Large Scale Nuclear Motion

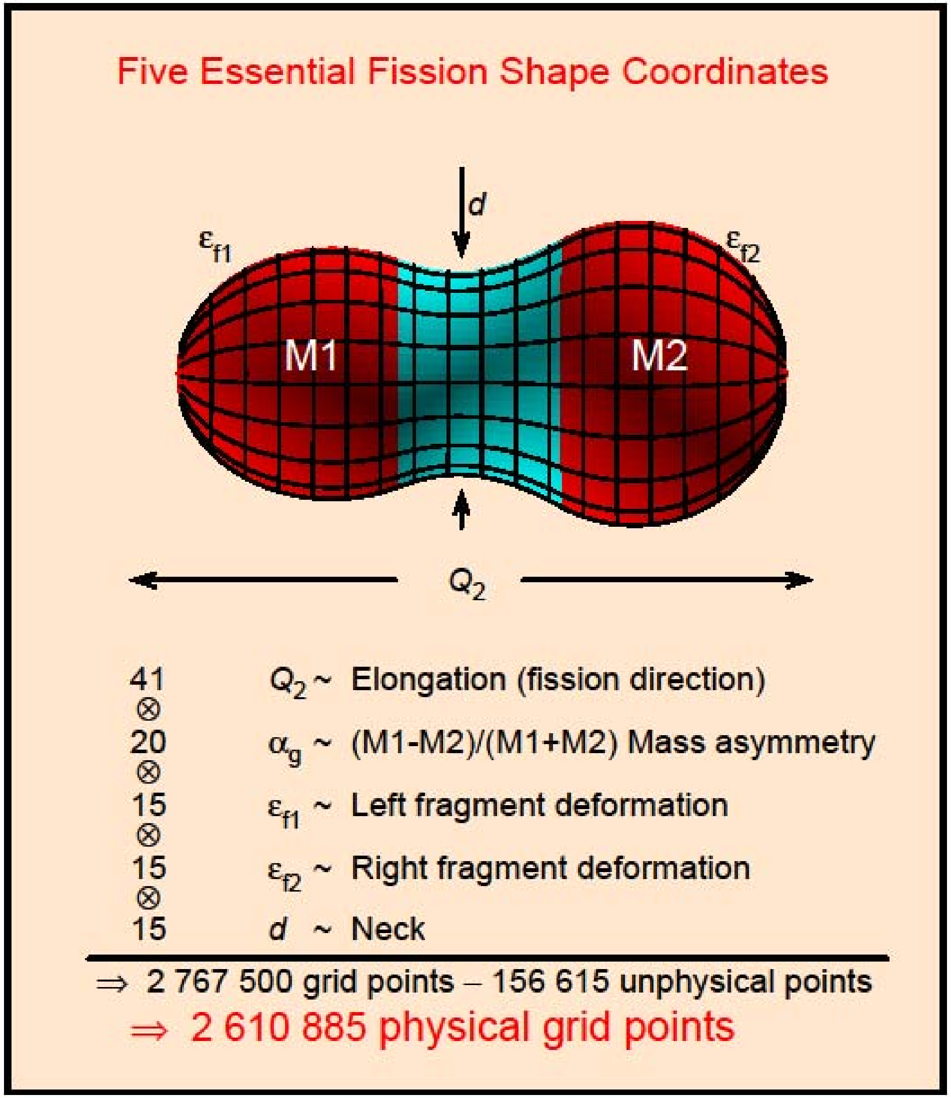
On the Way to Super Heavies

Hans Feldmeier, GSI

Outline

- Collective variables
- Energy landscape $V(q)$, mass tensor $M(q)$
- Dissipation fluctuation $\gamma(q)$, $D(q)$
- How to make heavy system fuse
- Shell effects
- Quantum correlations (beyond mean field)
- Microscopic consistent input to $V(q)$,$M(q)$,$\gamma(q)$,$D(q)$

Collective Variables $q=\{q_1,q_2, \dots\}$



Example with axial symmetry:

