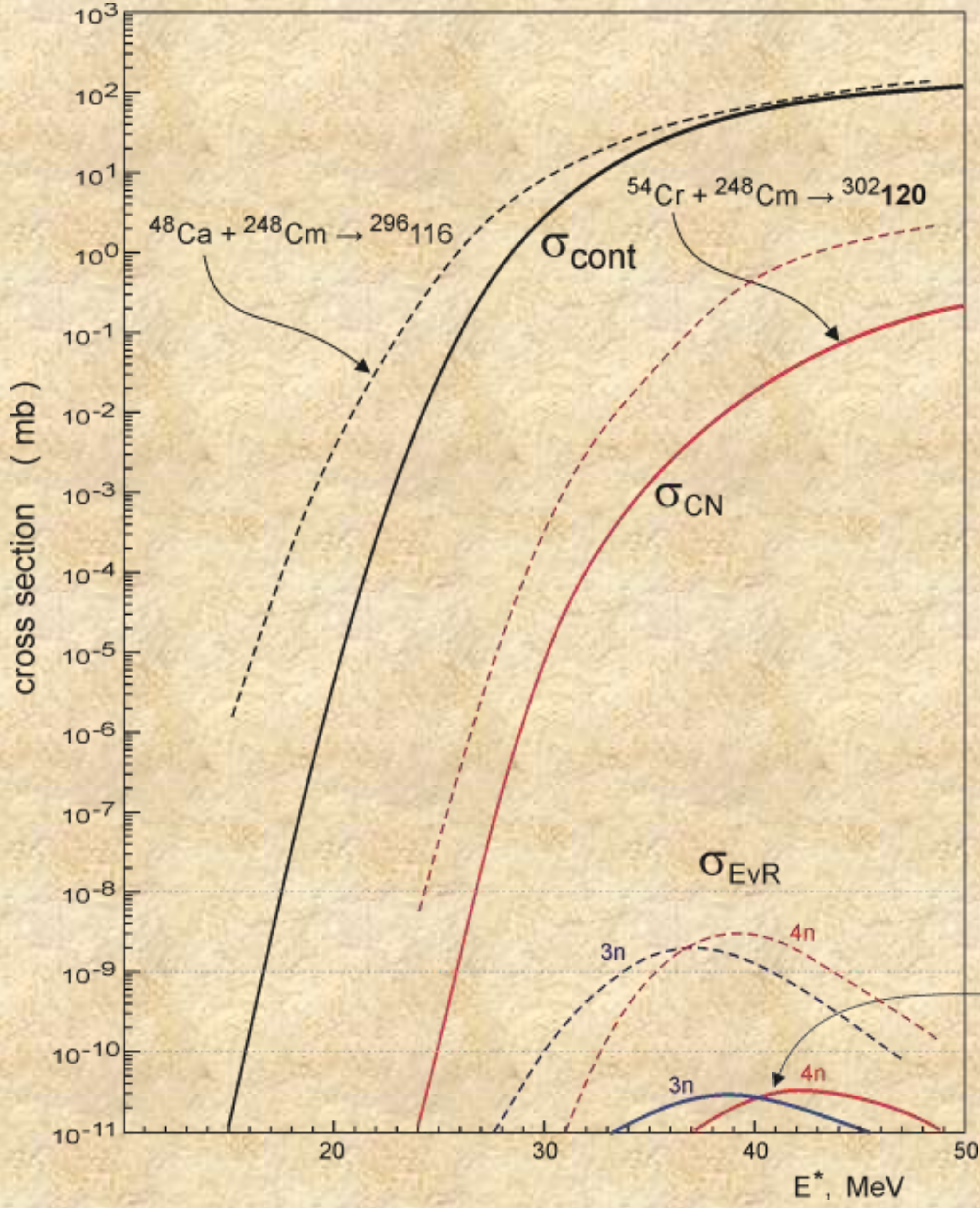
Fusion of "fission fragments": $^{136}Xe + ^{136}Xe \rightarrow {}^{272}108$



