A new theoretical approach to low-energy fission based on general laws of quantum and statistical mechanics

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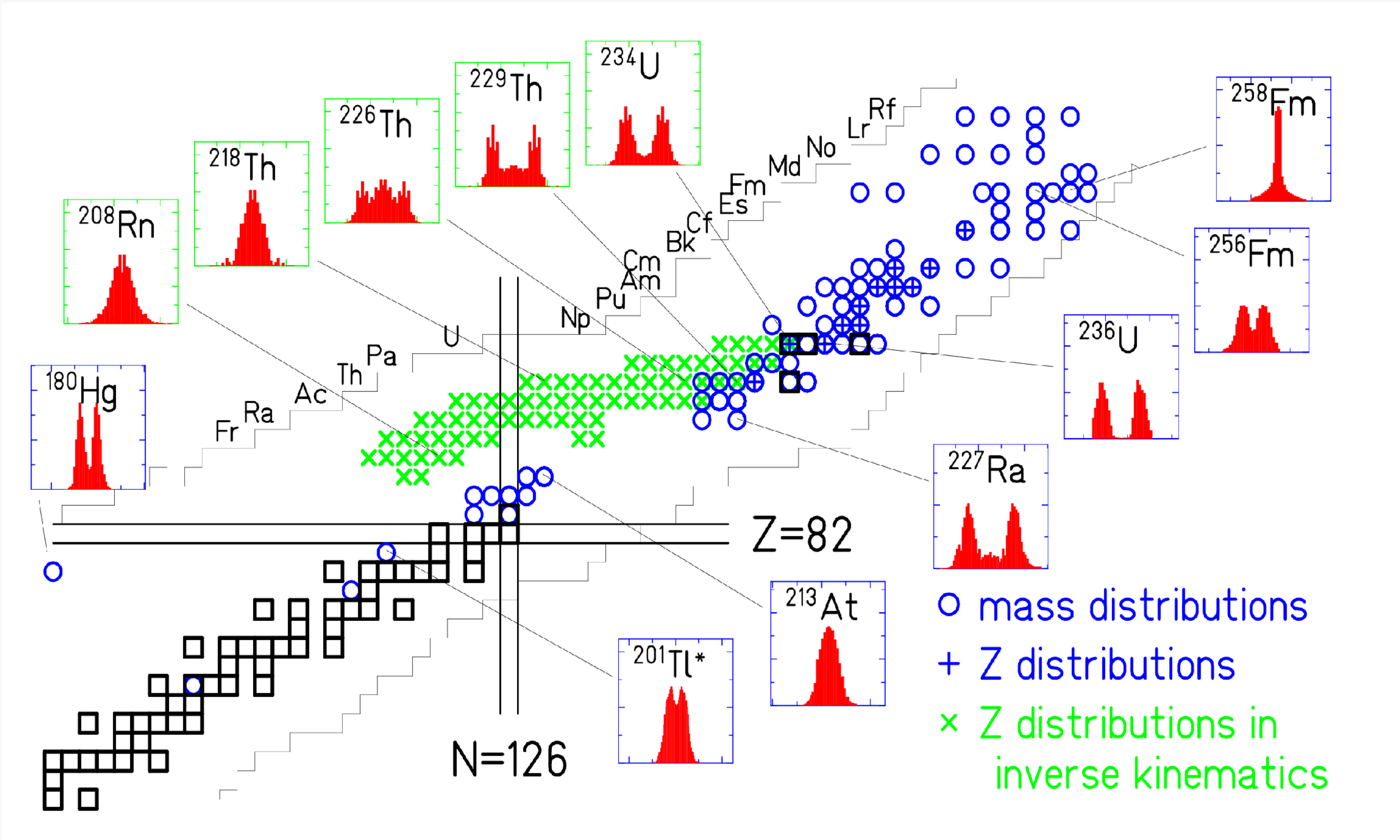
Contribution to the meeting of the WPEG subgroup
“Improved Fission product yield evaluation methodologies”
May 22, 2013
Issy-les-Moulineaux, France

Systematics of mass (and Z) distributions



A≥258: narrow single humped

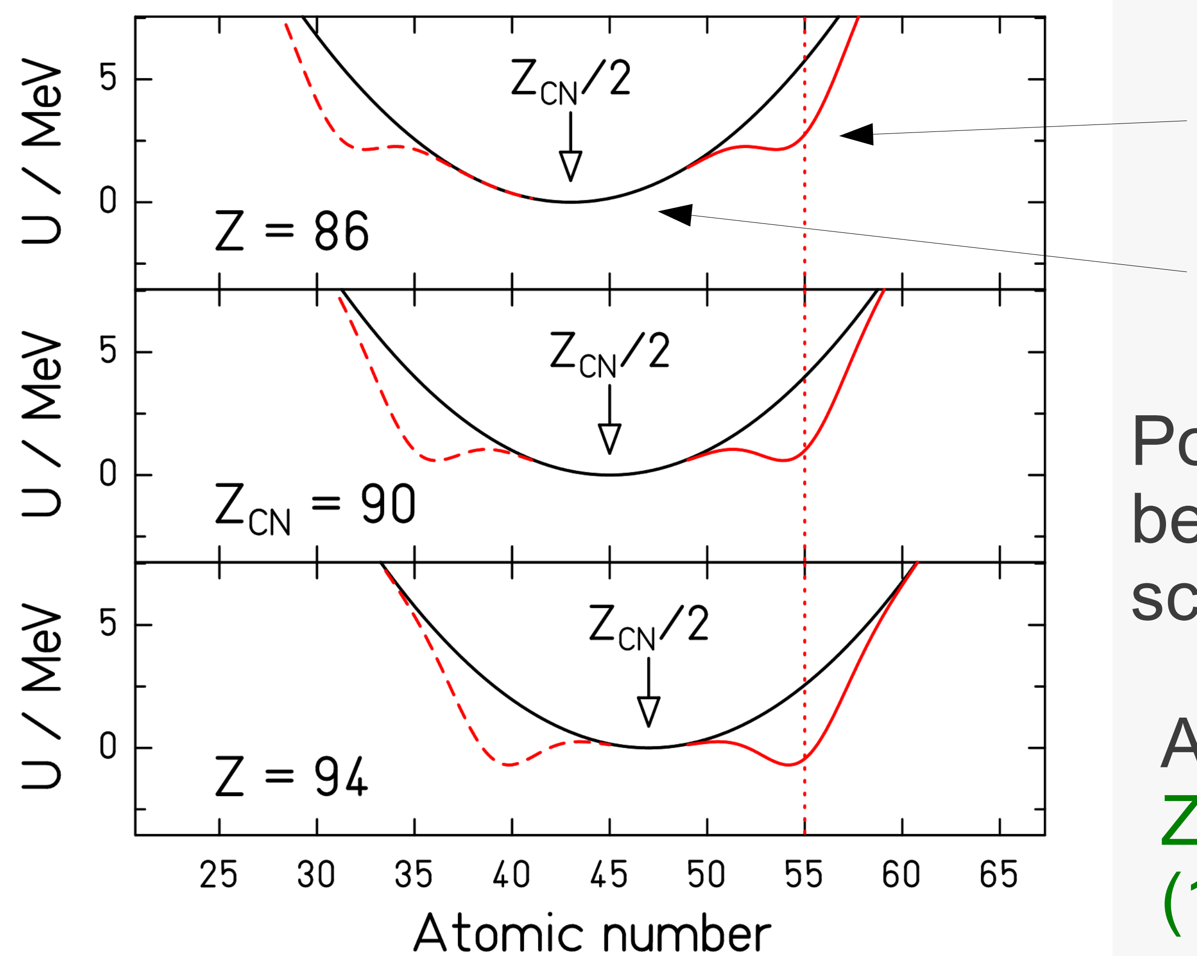
A>226 to *A*<258 : double humped; *A*(heavy)≈140 or *Z*(heavy)≈55.

Z=82 to *A*<226: single-humped

Z≈80: narrow double humped

Complex behaviour, but some global trends.
→ Search for explanation on a deeper level.

