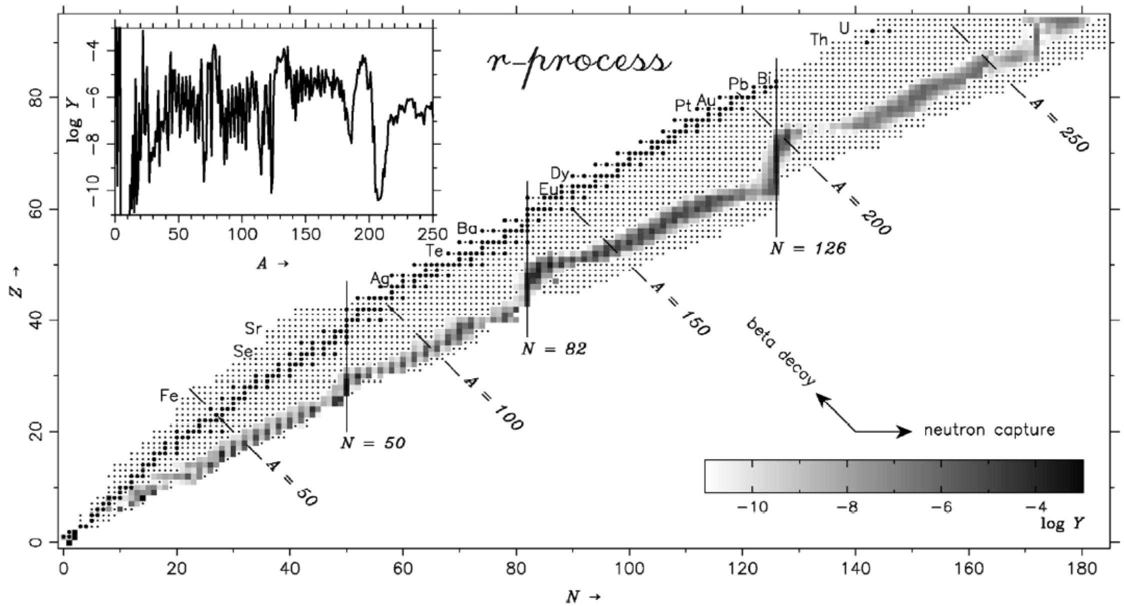
The Role of Fission in the r-Process Nucleosynthesis

Aleksandra Kelić

Overview

- Motivation
  - → Why fission could be important for r-process?
- Open questions in fission
  - → How well do we understand the fission process?
- Saddle-point masses
  - → Macroscopic-microscopic approaches
- Mass and charge distributions in fission
  - → GSI semi-empirical model
- How to proceed?

Motivation



S. Wanajo et al., NPA in print

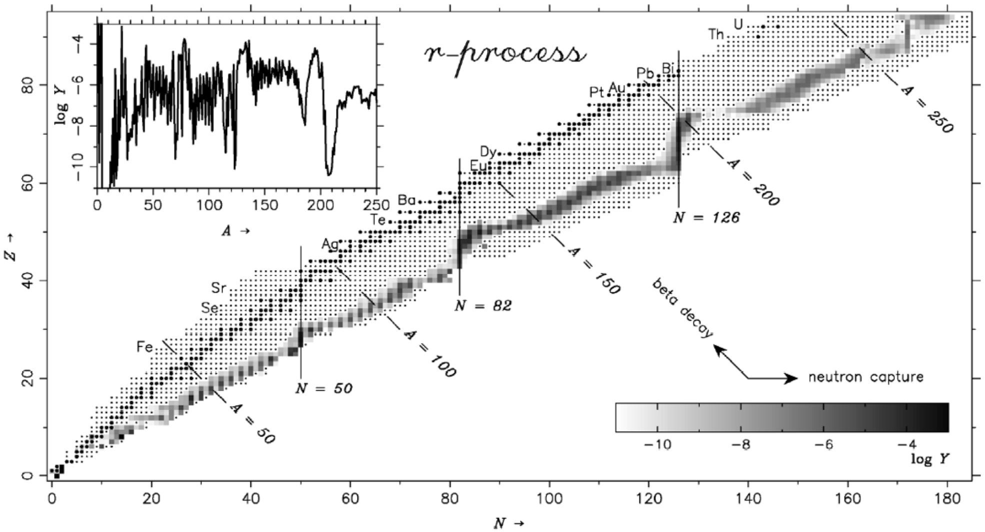
In the r-process, fission has the decisive influence on the termination of the r-process as well as on the yields of transuranium elements and, consequently, on the determination of the age of the Galaxy and the Universe [1]. In cases where high neutron densities exist over long periods, fission will also influence the abundances of nuclei in the region A ~ 90 and 130 due to the fission cycling [2,3].

[1] J.J. Cowan et al, *Phys. Rep. 208 (1991) 267*
[2] P.A. Seeger et al, *APJ. 11 Suppl. (1965) S121*
[3] T. Rauscher et al, *APJ. 429 (1994) 49*

Motivation

- What are the needed ingredients?
  - Fission barriers
  - Mass and charge division in fission
  - Nuclear viscosity
  - ....

