The role of fission in the r-process nucleosynthesis

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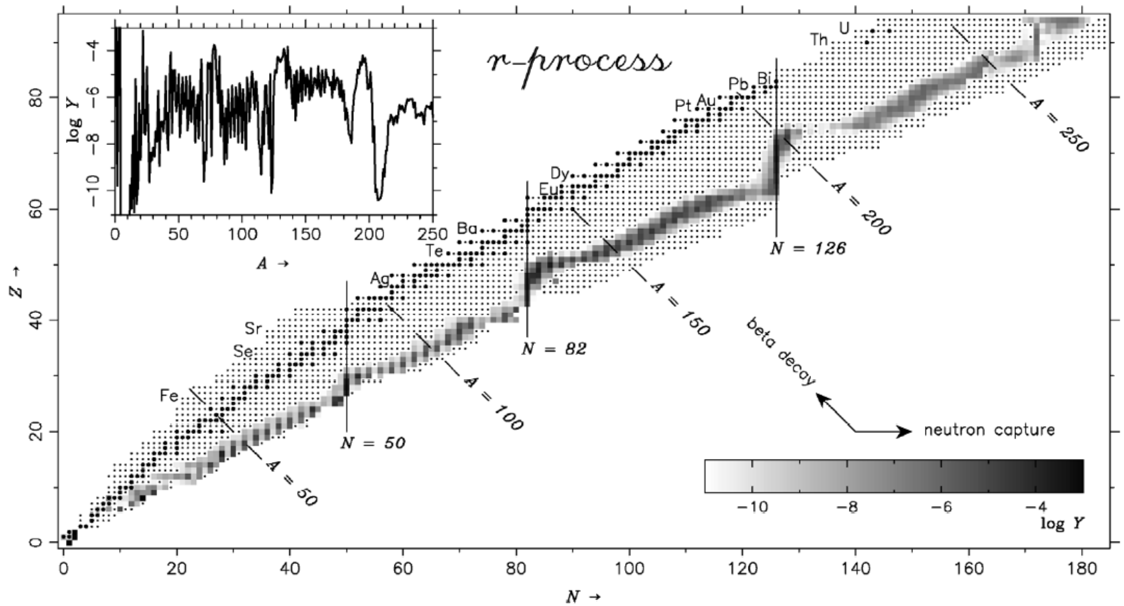
Motivation



S. Wanajo et al., NPA in print

- Fission could have influence on the A_{max} 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 could also influence the abundances of nuclei in the region $A \sim 90$ 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*

What do we need?

- What are the needed ingredients?
  - Fission barriers
  - Mass and charge division in fission
  - Fission dynamics

Covered in this talk

- Importance of nuclear structure at large deformations

- And all this for heavy, very neutron-rich nuclei

How well can we describe fission?

⇒ Empirical systematics

- Problem is often too complex

⇒ Theoretical models

- Way to go!
- But, not always precise enough and still very time consuming
- Encouraging progress in a full microscopic description of fission:
  - → H. Goutte et al., PRC 71 (2005) 024316
  - → J.M. Pearson and S. Goriely, NPA in print