q_1 elongation

q_2 neck

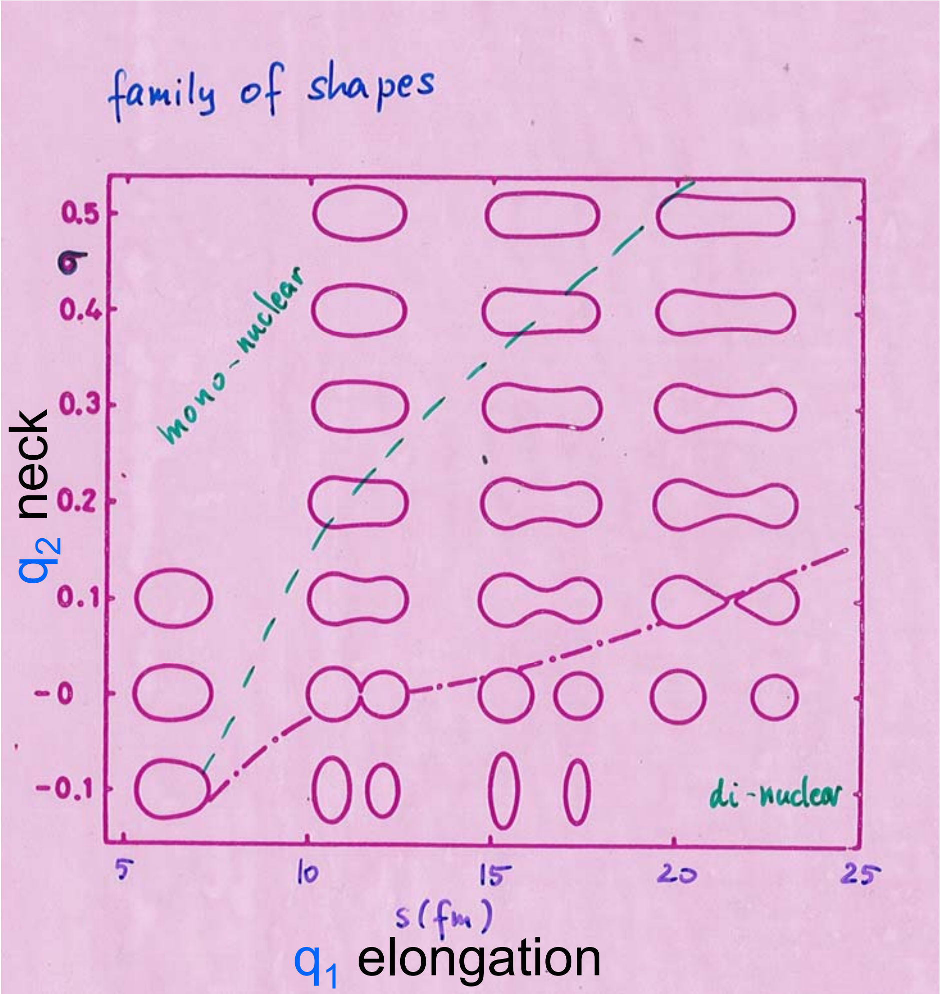
q_3 mass asymmetry

q_4 deformation left

q_5 deformation right

Möller,Madland,Sierk,Iwamoto,Nature**409**(2007)785

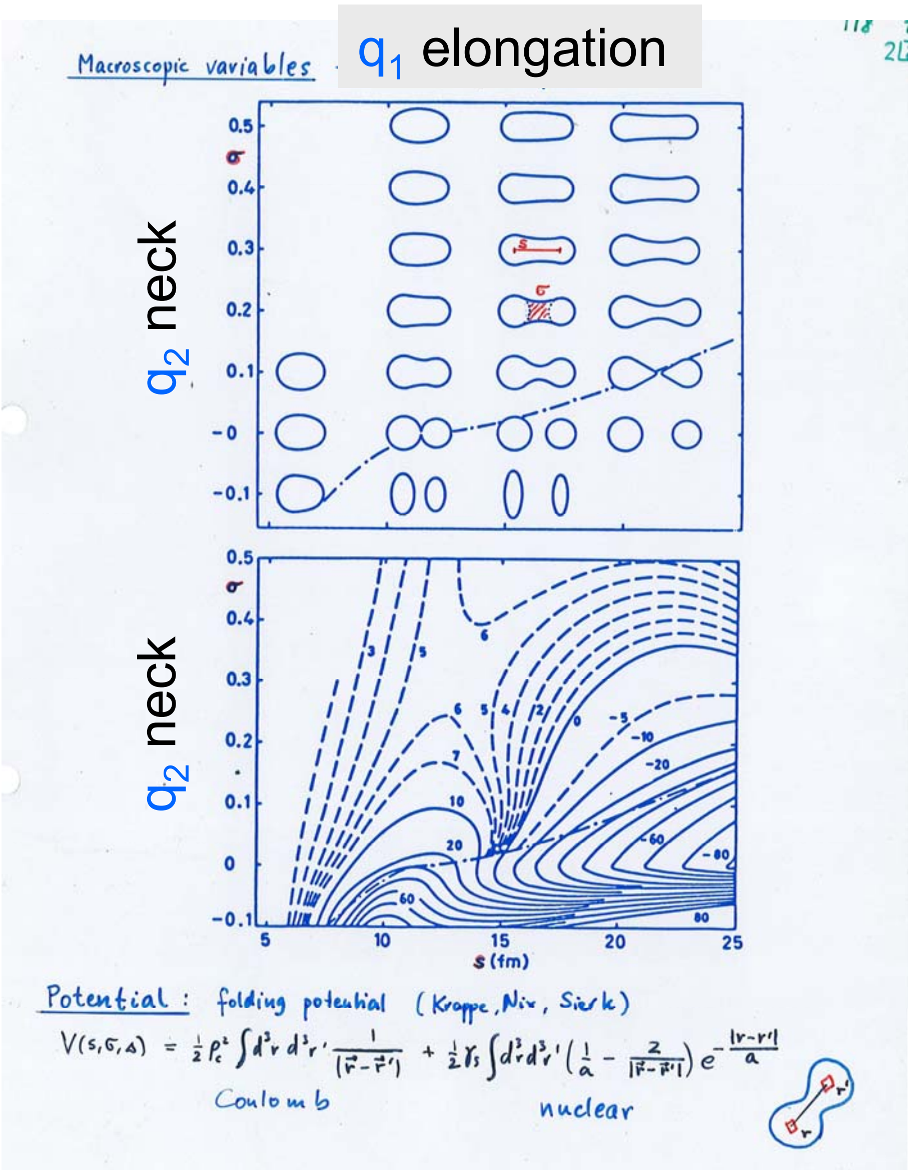
Collective Variables $q=\{q_1,q_2, \ldots\}$



- Family of shapes characterized by coll. variables
- like quadrupole, octupole etc. moments

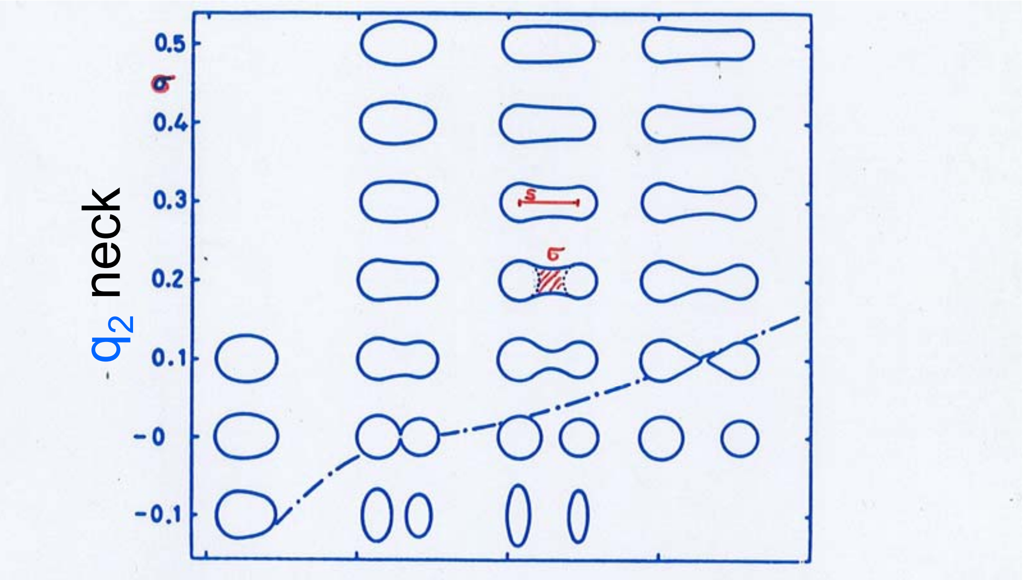
H.Feldmeier, Rep.Prog.Phys. **50**(1987)915

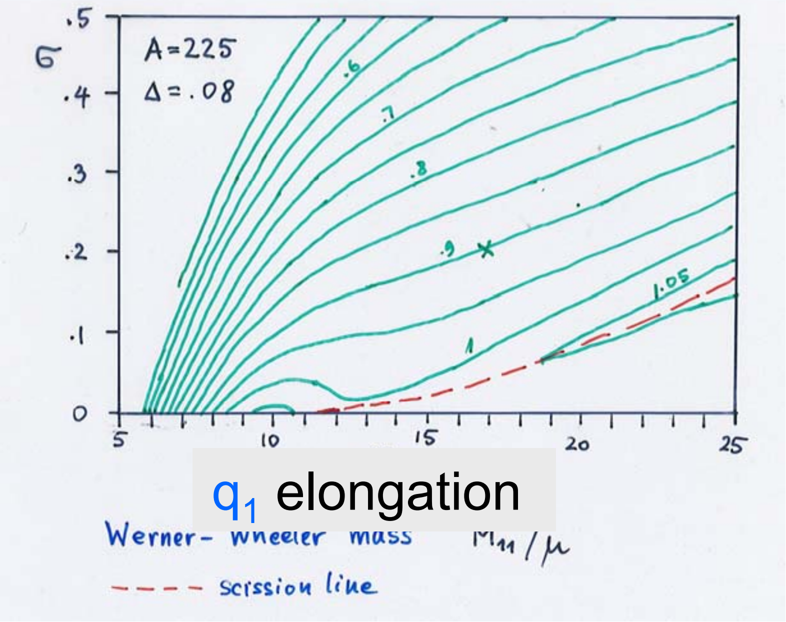
Energy Potential Landscape V(q)



- Lowest possible energy of quantum many-body system under constraints $\{q_1, q_2, \dots\}$
- V(q) includes all correlations: shell, pairing, vibrations etc.

