Superheavy Nuclei and Giant Quasi-atoms

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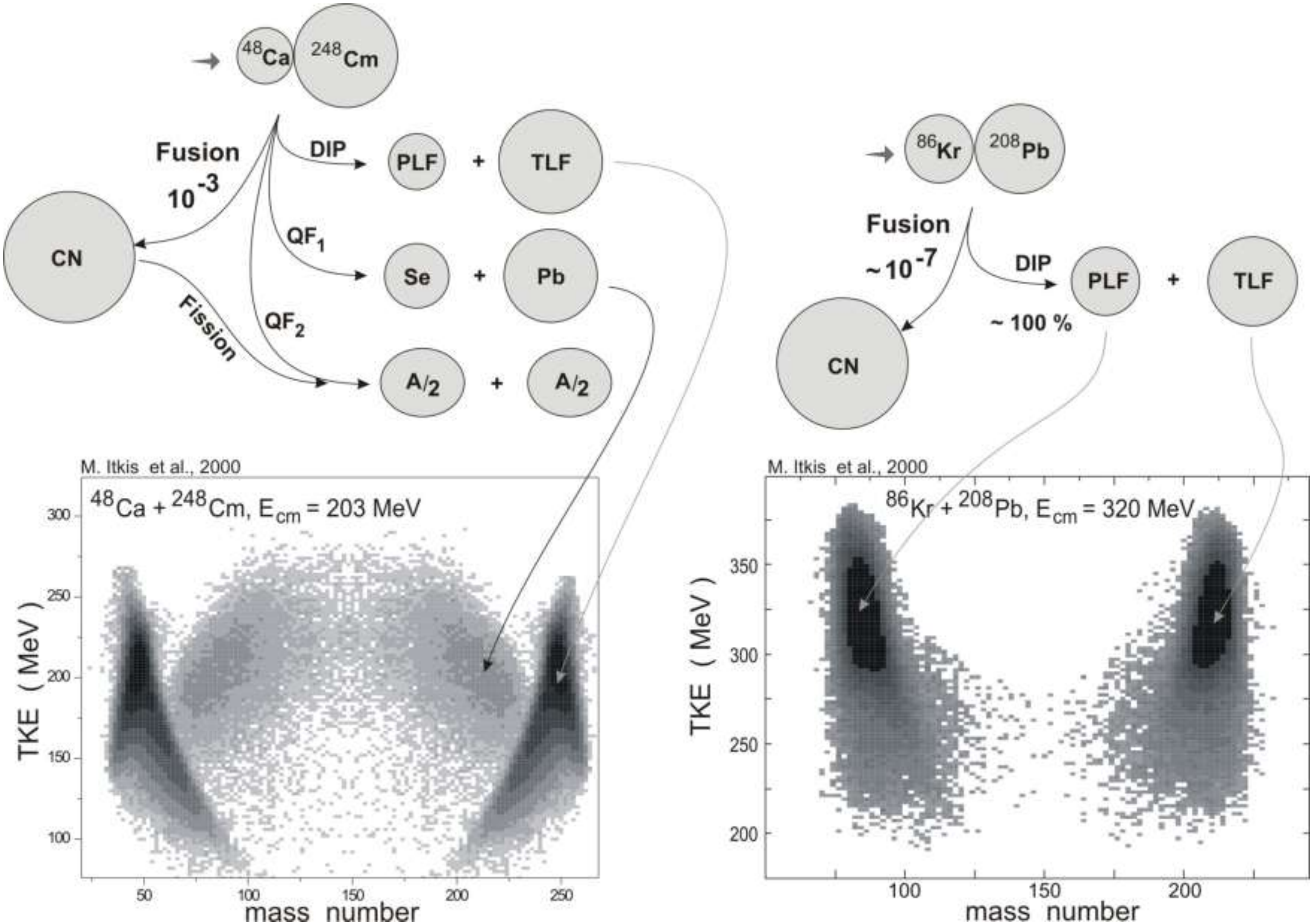
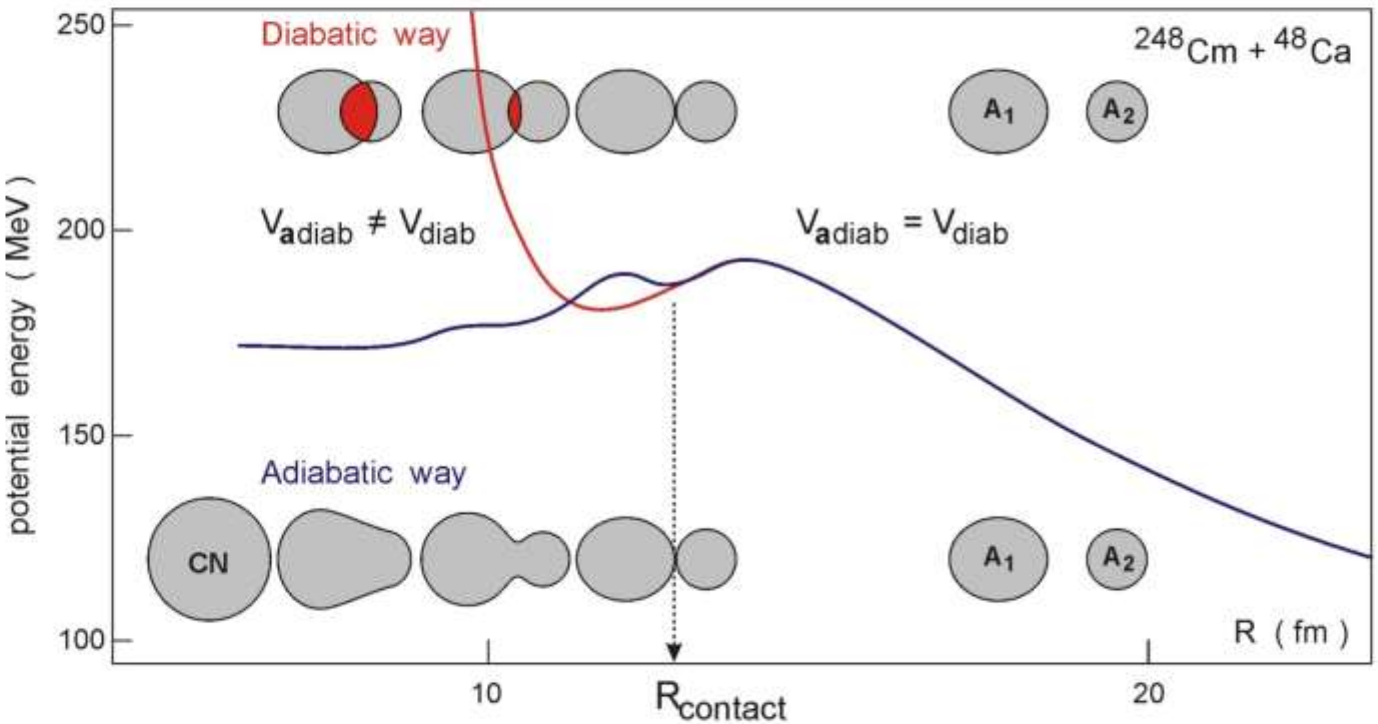
- **Unified description of Deep-Inelastic, Quasi-Fission and Fusion-Fission processes**
- **Super-Heavy Element formation**
- **Collisions of very heavy ions (U + Cm) at low energies**
- **Giant quasi-atoms and spontaneous positron formation**

Unified description is needed for Deep Inelastic, Quasi-Fission and Fusion-Fission processes



Diabatic and Adiabatic Potential Energy

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



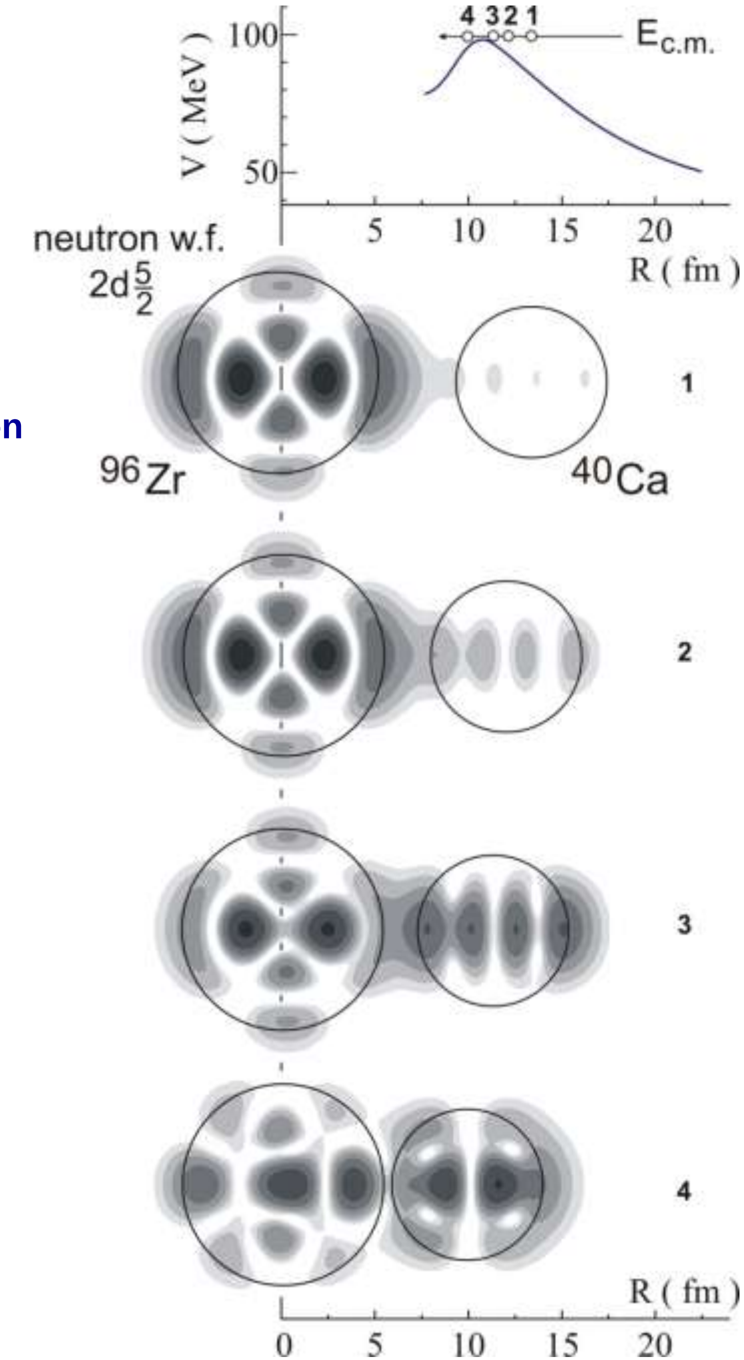
$$V_{adiabat}(R,\beta_1,\beta_2,\alpha,\ldots) = M_{TCSM}(R,\beta_1,\beta_2,\alpha,\ldots) - M(Proj) - M(Targ)$$

→ time-dependent potential energy

$$\mathbf{V}_{\text{fus-fis}}(t) = \mathbf{V}_{\text{diab}} \cdot e^{-\frac{t}{\tau_{relax}}} + \mathbf{V}_{\text{adiabat}} \cdot [1 - e^{-\frac{t}{\tau_{relax}}}]$$

What is behavior of valence neutrons in near-barrier fusion reactions ?

Time-dependent Schrödinger equation applied to valence neutron wave function



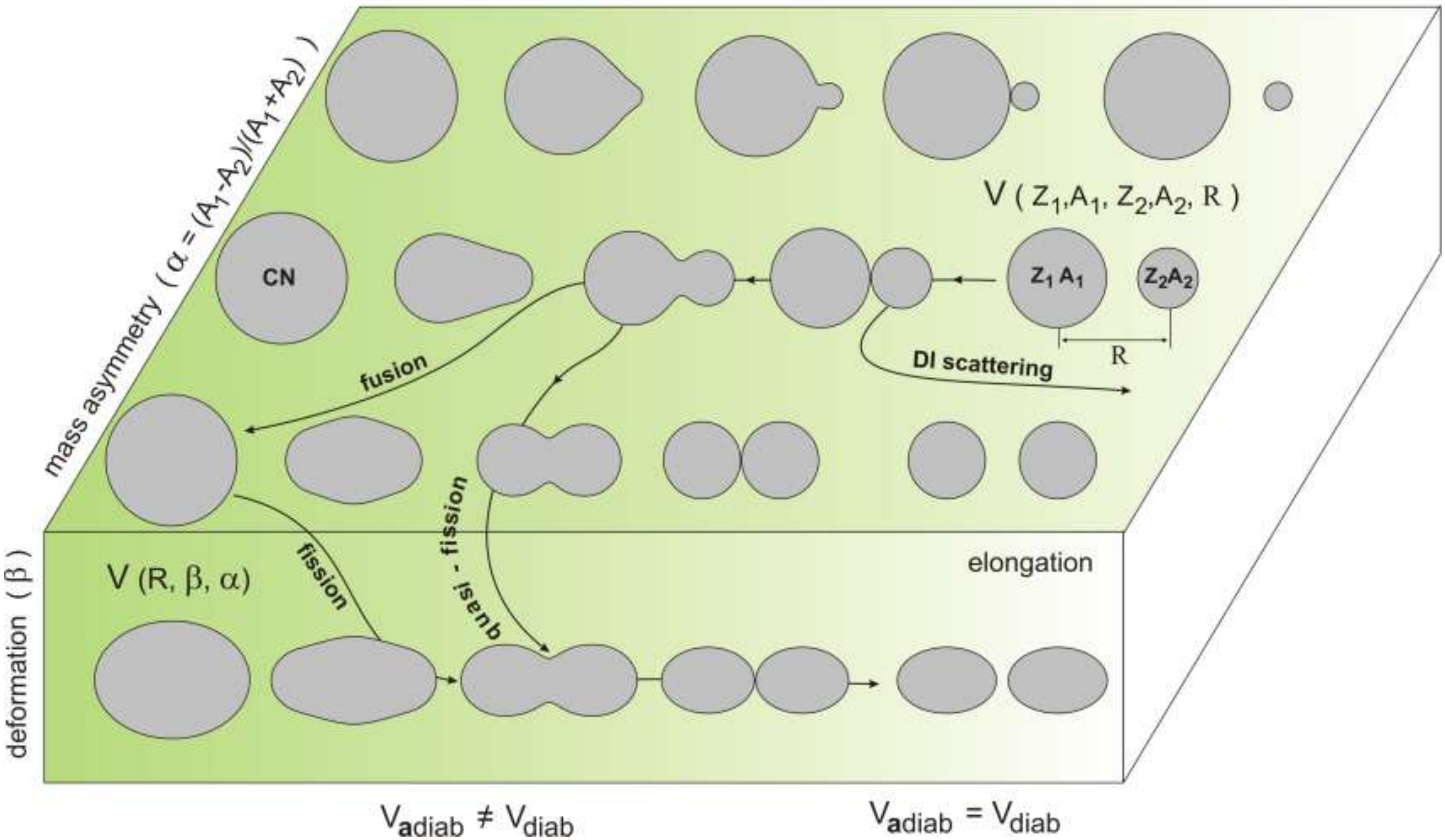
Wave functions of valence neutrons follow the two-center molecular states and spread over both nuclei **before** they reach and overcome the Coulomb barrier !

