Revealing Hidden Regularities with a General Approach to Fission

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Perspectives on Nuclear Data for the Next Decade

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Prefix

Prominent questions of this workshop:

- Can the pure microscopic models be used to produce evaluations with the required *accuracy*, and if not how can they be *improved* or *adjusted*?
- Is there any way to improve the *predictive power* of phenomenological approaches thanks to microscopic outputs?

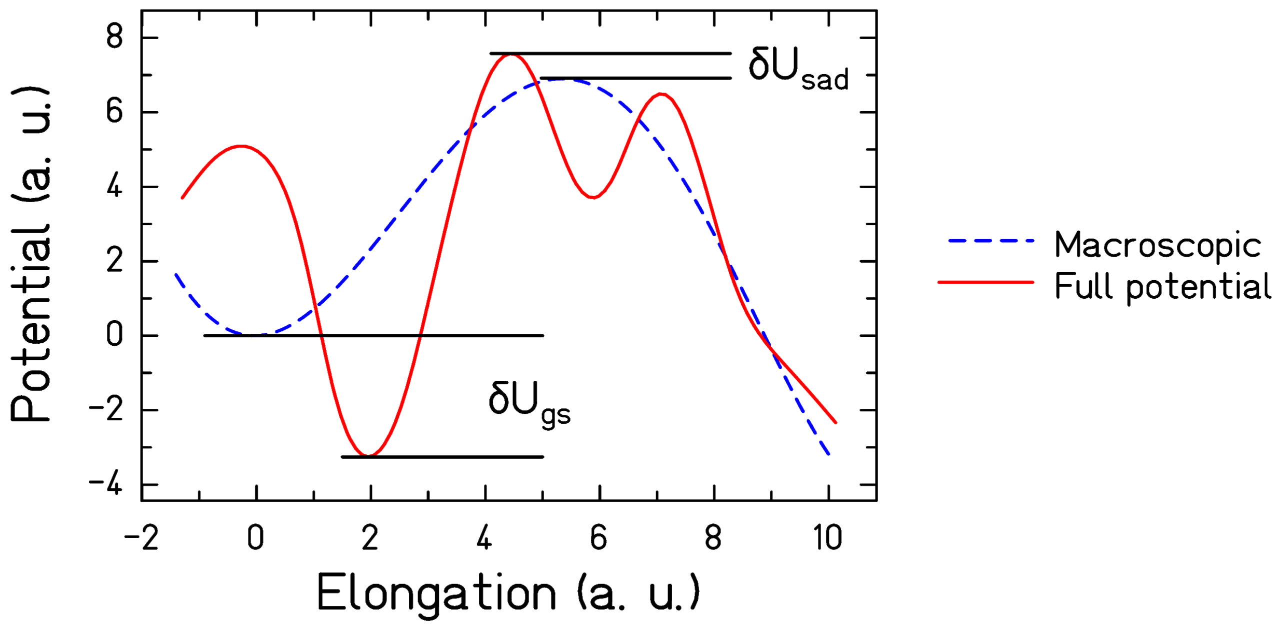
A possible answer:

- Apply global theoretical models on the basis of *universal laws of physics* and *mathematics*.

K.-H. Schmidt et al., JEFF Report 24 (2014), NEA, Paris.

1. Topographic theorem

Topographical property of fission barriers



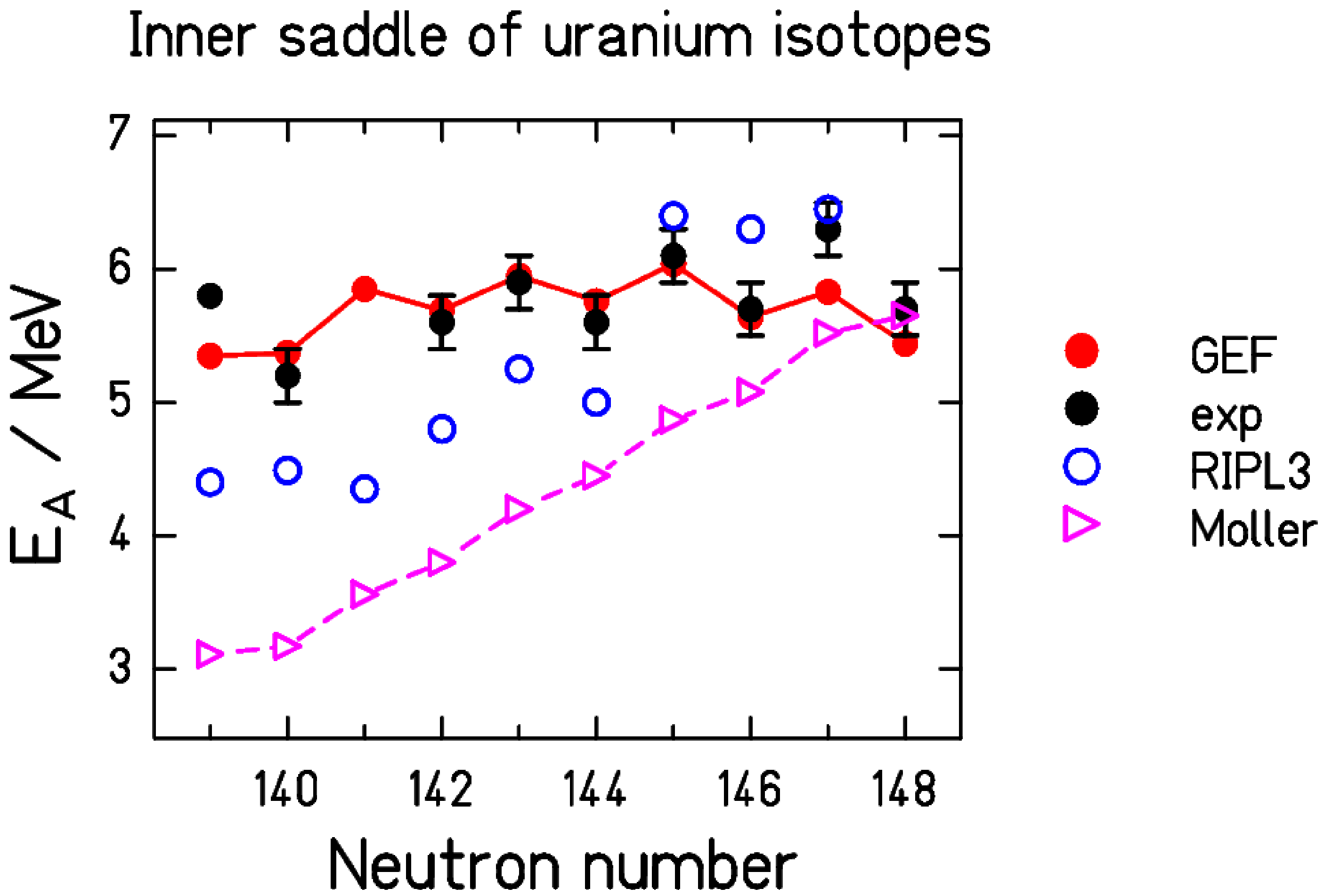
Topographic theorem of Myers & Swiatecki:

