Fission -
A complete laboratory

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Joliot-Curie School
“Physics on the femtometer scale”

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Lay out

- From discovery to application
- Quasi-bound and unbound regions
  (Challenges to describe a decaying system)
- Selected features
  (New results, new ideas)
  - Mass distributions
  - Prompt neutron yields
  - Even-odd effect in Z yields
- Experimental approaches
  (Recent achievements and plans)

Discovery of fission

O. Hahn, F. Straßmann, Naturw. 27 (1939) 89

U + n → identification of Ba

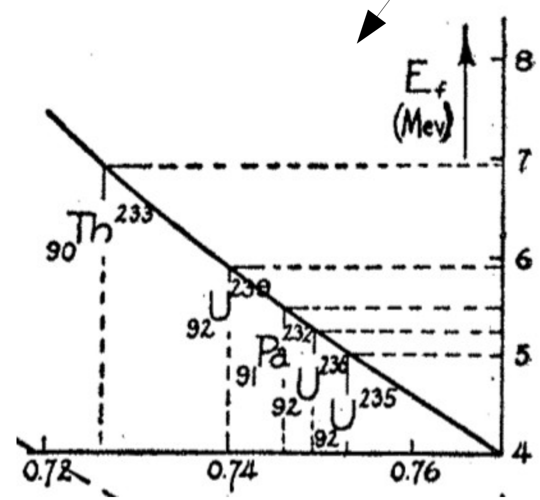
Image: Wikipedia

N. Bohr, J. A. Wheeler, Phys. Rev. 56 (1939) 426

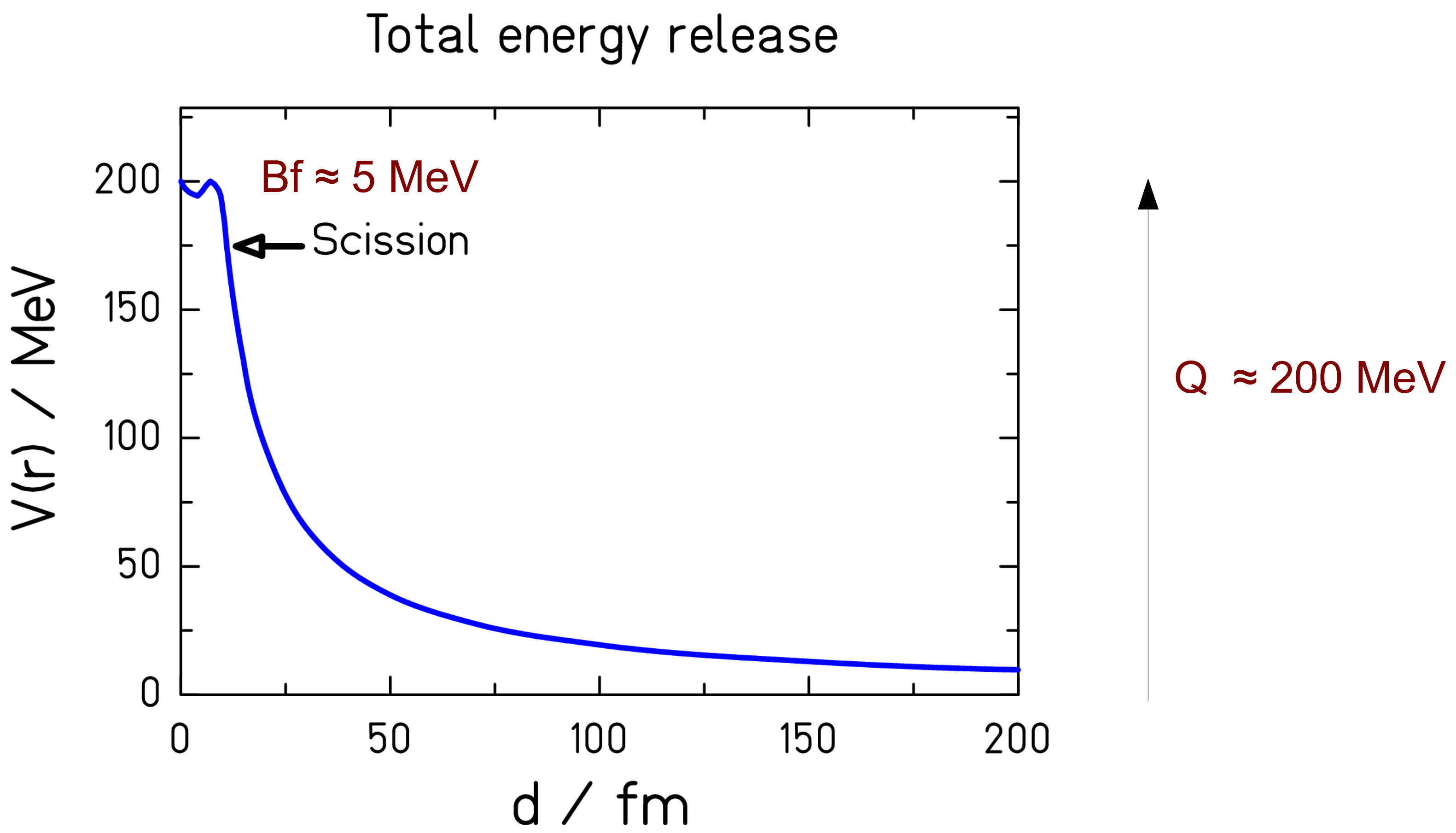
Estimation of Q value and B_f

Original	Two Products	Division	Subsequent
$_{28}Ni^{61}$	$_{14}Si^{30,\ 31}$	−11	2
$_{50}Sn^{117}$	$_{25}Mn^{58,\ 59}$	10	12
$_{68}Er^{167}$	$_{34}Se^{83,\ 84}$	94	13
$_{82}Pb^{206}$	$_{41}Nb^{103,\ 103}$	120	32
$_{92}U^{239}$	$_{46}Pd^{119,\ 120}$	200	31

Decay heat



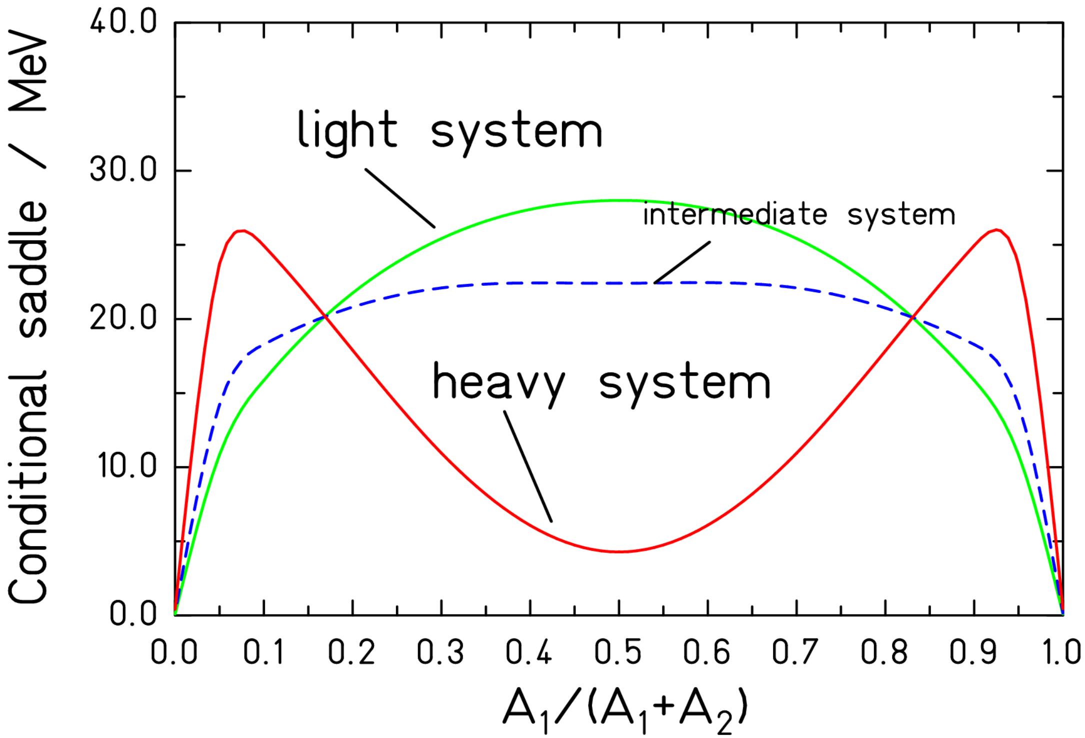
Fissionable nuclei are hardly bound



Inside scission point:
Nuclear + Coulomb potential

Outside scission point:
Coulomb potential (1/r)

Why was the discovery of fission a surprise?



Light nuclei are governed by surface energy (like any uncharged liquid).
The Coulomb repulsion of *homogeneously charged* nuclei drives heavy nuclei apart.
Low barrier for symmetric split.

Energy release by fusion or fission

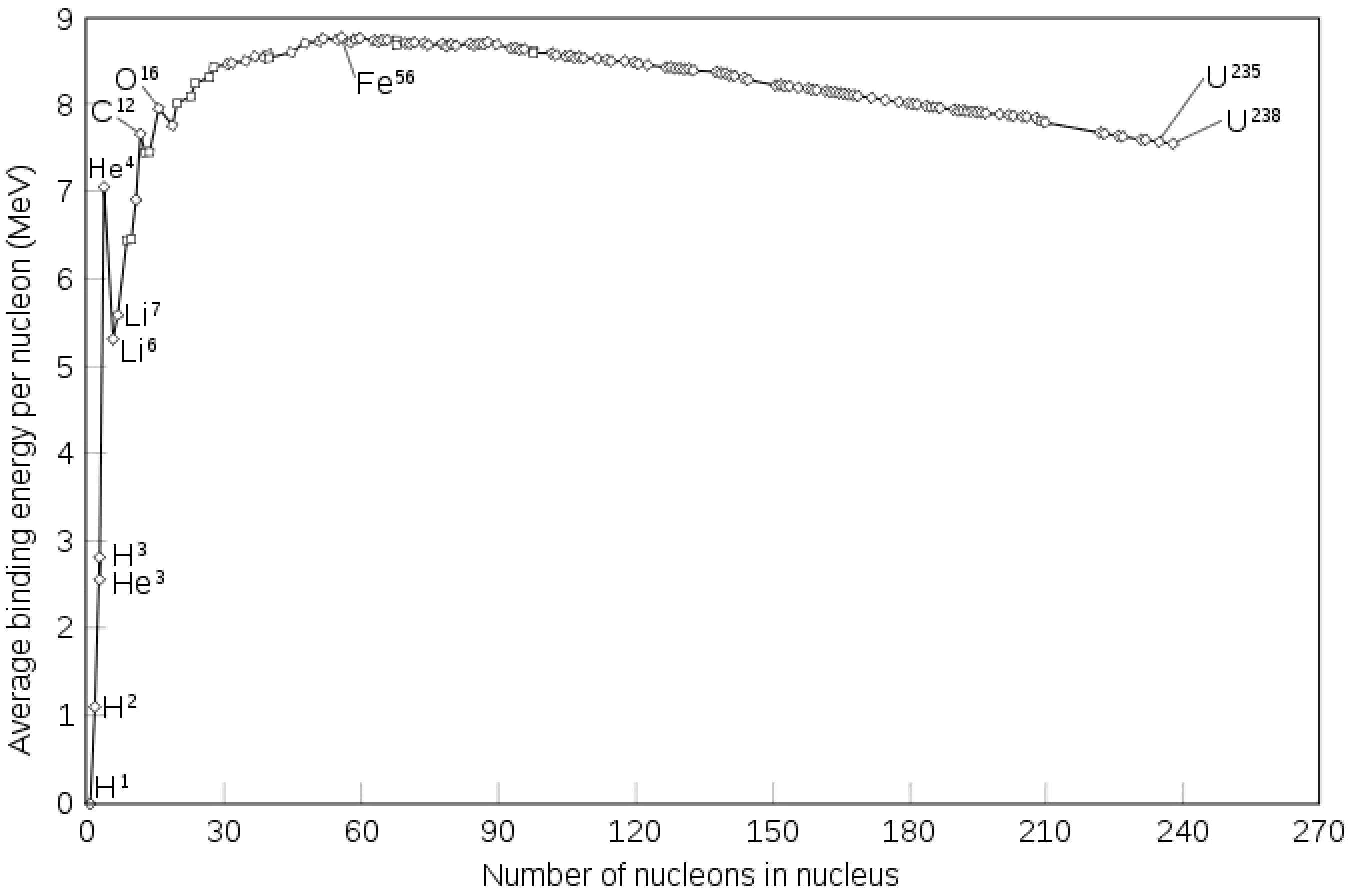
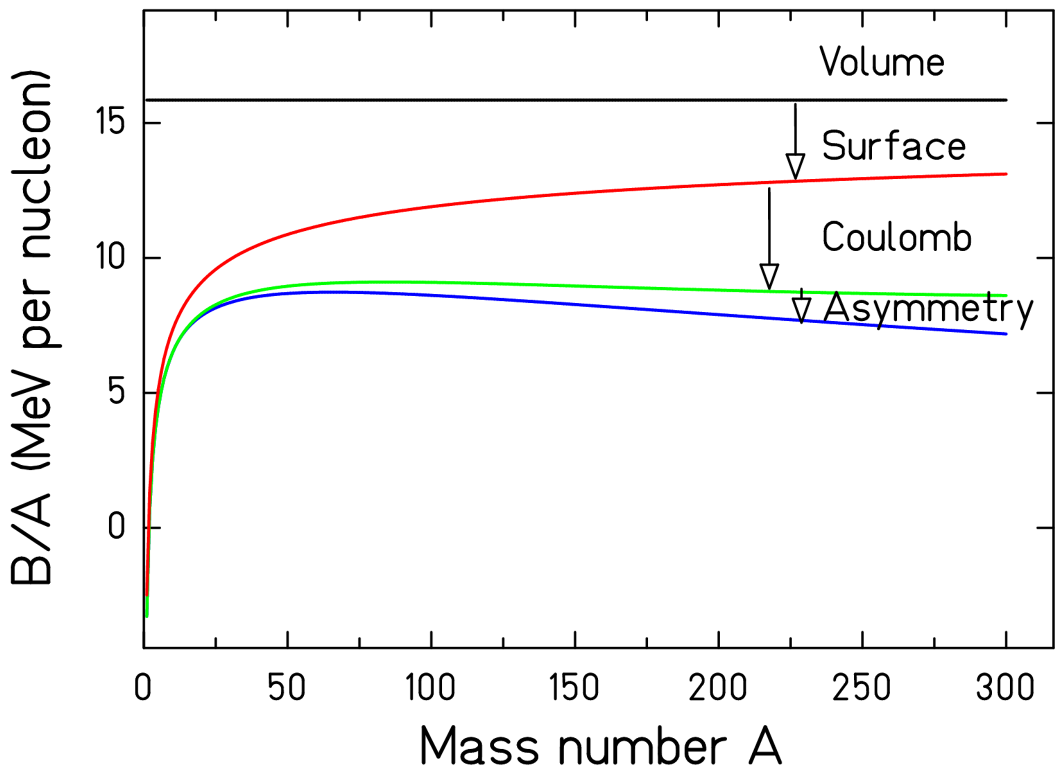


Image: Wikimedia Commons

Light nuclei and heavy nuclei are “fuel”. (Fusion or fission reactors)

Q value ≈ 200 MeV for fission of ^{235}U. (Large energy density!)

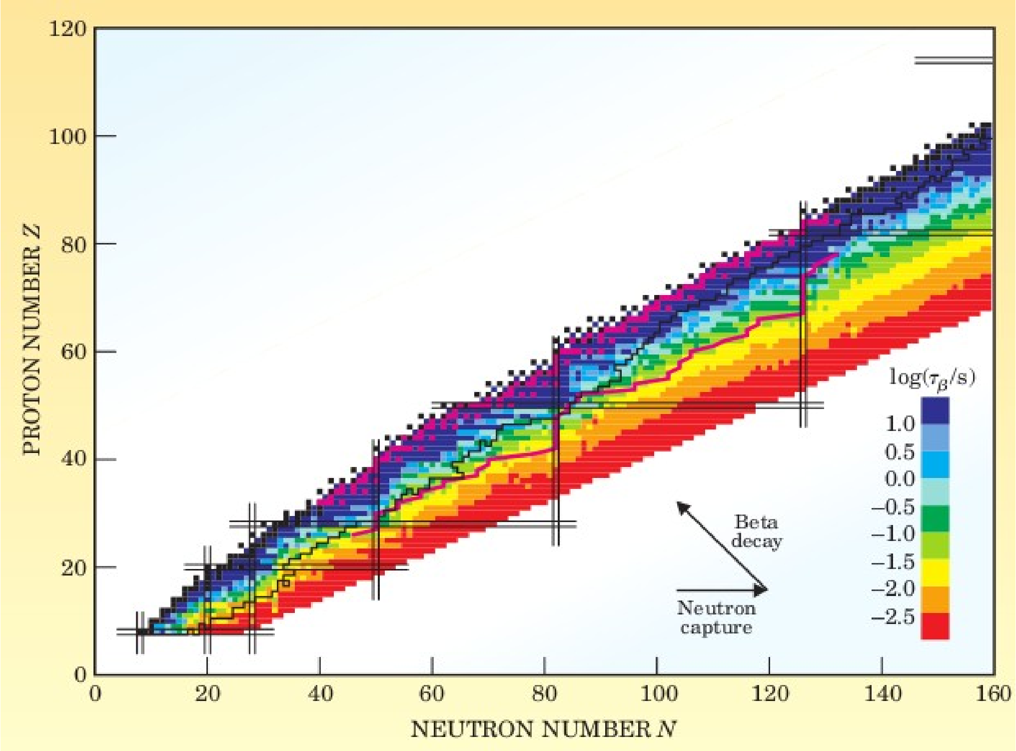
Binding energy (liquid drop model)



Surface energy decreases binding of *light* nuclei.

Coulomb energy decreases binding of *heavy* nuclei.

Origin of the stored energy



R. J. Cowan, F-K. Thielemann, Physics Today, 2004

Neutron capture in r-process.

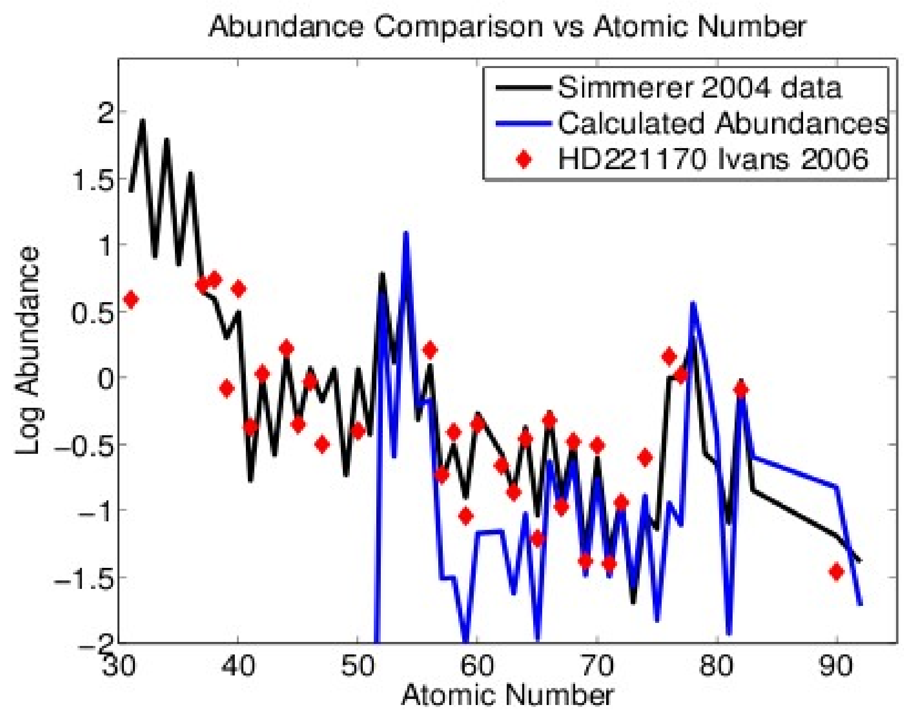
Huge neutron flux during a few seconds.