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

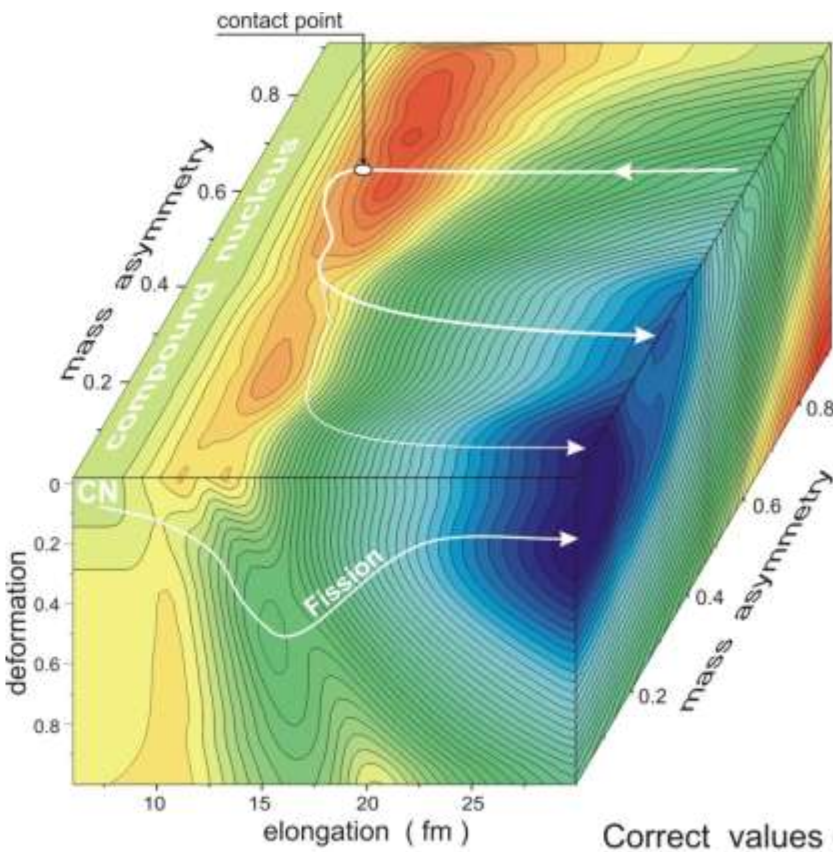
Variables ?

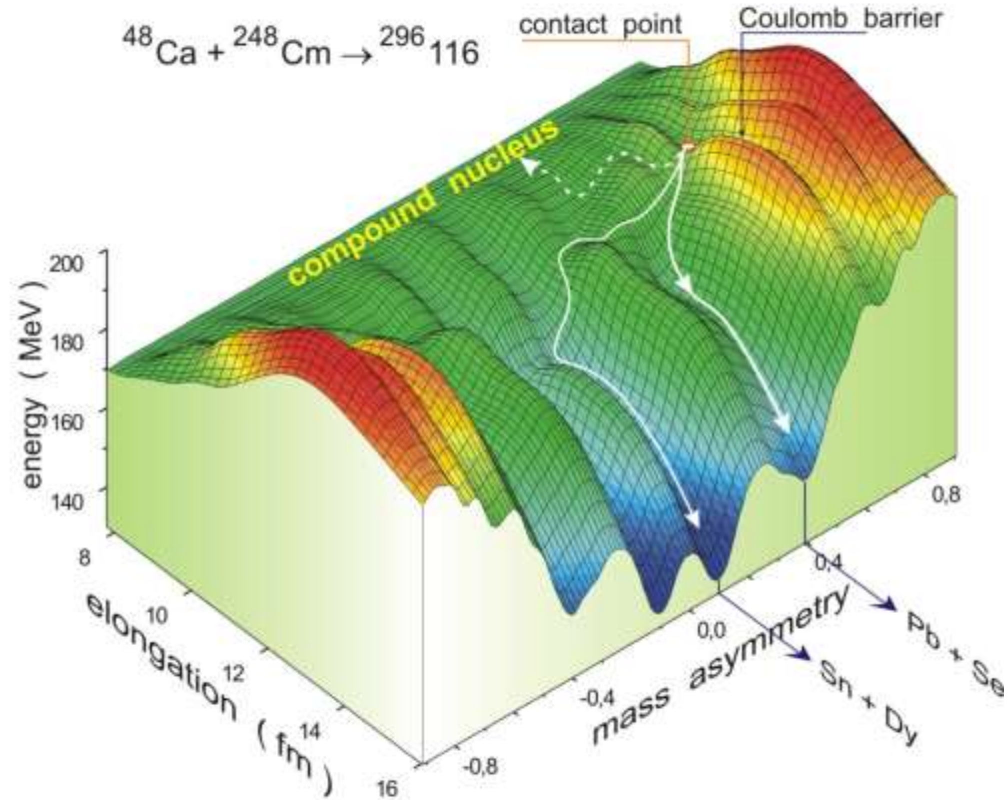
? - principal degrees of freedom: $\{ q_1, q_2, ...\}$,
? - potential energy surface: $V(q_1,q_2,...)$,
? - dynamic equations of motion: $dq_i / dt = ...$

Common (unified) for all the processes:
Deep Inelastic, Quasi-Fission, Fusion-Fission !!!



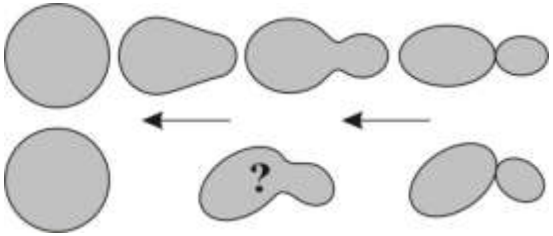
Potential Energy: Fusion, Fission and Quasi-Fission

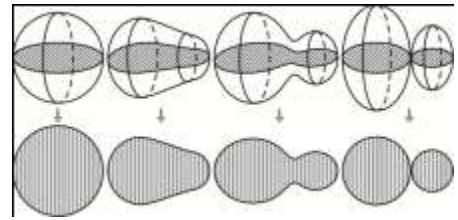


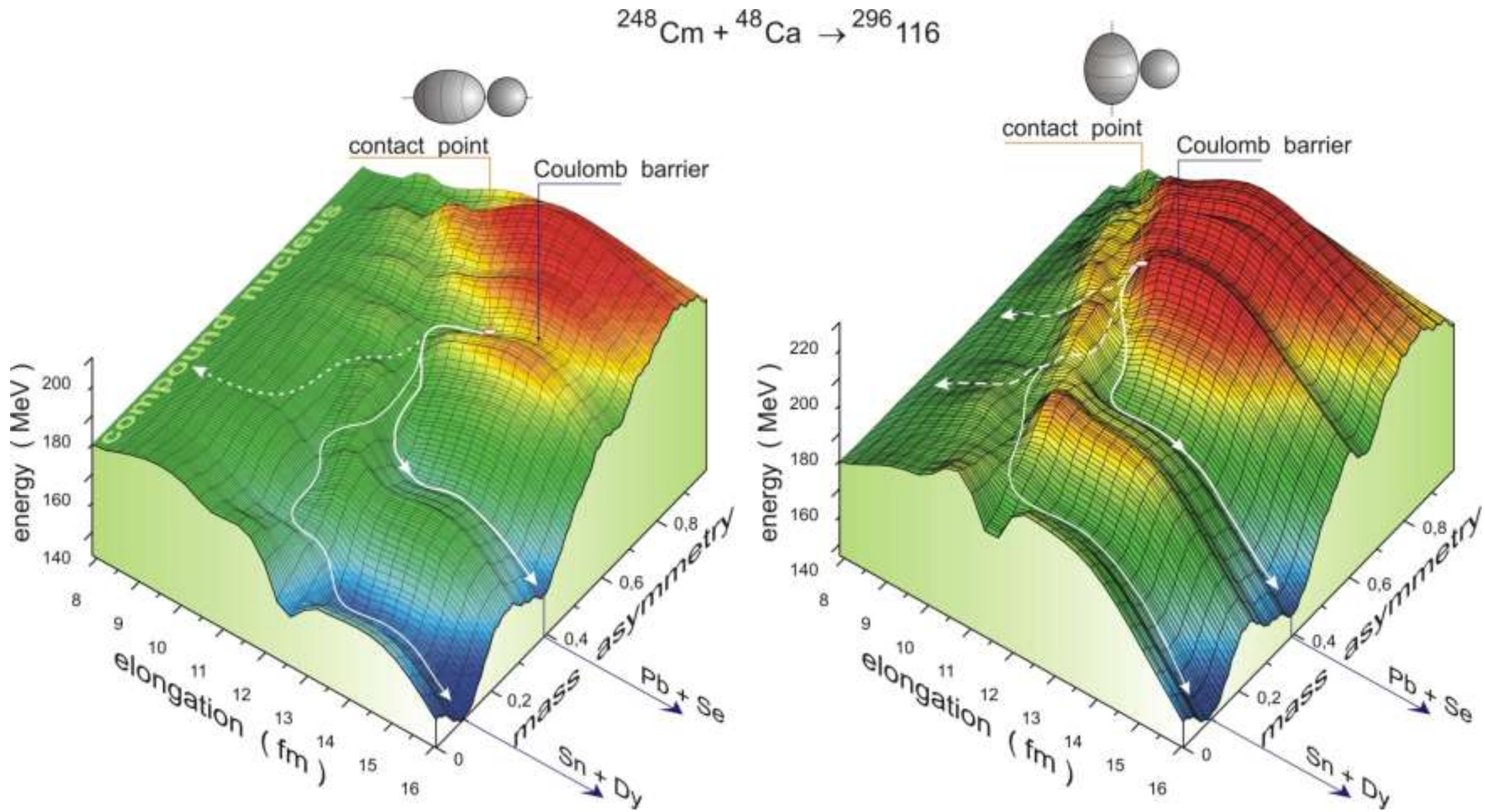


Correct values of the Coulomb barriers
and the height of the fission barrier of CN

Orientation effects







Equations of Motion. The problem of mass exchange

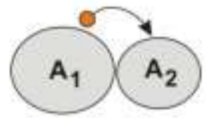
Variables: elongation R; deformations β_1, β_2; mass asymmetry α — Schrödinger, Newtonian, Langevin type

No problems with inertia parameters $M_R(R,\beta,\alpha)$, $M_\beta(R,\beta,\alpha)$ (Werner - Wheeler) →

$$\begin{cases} \dfrac{dR}{dt} = \dfrac{p_R}{M_R} \\ \dfrac{dp_R}{dt} = -\dfrac{\partial}{\partial R} V(R,\beta,\alpha) + \ldots \\ \dfrac{d\beta}{dt} = \dfrac{p_\beta}{M} \\ \dfrac{dp_\beta}{dt} = -\dfrac{\partial}{\partial \beta} V(R,\beta,\alpha) + \ldots \end{cases}$$

? mass-asymmetry α:

1) discrete nature
2) $M_\alpha\ (R \geq R_{contact}) \to \infty$



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

(L. Moretto, 1974)

Distribution function $\varphi(A,t)$ → Master equation

$$\frac{\partial \varphi}{\partial t} = \sum_{A'=A\pm 1} \lambda(A' \to A)\cdot\varphi(A') - \lambda(A \to A')\cdot\varphi(A)$$