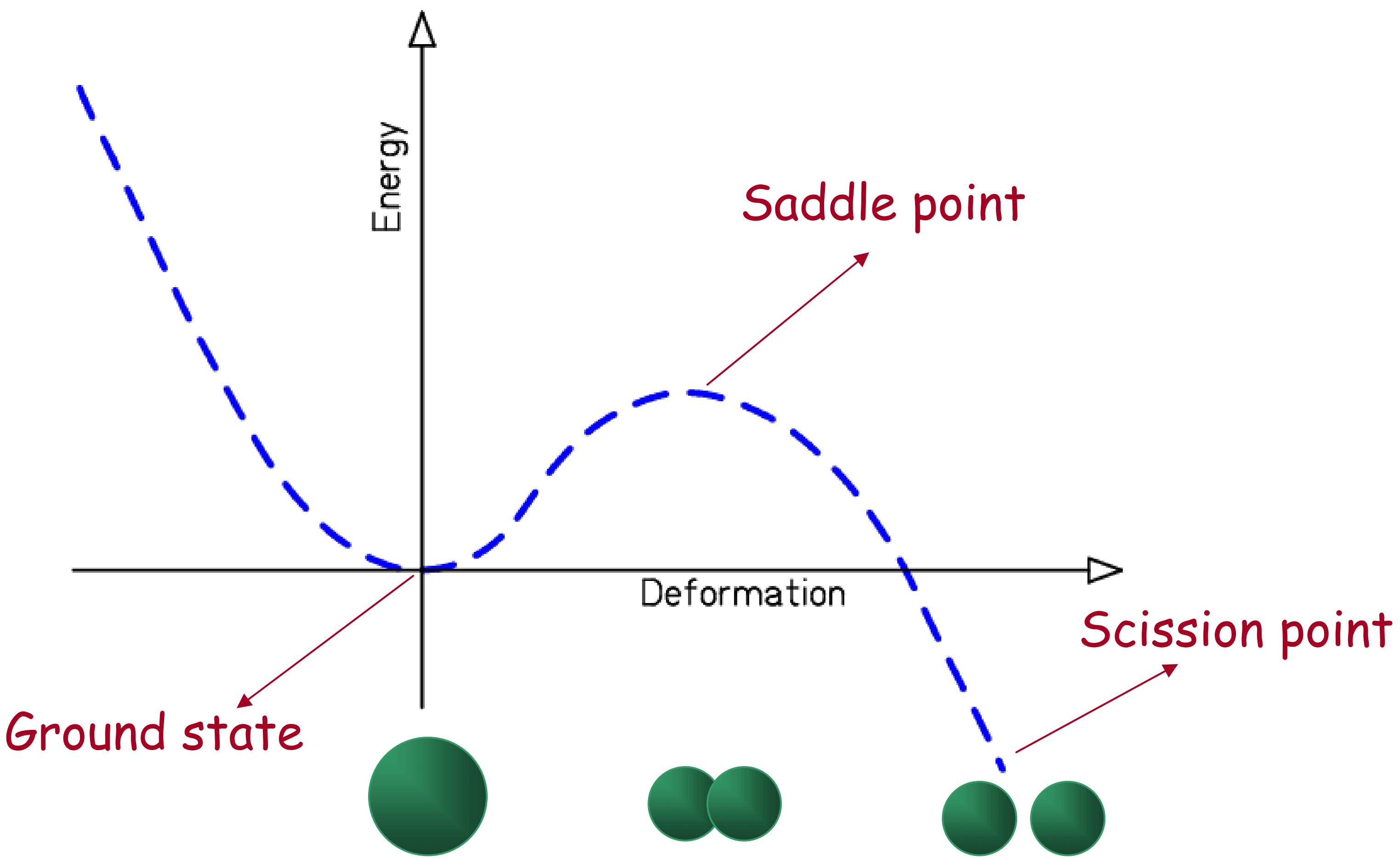
And all this for heavy, very neutron-rich nuclei (A>190, Z>84)!



–In order to understand the role of fission in r-process nucleosynthesis we must have proper understanding of fission also for the "Earth" nuclei.

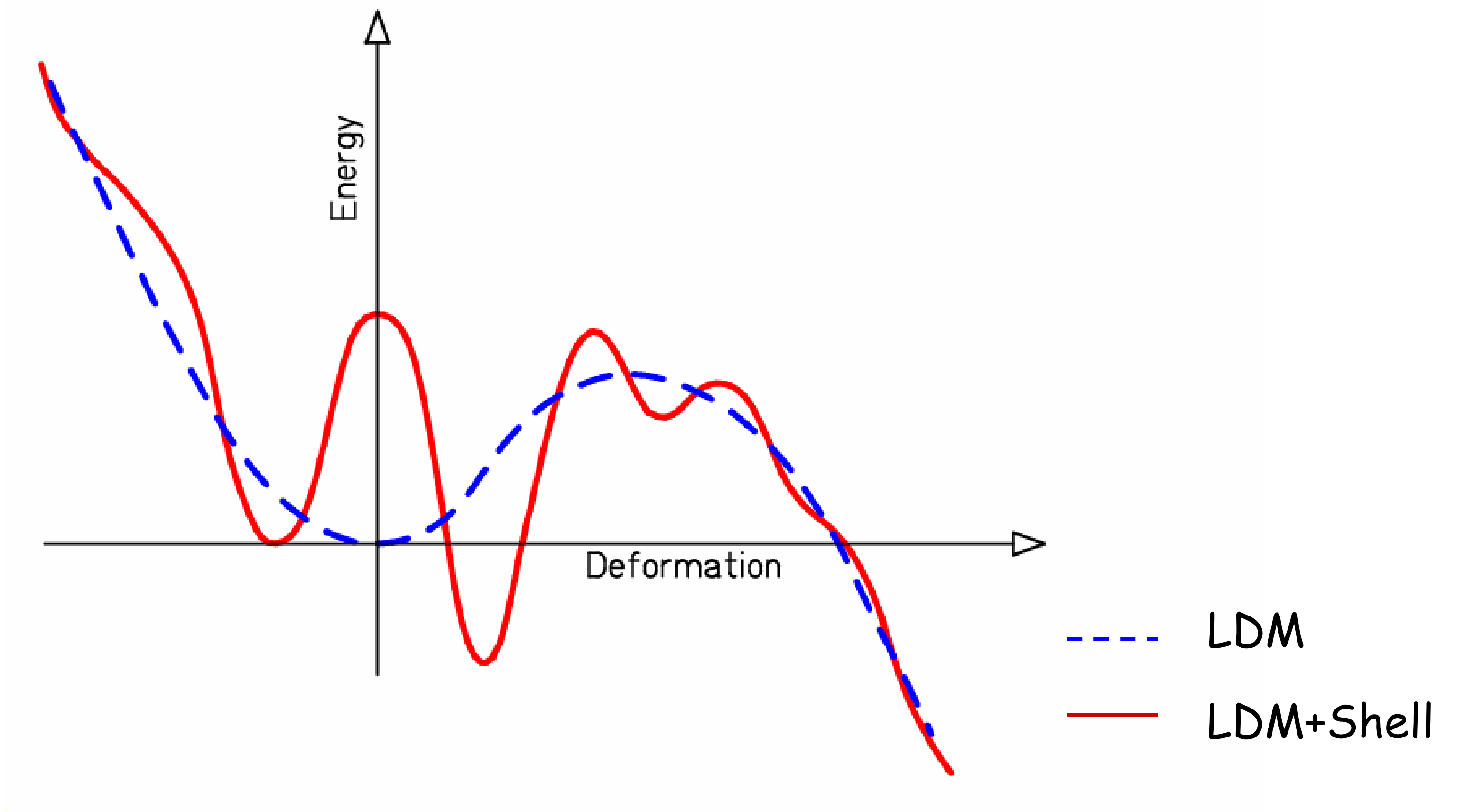
How well do we understand fission?