(Late stellar burning, supernova, other cosmic scenarios?)

r-process reaches to ^{238}U and beyond (SHE) → fission cycling

s-process stops at ^{209}Bi !

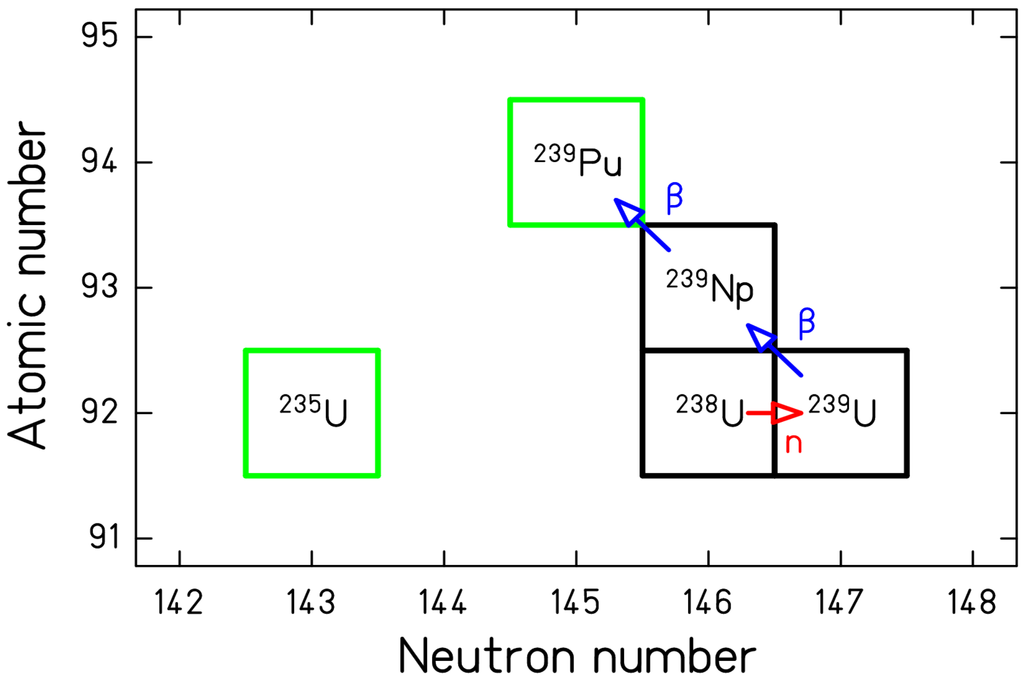
Fission cycling in the r process



J. Beun et al., arXiv/0607280 (2006)

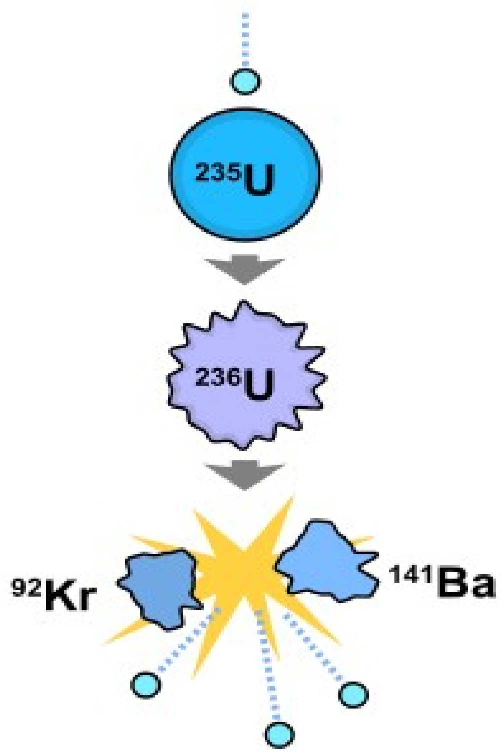
How far does the r process reach?
Is there “fission cycling”? → Traces in the element distributions!
Knowledge of fission barriers and fission-fragment distributions missing for nuclei on the r-process path.

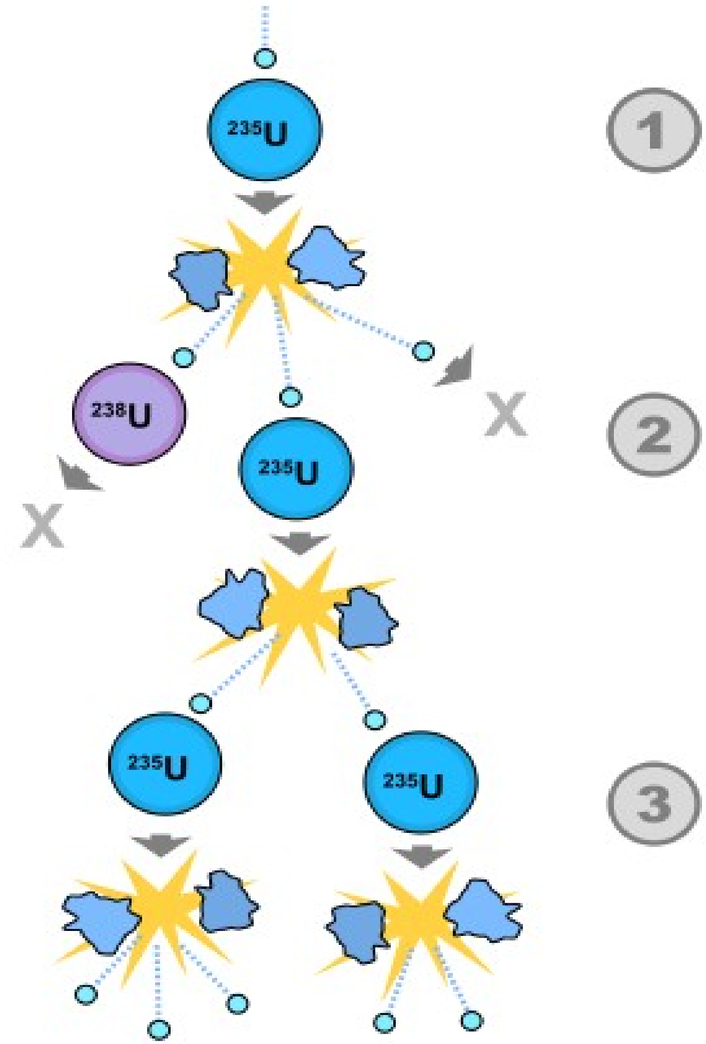
Breeding in a fission reactor



Man-made element synthesis in a reactor:
Neutron capture on ^{238}U as seed.
Production of ^{239}Pu and “minor actinides”.
Problems of radioactive waste and proliferation.

Induced fission and chain reaction

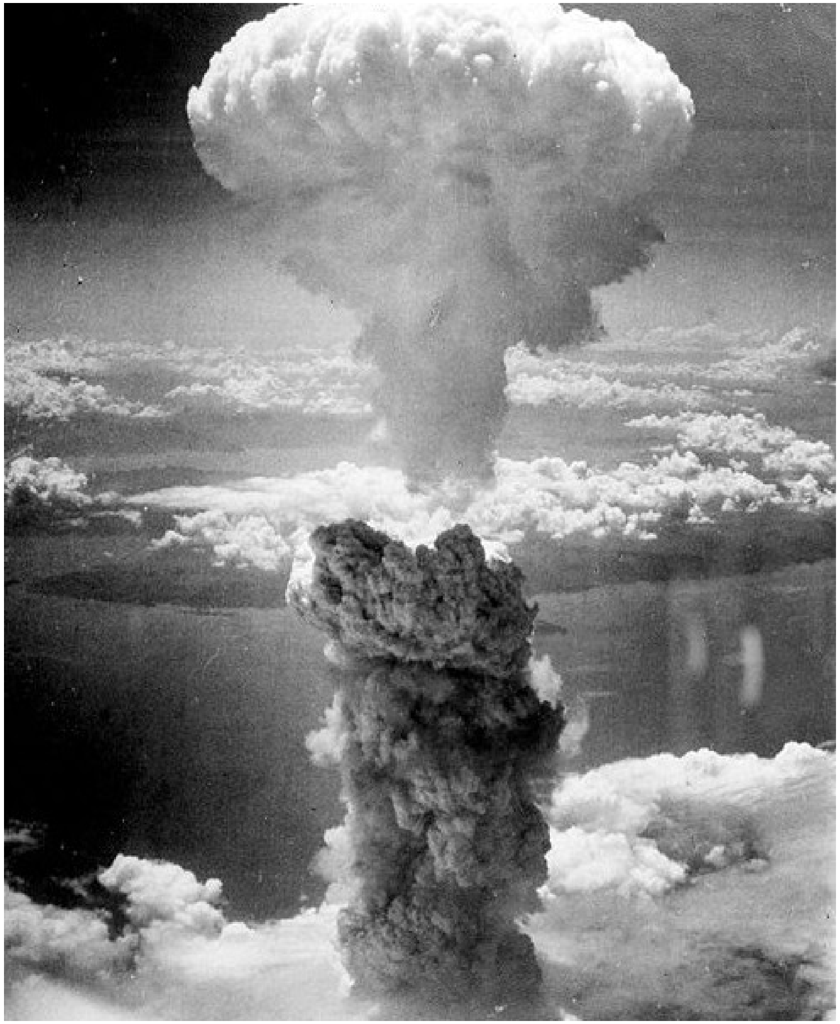




Images: Wikimedia Commons

Prompt neutrons induce controlled or explosive burning.

Use and abuse



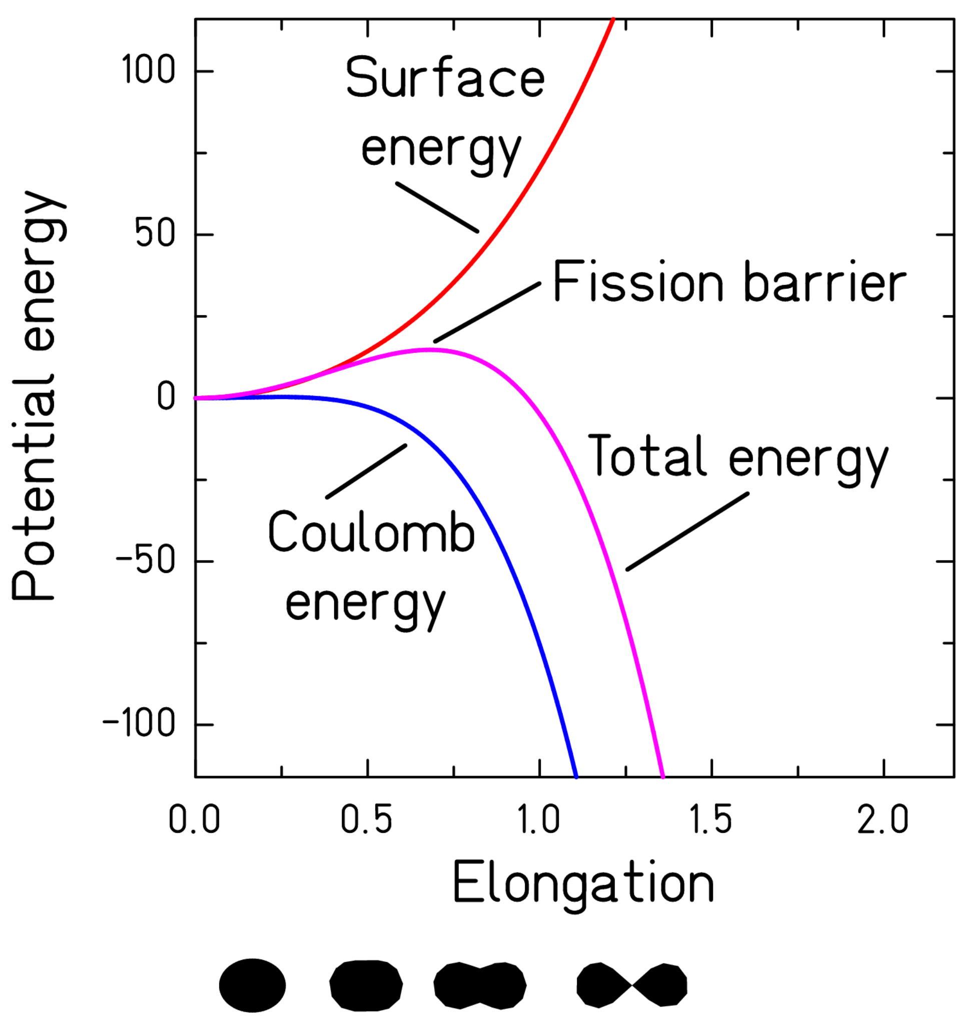
Images: Wikimedia Commons

Gigantic energy release.

Closer view on the physics of fission

(Selected aspects)

Stabilization by the fission barrier
(liquid drop)



Fission barrier vanishes for $Z^2/A > 50$

Small deformations:

$$\Delta E_s = E_{s0}\left(\frac{2}{5}\alpha_2^2 - \frac{4}{105}\alpha_2^3 \ldots\right)$$

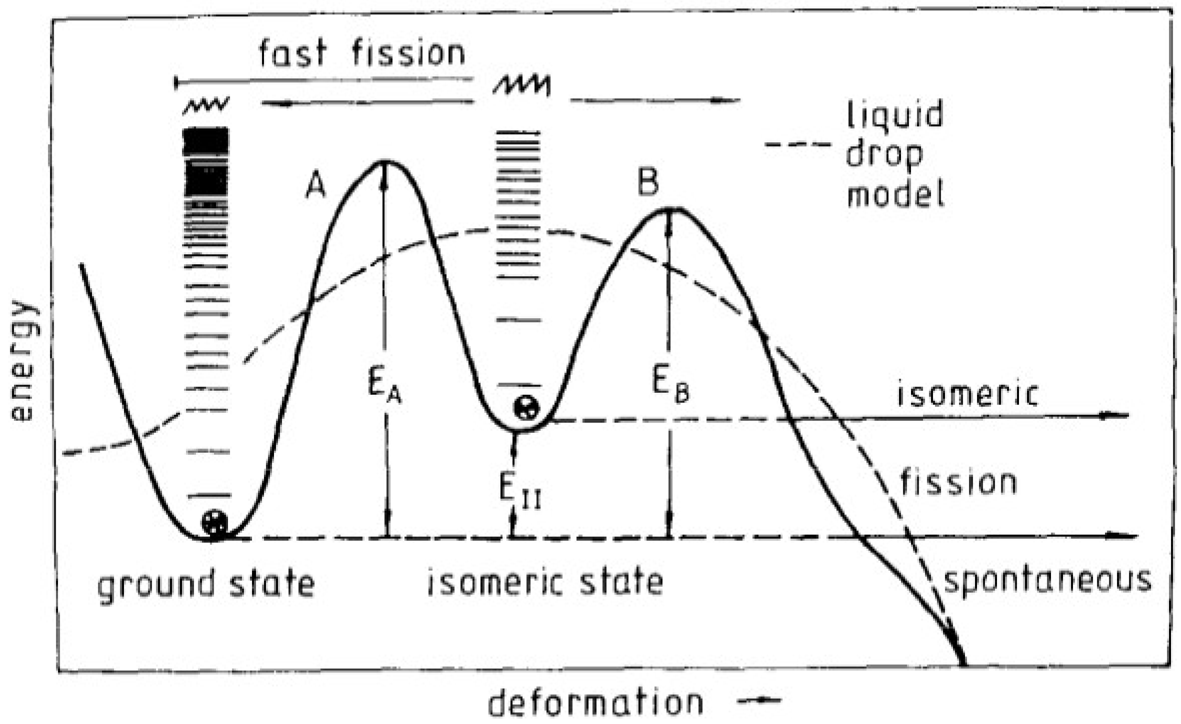
$$\Delta E_c = E_{c0}\left(\frac{1}{5}\alpha_2^2 - \frac{4}{105}\alpha_2^3 \ldots\right)$$

Surface and Coulomb energy → different behaviour.

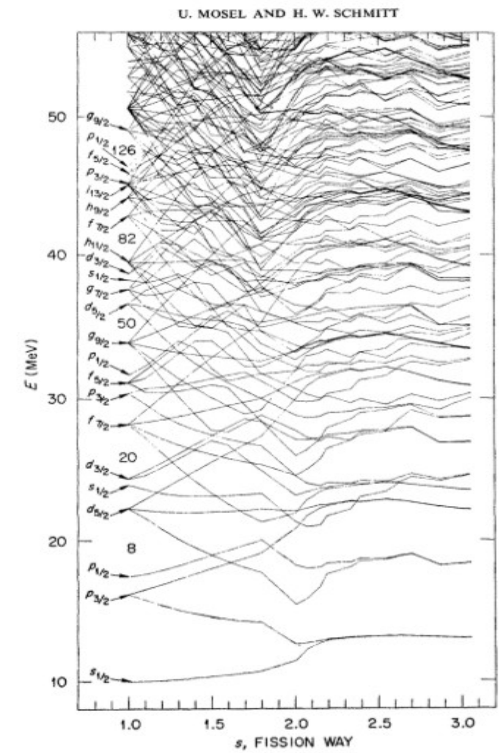
Large deformation:
Minimization in complex deformation space to find fission saddle.

Shell effects

Single-particle energies



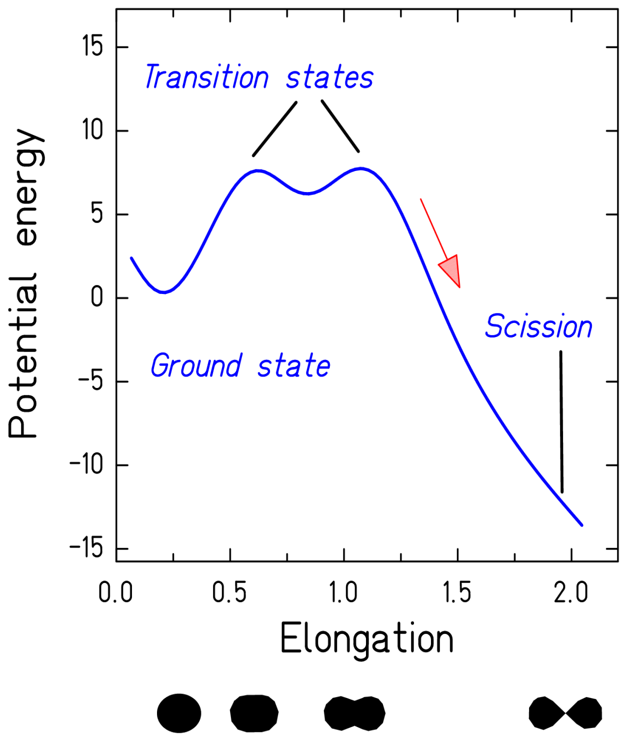
V. Strutinsky, Nucl. Phys. A 502 (1989) 67



Mosel and Schmitt,
Nucl. Phys. A 165 (1971) 73

- Shell effects modulate the liquid-drop energy (≈ 1%).
- Periodic in deformation, particle number etc.
- Defined by macroscopic-microscopic approach
  (Strutinsky method).