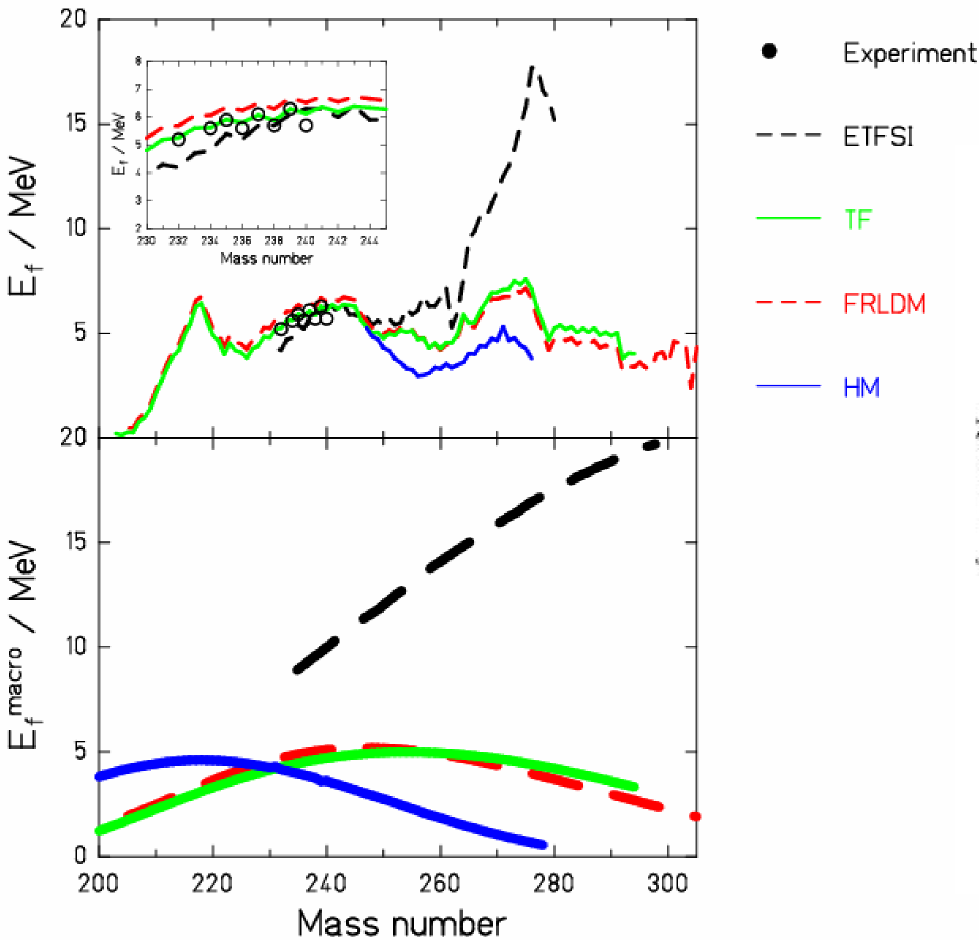
⇒ Semi-empirical models

- Theory-guided systematics

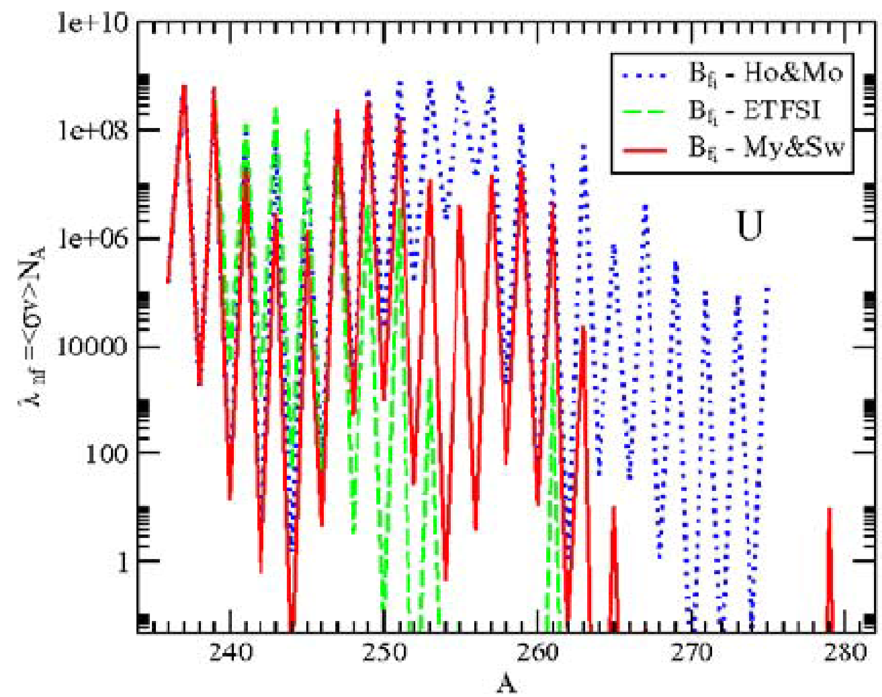
Saddle-point masses

Open problem

Limited experimental information on the height of the fission barrier



Neutron-induced fission rates for U isotopes

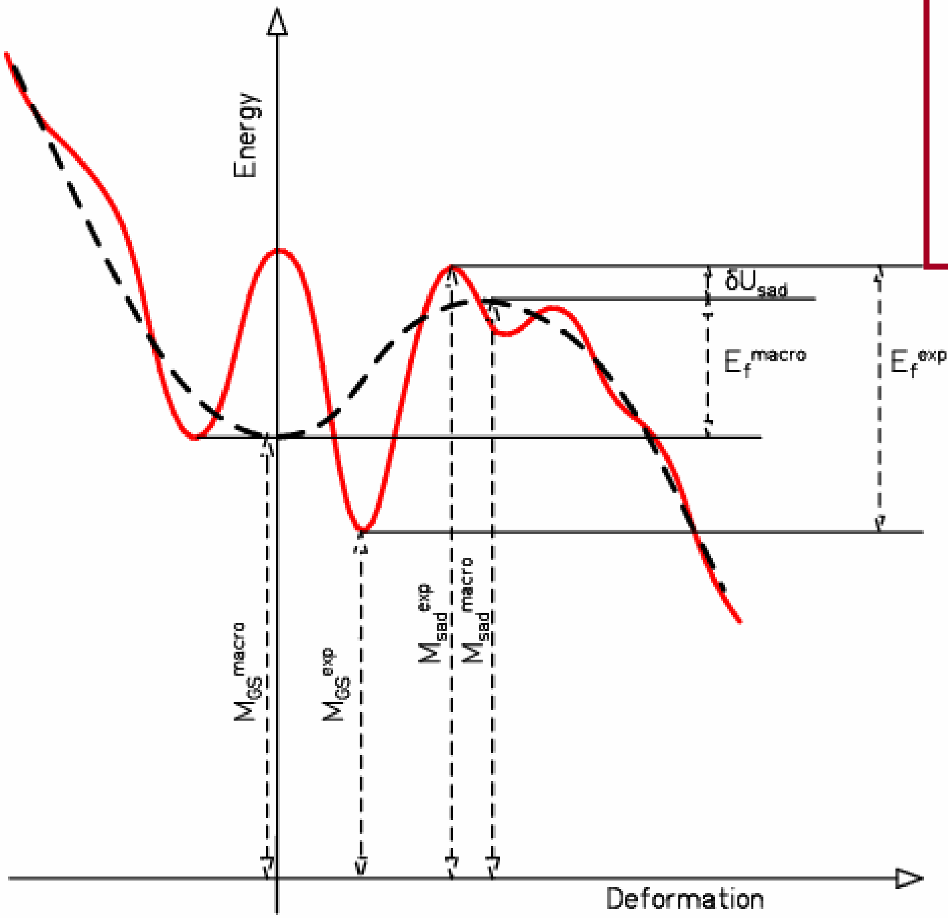


I. Panov et al., NPA 747 (2005) 633

Idea

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

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



M. Dahlinger et al., NPA376 (1982) 94

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

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]