An early idea

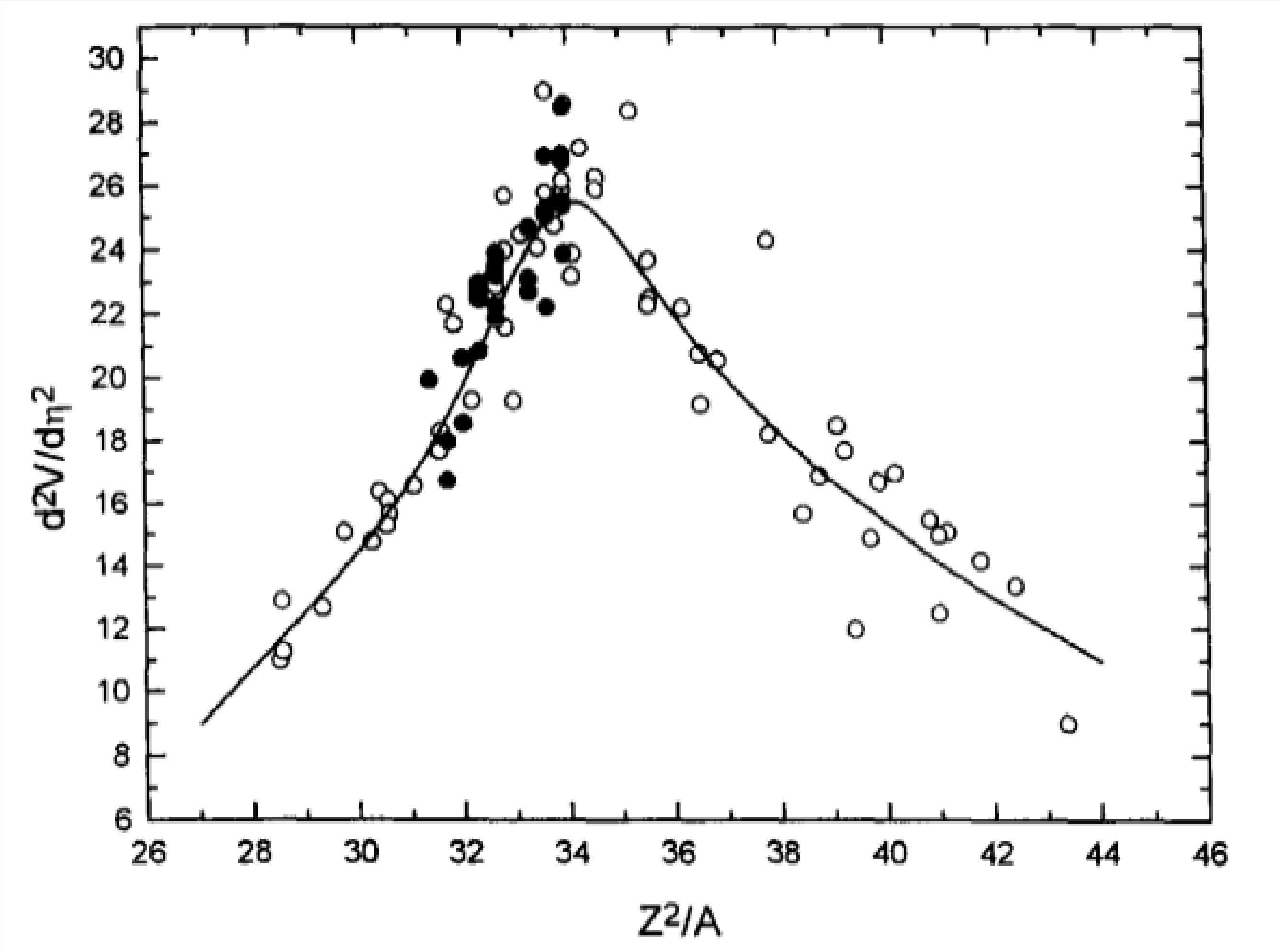


Potential “somewhere” between saddle and scission.

After M. Itkis et al. Z. Phys. A 320 (1985) 433 :

Competition between liquid-drop potential and shells explains transition from symmetric to asymmetric fission around A = 226.

Macroscopic potential



From measured σ_A of symmetric fission mode.

$$\sigma^2 = \frac{temperature}{stiffness}$$

(Harmonic oscillator in a heat bath.)

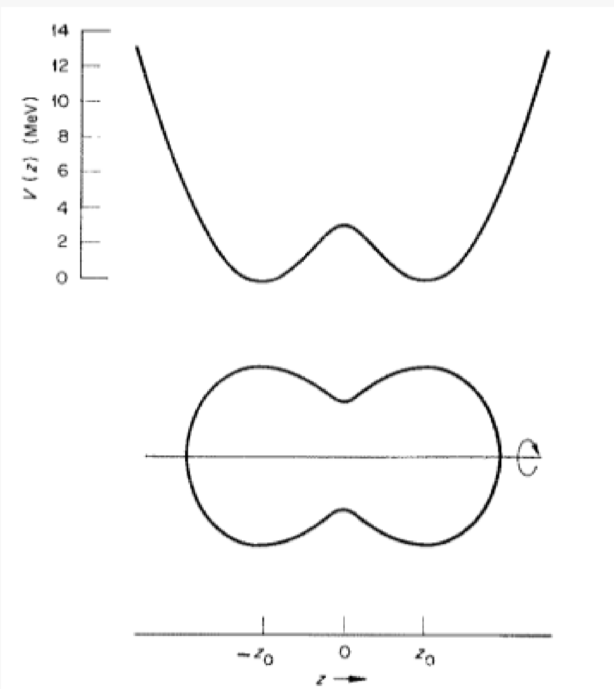
Mulgin et al., NPA 640 (1998) 375

Stiffness vs. mass asymmetry of the macroscopic potential.
A unique function of fissility.

Shells

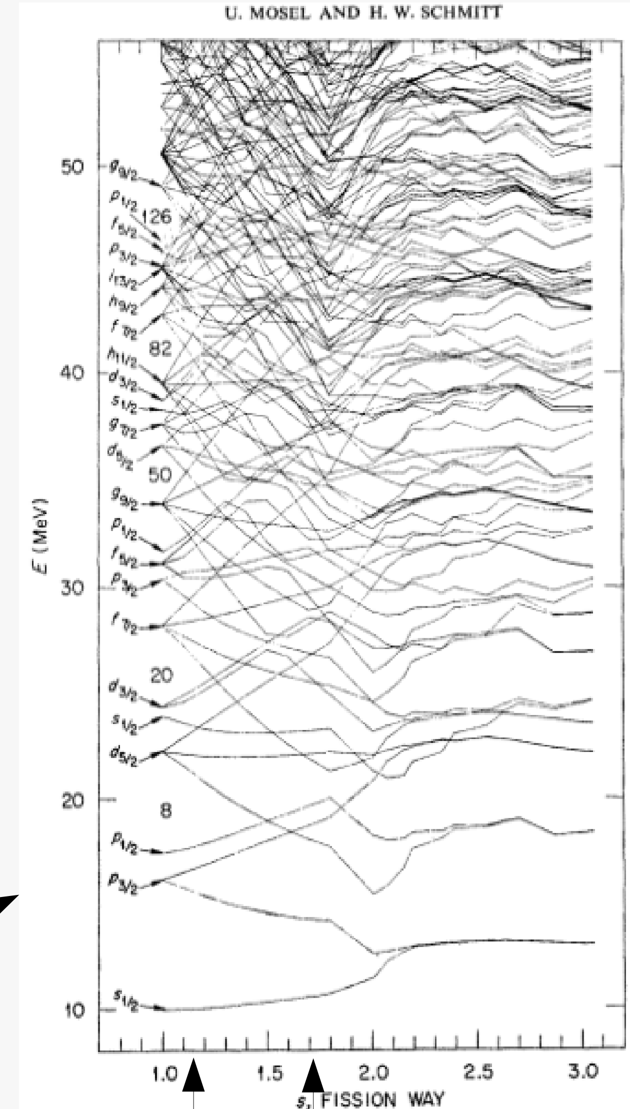
Two-centre shell model developed by:
Holzer, Mosel, Greiner (Nucl. Phys. A138 (1969) 241)

Allows continuous treatment from ground state to separated fragments.