Potential on the fission path



Around ground state and second minimum: (quasi)-bound system

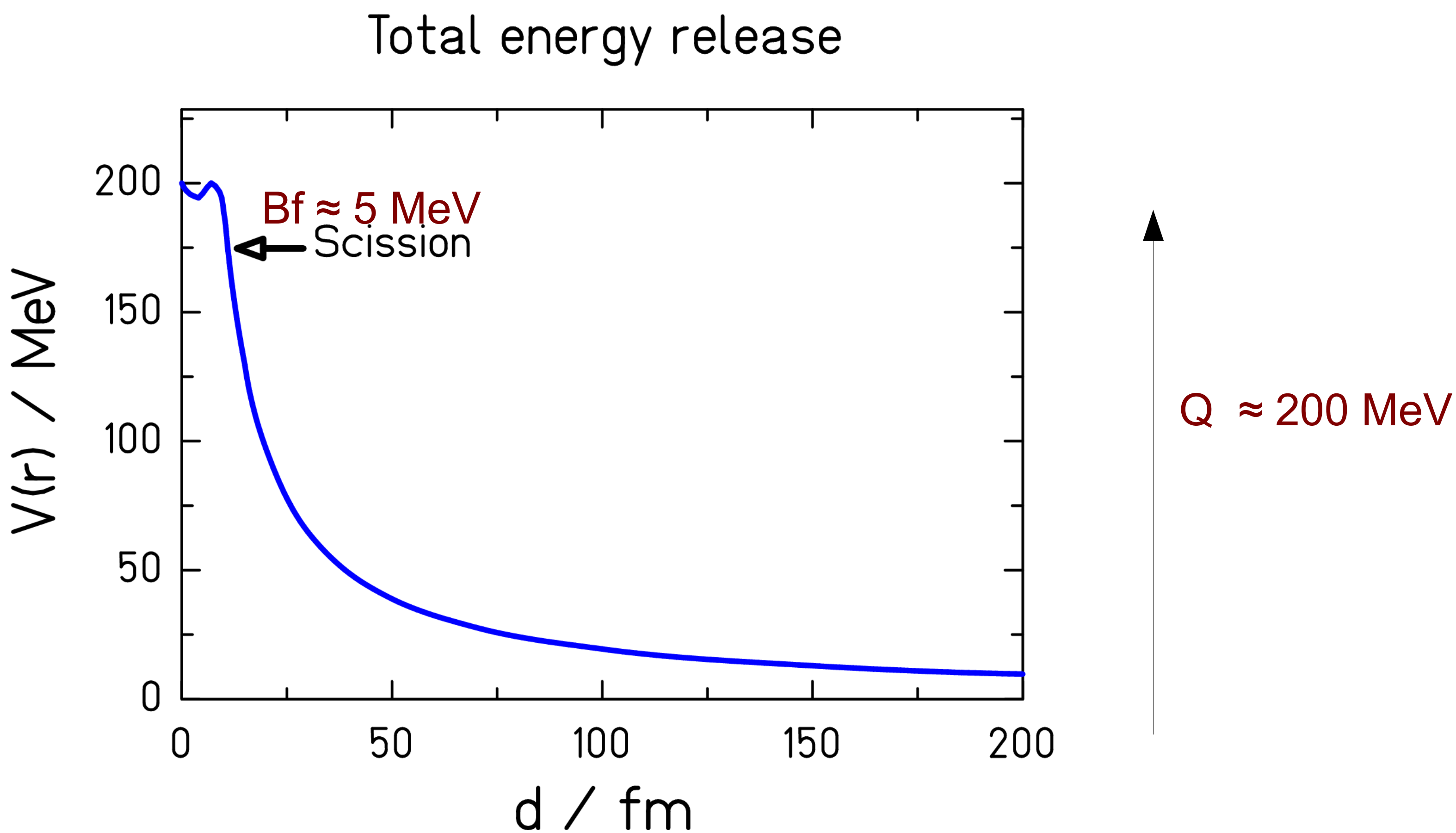
Above inner and outer barrier:
transition states (doorway states towards fission)

Beyond outer barrier:
unbound, no return,
descend towards scission

In all other collective coordinates:
(e.g. mass asymmetry, *N*-*Z*)
the system is bound!

Fission is a unique laboratory for a decaying mesoscopic system!

Fissionable nuclei are hardly bound

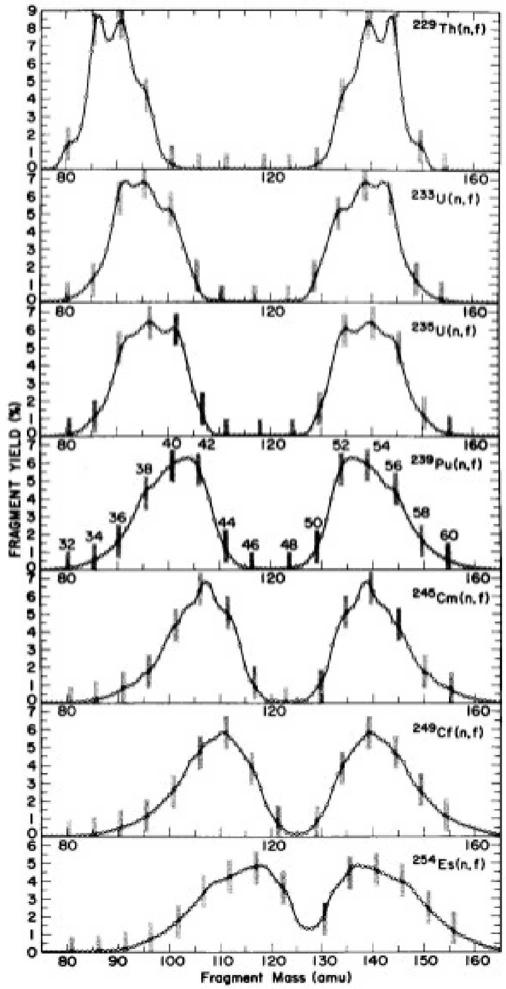


Fission is driven by a transformation of potential energy into other forms of energy, finally mostly ending up in kinetic and thermal energy.
→ Dissipative process + quantum mechanics.

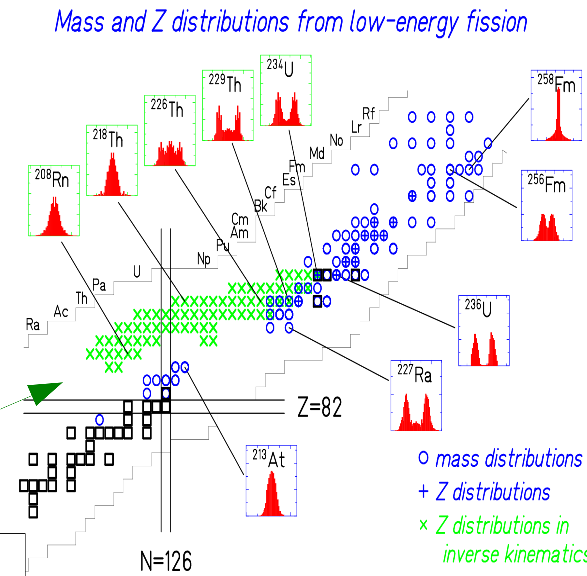
Observables:

1. Mass distribution of fission fragments

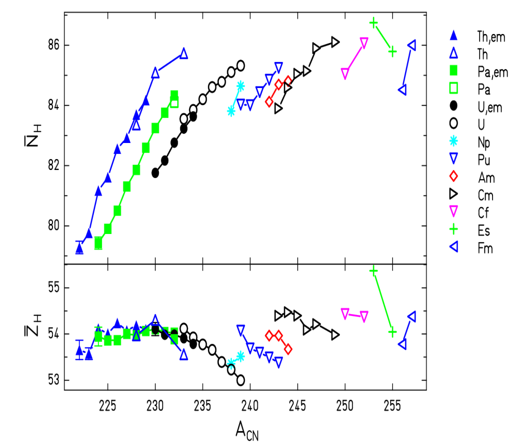
Division in asymmetric fission



J. P. Unik et al. Rochester (1973):
Asymmetric fission of most actinides.
Position of the heavy peak is stable in mass (A=140).
1% in BE → Huge effect in yields!

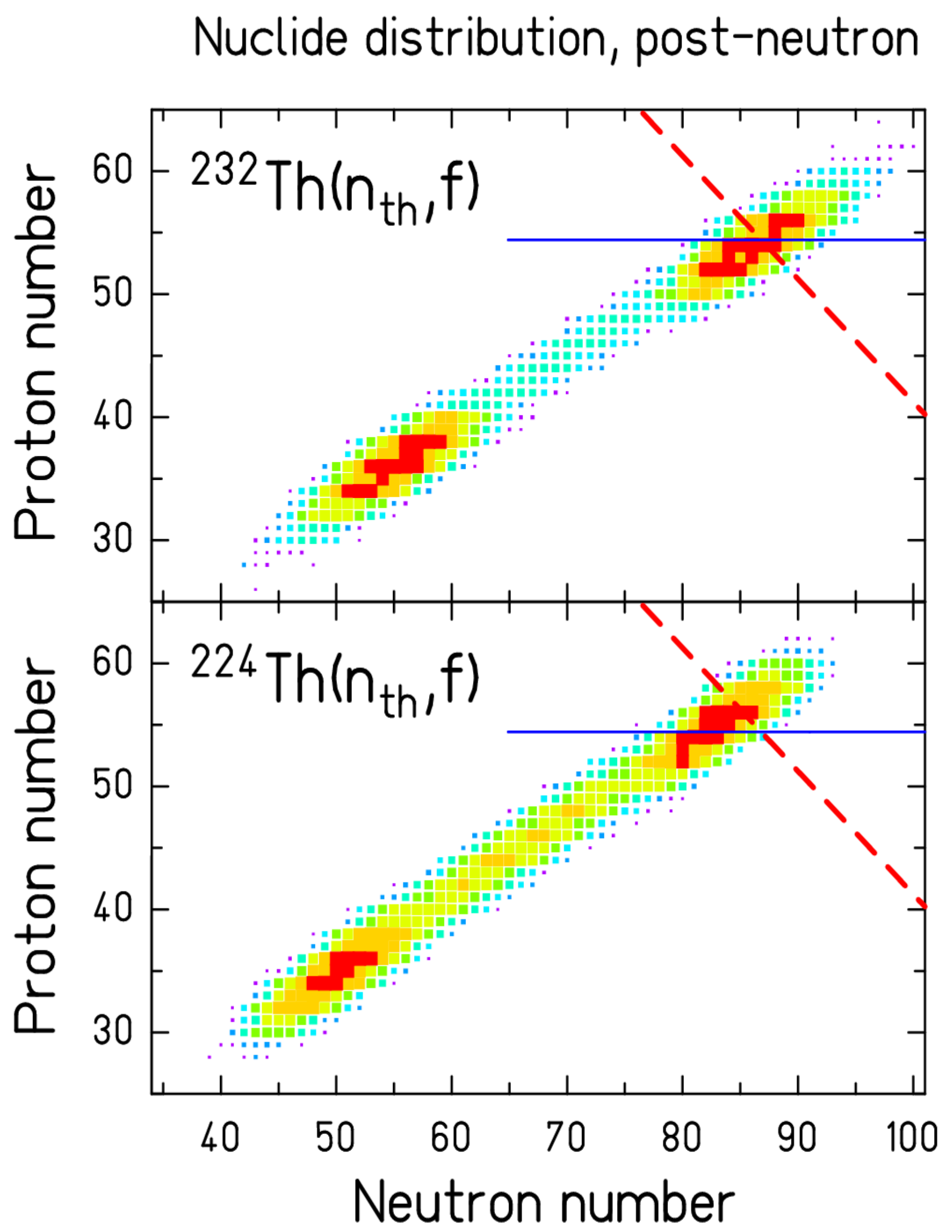


GSI experiment (2000) with Coulomb fission of relativistic secondary beams.



Refined analysis, new data:
(Böckstiegel et al. (2008): Position of heavy peak is stable in *Z* (*Z*=54).

A = 140 vs *Z* = 54



Fixed position at *Z*=54 revealed from data over long isotopic chains!

Nuclide distributions calculated with the GEF code (adapted to empirical systematics)

Theoretical approaches on mass distributions in fission

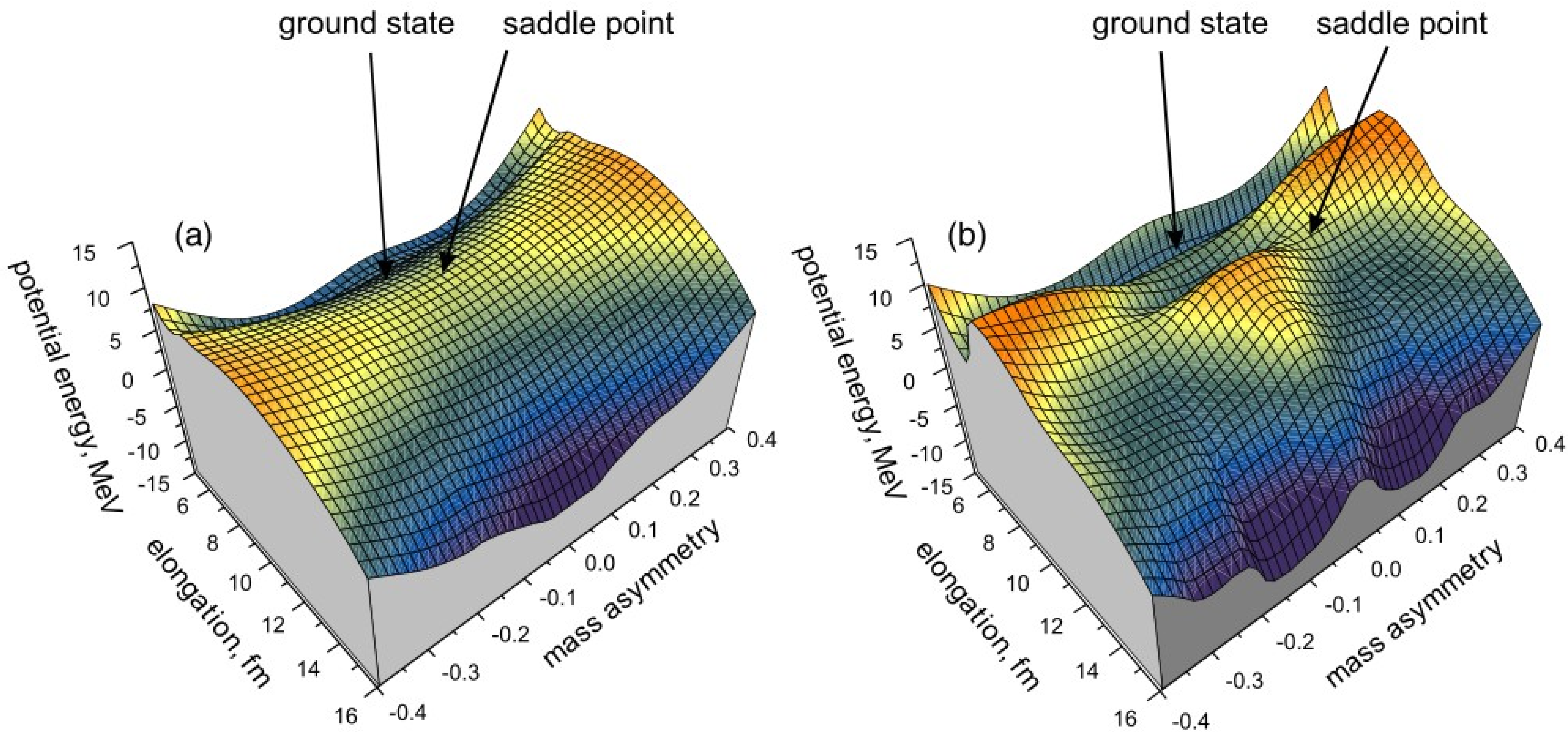
Static:

- Potential-energy landscape

Dynamic:

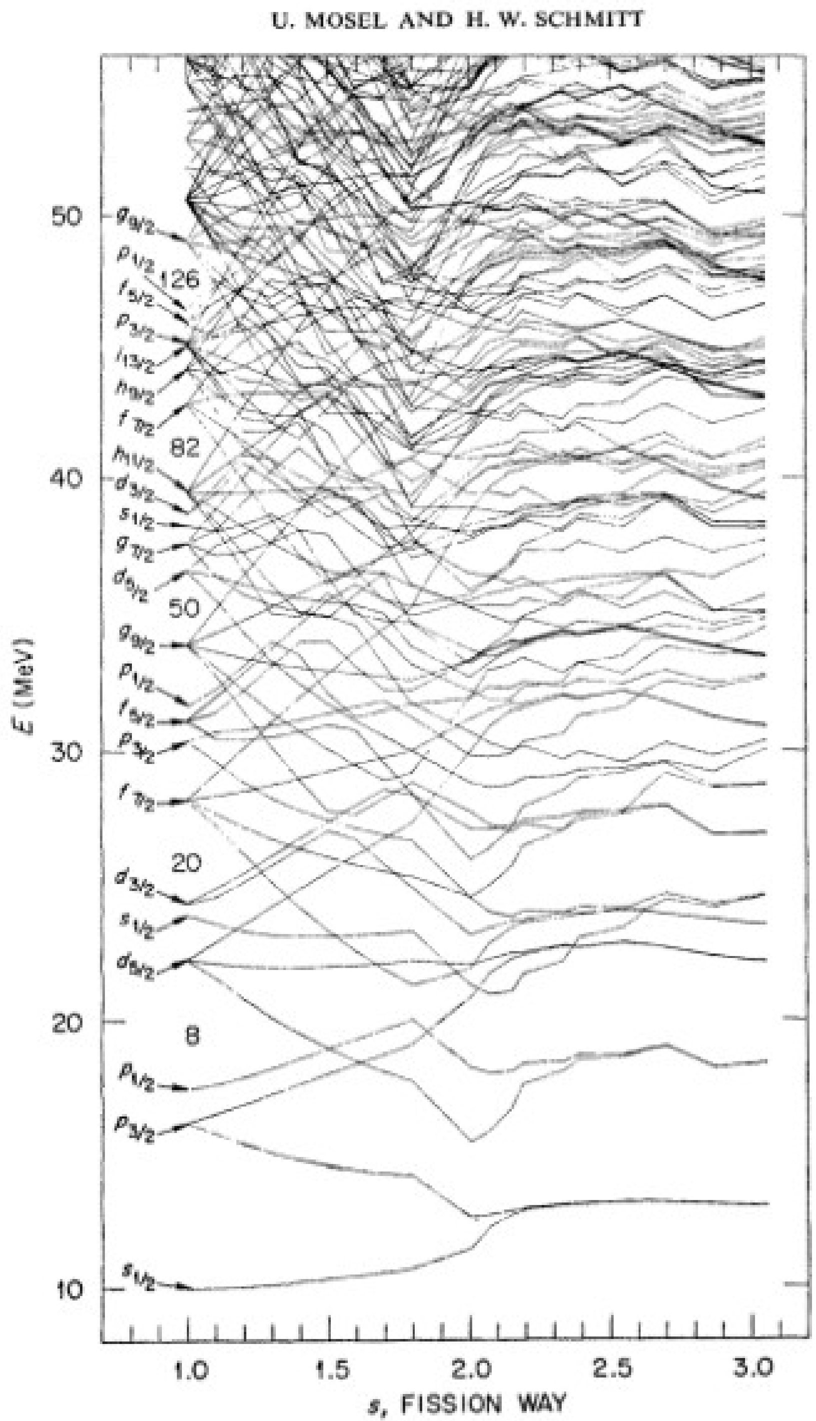
- Classical dissipation model
- Microscopic model

Two-centre shell model



Macroscopic + microscopic

Karpov et al., J. Phys. G 35 (2008) 035104

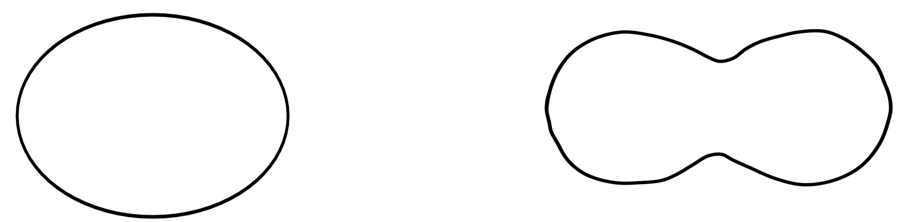


Influence of fragment shells

Single-particle levels in a two-centre shell-model calculation.

