New insights into the fission process by the study of relativistic nuclear collisions

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Outline

- Why studying fission
  - Basic research
  - Applications (astrophysics, RIB production, spallation sources...)
- Fission experiments at the FRS@GSI
- FRS results
  - Mass and/or charge distributions
  - Dissipation ⇨ Talk Christelle Schmitt
- Fission barriers of exotic nuclei
- Summary and outlook

Motivation

Basic research

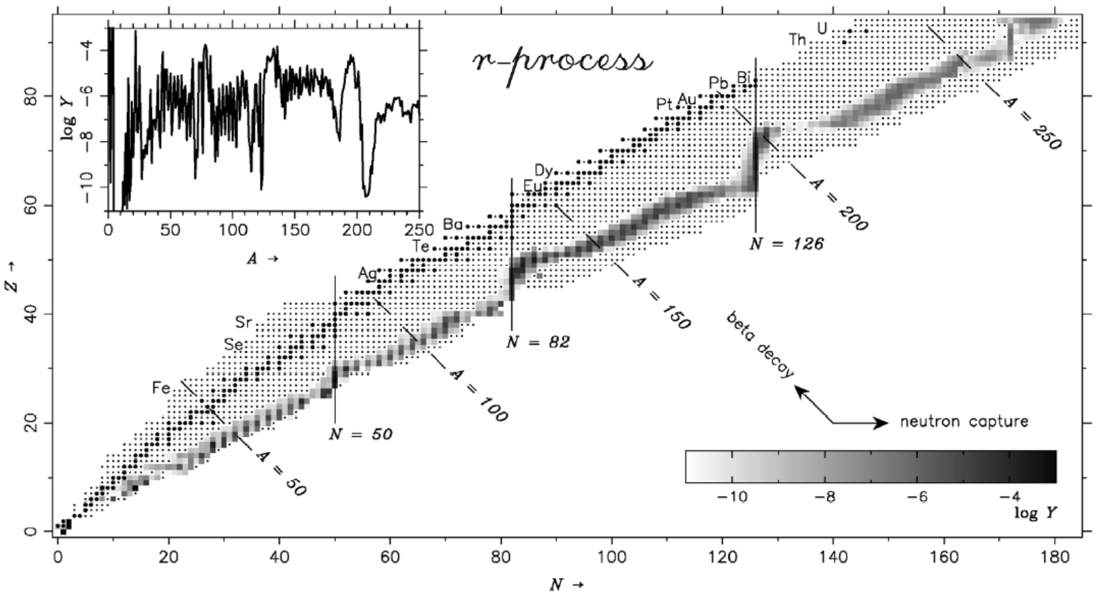
Fission corresponds to a large-scale collective motion where both static and dynamic properties play important role

Excellent tool to study, e.g.

- Nuclear structure effects at large deformations
- Fluctuations in charge polarisation
- Viscosity of nuclear matter

Motivation

Astrophysics - r-process and nucleosynthesis



Wanajo et al, NPA in press

- Trans-uranium elements [1]
- r-process endpoint [2]
- Fission cycling [3]

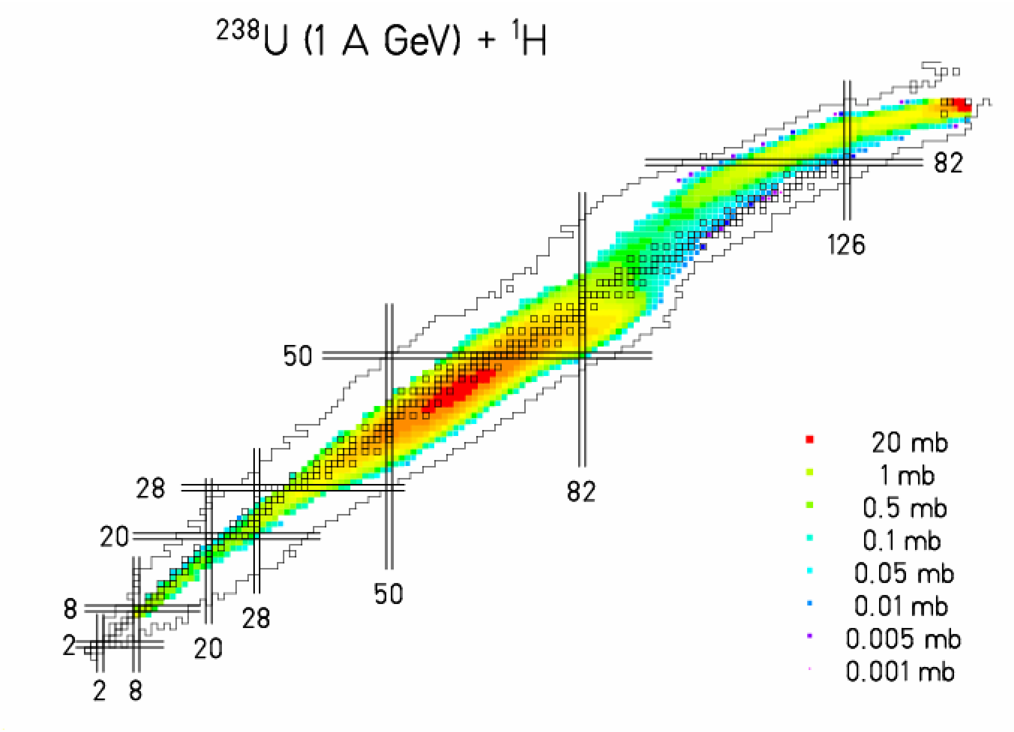
1) Cowan et al, Phys. Rep. 208 (1991) 267;
2) Panov et al., NPA 747 (2005) 633
3) Seeger et al, APJ 11 Suppl. (1965) S121
4) Rauscher et al, APJ 429 (1994) 49

Challenge - fission properties (e.g. fission barriers, fission-fragment distributions) for nuclei not accessible in laboratory.

Motivation

RIB production

Fragmentation method, ISOL method



Data measured at FRS*

* Ricciardi et al, PRC 73 (2006) 014607; Bernas et al., NPA 765 (2006) 197; Armbruster et al., PRL 93 (2004) 212701; Taïeb et al., NPA 724 (2003) 413; Bernas et al., NPA 725 (2003) 213

www.gsi.de/charms/data.htm

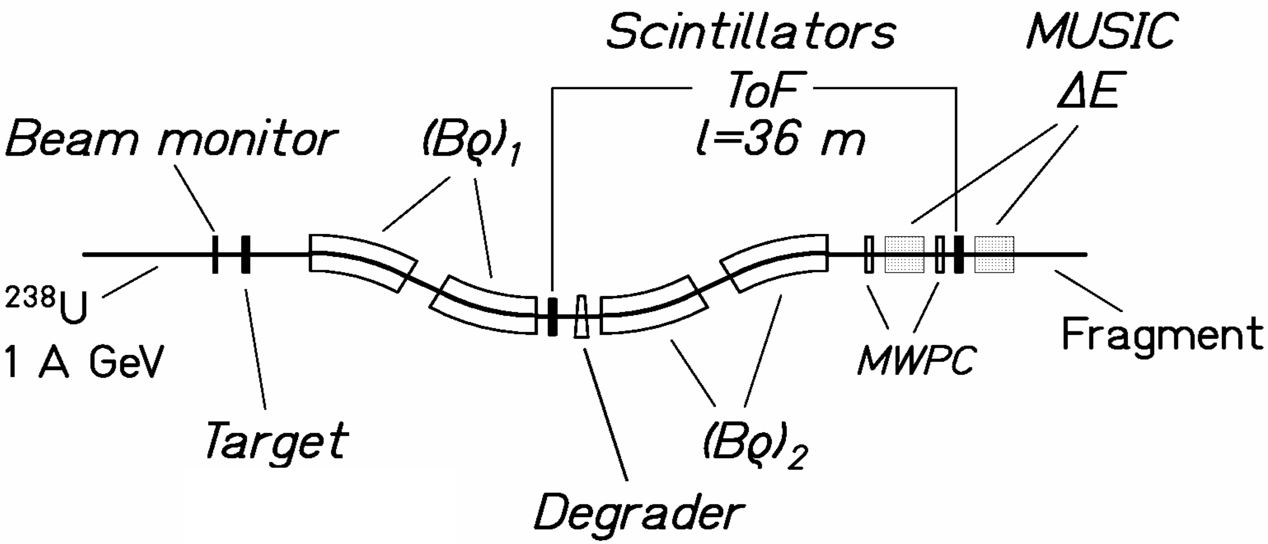
Challenge - need for consistent global description of fission and evaporation