U. Mosel, H. W. Schmitt
Nucl. Phys. A
165 (1971) 73

Single-particle levels
in a di-nuclear potential



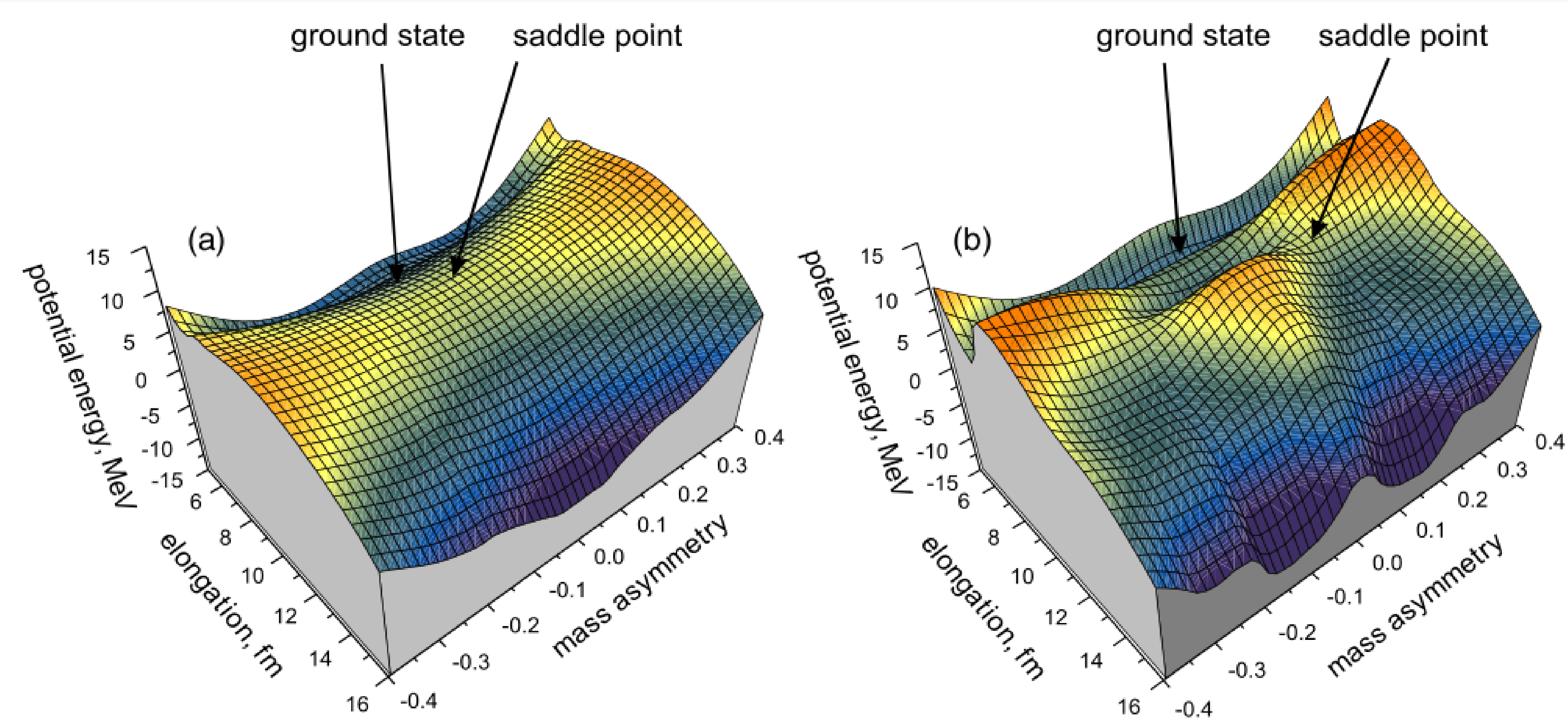
Ground state

Outer saddle

Early manifestation of fragment shells.