The shell effect at the barrier δU_{sad} is small (negligible?).

$$B_f \approx B_f(ld) - \delta U_{gs} = B_f(ld) - M_{gs}(exp) + M_{gs}(ld)$$

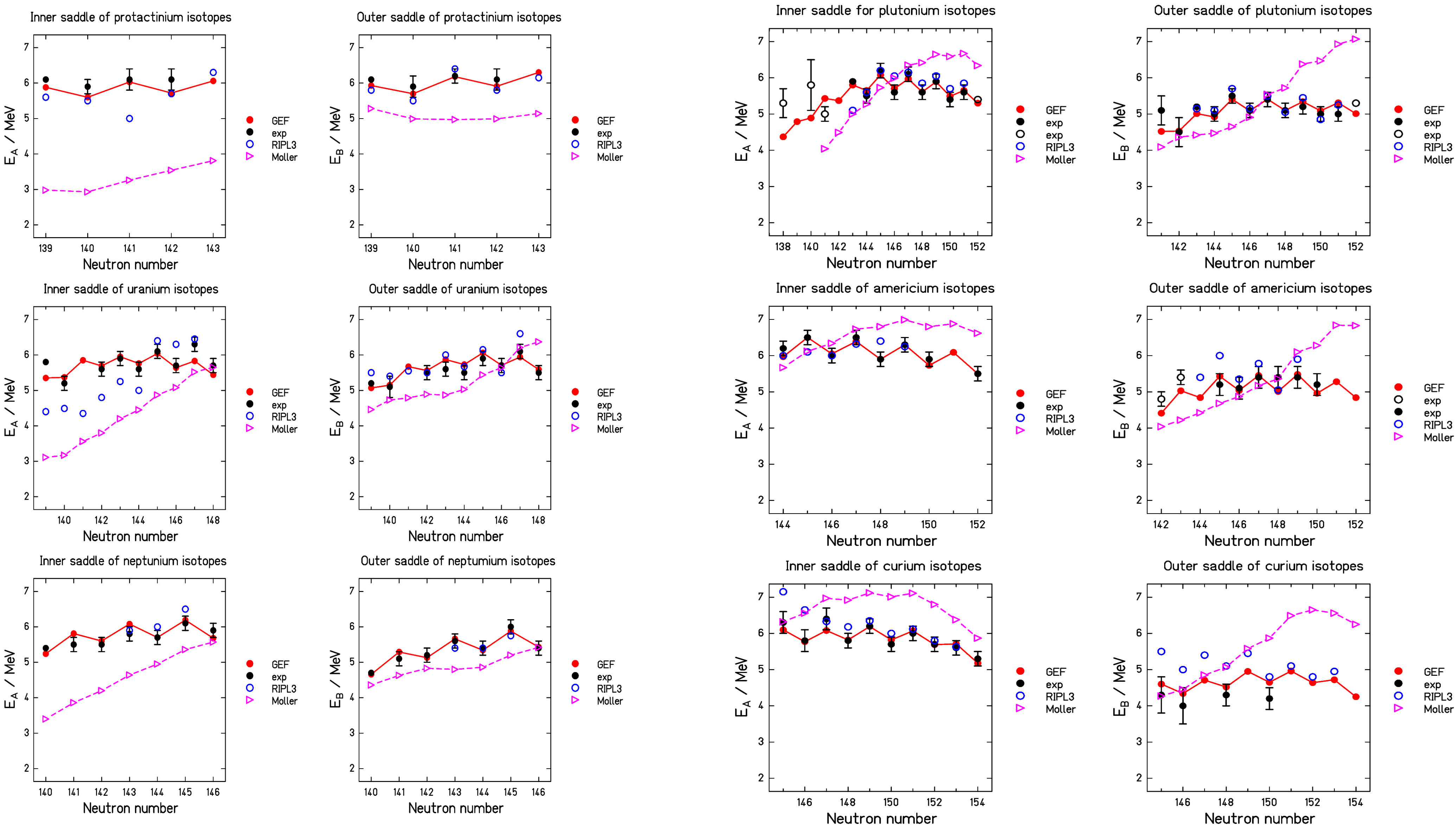
Only macroscopic energies from theory!

Fission barrier of U isotopes



GEF: K.-H. Schmidt et al., JEFF Report 24 (2014), NEA, Paris.
exp: S. Bjoernholm, J. E. Lynn, Rev. Mod. Phys. 52 (1980) 725.
RIPL 3: R. Capote et al., Nucl. Data Sheets 110 (2009) 3107.
Möller: P. Möller et al., Phys. Rev. C 79 (2009) 064304.

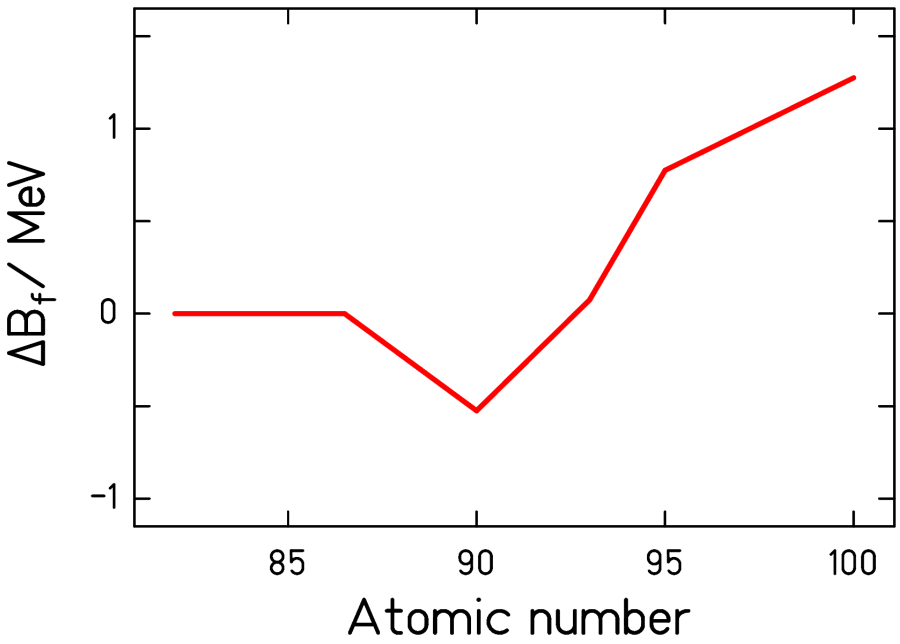
Systematics of fission barriers



Excellent agreement of "exp (●)" and "GEF (●)" corroborates both.
Theory of P. Möller et al.(---) deviates.