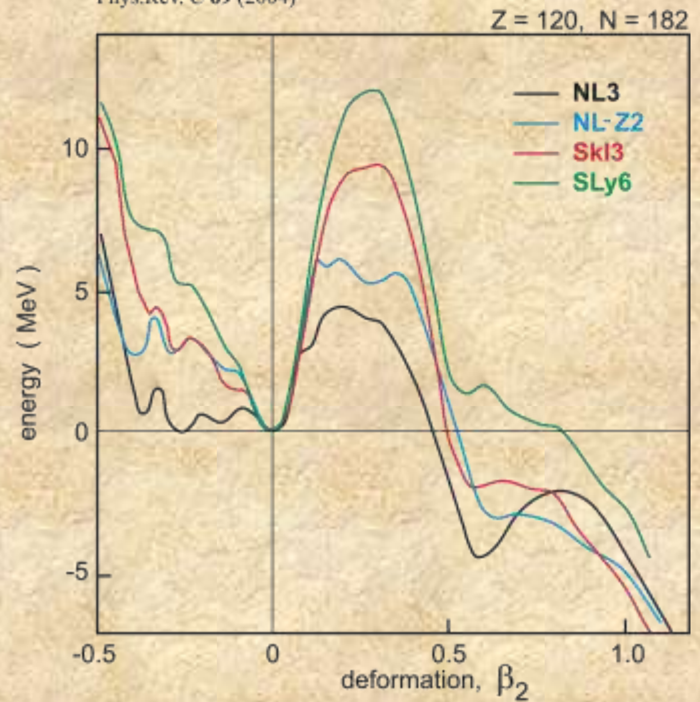


if OK then $^{132}Sn + ^{176}Yb \rightarrow {}^{308}120$

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



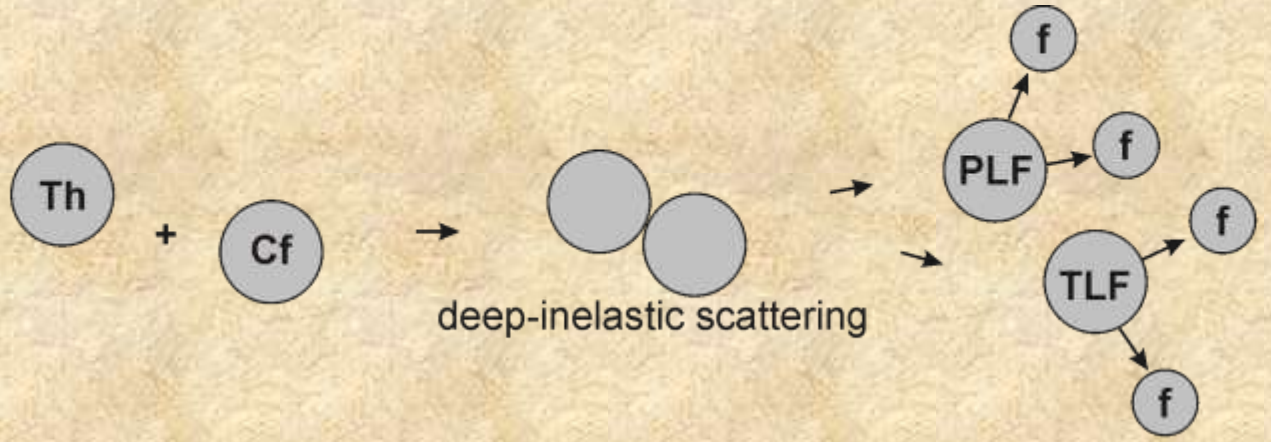
T. Bürvenich, M. Bender, A. Maruhn, and P.-G. Reinhard, Phys.Rev. C **69** (2004)