Fission experiments at FRS

Two types of experiments

Performed in inverse kinematics using relativistic (~ 1 *A* GeV) heavy-ion (up to ^{238}U) beams

Experimental setup 1



Θ^{max}	= 15 mrad
$\Delta p/p$	= ± 1.5 %

ToF ⇨ $\beta\gamma$

x_1, x_2 ⇨ $B\rho$

ΔE ⇨ Z

$$B\rho = \frac{m_0 c}{e} \cdot \frac{A}{Z} \cdot \beta \cdot \gamma$$

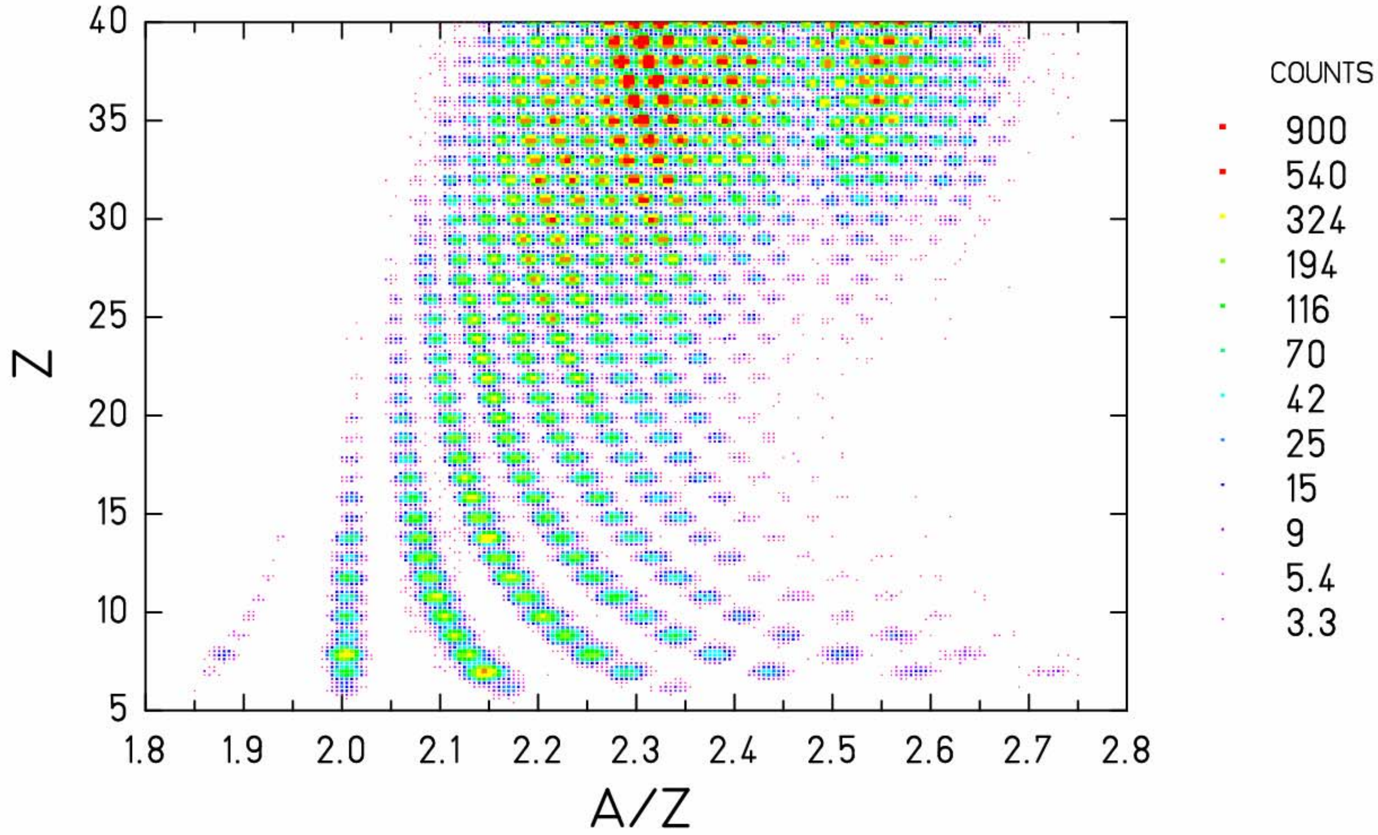
Resolution:

- $\Delta(\beta\gamma)/\beta\gamma \approx 5 \cdot 10^{-4}$
- $\Delta Z \approx 0.4$
- $\Delta A / A \approx 2.5 \cdot 10^{-3}$