Empirical adjustments

- Z-dependent modification of $B_f(ld)$:



- Fit of E_A-E_B
  $= 5.401 - 0.00666\, Z^3/A + 1.525\text{E-}6\, (Z^3/A)^2$
- Increased $\Delta_{sad} = 14 / \sqrt{A}$

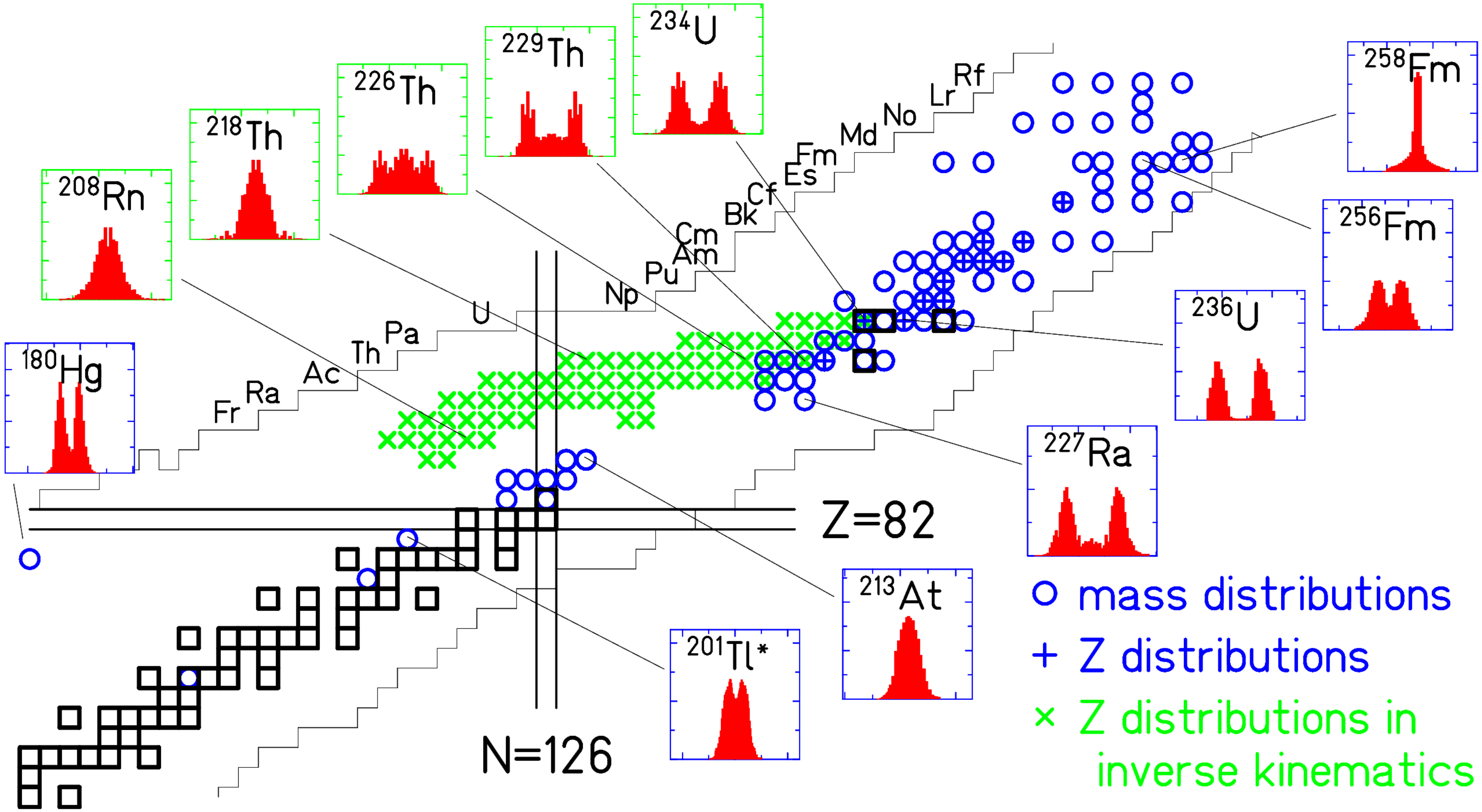
Chi-squared deviations (MeV)

	exp	RIPL 3	GEF	Goriely	Möller
exp	—	0.43	0.20	0.37	1.1
RIPL 3	0.43	—	0.46	0.46	1.0
GEF	0.20	0.46	—	0.38	1.1
Goriely	0.37	0.46	0.38	—	1.0
Möller	1.1	1.0	1.1	1.0	—

exp: S. Bjoernholm, J. E. Lynn, Rev. Mod. Phys. 52 (1980) 725.
(Experimental uncertainty ≈ 0.2 MeV)
RIPL3: R Capote et al., Nucl. Data Sheets 110 (2009) 3107.
GEF: K.-H. Schmidt et al., JEFF Report 24 (2014), NEA, Paris.
Goriely: S. Goriely et al., Phys. Rev. C79 (2009) 024612.
Möller:: P. Möller et al., Phys. Rev. C 79 (2009) 064304.