For s > 1.8, the wave functions of opposite parity become degenerate.

s = 1.7 : outer barrier



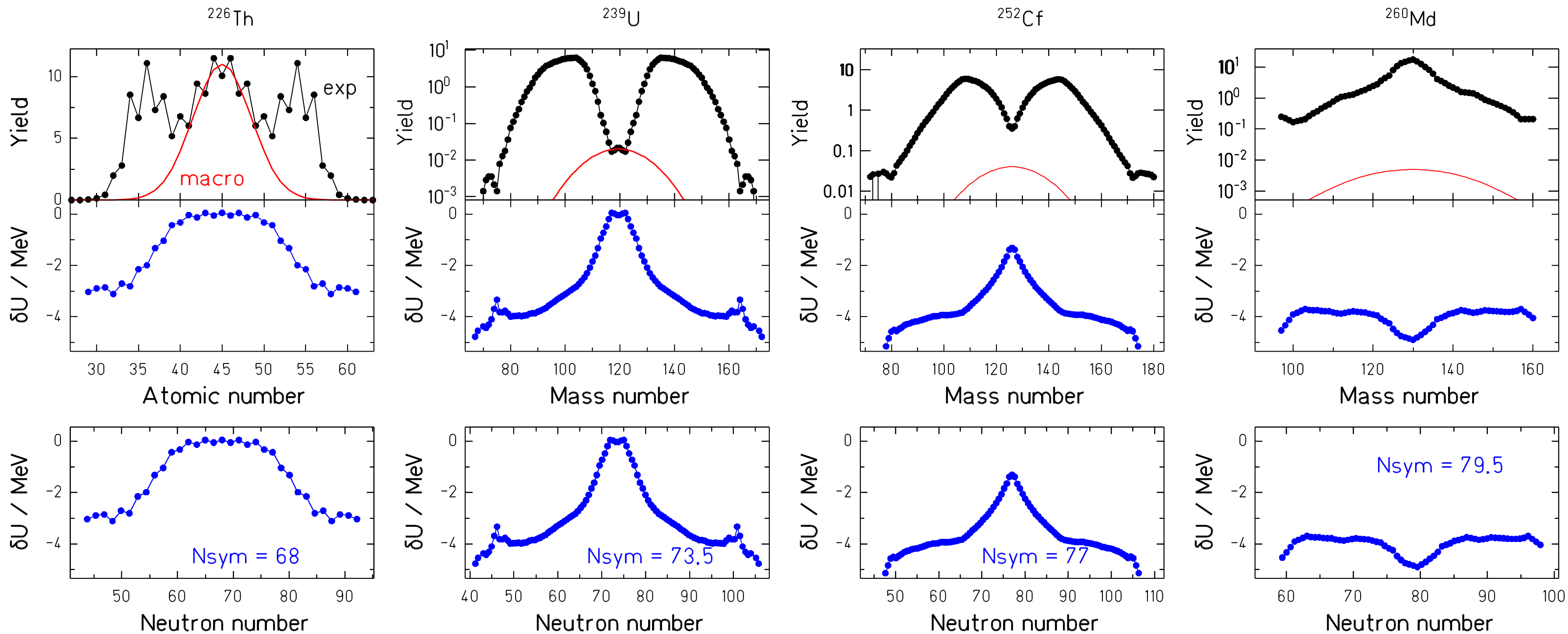
Qualitative change of wave functions !

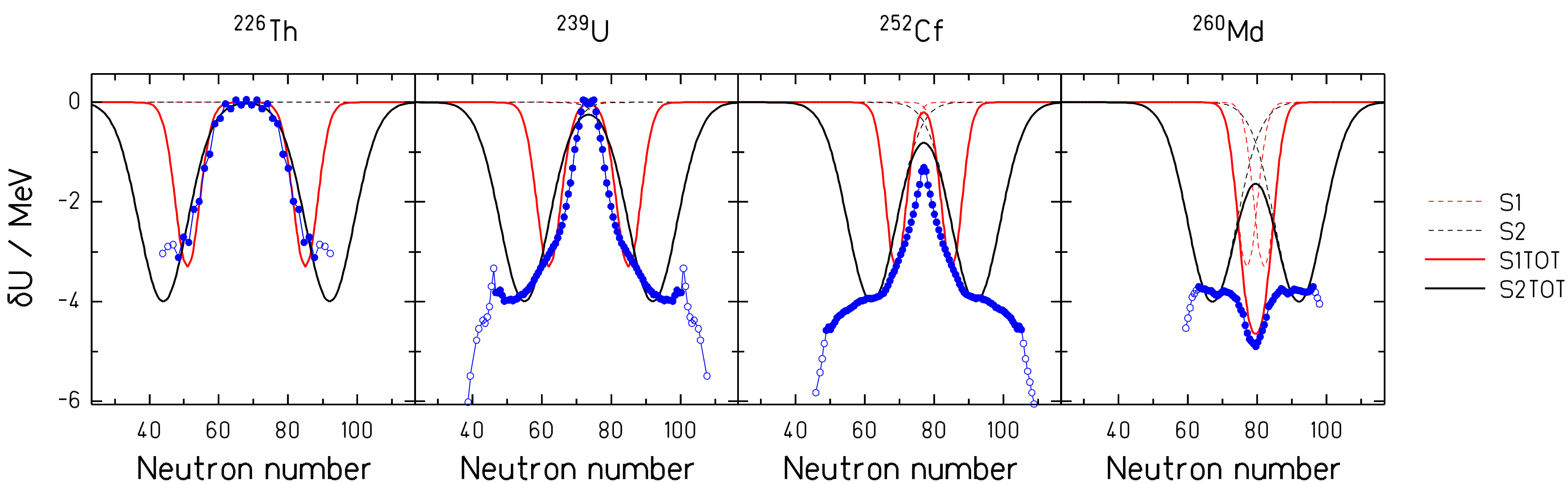
Nucleons are localized in the fragments very early

Mosel and Schmitt, Nucl. Phys. A 165 (1971) 73

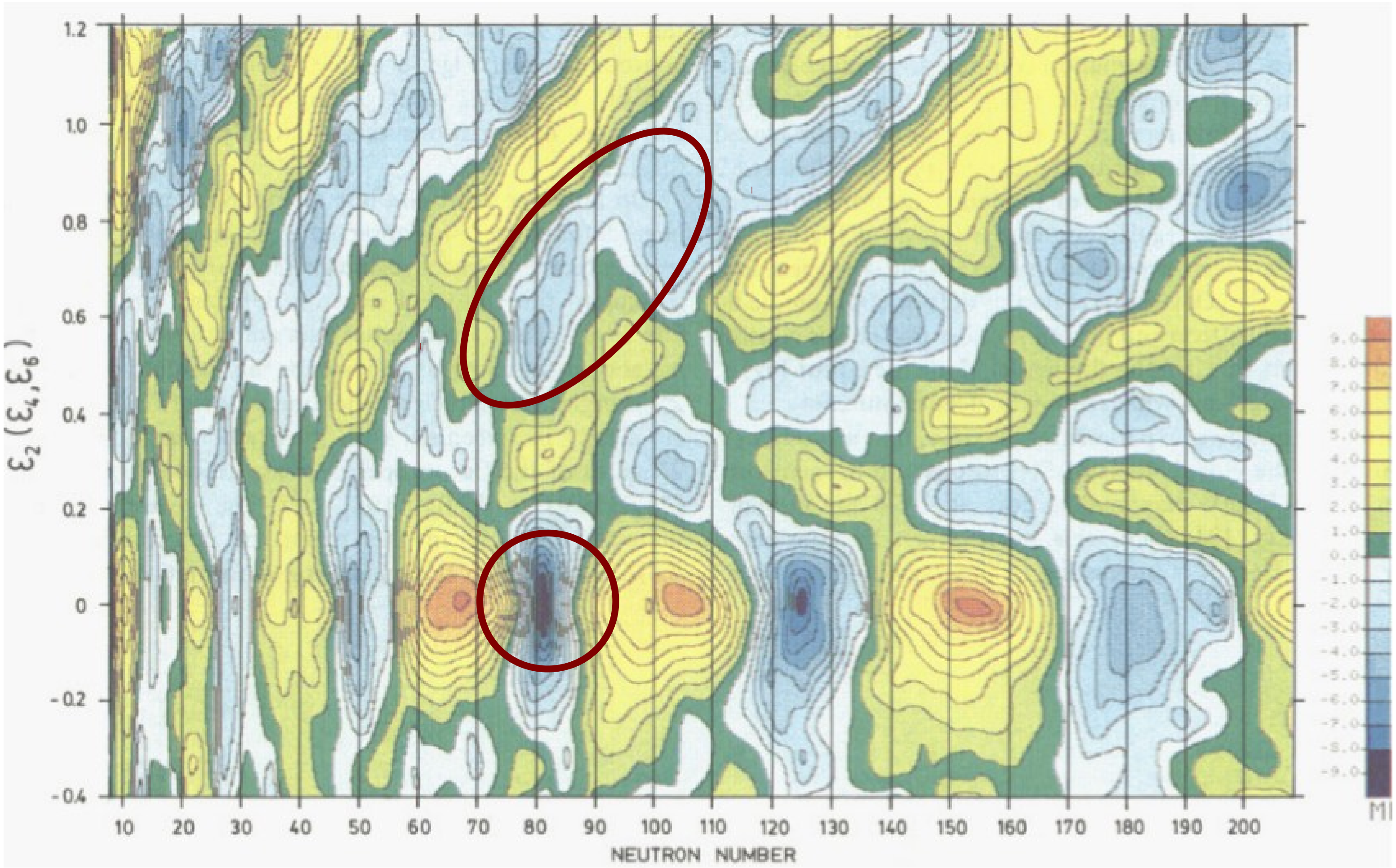
Separability principle

mac (CN) + mic (fragments) : same fragments → same shells!





Features of fragment shells: neutrons

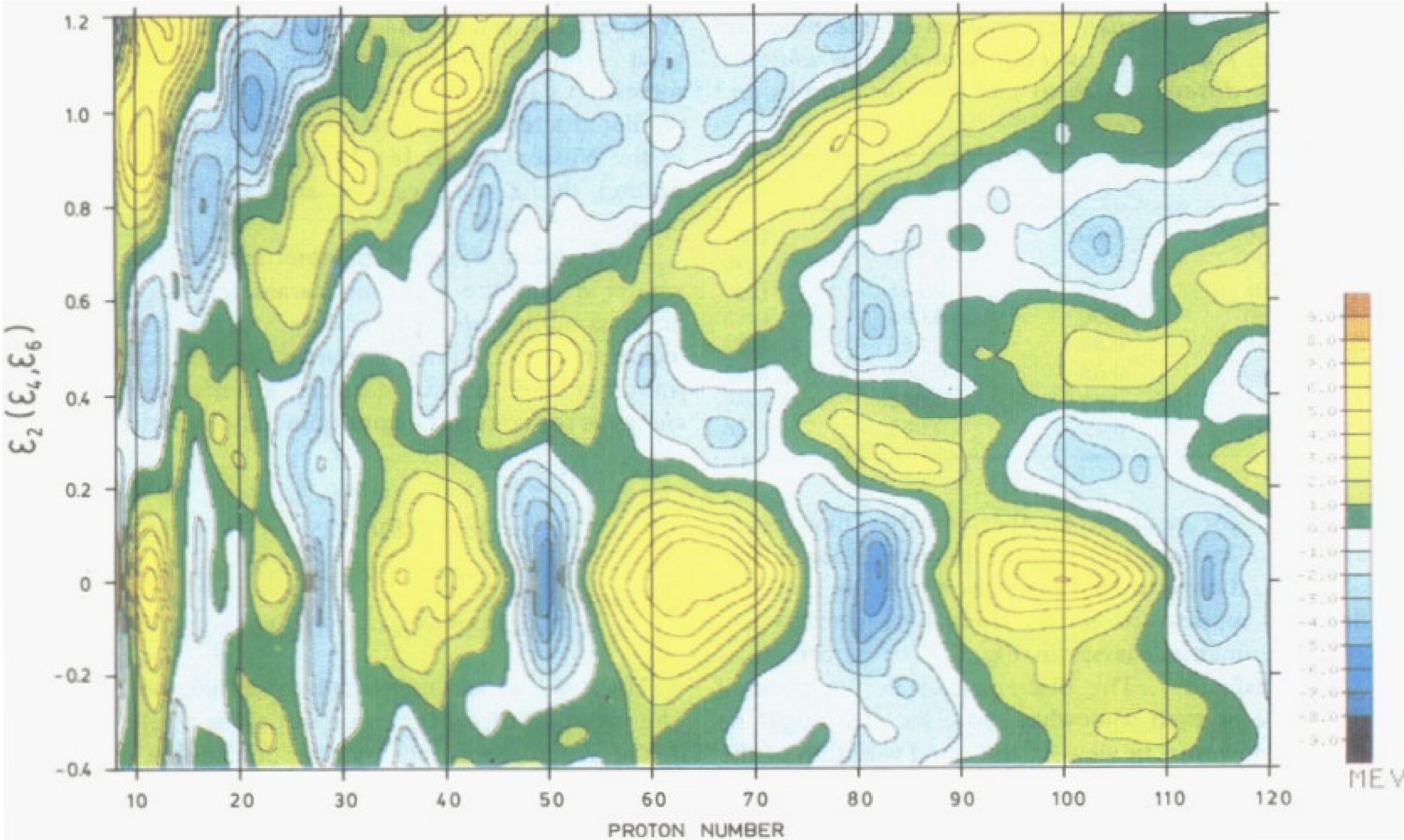


I. Ragnarsson et al., Phys. Scr. 29 (1984) 385,

Theory: Asym. fission attributed to N=82 and N≈90.

Incompatible with constant position at Z=54?

Features of fragment shells: protons



I. Ragnarsson et al., Phys. Scr. 29 (1984) 385

No indication for shell near Z = 54!

→ Challenge for theory.

Dynamical approach 1
Classical dissipative mechanics

Full treatment of all nuclear degrees of freedom too complex! ->
Explicit treatment of (a few) slow collective variables.
The other degrees of freedom are considered by a heat bath.

Langevin equations (simplified):

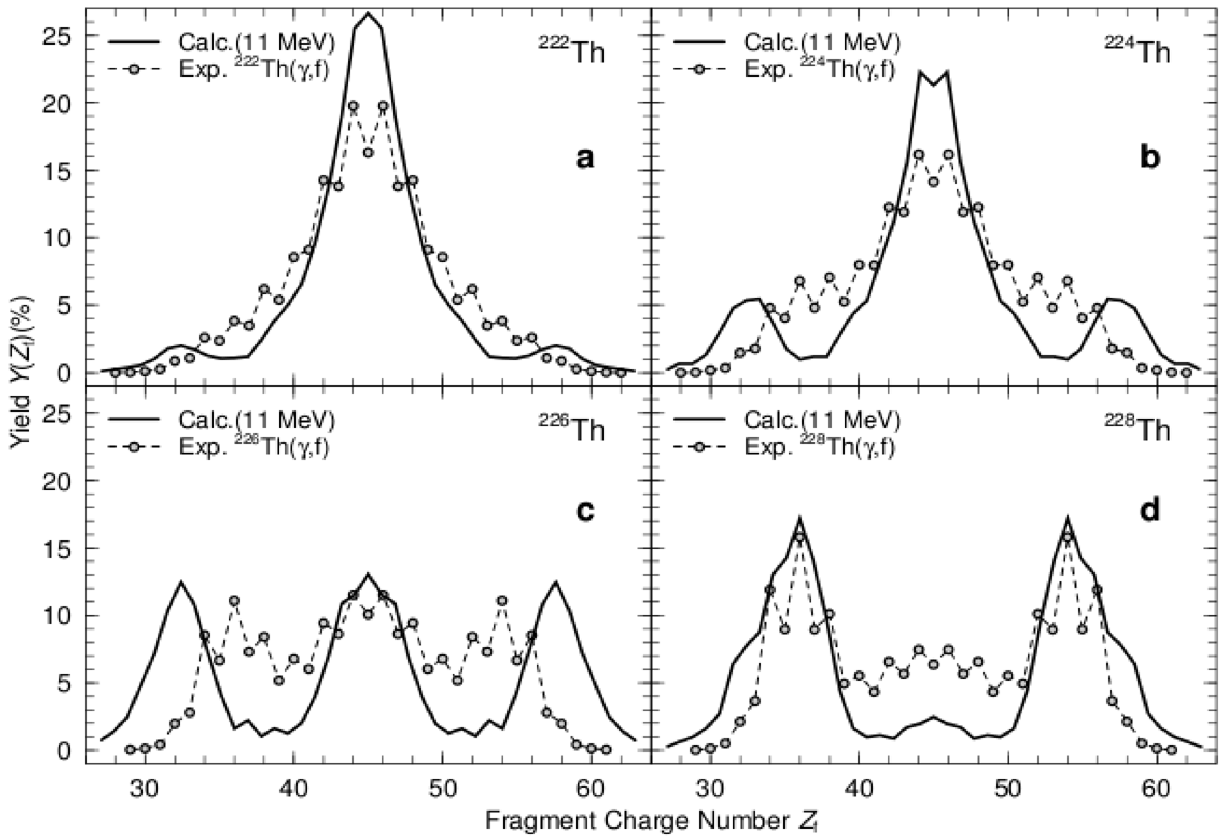
Change in "position" q is determined by momentum q:

$$\frac{dq}{dt} = \frac{p}{\mu(q)}$$

Change in momentum is determined by the forces:
inertia potential friction fluctuating term (heat bath)

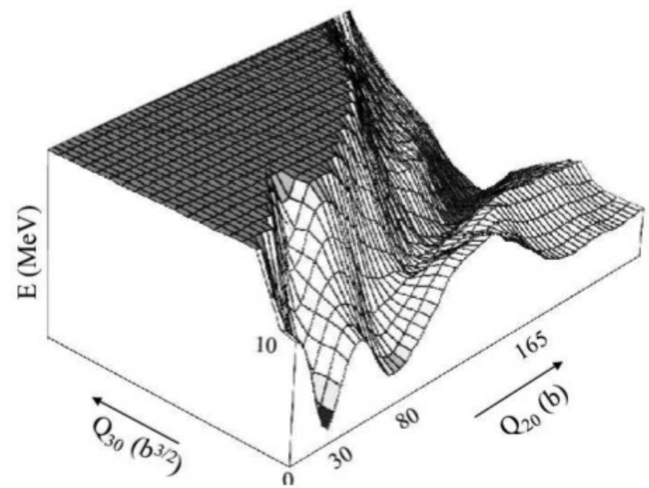
$$\frac{dp}{dt} = \frac{1}{2}\left(\frac{p}{\mu(q)}\right)^2 \frac{d\,\mu(q)}{dq} - T\frac{dS(q)}{dq} - \frac{\gamma(q)}{\mu(q)}p + \sqrt{D(q)}\,f_L(t)$$

Comparison with data



Randrup and Möller, Pys. Rev. Lett. 106 (2011) 132503
5-dimensional potential-energy surface, *N*/*Z* fixed,
simplified (overdamped) diffusion calculation
(Long computing times, 8 systems calculated.)

Dynamical approach 2
microscopic HFB - GCM



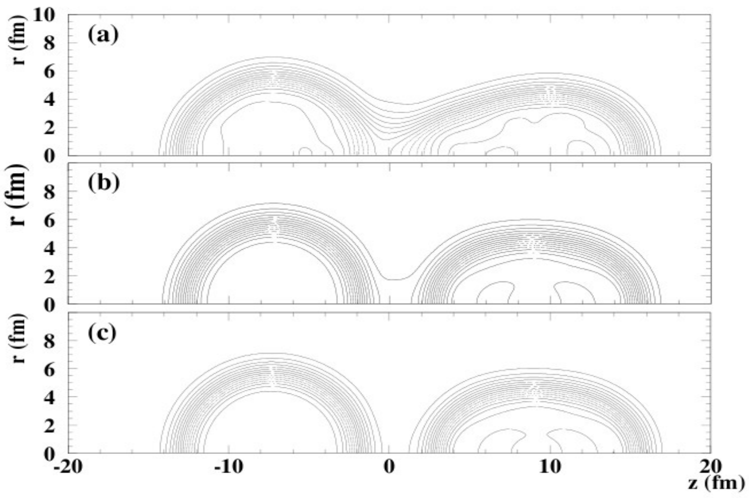
Constrained
(elongation, mass asymmetry)
time-dependent self-consistent
calculation.

Fully quantum-mechanical approach.