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

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

$$D^{(1)} = \int dA'(A'-A)\lambda(A \to A')$$

$$D^{(2)} = \frac{1}{2}\int dA'(A'-A)^2\lambda(A \to A')$$

$$\alpha = \frac{A_1 - A_2}{A_{CN}}$$

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

at $A = A \pm 1$

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

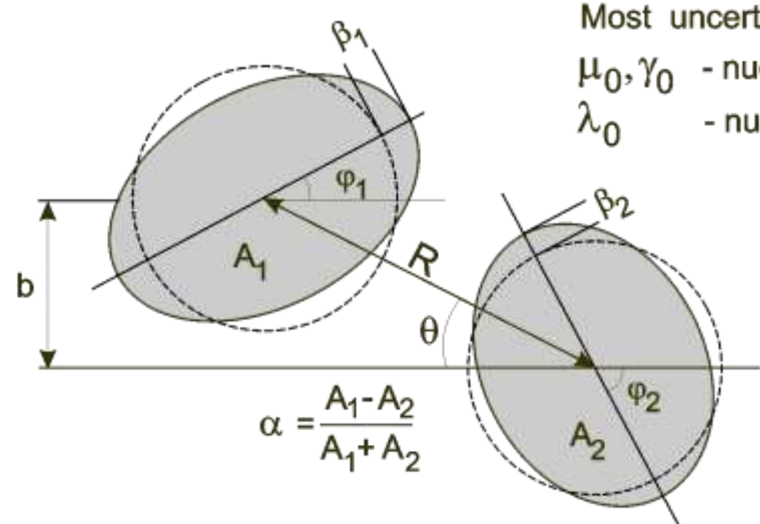
$$D^{(2)} = \frac{1}{2}[\lambda(A \to A+1) + \lambda(A \to A-1)]$$

transition probability

$$\lambda^{(\pm)} = \lambda_0 \sqrt{\frac{\rho(A\pm 1)}{\rho(A)}}\, P_{tr}(R; A \to A\pm 1) \approx \lambda_0 \exp\left(\frac{V(R,\beta,A\pm 1) - V(R,\beta,A)}{2T}\right) P_{tr}(R; A \to A\pm 1)$$

The system of coupled Langevin type Equations of Motion

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



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

Most uncertain parameters:

μ_0, γ_0 - nuclear viscosity and friction,

λ_0 - nucleon transfer rate

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

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

$$\frac{d\varphi_1}{dt} = \frac{\hbar L_1}{\Im_1}$$

$$\frac{d\varphi_2}{dt} = \frac{\hbar L_2}{\Im_2}$$

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

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

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

$$\frac{dp_R}{dt} = -\frac{\partial V}{\partial R} + \frac{\hbar^2\ell^2}{\mu_R R^3} + \left(\frac{\hbar^2\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial R} + \frac{p_{\beta_1}^2}{2\mu_{\beta_1}^2}\frac{\partial \mu_{\beta_1}}{\partial R} + \frac{p_{\beta_2}^2}{2\mu_{\beta_2}^2}\frac{\partial \mu_{\beta_2}}{\partial R} - \gamma_R \frac{p_R}{\mu_R} + \sqrt{\gamma_R T}\Gamma_R(t)$$

$$\frac{d\ell}{dt} = -\frac{1}{\hbar}\frac{\partial V}{\partial \vartheta} - \gamma_{\text{tang}}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1}a_1 - \frac{L_2}{\Im_2}a_2\right) R + \frac{R}{\hbar}\sqrt{\gamma_{\text{tang}} T}\Gamma_{\text{tang}}(t)$$

$$\frac{dL_1}{dt} = -\frac{1}{\hbar}\frac{\partial V}{\partial \varphi_1} + \gamma_{\text{tang}}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1}a_1 - \frac{L_2}{\Im_2}a_2\right) a_1 - \frac{a_1}{\hbar}\sqrt{\gamma_{\text{tang}} T}\Gamma_{\text{tang}}(t)$$

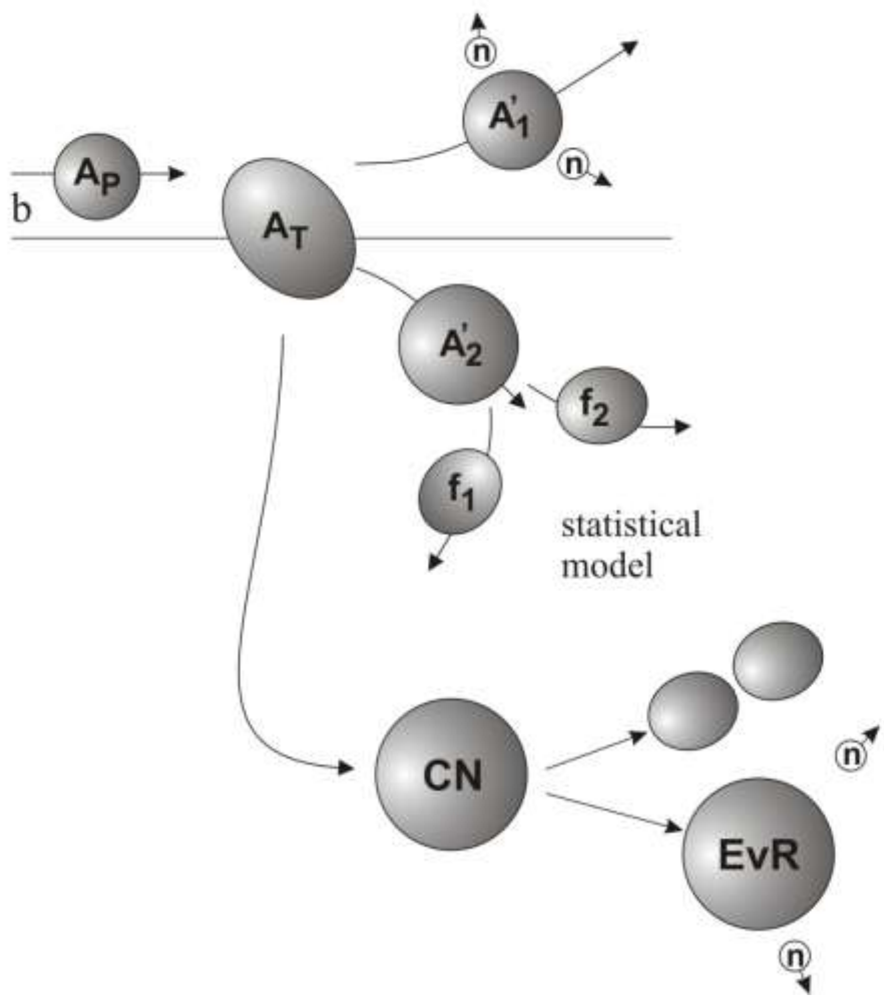
$$\frac{dL_2}{dt} = -\frac{1}{\hbar}\frac{\partial V}{\partial \varphi_2} + \gamma_{\text{tang}}\left(\frac{\ell}{\mu_R R} - \frac{L_1}{\Im_1}a_1 - \frac{L_2}{\Im_2}a_2\right) a_2 - \frac{a_2}{\hbar}\sqrt{\gamma_{\text{tang}} T}\Gamma_{\text{tang}}(t)$$

$$\frac{dp_{\beta_1}}{dt} = -\frac{\partial V}{\partial \beta_1} + \frac{p_{\beta_1}^2}{2\mu_{\beta_1}^2}\frac{\partial \mu_{\beta_1}}{\partial \beta_1} + \frac{p_{\beta_2}^2}{2\mu_{\beta_2}^2}\frac{\partial \mu_{\beta_2}}{\partial \beta_1} + \frac{\hbar^2 L_1^2}{2\Im_1^2}\frac{\partial \Im_1}{\partial \beta_1} + \left(\frac{\hbar^2\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial \beta_1} - \gamma_{\beta_1}\frac{p_{\beta_1}}{\mu_{\beta_1}} + \sqrt{\gamma_{\beta_1} T}\Gamma_{\beta_1}(t)$$

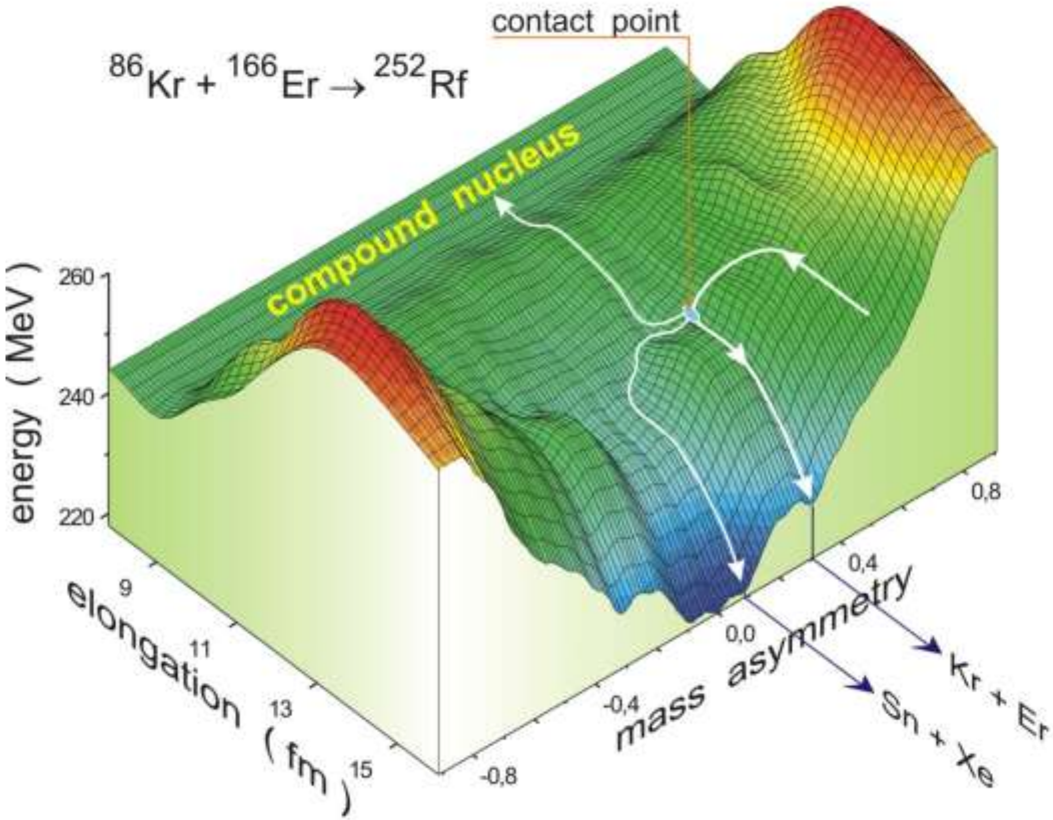
$$\frac{dp_{\beta_2}}{dt} = -\frac{\partial V}{\partial \beta_2} + \frac{p_{\beta_1}^2}{2\mu_{\beta_1}^2}\frac{\partial \mu_{\beta_1}}{\partial \beta_2} + \frac{p_{\beta_2}^2}{2\mu_{\beta_2}^2}\frac{\partial \mu_{\beta_2}}{\partial \beta_2} + \frac{\hbar^2 L_2^2}{2\Im_2^2}\frac{\partial \Im_2}{\partial \beta_2} + \left(\frac{\hbar^2\ell^2}{2\mu_R^2 R^2} + \frac{p_R^2}{2\mu_R^2}\right)\frac{\partial \mu_R}{\partial \beta_2} - \gamma_{\beta_2}\frac{p_{\beta_2}}{\mu_{\beta_2}} + \sqrt{\gamma_{\beta_2} T}\Gamma_{\beta_2}(t).$$

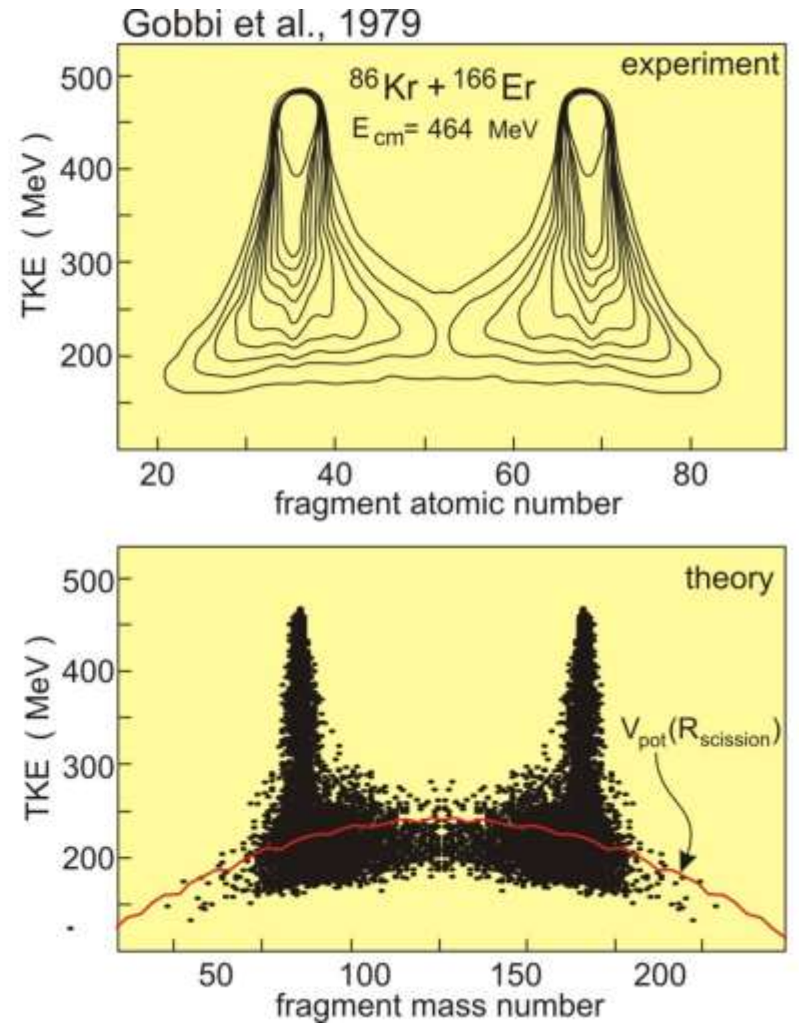
Simulation of experiment and cross sections