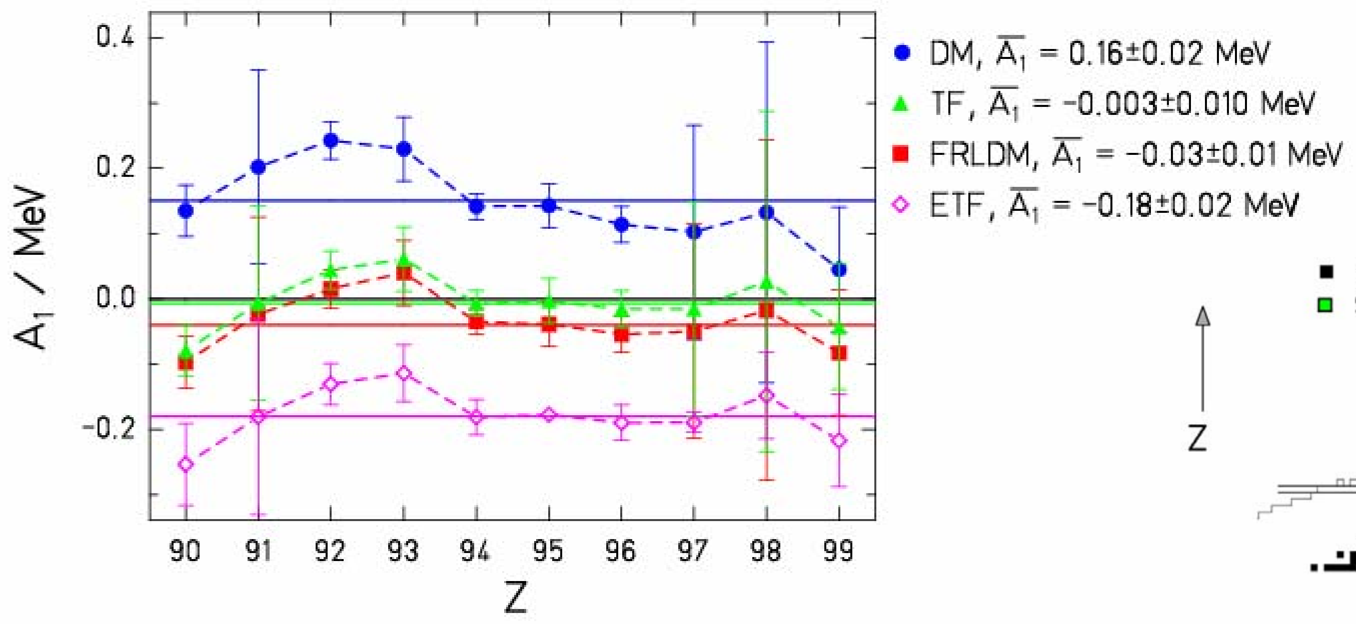
3.) **Thomas-Fermi model** (TF) [Myers&Swiatecki 1996, 1999]

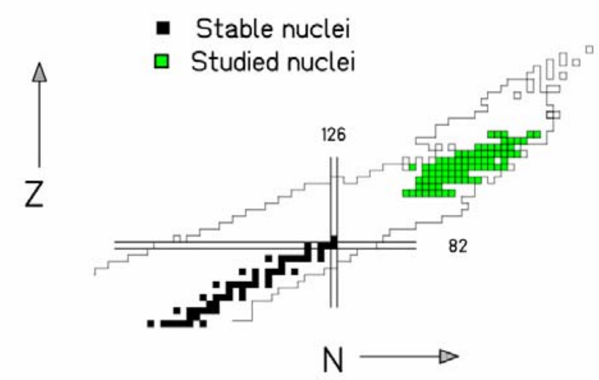
4.) **Extended Thomas-Fermi model** (ETF) [Mamdouh et al. 2001]