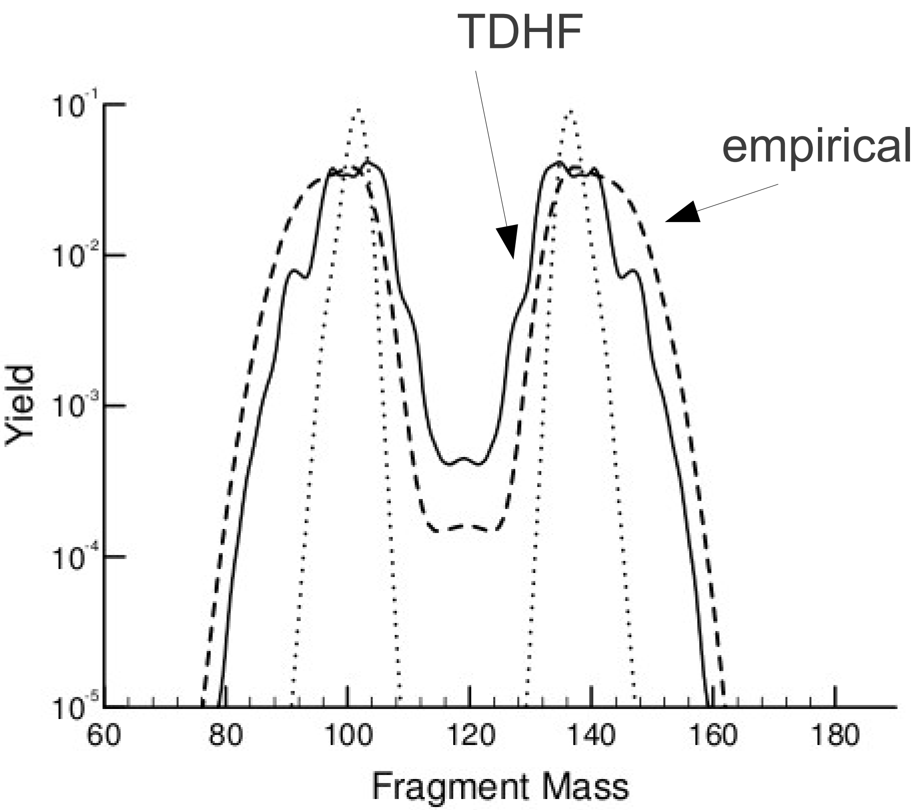
Dynamics does not yet allow for dissipation (transition from potential/kinetic energy to single-particle excitations).

H. Goutte et al., Phys. Rev. C 71 (2005) 024316

Results



Dynamics around scission.



Mass distribution
(^{238}U, 2.4 MeV above Bf)

No dissipation, *N*/*Z* fixed,
Requires long computing times.
No other systems calculated
up to now.

H. Goutte et al., Phys. Rev. C 71 (2005) 024316

Models on fission dynamics: Status

Calculated potential-energy landscapes explain gross features of the mass distributions (e.g. symmetric-asymmetric components).

Advanced dynamical theories are far from studying and explaining detailed and systematic experimental findings
(e.g. the constant position at Z=54 of the heavy fragment).

Problem: Most highly developed theoretical tools in nuclear physics are restricted to bound systems.

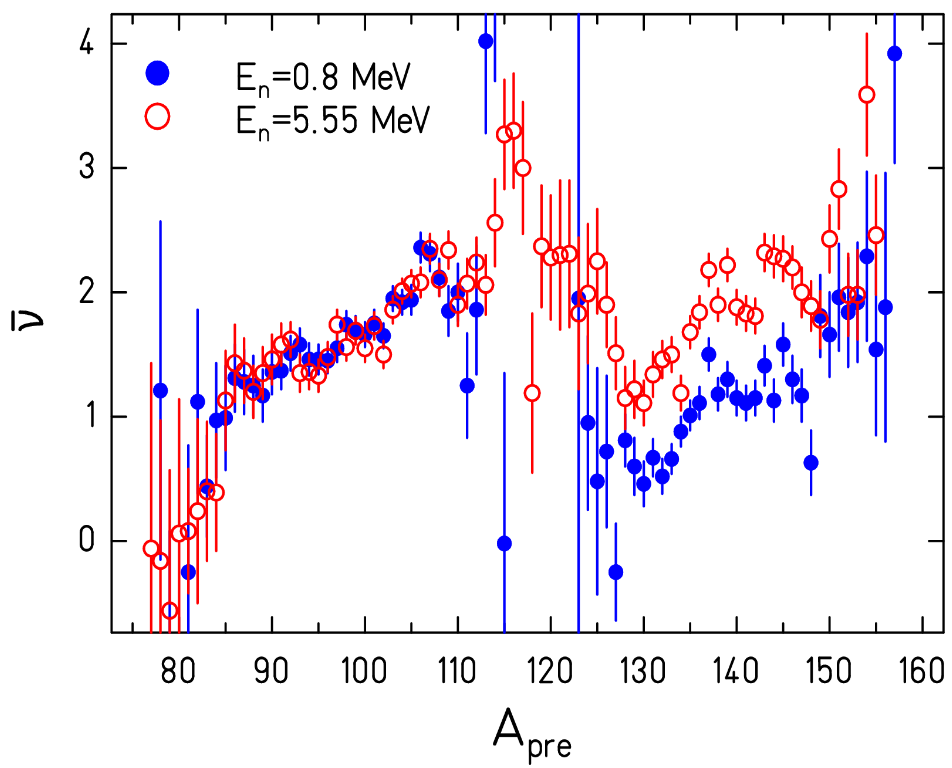
Description of open (quasi-bound) systems is still a challenge.
In particular difficulties in modelling dissipation.

Motivation to have an eye on therrmodynamical aspects! (Efficient method to consider laws of statistical mechanics.)

Observables:

2. Prompt neutron yields

Prompt neutrons in $^{237}Np(n,f)$

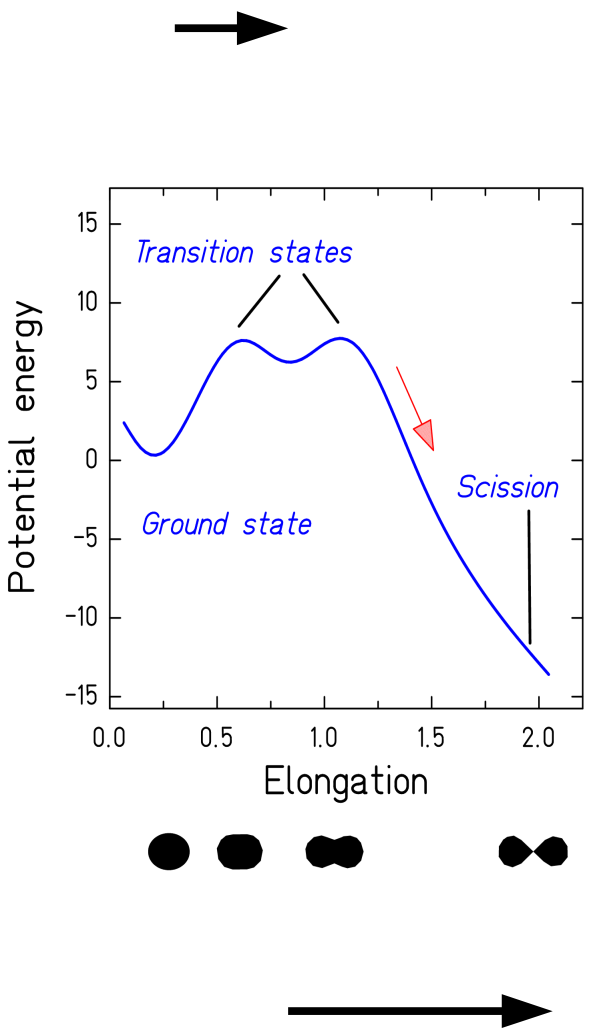


A. A. Naqvi et al., Phys. Rev. C 34 (1986) 218

Mass dependence: saw-tooth

Energy dependence: only in heavy fragment

Evolution towards scission



Saddle: $E^*_{sad} = E^*_{CN} - B_f$

Scission:

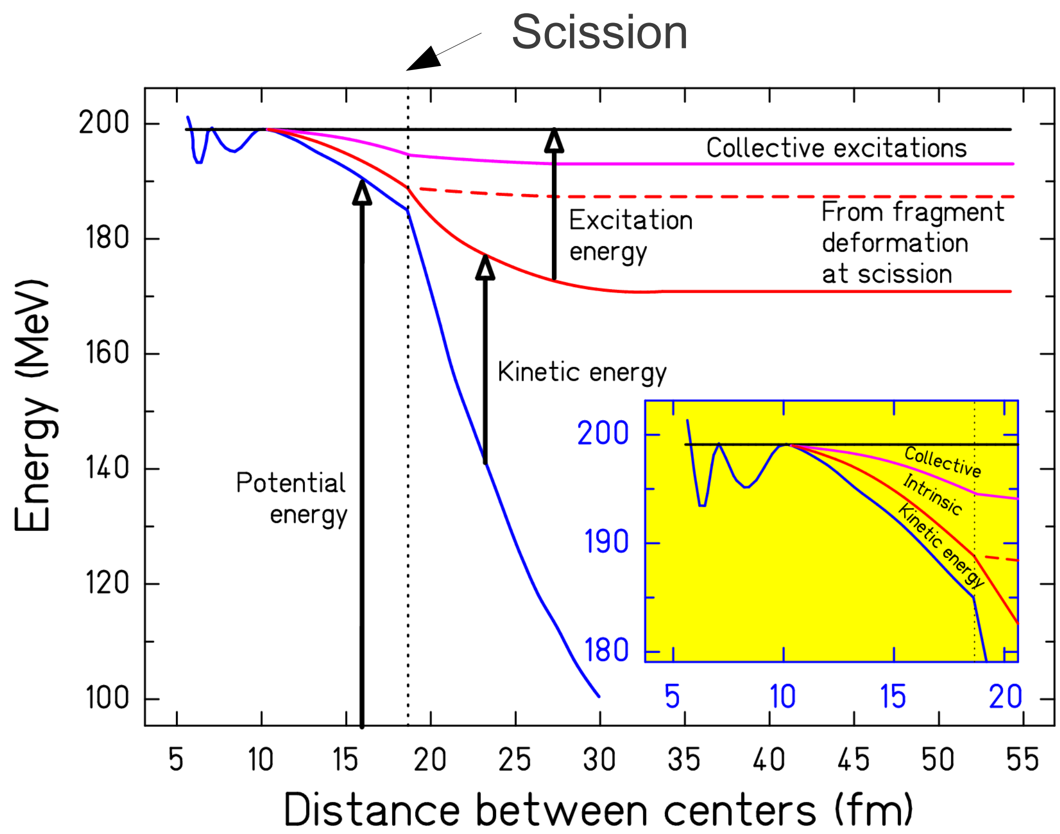
Energy release from saddle to scission ends up in:

1. $E^*_{scission} = E^*_{sad} + E_{dissipation}$

2. excitation of collective modes

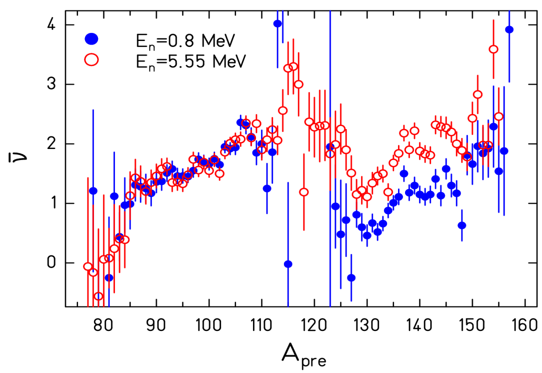
3. kinetic energy

Sources of final excitation energy



E* is accumulated all along the fission process.

Energies at scission feeding prompt neutron emission from fragments



Prompt neutron emission has several sources!

Division between fragments is complex.

- **Deformation energy** (with respect to ground state of fragments): saw-tooth behaviour (feature of shells!)
- **Collective excitations** (e.g. rotations): approx. equal shares
- **Intrinsic excitations:** **division acc. to hermodynamical equilibrium (T_1=T_2) ?**

Requires a closer look on the pre-scission configuration.

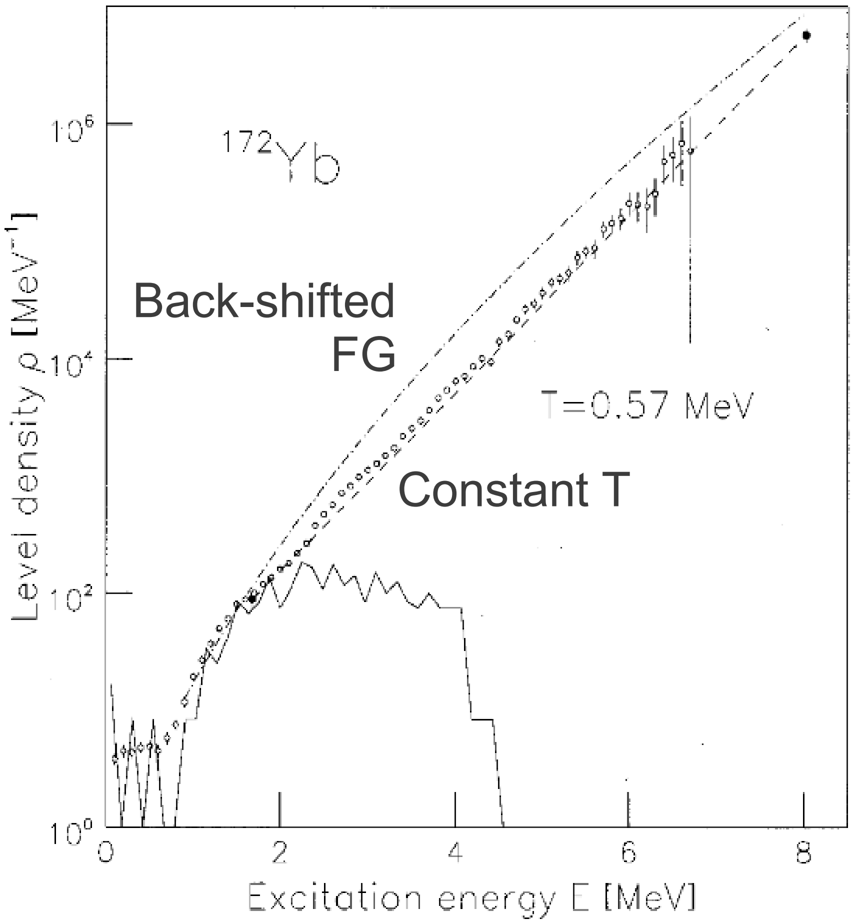
Non-consistent properties (before/after fission)

	Mono-nucleus	Fragments
Shells	One object	Separate objects
Pairing	$12/\mathrm{Sqrt}(A_{CN})$	$12/\mathrm{Sqrt}(A_{fragment})$
Congruence energy	(N-Z)/A	(N-Z)/A

Theoretical studies on the gradual transition:
U. Mosel, H. Schmitt, Phys. Rev. C 4 (1971) 2185.
H. J. Krappe, S. Fadeev, Nucl. Phys. A 690 (2002) 431.
W. D. Myers, W. J. Swiatecki, Nucl. Phys. A 612 (1997) 249.

Fragments acquire their individual properties well before scission!

Constant temperature of nuclei



M. Guttormsen et al., Phys. Rev. C 63 (2001) 044301
"Oslo method"

Rather exact constant-temperature behaviour:

$$\rho(E^*) \propto \exp(E^*/T)$$

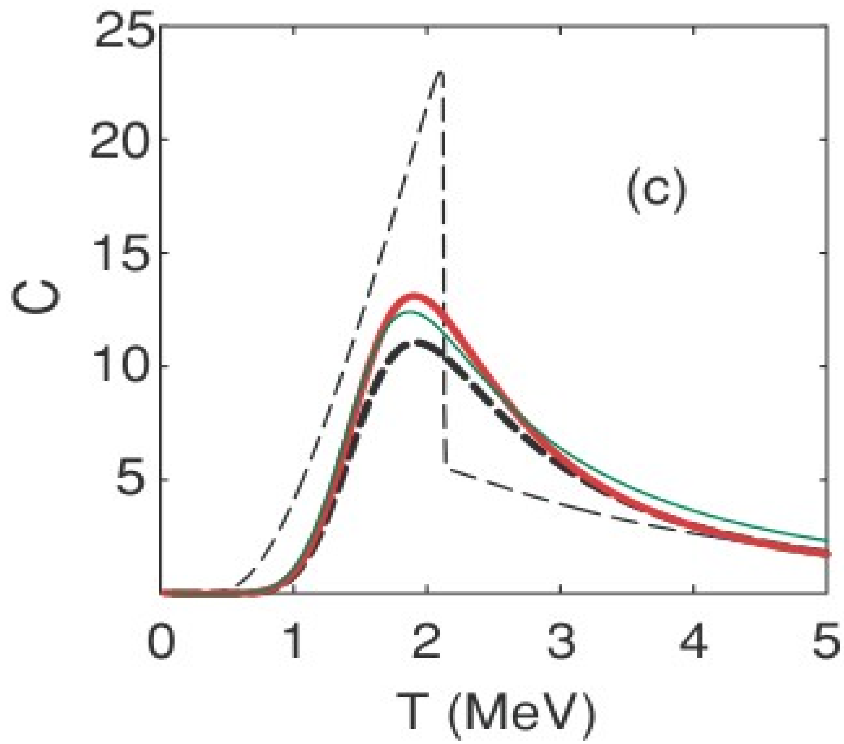
Effective number of degrees of freedom:

$$n_{eff} \propto E^*$$

(Phase transition: Melting of pairs)

Voinov et al. PRC 79 (2009) 031301:
Constant temperature up to 20 MeV!

Theory: Heat capacity



Quang Hung et al.,
PRC 81 (2010) 057302

Increased heat capacity due to melting of pairs.
(T=const. would correspond to C = delta function !)

Some discrepancy between experiment and theory.

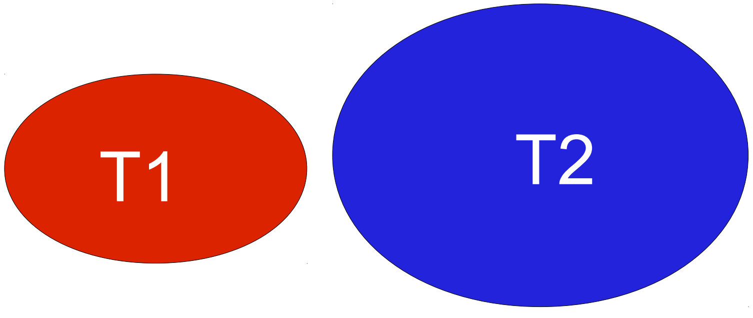
Application to fission

Each of the nascent fragments has an energy-independent temperature.

$$T \propto A^{-2/3} \quad \text{(v. Egidy)}$$

(Some additional influence of shell effects.)