Mass Tensor

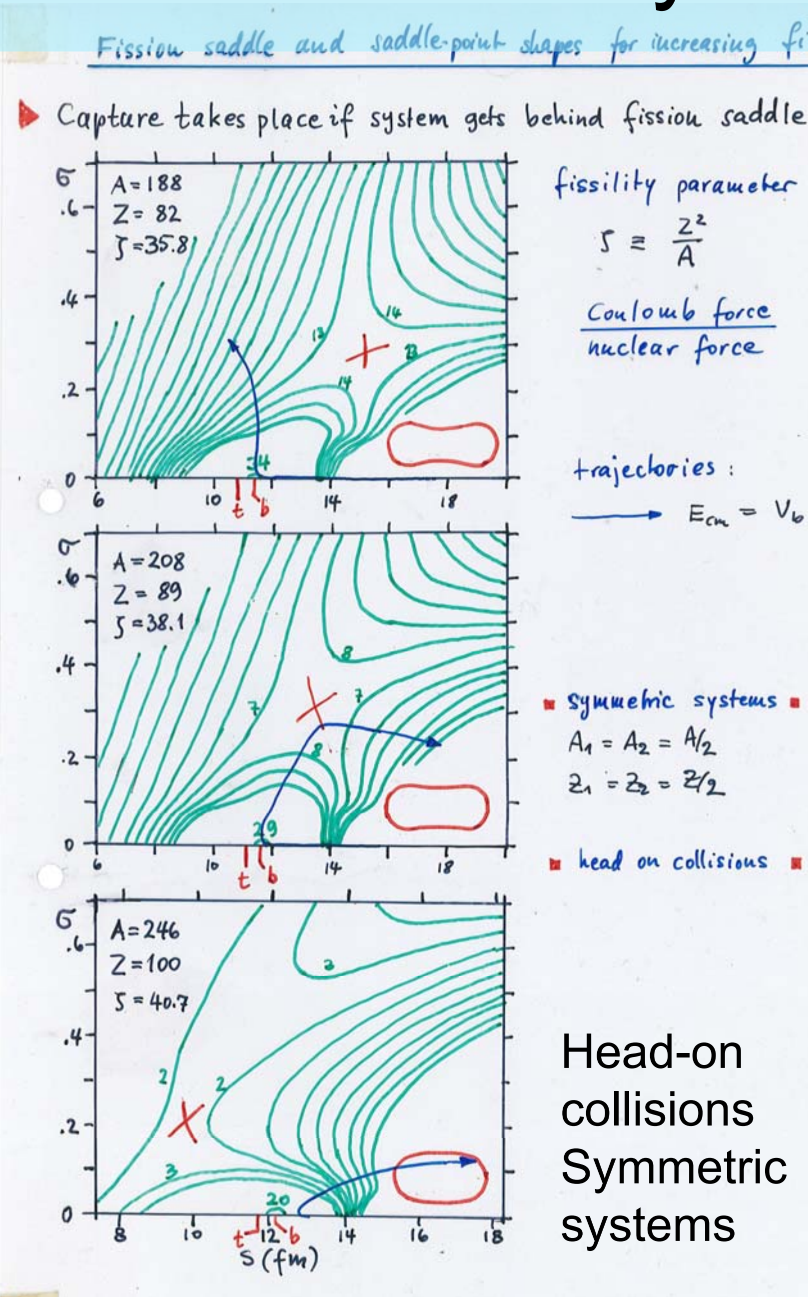




Inertial mass tensor M(q)
Collective kinetic energy

$$T_{coll} = \frac{1}{2} \sum_{ij} \dot{q}_i M_{ij}(q) \dot{q}_j$$

Fissility and Fission Barrier

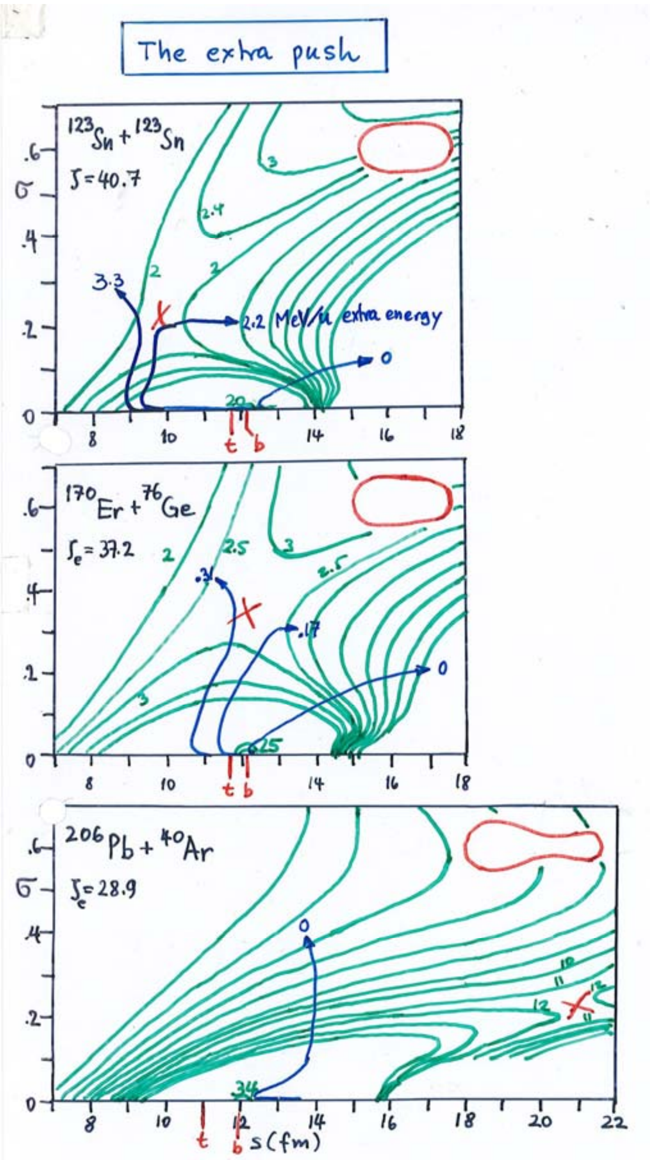


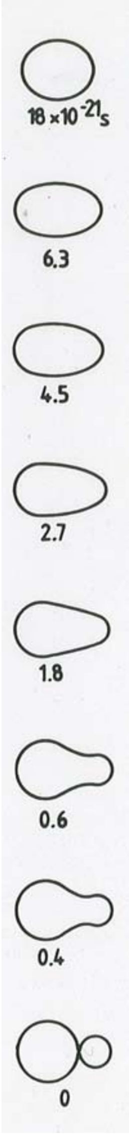
Head-on collisions Symmetric systems

- Fissility $\zeta = Z^2/A$: measure for ratio Coulomb/Surface energy
- Fission barrier (χ) prevents spontaneous fission
- Excited compound nucleus can fluctuate across fission barrier (χ)
- Below $\zeta \approx 38$ symmetric system will fuse automatically from top of Coulomb barrier
- For $\zeta > 38$ more beam energy will drive system behind saddle,