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

Results

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





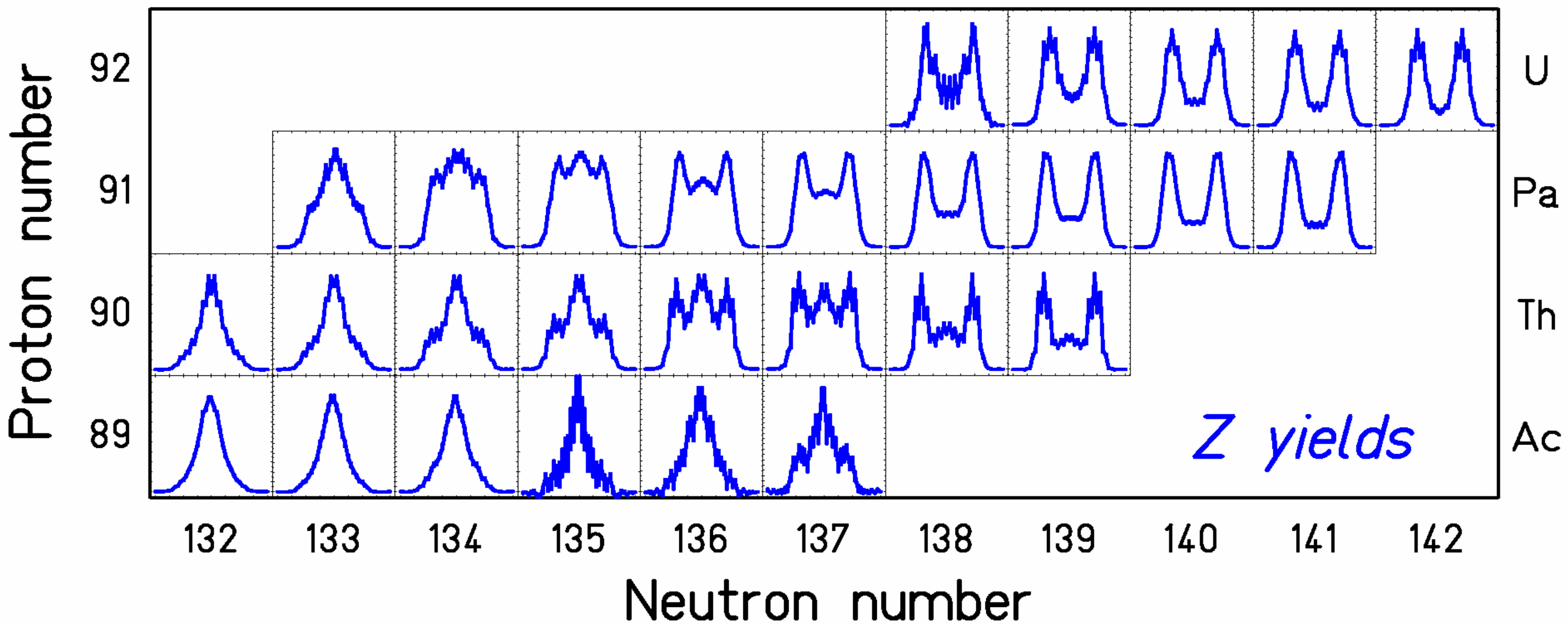
⇒ The most realistic predictions are expected from the TF model and the FRLD model.

⇒ 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

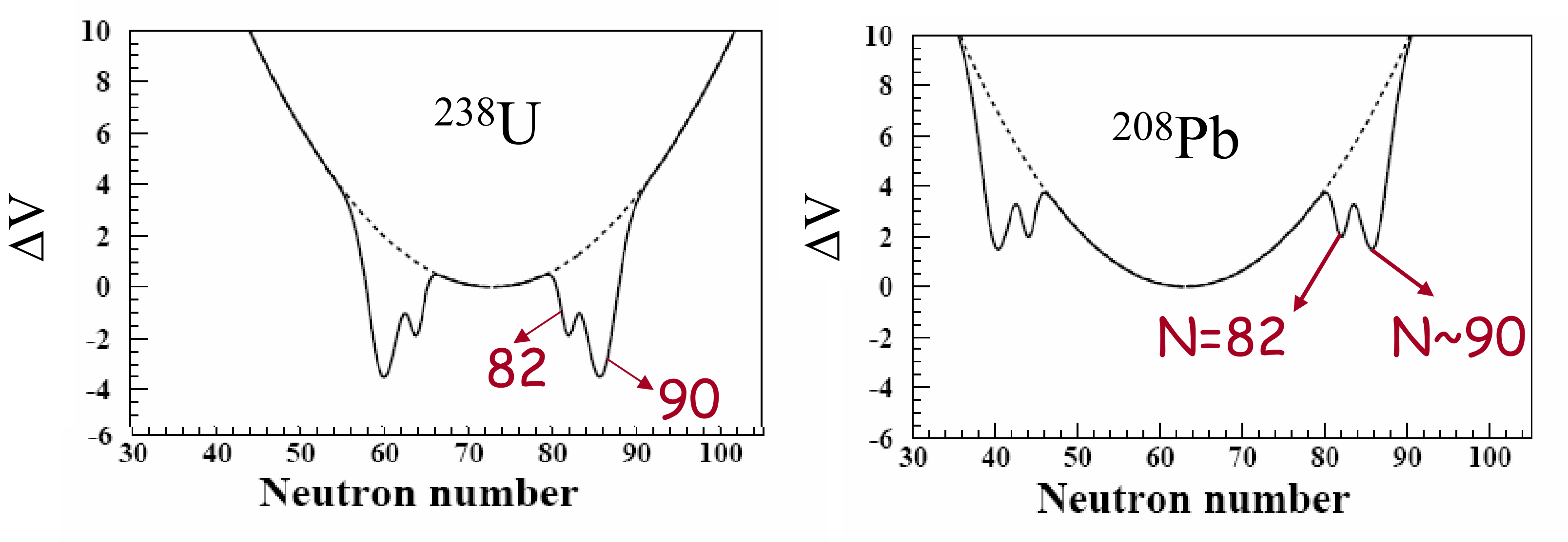
Experimental survey by use of secondary beams of radioactive isotopes



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.



