The role of fission in the r-process nucleosynthesis

- or -

What do we need to know about fission

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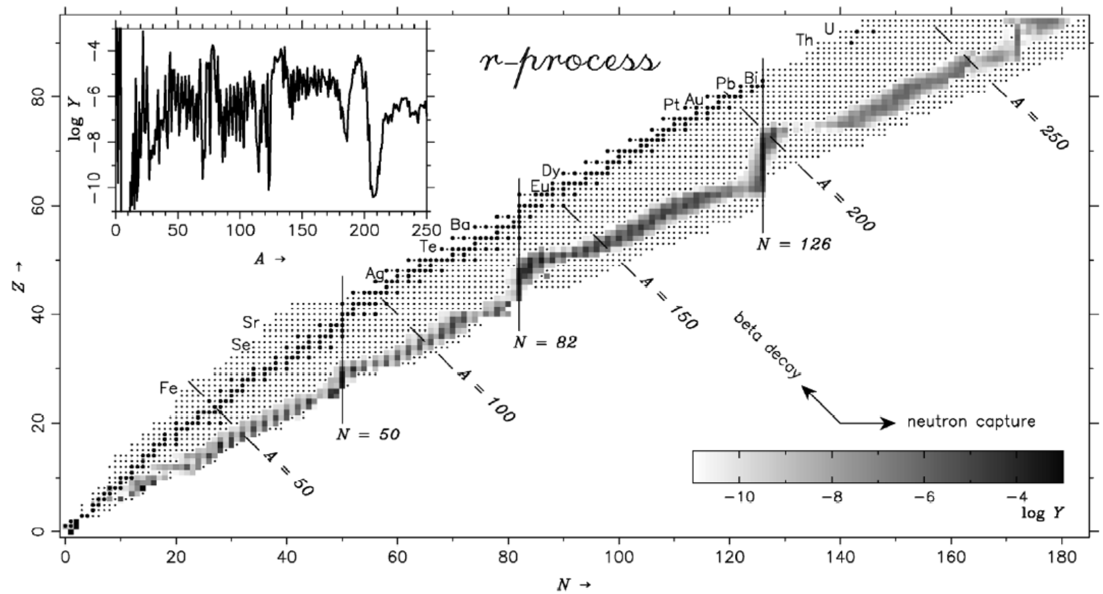
Importance of fission

Trans-U elements ? 1)

r-process endpoint ? 2)

Fission cycling ? 3, 4)



S. Wanajo et al., NPA in press

1) Cowan et al, Phys. Rep. 208 (1991) 267
2) Panov et al., NPA 747 (2005) 633
3) Seeger et al, APJ 11 Suppl. (1965) S121
4) Rauscher et al, APJ 429 (1994) 49

See also poster by I. Panov (ID 142)

What do we need?

- Fission probabilities ⇨ fission barriers, masses, nuclear level density
- Fission-fragment distributions

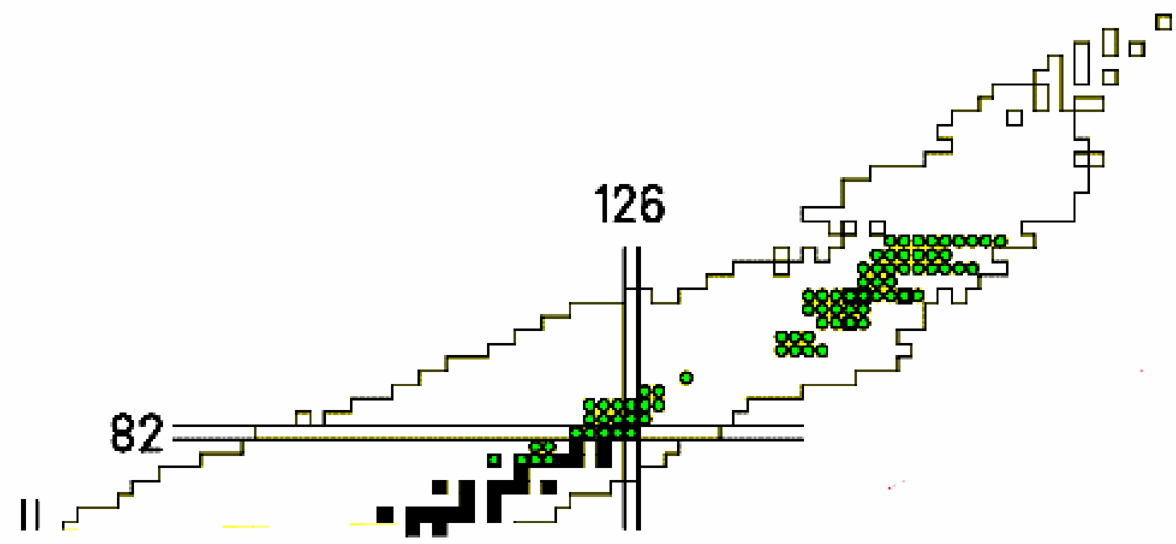
Challenge for experiment and theory

- Large-scale collective motion
- Nuclear structure effects (shell effects, pairing...) at large deformations
- Fission dynamics
- All this for nuclei not accessible in laboratory

Fission barriers

Strong influence on the fission contribution to the r-process nucleosynthesis

Experimental information



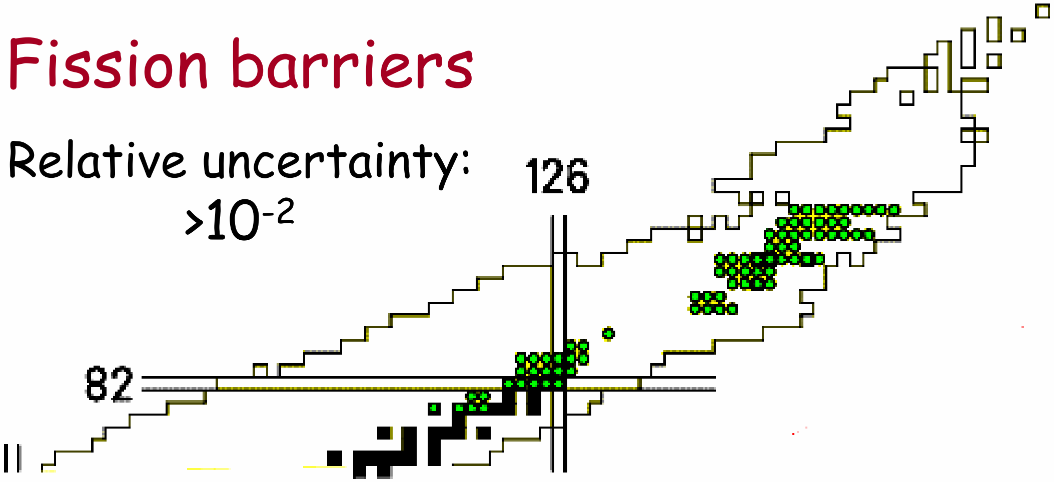
Relative uncertainty: $>10^{-2}$

Available data on fission barriers, $Z \geq 80$ (RIPL-2 library)