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



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





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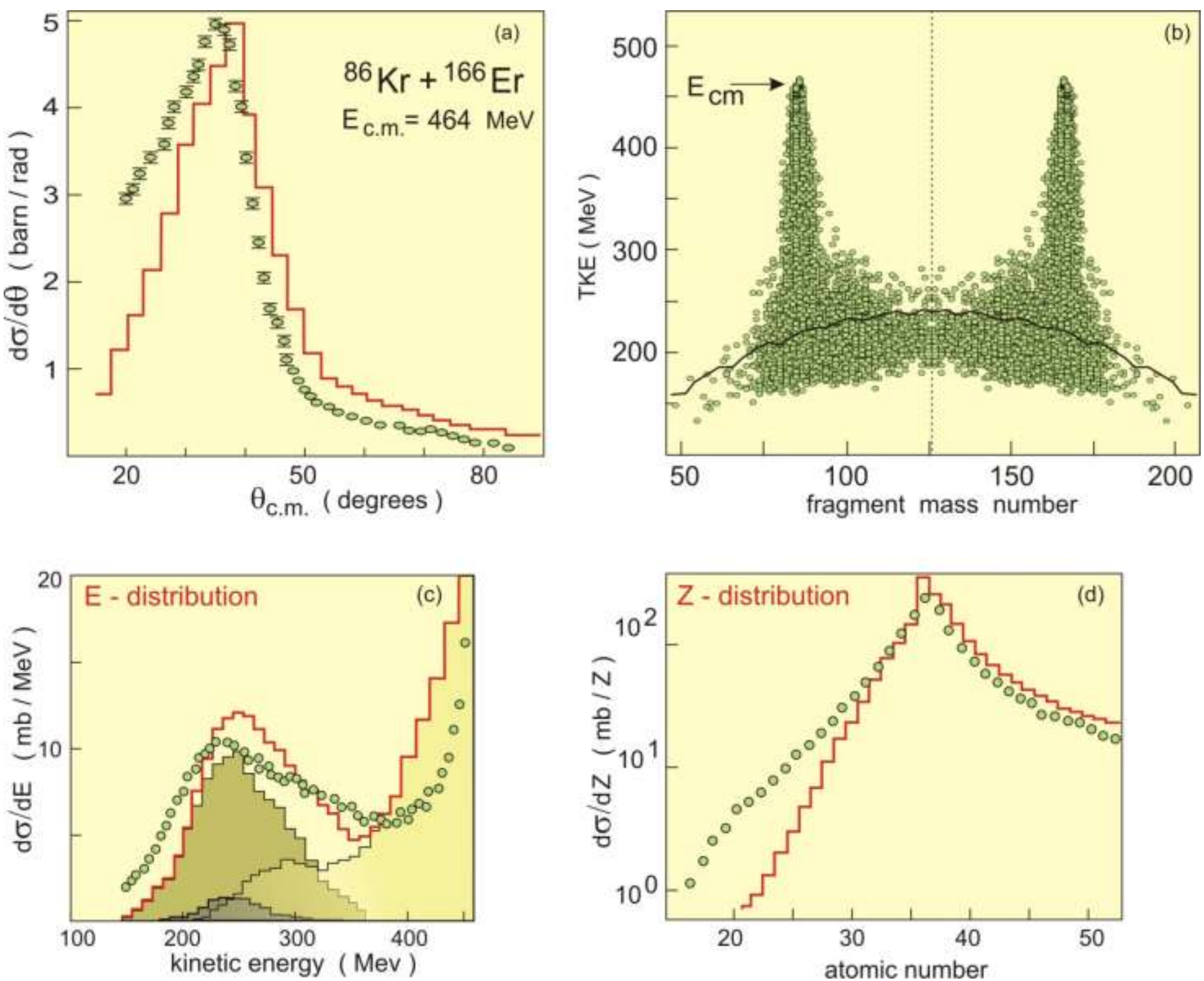
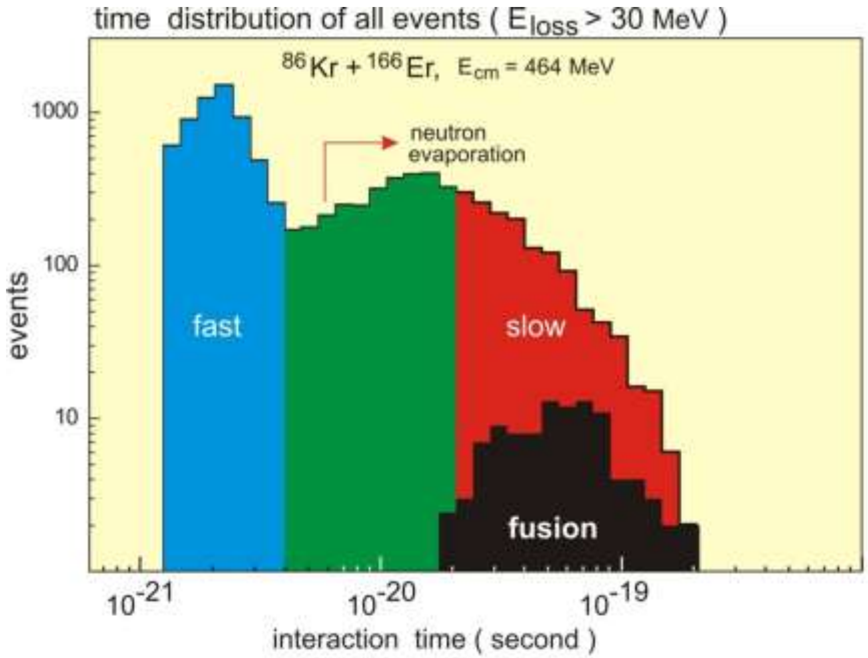
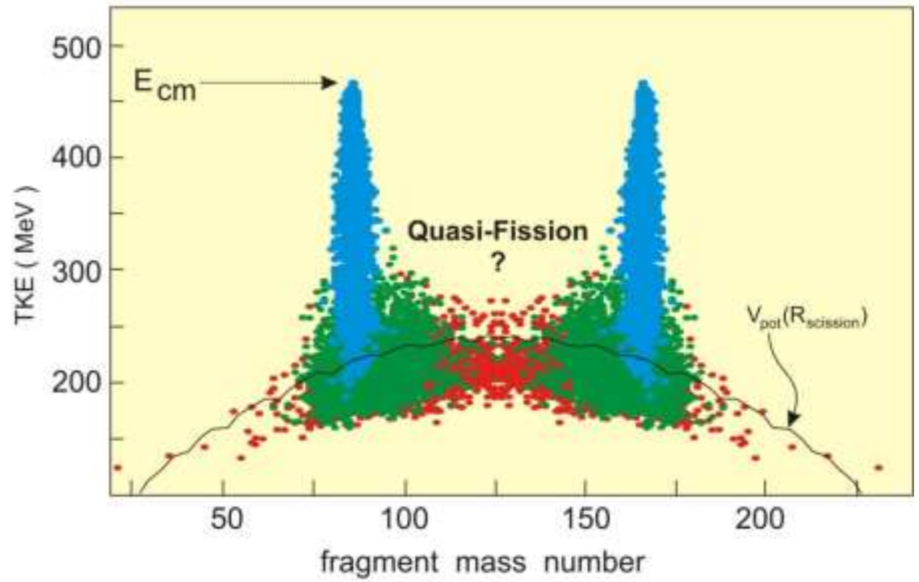
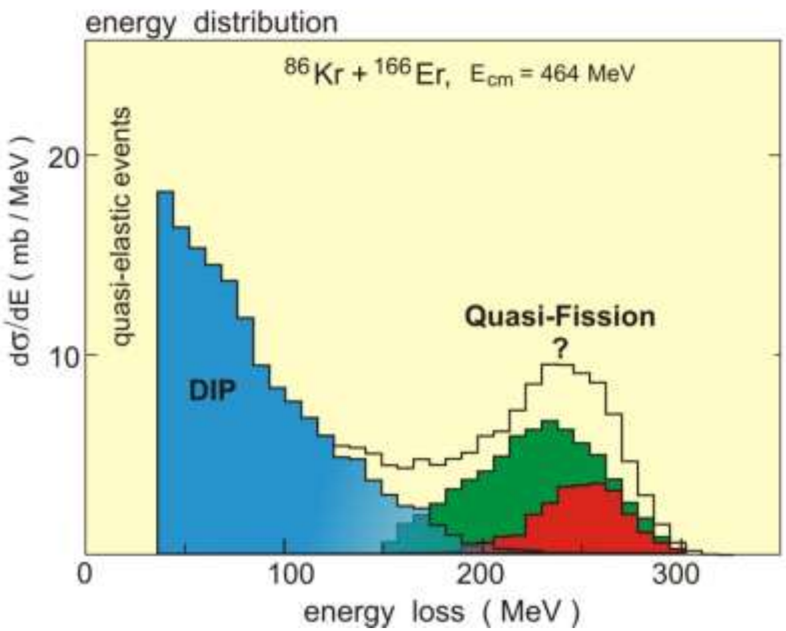
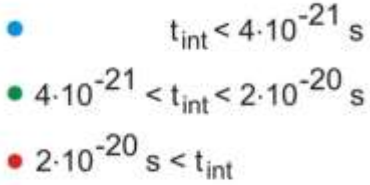


^{86}Kr + ^{166}Er collision at E_{cm} = 464 MeV (time analysis)









What can we learn ?

from comparison with experimental data:

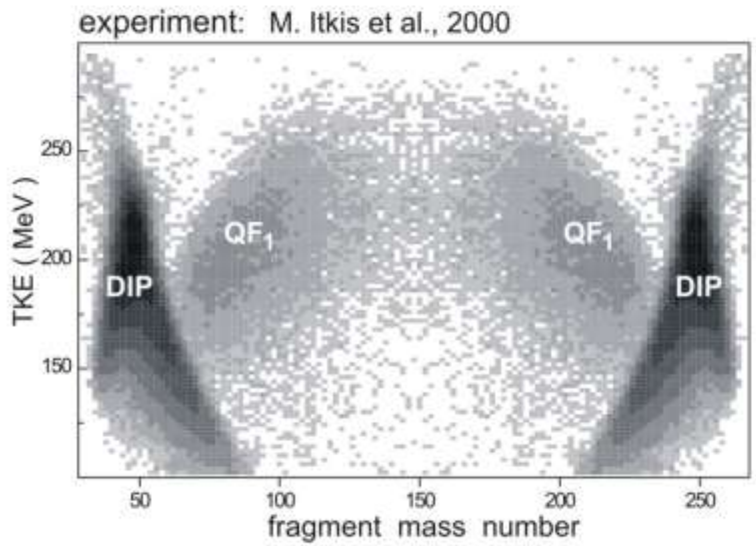
nuclear viscosity $\mu_0 \sim \mathbf{1} \div \mathbf{3} \cdot 10^{-22}$ MeV·s·fm^{-3}

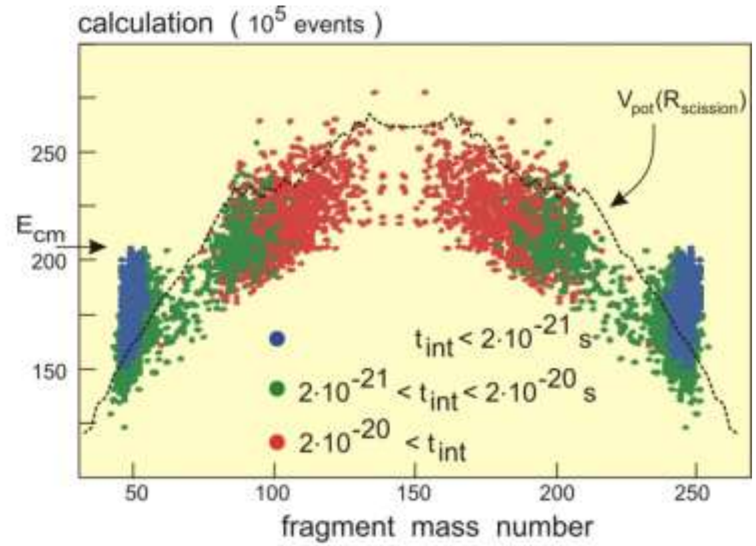
depends on excitation energy (nuclear temperature)