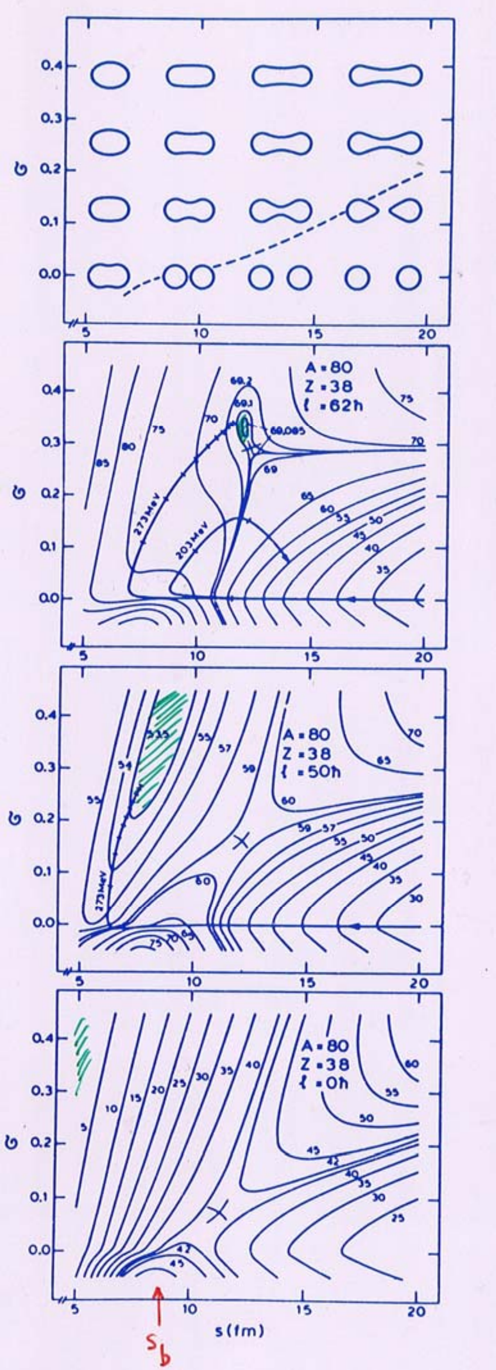
  but compound nucleus highly excited, will fluctuate across low fission barrier (χ)

Why Light on Heavy ?





- Drive system behind the conditional saddle (χ) for given mass asymmetry
- to get finally behind unconditional saddle
- But don‘t heat up the compound nucleus too much, otherwise it fluctuates out again across the low unconditional saddle



Finite Impact Parameter b (not head-on)

- Larger b (or ℓ) gives more cross section

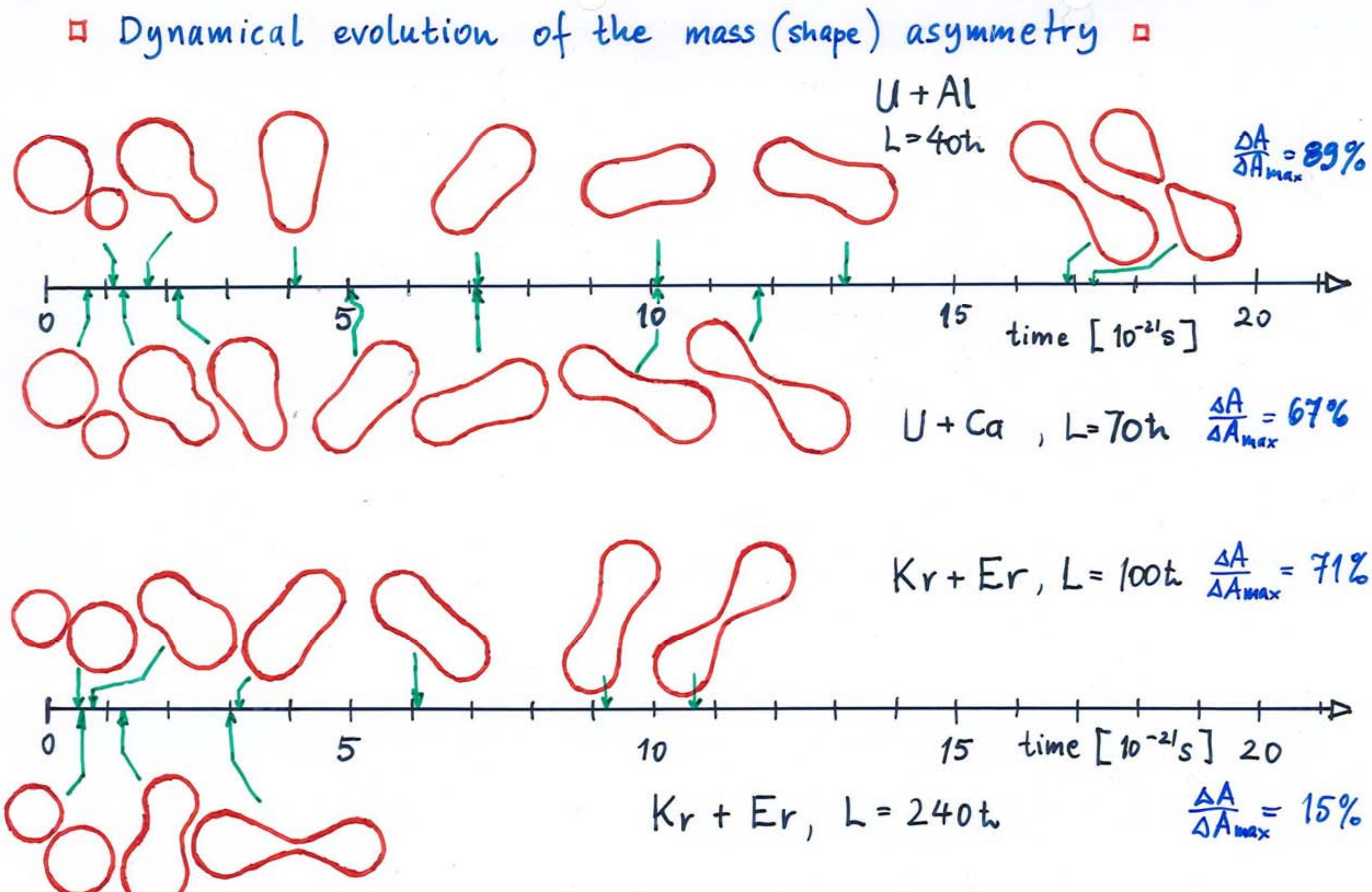
  $\sigma = \pi b^2$

- For $\ell > \ell_{crit}$ pocket for rotating compound nucleus disappears
- But don't heat up the compound nucleus too much, otherwise it fluctuates out again across the low saddle

