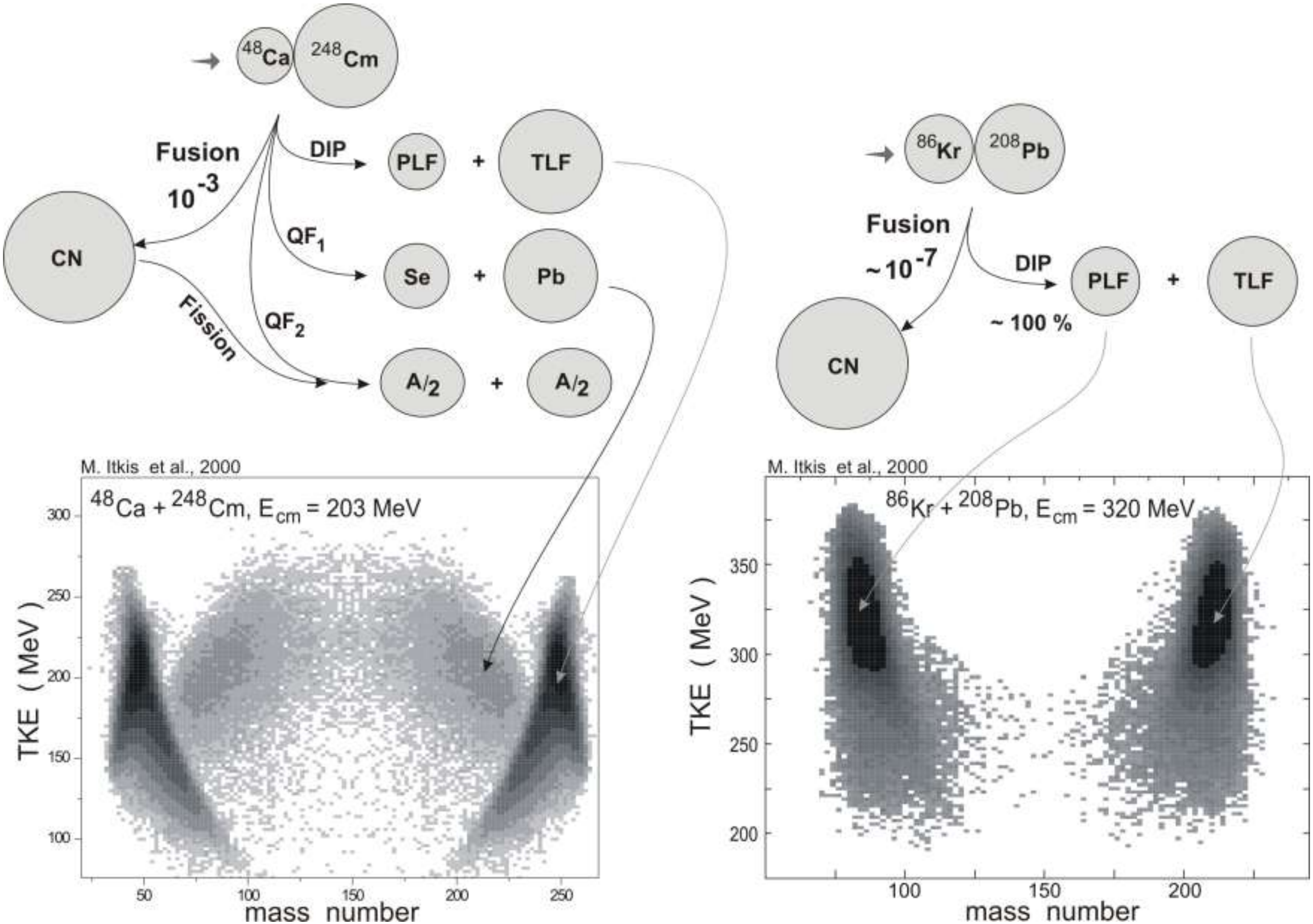
Low-energy fusion-fission dynamics of heavy nuclear systems

Valery Zagrebaev

***JINR** (Dubna)*

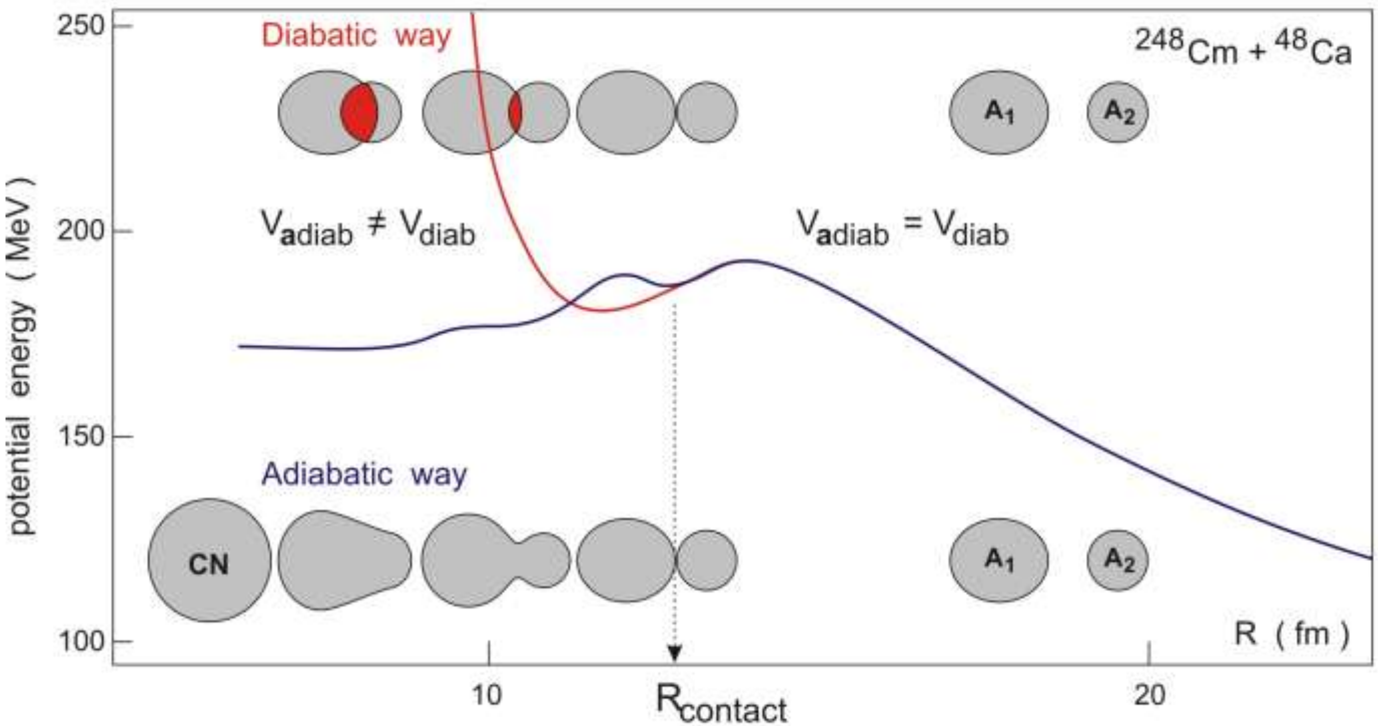
- **Unified description of Deep-Inelastic, Quasi-Fission and Fusion-Fission processes**
- **What can we learn from experiments on Deep-Inelastic scattering ?**
- **Quasi-fission, Fusion and Super-Heavy Element formation**
- **Collisions of very heavy ions (U + Cm, …) at low energies**
- **New experiments scheduled in Dubna for 2006**

Strongly coupled
Deep Inelastic, Quasi-Fission, and Fusion-Fission processes



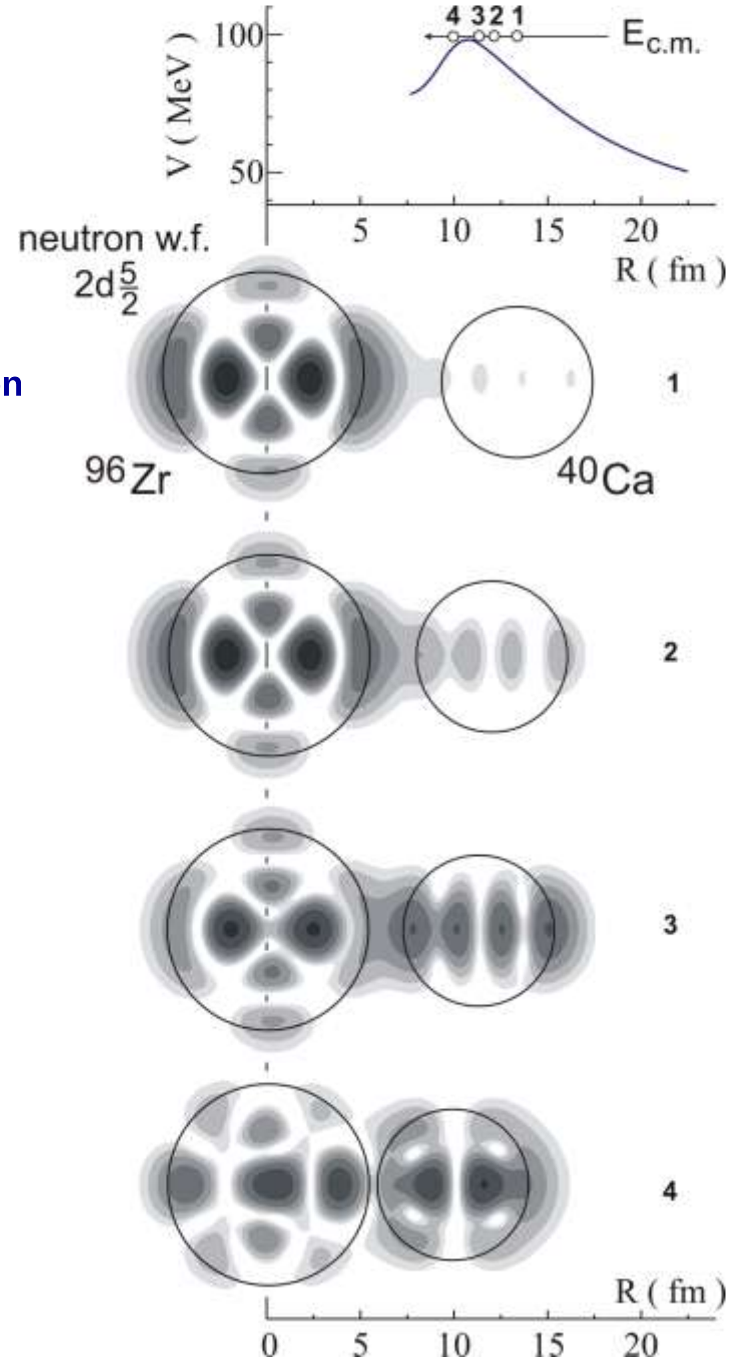
Diabatic and Adiabatic Potential Energy

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



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

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

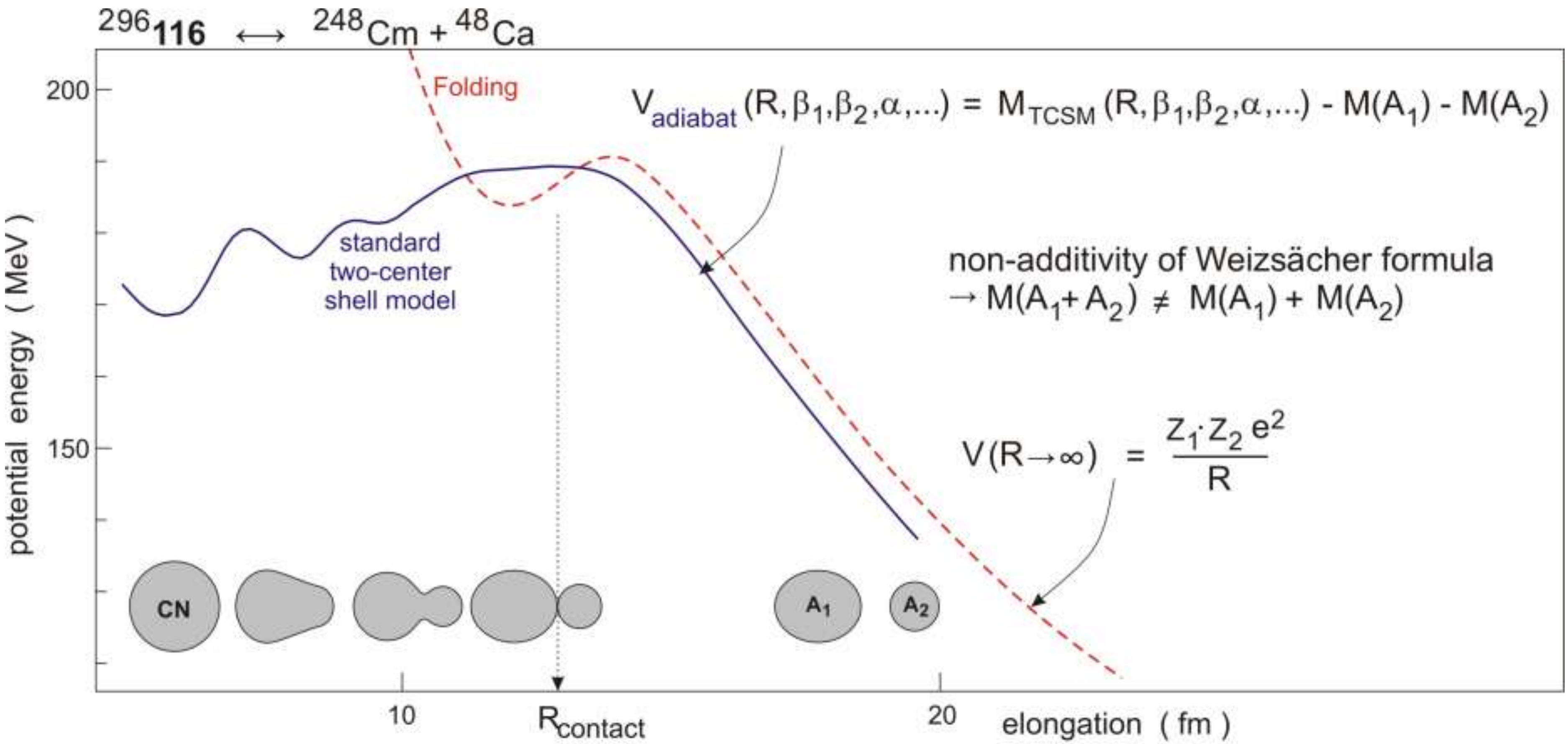


Time-dependent Schrödinger equation for valence neutron wave function

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.