But, only one fragment

Nuclide identification

$^{238}U + ^{1}H$ at 1 *A* GeV



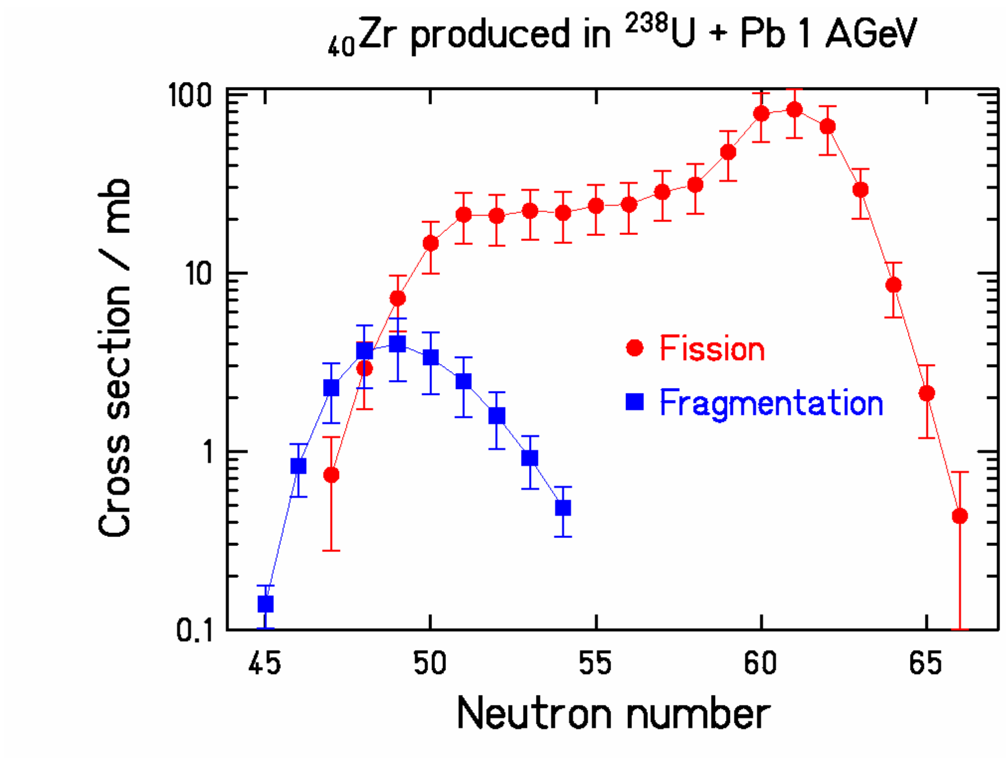
M.V. Ricciardi, PhD thesis

Production mechanism

Fragment kinematic properties + limited angular acceptance of the FRS

⇓

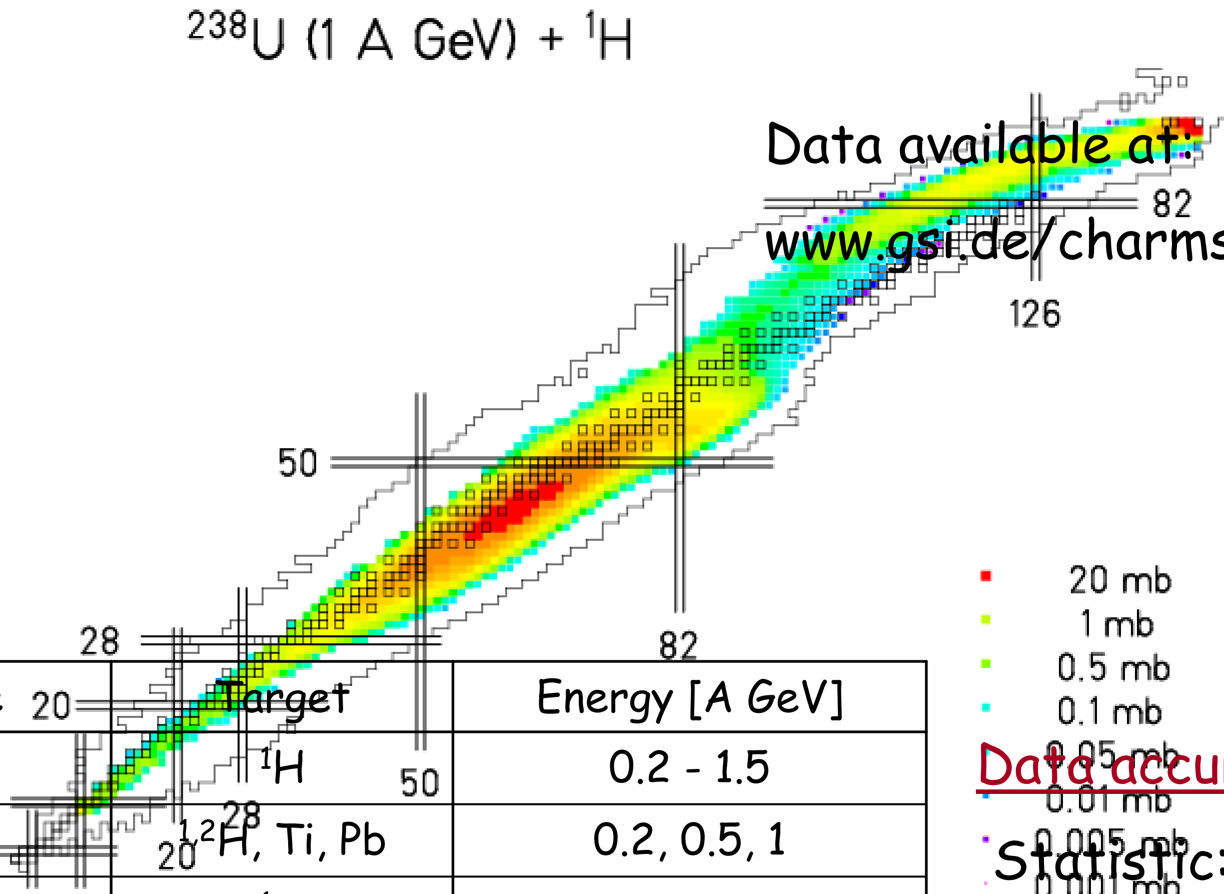
Information on reaction mechanism



Enqvist et al., NPA 658 (1999) 47

As a result ⇨ for each nucleus: productions cross section, velocity and production mechanism

Measured cross sections - one example



Data available at:
www.gsi.de/charms/data.htm

Projectile	Target	Energy [A GeV]
^{56}Fe	^{1}H	0.2 - 1.5
^{136,124}Xe	^{1,2}H, Ti, Pb	0.2, 0.5, 1
^{197}Au	^{1}H	0.8
^{208}Pb	^{1,2}H, Ti	0.5, 1
^{238}U	^{1,2}H, Be, Ti, Pb	0.75, 1

Data accuracy

Statistic: ~ 3%

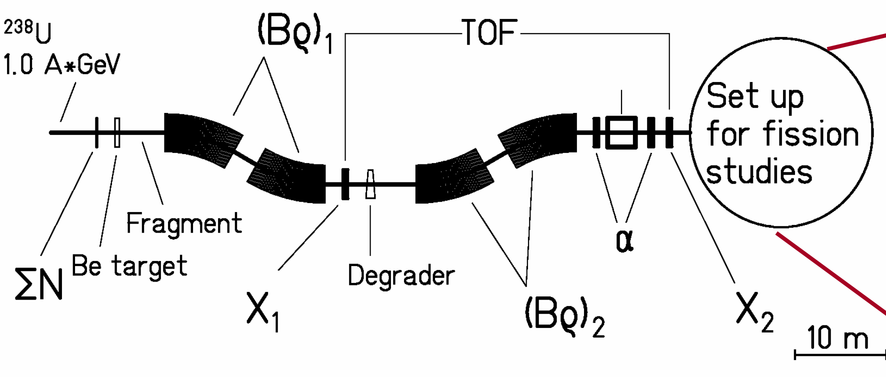
Systematic: 9 - 15 %

* Ricciardi et al, PRC 73 (2006) 014607; Bernas et al., NPA 765 (2006) 197; Armbruster et al., PRL 93 (2004) 212701; Taïeb et al., NPA 724 (2003) 413; Bernas et al., NPA 725 (2003) 213