Experimental information

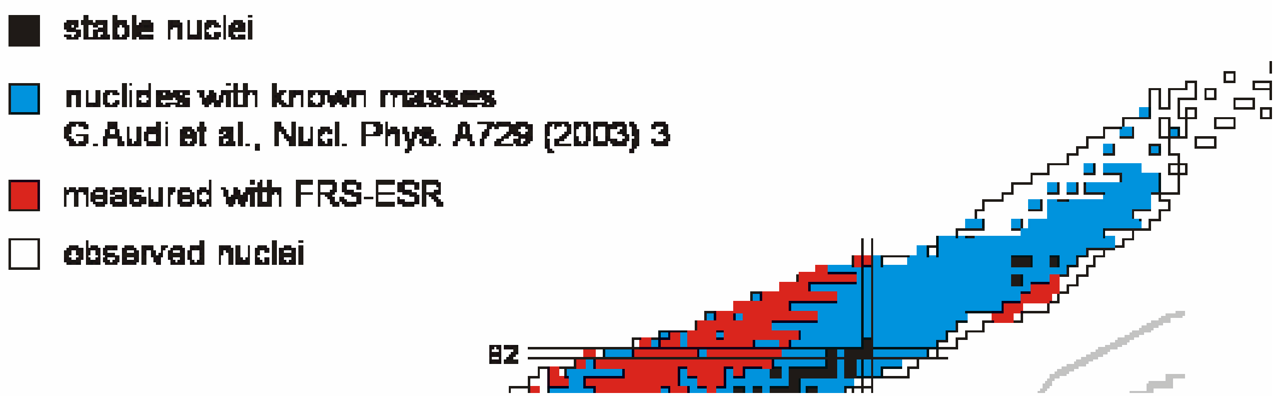
Fission barriers

Relative uncertainty:
$>10^{-2}$



GS masses

Relative uncertainty:
10^{-4} - 10^{-9}



Courtesy of C. Scheidenberger

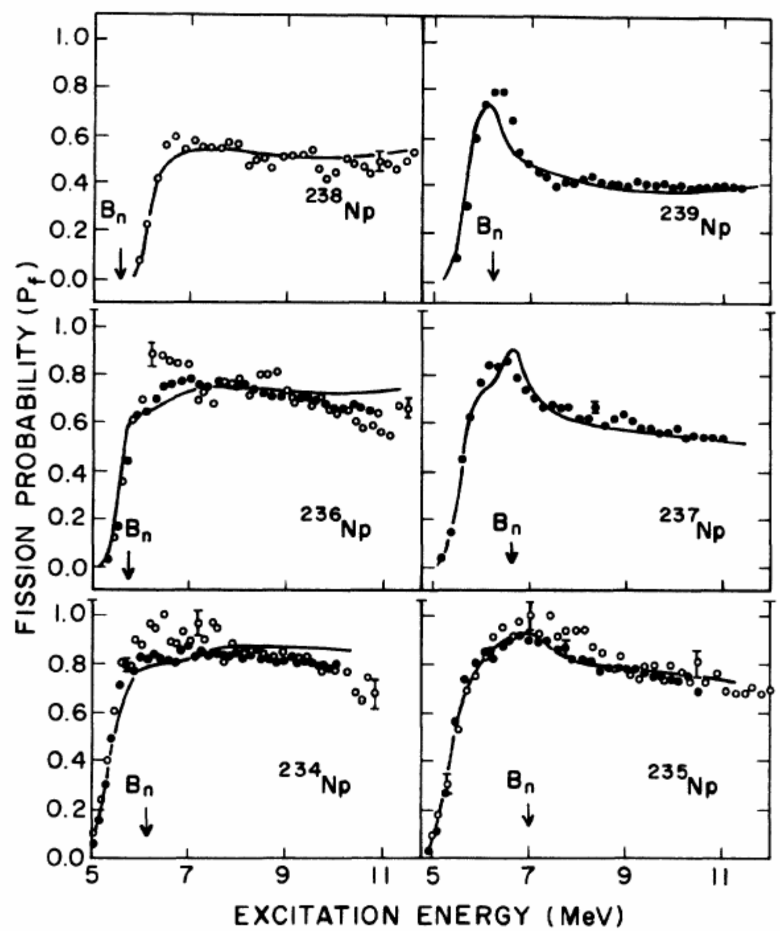
Experiment - Difficulties

•Experimental sources:

Energy-dependent fission probabilities

•Extraction of barrier parameters:

Requires assumptions on level densities



Gavron et al., PRC13 (1076) 2374

Theory

• Recently, important progress on calculating the potential surface using microscopic approach (e.g. groups from Brussels, Goriely et al; Bruyères-le-Châtel, Goutte et al; Madrid, Pèrez and Robledo; ...):

- Way to go!
- But, not always precise enough and still very time consuming

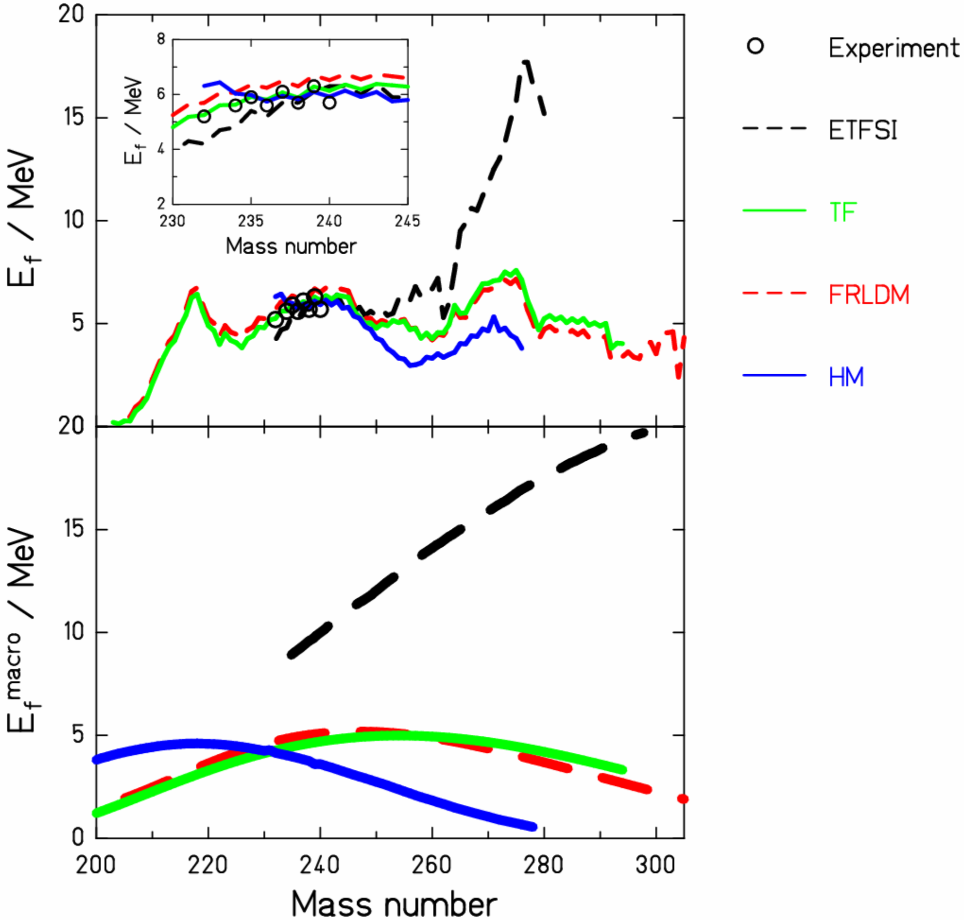
• Another approach ⇨ microscopic-macroscopic models (e.g. Möller et al; Myers and Swiatecki; Mamdouh et al; ...)