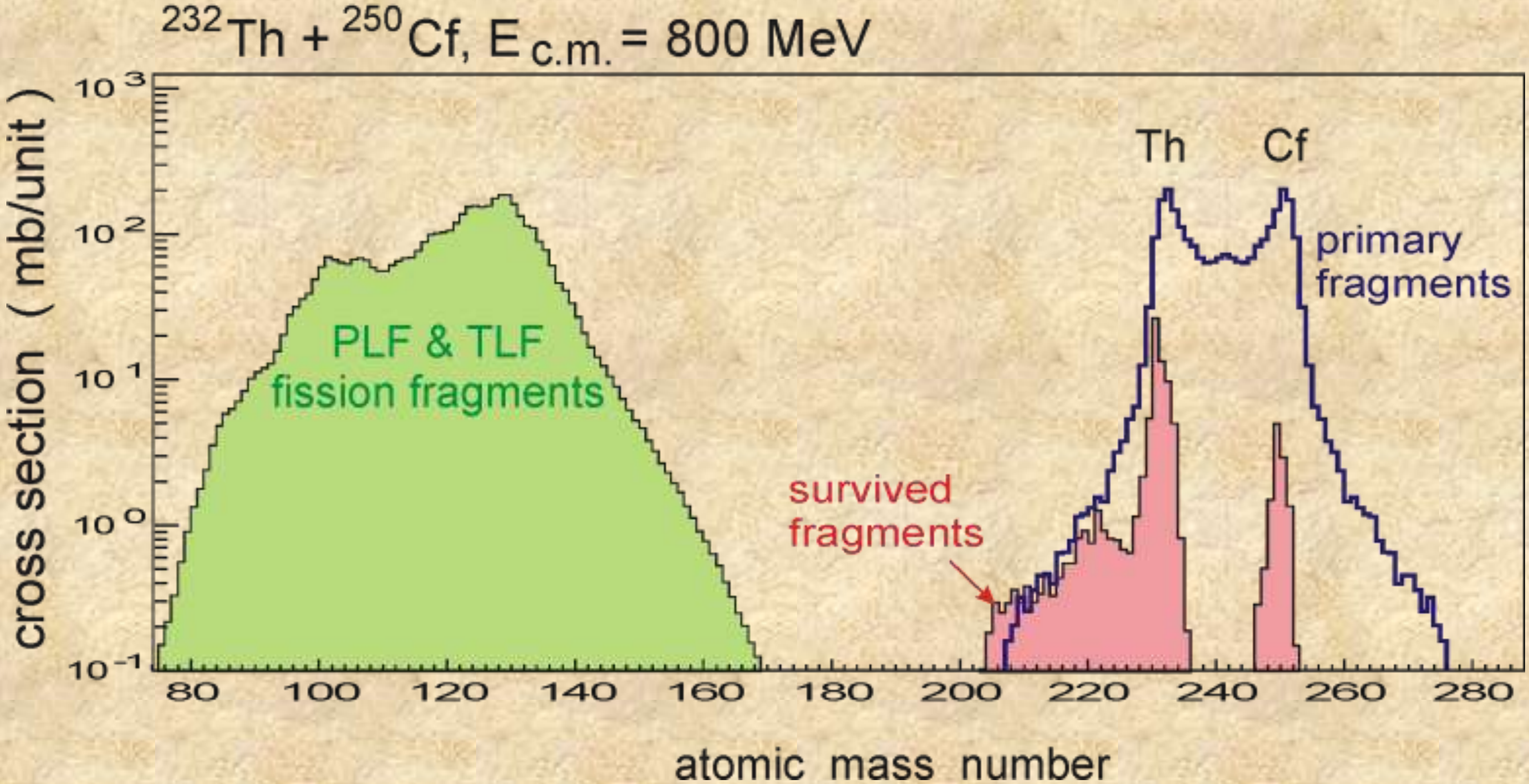


Fission barriers of ^{302}**120**

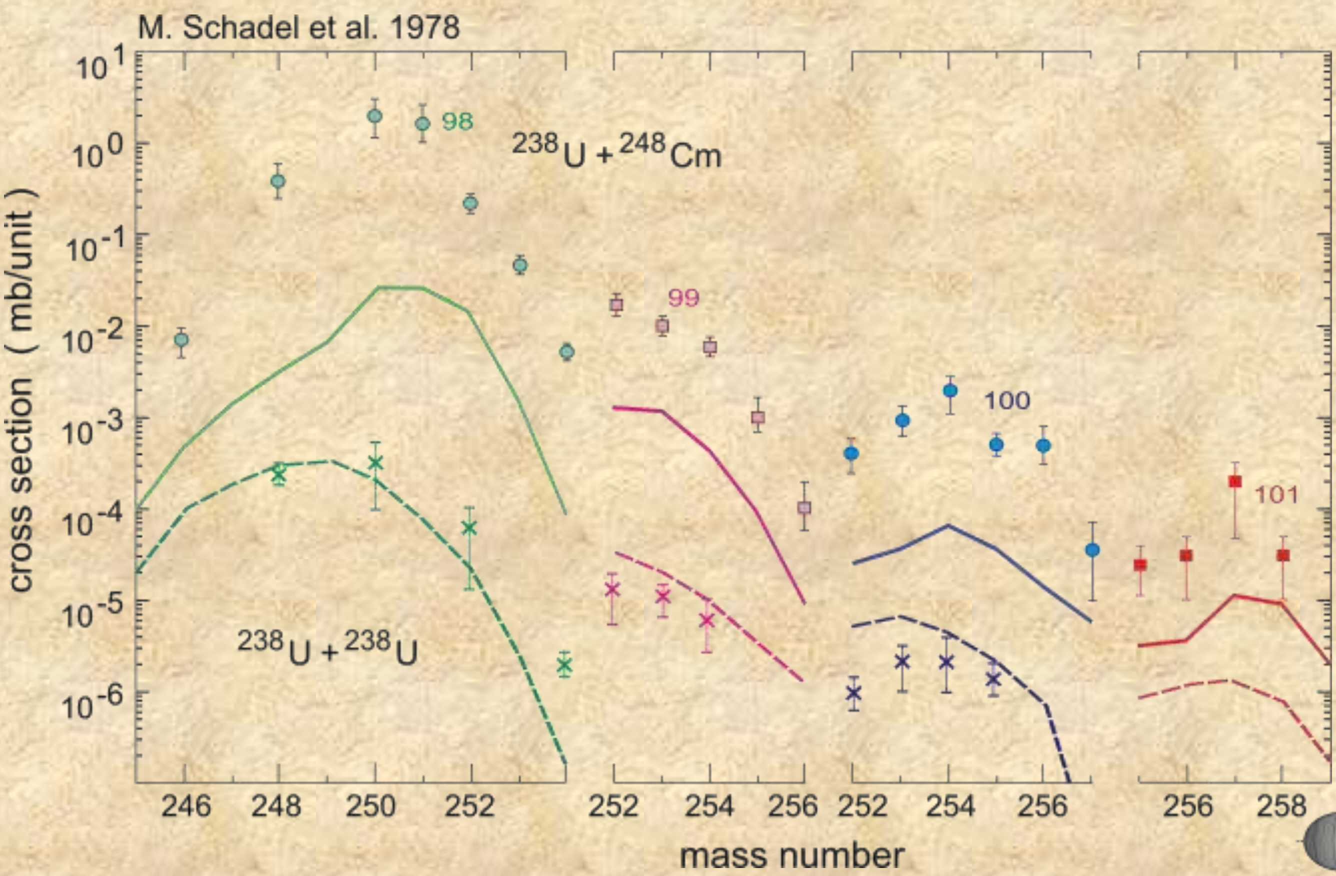
B_{fis}, MeV	Model
~ **6**	A. Sobiscewski