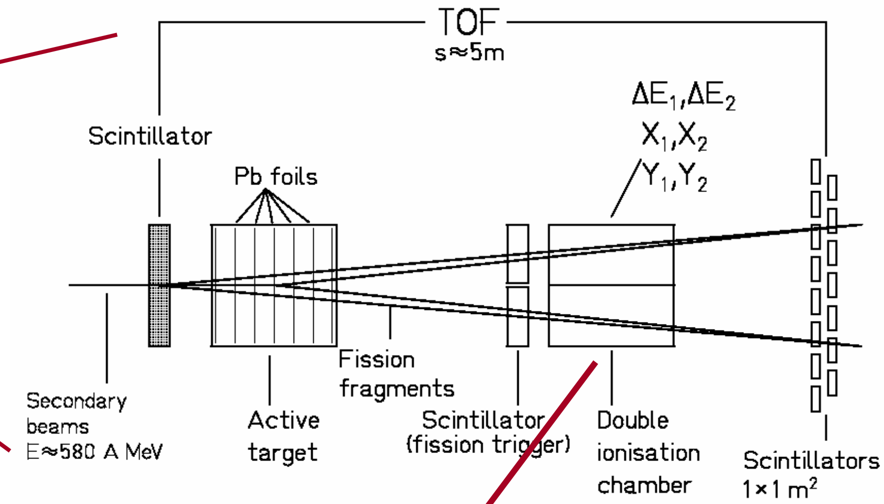
www.gsi.de/charms/data.htm

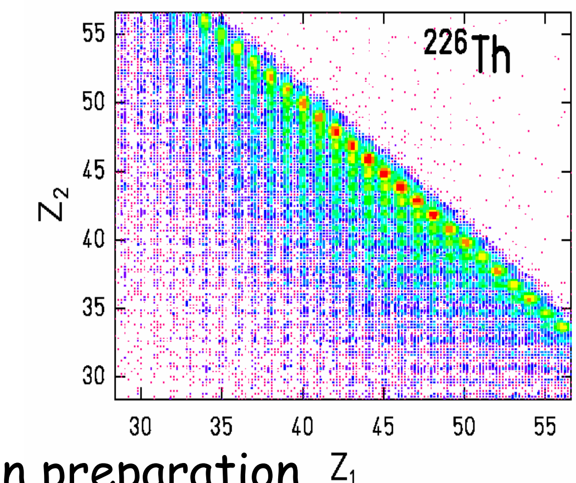
Experimental setup 2

1st Production and identification of secondary beams



2nd Identification of both fission fragments



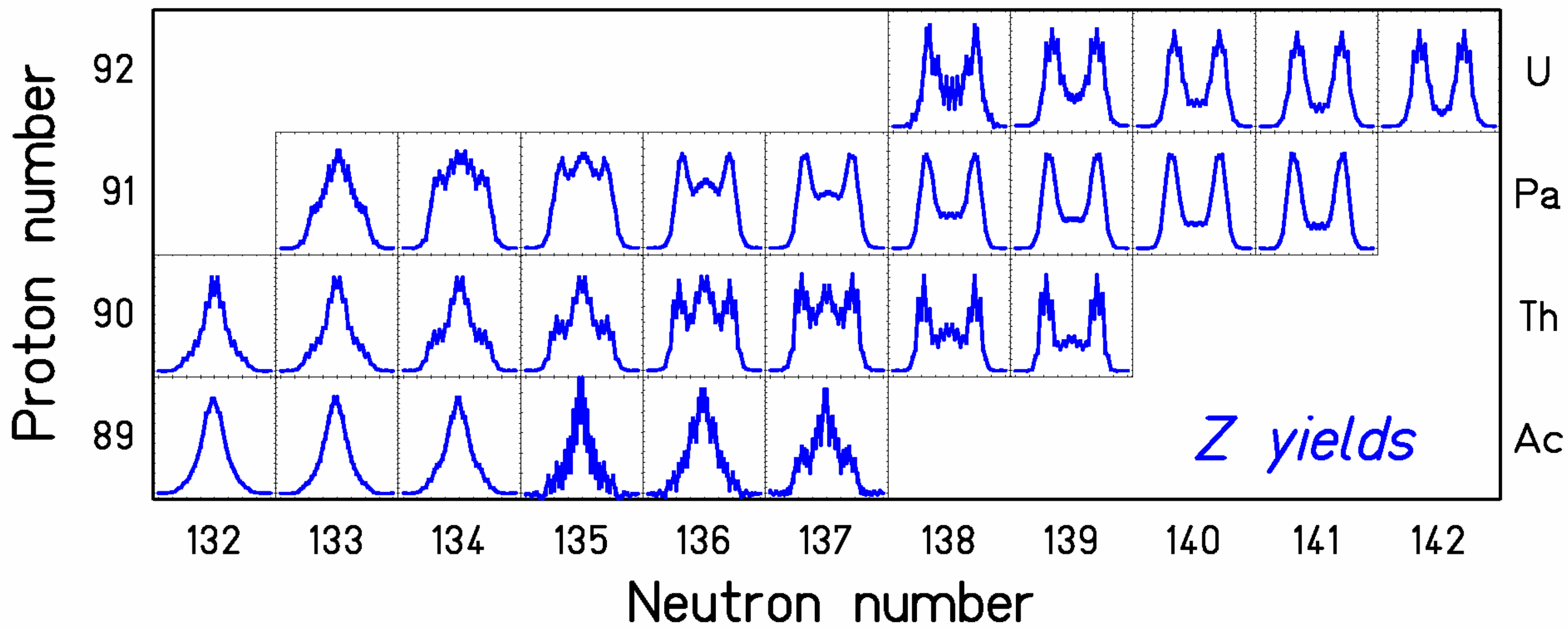


Ch. Schmitt, in preparation

- EM fission
- Nuclear fission

Measured Z-distributions

More than 70 secondary beams studied: from Z=85 to Z=92



Schmidt et al., NPA 665 (2000) 221

Mass and charge division in fission

How can we describe exp data?

⇒ 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) ⇨ Time-dependent HF calculations with GCM

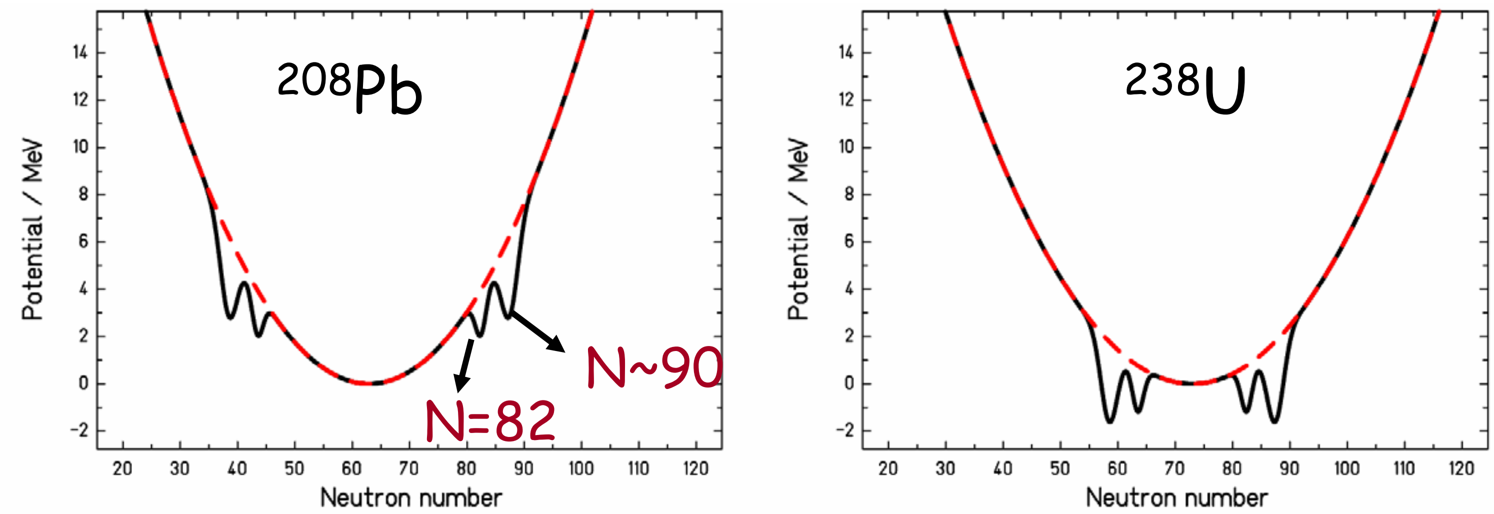
⇒ Semi-empirical models - Theory-guided systematics

Macroscopic-microscopic approach

- Transition from single-humped to double-humped explained by macroscopic and microscopic properties of the potential-energy landscape near outer saddle.