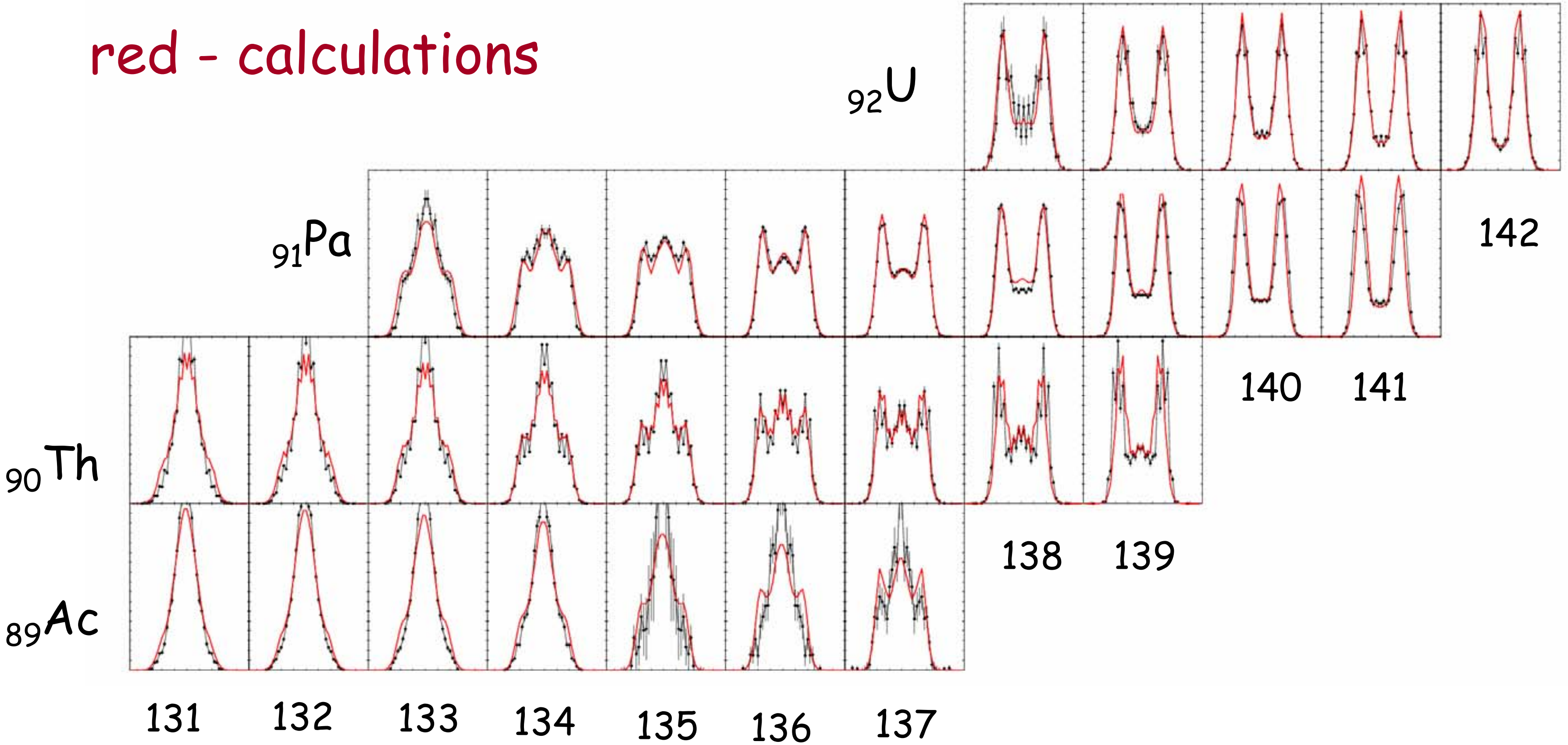
- For each fission fragment we get:
    - Mass
    - Charge
    - Velocity
    - Excitation energy

Comparison with existing data

Fission of secondary beams after the EM excitation:

black - experiment

red - calculations

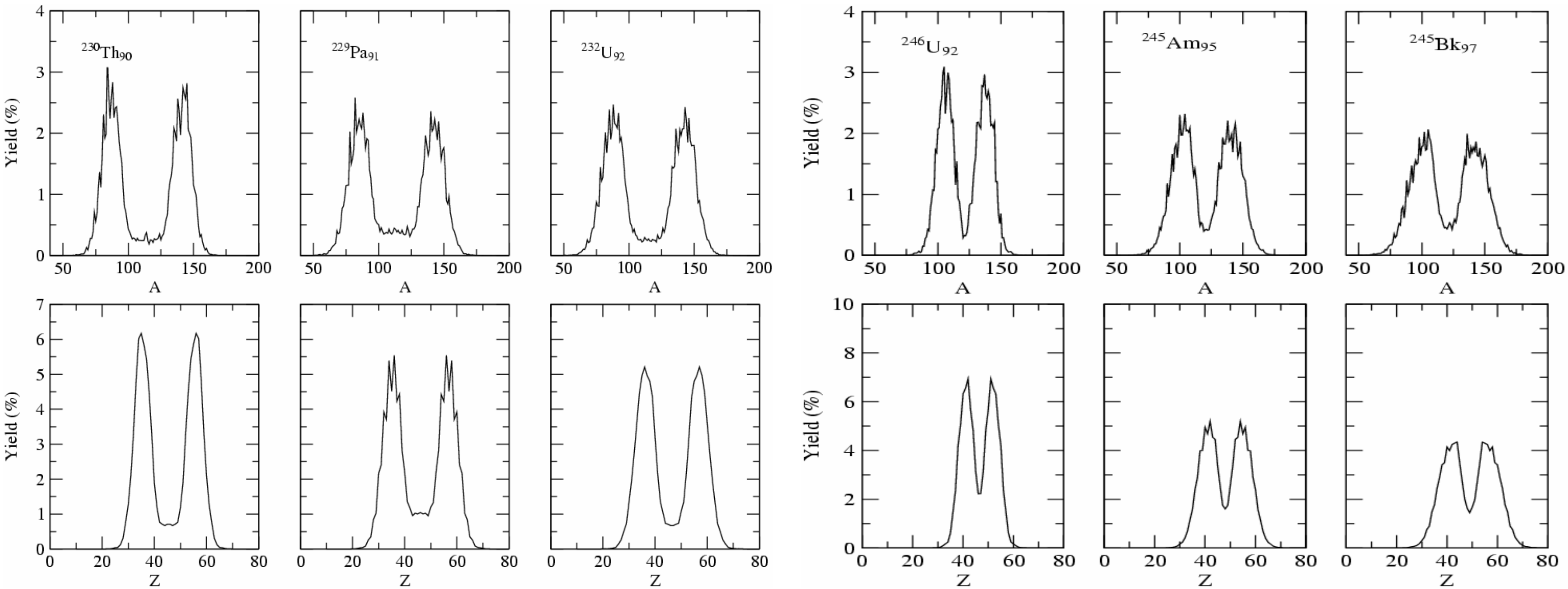


Application in astrophysics - first step

A and Z distributions in neutrino-induced fission of r-process nuclei

1. ν-nucleus interaction $\rightarrow$ RPA

2. Deexcitation $\rightarrow$ GSI code ABLA



N. Zinner

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 at GSI

→ Close collaboration between experiment and theory

Additional slides

Microscopic approach to fission

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

HFB + time-dependent generator coordinate method:

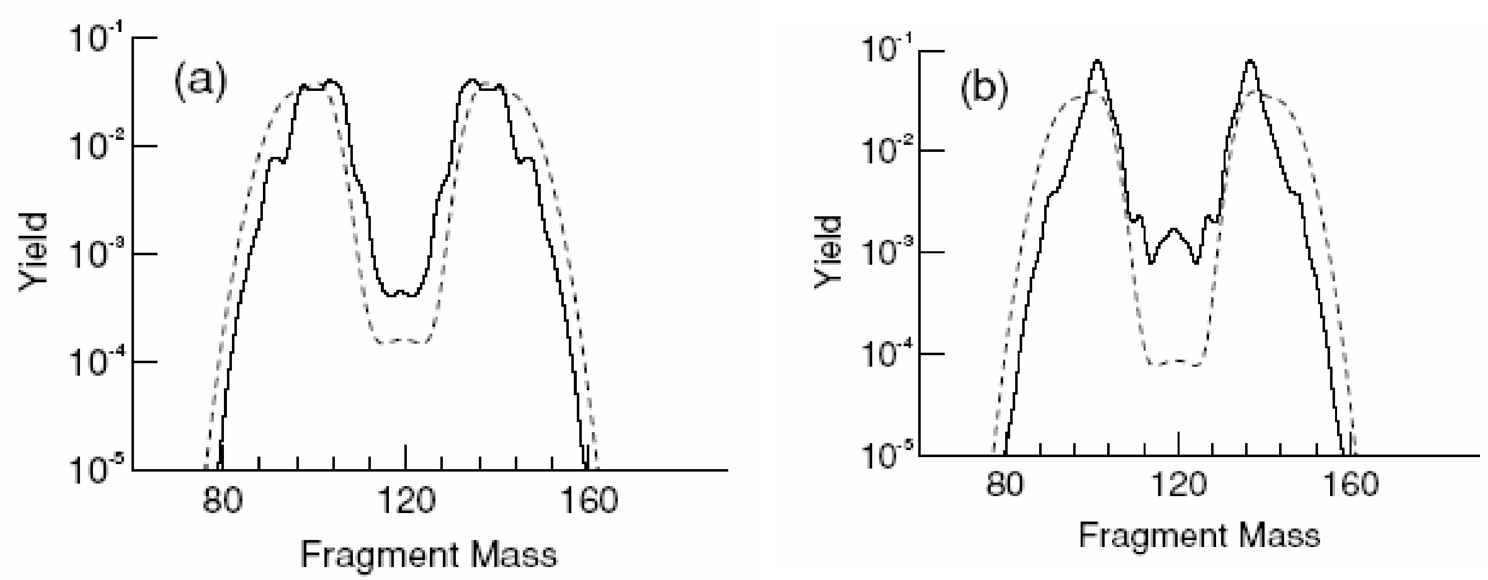
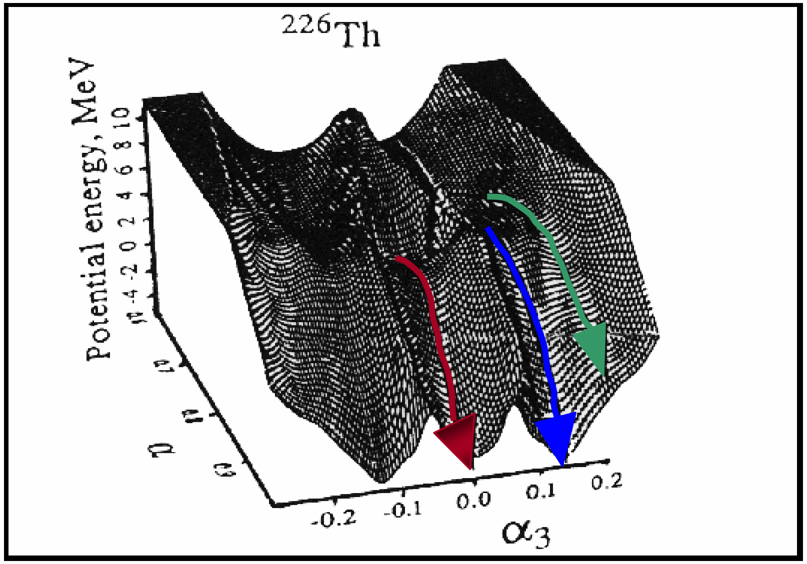