Liquid-drop model → interplay between the Coulomb and surface energy



How well do we understand fission?

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



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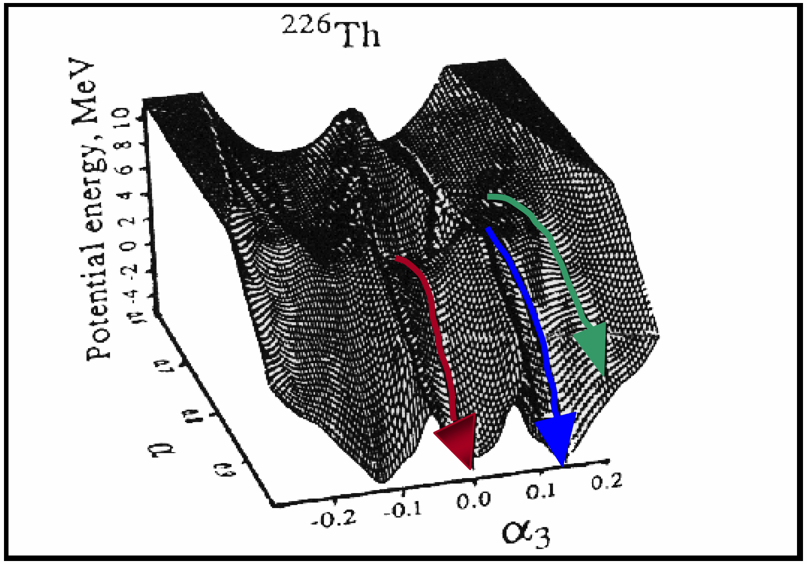
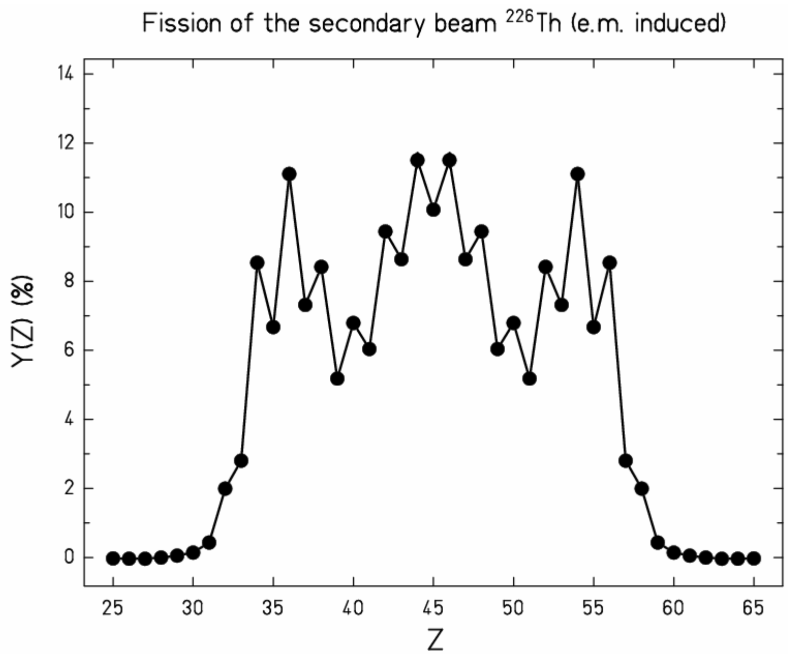


M.G. Itkis et al., Proc. Large-scale collective motion of atomic nuclei, Brolo, 1996



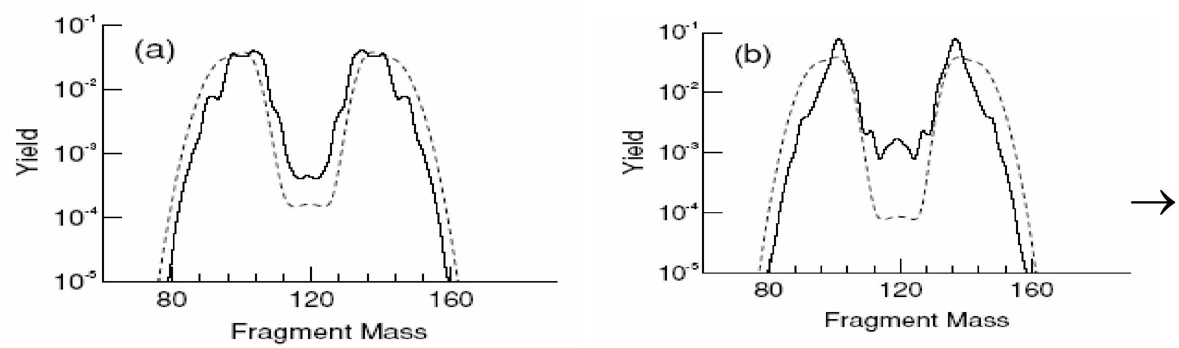
K.-H. Schmidt et al., NPA 665 (2000) 221

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

How well can we describe fission?

⇒ 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:



→ H. Goutte et al., PRC 71 (2005) 024316

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.