• Common for all approaches:

Limited experimental information on the height of the fission barrier ⇨ in any theoretical model the constraint on the parameters defining the dependence of the fission barrier on neutron excess is rather weak.

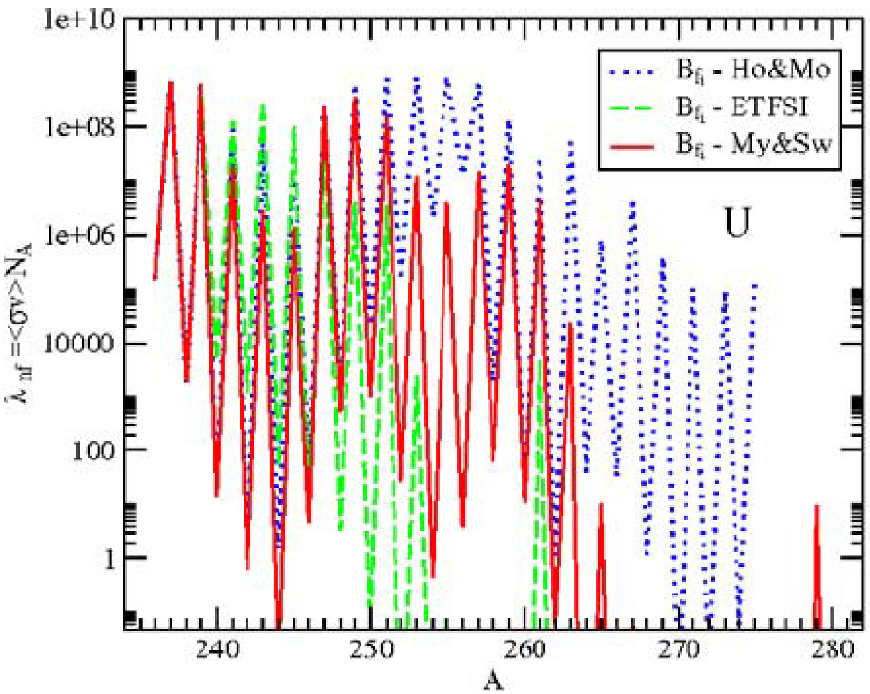
Open problem

Limited experimental information on the height of the fission barrier



Kelić and Schmidt, PLB 643 (2006)

Neutron-induced fission rates for U isotopes

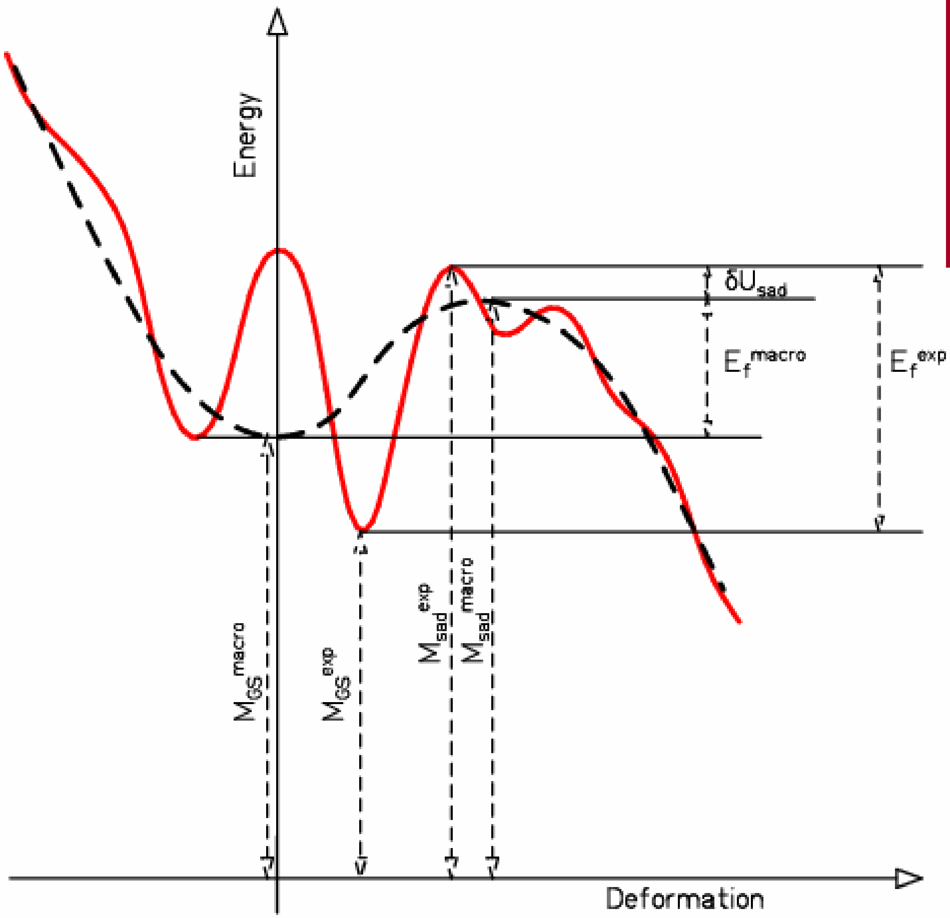


Panov et al., NPA 747 (2005)

Idea

Predictions of theoretical models are examined by means of a detailed analysis of the isotopic trends of ground-state and saddle-point masses.

$$\delta U_{sad} = \underbrace{E_f^{\exp} + M^{\exp}}_{\text{Experimental saddle-point mass}} - (\underbrace{M^{macro} + E_f^{macro}}_{\text{Macroscopic saddle-point mass}})$$

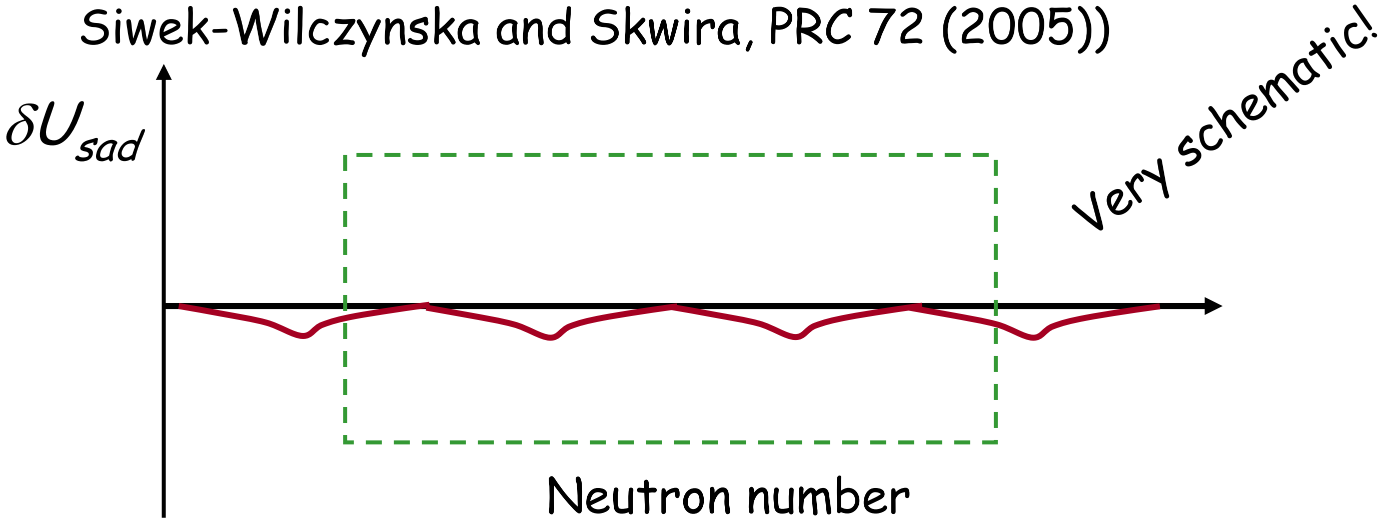


$\delta U_{sad} \leftrightarrow$ Empirical saddle-point shell-correction energy

Idea

$\delta U_{sad} \leftrightarrow$ Empirical saddle-point shell-correction energy

1. Shell corrections have local character
2. δU_{sad} should be very small (e.g Myers and Swiatecki PRC 60 (1999); Siwek-Wilczynska and Skwira, PRC 72 (2005))