Macroscopic part: property of CN

Microscopic part: properties of fragments*



* Maruhn and Greiner, Z. Phys. 251 (1972) 431, PRL 32 (1974) 548; Pashkevich, NPA 477 (1988) 1;

Macroscopic-microscopic approach

Ingredients of the fission model:

- Level densities
- Assumption on dynamics ⇨ Mass split at outer saddle, N/Z of fragments at scission
- Potential fitted to data ⇨ Curvature of macroscopic part: systematics by Rusanov et al. Curvatures, strengths and positions of two microscopic contributions as free parameters

For each fission fragment we get:

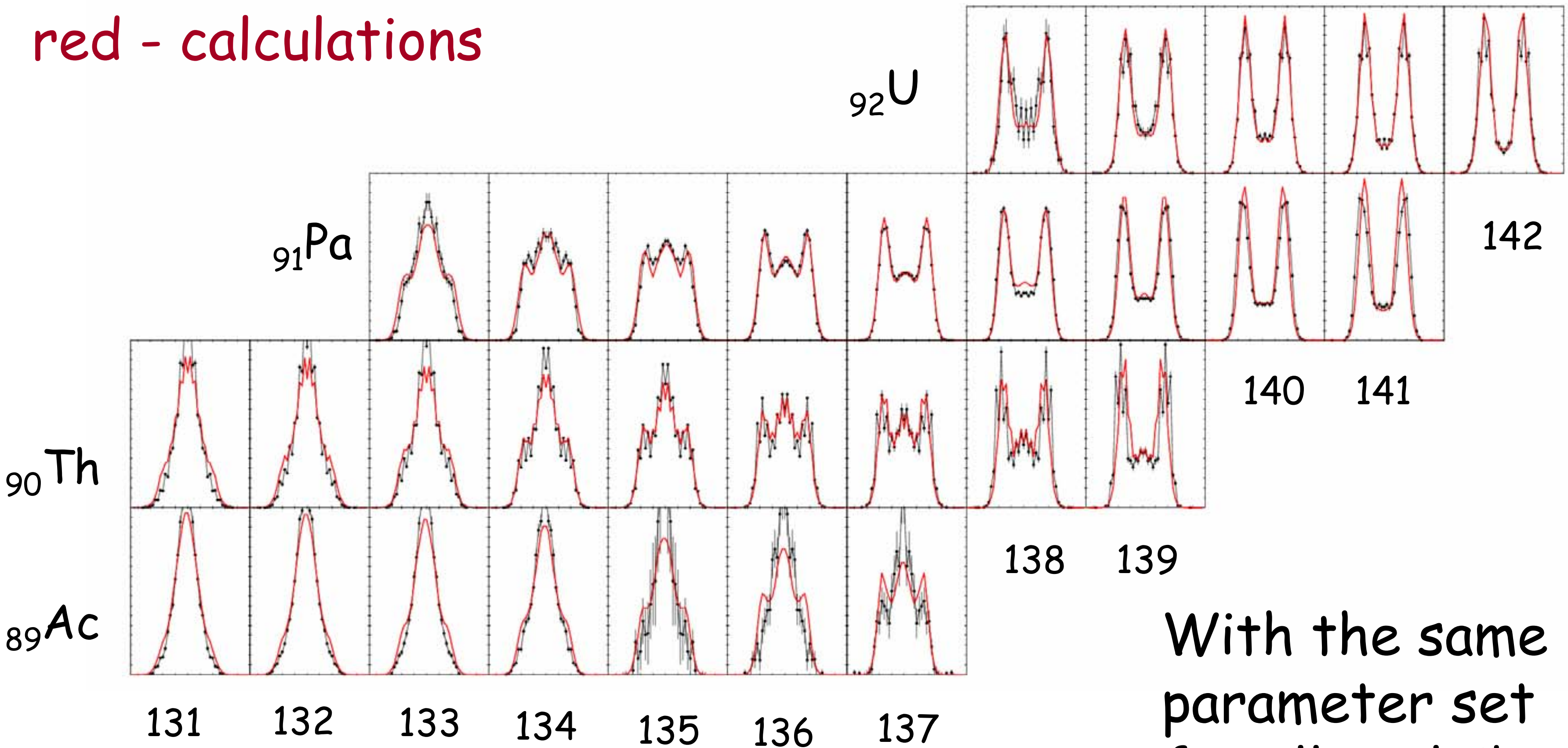
- Mass
- Nuclear charge
- Velocity
- Excitation energy

Comparison with data

Fission of secondary beams after the EM excitation:

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

red - calculations

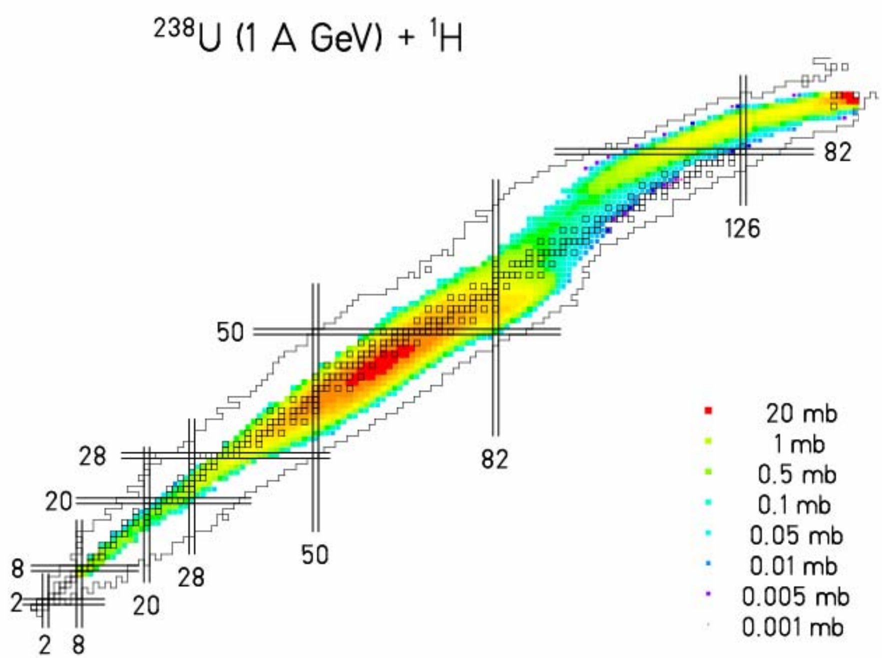


With the same parameter set for all nuclei!

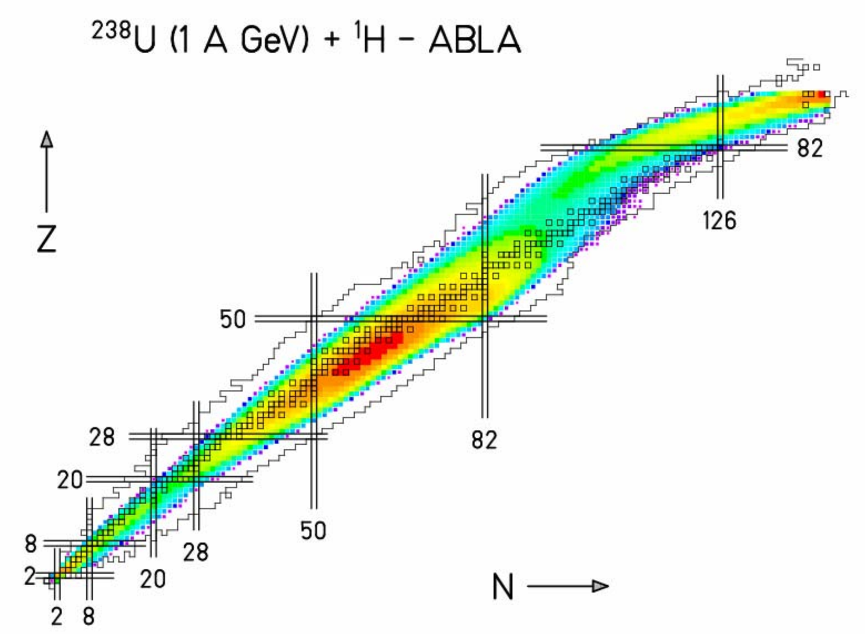
Comparison with data

^{238}U (1 A GeV) + ^{1}H

Experimental data:

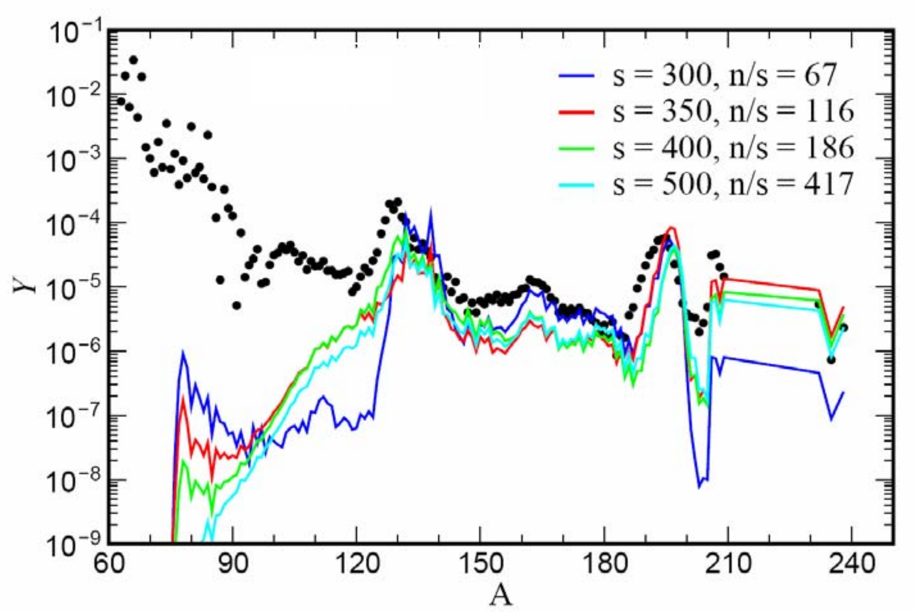


Model calculations (model developed at GSI):



Application

Global character of the approach ⇨ Extrapolation in unknown regions, such as very neutron-rich nuclei on r-process path.



r-process network calculations* performed by Gabriel Martinez-Pinedo (GSI):

n-induced, ν-induced, β-delayed, spontaneous fission included

For more details, see:

*Martinez-Pinedo et al, Proc. of Conference Nuclei in Cosmos IX, CERN, June 2006

Borzov et al, *ibid*

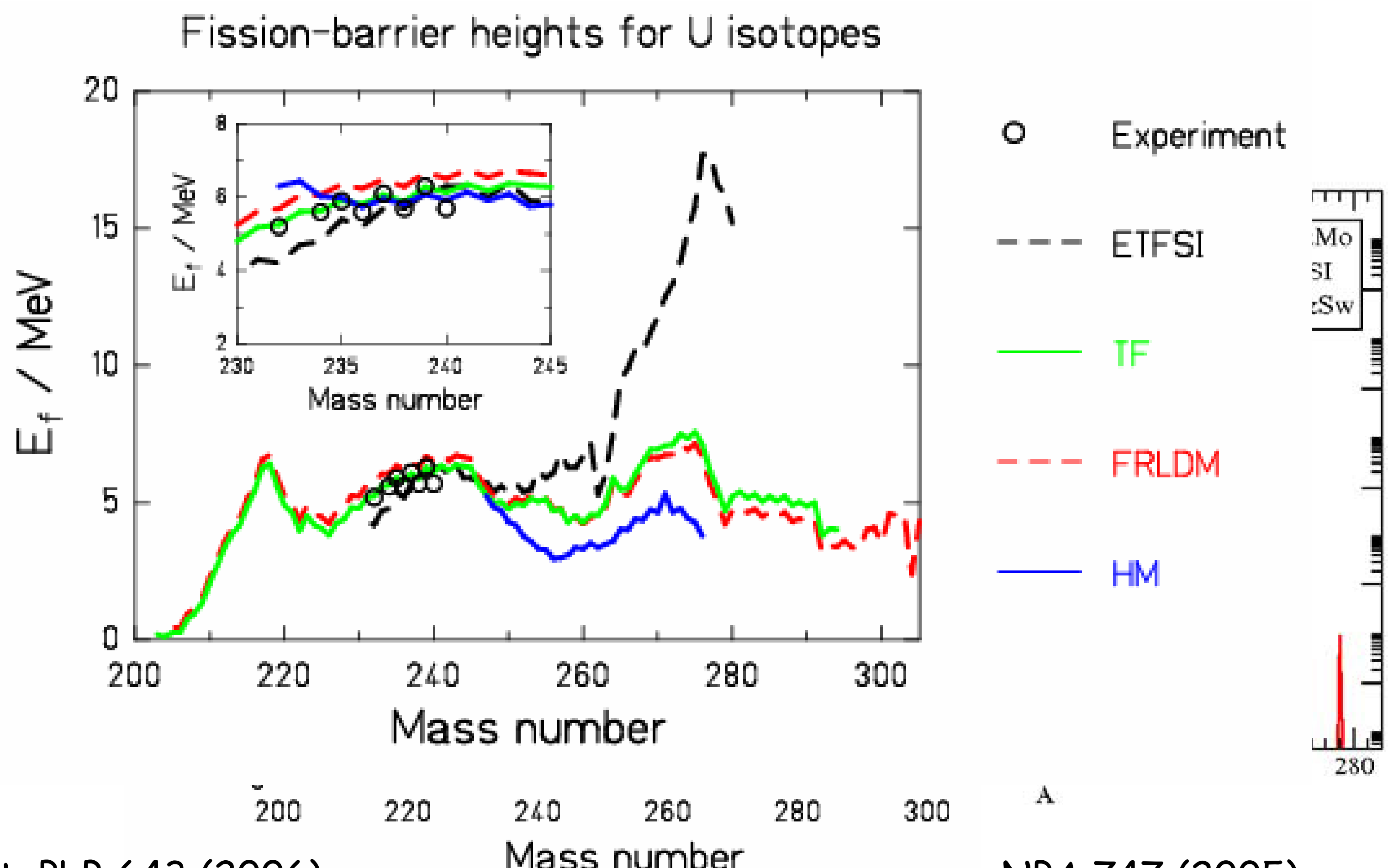
Kelić, Zinner et al, PLB 616 (2005) 48

Fission barriers

Difficulties when extrapolating in unknown regions (e.g. r-process, super-heavies)