Potential energy landscape

2-dim. calculation by A. Karpov, 2008



liquid-drop potential

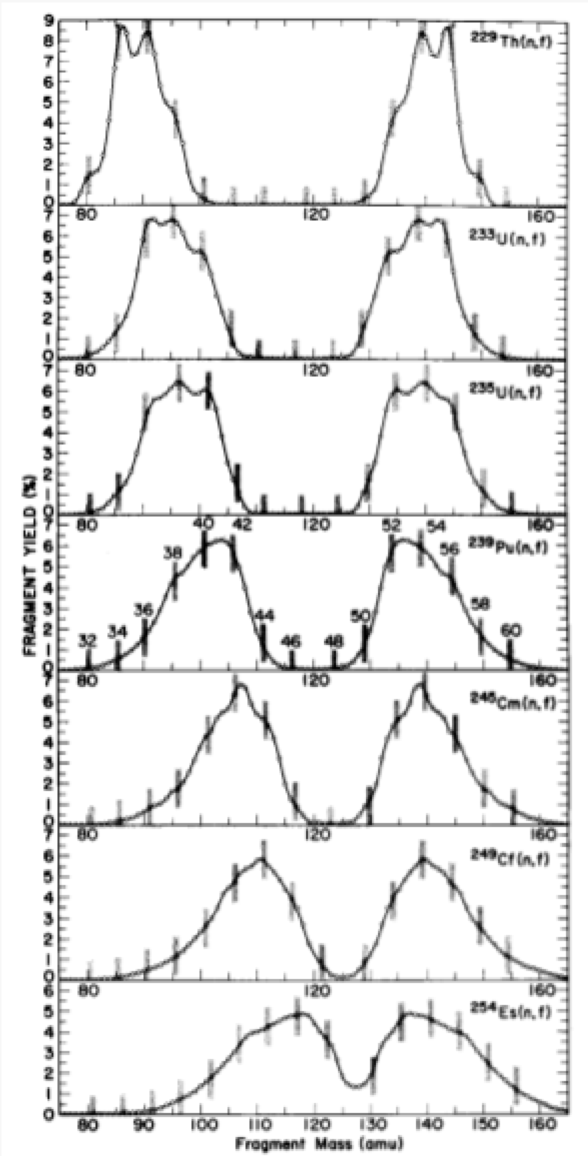
With shell effects

Property of the CN

Shells behind outer saddle:
Property of the nascent fragments

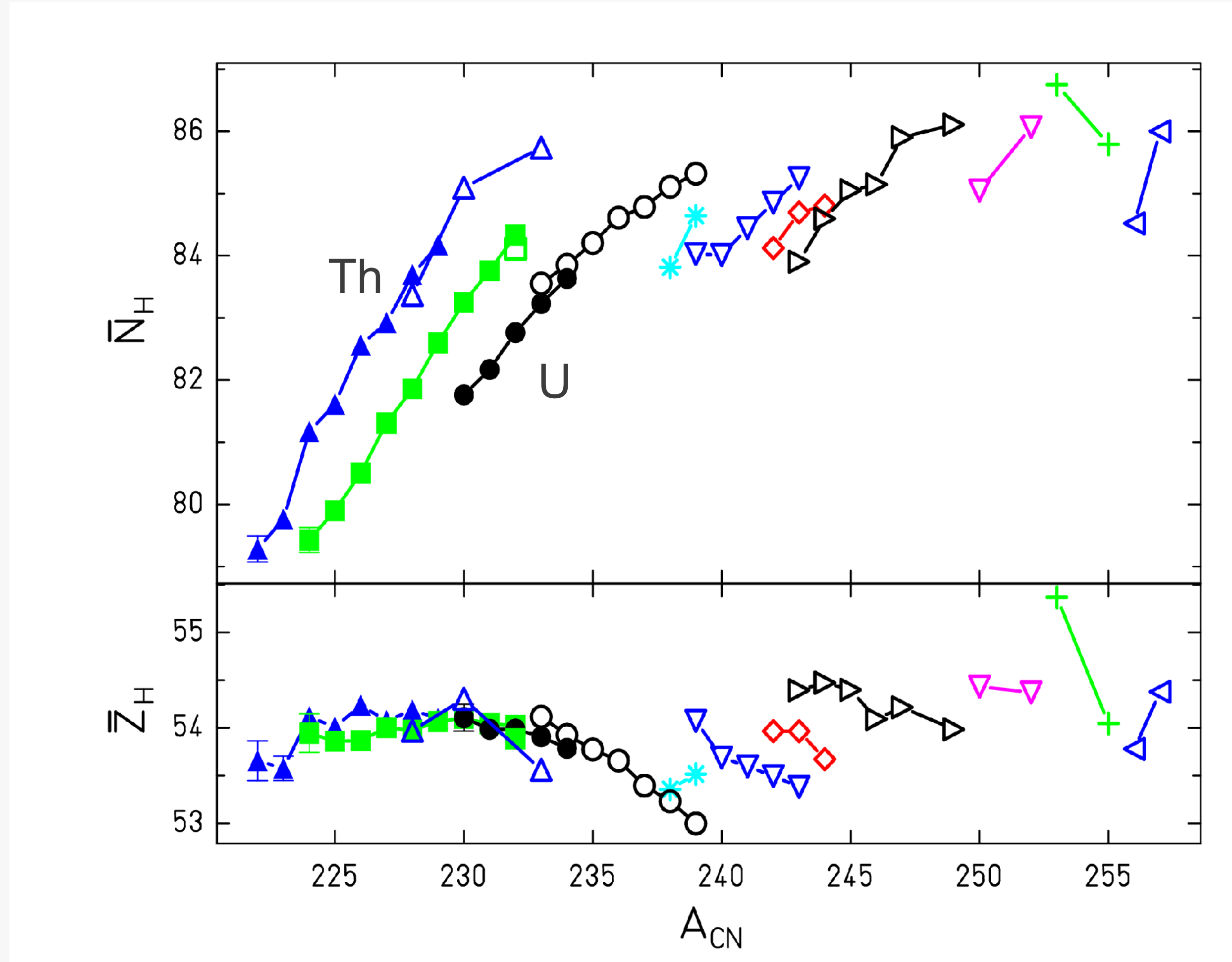
→ **Separability principle**

Empirical information on the main shells



Unik et al., 1973

<A> ≈ 140



Böckstiegel et al., NPA 802 (2008) 12

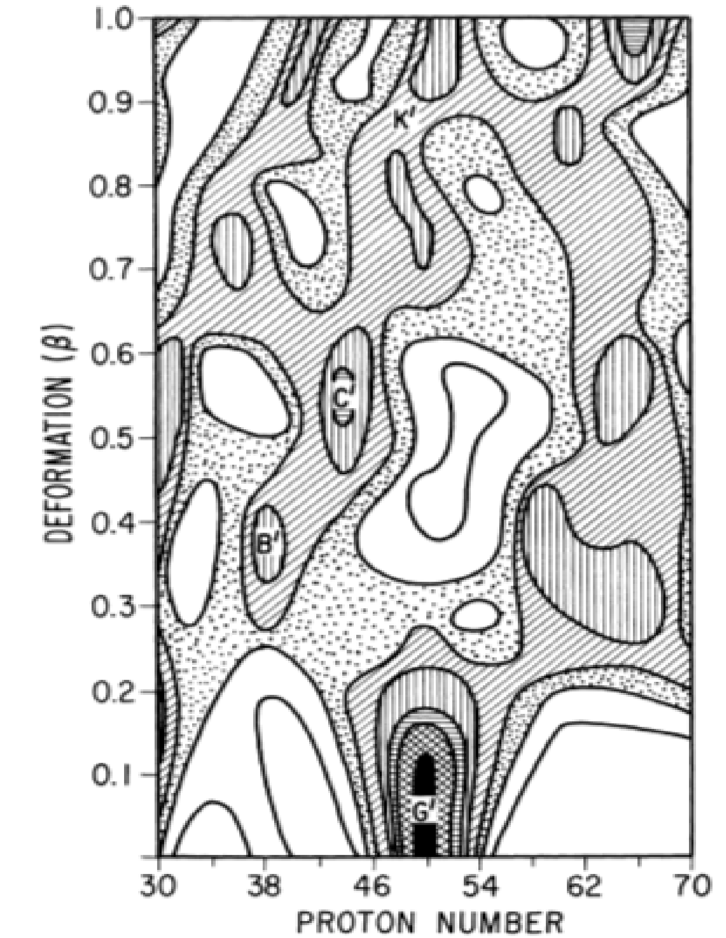
GSI data with long isotopic chains:

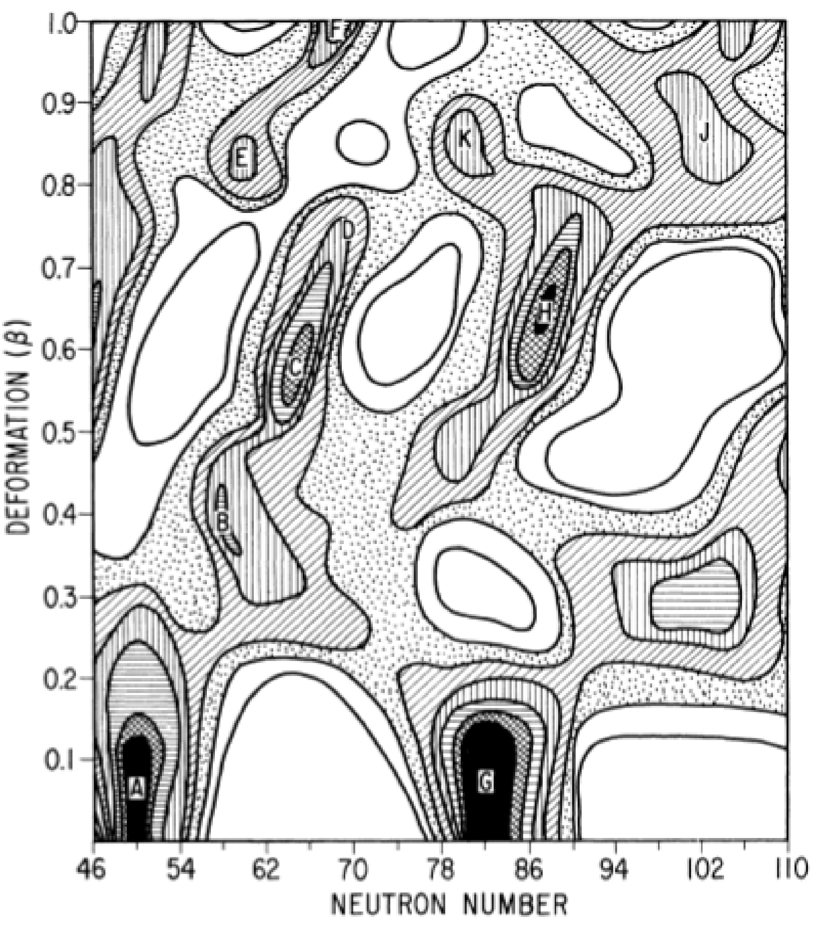
New empirical result: <Z> ≈ 54

Strong variation of <A> !

Theory: Attributed to fragment shell!

Fragment shells





Wilkins et al., Phys. Rev. C 14 (1976) 1832
(Other calculations give similar results.)