Typical Times

quasi fission

deep inelastic



H.Feldmeier, Rep.Prog.Phys. **50**(1987)915

Model Ingredients

Conservative part

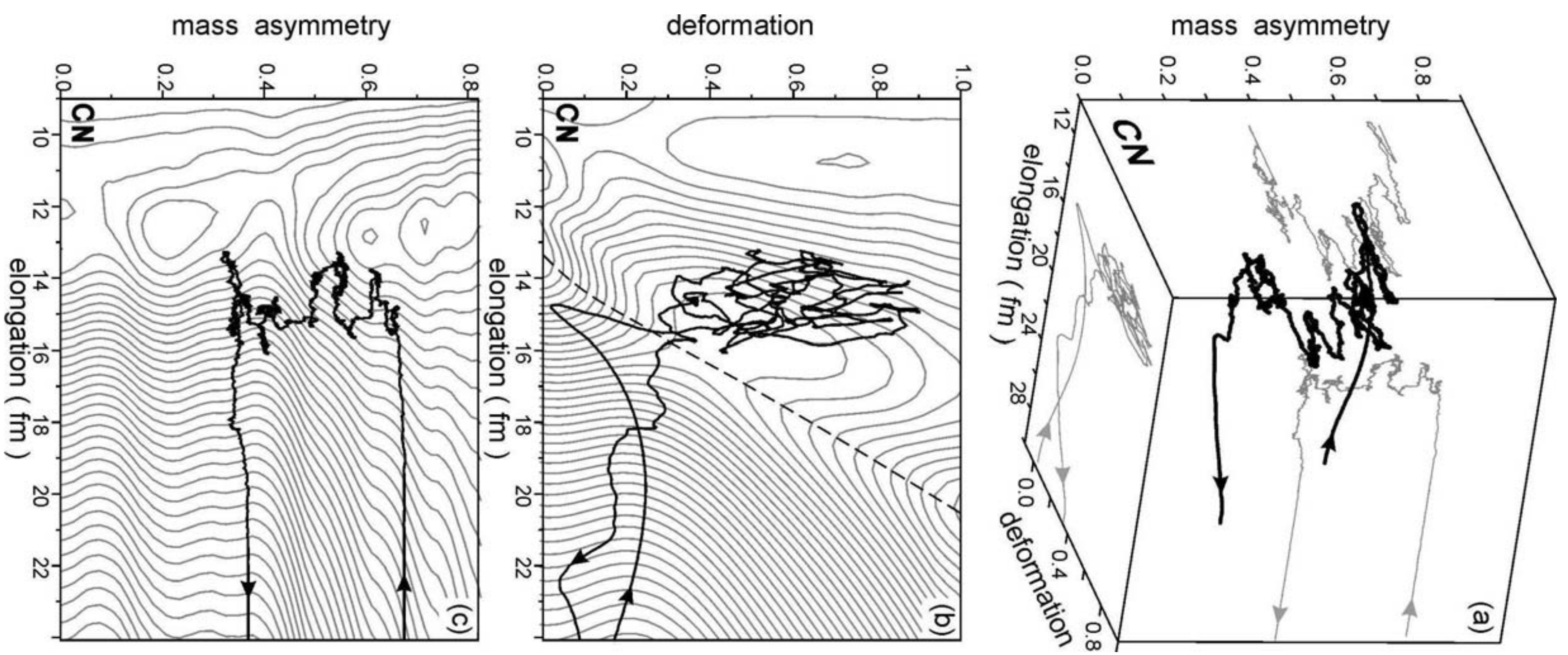
- $q=\{q_1,q_2, \ldots\}$ collective variables
- $V(q)$ adiabatic energy (landscape)
- $\dot{q}_i=dq_i/dt$ velocities
- $p_i = \Sigma_j M_{ij}(q)\, \dot{q}_j$ collective momenta, $M_{ij}(q)$ mass tensor

Dissipative forces

- $X_i(t) = A_i(q,p) + \delta X_i(t)$ irregular force between intrinsic and coll. variables
- $A_i(q,p) = < X_i(t) > \approx \Sigma_j \gamma_{ij}(q)\, p_j$ friction force, $\gamma_{ij}(q)$ friction tensor
- $< \delta X_i(t)\, \delta X_j(s) > = 2\, D_{ij}(q)\, \delta(t-s)$, diffusion tensor $D_{ij}(q)$

Langevin Equation with Fluctuating Force

- $dq_i/dt = \Sigma_j\, M(q)^{-1}{}_{ij}\, p_j$
- $dp_i/dt = -\, dV(q)/dq_i + \Sigma_j\, \gamma_{ij}(q)\, p_j + \delta X_i(t)$



$^{48}Ca + {}^{248}Cm$ @ 210 AMeV
fluctating path → quasi fission

Zagrebaev, Greiner, PRC**78**(2008)034610

The 3 Steps to Evaporation Residue (SHE)

Zagrebaev, Greiner, PRC**78**(2008)034610

$$\sigma_{\mathrm{ER}}^{xn}(E) = \frac{\pi}{k^2} \sum_{l=0}^{\infty} (2l+1) P_{\mathrm{cont}}(E,l) P_{\mathrm{CN}}(E^*,l)\, P_{xn}(E^*,l).$$

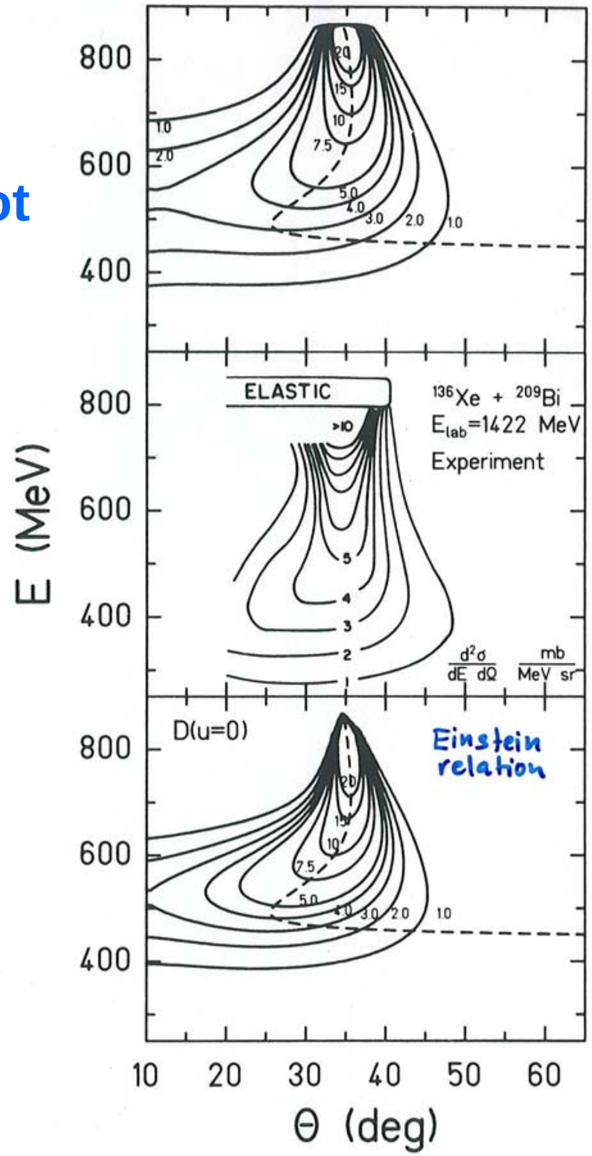
1. Get the nuclei into intimate contact
2. Get them behind the fission saddle
3. Hope that they cool down fast enough by neutron evaporation before they fission