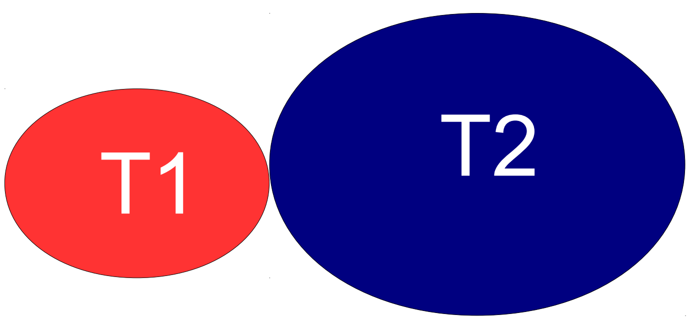
$$A_1 < A_2 \;\rightarrow\; T_1 > T_2$$



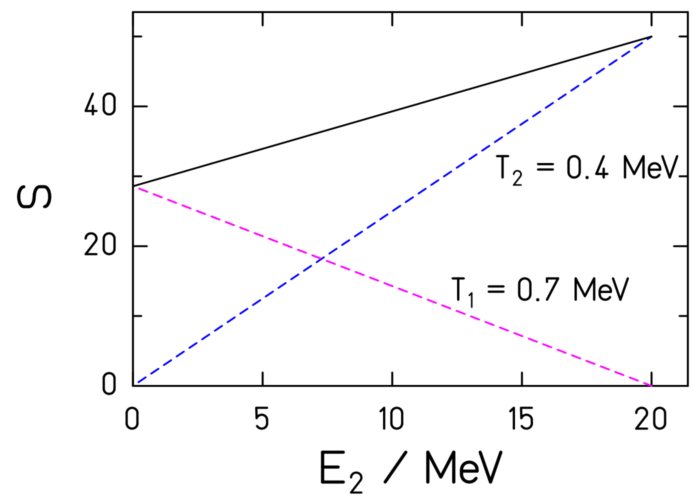
Entropy considerations

$$S = S_1 + S_2 = \frac{E_1^*}{T_1} + \frac{E_2^*}{T_2} = \frac{E_1^*}{T_1} + \frac{E^* - E_1^*}{T_2} = \frac{E^* T_1 + (T_2 - T_1)\cdot E_1^*}{T_1 \cdot T_2}$$

T1 > T2



E1 → 0



S: linear function of energy partition:

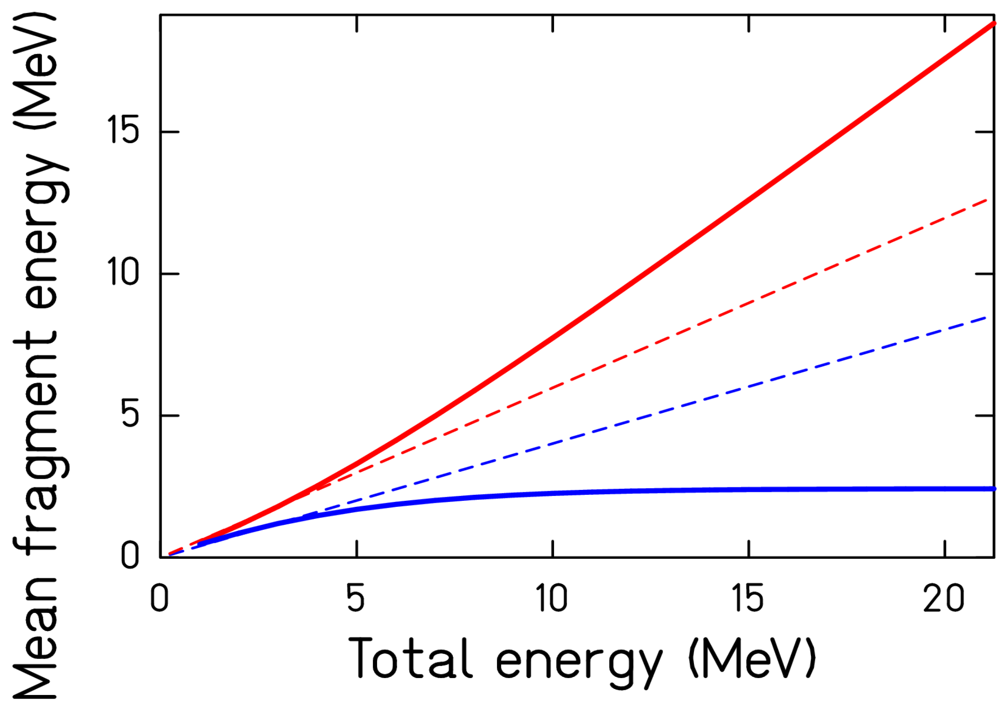
All energy flows to the "colder" (heavy) fragment.

Energy sorting!

K.-H. Schmidt. B. Jurado, PRL 104 (2010) 212501,

K.-H. Schmidt, B. Jurado, PRC 83 (2011) 061601

More exact result for T = const.



94Sr and 140Xe

Fermi gas

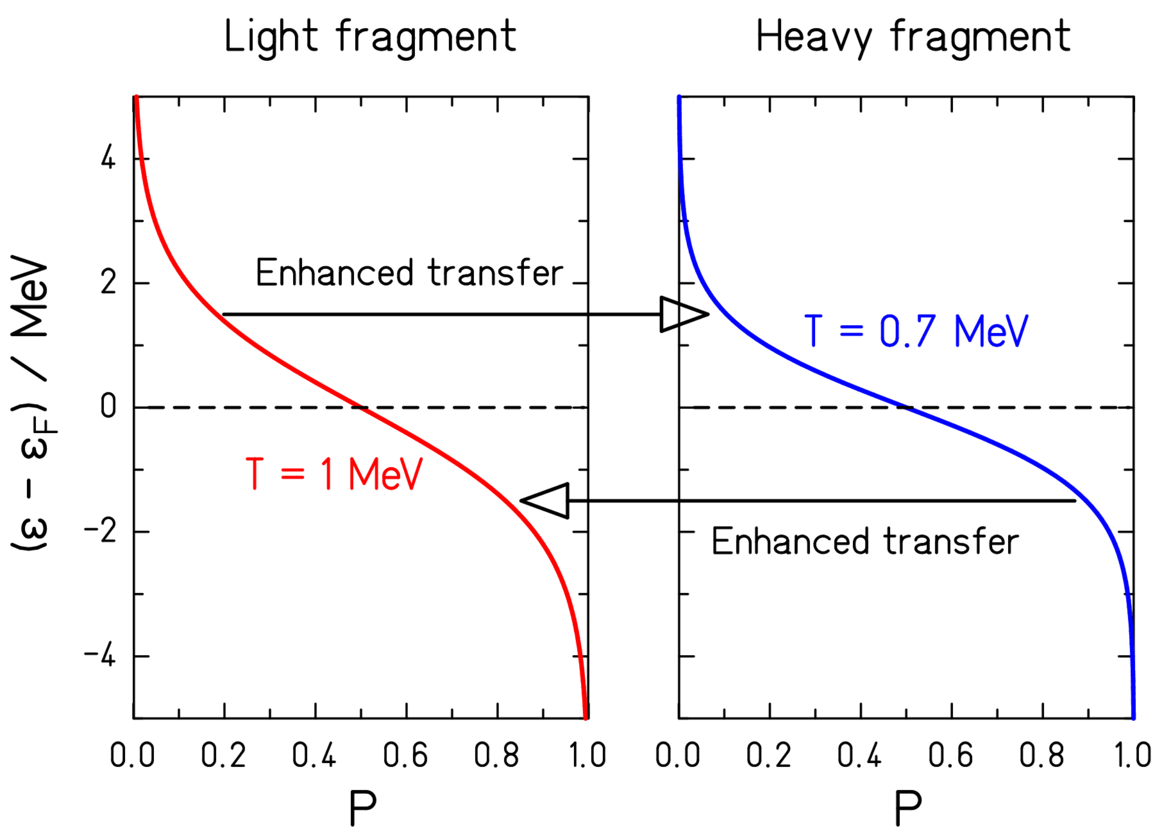
K.-H. Schmidt,
B. Jurado,
PRC 83 (2011) 061601

Directly based on statistical mechanics (number of available states).

Energy sorting is not complete due to properties of finite nuclei.

Microscopic view on energy transfer

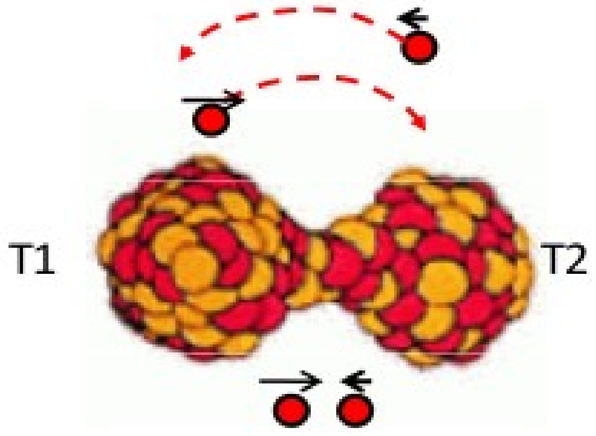
Single-particle occupation functions: (Fermi levels are equal: no net mass transfer.)



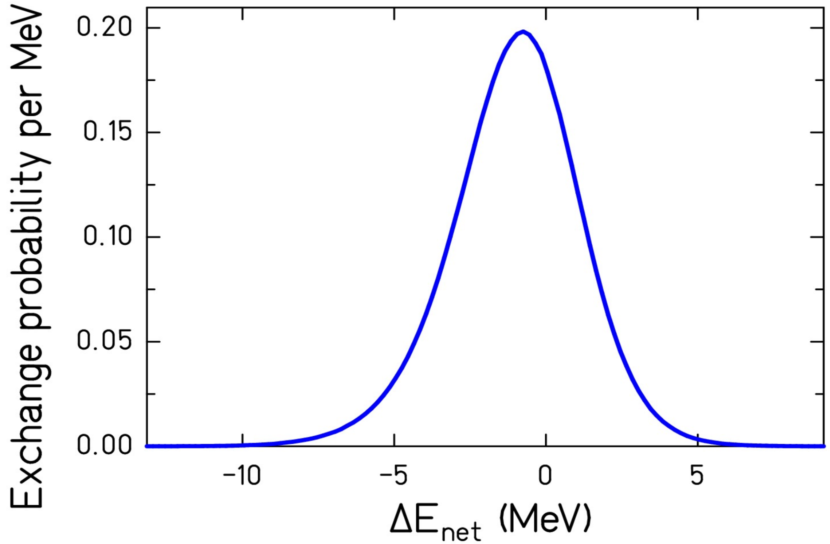
2 possible scenarios:

- Breaking of pairs (if pairing reaches through the neck and the separate nucleons remain in different fragments)
- Nucleon transfer transports energy from hotter to colder nascent fragment due to different occupation functions.

Mechanism of energy transfer



Nucleon exchange

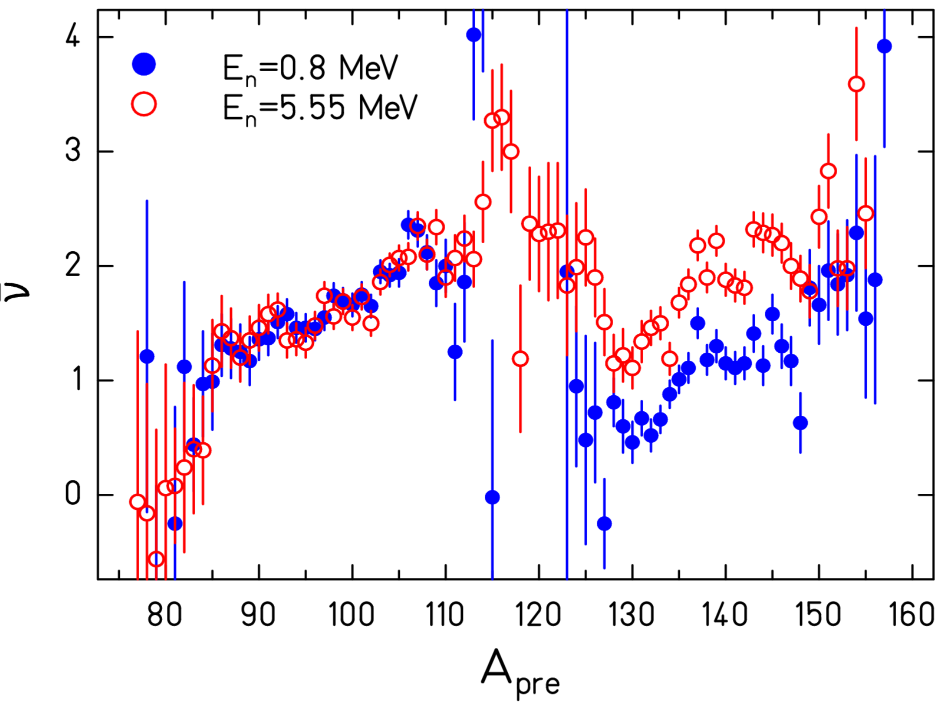


*E** transported per exchange
(T_1 = 1 MeV, T_2 = 0.7 MeV)

Large steps, large fluctuations
(assure thermal averaging)

K.-H. Schmidt, B. Jurado, Phys. Rev. C 82 (2011) 014607

$^{237}Np(n,f)$ prompt neutron yields



Naqvi et al., PRC 34 (1986) 218

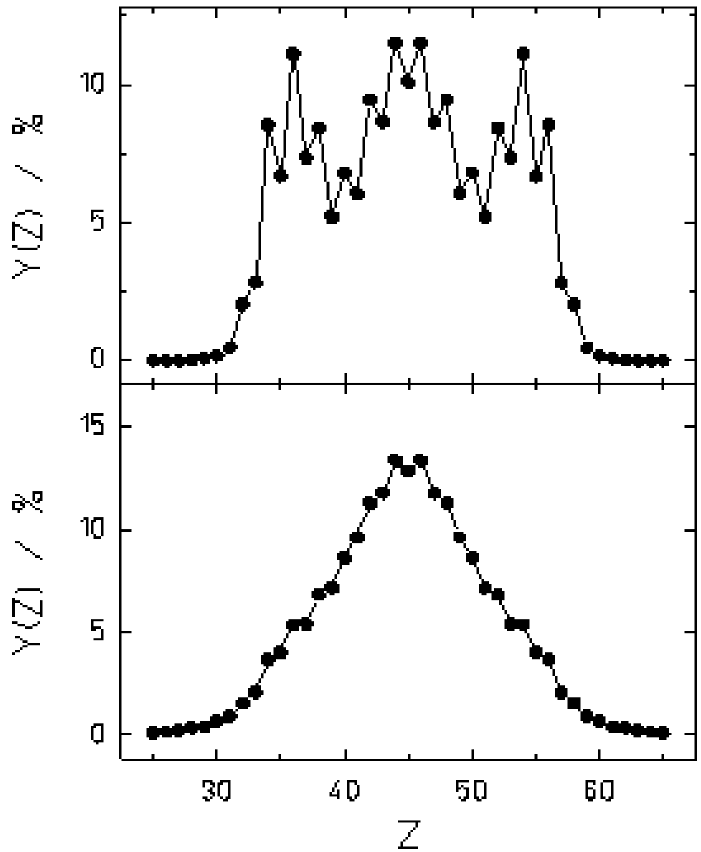
The additional energy of the more energetic neutron ends up in the heavy fragment. → Proof of energy sorting!

Previous attempts with Fermi-gas level density $\rho(E^*) \propto \exp(2\sqrt{a E^*})$ could not explain! (→ $E_1^*/E_2^*=A_1/A_2$)

Observables:

3. Even-odd effect in Z yields (defined at scission)

Structure in Z yields



Fission of ^{226}Th

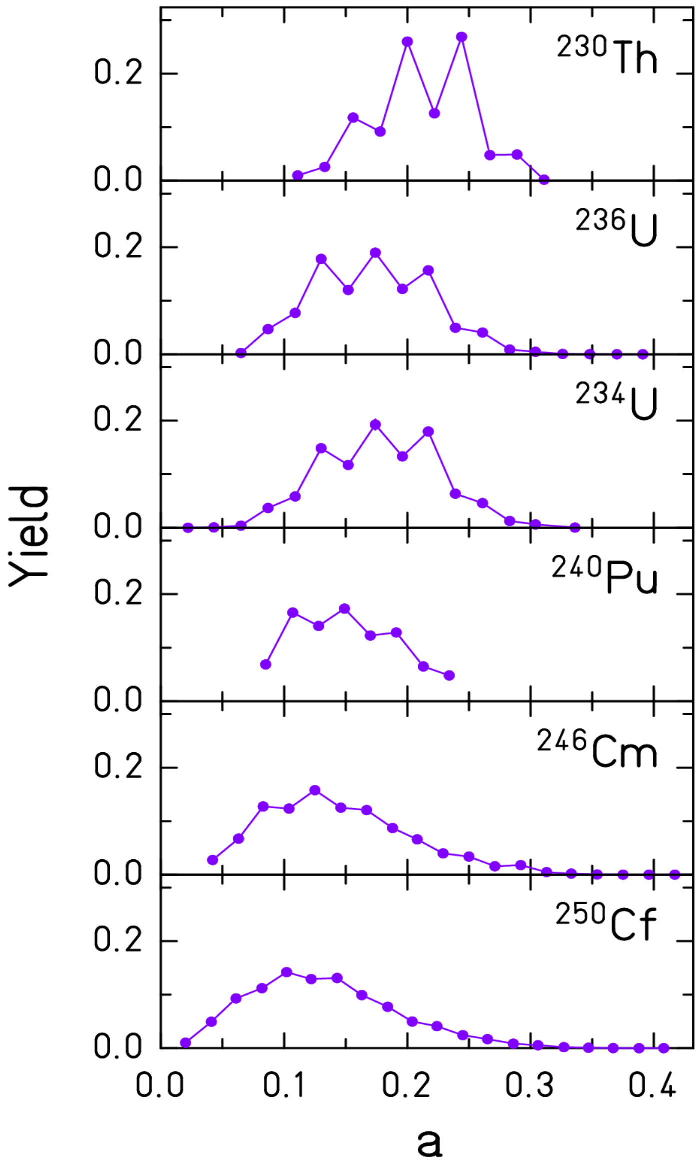
Coulomb fission
E* ≈ 10 MeV

Nuclear-induced fission
E* ≈ 25 MeV

Modes and even-odd effect

Pairing gap Δ≈10-3 of BE → up to 50 % in the yields!

Systematics of even-odd effect



Caamano et al., J. Phys. G. 38 (2011) 035101

Only few systems measured.

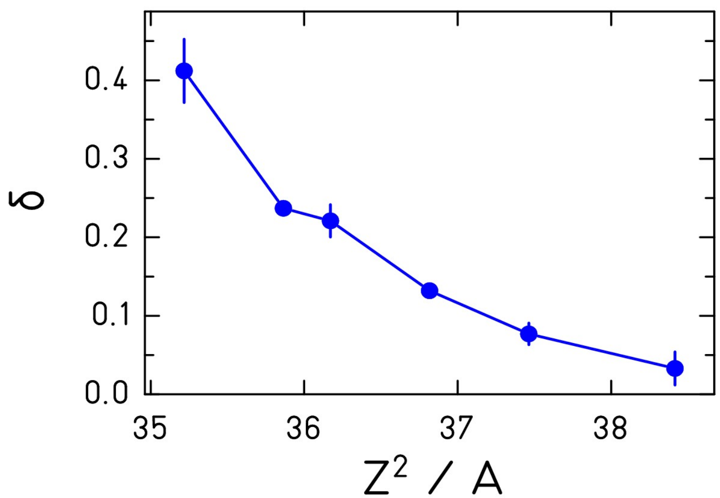
Strong variation from $^{229}Th(n_{th},f)$ to $^{249}Cf(n_{th},f)$.