Shortcoming of Macro-Microscopic Potential Energy

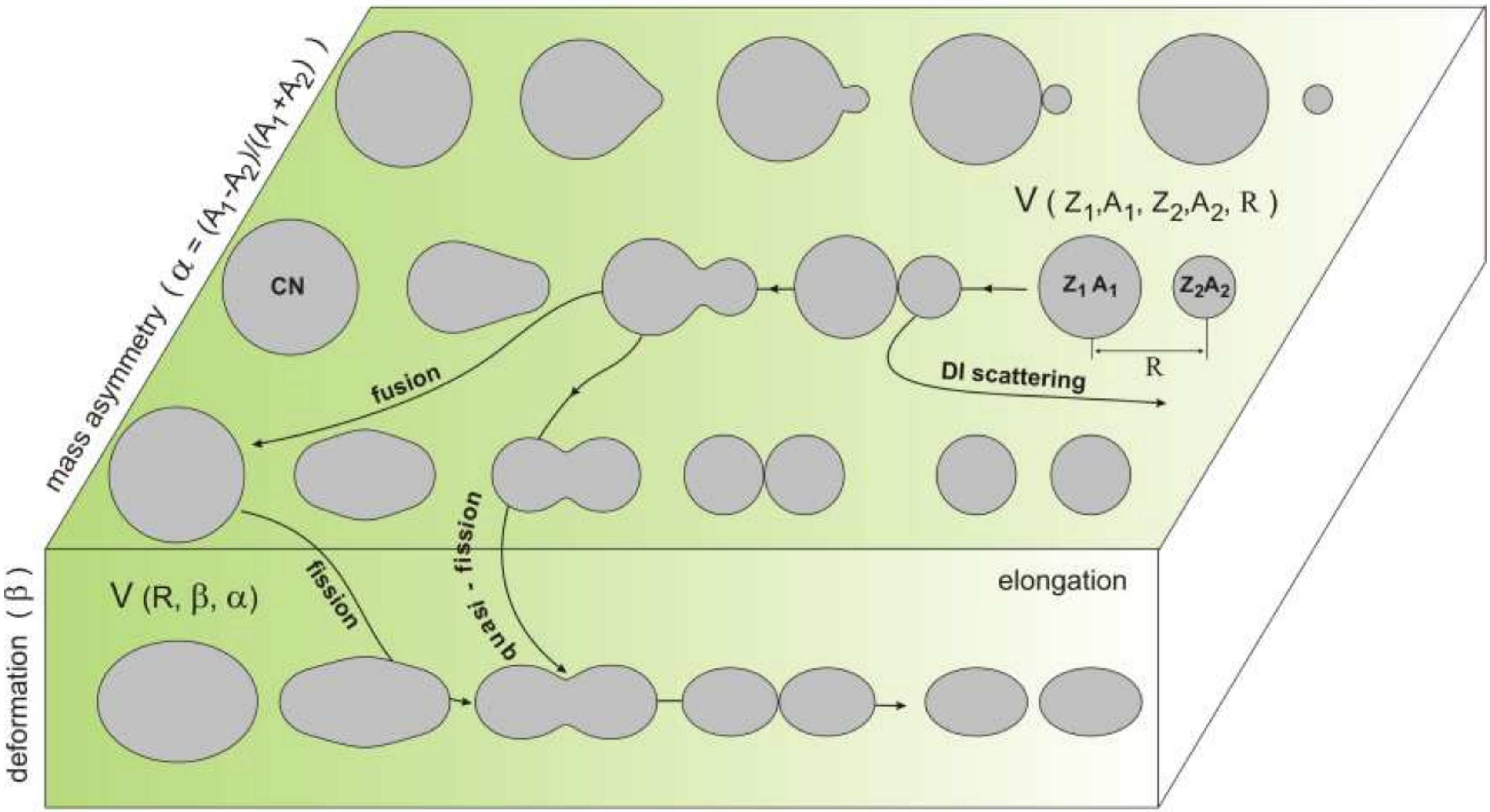


→ **extended two-center shell model** (Zagrebaev, Karpov et al.)

Variables ? Potential Energy ? Equations of Motion ?

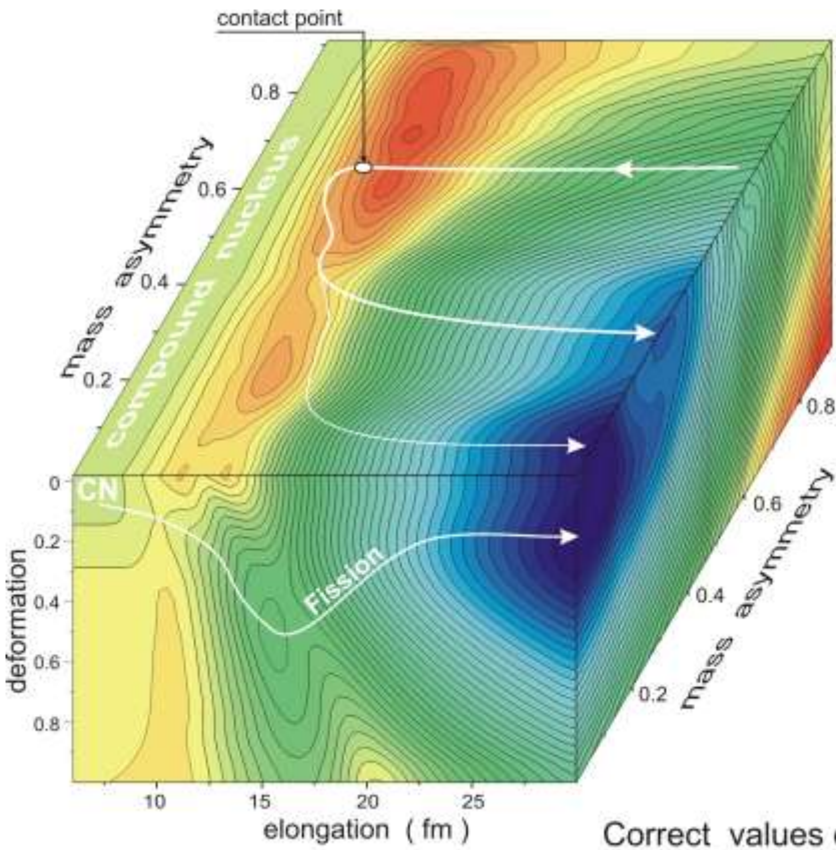
? - principal degrees of freedom: $\{ q_1, q_2, ...\}$,
? - potential energy surface: $V(q_1, q_2, ...)$,
? - dynamic equations of motion: $dq_i / dt = ...$

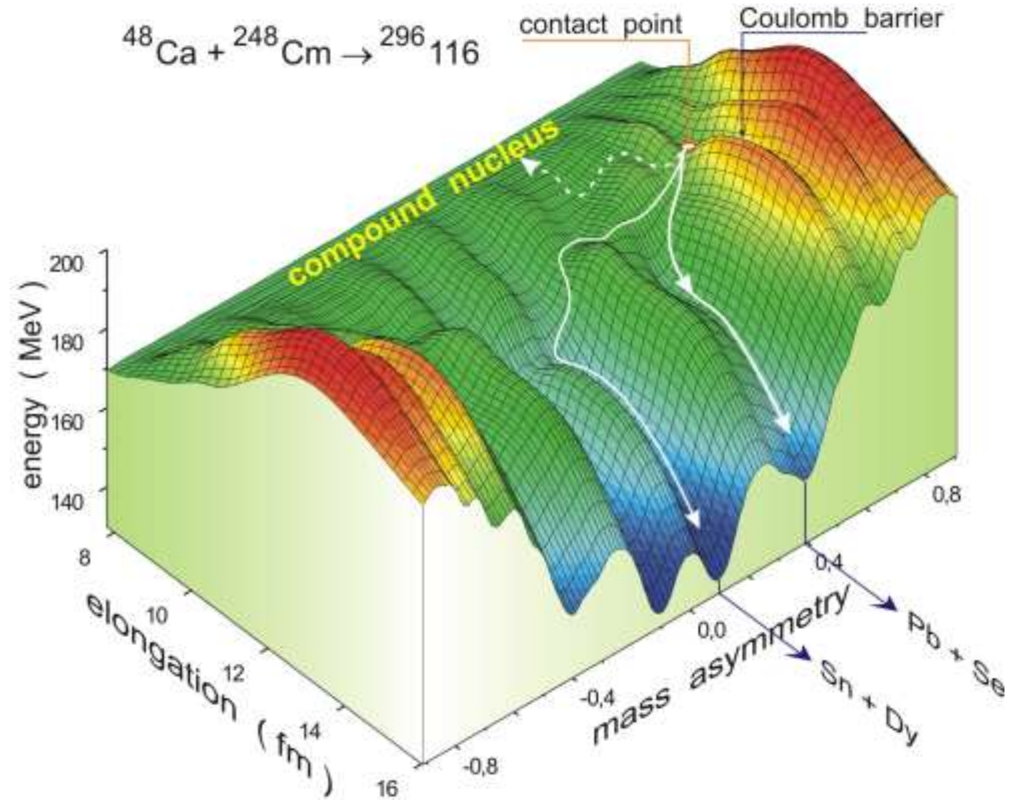
Common (unified) for all the processes:
Deep Inelastic, Quasi-Fission, Fusion-Fission !!!



$V_{adiab} \neq V_{diab}$ $V_{adiab} = V_{diab}$

Potential Energy: Fusion, Fission and Quasi-Fission





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

Equations of Motion. The problem of mass exchange

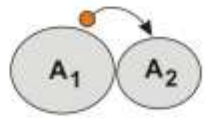
Variables: elongation R
deformations β_1, β_2
mass asymmetry α

Schrödinger, Newtonian, Langevin type

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

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

? mass-asymmetry α:
1) discrete nature
2) $M_\alpha\ (R \geq R_{contact}) \rightarrow \infty$



$A_1 \rightarrow A_1 - 1$
$A_2 \rightarrow A_2 + 1$

(L. Moretto, 1974)
Distribution function $\varphi(A,t)$ → Master equation
$$\frac{\partial \varphi}{\partial t} = \sum_{A'=A\pm 1} \lambda(A' \rightarrow A)\cdot\varphi(A') - \lambda(A \rightarrow A')\cdot\varphi(A)$$

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

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

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

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

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

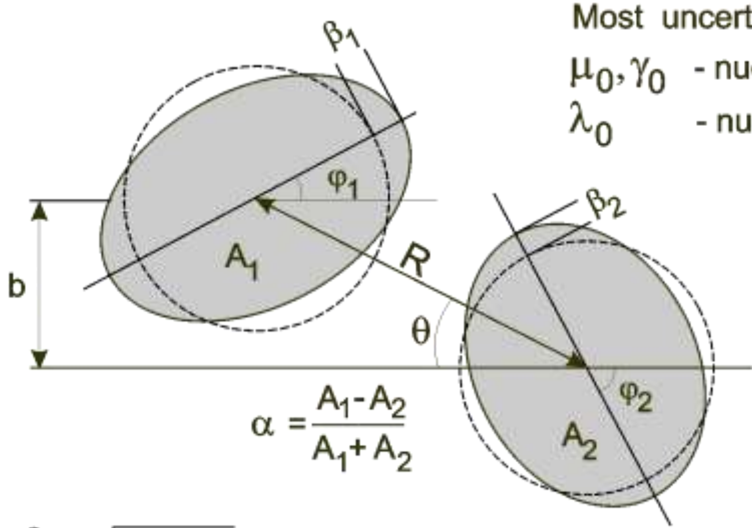
$$D^{(2)} = \frac{1}{2}\int dA'(A' - A)^2\lambda(A \rightarrow A')$$

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

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

The system of coupled Langevin type Equations of Motion

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



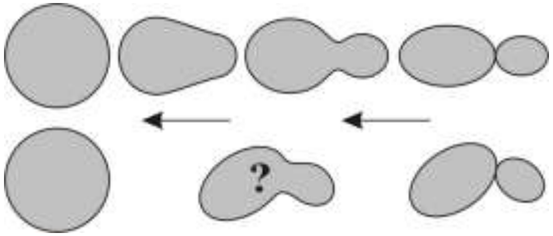
Most uncertain parameters:

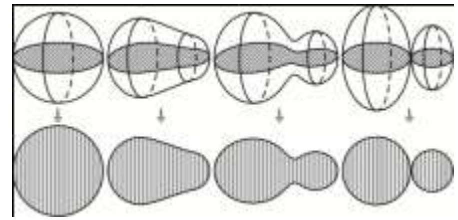
μ_0, γ_0 - nuclear viscosity and friction,