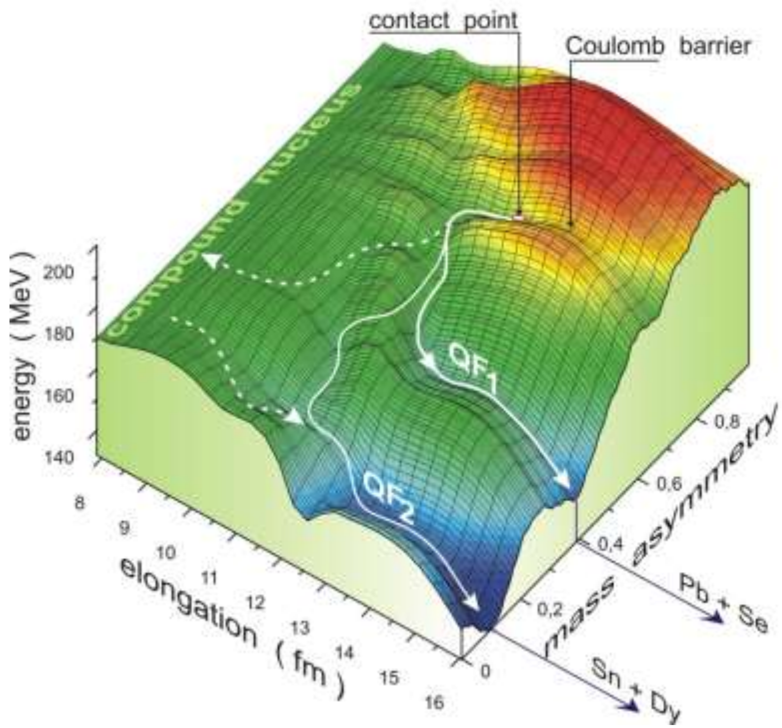
nucleon transfer rate $\lambda_0 \lesssim \mathbf{0.1} \cdot 10^{22}$ s^{-1}

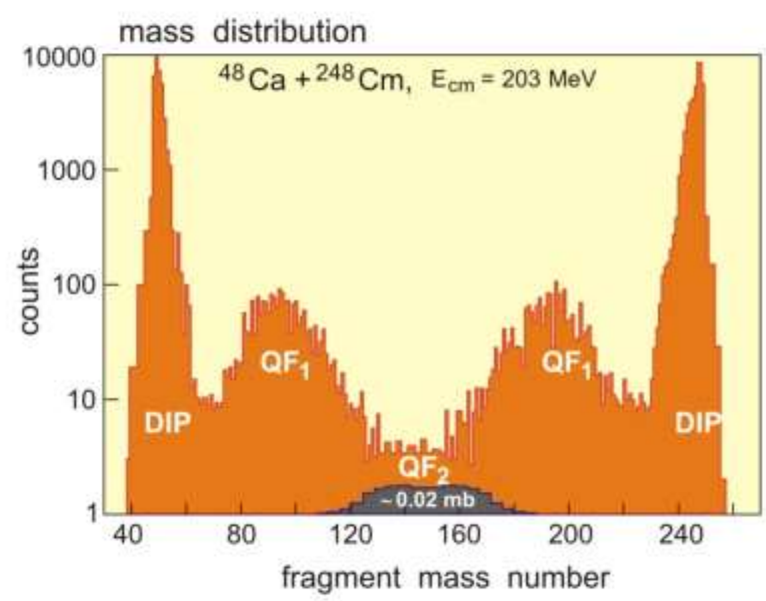
less than those used in "diffusion models"

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

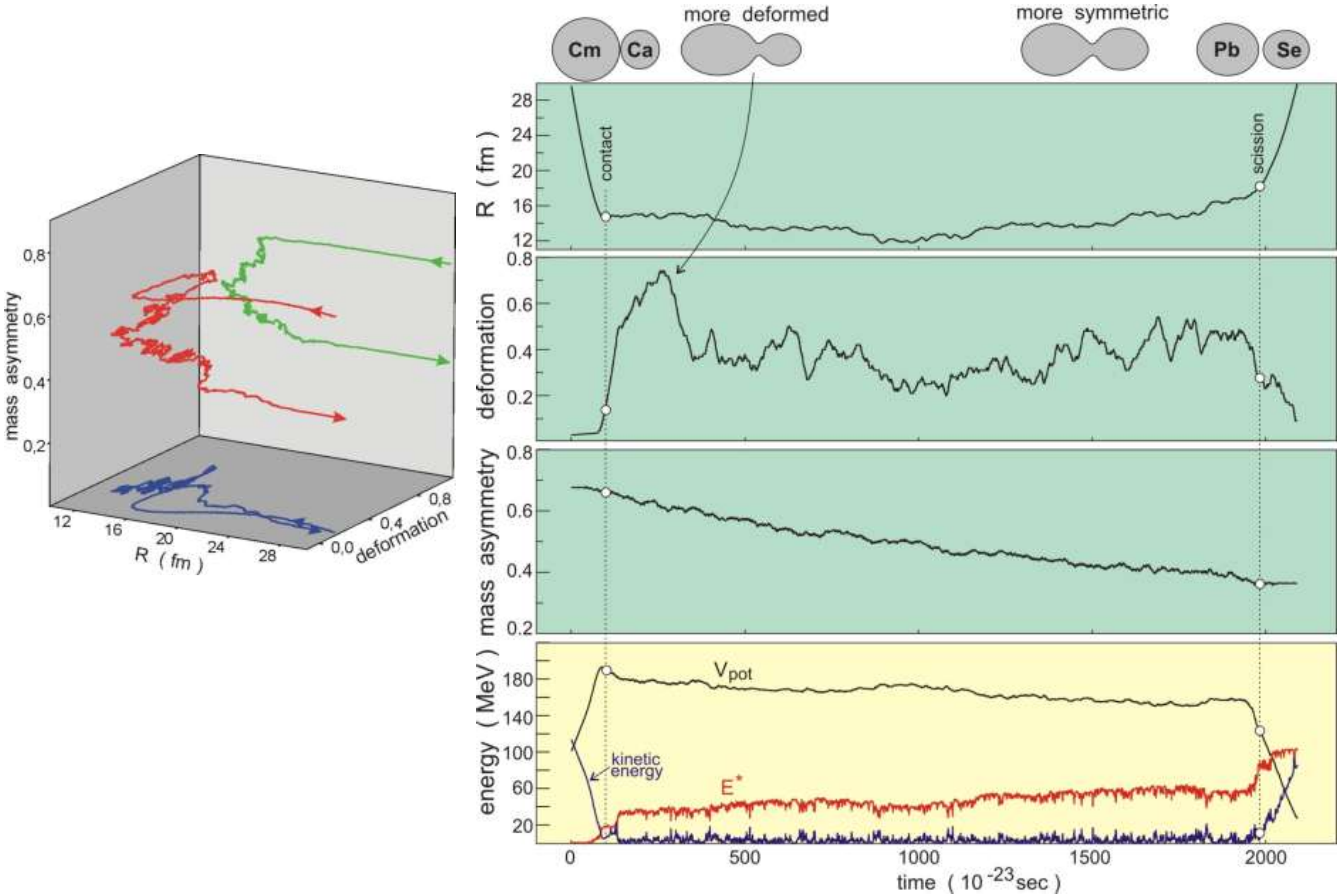






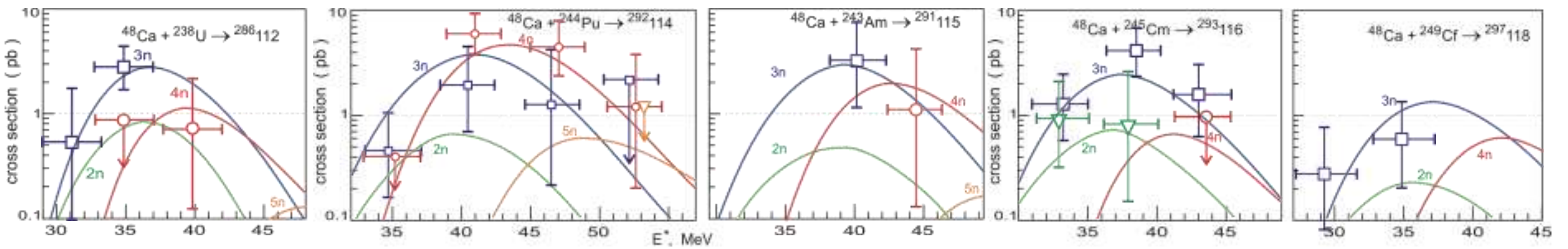


$^{48}Ca + ^{248}Cm$ collision at E_{cm} = 203 MeV (one trajectory)

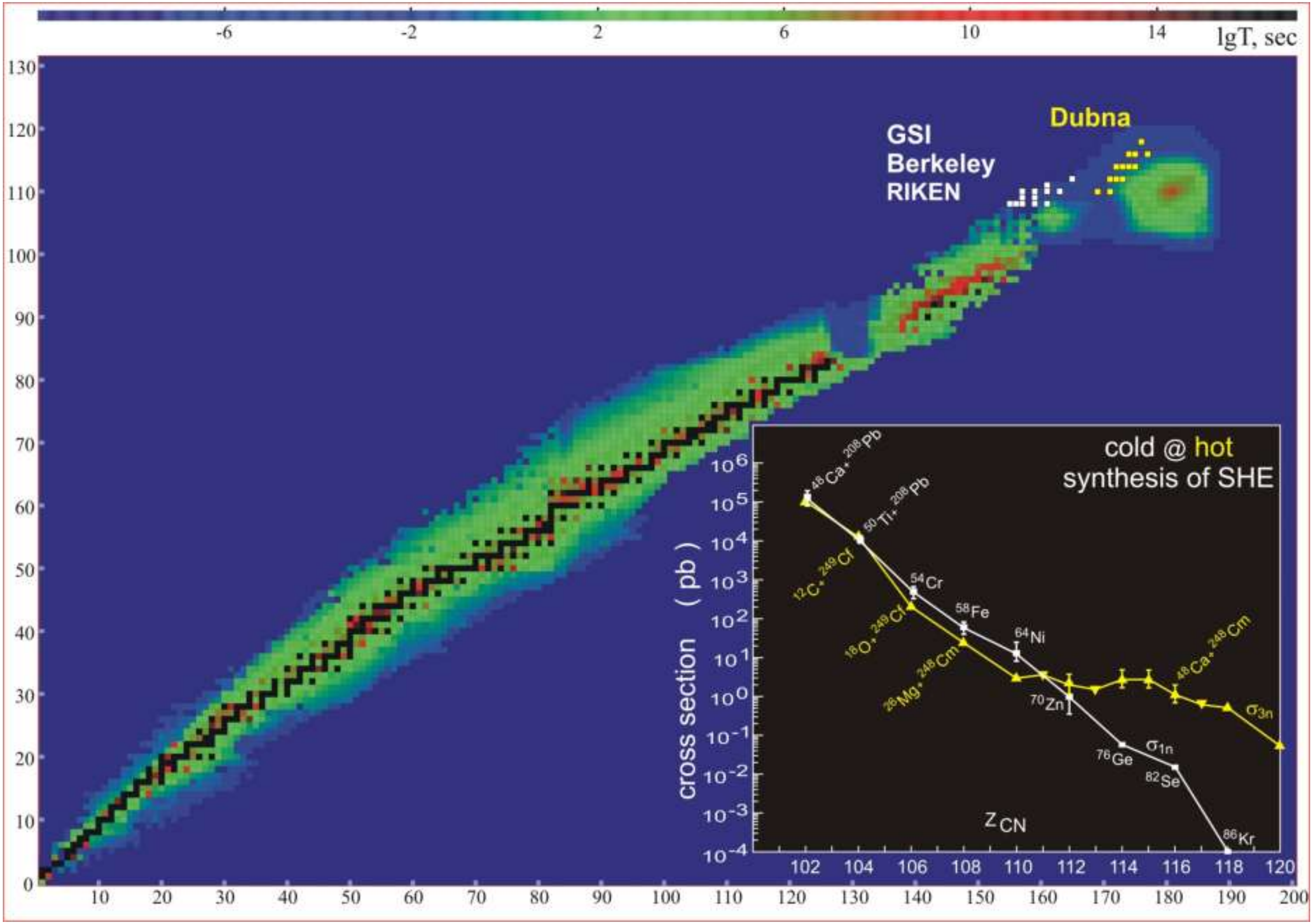


Predictive power of the theory

2003 - 2005 2002 (3n ? 4n ?)