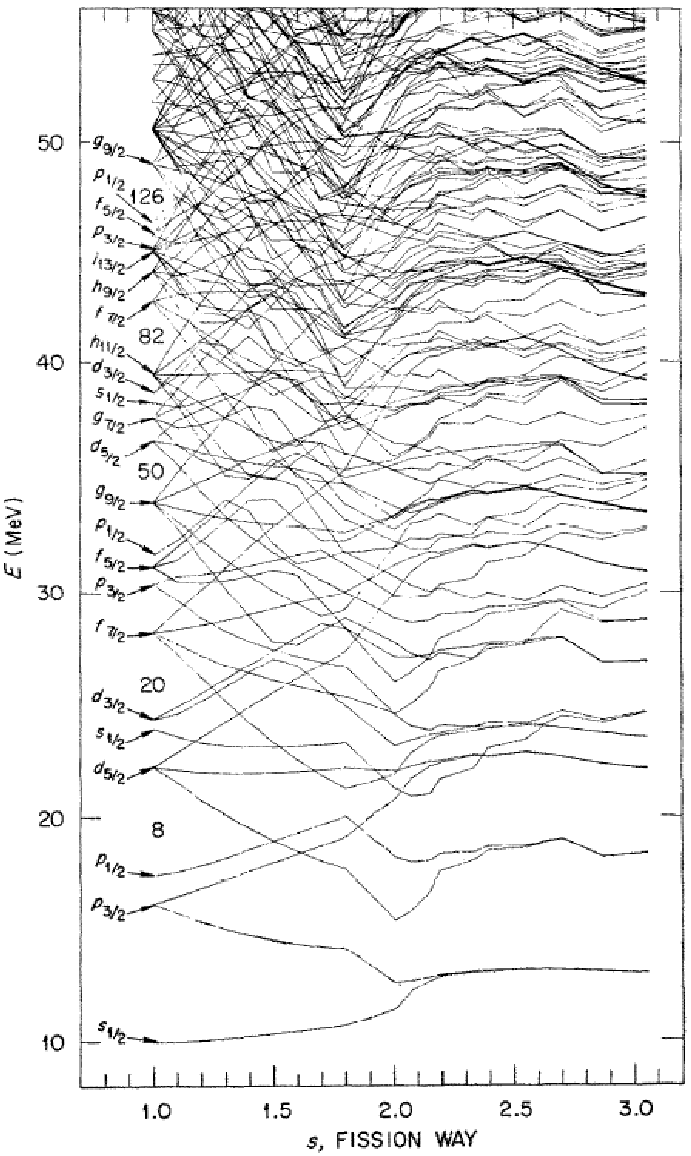
2. Fragment shells

Systematics of mass (Z) distributions



Complex variation of shapes

Early influence of fragment shells



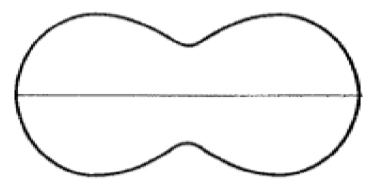
Ground state

Second barrier

Scission

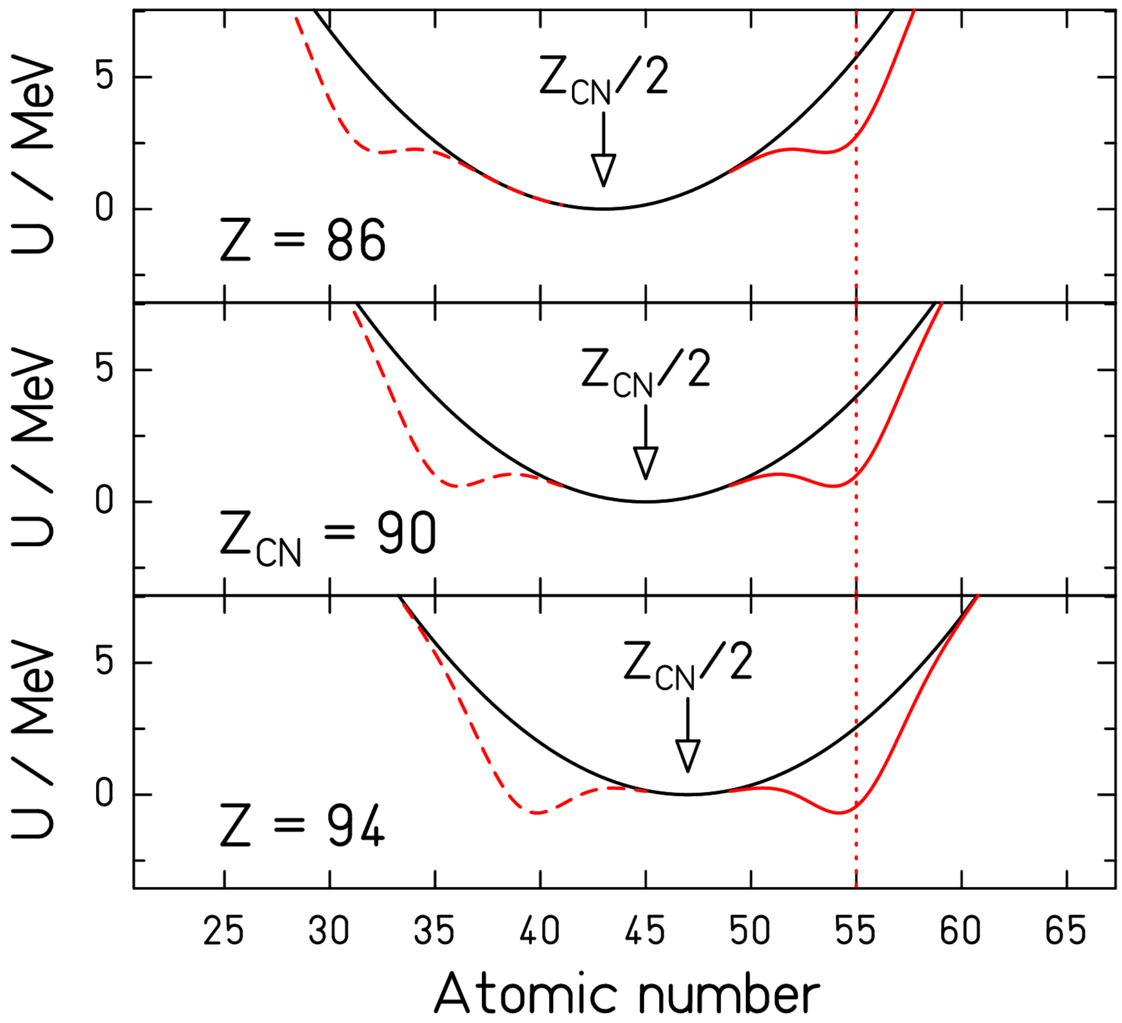
Neutron shell-model states in 2-center shell model