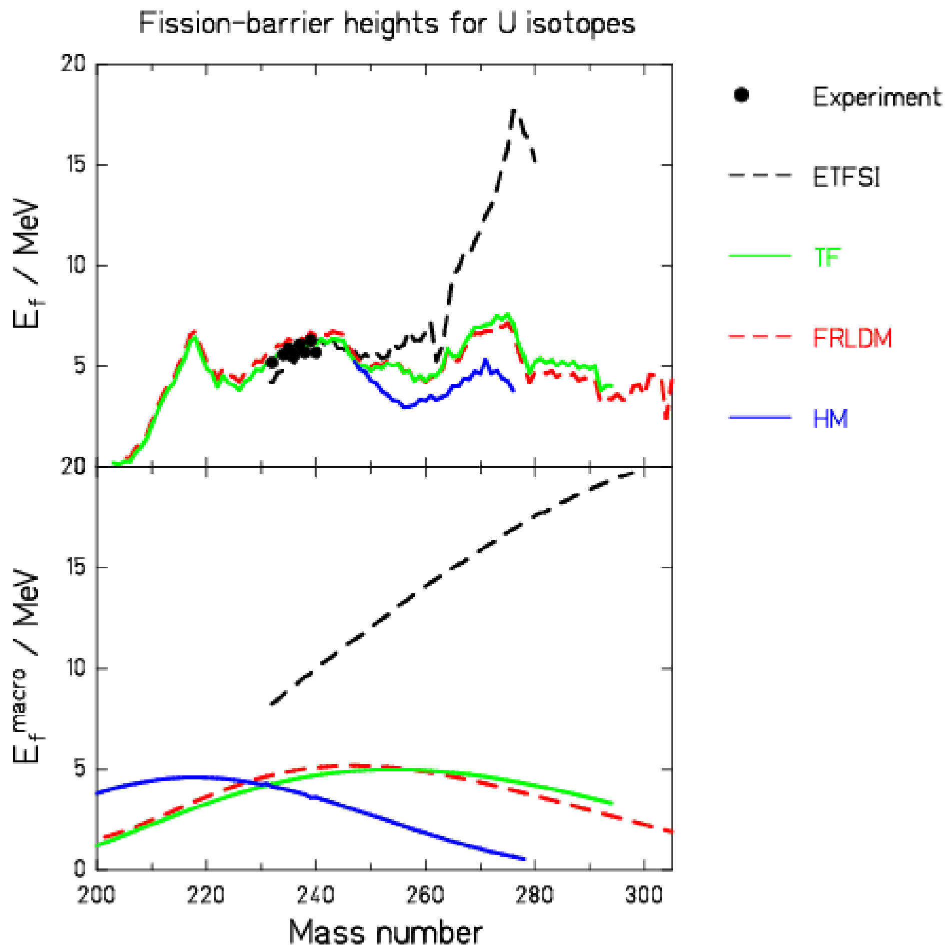
⇒ <u>Semi-empirical models - Theory-guided systematics</u>

Saddle-point masses

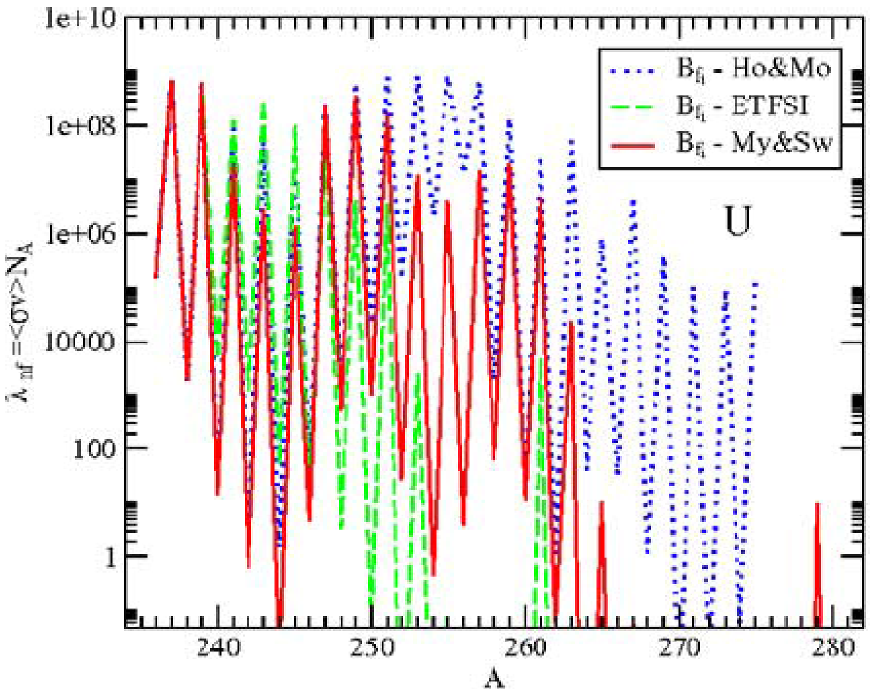
Strong influence on the fission contribution to the r-process nucleosynthesis

Open questions

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.



Neutron-induced fission rates for U isotopes

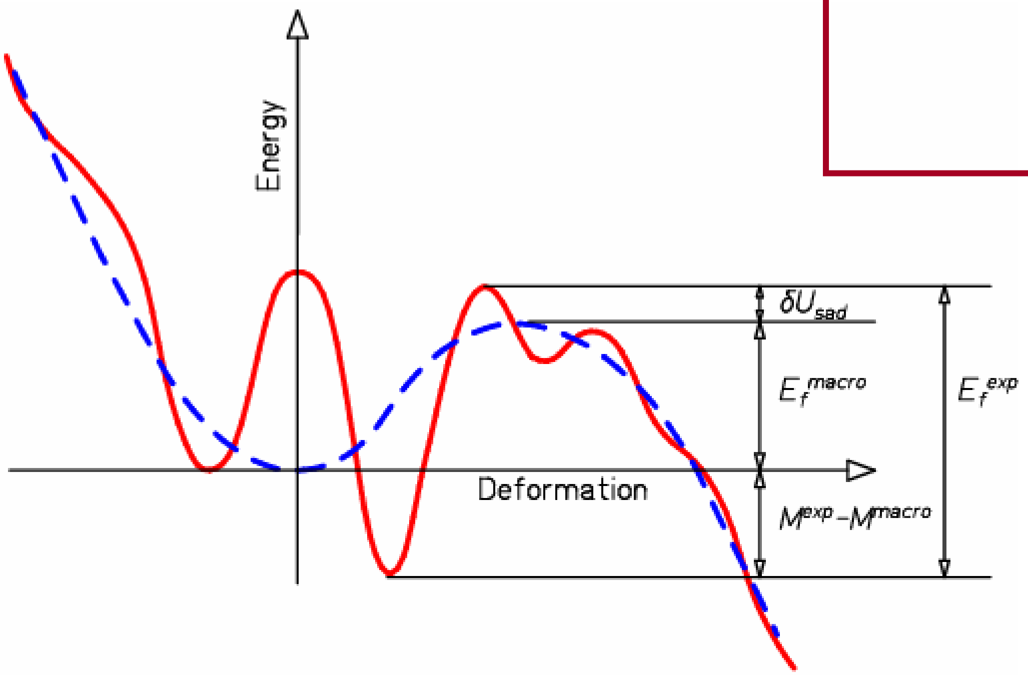


I. Panov et al., NPA 747 (2005) 633

Idea

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

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



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

Idea

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

1. Shell corrections have local character
2. According to the topographic theorem* δU_{sad} is very small

$\Rightarrow$ The saddle-point mass is essentially a macroscopic quantity, not much affected by shell effects.