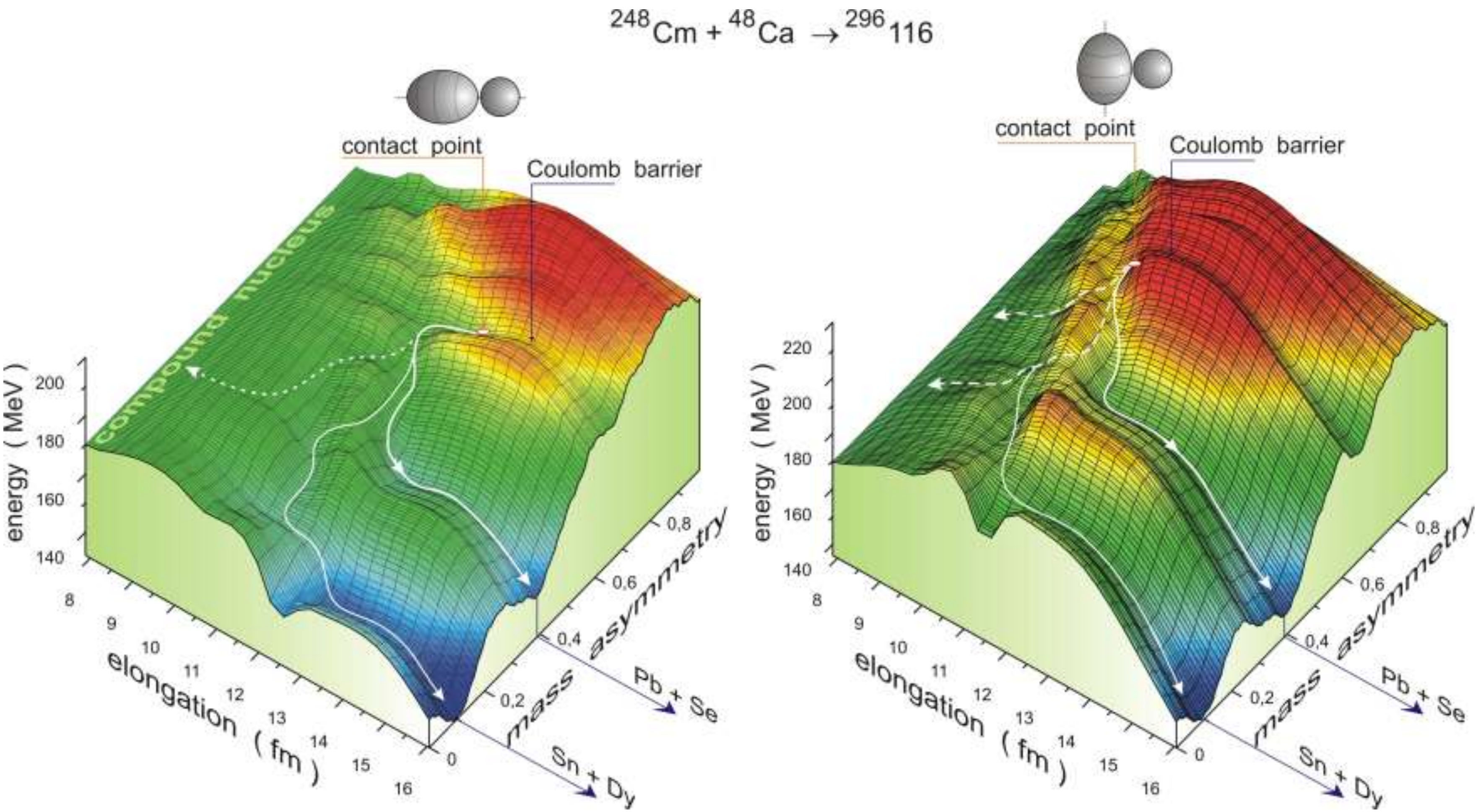
λ_0 - nucleon transfer rate

$$
\begin{aligned}
\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_{\rm 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_{\rm tang} T}\,\Gamma_{\rm tang}(t) \\
\frac{dL_1}{dt} &= -\frac{1}{\hbar}\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}{\hbar}\sqrt{\gamma_{\rm tang} T}\,\Gamma_{\rm tang}(t) \\
\frac{dL_2}{dt} &= -\frac{1}{\hbar}\frac{\partial V}{\partial \varphi_2} + \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_2 - \frac{a_2}{\hbar}\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} + \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).
\end{aligned}
$$

Orientation effects

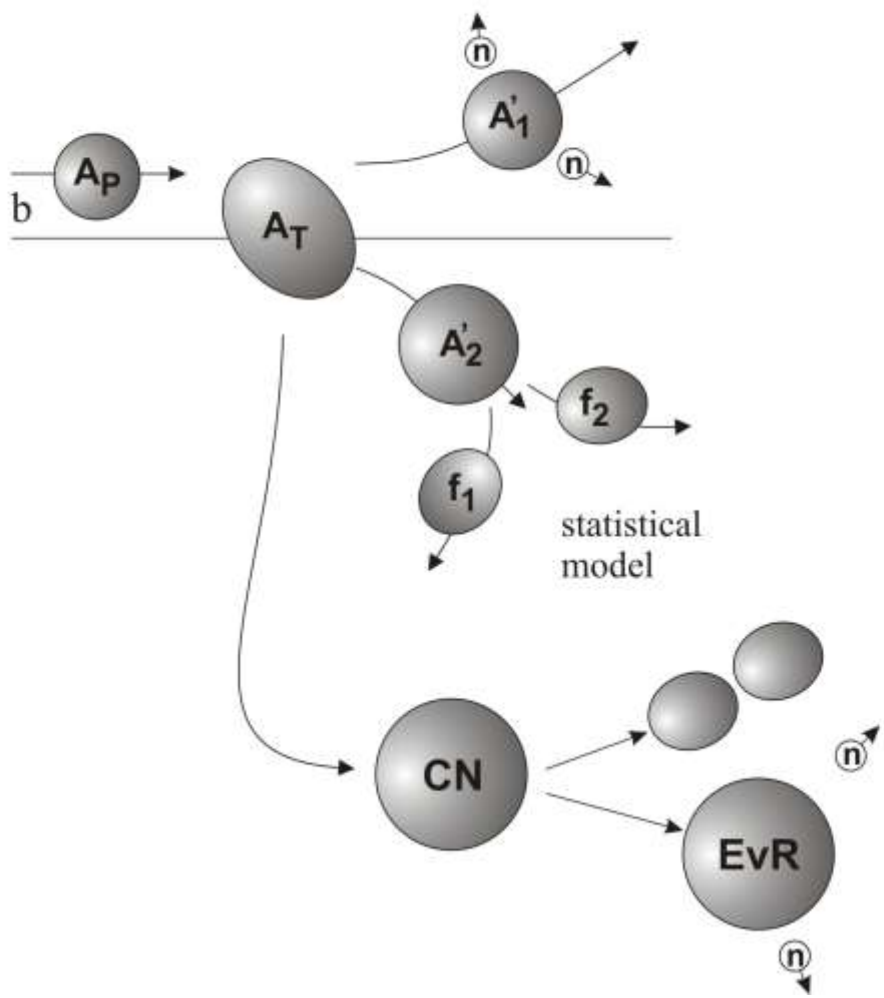






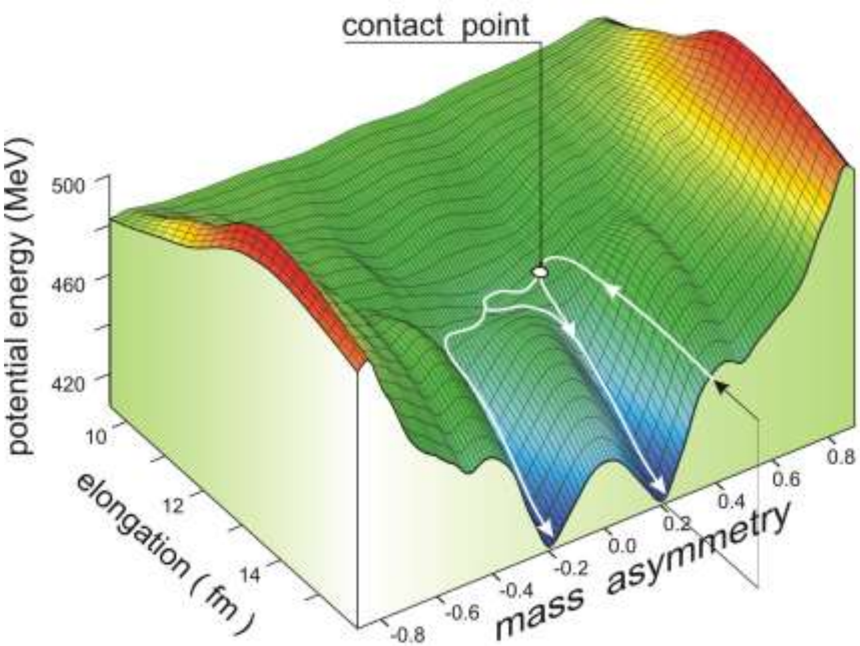
Cross sections and decay of primary fragments

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

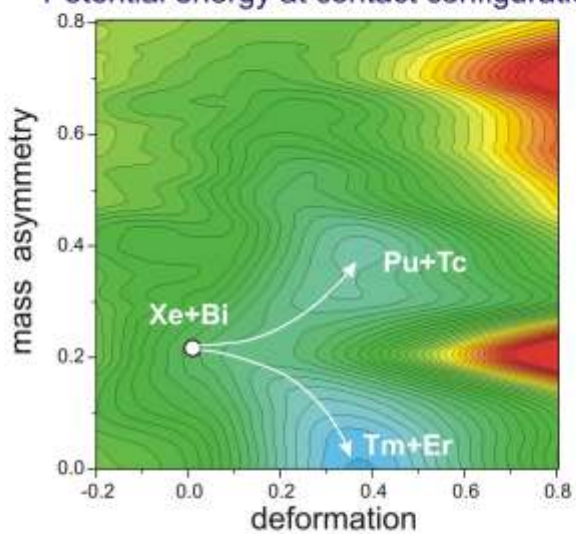


Collisions of heavy nuclei (no CN formation)

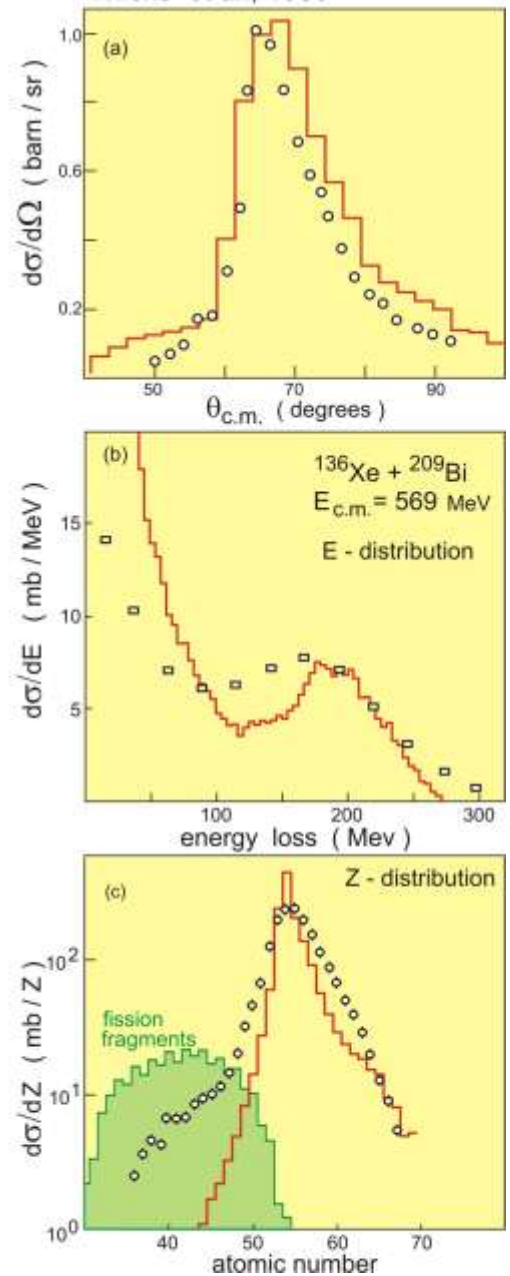
$^{136}Xe + ^{209}Bi \rightarrow ^{345}137$



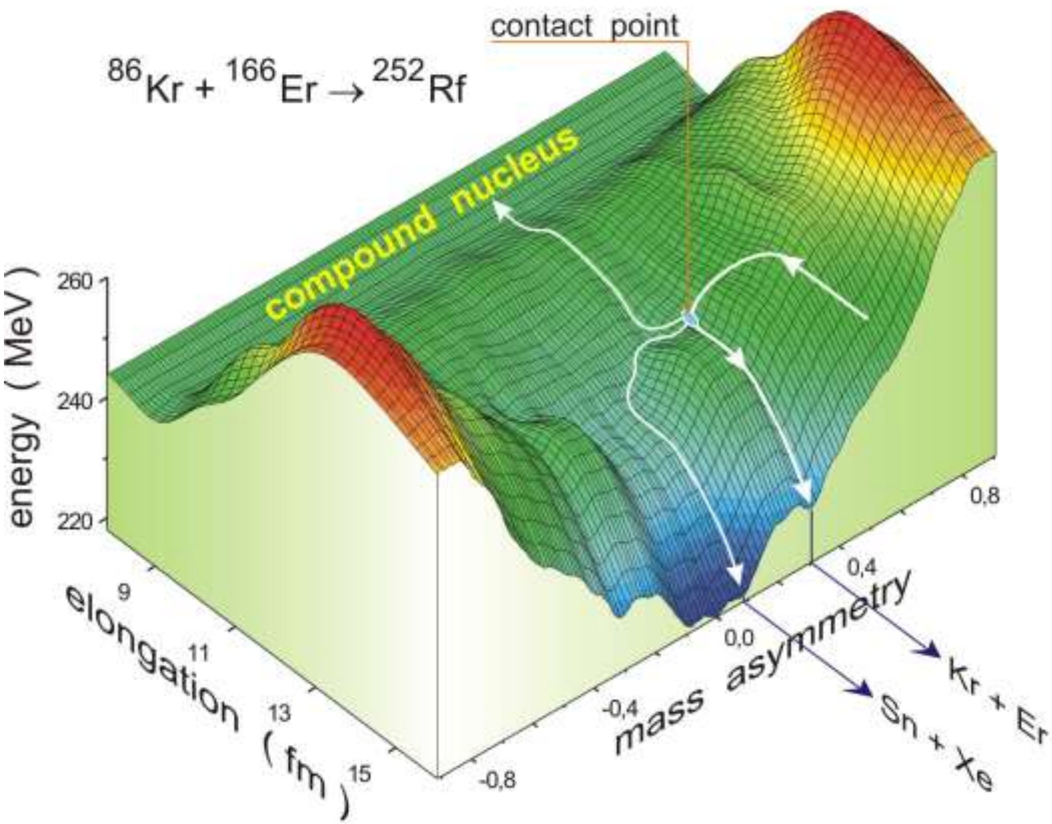
Potential energy at contact configuration