⇨ $\langle \partial(\delta U_{sad})/\partial N \rangle_N \approx 0$

Any general trend would indicate shortcomings of the model.

Kelić and Schmidt, PLB 643 (2006)

Studied models

1) **Droplet model** (DM) [Myers 1977], which is a basis of often used results of the Howard-Möller fission-barrier calculations [Howard&Möller 1980]

2) **Finite-range liquid drop model** (FRLDM) [Sierk 1986, Möller et al 1995]

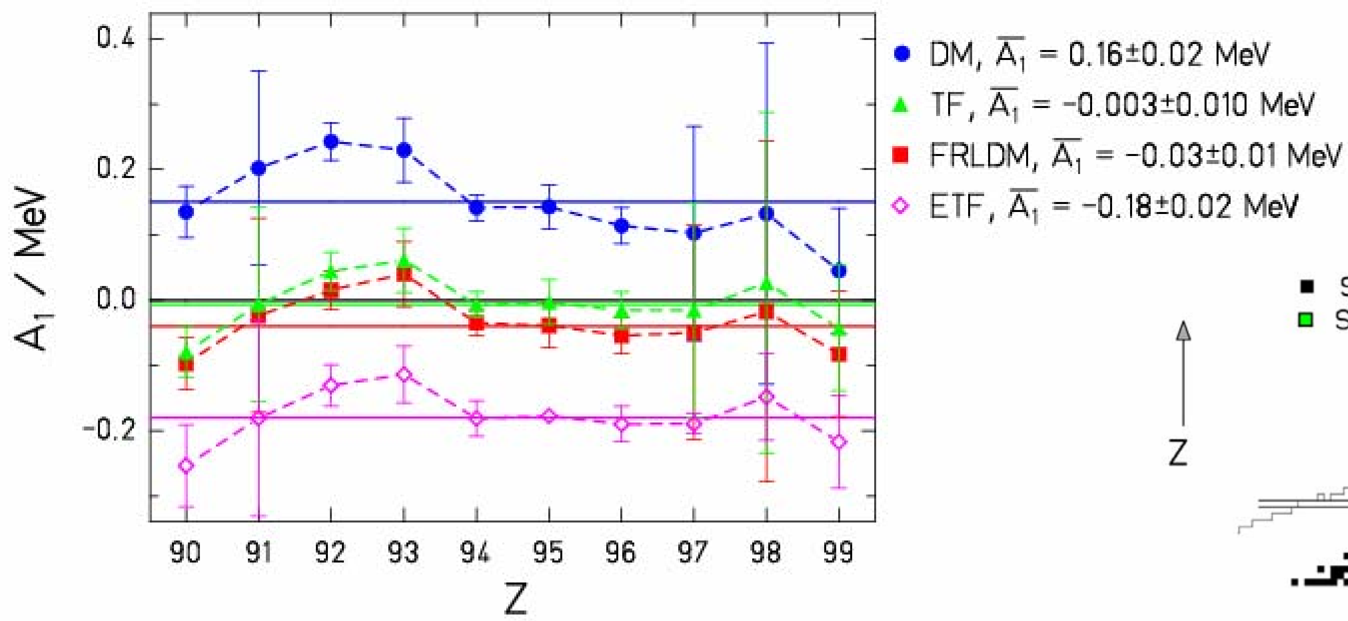
3) **Thomas-Fermi model** (TF) [Myers and Swiatecki 1996, 1999]

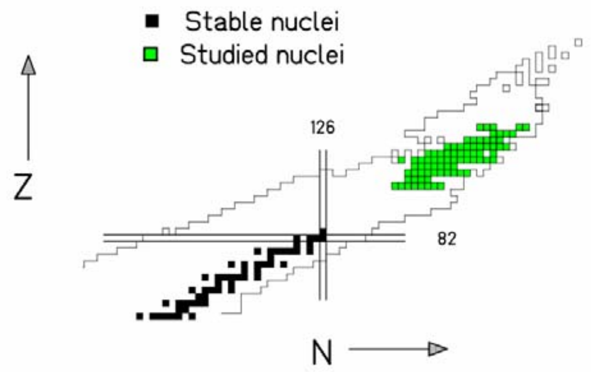
4) **Extended Thomas-Fermi model** (ETF) [Mamdouh et al. 2001]

W.D. Myers, „Droplet Model of Atomic Nuclei", 1977 IFI/Plenum
W.M. Howard and P. Möller, ADNDT 25 (1980) 219.
A. Sierk, PRC33 (1986) 2039.
P. Möller et al, ADNDT 59 (1995) 185.
W.D. Myers and W.J. Swiatecki, NPA 601(1996) 141
W.D. Myers and W.J. Swiatecki, PRC 60 (1999) 0 14606-1
A. Mamdouh et al, NPA 679 (2001) 337

Results

Slopes of δU_{sad} as a function of the neutron excess





⇒ The most realistic predictions are expected from the TF model and the FRLD model

⇒ Further efforts needed for the saddle-point mass predictions of the droplet model and the extended Thomas-Fermi model

Kelić and Schmidt, PLB 643 (2006)

Mass and charge division in fission

Experimental information

• Particle-induced fission of long-lived targets and spontaneous fission (~ 80 nuclei)

Available information:

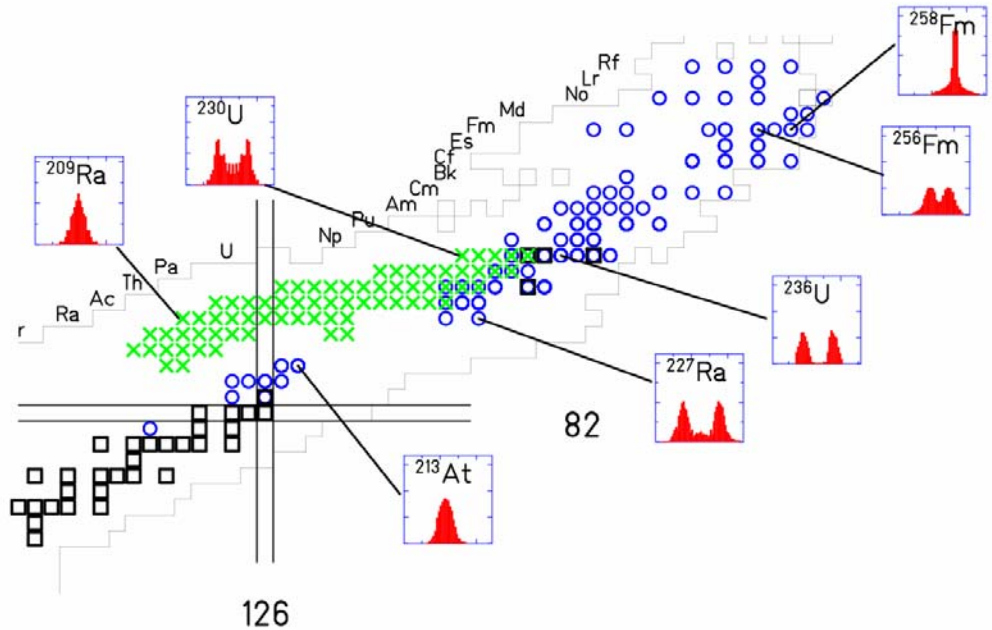
- A(E*) in most cases

- A and Z distributions of light fission group only in the thermal-neutron induced fission on the stable targets