Followed over a large enough region of neutron numbers, in case of <u>a realistic macroscopic model δU_{sad} should show only local, small variations</u>. Any general trend would indicate severe shortcomings of the model.

* W.D. Myers and W.J. Swiatecki, Phys. Rev. C60 (1999) 014606-1

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]

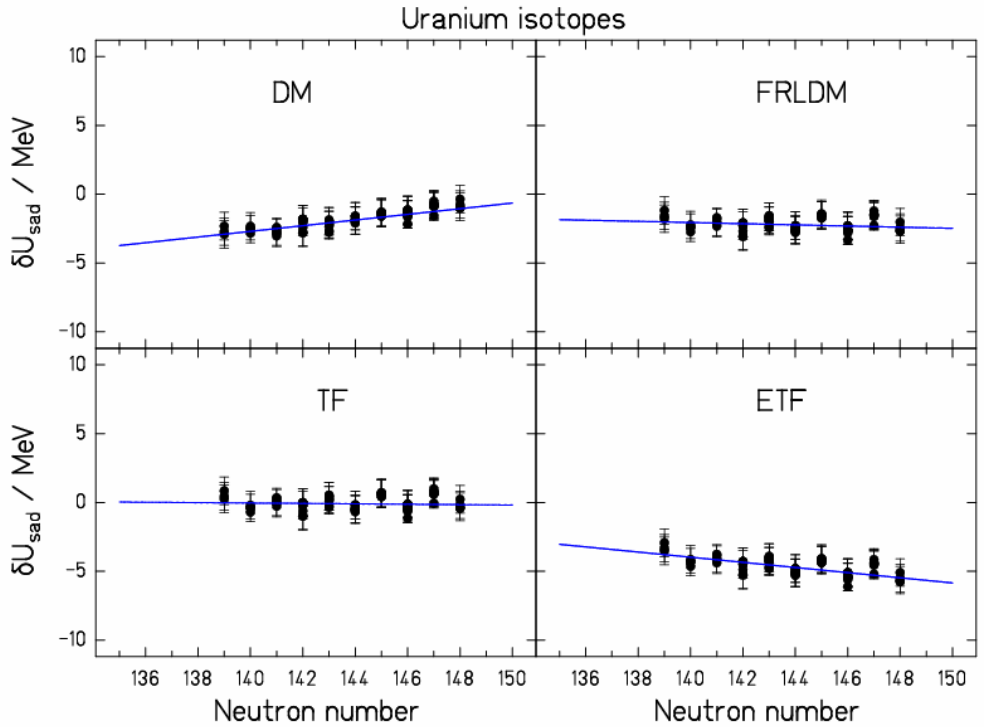
3.) **Thomas-Fermi model** (TF) [Myers&Swiatecki 1996, 1999]

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

Example for uranium

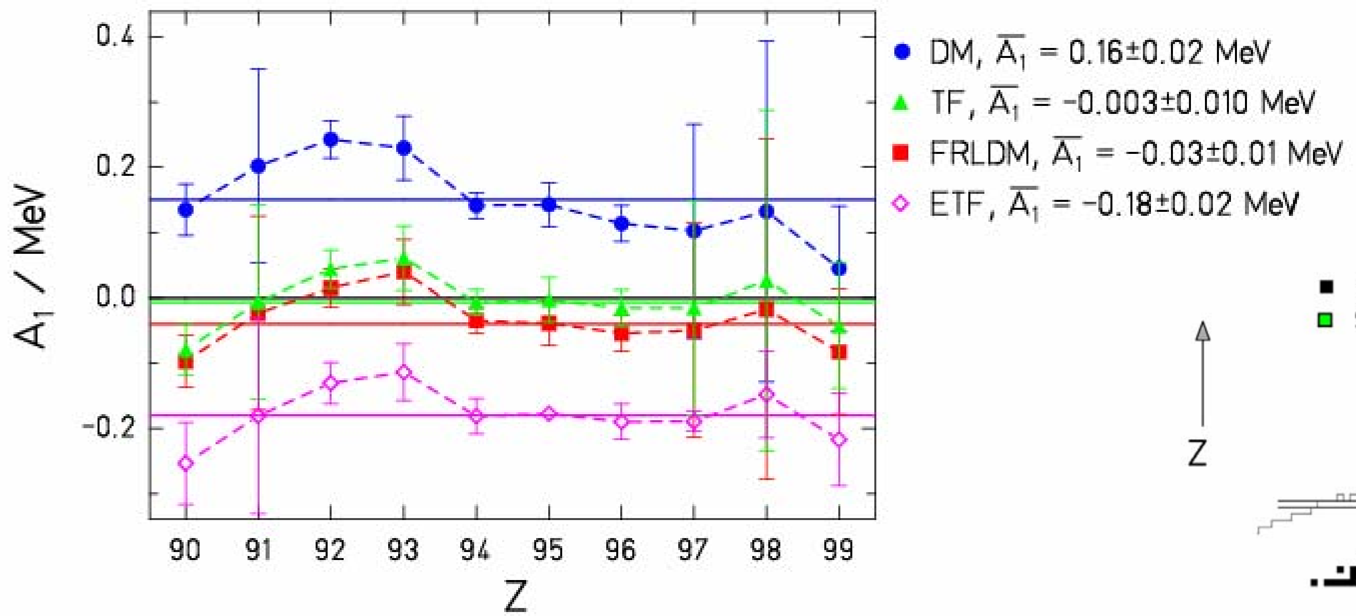
δU_{sad} as a function of a neutron number

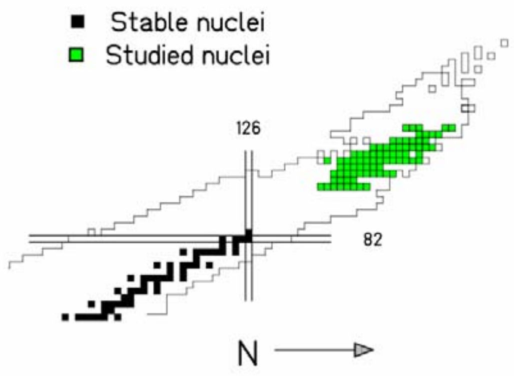


A realistic macroscopic model should give almost a zero slope!