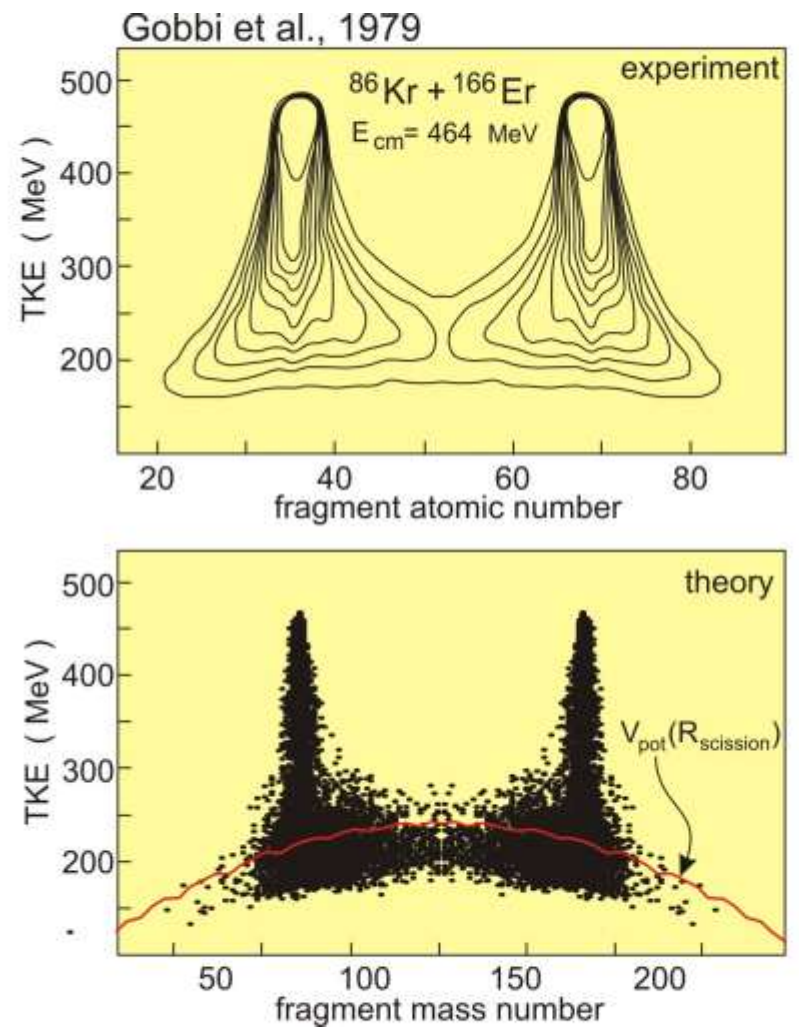


Wilcke *et al.*, 1980



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





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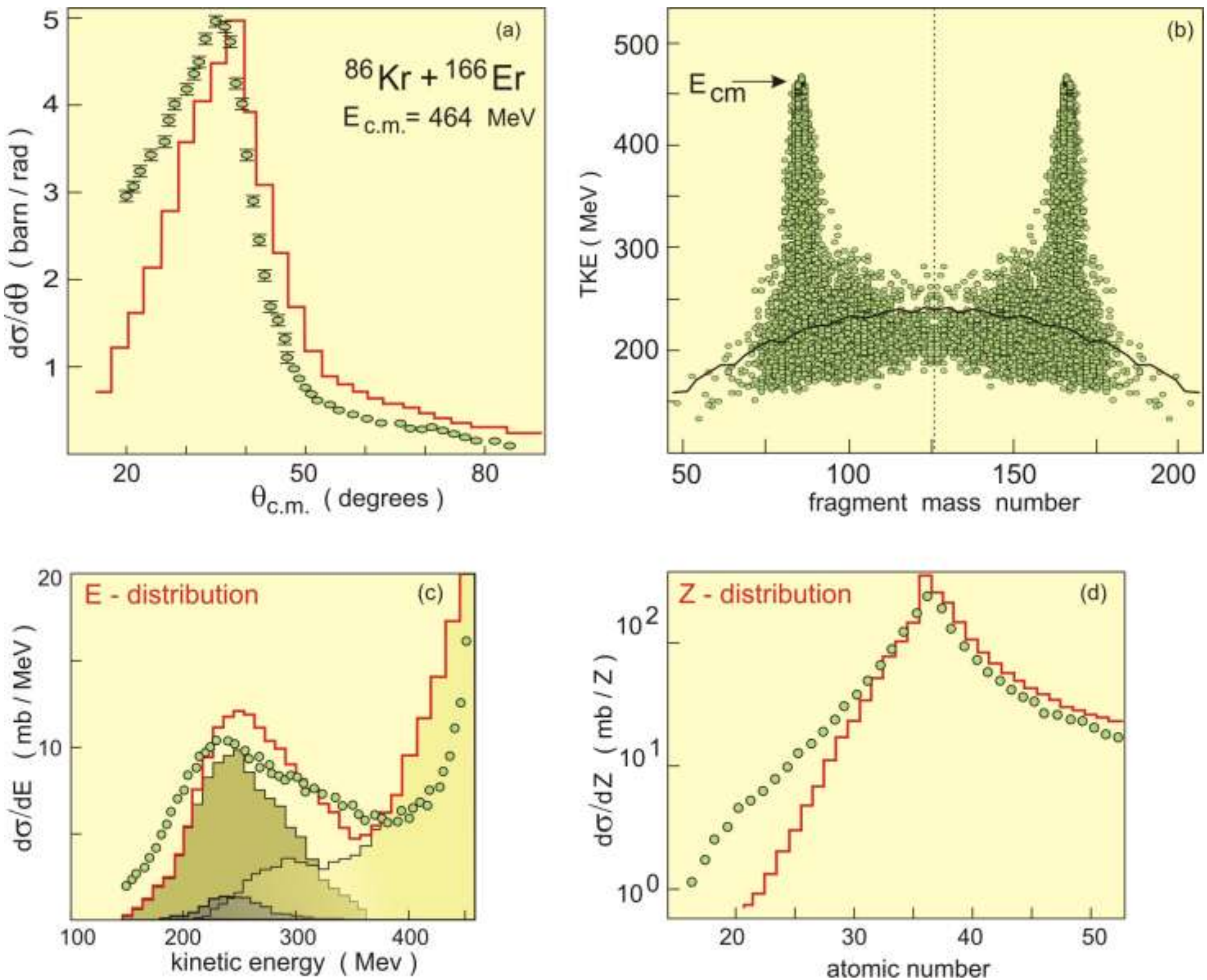
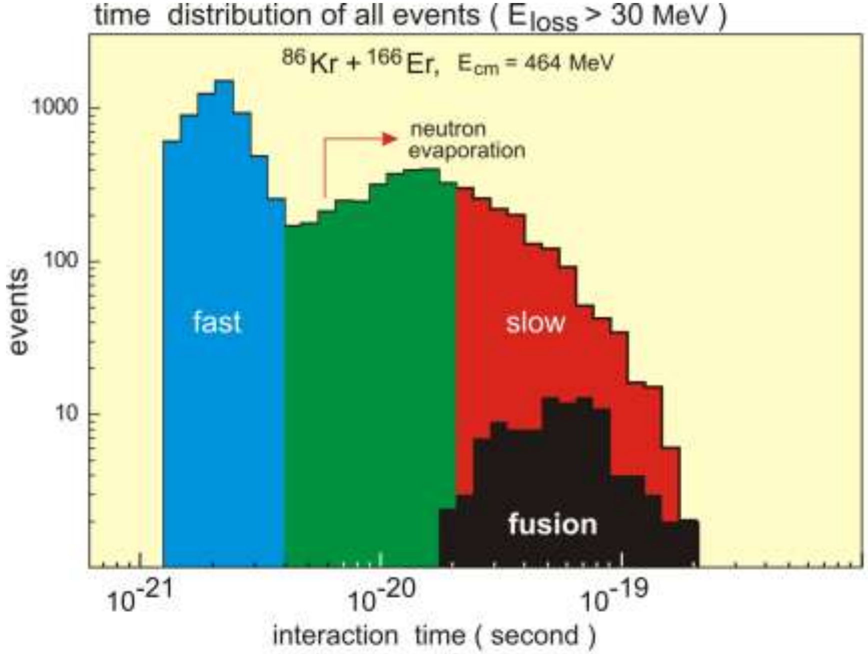
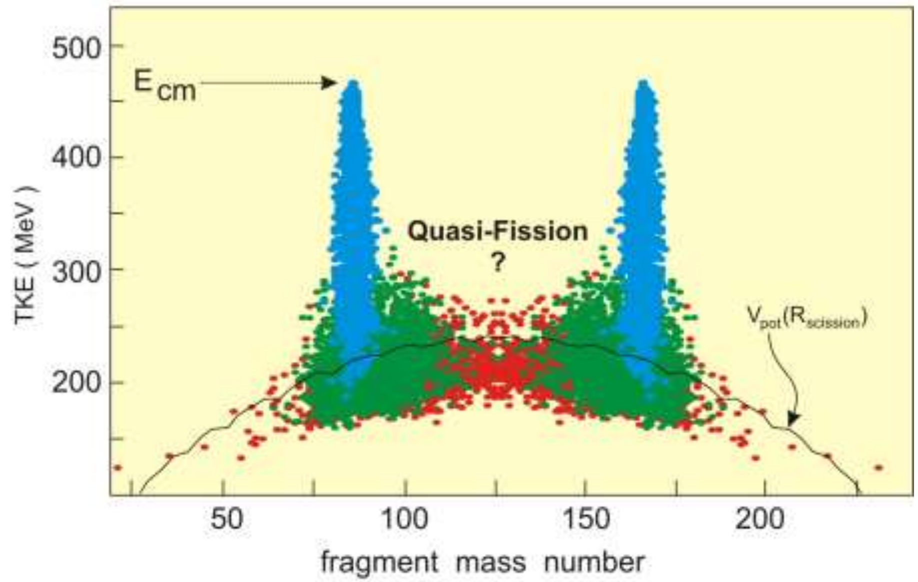
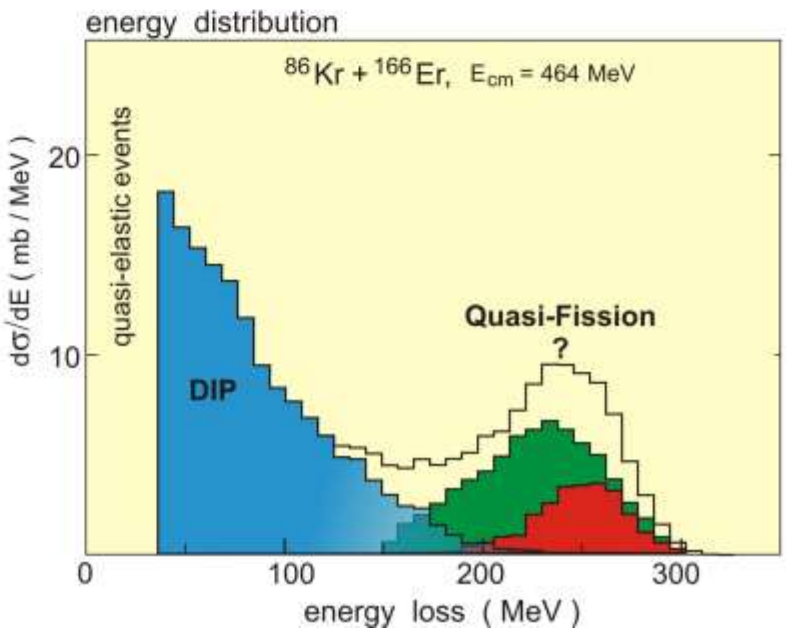


$^{86}Kr + ^{166}Er$ collision at E_{cm} = 464 MeV (time analysis)







- $t_{int} < 4\cdot10^{-21}$ s
- $4\cdot10^{-21} < t_{int} < 2\cdot10^{-20}$ s
- $2\cdot10^{-20}$ s $< t_{int}$

from comparison with experimental data:

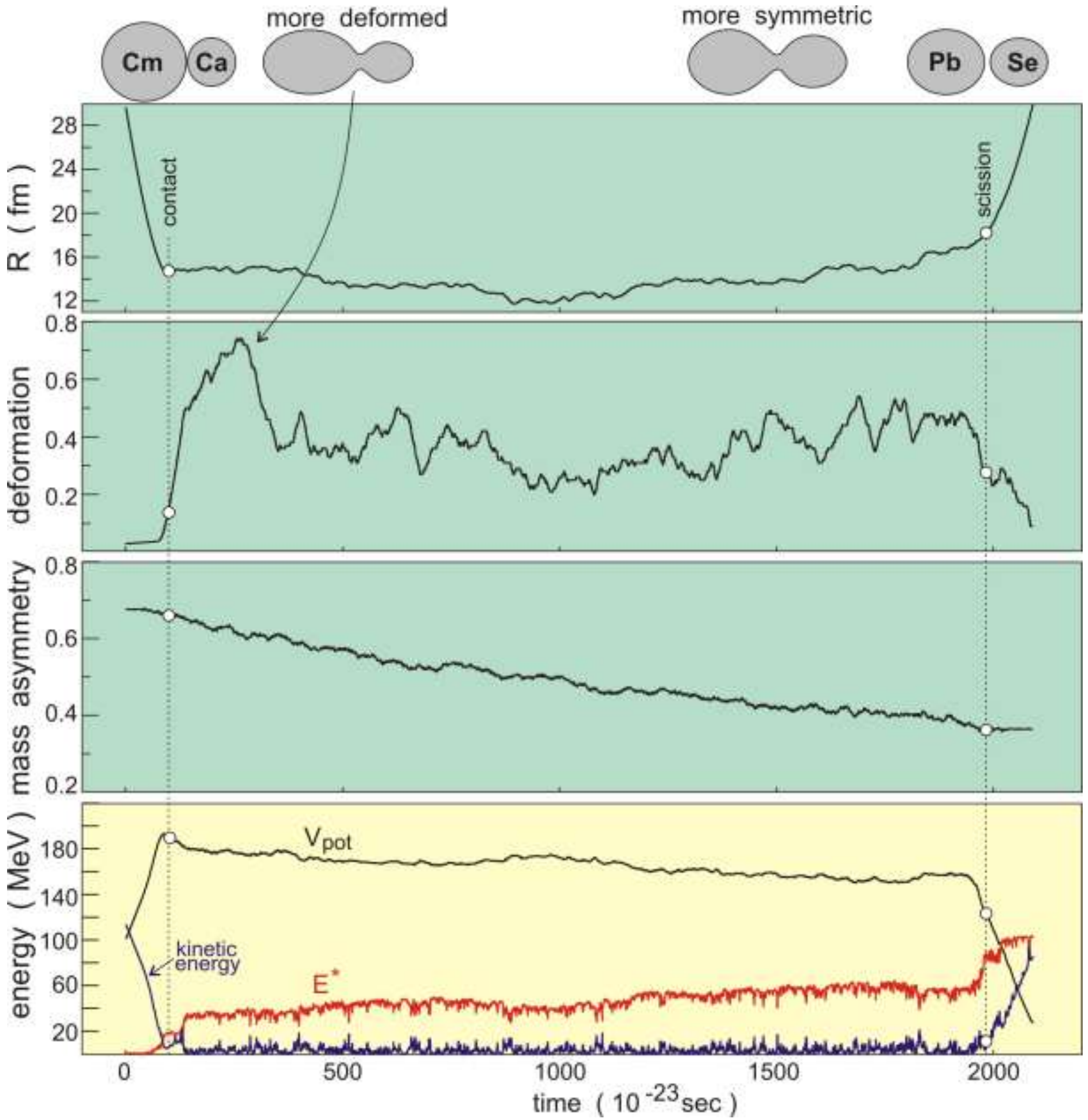
nuclear viscosity $\mu_0 \sim \mathbf{1 \div 3} \cdot 10^{-22}$ MeV·s·fm^{-3}

depends on excitation energy (nuclear temperature)

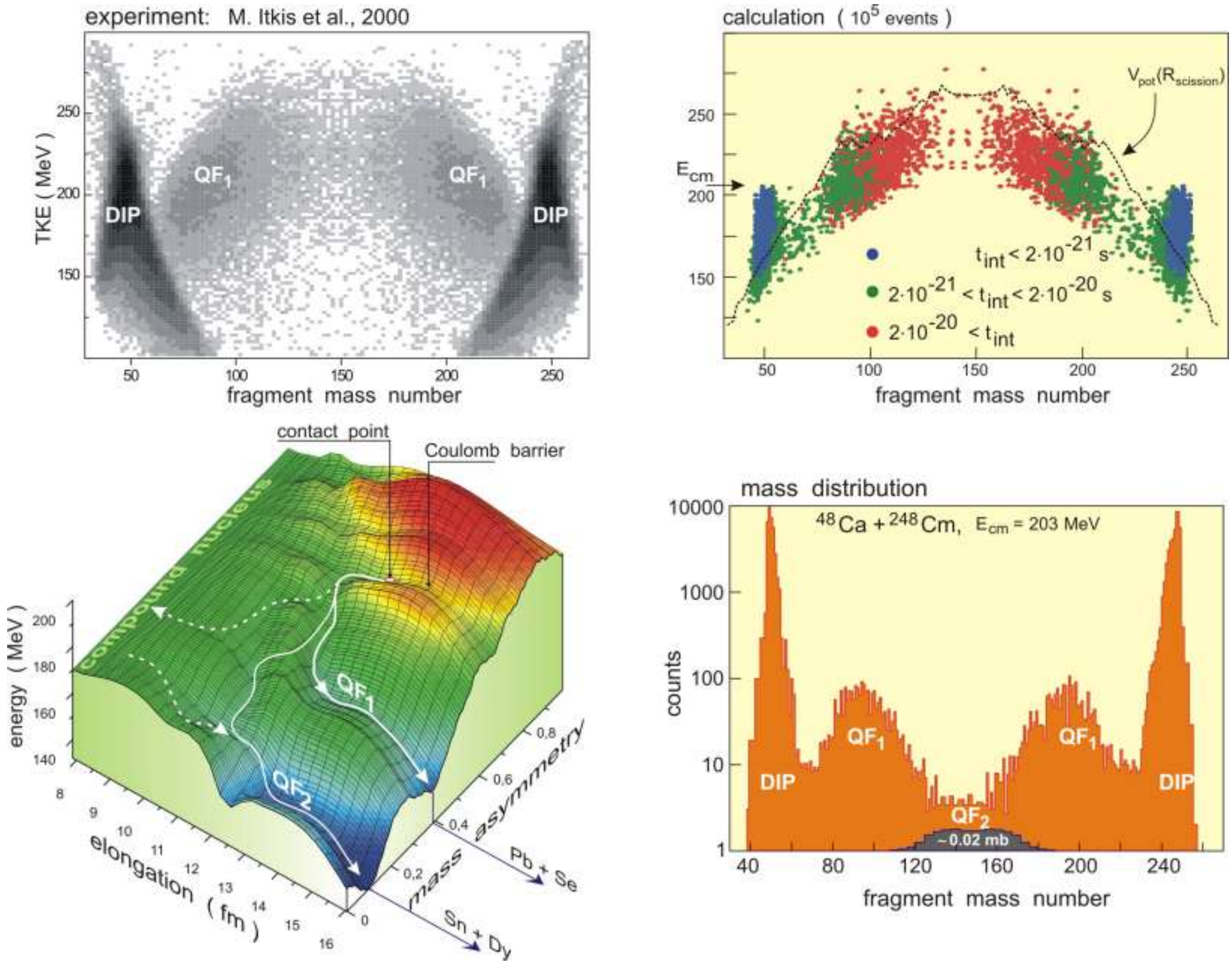
nucleon transfer rate $\lambda_0 \lesssim \mathbf{0.1} \cdot 10^{22}$ s^{-1}

less than those used in "diffusion models"

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

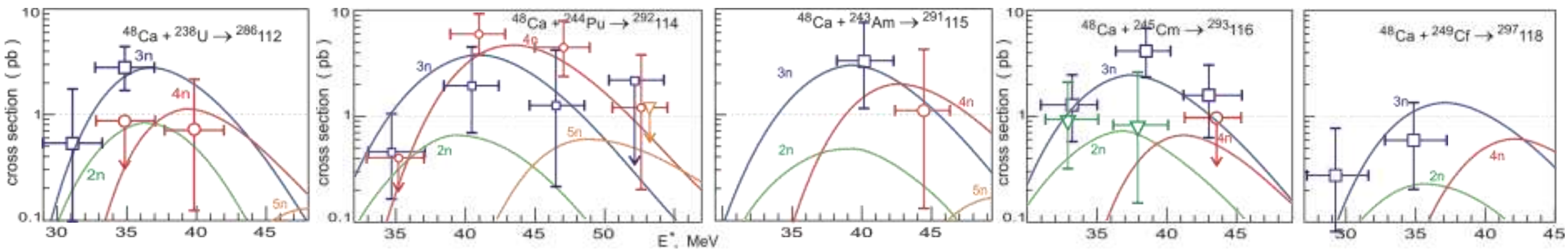


$^{48}Ca + ^{248}Cm$ collision at E_{cm} = 203 MeV

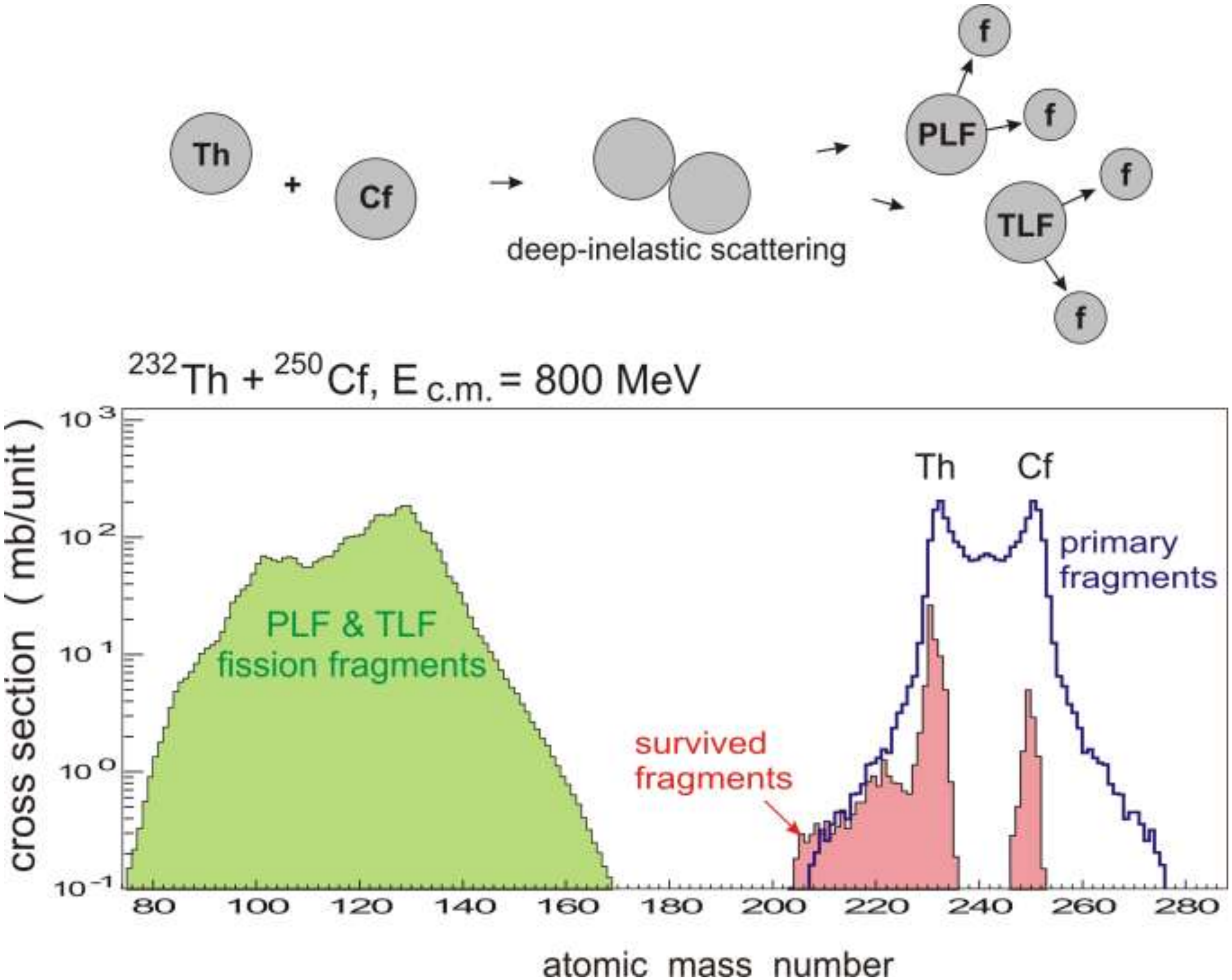


Predictive power of the theory

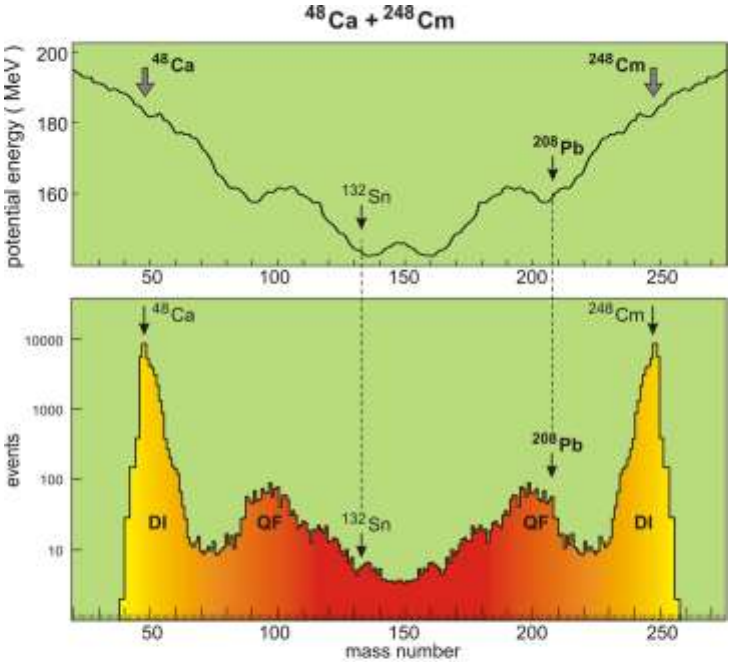
2003 - 2005 2002 (3n ? 4n ?)