No fragment shell at Z = 54 predicted → puzzle for theory

Test of the separability principle

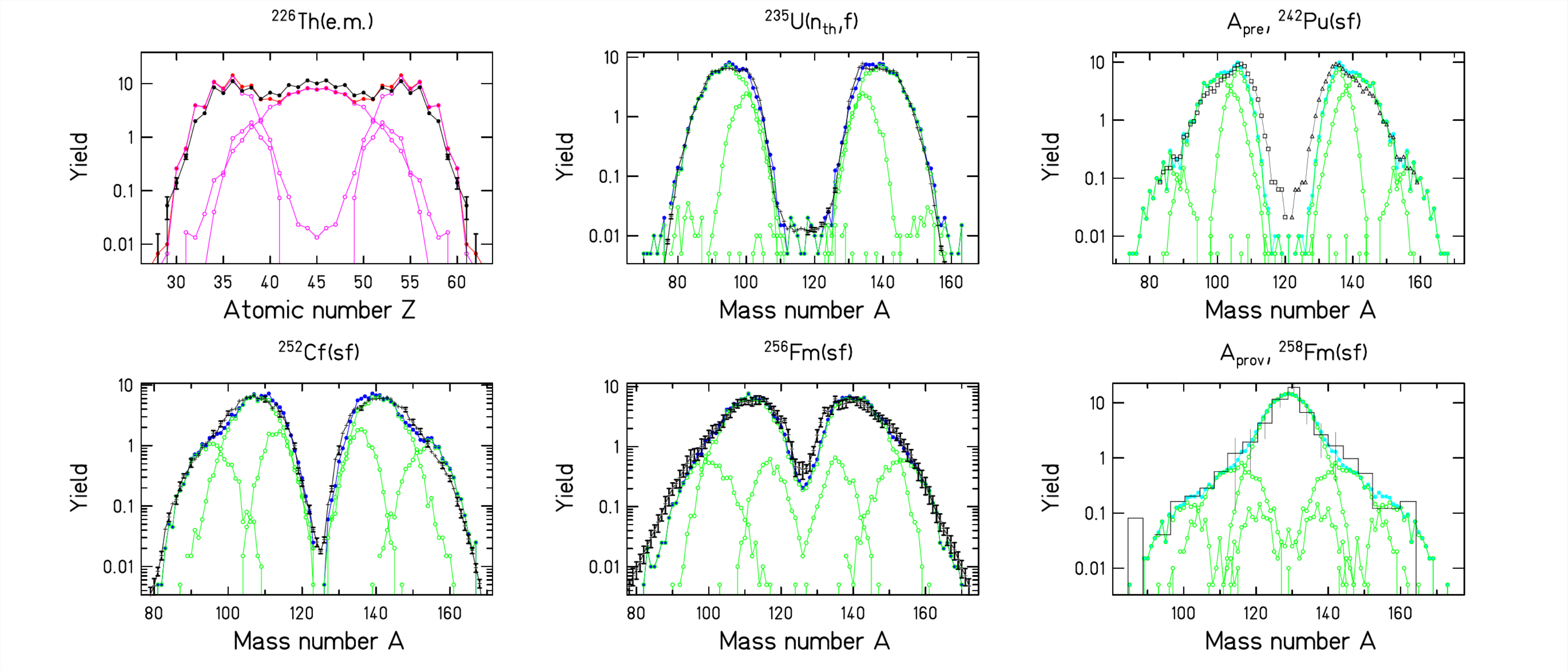
Deduce macroscopic potential from yield and shape of symmetric mode.

Deduce fragment shells (Zlight, Zheavy, Nlight,Nheavy) from yields and shapes of asymmetric modes (all systems).
(Shells depend only on the fragment, not on the CN!)

Idea: Mass distribution is given by quantum oscillator in mass asymmetry in a heat bath (nuclear temperature).
Superposition of the different fission valleys.

Dynamics: The deduced potential includes dynamical effects (friction and inertia).

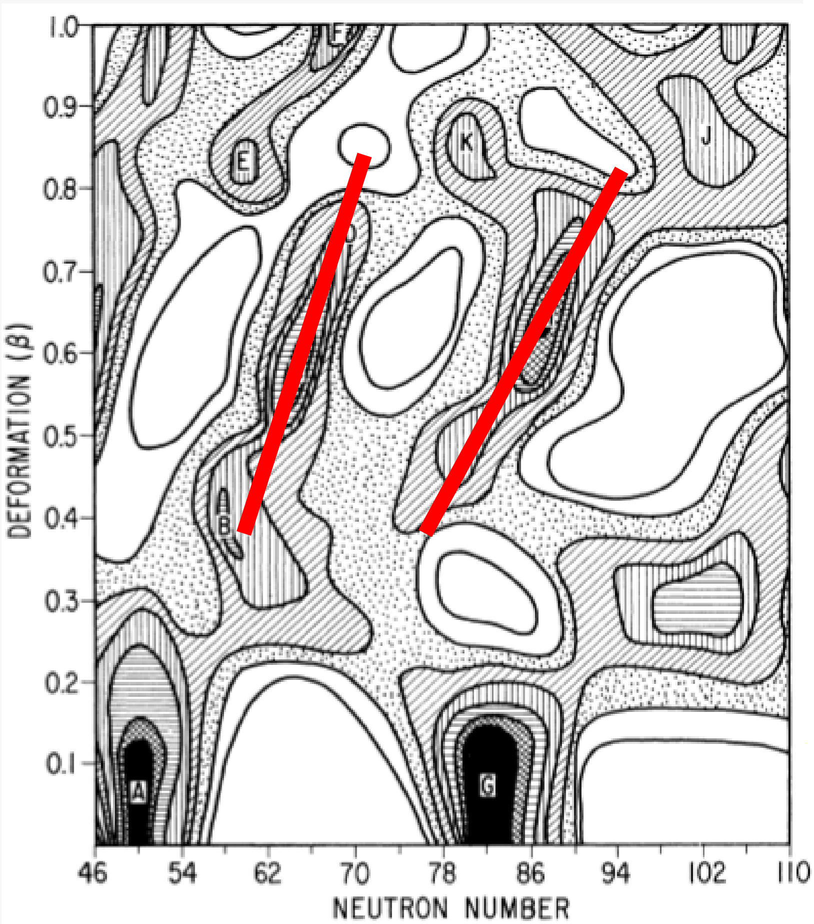
Hidden simplicity of fission !

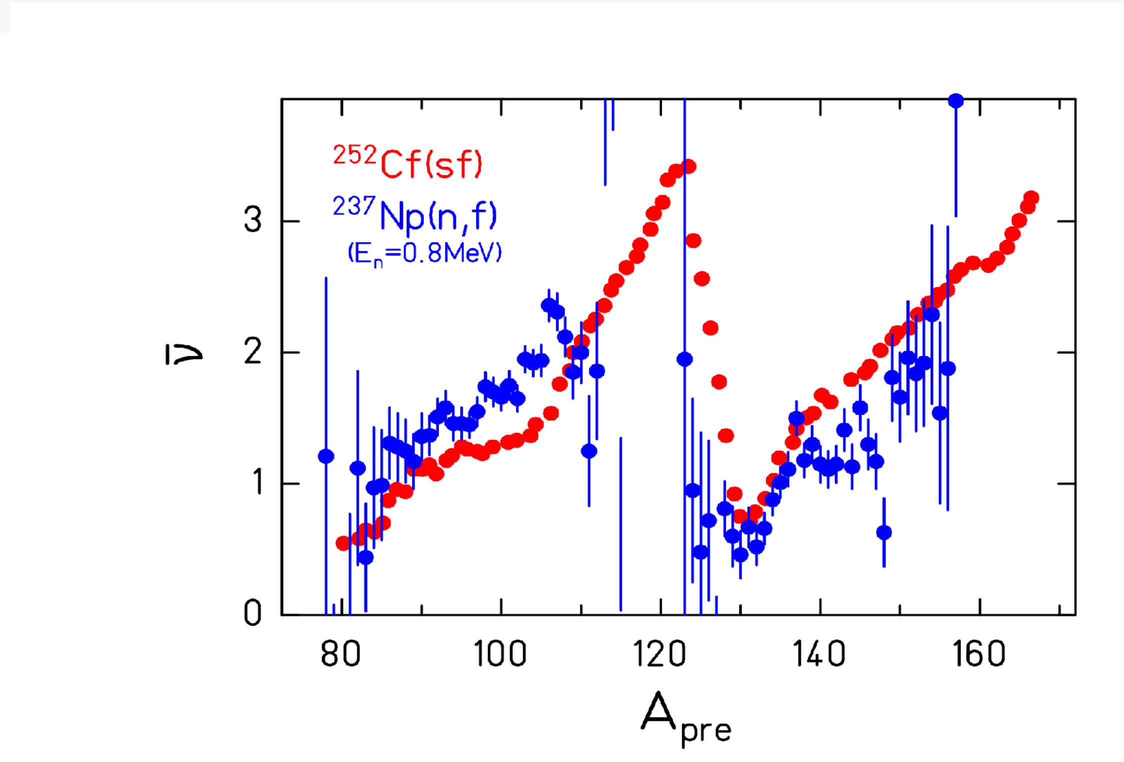


Variety of mass (*Z*) distributions very well described with the same fragment shells (*Z*≈51, *Z*≈55, *Z*≈59, *Z*≈42)!
(All distributions obtained with the same parameter set: position, depth and width of shells.)