•EM fission of secondary beams at GSI (~ 100 nuclei)

Available information:

- Z distributions at one energy



Available data far from r-process path!

How well can we describe exp data?

⇒ Empirical systematics - Problem is often too complex

⇒ Theoretical model - Way to go, but not always precise enough and still very time consuming. Encouraging progress for a full microscopic description of fission:

Time-dependent HF calculations with GCM:
Goutte et al., PRC 71 (2005)

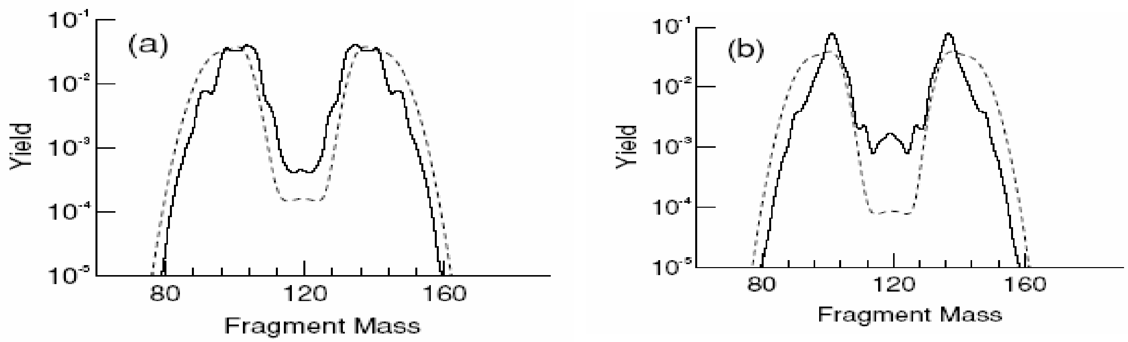
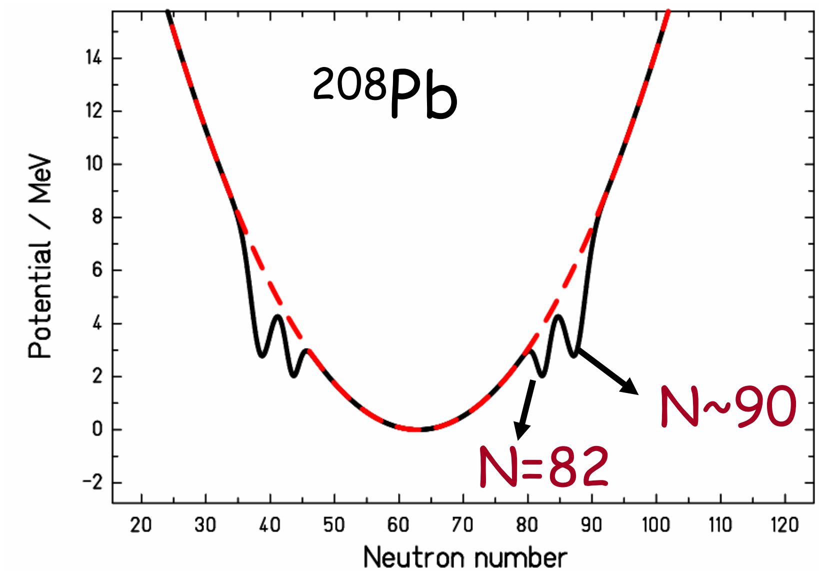


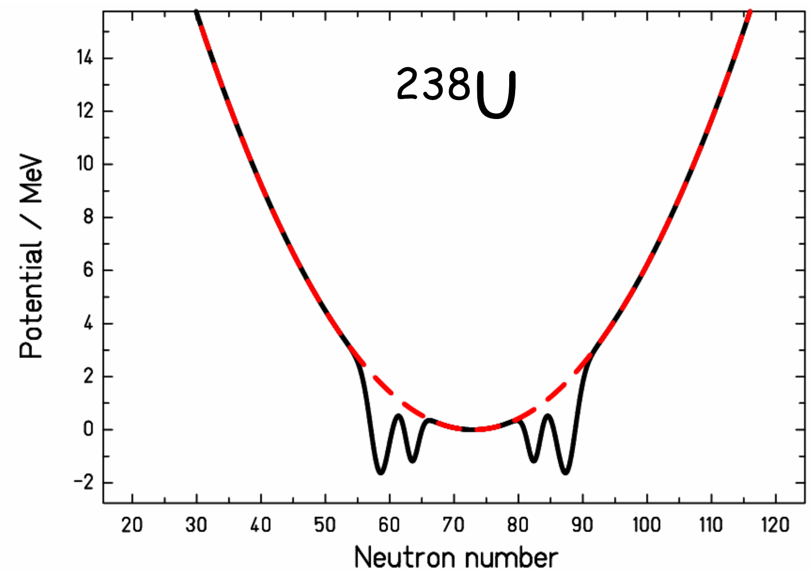
FIG. 14. Theoretical mass distributions (solid lines) are compared with the Wahl evaluations of neutron-induced fission of ^{238}U [24] (dashed lines). Excitation energies of the compound ^{238}U nucleus measured above the barrier are (a) $E = 2.4$ MeV, (b) $E = 1.1$ MeV.

⇒ Semi-empirical models - Theory-guided systematics

Macroscopic-microscopic approach

- Transition from single-humped to double-humped explained by macroscopic (fissionning nucleus) and microscopic (nascent fragments) properties of the potential-energy landscape near the saddle point.