Unified microscopic model desirable to go from 1. to 2. to 3. smoothly

Liouville Fokker Planck Equation

Fluctuations in Relative Momentum

Wilczynski plot



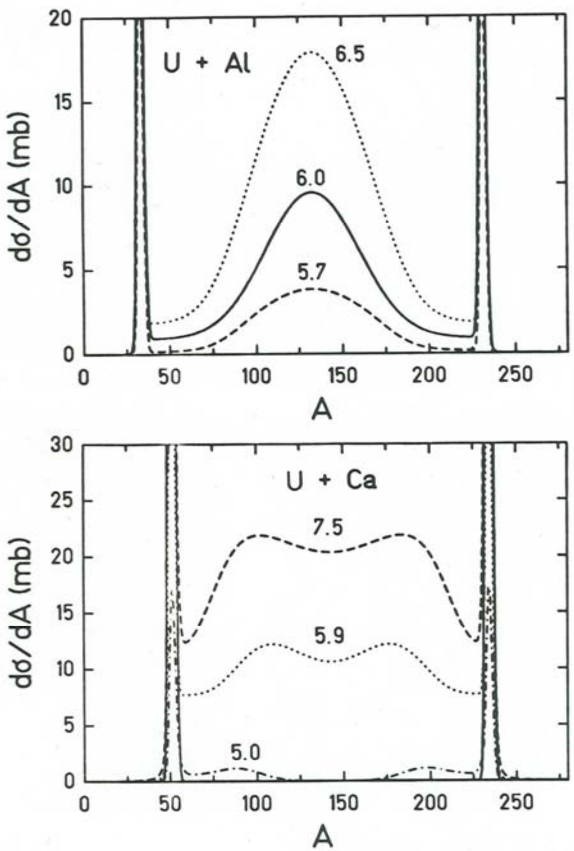
Double-differential cross section for $^{136}Xe + ^{209}Bi$. Upper part: result from the particle exchange model including the nonequilibrium velocity part. Centre part: experimental cross section. Lower part: result of a calculation where the Einstein relation has been enforced by setting $\Delta\vec{u} = 0$ at all times in the expression for the diffusion coefficient.