GEF code: www.khs-erzhausen.de

Fragment deformation → prompt neutrons





Naqvi et al, 1986 / Zeynalova et al., 2012

Wilkins et al., Phys. Rev. C 14 (1976) 1832

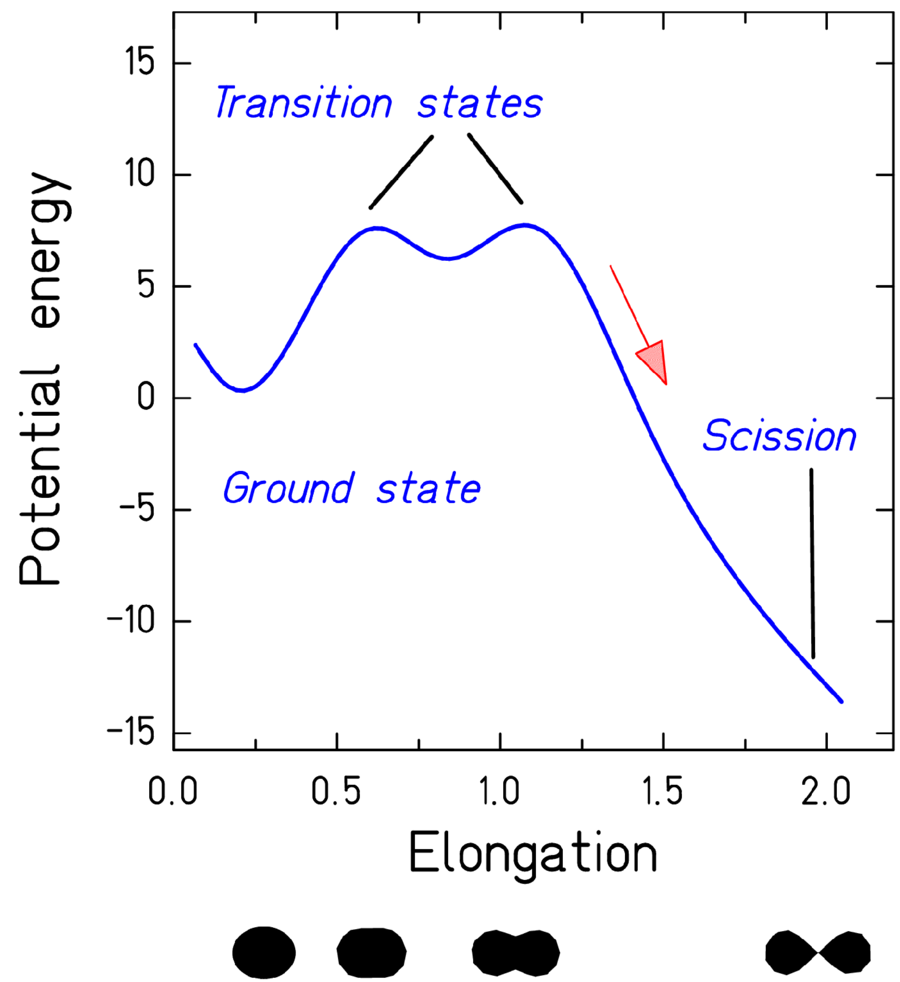
General systematics of deformed shells:
Correlation particle number ↔ deformation

Deformation at scission determined by fragment, not by CN.
Confirms separability principle.

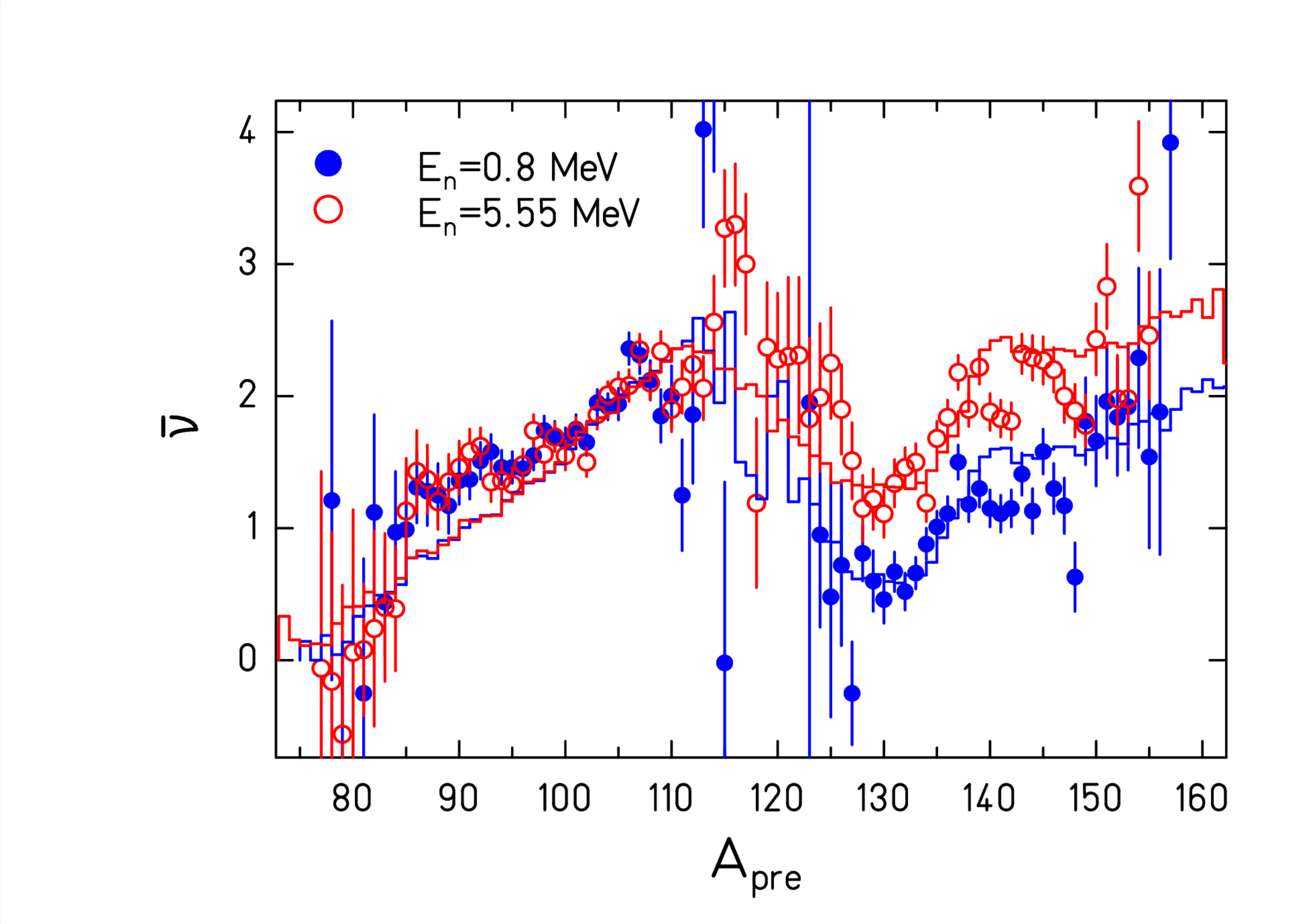
Thermodynamics:
How does heat divide between fragments ?

Variation of initial E*.