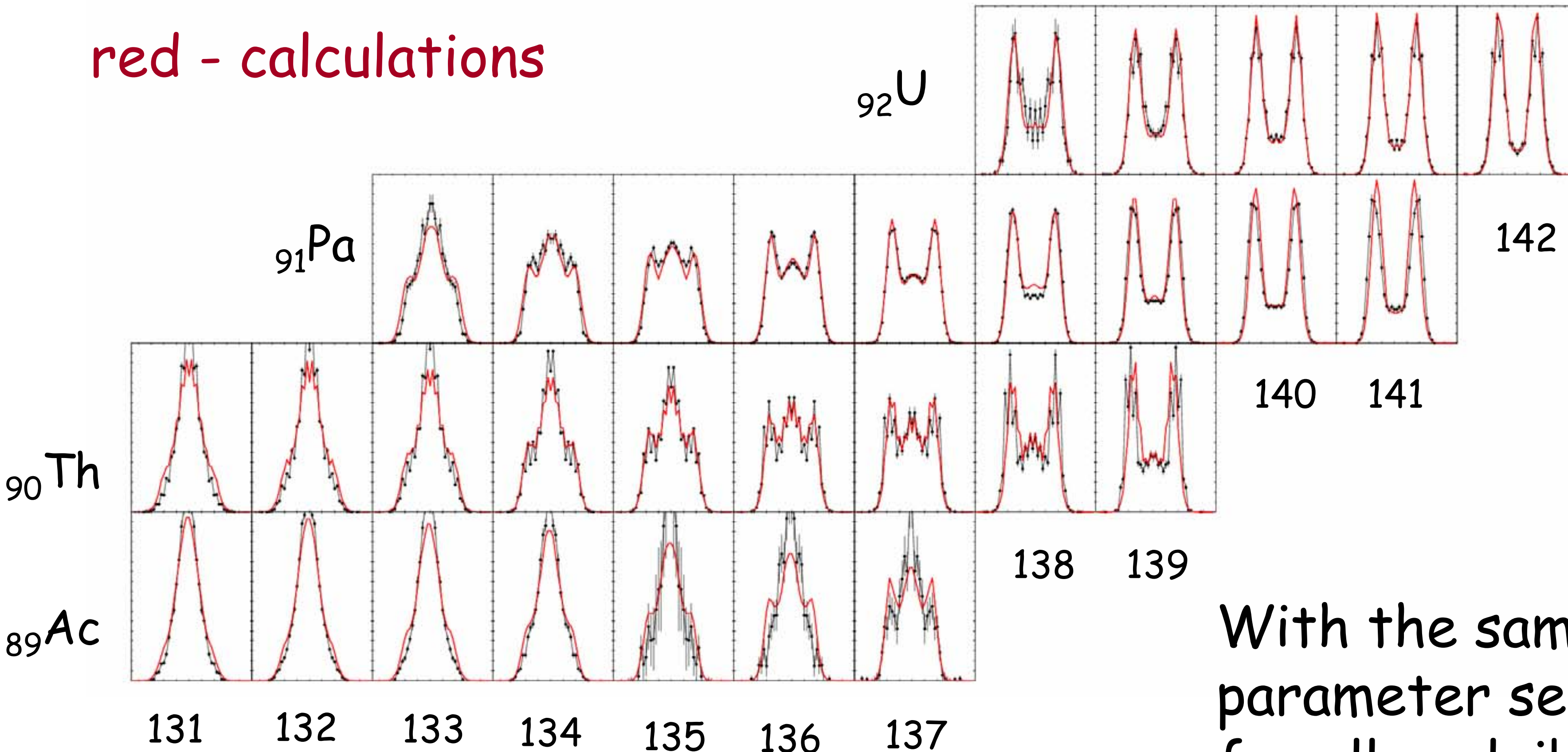
- For each fission fragment we get:
    - Mass
    - Charge
    - Velocity
    - Excitation energy

Comparison with data

Fission of secondary beams after the EM excitation:

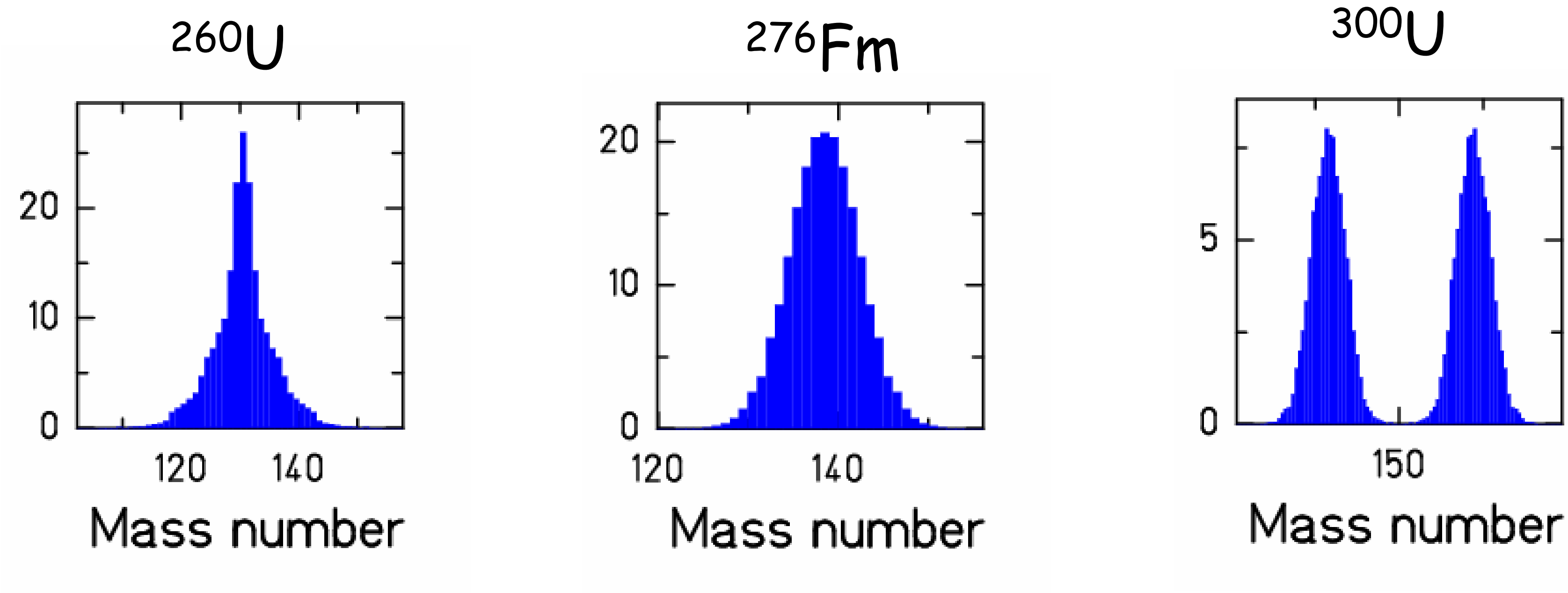
black - experiment (Schmidt et al, NPA 665 (2000))

red - calculations



With the same parameter set for all nuclei!

Applications



FF masses and nuclear charges, number of emitted pre- and post-scission particles used as input for r-process network calculations

⇨ talk by Gabriel Martinez-Pinedo

Conclusions

- Further experimental and theoretical efforts are needed

- Important progress have been made in microscopic description of fission, but for applications one still has to rely on microscopic-macroscopic models

- Need for more precise and new experimental data using new techniques and methods ⇨ basis for further developments in theory

Special thanks to:

Karl-Heinz Schmidt (GSI) and CHARMS collaboration*

Karlheinz Langanke, Gabriel Martinez-Pinedo (GSI)

Nikolaj Zinner (Aarhus)

* www.gsi.de\charms

Additional slides

What do we need?