Results

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





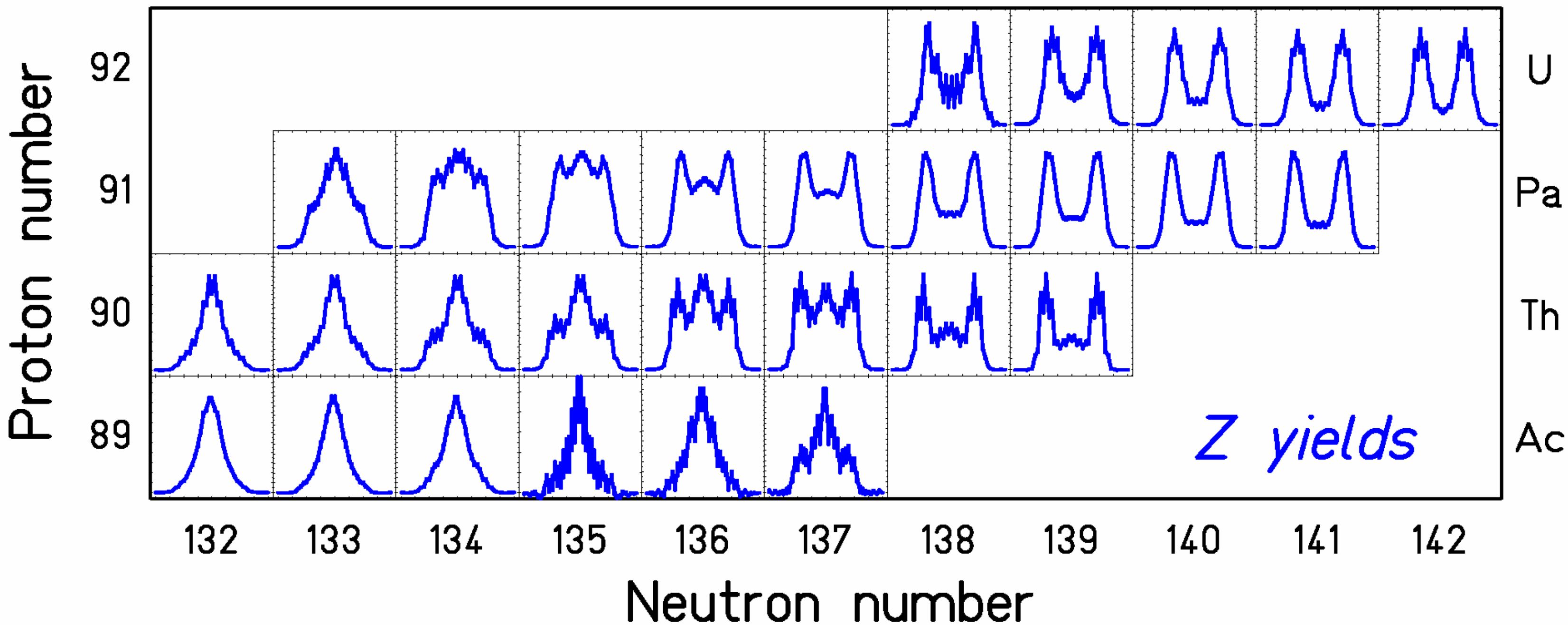
⇒ The most realistic predictions are expected from the TF model and the FRLD model.

⇒ Inconsistencies in the saddle-point mass predictions of the droplet model and the extended Thomas-Fermi model.

Mass and charge division in fission

Measured fission-fragment Z distributions

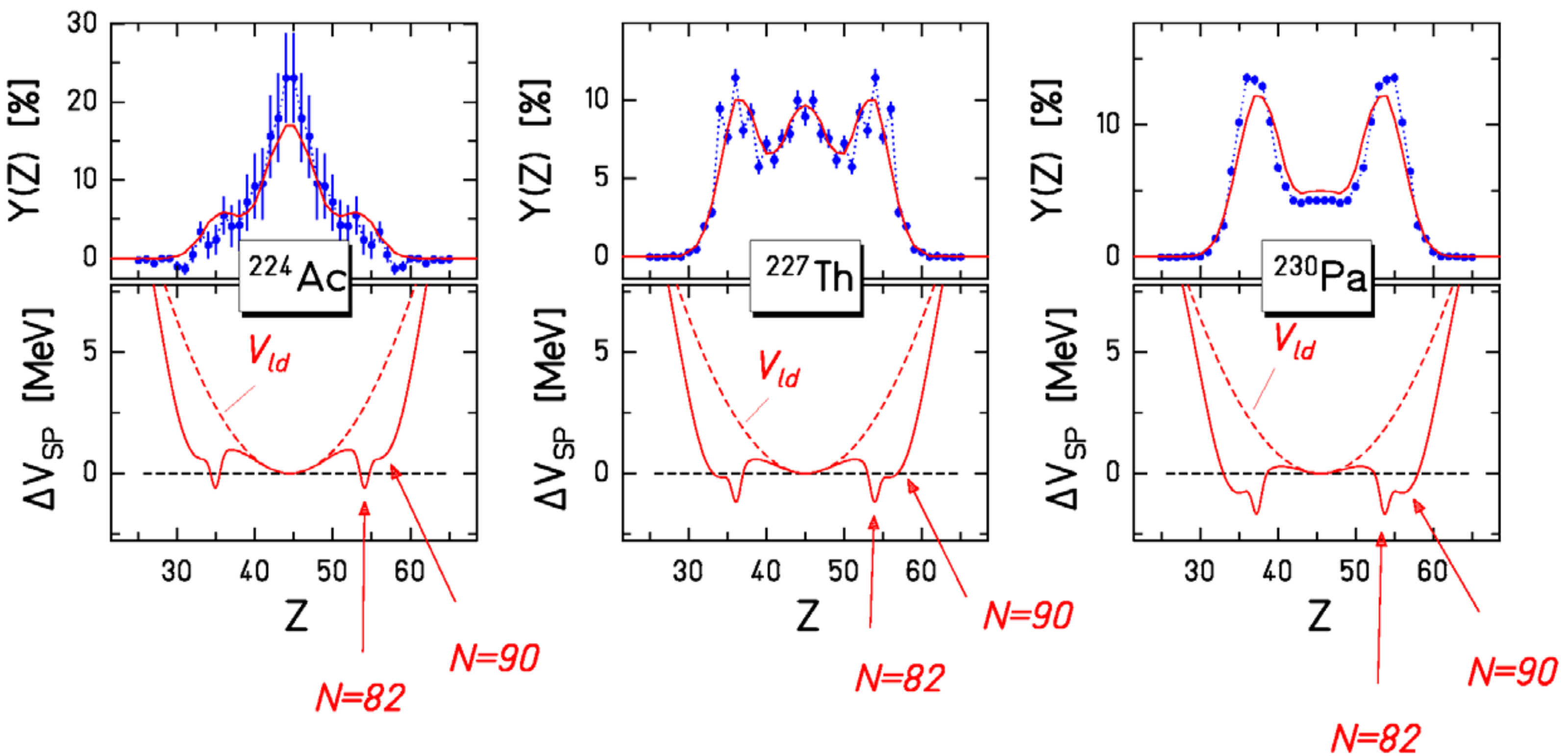
Experimental survey by use of secondary beams of radioactive isotopes