$^{136}Xe + ^{209}Bi$

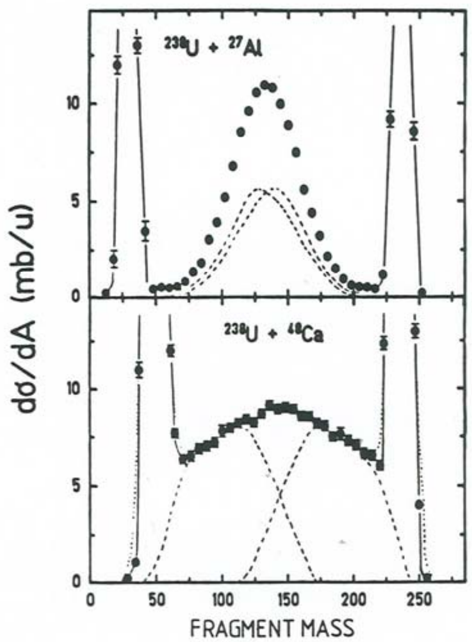
$E_{lab} = 1422$ MeV

H.Feldmeier, Rep.Prog.Phys. **50**(1987)915

Drift and Fluctuations in Mass Number



Diffusion plot

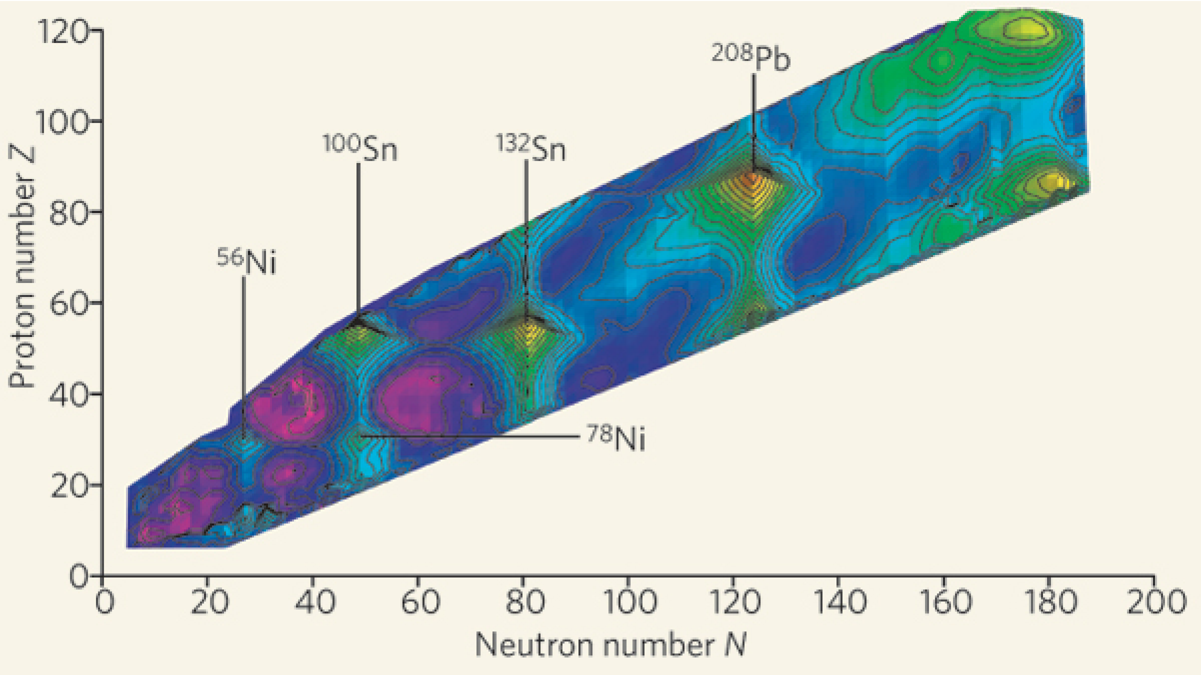


quasi fission

deeply inelastic with large mass drift

H.Feldmeier, Rep.Prog.Phys. **50**(1987)915

Shell Effects

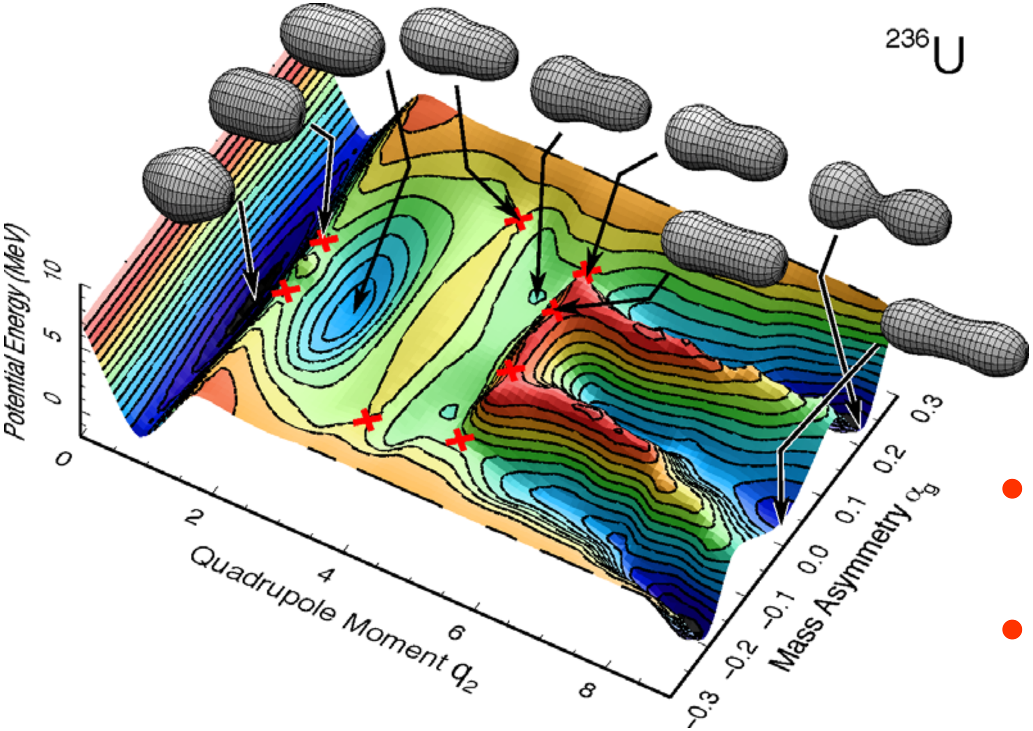


Extra bindung due to shell effects up to 10 MeV

Total binding from macroscopic part A*8 MeV (up to 2400 MeV)

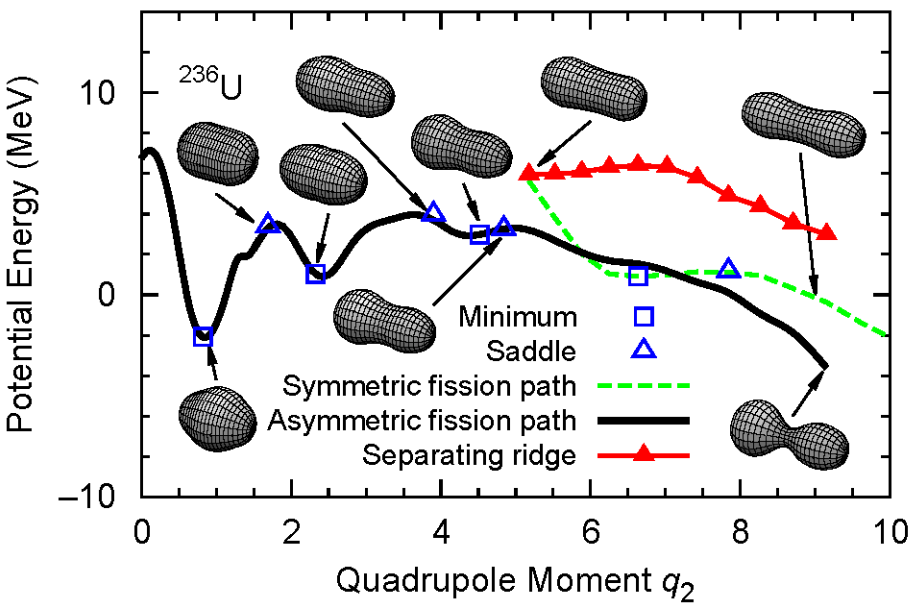
Bengtsson,Möller,Nature **449**(2007)41

- Shell effects exist not only in ground state but also at fission barrier
- Only the energy difference matters for stability of super heavies
- Calculate fission barriers !



Microscopic-Macroscopic Energy

- Asymmetric fission due to shell effects
- Energy landscape alone tells that high saddles at mass symmetry prevent asymmetric fission
- Diffusion and dynamics needed for mass distribution



Ichikawa,Iwamoto,Möller,Sierk, arXiv[nucl-th] 1203.2011v1

Microscopic Correlation Energies

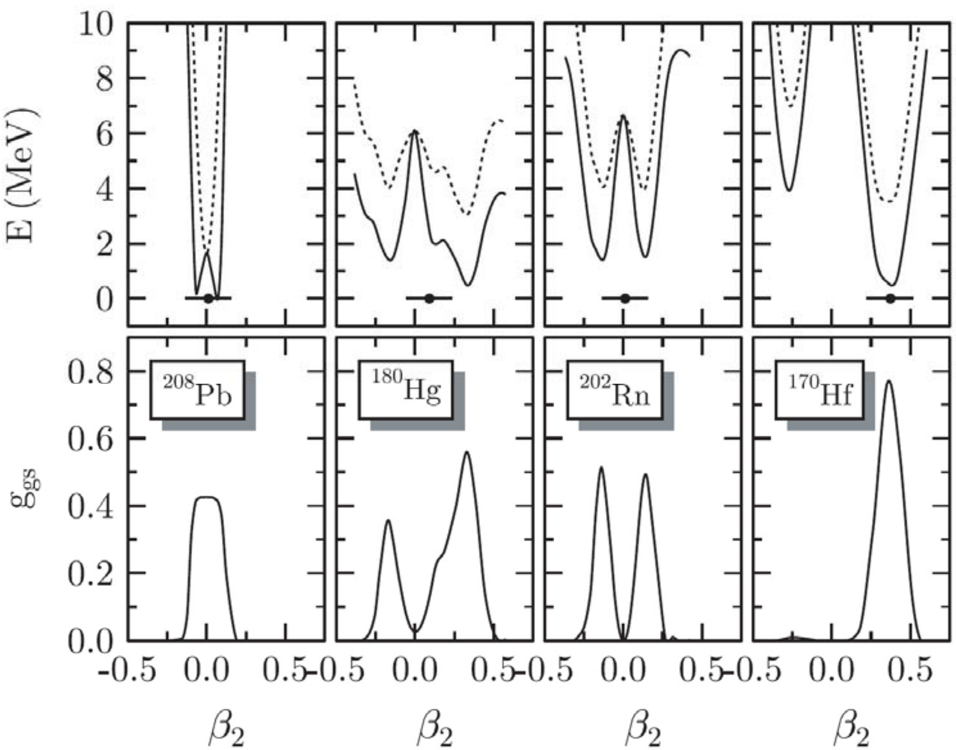


FIG. 3. Upper panel: Topography of unprojected/projected energy landscapes for typical heavy nuclei. The dotted curve denotes the energy after projection on the particle number only; the solid curve denotes the energy after projection on both particle number and angular momentum $J = 0$. The filled circle denotes the energy of the $J = 0$ projected GCM ground state. Lower panel: Collective $J = 0$ ground-state wave function. All curves and markers are drawn versus the average axial quadrupole deformation of the mean-field states they are constructed from.

Ground state:

- ΔE ≈ - 2 MeV due to project. on J=0
- ΔE ≈ - 0.1… - 2 MeV due to mixing of states with different quadrupole mom.

Scission saddle

- What are the those numbers at fission saddle ?