~ **7**	P. Möller et al.
~ **6**	RMF
~ **11**	SkHF

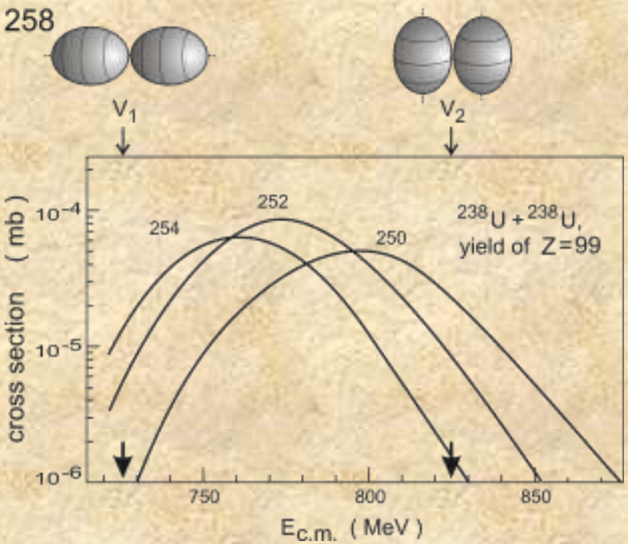
Collision of very heavy (transactinide) nuclei ?