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



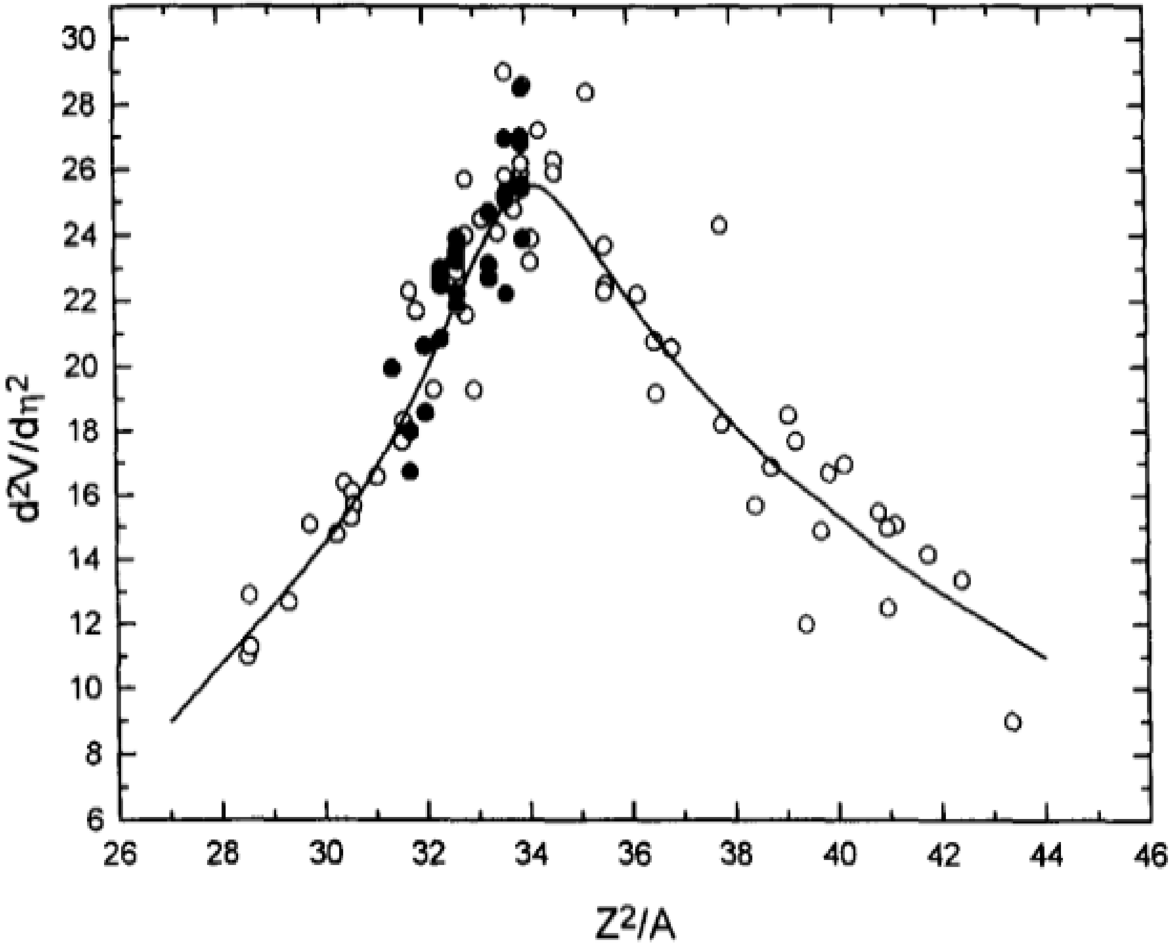
- Single-particle levels near second barrier resemble those of separated fragments.
- Quantum-mechanical effect of necked-in shape.

Shape transitions with fragment shells



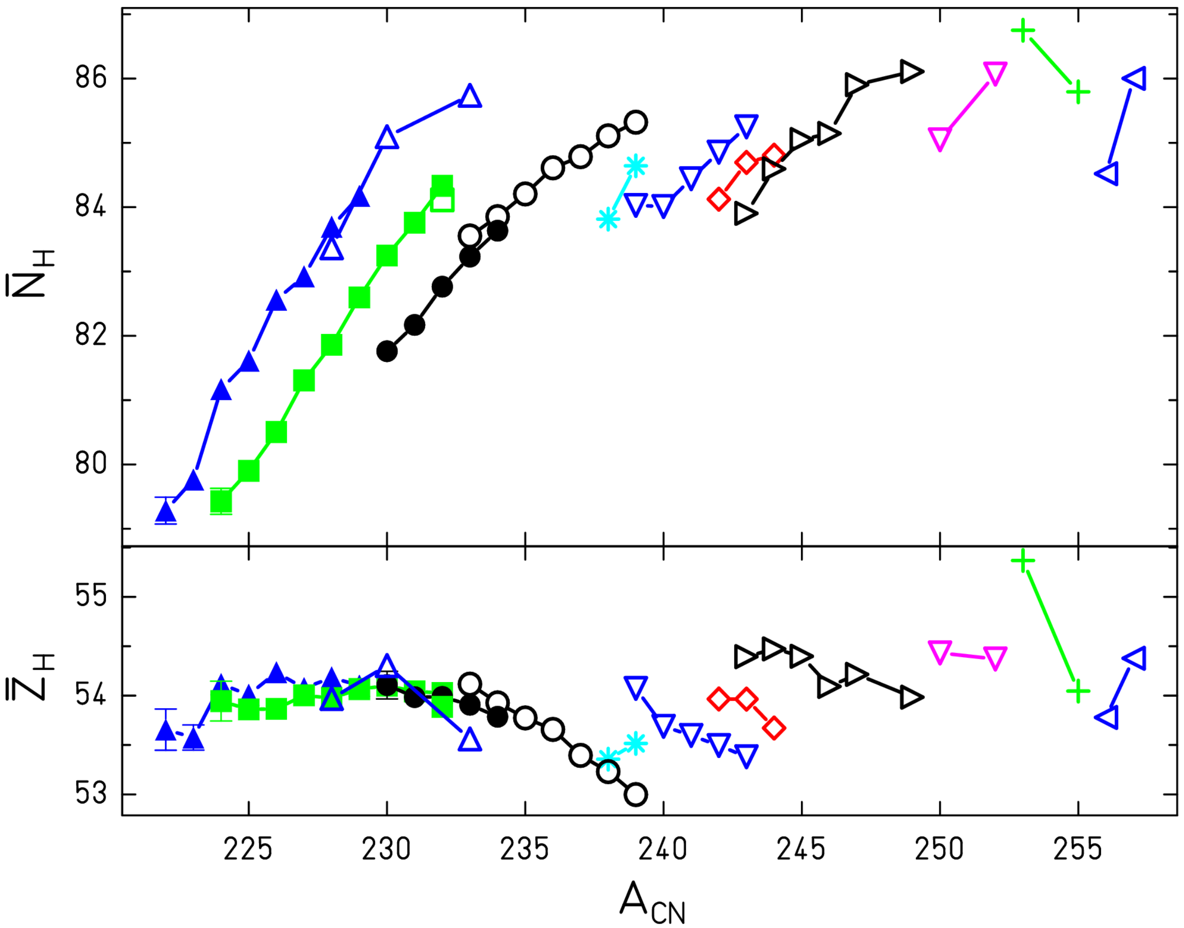
Interplay between macroscopic potential and shells explains transition from symmetric to asymmetric fission