Different entrance channels:

- n-induced fission

(e.g. Panov et al, NPA 747)

- beta-delayed fission

(e.g. Staudt and Klapdor-Kleingrothaus, NPA 549; Panov et al, NPA 747)

- neutrino-induced fission

(e.g. Kolbe et al, PRL 92; Kelić, Zinner et al, PLB 616)

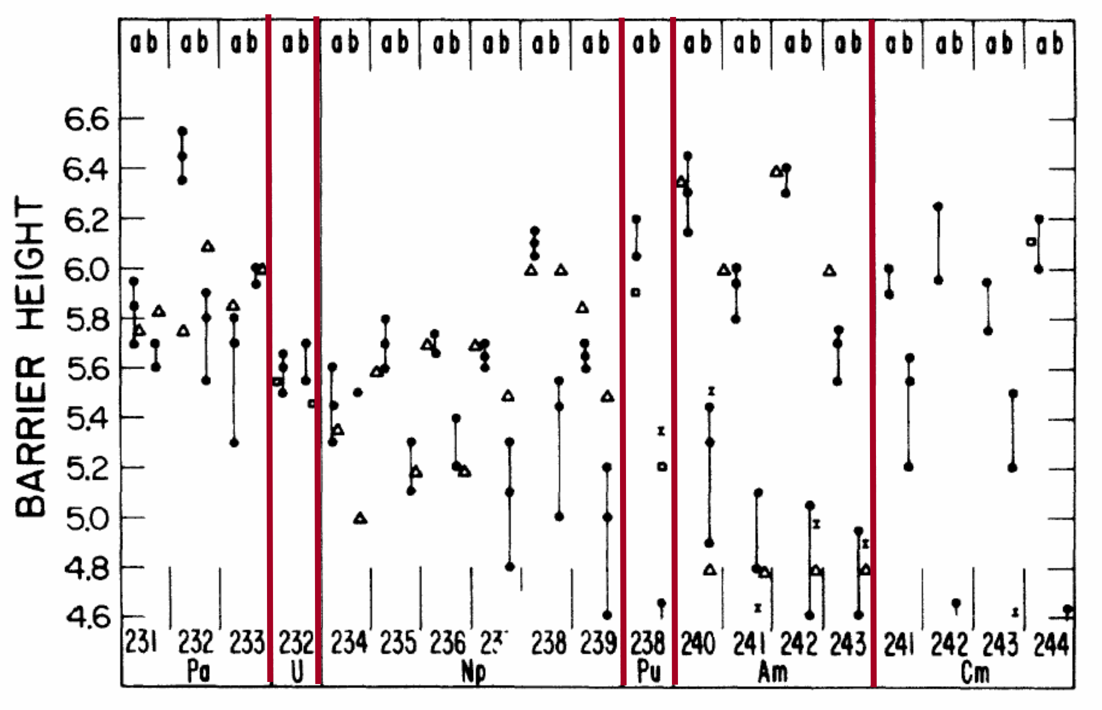
- spontaneous fission

(e.g. Ohnishi, Prog. Theor. Phys. 47)

Experiment - Difficulties

Extraction of barrier parameters:

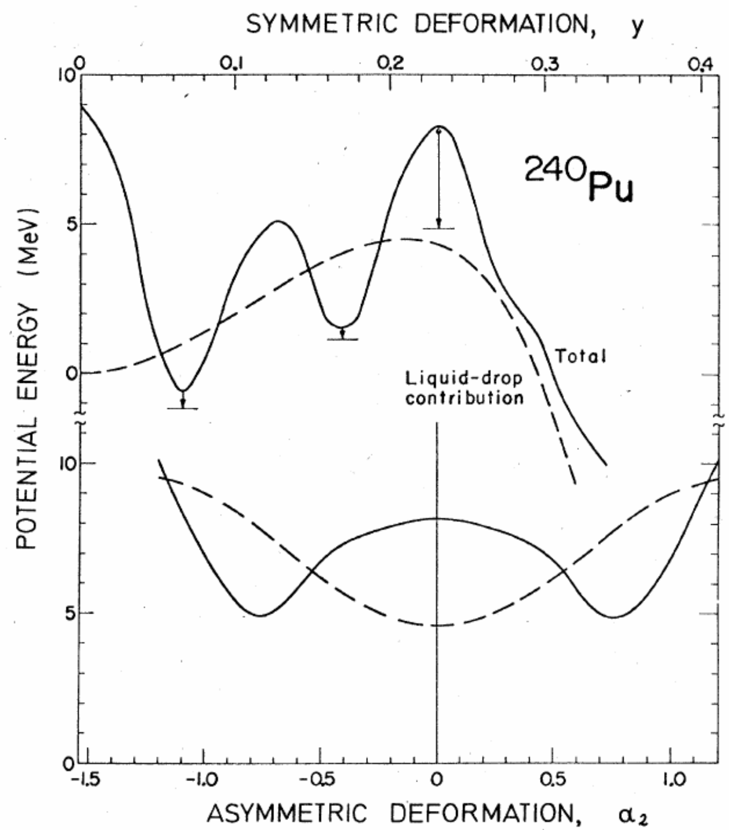
Requires assumptions on level densities.



Gavron et al., PRC13

Theoretical difficulties

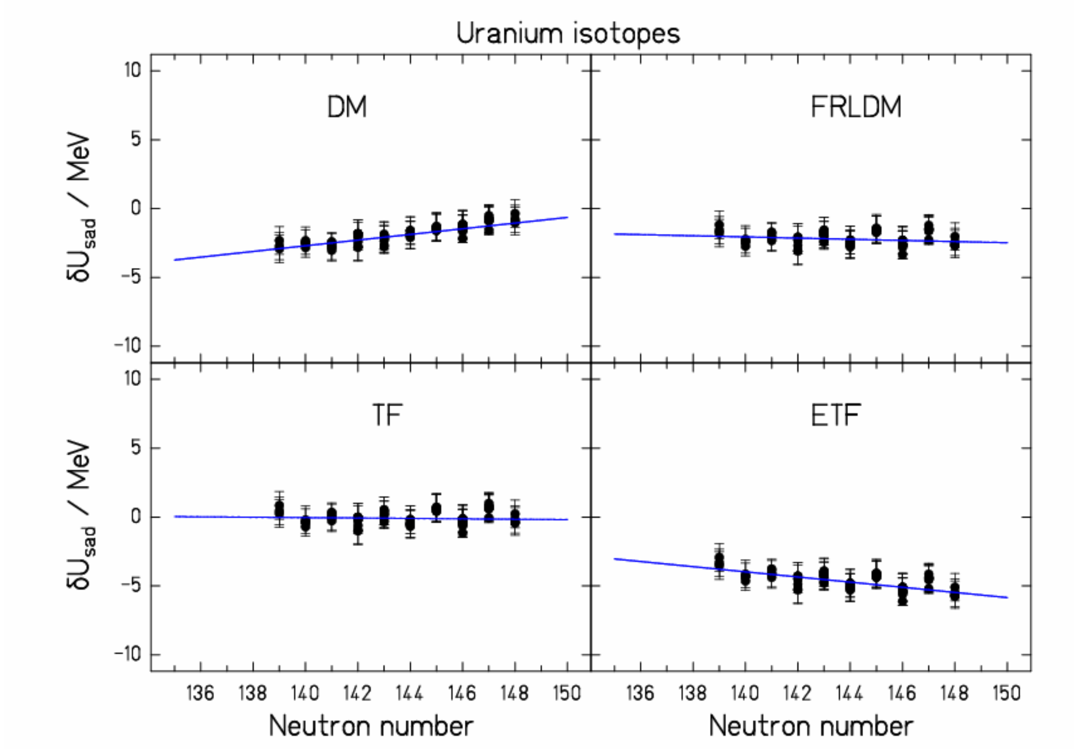
Dimensionality (Möller et al, PRL 92) and **symmetries** (Bjørnholm and Lynn, Rev. Mod. Phys. 52) of the considered deformation space are very important!