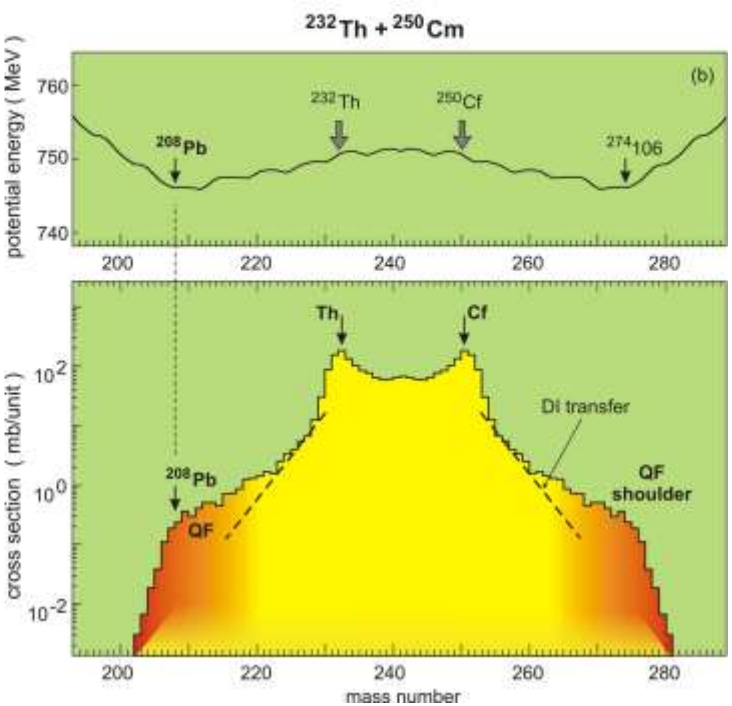
Collision of very heavy (transactinide) nuclei ?



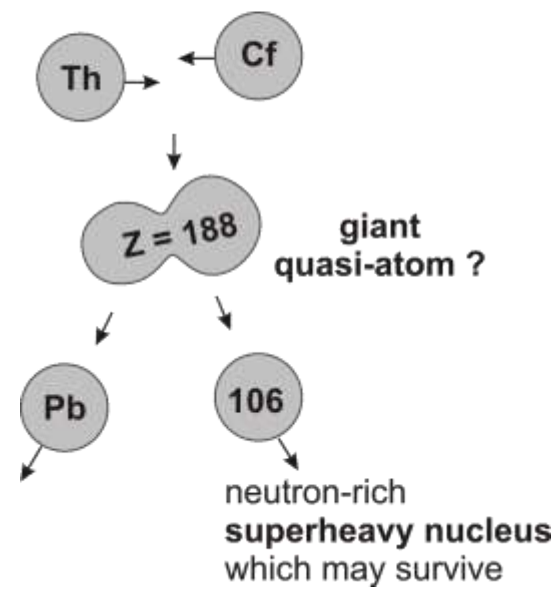
Production of neutron-rich superheavy nuclei and giant quasi-atoms



normal
(symmetrizing)
quasi-fission



"inverse"
(antisymmetrizing)
quasi-fission



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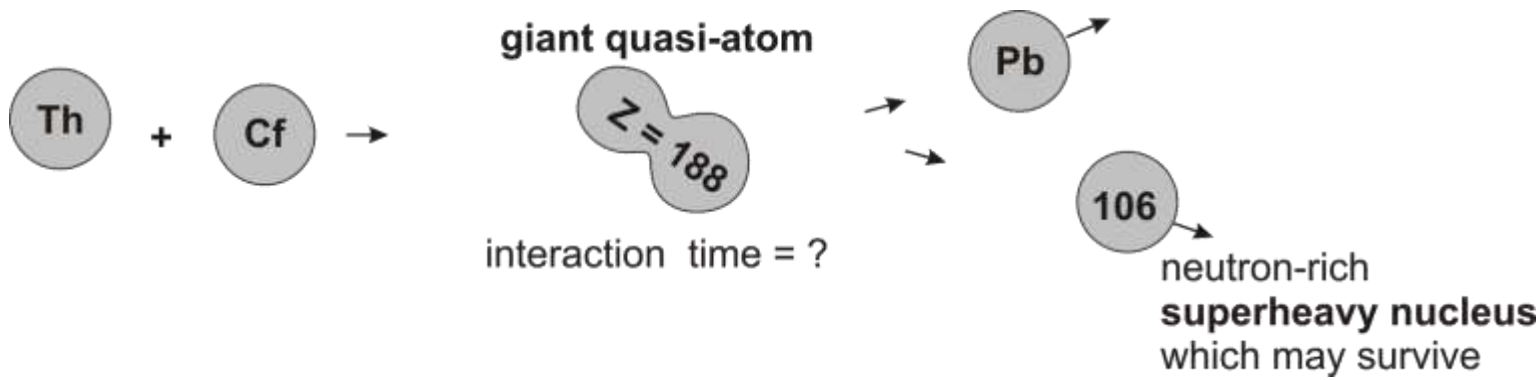
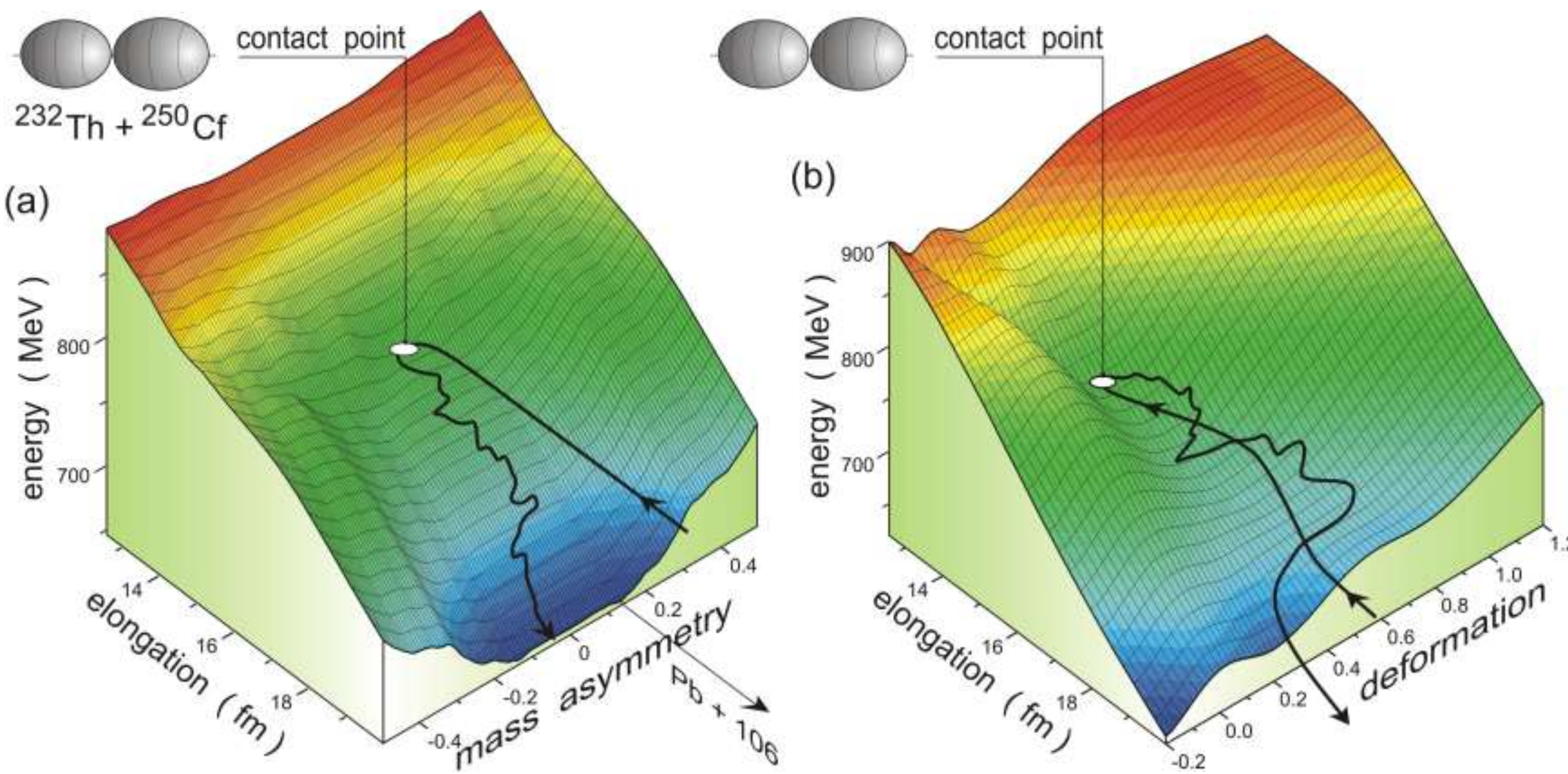
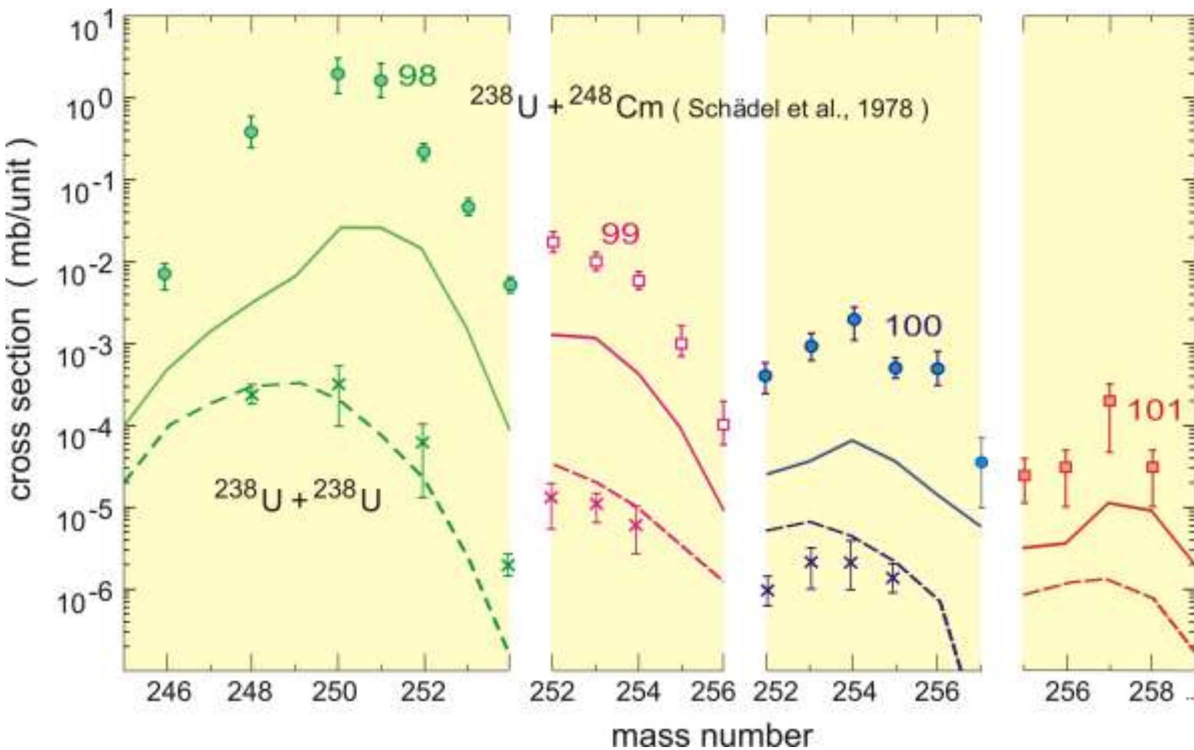
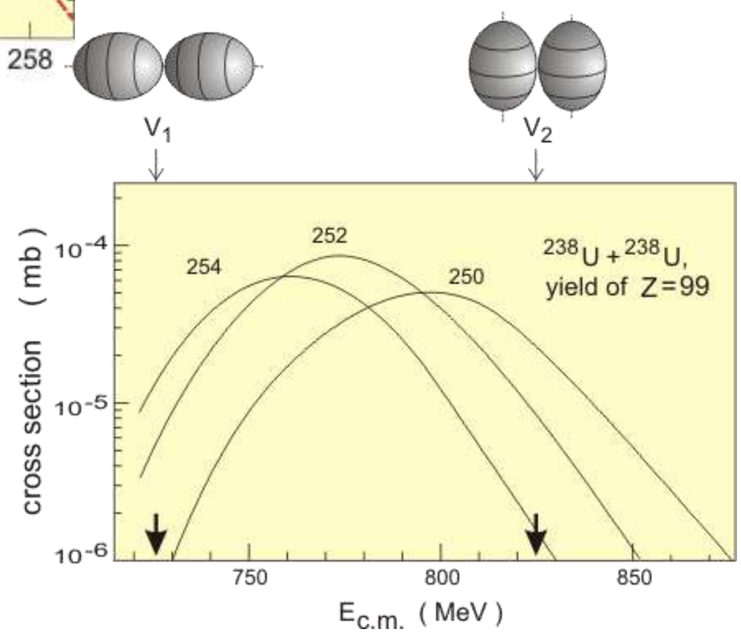