Macroscopic potential



Curvature of potential deduced from systematics of mass distributions (symmetric component) (Rusanov et al., 1990)

Position of asymmetric component



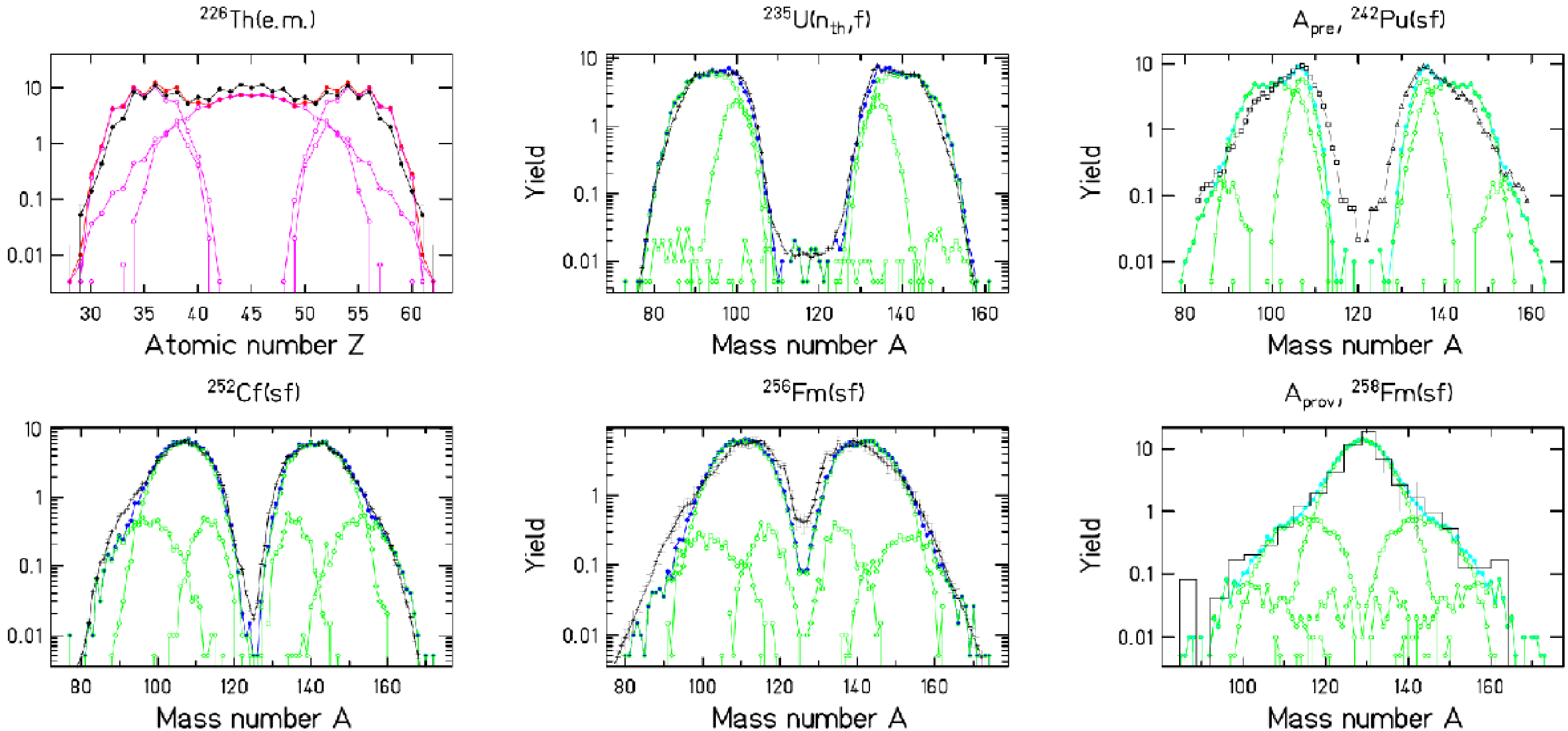
C. Böckstiegel et al., Nucl. Phys. A 802(2008) 12

Position of asymmetric component is stable close to <Z> = 54.

Extraction of fragment shells from fragment distributions

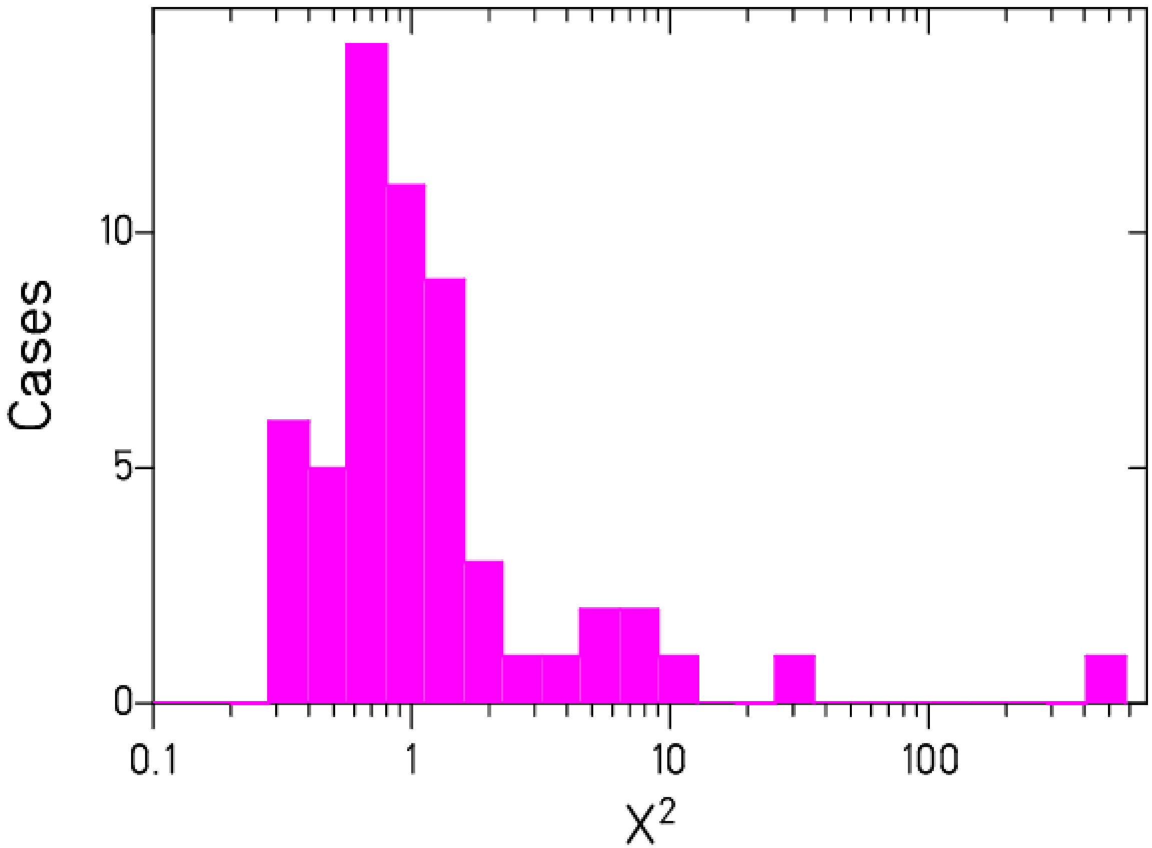
Position	Z ≈ 42	Z ≈ 52 (S1)	Z ≈ 55 (S2)	Z ≈ 58 (SA)
Strength	-1.3 MeV	-4.6 MeV	-4.0 MeV	-6.0 MeV