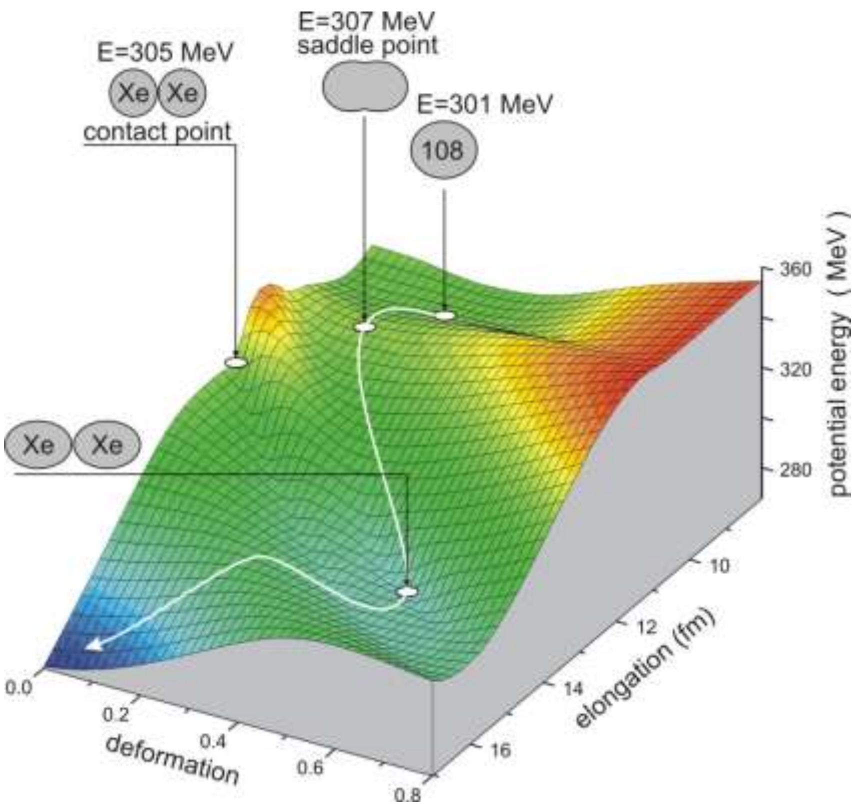


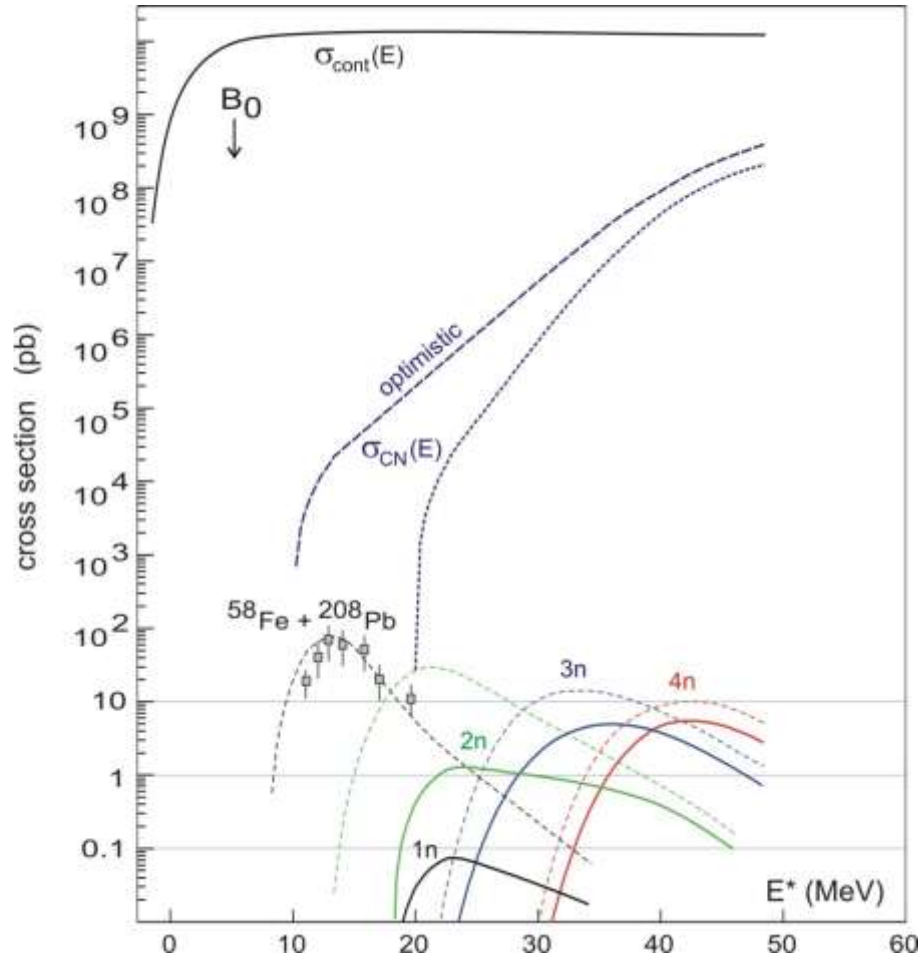
On the way to the first Island of Stability



New ways to the Island of Stability

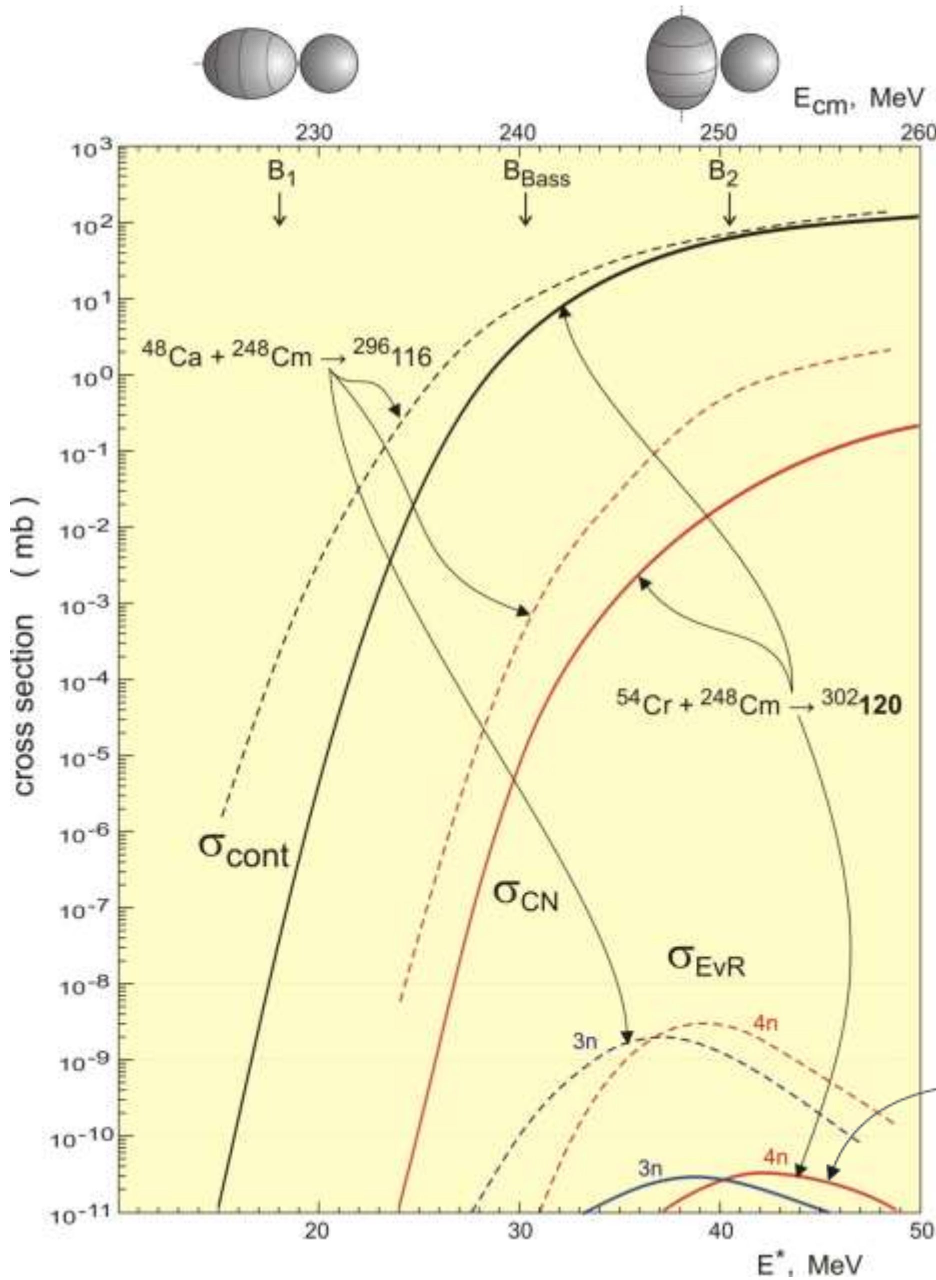
$^{136}Xe + ^{136}Xe \rightarrow ^{272}108$



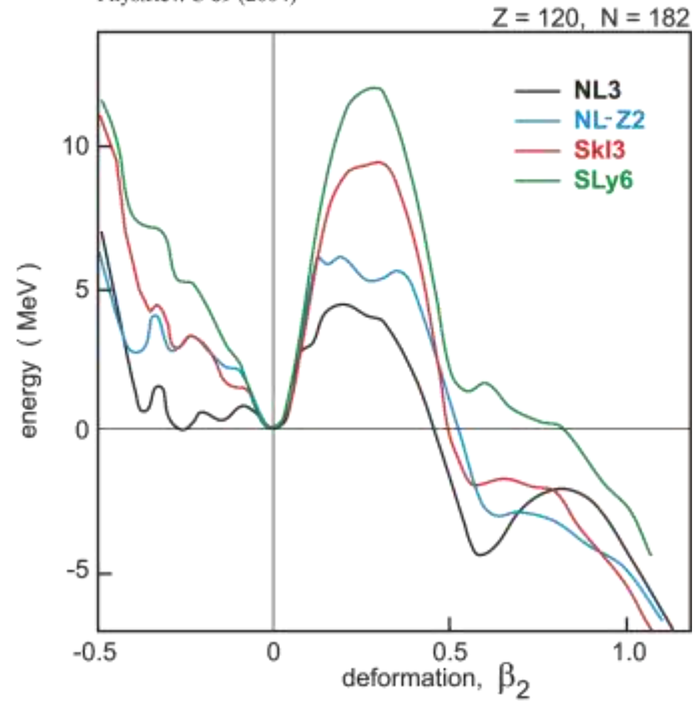


if OK then $^{132}Sn + ^{176}Yb \rightarrow ^{308}120$

Synthesis of 120: $^{54}Cr + ^{248}Cm \rightarrow ^{302}120$ or $^{64}Ni + ^{238}U \rightarrow ^{302}120$



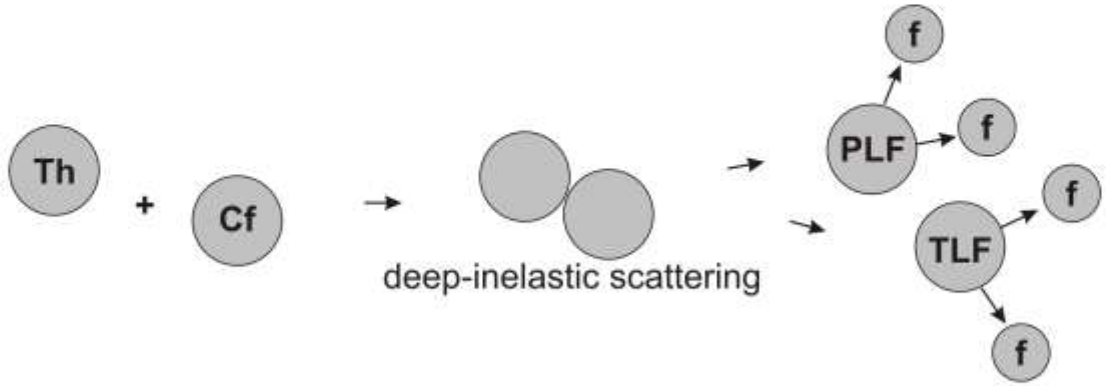
T. Bürvenich, M. Bender, A. Maruhn, and P.-G. Reinhard, Phys.Rev. C **69** (2004)