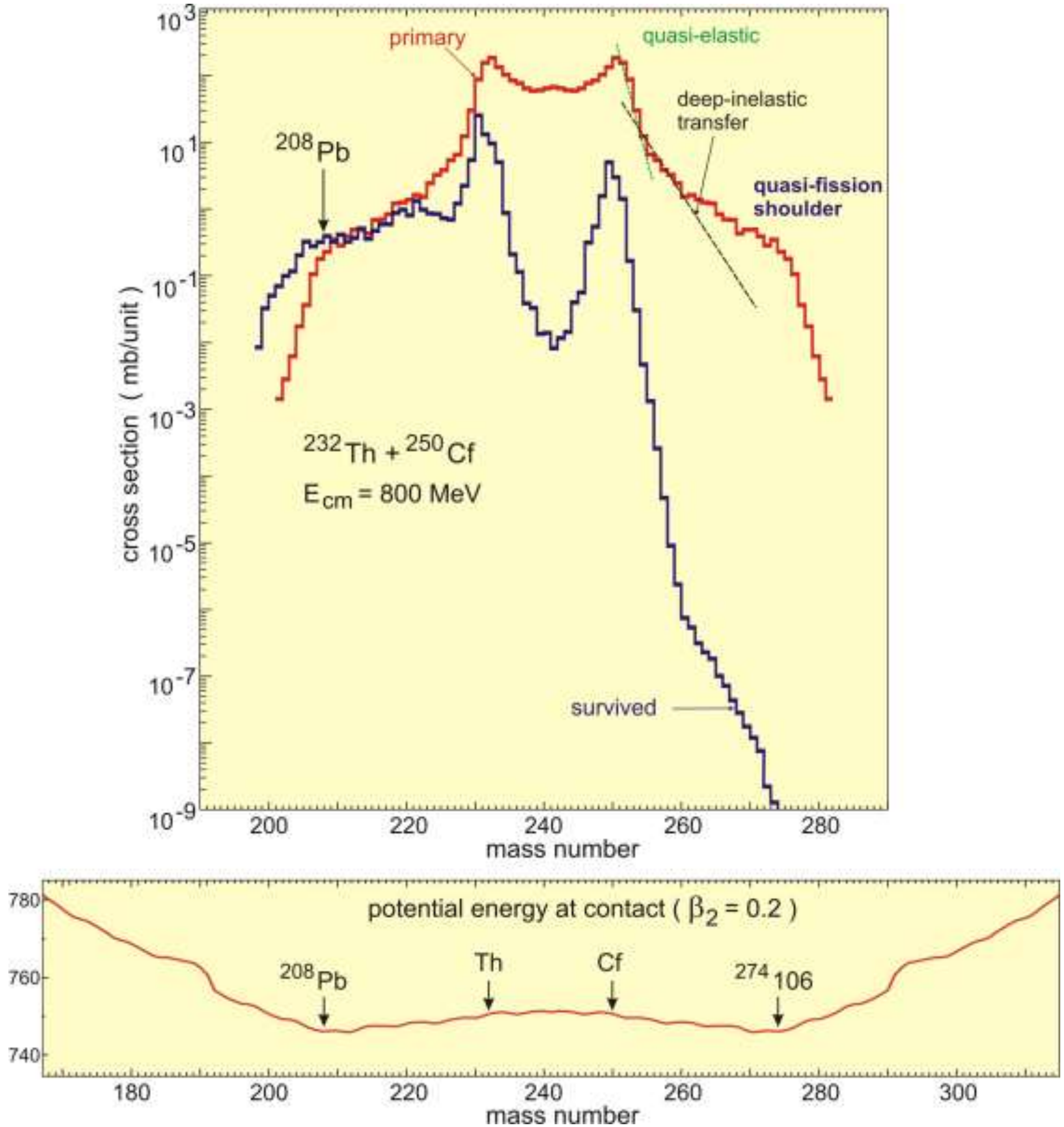


Comparison with available experimental data

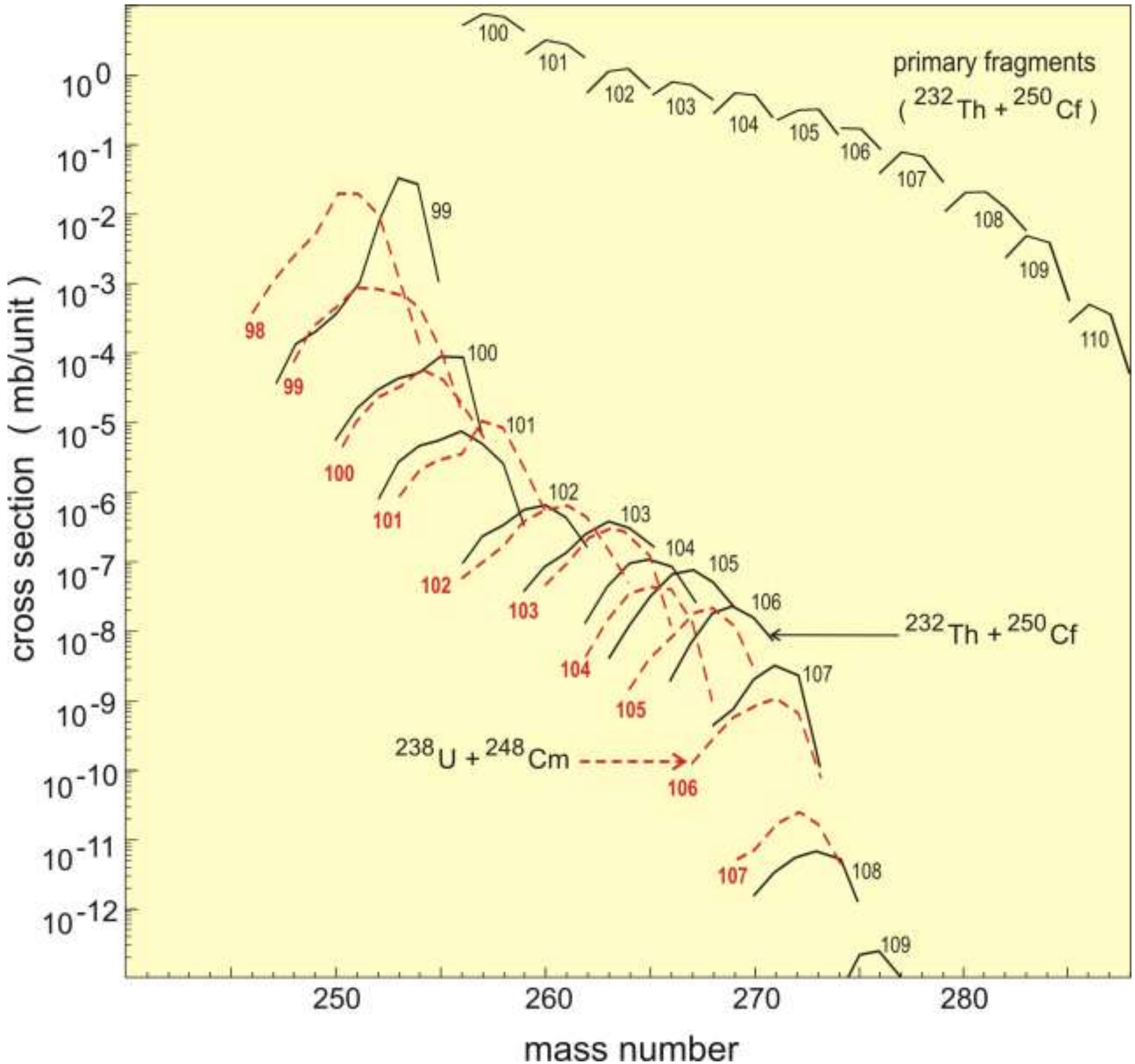




Deep-Inelastic and Quasi-Fission processes in very-heavy-ion damped collisions



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



Experiments to be performed in Dubna in 2006

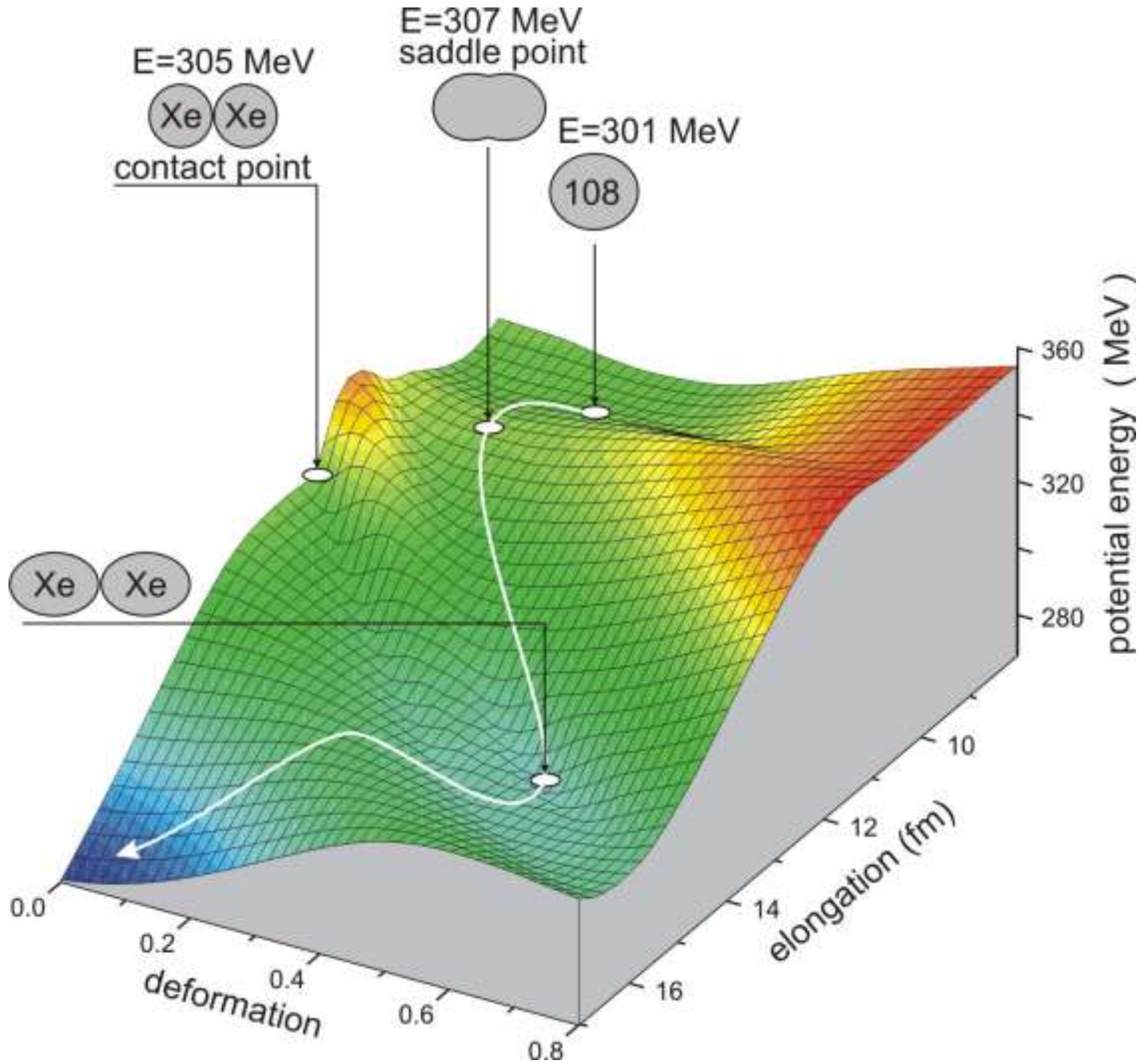
- **Fusion of fission fragments:**

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

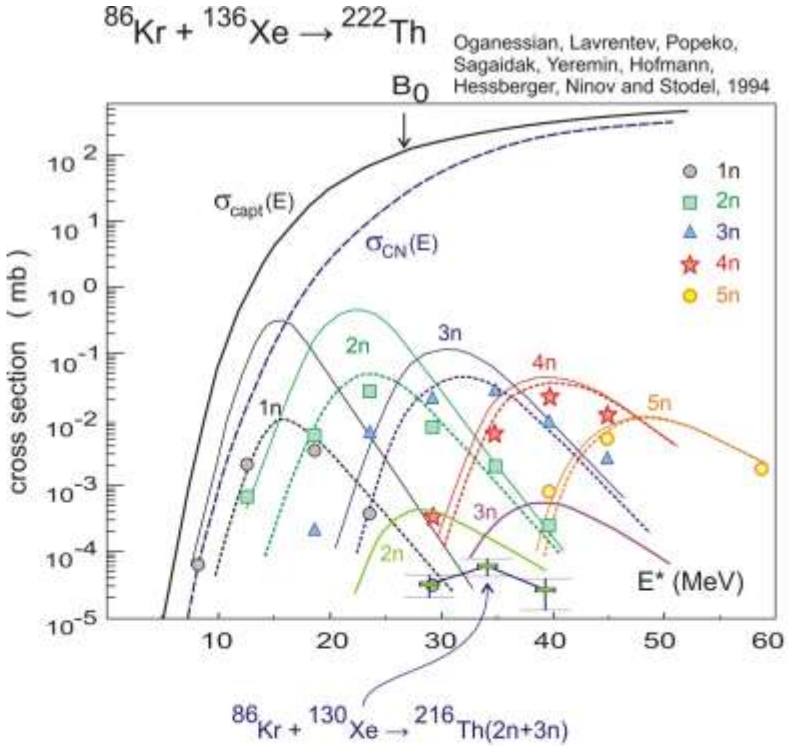
- **Synthesis of 120:**

  $^{54}Cr + ^{248}Cm \rightarrow ^{302}120$

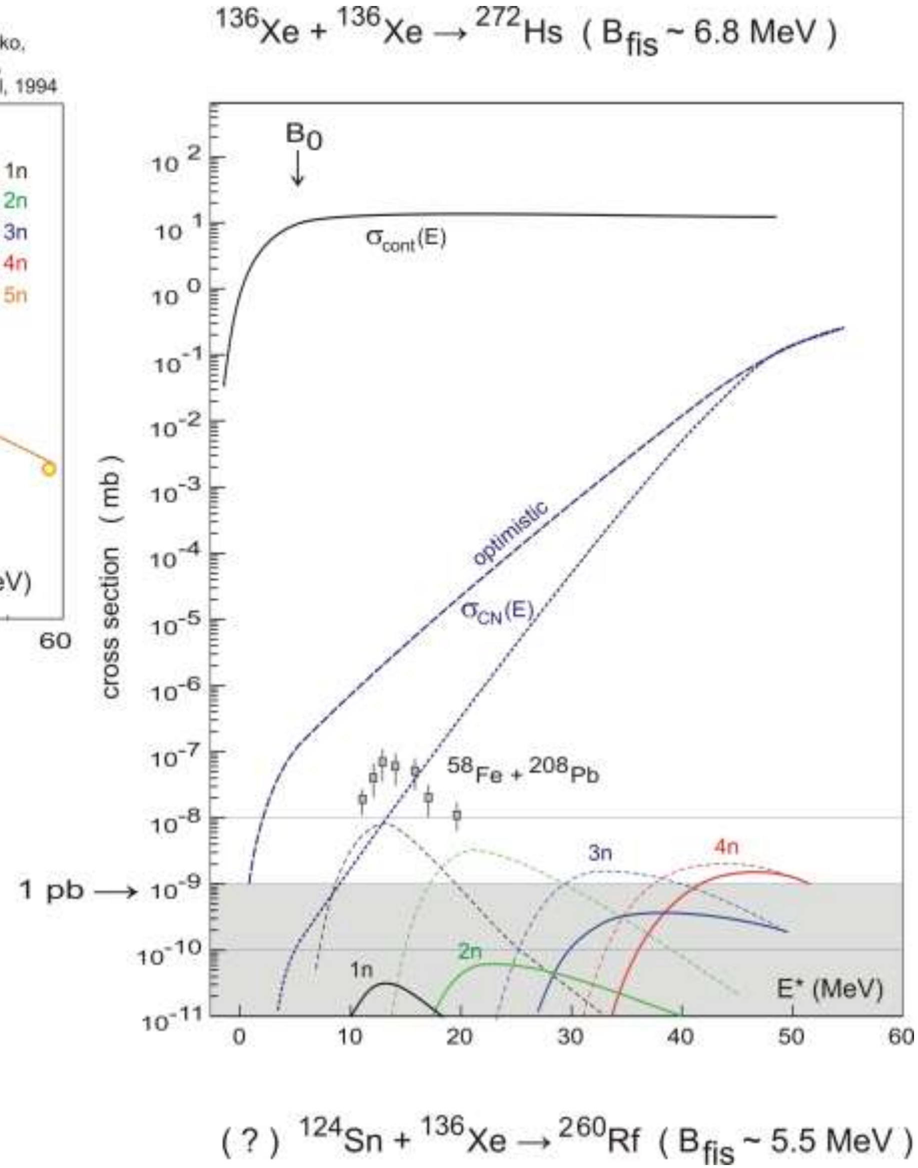
$^{136}Xe + ^{136}Xe \rightarrow ^{272}108$



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



"...some additional hindrance effect in the fusion dynamics of this reaction is still not clear." (Zagrebaev et al., PRC, 2002)