Comparison with data: mass distributions



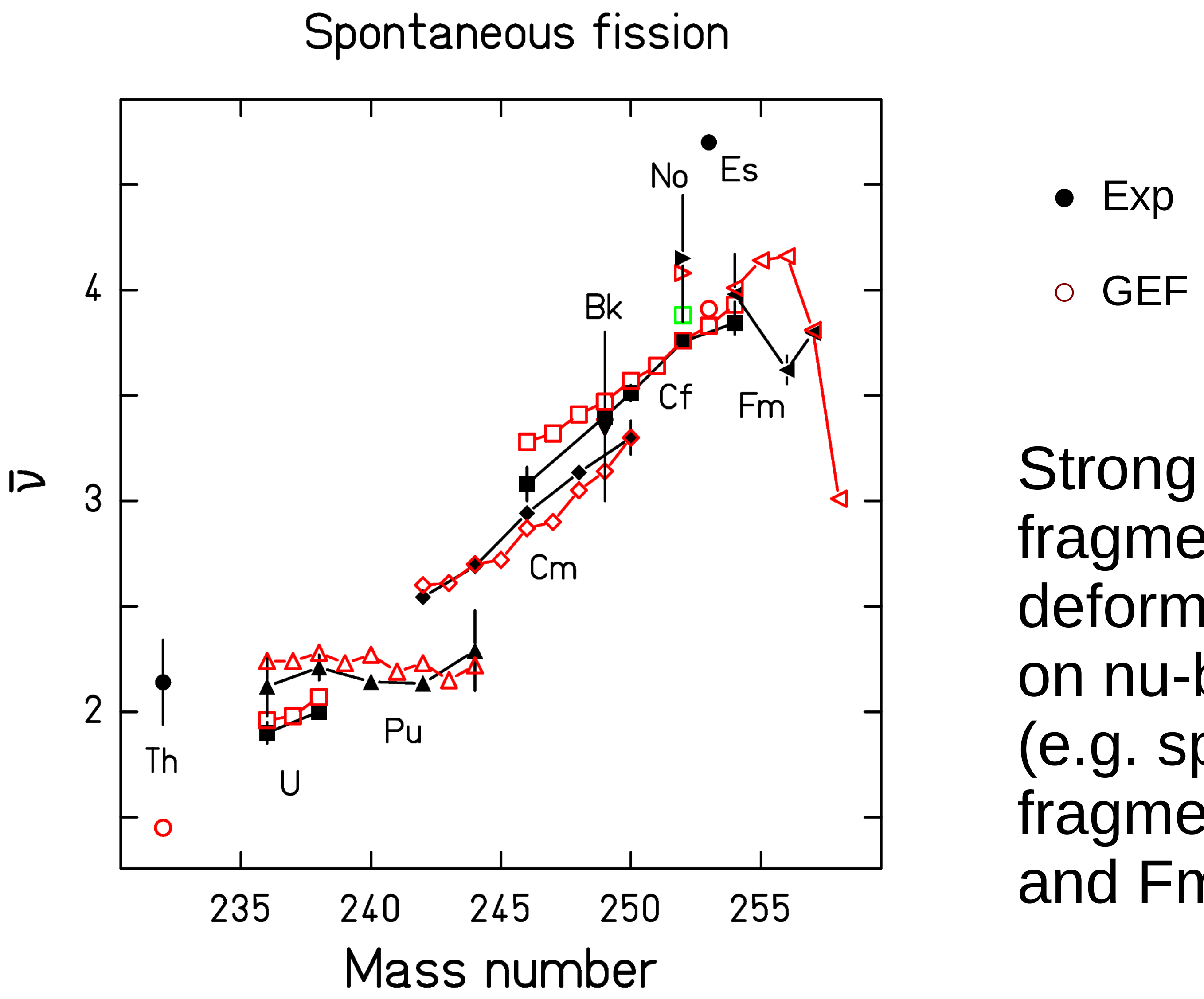
Good reproduction of different shapes with the same parameter set

Chi-squared deviations



- Among the 9 discrepant cases, only 1 (229Th(nth,f) can be attributed to a deficiency of the model.