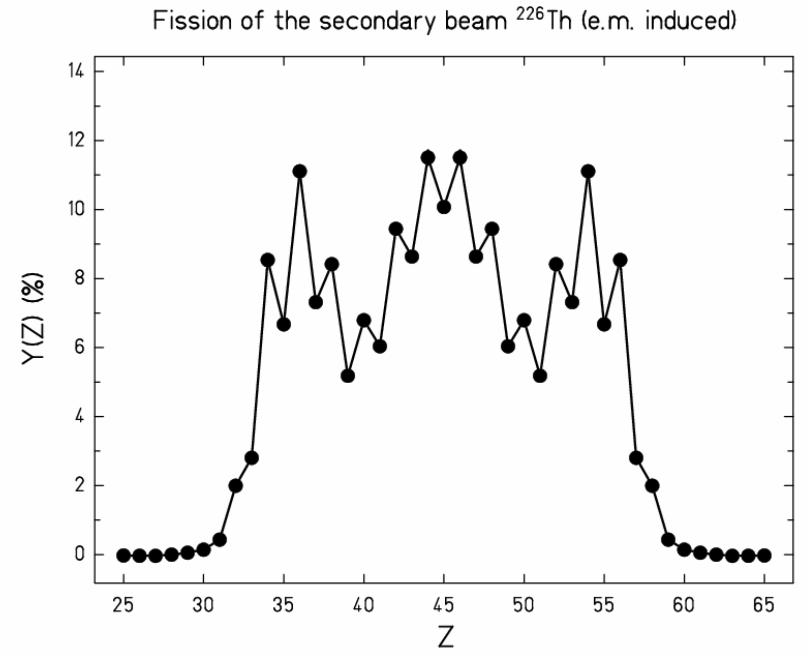
FIG. 14. Theoretical mass distributions (solid lines) are compared with the Wahl evaluations of neutron-induced fission of ^{238}U [24] (dashed lines). Excitation energies of the compound ^{238}U nucleus measured above the barrier are (a) $E = 2.4$ MeV, (b) $E = 1.1$ MeV.