Not only nucleons, but also thermal energy can be exchanged between nascent fragments until scission.



Heat moves to heavy fragment

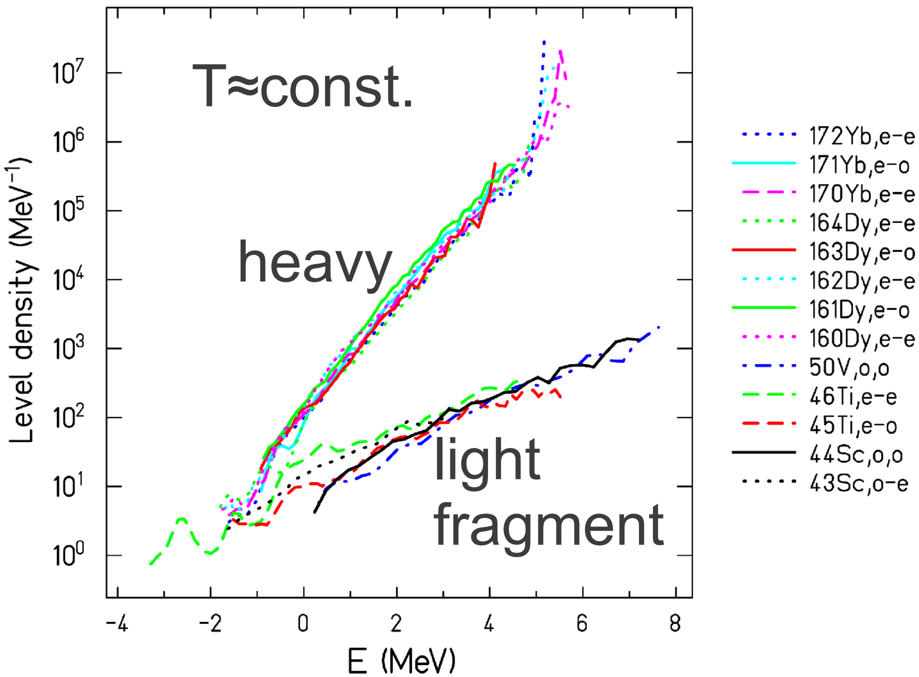


Naqvi et al., PRC 34 (1986) 21

Theory associates this result with new data on level densities:

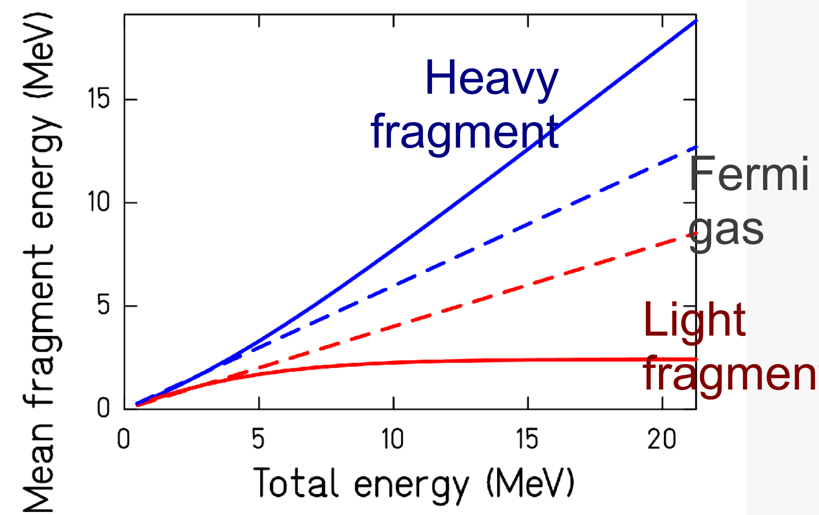
Statistical mechanics (energy sorting)

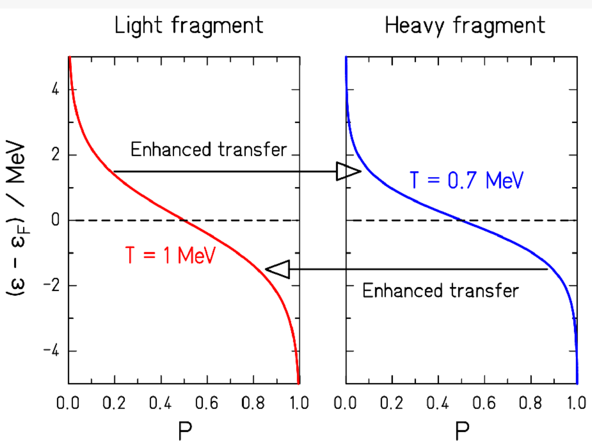
Nascent fragments: two thermostats!

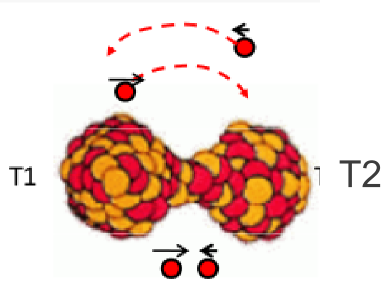


Guttormsen et al.

Schmidt, Jurado, PRC83 (2010) 061601

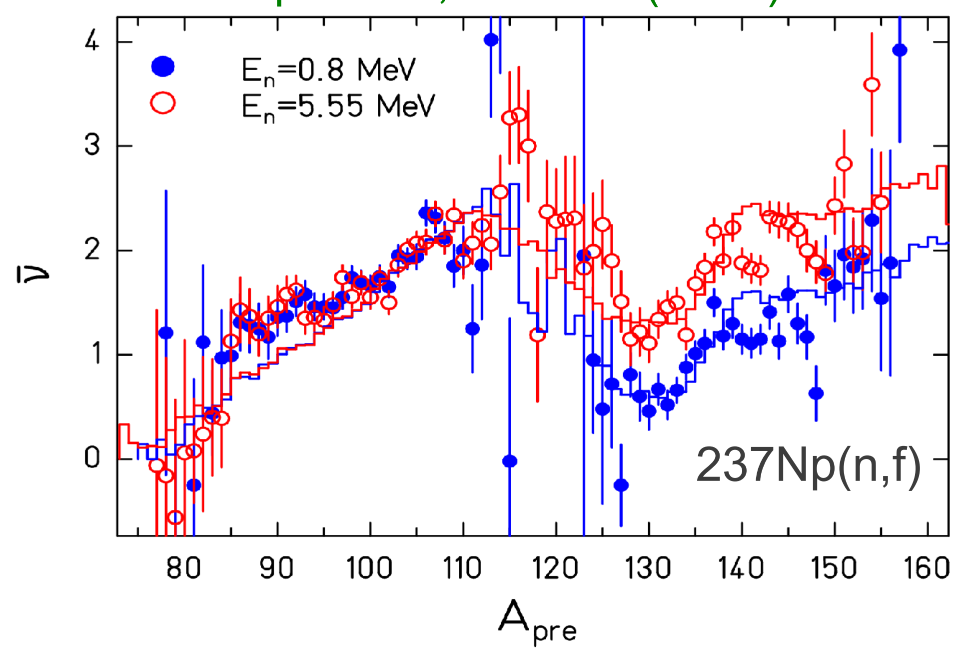






Heat transport (Randrup NPA 327 (1979) 490)

Naqvi et al., PRC 34 (1986) 21



Nuclear data:
GEFY - Library of fission-fragment yields

Tables of fission-fragment yields in ENDF format are provided for technical applications:
www.khs-erzhausen.de/GEFY.html or
www.cenbg.in2p3.fr/GEFY

Spontaneous and n-induced fission (E_n=thermal to 20 MeV)

About 40 specifically adjusted parameters *for all systems*.
(Compared to 30 to 60 parameters *for each system* in Wahl's empirical description.)

Quality is competitive with purely empirical descriptions:
1. Good reproduction of experimental data.
2. High predictive power due to validity of general laws.