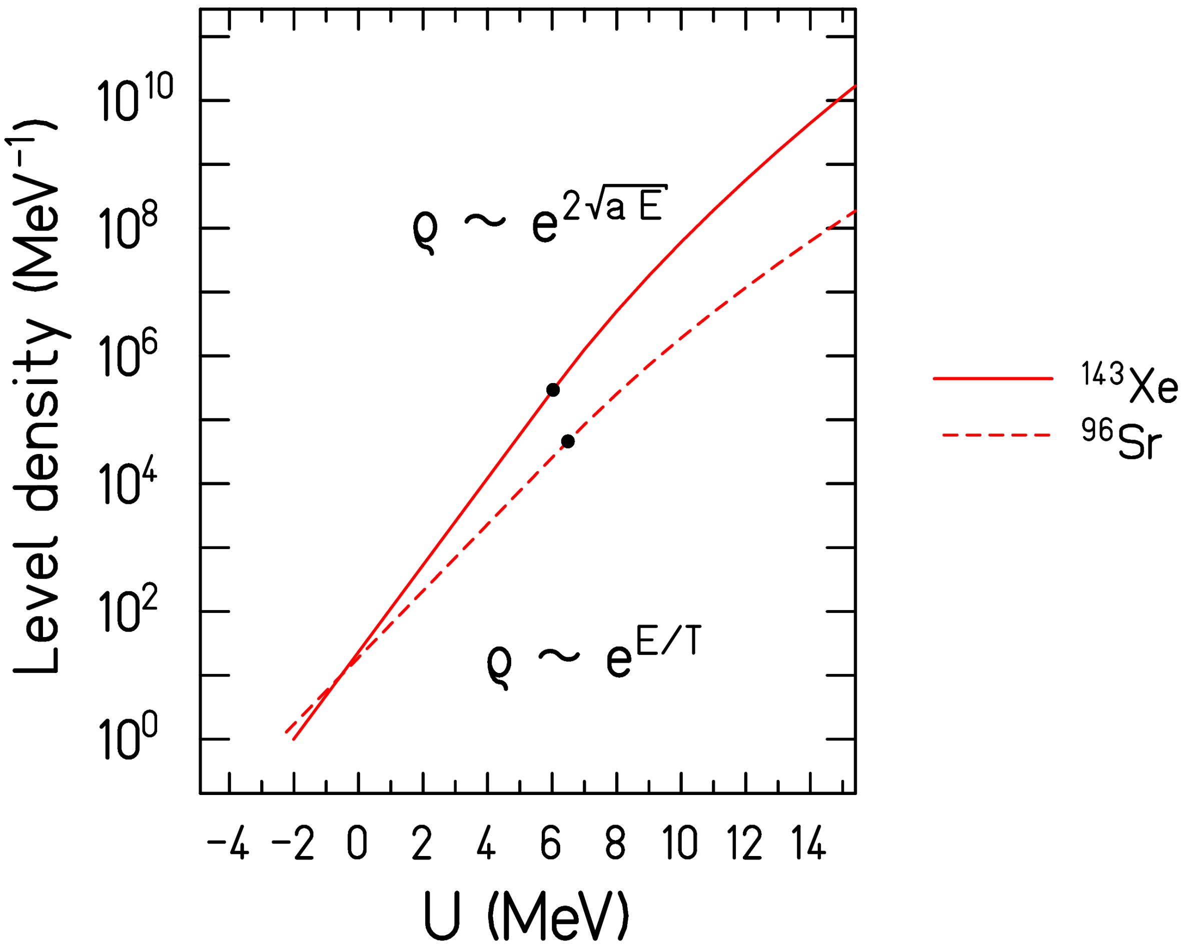
Prompt-neutron multiplicities system dependence



Strong influence of fragment deformation on nu-bar (e.g. spherical fragments for Pu and Fm isotopes).

3. Energy sorting

Level densities



Increased heat capacity by pairing correlations.

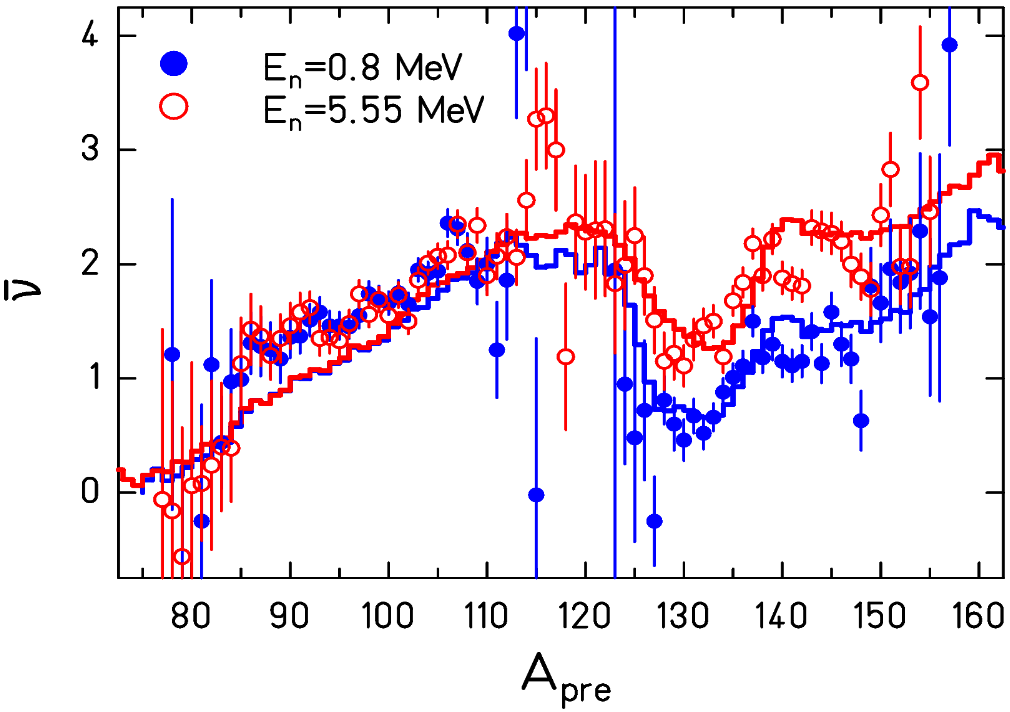
Heating leads to pair breaking → creation of additional degrees of freedom.

(Nearly constant temperature.)

U = Eexc corrected for even-odd staggering.

K.-H. Schmidt, B. Jurado, Phys. Rev. C 86 (2012) 044322

Prompt-neutron multiplicities A and E dependence



^{237}Pu(n,f)

Data: A. A. Naqvi et al., Phys. Rev. C 34 (1986) 21.
Calculation: K.-H. Schmidt, B. Jurado, Phys. Rev. Lett. 104 (2010) 21251.
Nascent fragments: 2 microscopic thermostats in contact.
Energy increment ends up in heavy fragment (lower T).
Energy sorting driven by entropy.

Conclusion

- Higher-level laws of mathematics and physics allow a better understanding of general properties and a good quantitative description of fission observables.
- Considering empirical information, global laws of mathematics and physics in addition to microscopic models is a way to overcome limitations in precision, complexity and predictive power of the different approaches.
- For a more detailed discussion see
  K.-H. Schmidt, B. Jurado, Ch. Amouroux,
  JEFF-Report 24, NEA Data Bank, Paris (June 2014)
  https://www.oecd-nea.org/databank/docs/2014/db-doc2014-1.pdf