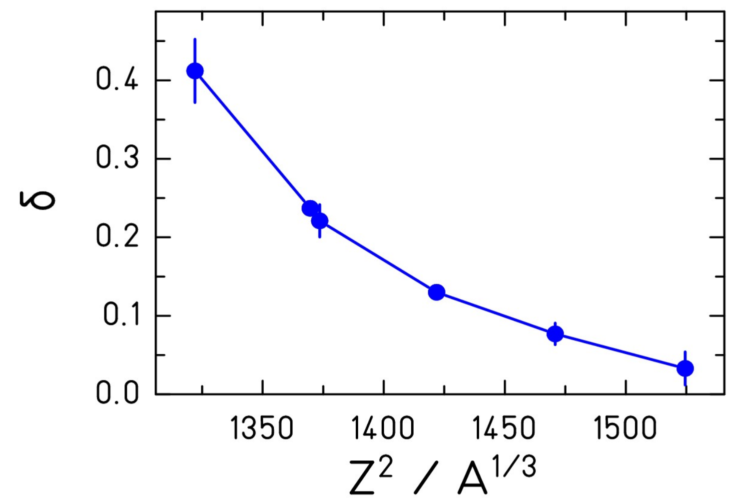
Asymmetry parameter:

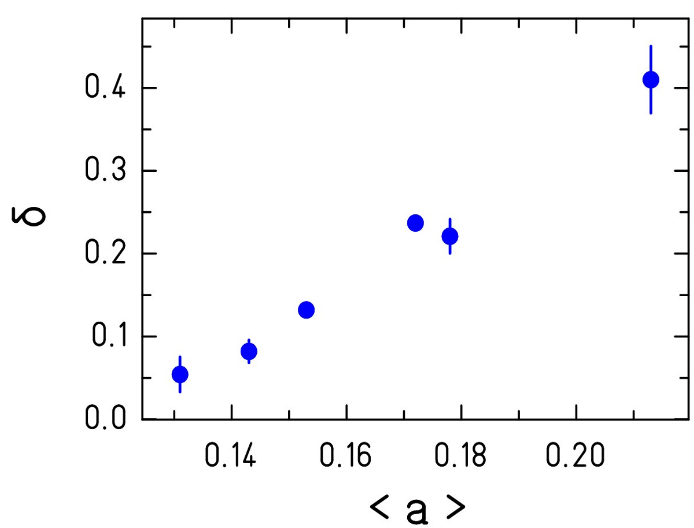
$$a = \frac{Z_{heavy} - Z_{light}}{Z_{heavy} + Z_{light}}$$

Dependencies and correlations

Caamano et al., J. Phys. G. 38 (2011) 035101







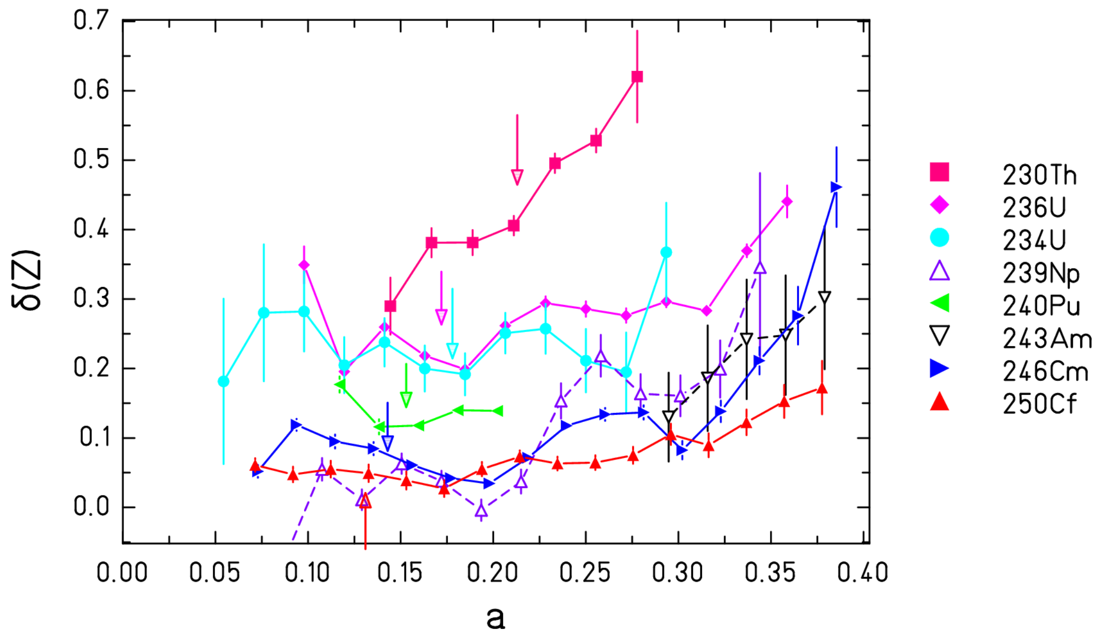
No clear answer on the origin of the even-odd effect.

Global even-odd effect

$$\delta = \frac{\sum_{even} Y_Z - \sum_{odd} Y_Z}{\sum_{all} Y_Z}$$

Refined analysis

$\delta(Z)$ = local even odd effect
(4-point logarithmic difference)



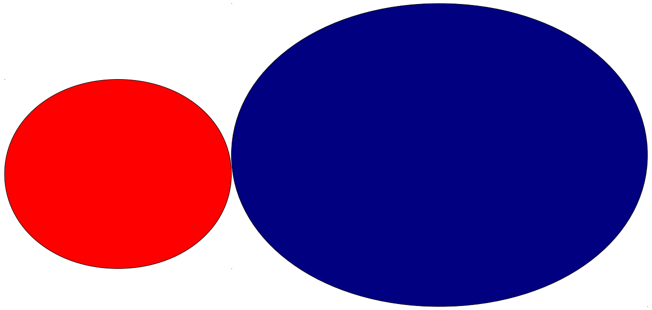
Conclusion:
1. Even-Z fragments are generally enhanced in the light fragment.
2. The even-odd effect grows with asymmetry.
3. The even-odd effect globally decreases for heavier systems.
4. The even-odd effect of odd-Z fissioning systems is similar.

Caamano et al., J. Phys. G. 38 (2011) 035101

Entropy gain by forming a light fragment with even Z and even N

Even-odd effect → Enhanced production of even-even nuclei in the ground state!

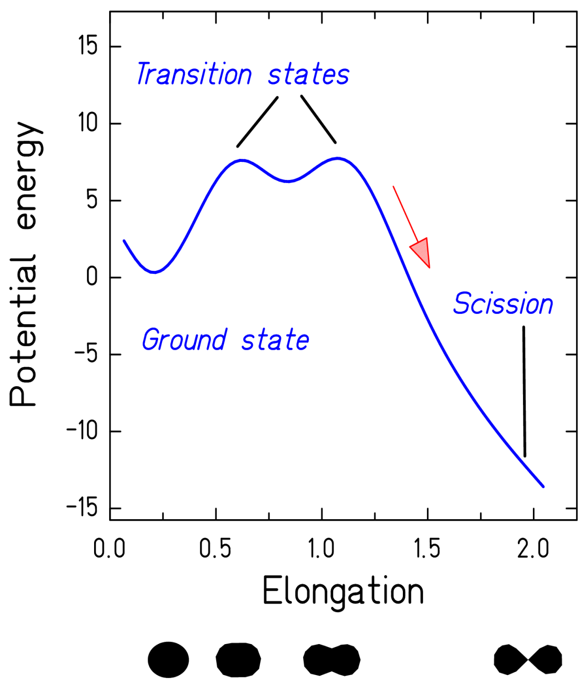
Assume the light fragment has arrived at $E^*_1 = 0$, but Z and/or N are odd.

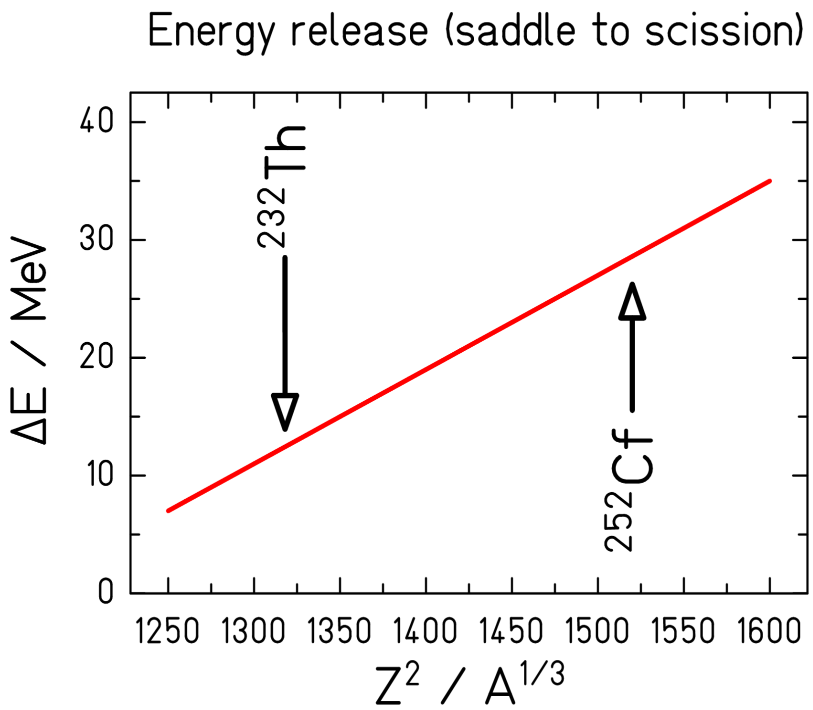
$E^*_1=0$  $E^*_2 = E^*_{tot}$

The system can still gain considerable entropy by exchanging eventually 1 proton and 1 neutron to form an even-even light fragment!

Entropy gain up to $\Delta S = 2 \cdot \Delta / T_2$!

Potential energy gain from saddle to scission





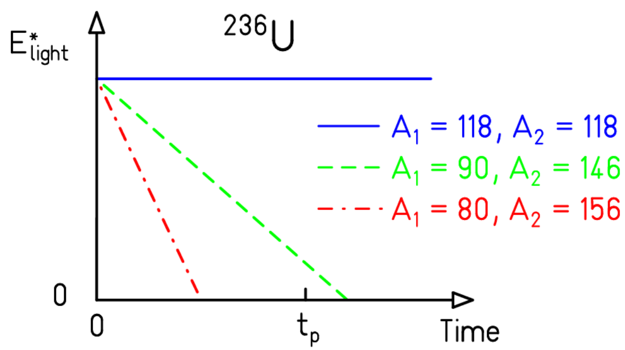
Asghar, Hasse, J. Phys. Coll. 1984

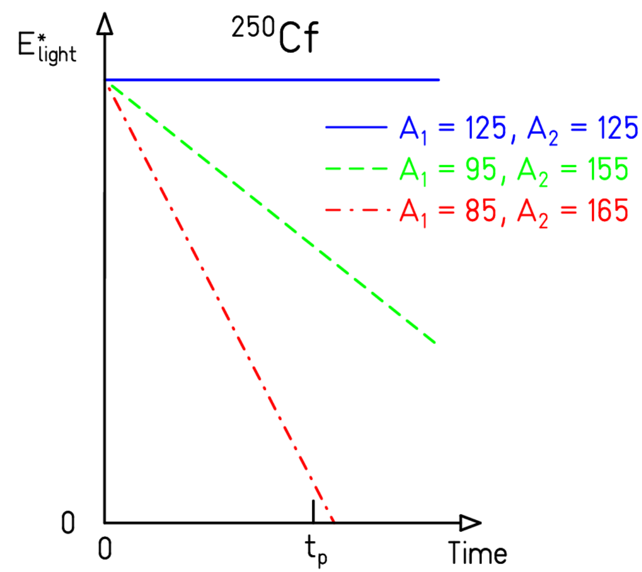
Dissipated energy is expected to scale with the energy release.

Time evolution of energy sorting

$$\frac{\mathrm{d}\, E_{transfer}}{\mathrm{d}\, t} \propto \frac{\Delta T}{\text{heat resistance}} + F$$

Assumption: heat resistance is const.
F = fluctuating term.

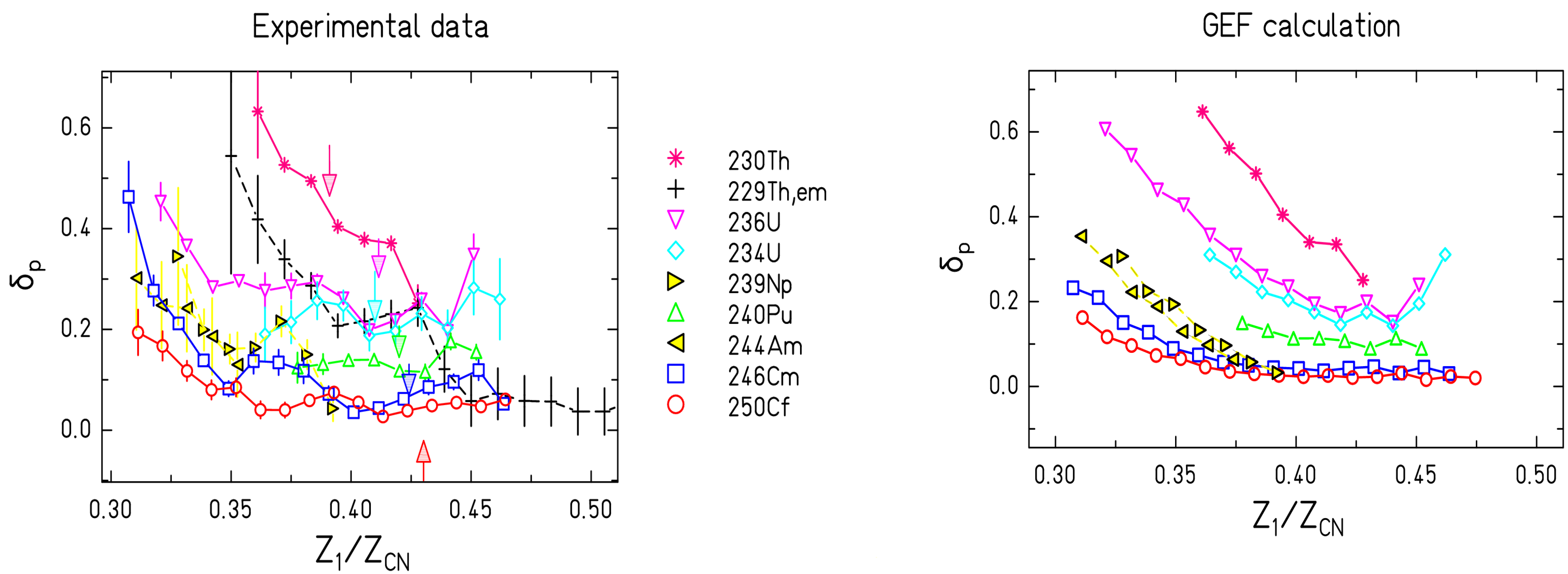




Energy sorting needs time.

Time window for proton transfer closes at t_p due to growing Coulomb barrier.

Model vs. data



Schematic model (threshold behaviour of asymmetry-generated even-odd effect with fluctuations) reproduces the empirical features!

Model included in the GEF code (www.cenbg.in2p3.fr/GEF)

K.-H. Schmidt, B. Jurado arXiv:1007.0741v1 [nucl-th]

New interpretation of saddle-scission dynamics in terms of thermodynamics

Experimental signatures:

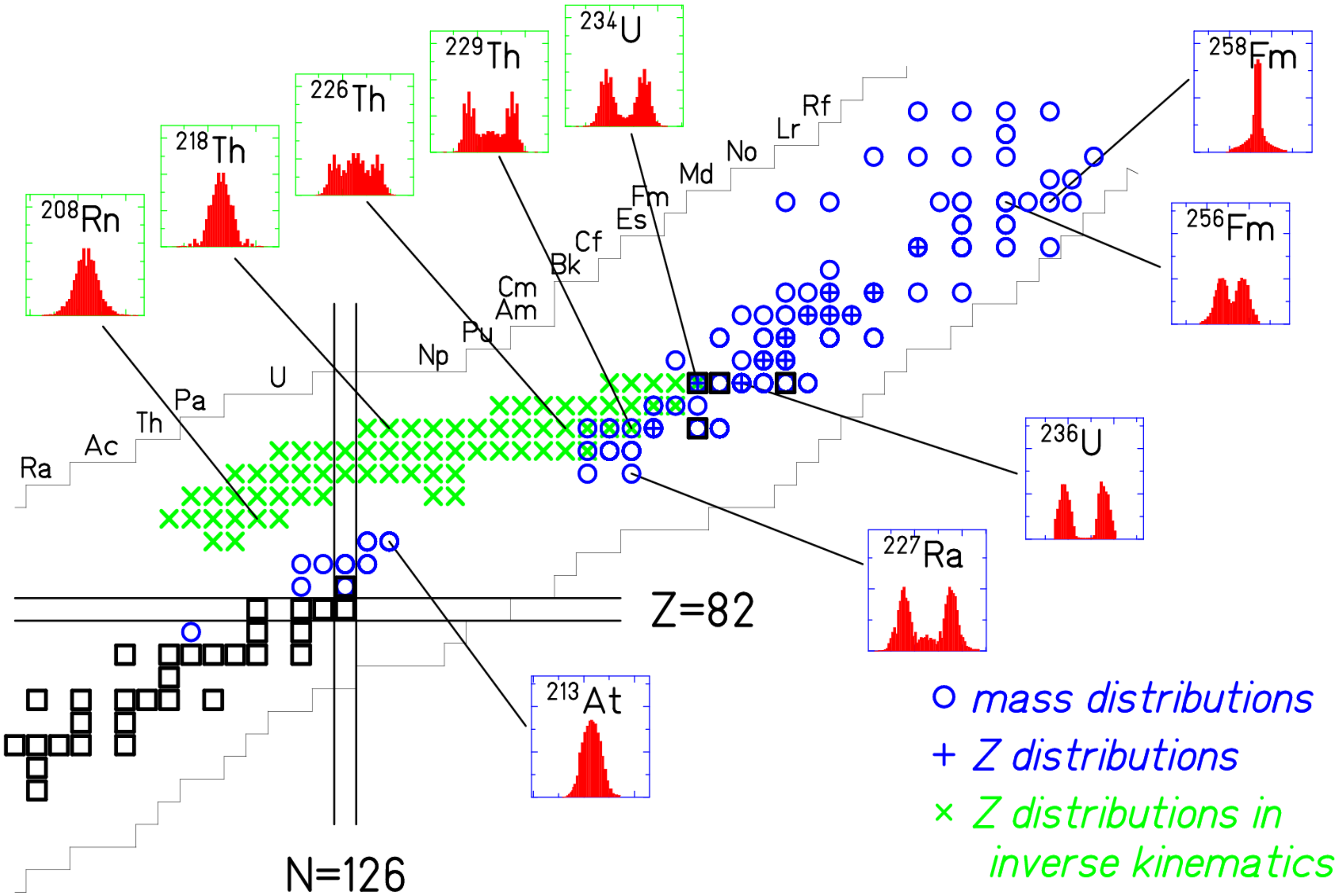
- prompt neutron yields
- even-odd effect

reveal complex dynamical processes on the descent from saddle to scission.

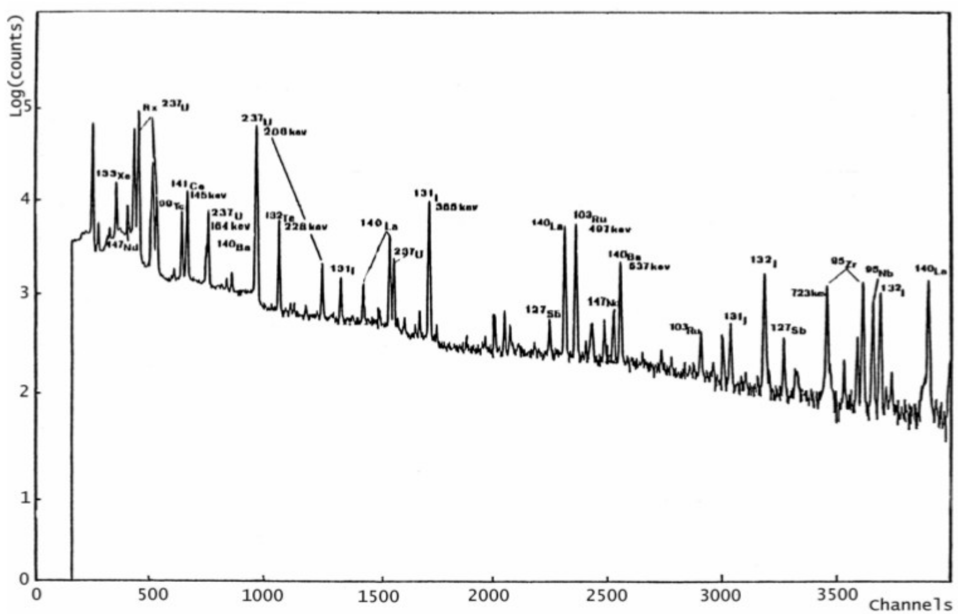
Even-odd effect in fission is a new kind of nuclear clock which links heat transfer through the neck in the regime of strong pairing correlations with saddle-to-scission time.