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

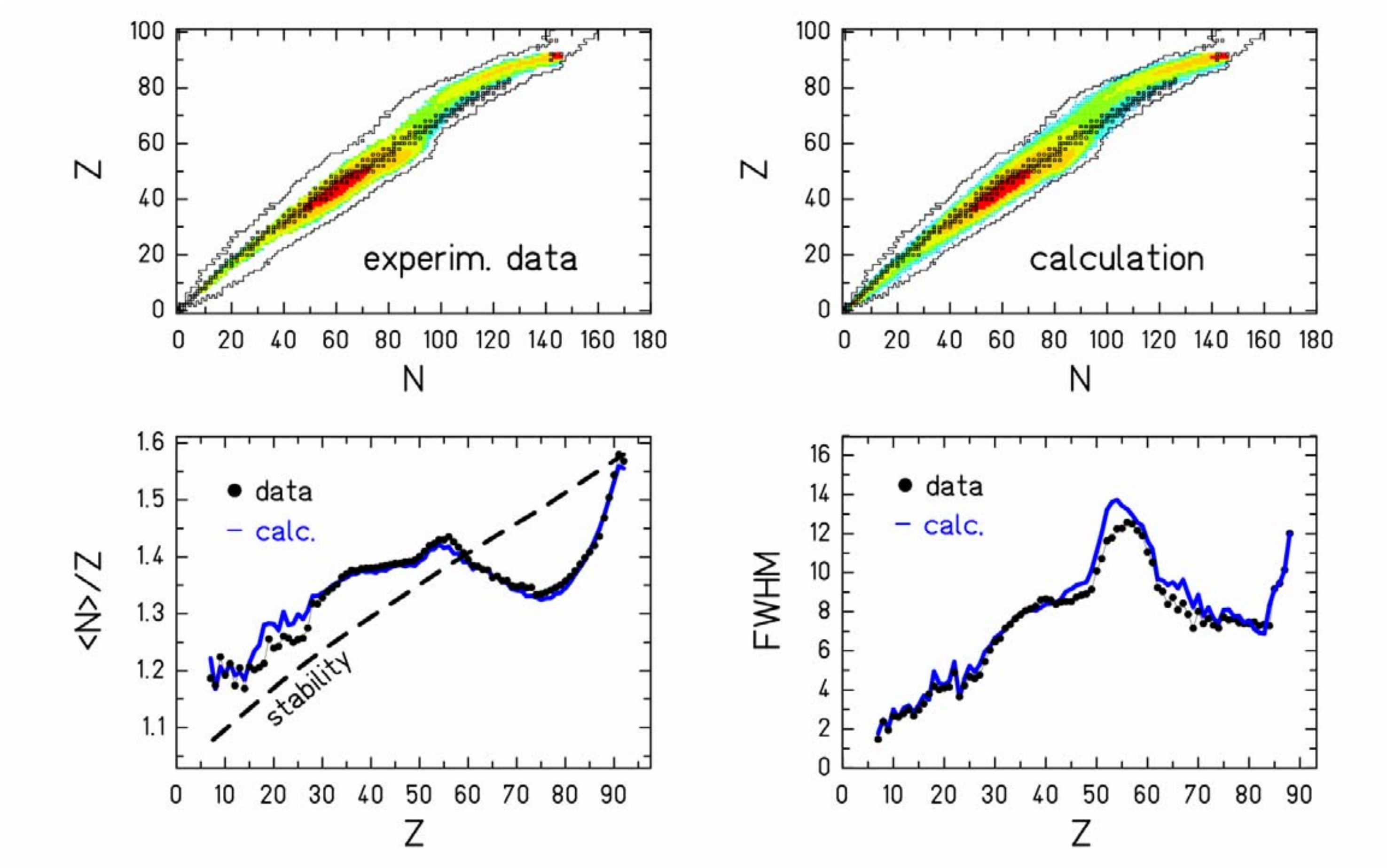


K.-H. Schmidt et al., NPA 665 (2000) 221

Comparison with data

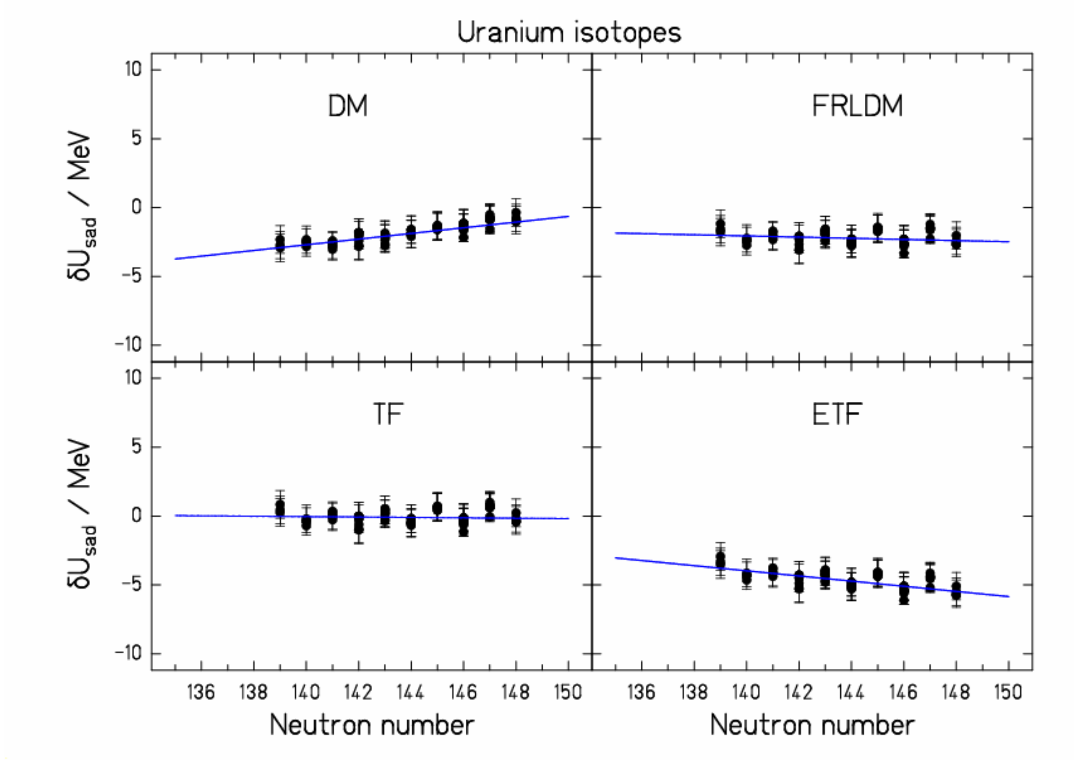
How does the model work in more complex scenario?

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



Example for uranium

δU_{sad} as a function of a neutron number



A realistic macroscopic model should give almost a zero slope!