Open problem

Limited experimental information on the height of the fission barrier

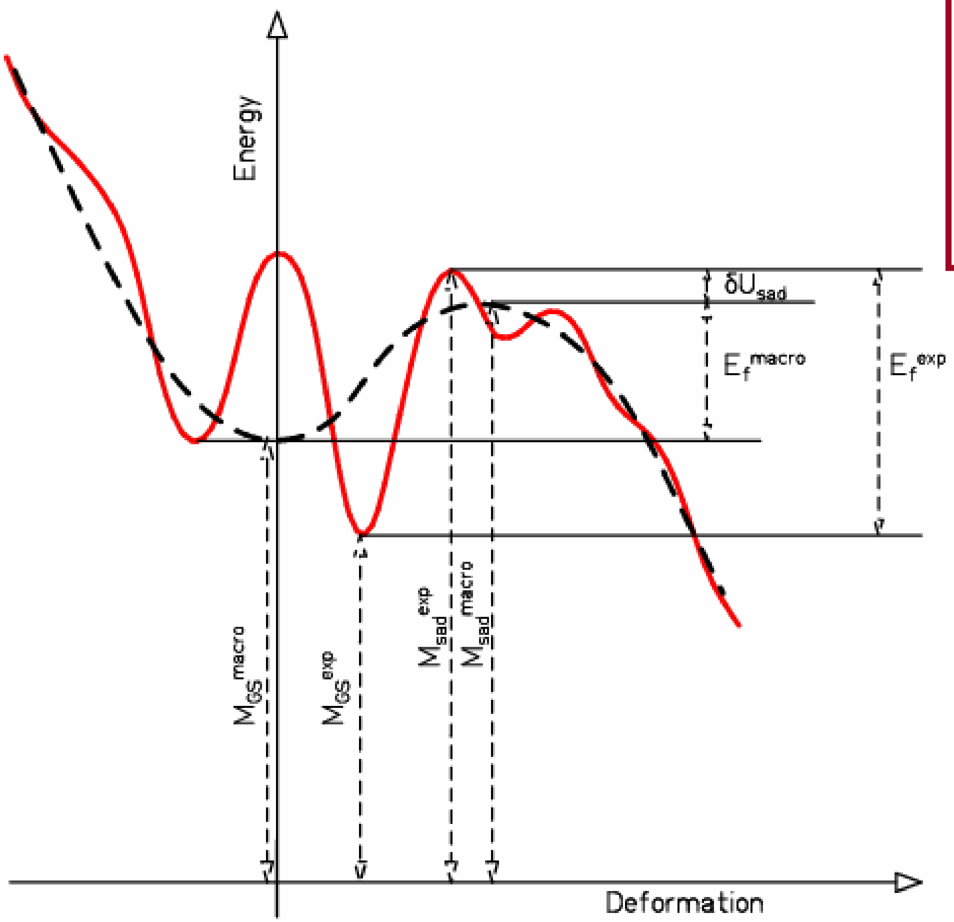


Kelić and Schmidt, PLB 643 (2006)

…, NPA 747 (2005)

Idea

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



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

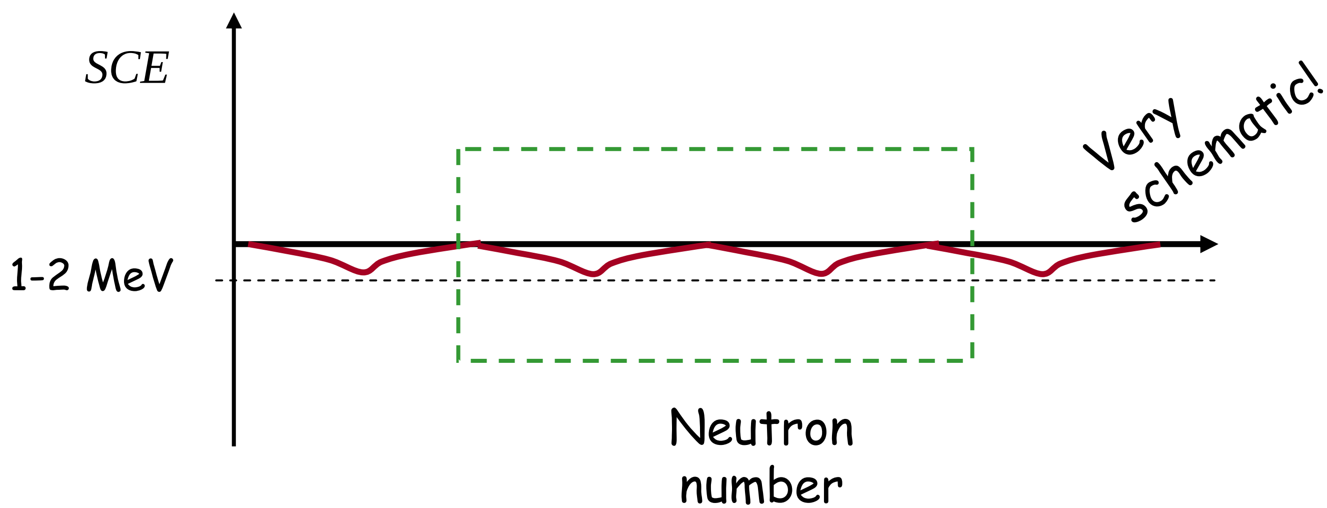
$\delta U_{sad} \leftrightarrow$ Empirical saddle-point shell-correction energy

Idea

What do we know about saddle-point shell-correction energy?

1. Shell corrections have local character

2. Shell-correction energy at SP should be very small (e.g Myers and Swiatecki PRC 60 (1999); Siwek-Wilczynska and Skwira, PRC 72 (2005))



If an model is realistic ⇨ Slope of δU_{sad} as function of N should be ~ 0

Any general trend would indicate shortcomings of the model.

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]

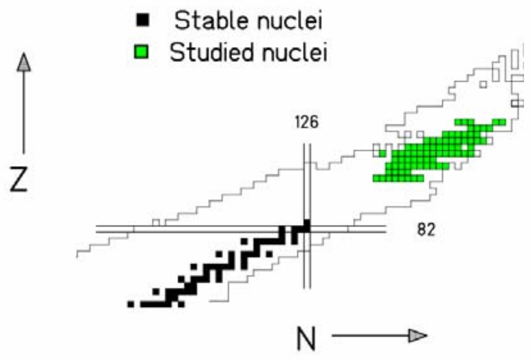
3) **Thomas-Fermi model** (TF) [Myers and Swiatecki 1996, 1999]

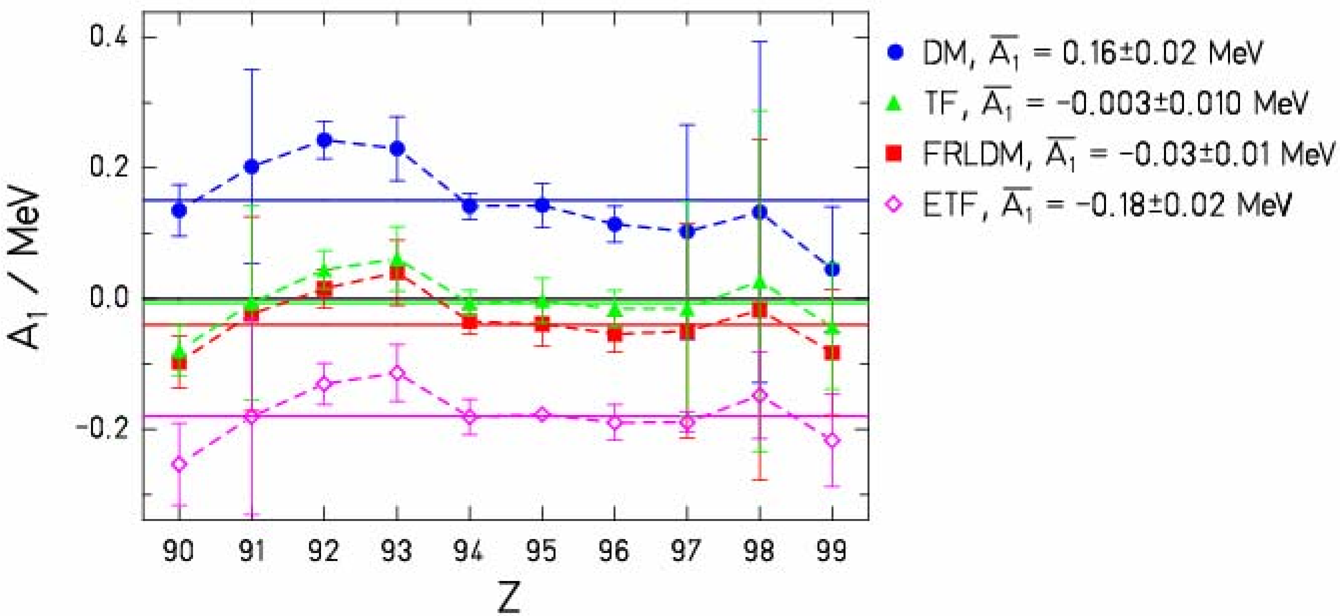
4) **Extended Thomas-Fermi model** (ETF) [Mamdouh et al. 2001]

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

Conclusions

- Good description of mass and charge division in fission based on a macroscopic-microscopic approach, which allows for robust extrapolations