Experimental techniques

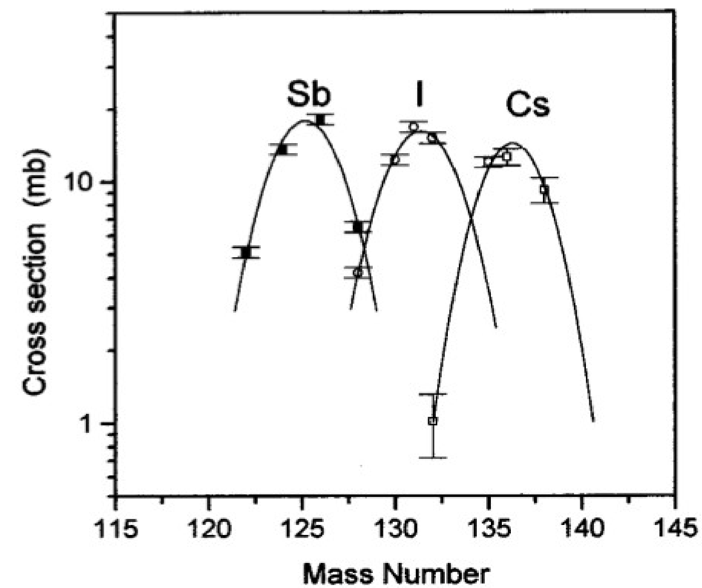
Mass and Z distributions from low-energy fission



Off-line gamma spectroscopy



Laurec et al., NDS 111 (2010) 2965

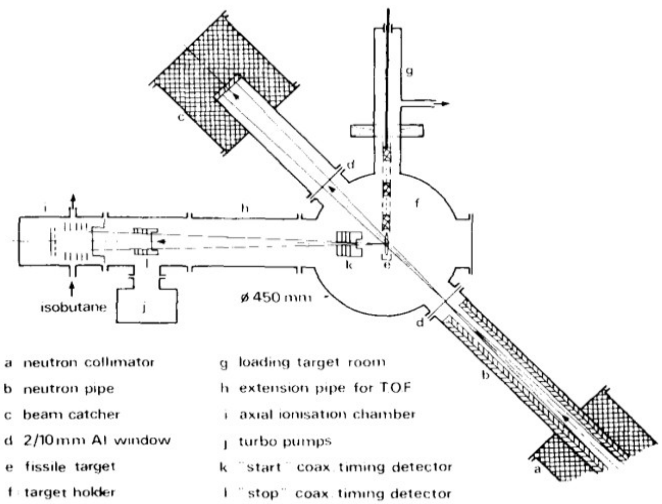


Gubbi et al., PRC 59 (1999) 3224

Independent yields for different initial energies
Too slow for short-lived fission products
Relies on spectroscopic information
(Almost) no information on kinematics

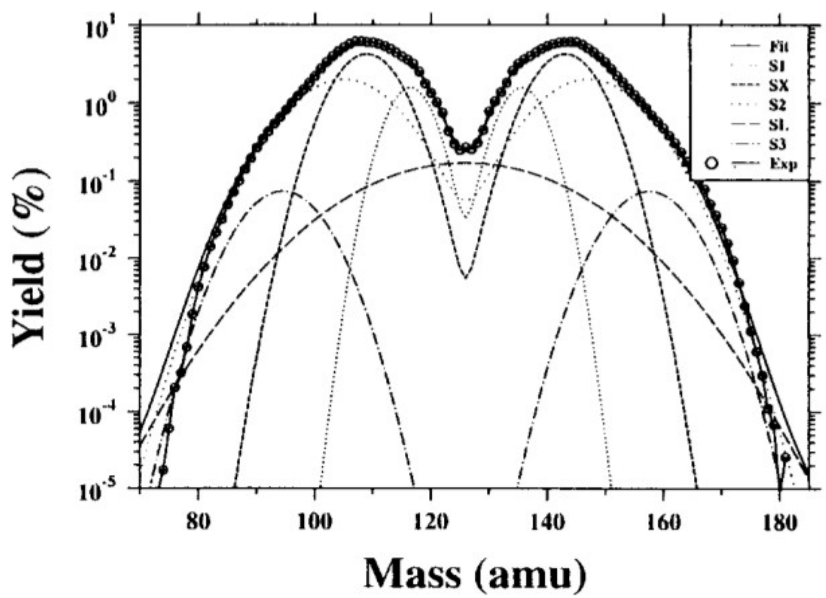
Double energy / double TOF

The Cosi-Fan-Tutte set-up



Bucheneb et al., NPA 502 (1989) 261c

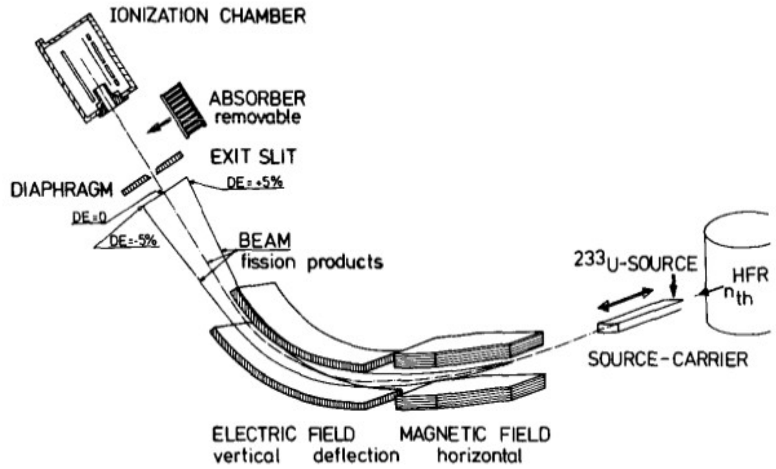
Decomposition in fission channels



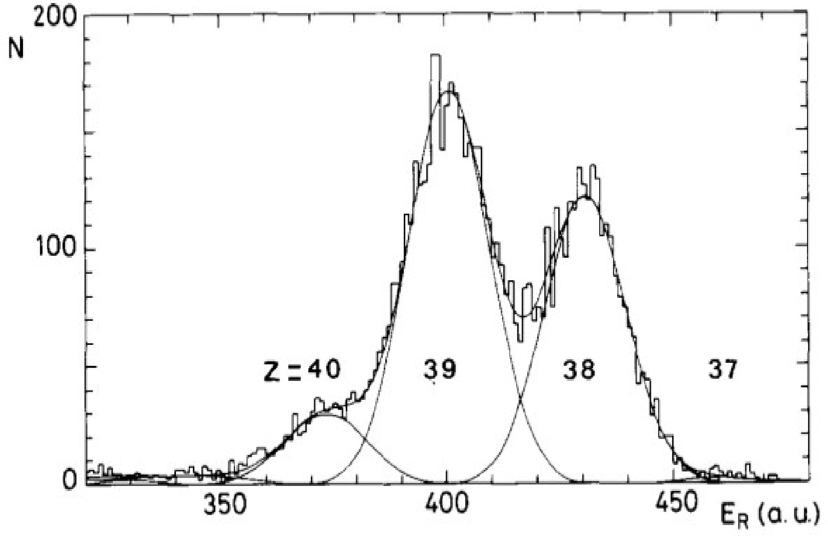
Hambsch in NPA 654 (1999) 855c

Pre-neutron / post-neutron masses (ΔA ≈ 2)
Prompt neutron yields can be deduced
Kinematical information (TKE)

Lohengrin



Lohengrin: Spectrograph at
ILL high-flux reactor
U. Quade et al., NPA 487 (1988) 1

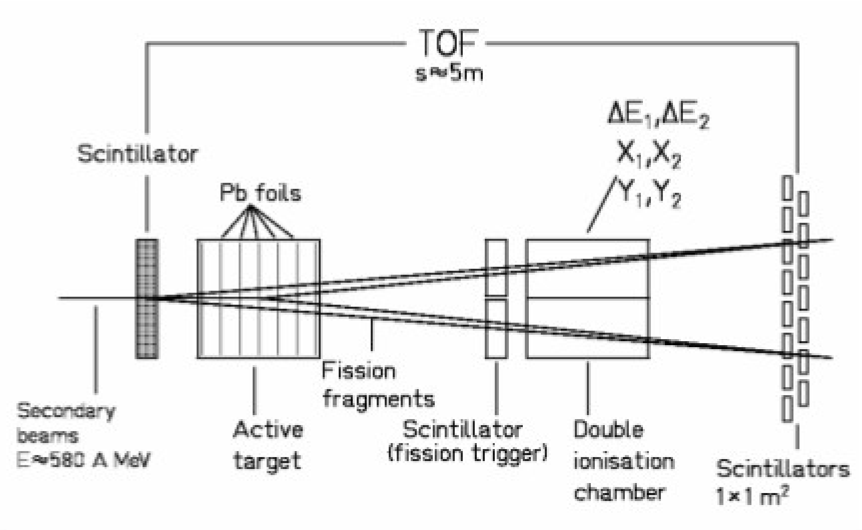


ΔE spectrum

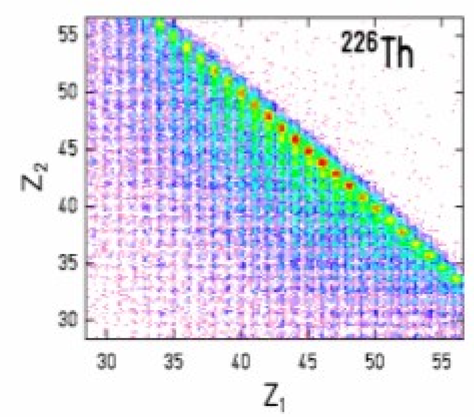
Djebara et al., NPA 496 (1989) 346

Good Z resolution in light fragments.
Restricted to (n_{th},f) and long-lived targets.

Coulomb fission of relativistic ^{238}U projectile fragments

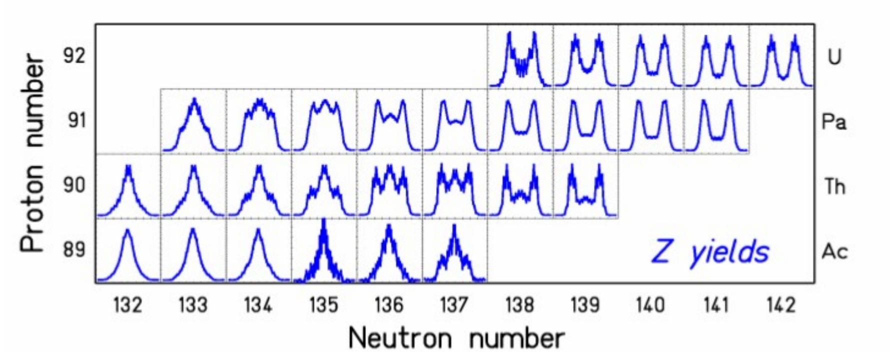


The detectors



Identification of both fragments in Z

Systematic measurement of Z distributions with secondary beams (GSI experiment)



Fission induced by electromagnetic excitations, E* ≈ 11 MeV

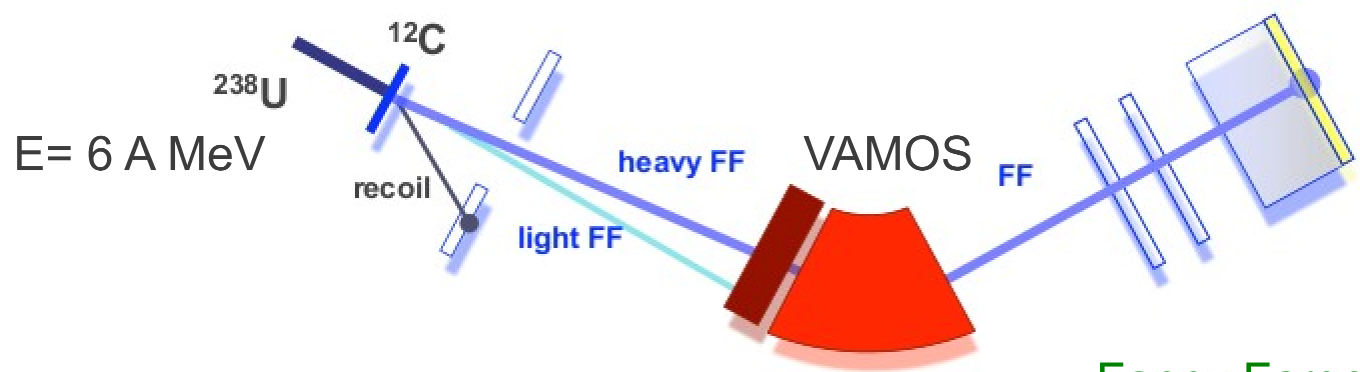
Access to radioactive nuclei (A<238)

Excellent Z resolution

Mapping symm. - asymm. fission

Schmidt et al., NPA 665 (2000) 221

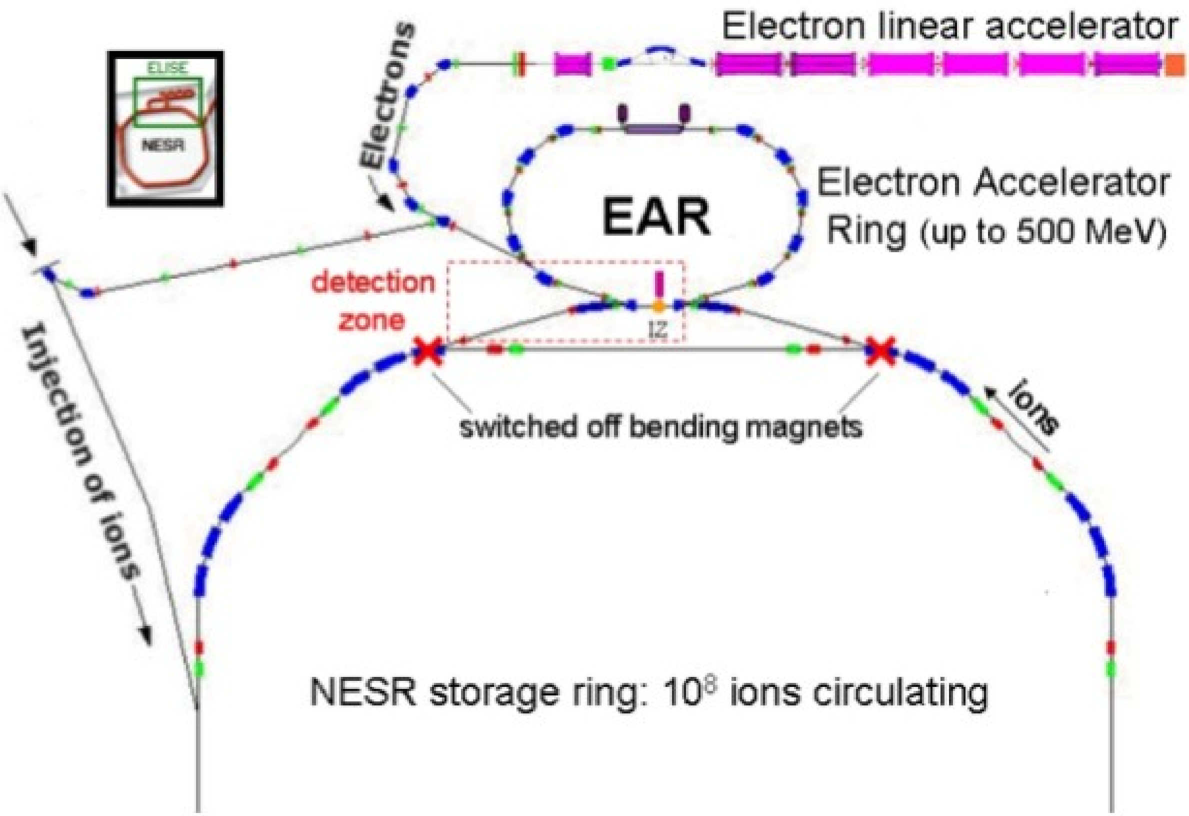
Transfer in inverse kinematics



Fanny Farget et al., GANIL, 2011

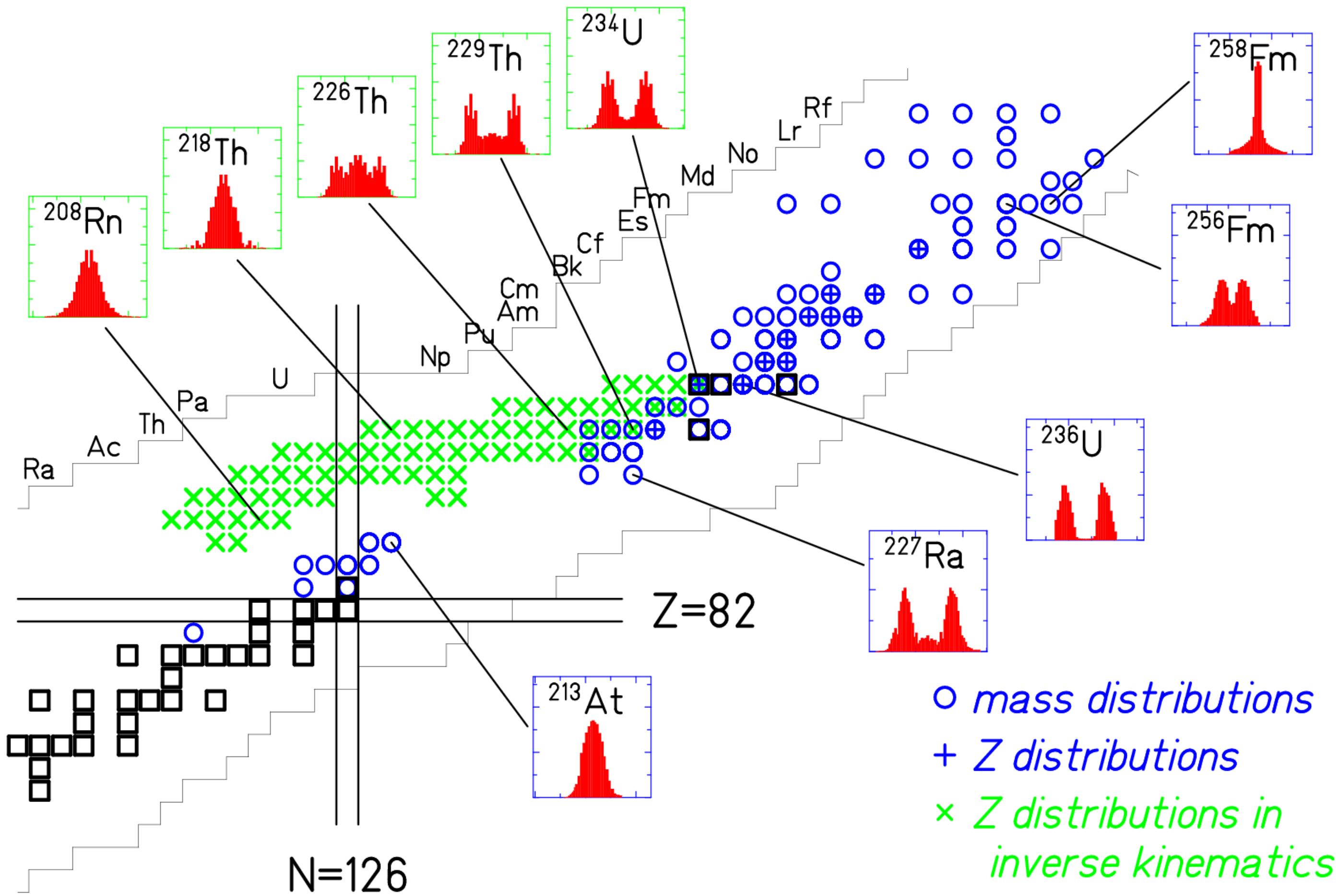
Access to nuclei around ^{238}U
Good A and Z resolution
Well-defined excitation energy

FELISE at FAIR



Fission of ^{238}U fragments in inverse kinematics induced by tagged photons

Mass and Z distributions from low-energy fission



Summary

Mankind learned to exploit heavy nuclei as fuel.

- Energy production with good CO_2 balance (+)
- Radioactive waste (-), risk (-)
- Physics of fission still badly understood → fission cycling

Fascinating physics of a quasi-bound system

- Dynamics with shell structure and residual interactions
- Most advanced concepts of nuclear physics not applicable to non-equilibrium processes – need for novel concepts

Theory I: Statics (potential energy surface)

- Two-centre shell model
- Early influence of fragment shells and other fragment properties

Theory II: Fission dynamics (descend towards scission)

- Classical dissipation equation (no QM, 5-dim. is still not sufficient.)
- Microscopic dynamical model (HFB) (2-dim., no dissipation yet)
- New: Thermodynamics (discovery of energy sorting, new insight into dynamical aspects of fission)