Bjørnholm and Lynn, Rev. Mod. Phys. 52

Example for uranium

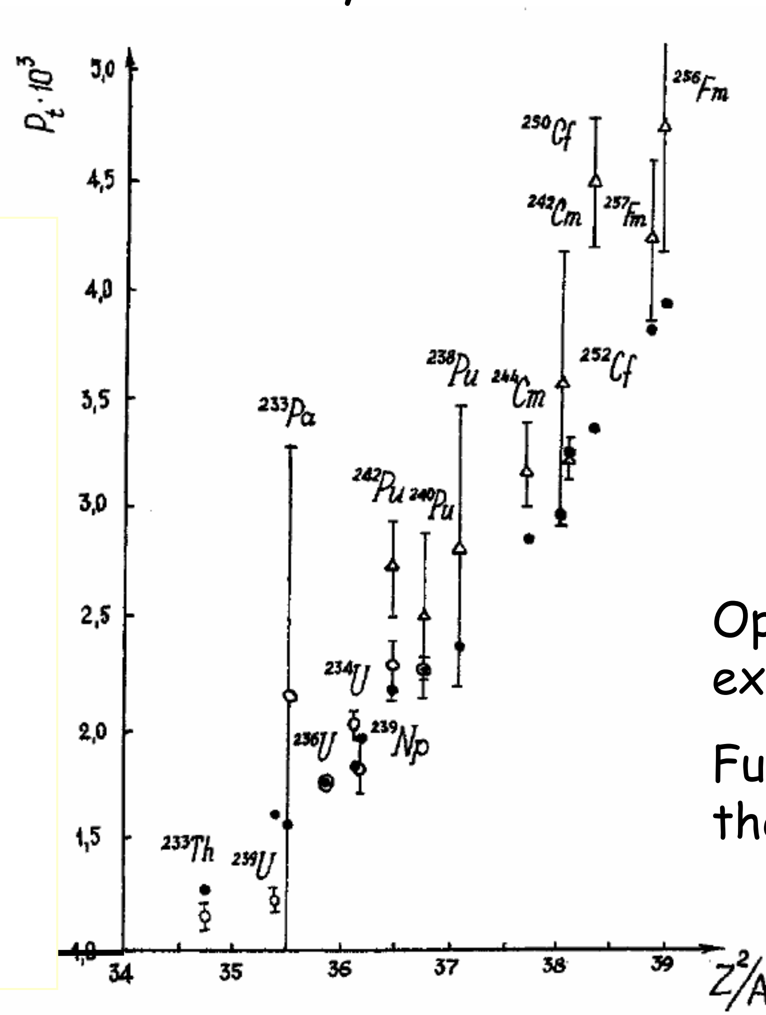
δU_{sad} as a function of a neutron number



A realistic macroscopic model should give almost a zero slope!

Ternary fission

Ternary fission ⇨ less than 1% of a binary fission



Open symbols - experiment

Full symbols - theory

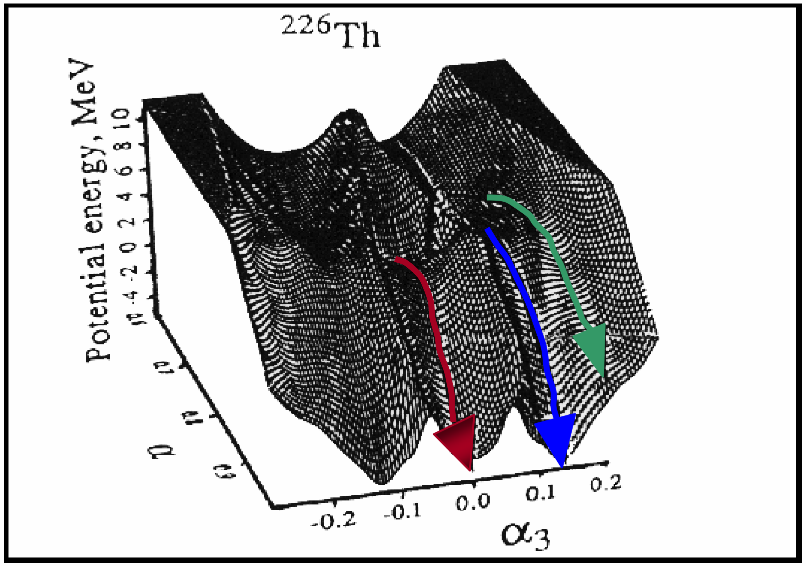
Rubchenya and Yavshits, Z. Phys. A 329 (1988) 217

Theory

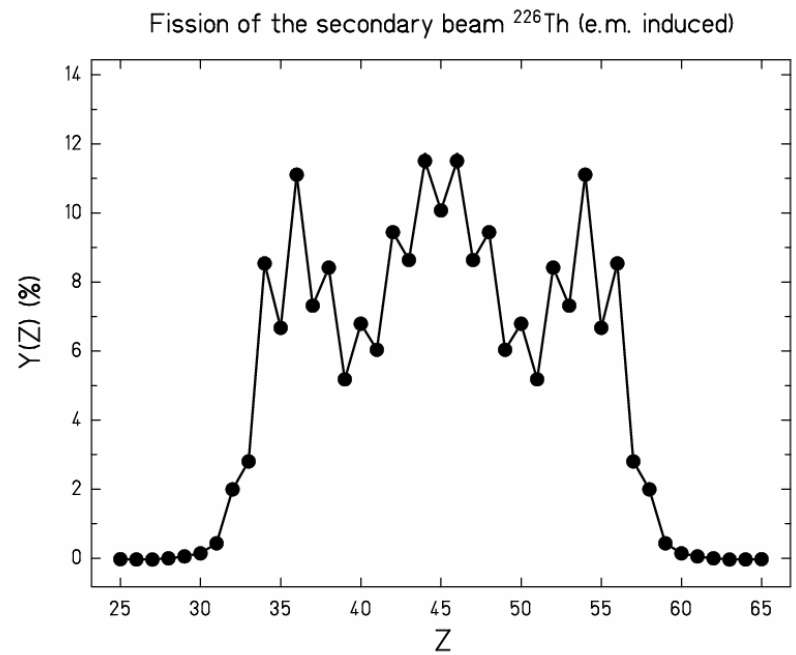
- Strutinsky-type calculations of the potential-energy landscape (e.g. P. Möller)
  - \+ Good qualitative overview on multimodal character of fission.
  - \- No quantitative predictions for fission yields.
  - \- No dynamics
- Statistical scission-point models (e.g. Fong, Wilkins et al.)
  - \+ Quantitative predictions for fission yields.
  - \- No memory on dynamics from saddle to scission.
- Statistical saddle-point models (e.g. Duijvestijn et al.)
  - \+ Quantitative predictions for fission yields.
  - \- Neglecting dynamics from saddle to scission.
  - \- Uncertainty on potential energy leads to large uncertainties in the yields.
- Time-dependent Hartree-Fock calculations with GCM (Goutte)
  - \+ Dynamical and microscopic approach.
  - \- No dissipation included.
  - \- High computational effort.

How well do we understand fission?

Influence of nuclear structure (shell corrections, pairing, ...)



M.G. Itkis et al., Proc. Large-scale collective motion of atomic nuclei, Brolo, 1996



K.-H. Schmidt et al., NPA 665 (2000) 221

Also dynamical properties (e.g. viscosity) play important role!