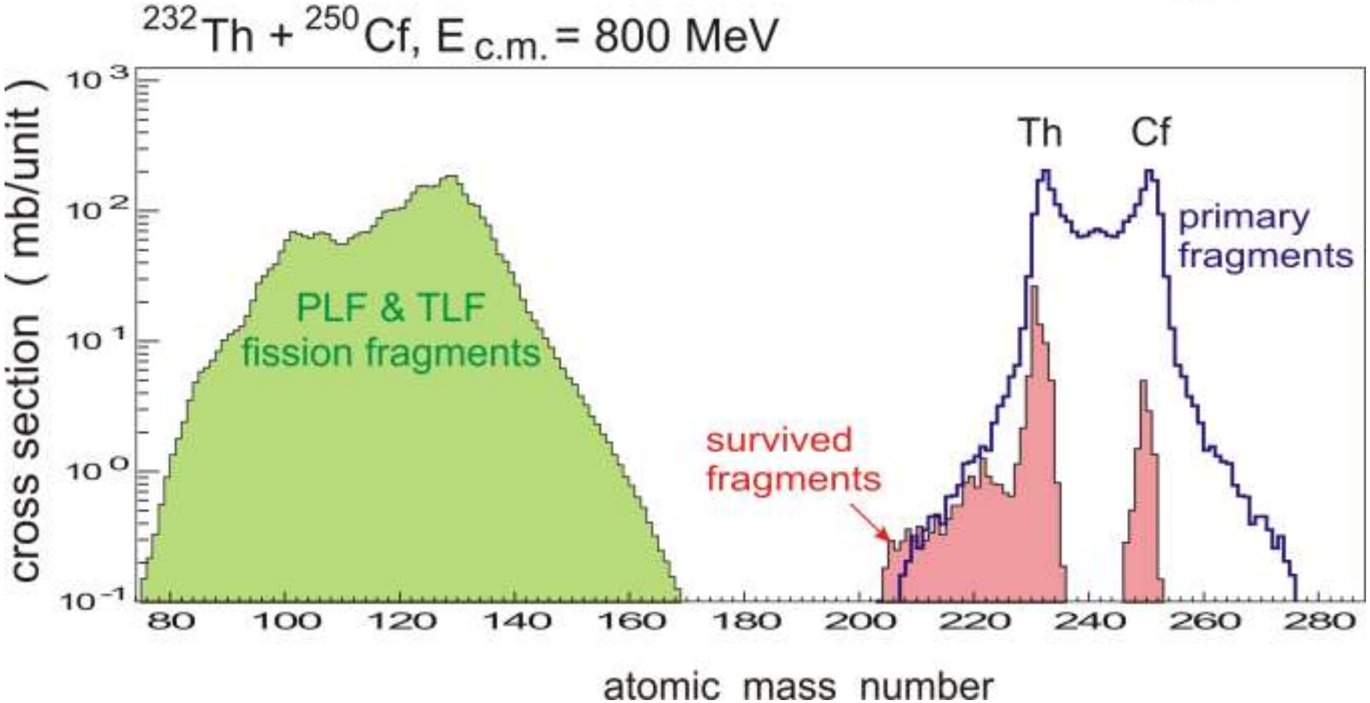


Fission barriers of ^{302}**120**

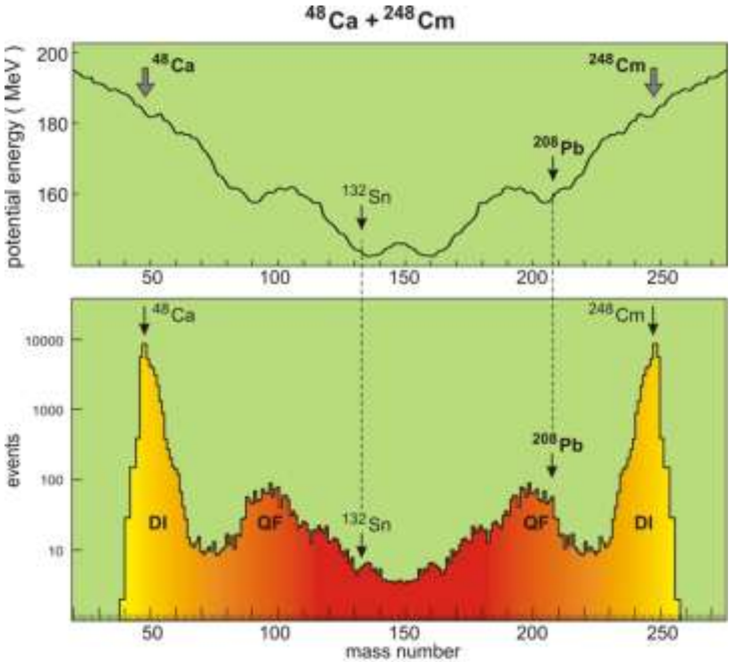
B_{fis}, MeV	Model
~ **6**	A. Sobiscewski
~ **7**	P. Möller et al.
~ **6**	RMF
~ **11**	SkHF

Collision of very heavy (transactinide) nuclei

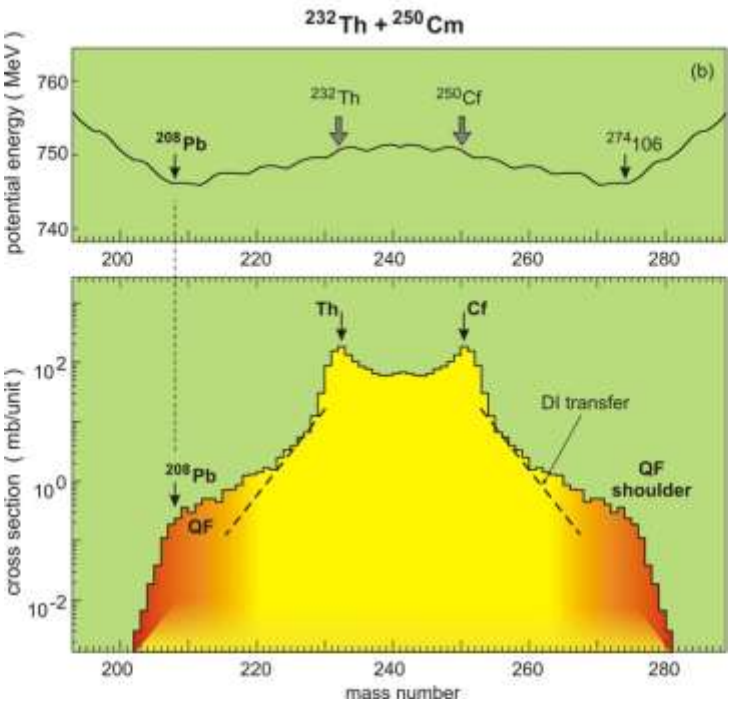




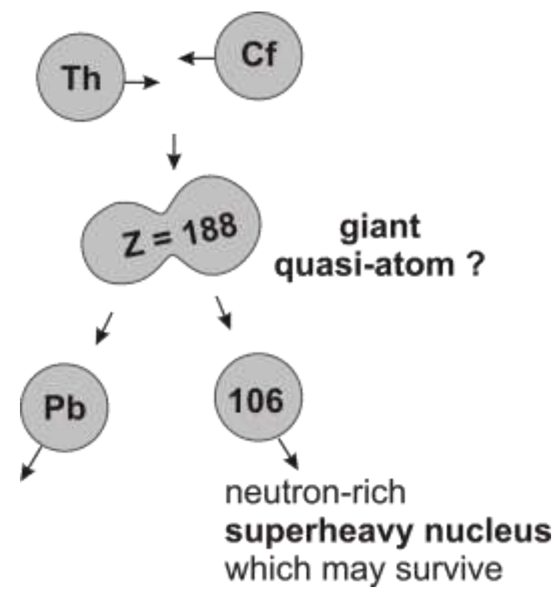
Production of neutron-rich superheavy nuclei and giant quasi-atoms