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

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.

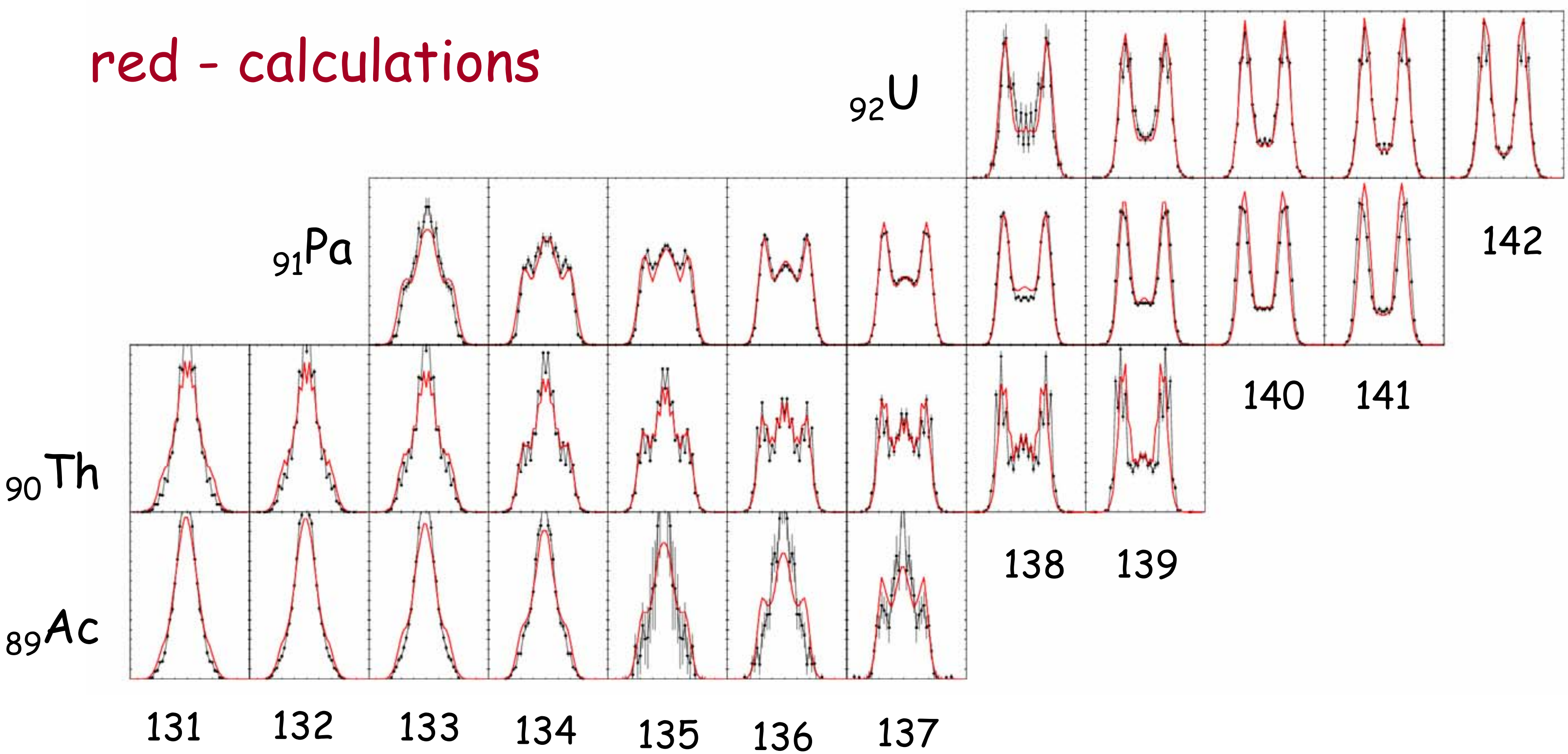


Comparison with data

Fission of secondary beams after the EM excitation:

black - experiment

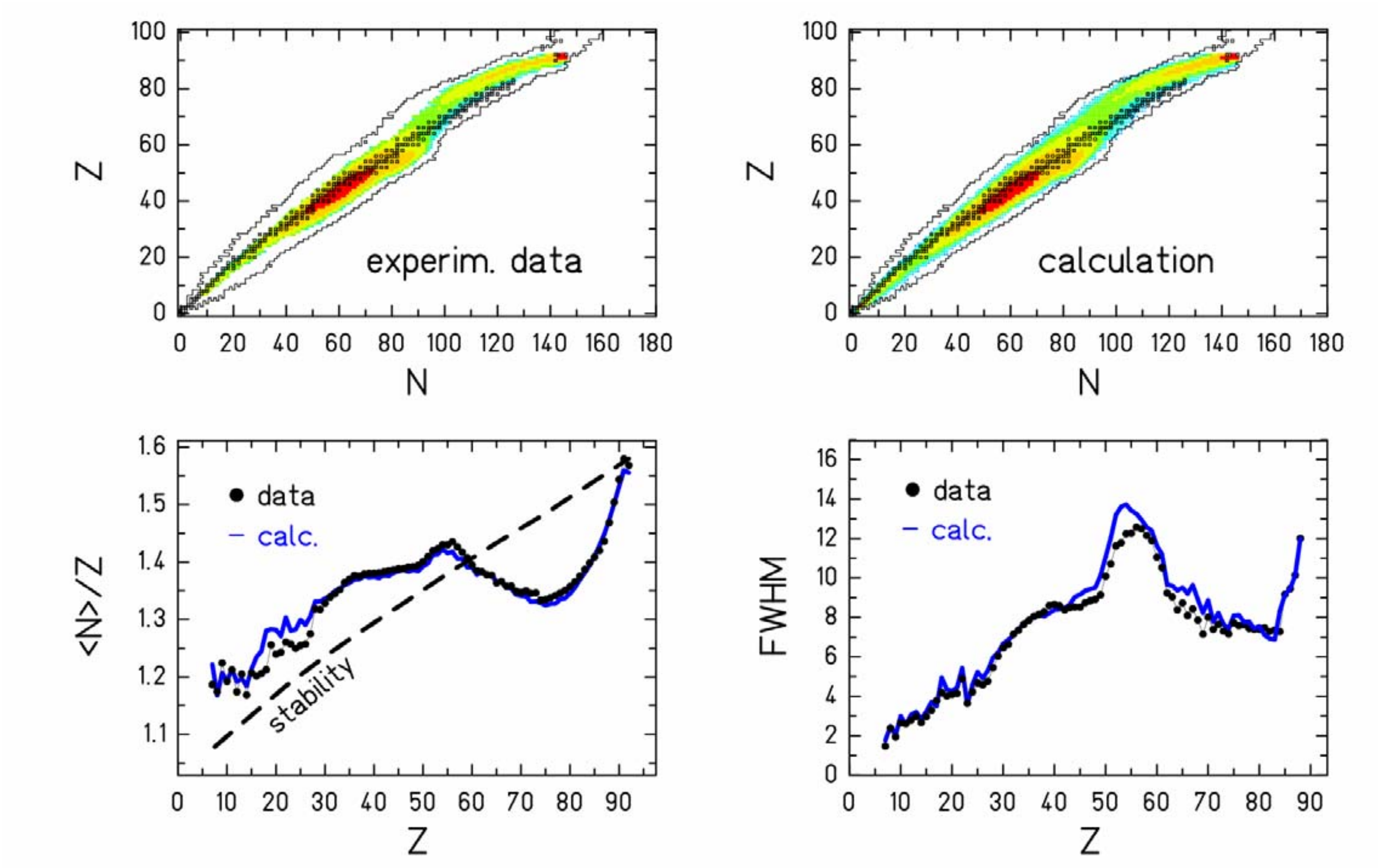
red - calculations



Comparison with data

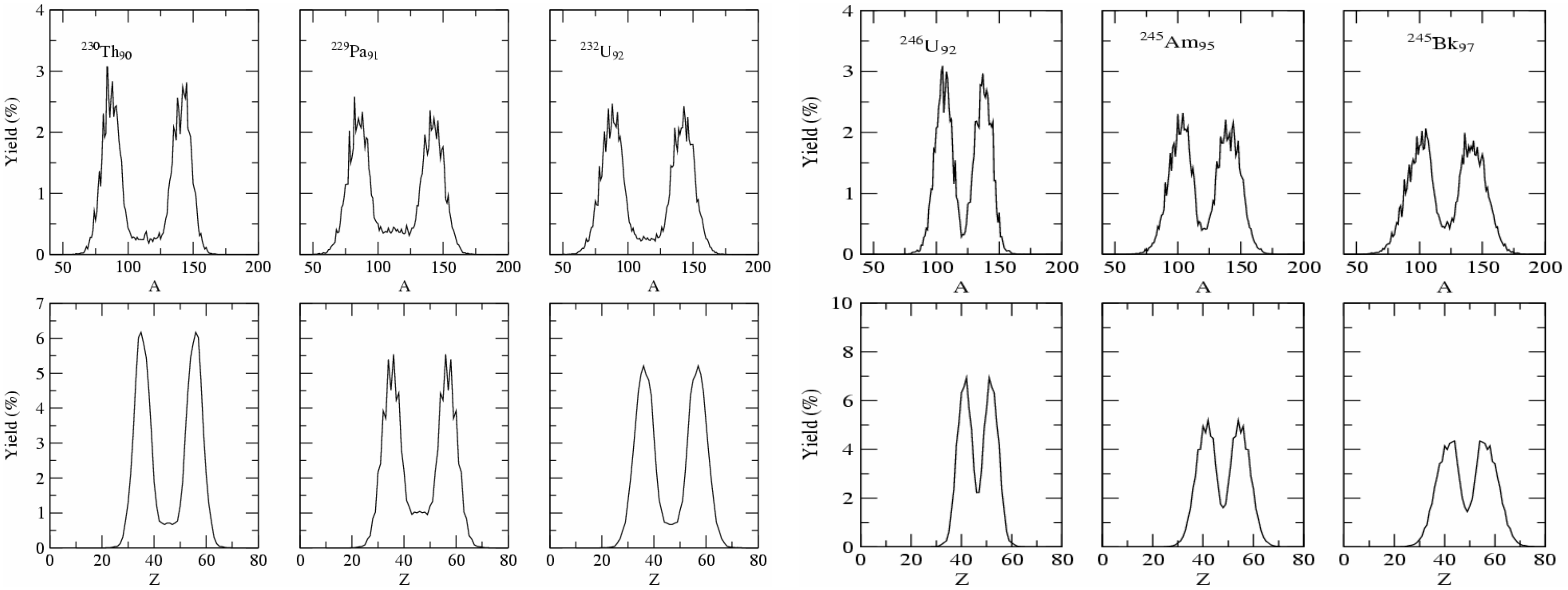
How does the model work in more complex scenario?

^{238}U+p at 1 *A* GeV



Applications in astrophysics - first step

Mass and charge distributions in neutrino-induced fission of r-process progenitors $\Rightarrow$



Phys. Lett. B616 (2005) 48

How to continue

→ Detailed r-process network calculations (N. Zinner and D. Mocelj)

→ New experimental data

- Mass AND charge distributions of both fission fragments at different, well defined excitation energies
- Light particles and gammas emitted in coincidence

⬇

FAIR facility - High-energy branch, e-Ion collider

→ Close collaboration between experiment and theory

Conclusions

- Indications that the TF model and the FRLD model give the most realistic predictions of saddle-point masses

- Good description of mass and charge division in fission based on a macroscopic-microscopic approach

- Detailed r-process network calculations needed

- Ultimate goal → full microscopic description of fission; strong input from theory and experiment

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Karl-Heinz Schmidt

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