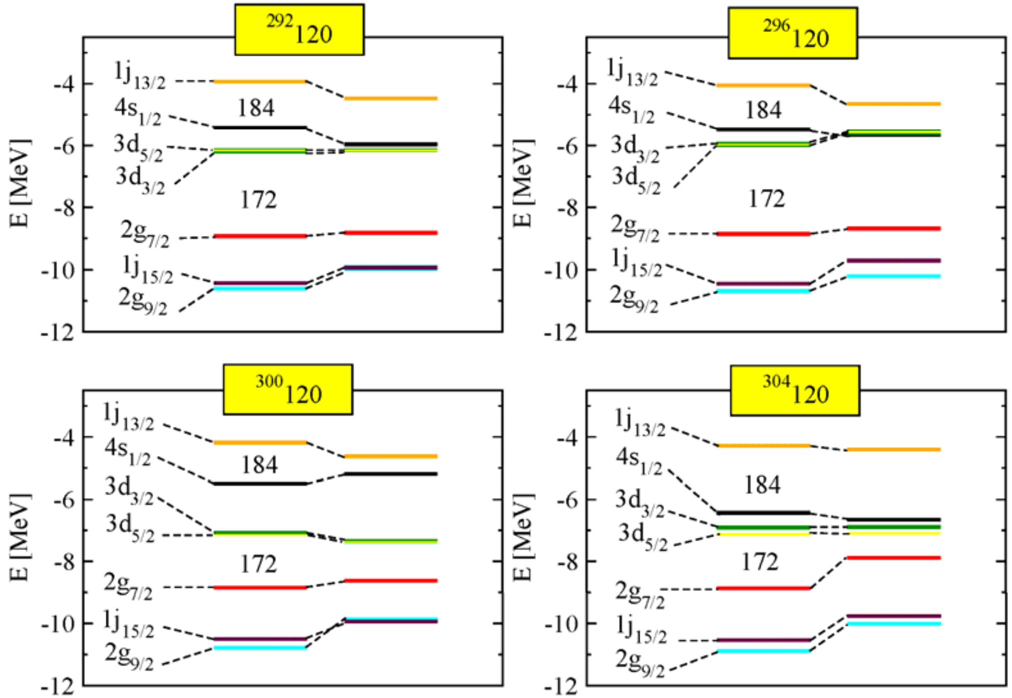
  Here ΔE not necessarily negative

- The difference matters for stability

Bender, Bertsch, Heenen, PRC**73**(2006)034322

Shell evolution in superheavy Z = 120 isotopes: Quasiparticle-vibration coupling (QVC) in a relativistic framework

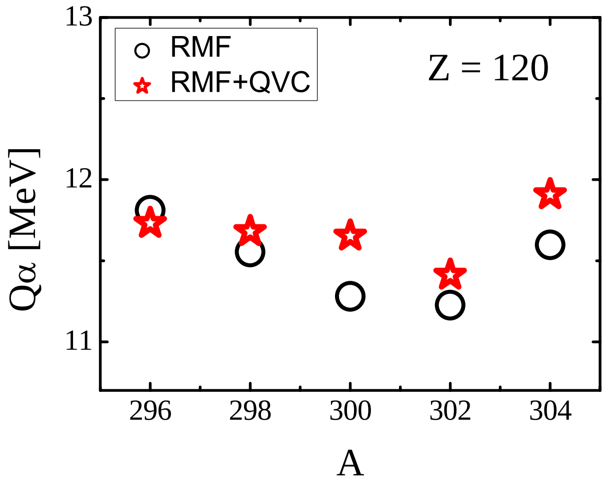
1. Relativistic Mean Field + Pairing (MF): spherical minima
2. coexistence of pairing and (sub)shell closure
3. A=300, neutrons no clear shell gap in MF (left)
4. With additional coupling to vibrational modes (right) larger gap (~100 phonons below 15 MeV)



Vibrational corrections to binding energy

$$E_{VC} = -\sum_{\mu} \Omega_{\mu} \sum_{k_1 k_2} |Y^{\mu}_{k_1 k_2}|^2$$

seen in α-decay Q-values



Vibrational corrections:

1. Impact on the shell gaps
2. Smearing out the shell effects

Shell stabilization & vibration (?)

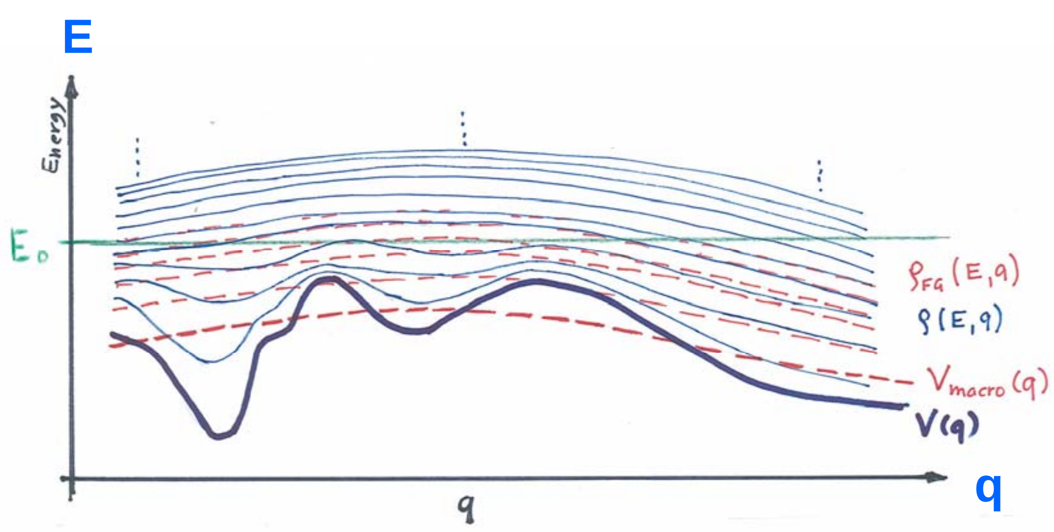
What is the situation at fission saddle ?

E.Litvinova, PRC 85, 021303(R) (2012)

Diffusive Limit

Diffusive limit:

- When collective kinetic energy negligible, system is diffusing in an energy landscape (random walk)
- Valid approximation from compound nucleus up across saddle and down to close to scission,
  only when neck snaps collective kinetic energy is picked up again



Input to diffusion model:

- V(q) with shell and pairing effects
- Level densities ρ(E,q) with shell and pairing effects
- Transition rates q → q+dq
- Consistently from unified microscopic model

Summary and Outlook

Minimum request (without dynamics):

Microscopic models should look at ground state and fission barrier to guide experiment, $V(q)$

Dynamics:

Entrance to fusion and fission: Large scale nuclear motion with fluctuations

- $V(q)$ adiabatic energy landscape
- $M_{ij}(q)$ collective inertia (mass)
- $X_i(q,p)=\Sigma_j \gamma_{ij}(q)\, p_j + \delta X_i(t)$ dissipation, fluctuation

Get macroscopic transport properties from one microscopic picture, consistent and unified

Simplification: Diffusive motion (e.g. escape from compound nucleus down to scission):

- $V(q)$
- Level density
- Transiton rates $q \longrightarrow q+dq$

Get all from one microscopic picture in a consistent and unified way