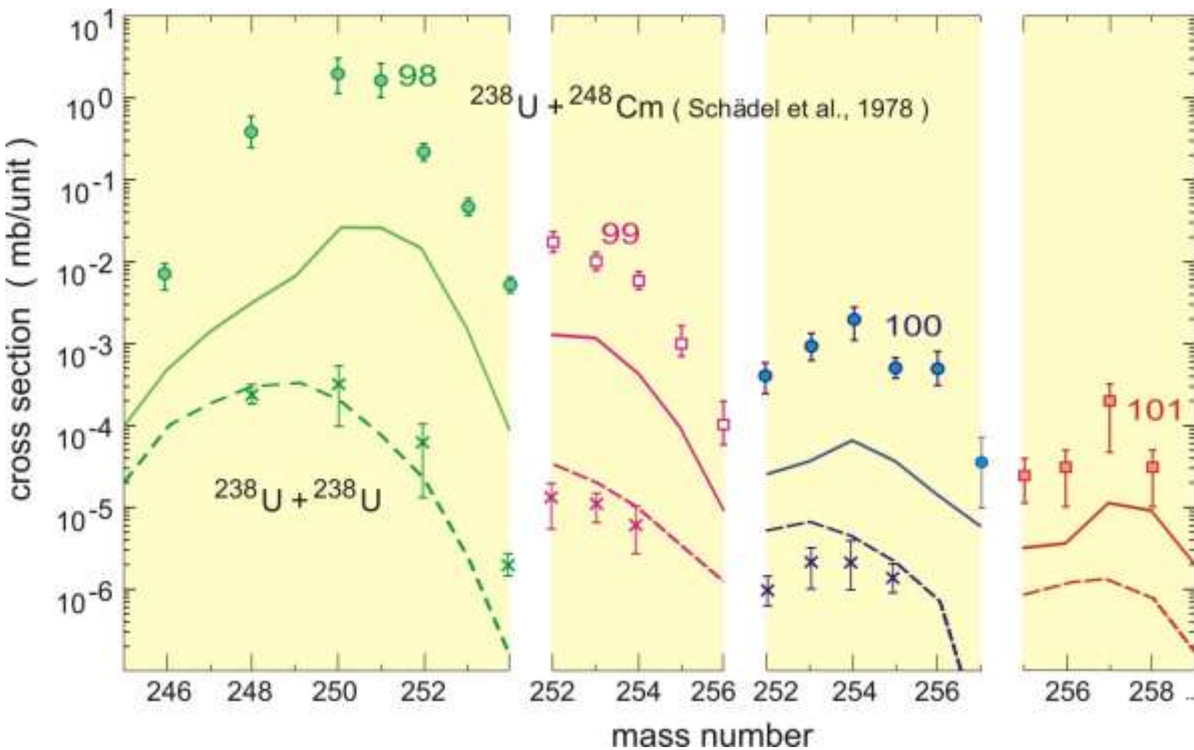
normal
(symmetrizing)
quasi-fission

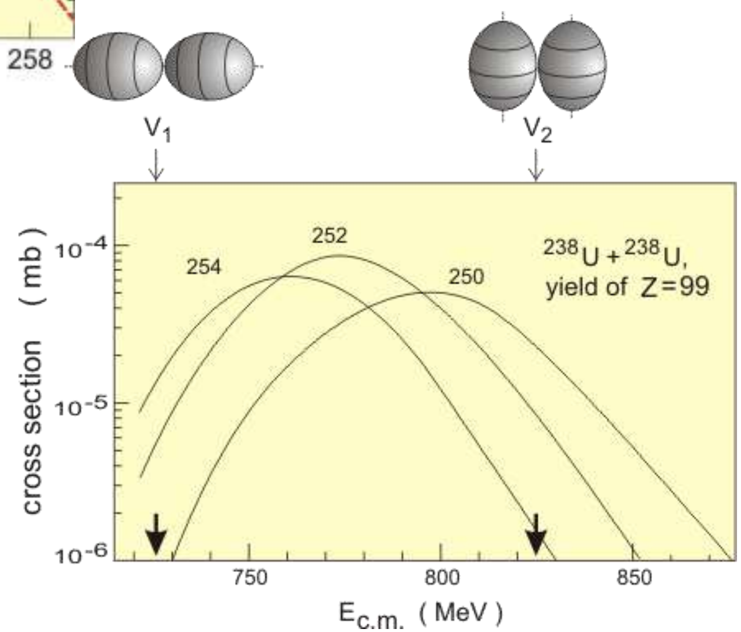


"inverse"
(antisymmetrizing)
quasi-fission

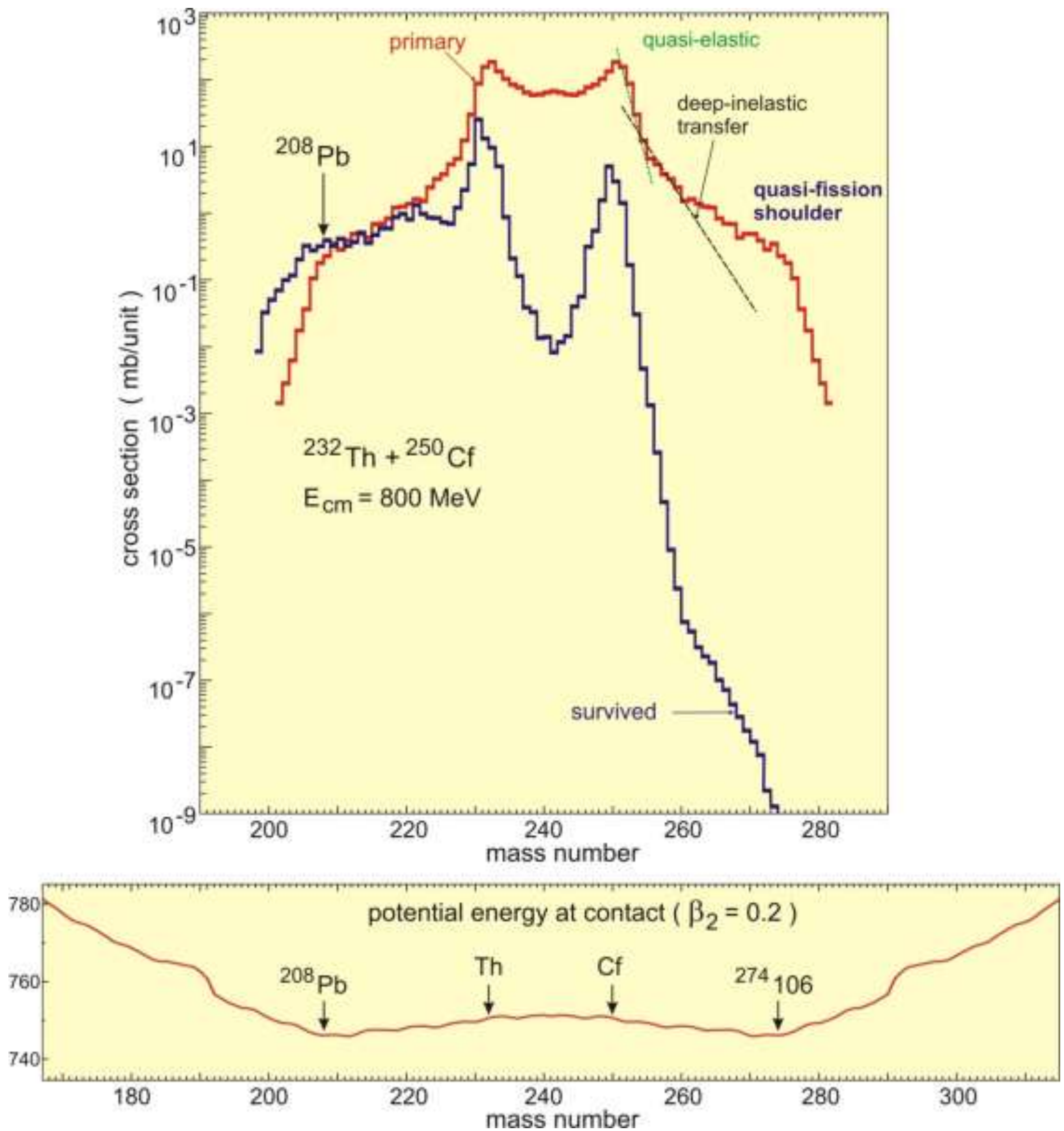


Comparison with available experimental data

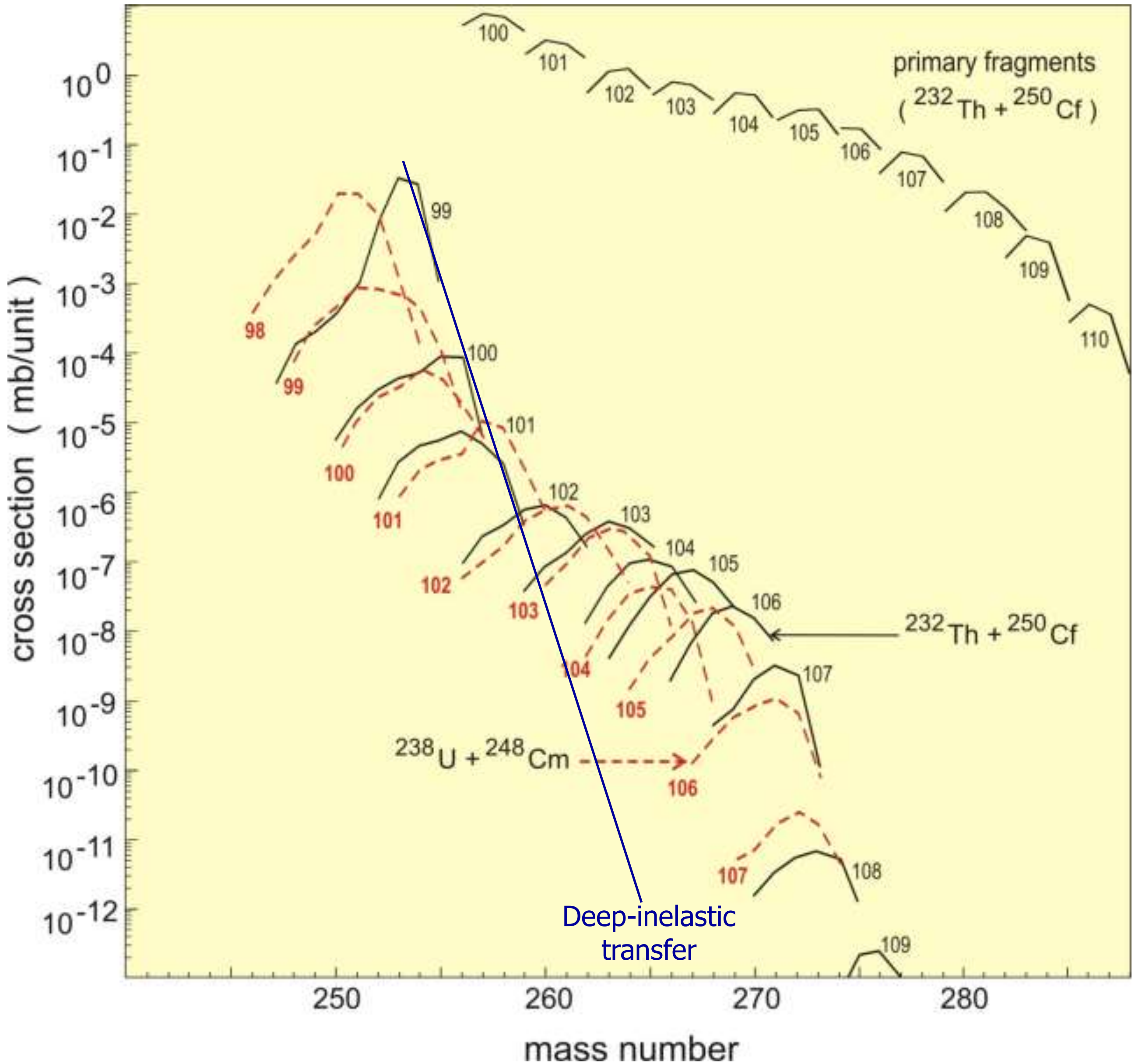




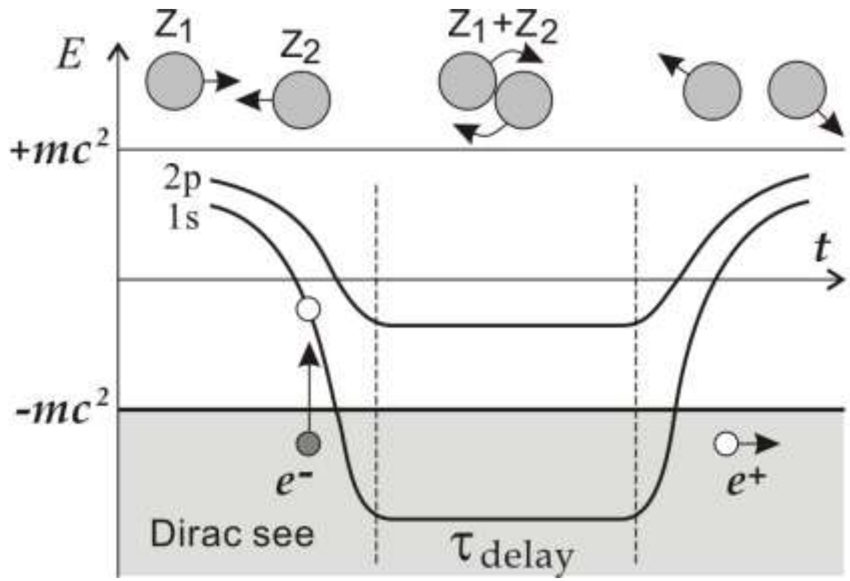
Deep-Inelastic and Quasi-Fission processes in very-heavy-ion damped collisions

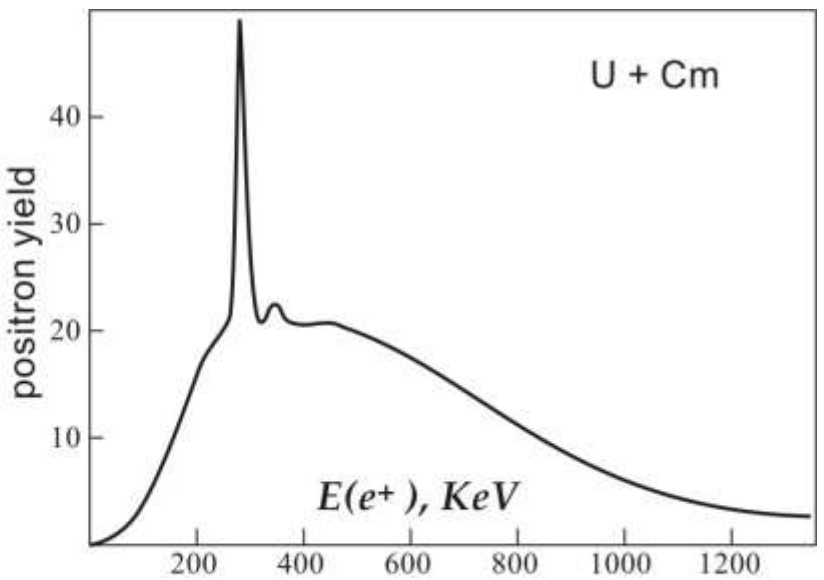


Isotopic yield of SHE in very-heavy-ion damped collisions



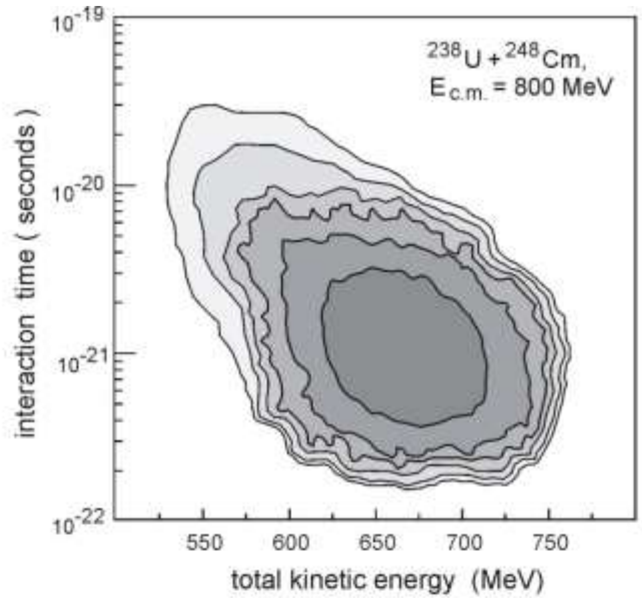
Spontaneous positron formation: fundamental QED process

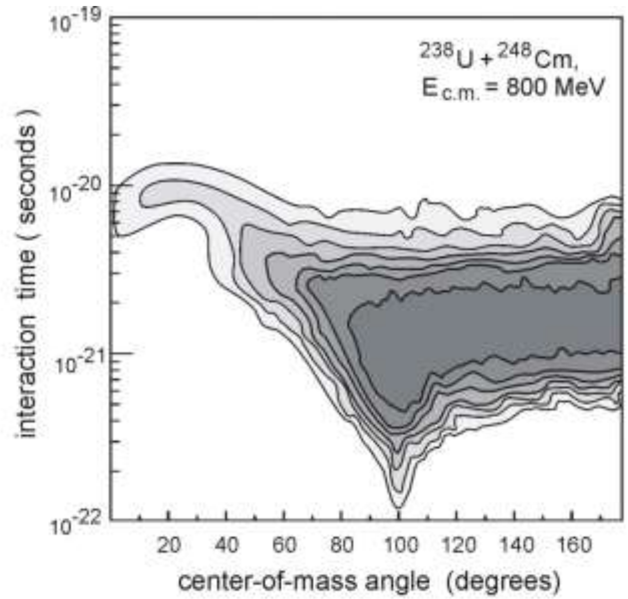


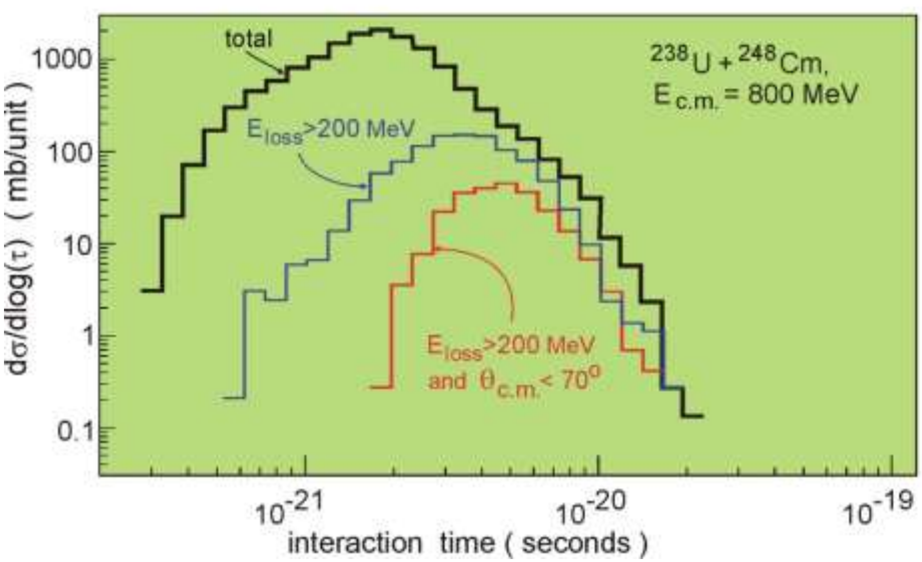


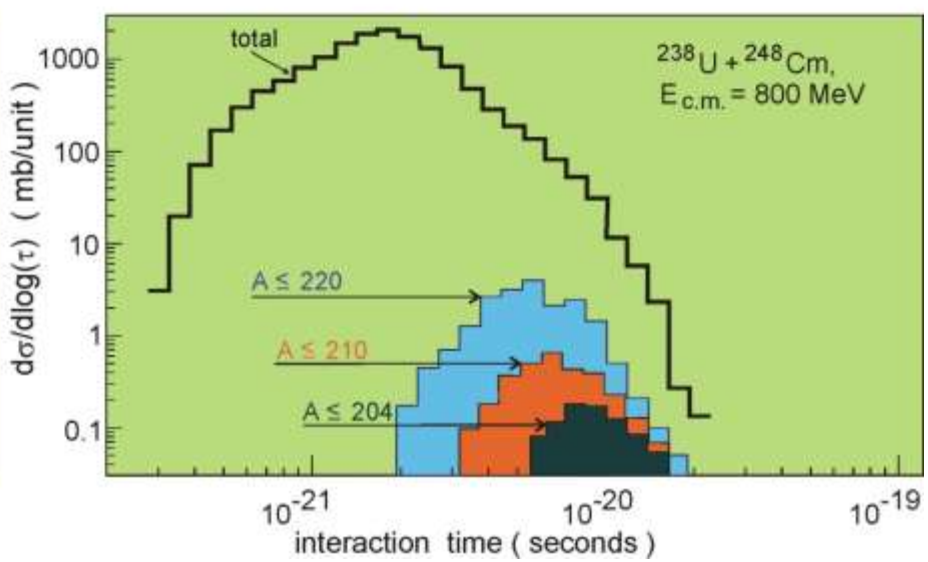
Greiner, Reinhard, 1981

What are the triggers for long reaction time ?









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.

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. Accurate estimations of the probabilities for **super-heavy element formation** can be obtained now.

Low energy collisions of transuranium nuclei:
Production of **long-lived neutron-rich SHE** seems to be quite possible ("inverse quasi-fission" process).
Spontaneous positron emission from a supercritical electric field of giant quasi-atoms.