GEFY tables

GEFY_94_239_n.dat

Datei Bearbeiten Suchen Optionen Hilfe

```
 GEFY-3.3   N-INDUCED FISSION PRODUCT YIELDS FILE Mar 2013          3597 0  0     0
 9.423900+4 2.369990+2         -1          1         99           13597 1451     1
 0.000000+0 1.000000+0          0          0          0           63597 1451     2
 1.000000+0 2.000000+7          1          0         11           13597 1451     3
 0.000000+0 0.000000+0          0          0         35           33597 1451     4
 94-Pu-239 CENBG,NEA   EVAL-MAR13 K.H.SCHMIDT                       3597 1451     5
                       DIST-AUG11 DIST-MAR13                        3597 1451     6
----GEFY-3.3           MATERIAL 3597                                3597 1451     7
-----NEUTRON-INDUCED FISSION PRODUCT YIELDS                         3597 1451     8
------ENDF-6 FORMAT                                                 3597 1451     9
******************************************************************3597 1451    10
**  Fission yields obtained with the GEF code, version 2013/1.6 **3597 1451    11
** Isomers and cumul. yields based on JEFF3.1.1 decay data file **3597 1451    12
** Developed at CEN Bordeaux Gradignan 2009,2010,2011,2012,2013 **3597 1451    13
**            Karl-Heinz Schmidt, Beatriz Jurado                **3597 1451    14
******************************************************************3597 1451    15
 The development of the GEF code has been supported by the          3597 1451    16
 European Union (EFNUDAT and ERINDA projects) and the               3597 1451    17
 OECD Nuclear Energy Agency.                                        3597 1451    18
                                                                    3597 1451    19
 The authors, the European Union and the Nuclear Energy Agency      3597 1451    20
 cannot accept responsibility for loss occasioned to any            3597 1451    21
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 contained in the data or its completeness or accuracy.             3597 1451    23
                                                                    3597 1451    24
 References:                                                        3597 1451    25
 - K.-H. Schmidt and B. Jurado                                      3597 1451    26
   General Model Description of Fission Observables                 3597 1451    27
   Final EFNUDAT report, CENBG, October 2010                        3597 1451    28
   http://www.cenbg.in2p3.fr/GEF                                    3597 1451    29
 - K.-H. Schmidt and B. Jurado                                      3597 1451    30
   Entropy-driven excitation-energy sorting in superfluid fission   3597 1451    31
   dynamics, Phys. Rev. Lett. 104 (2010) 212501                     3597 1451    32
 - K.-H. Schmidt and B. Jurado                                      3597 1451    33
   Thermodynamics of nuclei in thermal contact                      3597 1451    34
   Phys. Rev. C 83 (2011) 014607                                    3597 1451    35
 - K.-H. Schmidt and B. Jurado                                      3597 1451    36
   New insight into superfluid nuclear dynamics from the even-odd   3597 1451    37
   effect in fission, arXiv:1007.0741v1 [nucl-th] (2010)            3597 1451    38
                                                                    3597 1451    39
                                1        451         42           03597 1451    40
                                8        454      11859           03597 1451    41
                                8        459      11859           03597 1451    42
 0.000000+0 0.000000+0          0          0          0           03597 1   099999
                                                                    3597 0  0     0
```

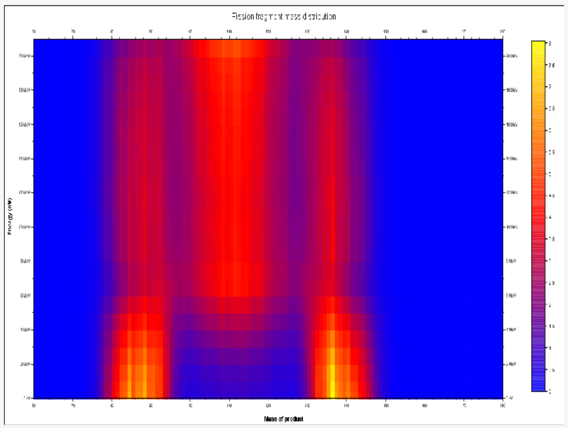
Mass distributions vs. energy

En

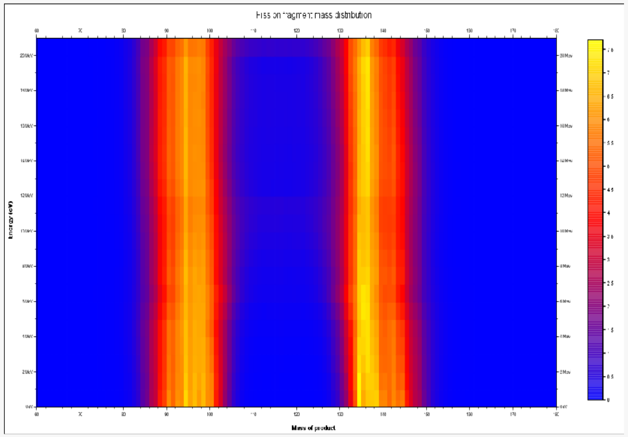
20
MeV

0
MeV

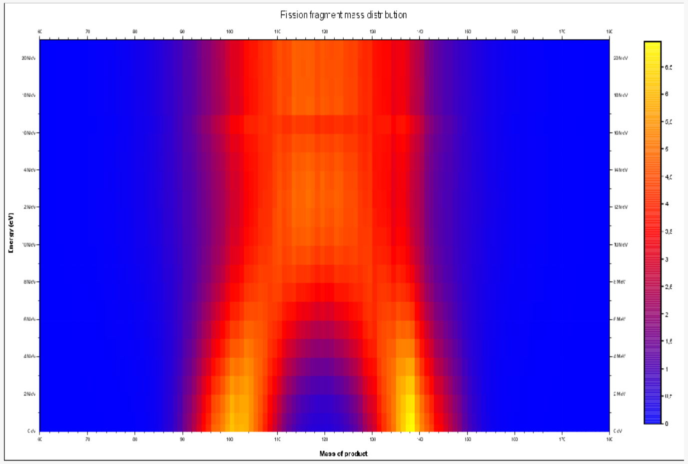
225Th



235U



241Cf



Fragment mass

Figure produced from GEFY tables
with the test version of JANIS.

Summary

General law of quantum mechanics: (→ mass division)
Localisation of wave functions in di-nucleus.
Early influence of fragment shells.

Application:
Separability principle (mac. and mic. properties).
Hidden simplicity of fission-channel properties.

General law of statistical mechanics: (→ heat division)
Dynamics driven by entropy.

Application:
Energy sorting. Also decisive for even-odd effect!

General conclusion:
Microscopic modelling of individual systems is blind to the power of general laws.

Application of general laws and careful analysis of firm empirical systematics puts the physics into a global context and leads to a better understanding.

GEFY: global set of fission-fragment yields.

Relevant publications

- [1] Experimental evidence for the separability of compound-nucleus and fragment properties in fission, K.-H. Schmidt, A. Kelic, M. V. Ricciardi, Europh. Lett. 83 (2008) 32001
- [2] Nuclear-fission studies with relativistic secondary beams: analysis of fission channels, C. Boeckstiegel et al., Nucl. Phys. A 802 (2008) 12
- [3] Shell effects in the symmetric-modal fission of pre-actinide nuclei, S. I. Mulgin, K.-H. Schmidt, A. Grewe, S. V. Zhdanov, Nucl. Phys. A 640 (1998) 375
- [4] Entropy-driven excitation-energy sorting in superfluid fission dynamics, K.-H. Schmidt, B. Jurado, Phys. Rev. Lett. 104 (2010) 212501
- [5] New insight into superfluid nuclear dynamics from the even-odd effect in fission, K.-H. Schmidt, B. Jurado, arXiv:1007.0741v1 [nucl-th]
- [6] Thermodynamics of nuclei in thermal contact, K.-H. Schmidt, B. Jurado, Phys. Rev. C 82 (2011) 014607
- [7] Final excitation energy of fission fragments, K.-H. Schmidt, B. Jurado, Phys. Rev. C 83 (2011) 061601(R)
- [8] Inconsistencies in the description of pairing effects in nuclear level densities, K.-H. Schmidt, B. Jurado, Phys. Rev. C 86 (2012) 044322