Synthesis of $^{302}120$

$^{54}Cr + ^{248}Cm \rightarrow ^{302}120$ (30 MeV)

$^{58}Fe + ^{244}Pu \rightarrow ^{302}120$ (31 MeV)

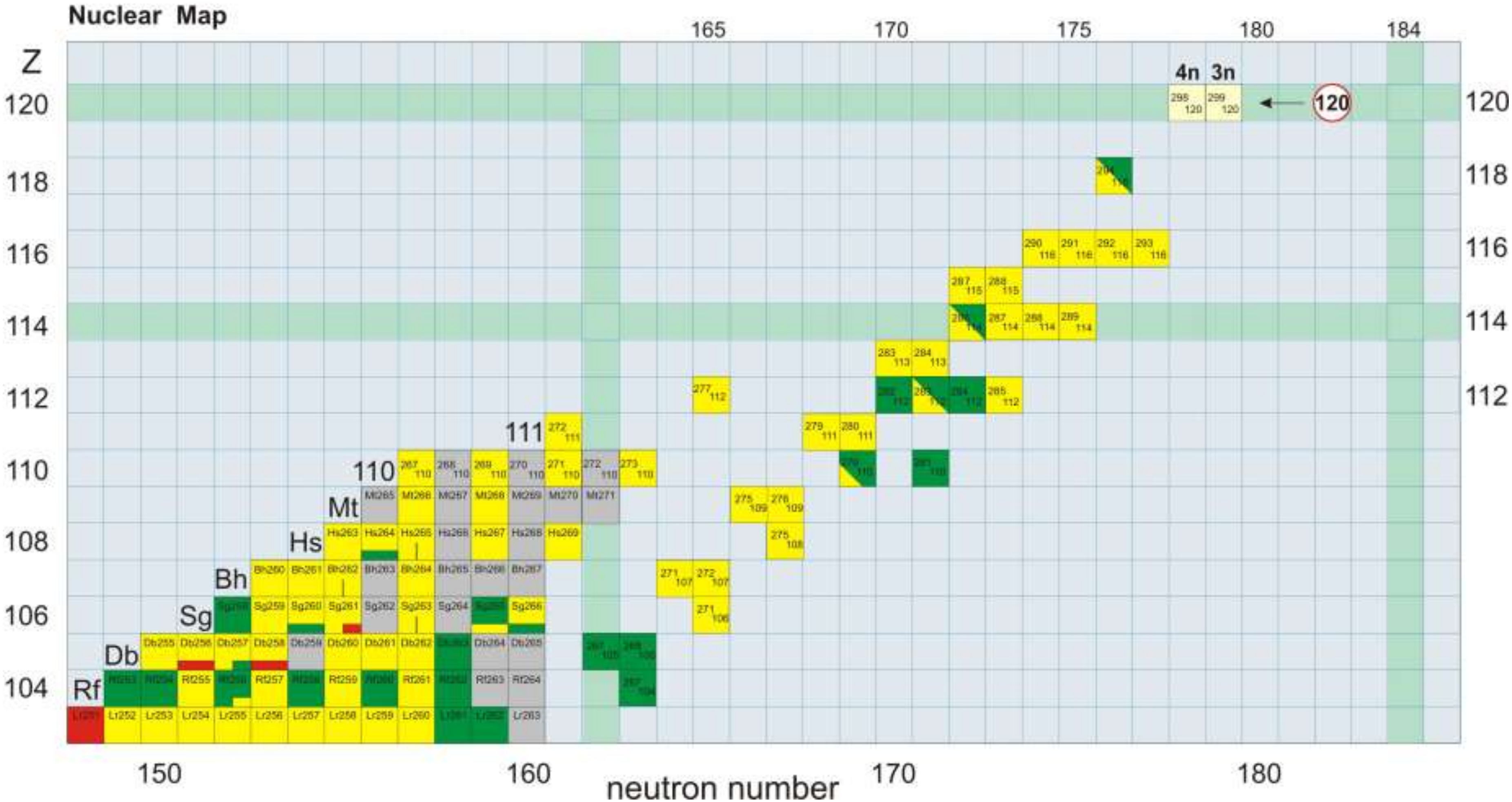
$^{64}Ni + ^{238}U \rightarrow ^{302}120$ (26 MeV)

(3n) $\rightarrow ^{299}120$

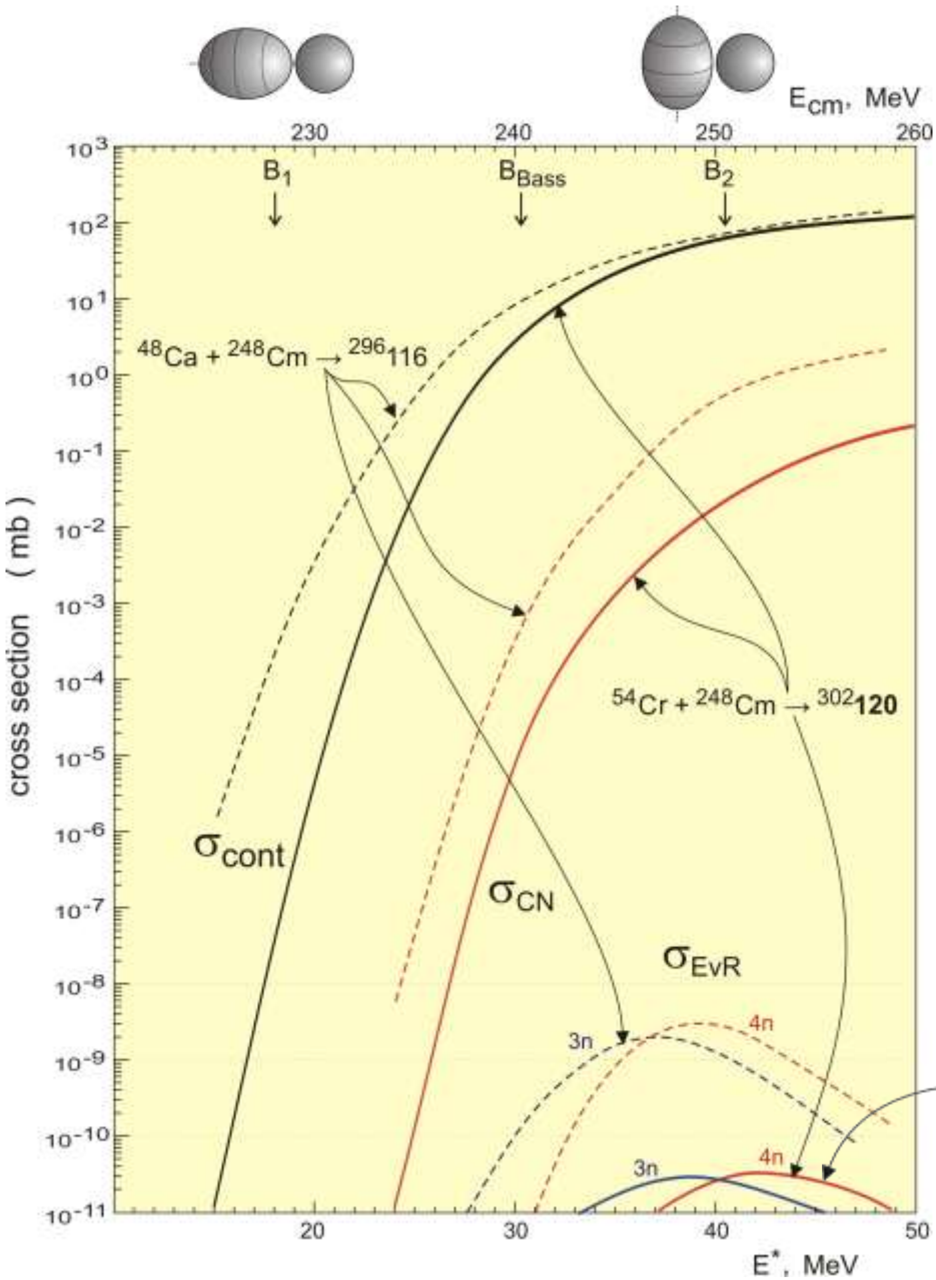
(4n) $\rightarrow ^{298}120$

$Q_{\alpha} \sim 13$ MeV

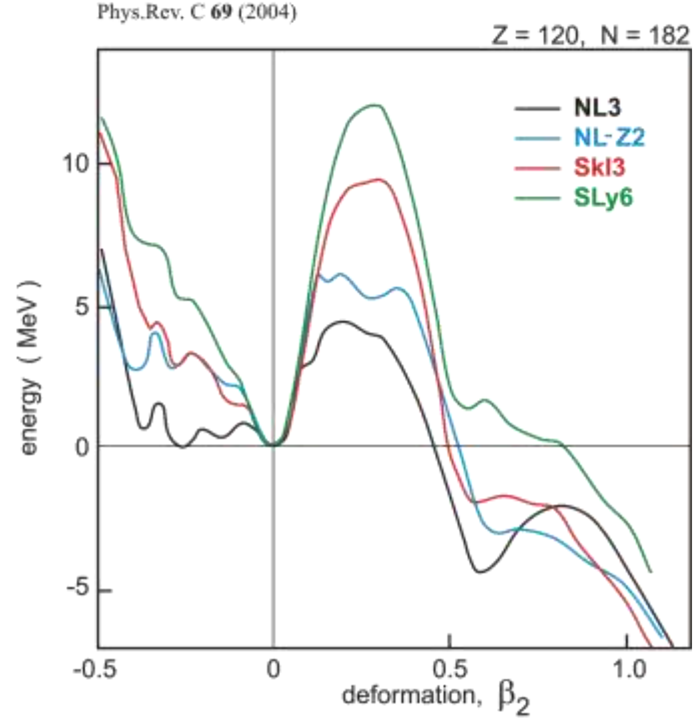
$T_{1/2} \sim 10 \div 100\ \mu s$ (!?)



Cross sections of the reactions leading to $^{302}120$



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

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.

- 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.
  Spontaneous positron emission from a supercritical electric field of long-lived quasi-atoms formed in these reactions is also quite expected.
  … many other possibilities …