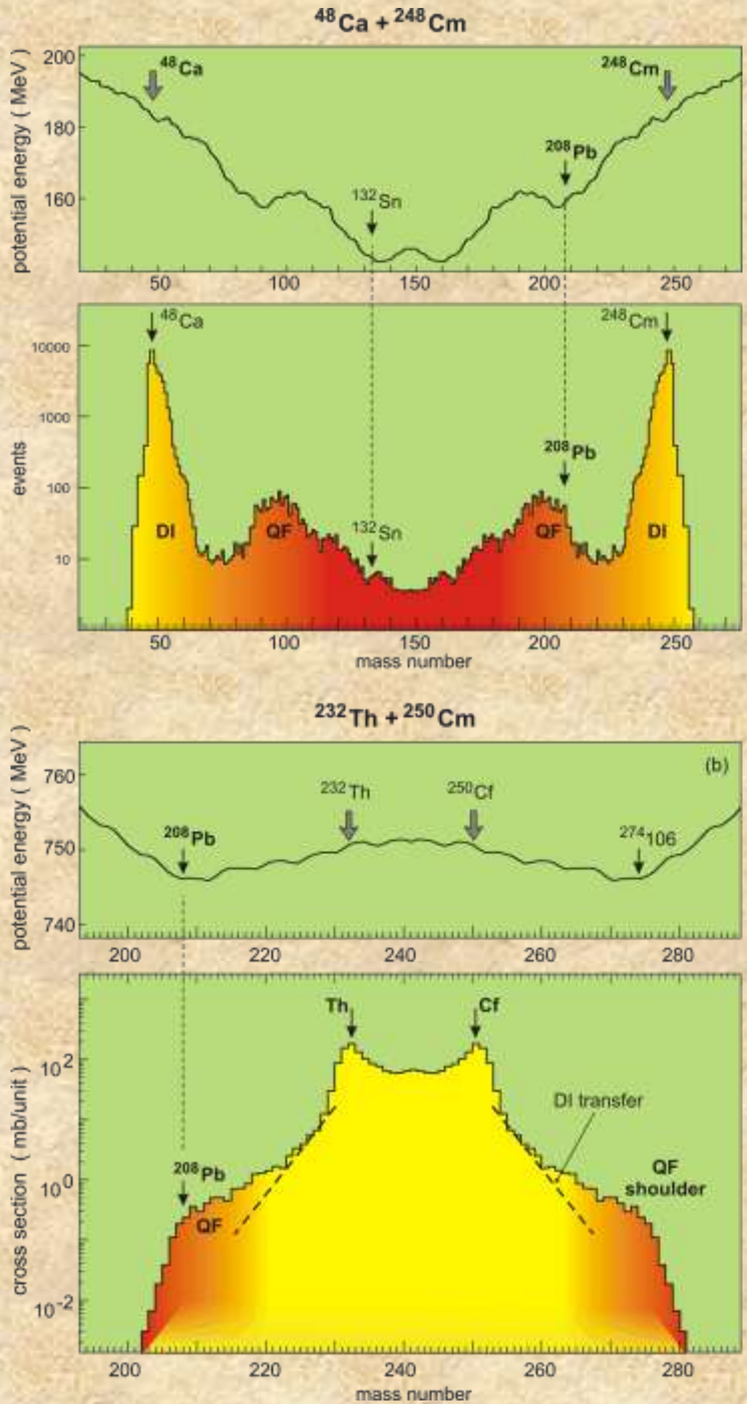


Comparison with available experimental data



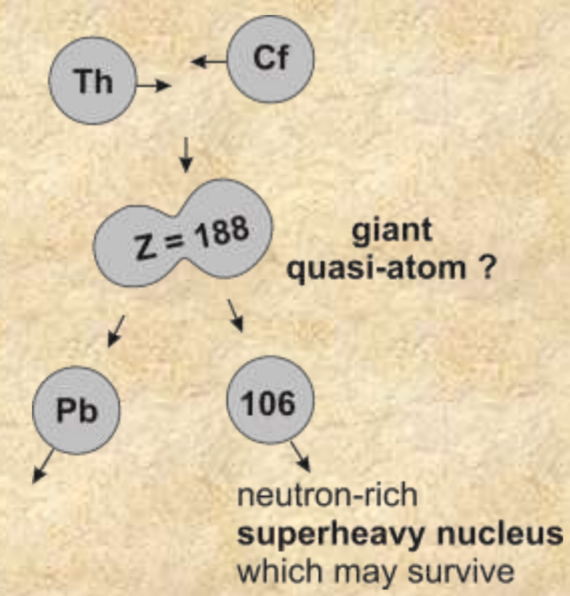


Inverse (antisymmetrizing) qasi-fission process

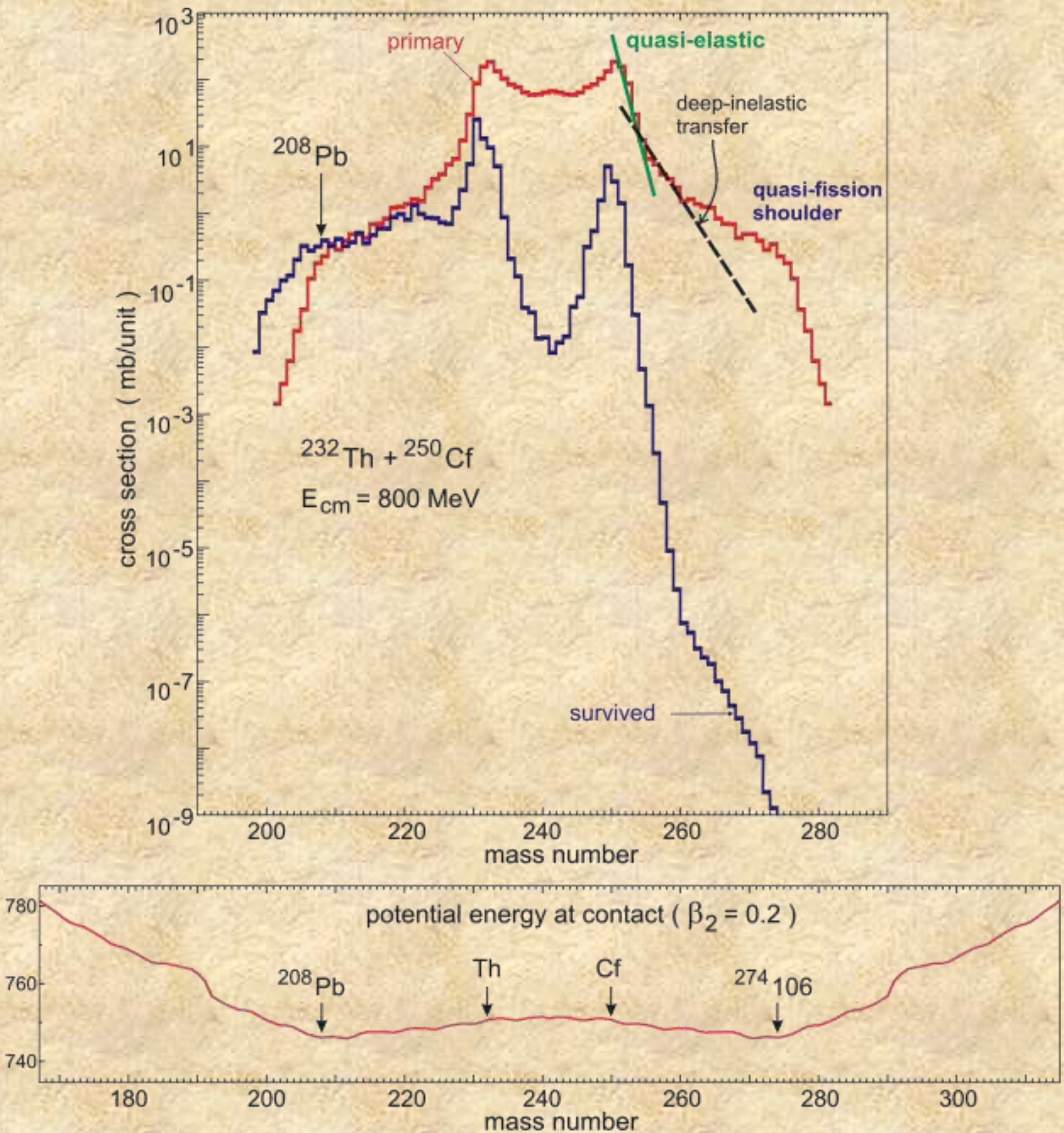


normal
(symmetrizing)
quasi-fission

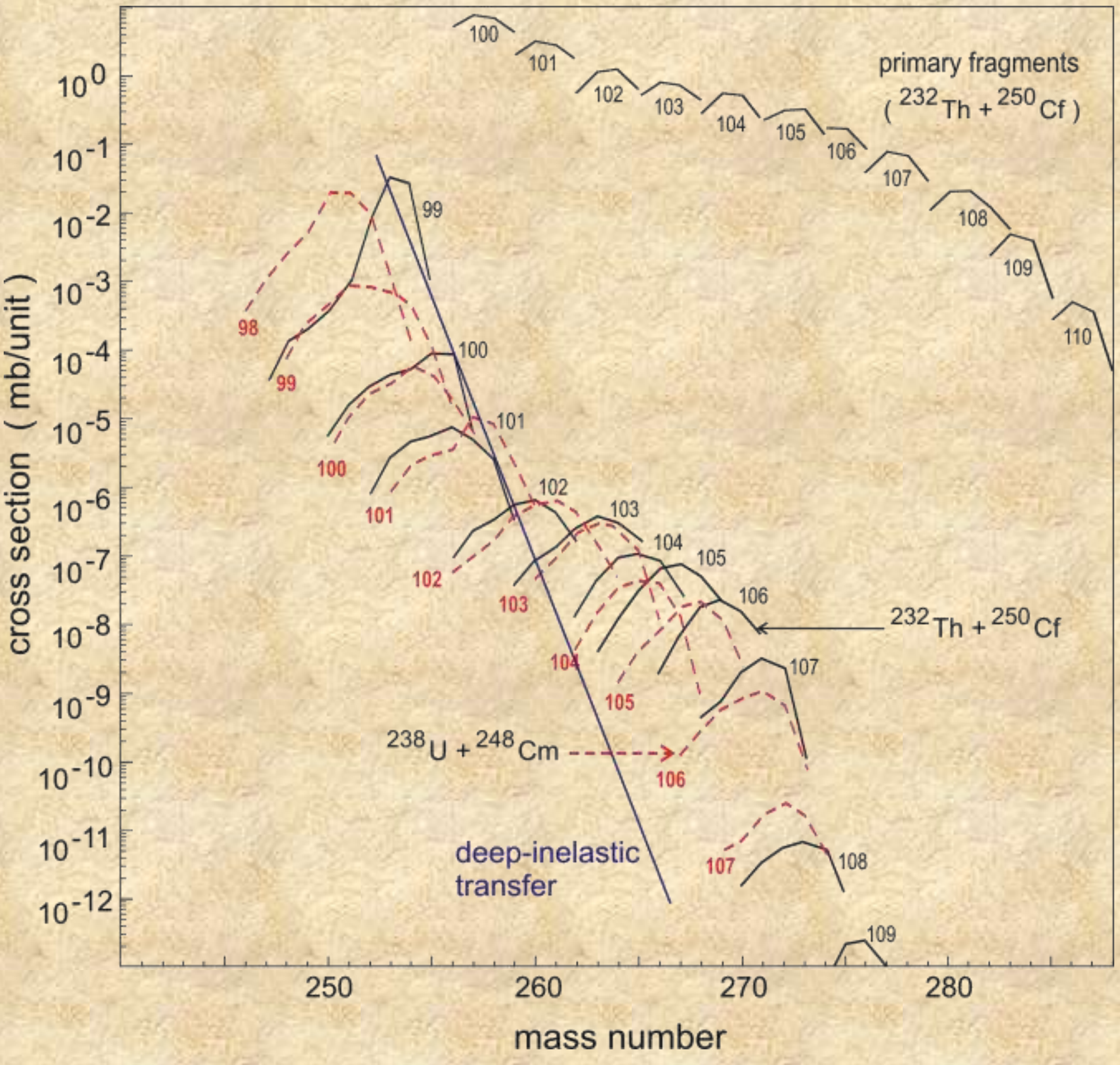
"inverse"
(antisymmetrizing)
quasi-fission



Deep-Inelastic and Quasi-Fission processes in very-heavy-ion damped collisions



Isotopic yield of SHE in very-heavy-ion damped collisions



Summary

- For heavy nuclear system it is extremely important to perform a **combined (unified) analysis** of all strongly coupled channels: Deep-Inelastic scattering, Quasi-Fission, Fusion and regular Fission. This ambitious goal has now become possible.

- A unified potential energy surface and a unified set of dynamic equations are proposed for the simultaneous description of DI and Fusion-Fission processes.
  For the first time the whole evolution of the heavy nuclear system can be traced starting from the approaching stage and ending in DI, QF, and/or Fusion-Fission channels.

- 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**.

- Accurate estimations of the probabilities for **super-heavy element** formation can be obtained now. The mechanisms of quasi-fission and fusion-fission processes can be clarified much better than before . Determination of such fundamental characteristics of nuclear dynamics as the nuclear viscosity and the nucleon transfer rate is now possible.

- Low energy collisions of transuranium nuclei: **Production of long-lived neutron-rich SHE** seems to be quite possible due to a large mass and charge rearrangement in the "**inverse quasi-fission**" process caused by the Z=82 and N=126 nuclear shells.