- According to a detailed analysis of the isotopic trends of saddle-point masses indications have been found that the Thomas-Fermi model and the FRLDM model give the most realistic predictions in regions where no experimental data are available

- Need for more precise and new experimental data using new techniques and methods (e.g. R3B and ELISE at FAIR) ⇨ basis for further developments in theory

CHARMS collaboration*

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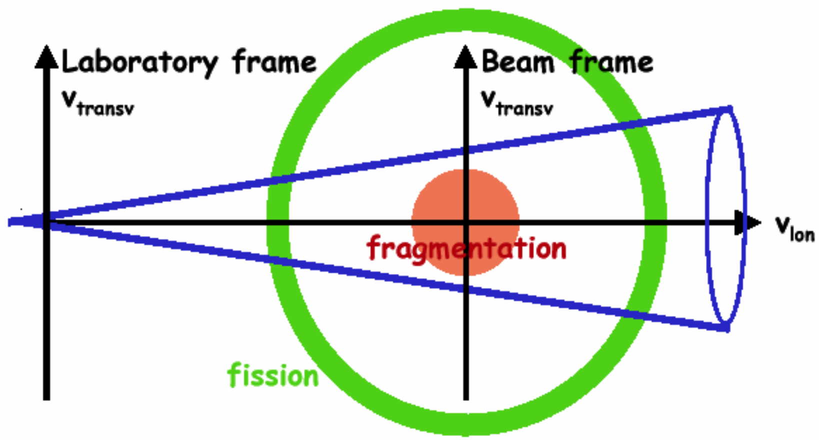
Andreas Heinz
Yale University, USA

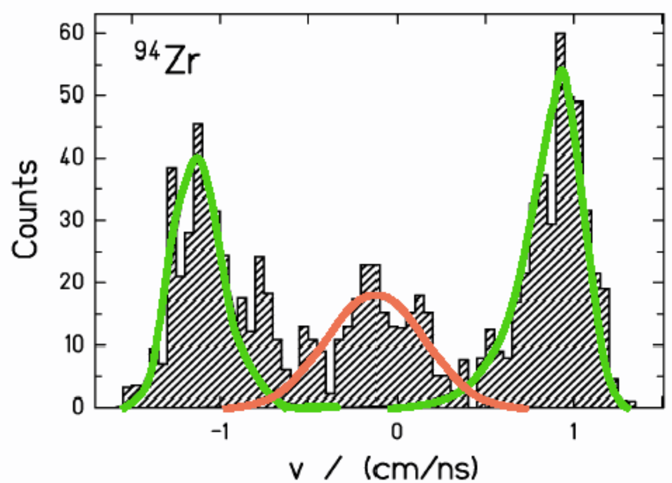
* Collaboration for High-Accuracy experiments on nuclear-reaction Mechanisms with magnetic Spectrometer: **www.gsi.de/charms**

Additional slides

Kinematics

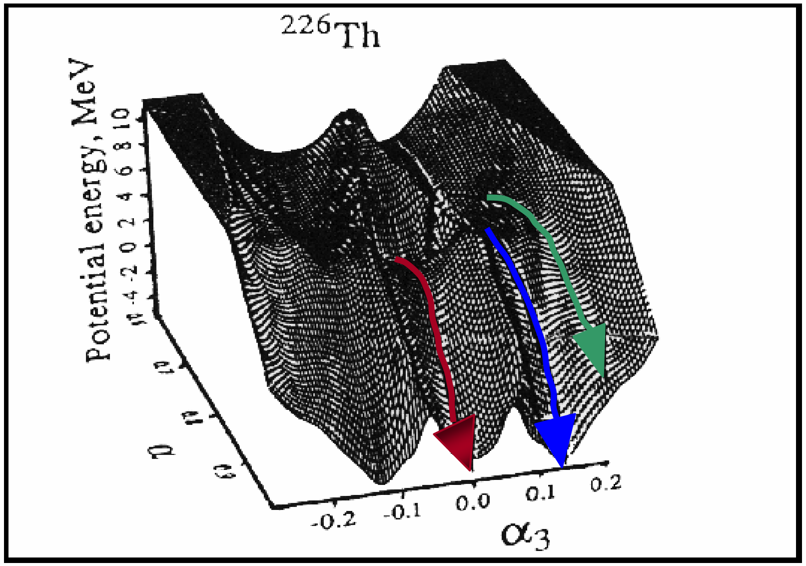


^{238}U+Pb, 1 A GeV

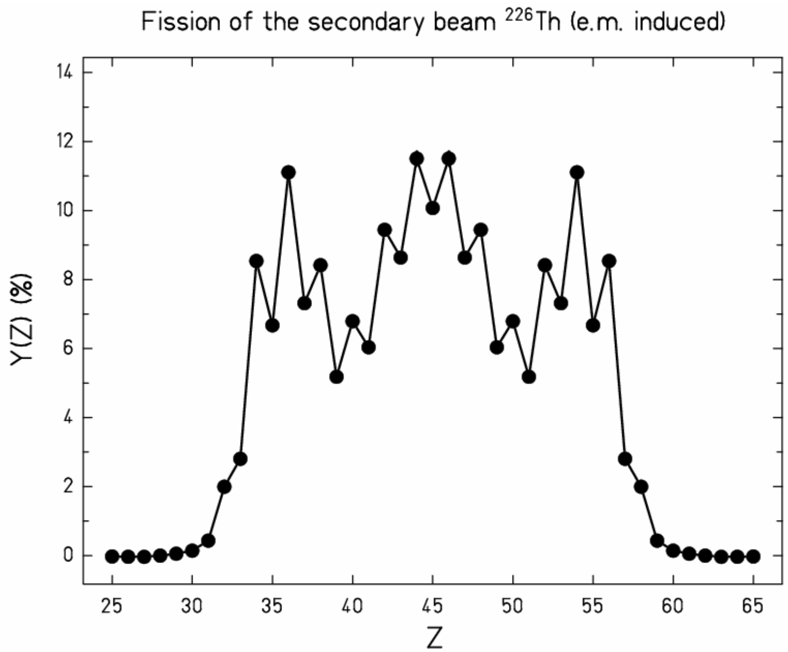


How well do we understand fission?

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



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



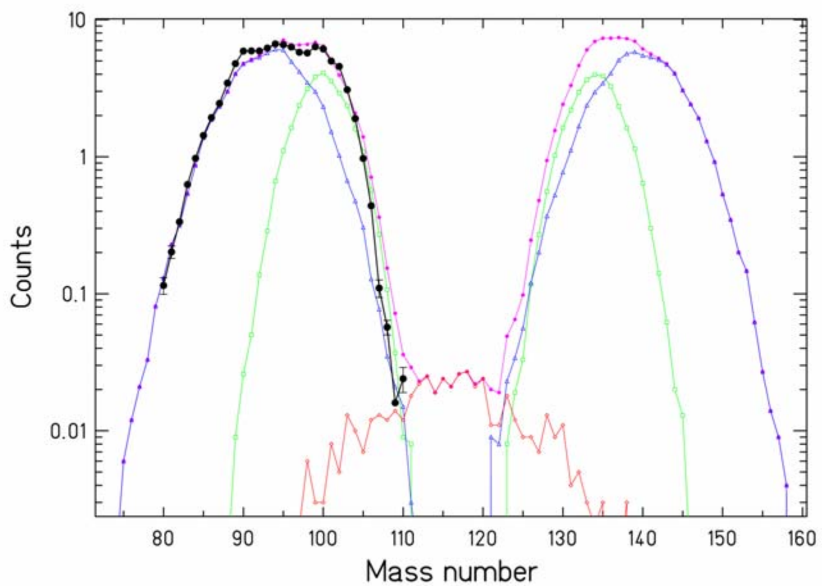
K.-H. Schmidt et al., NPA 665 (2000) 221

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

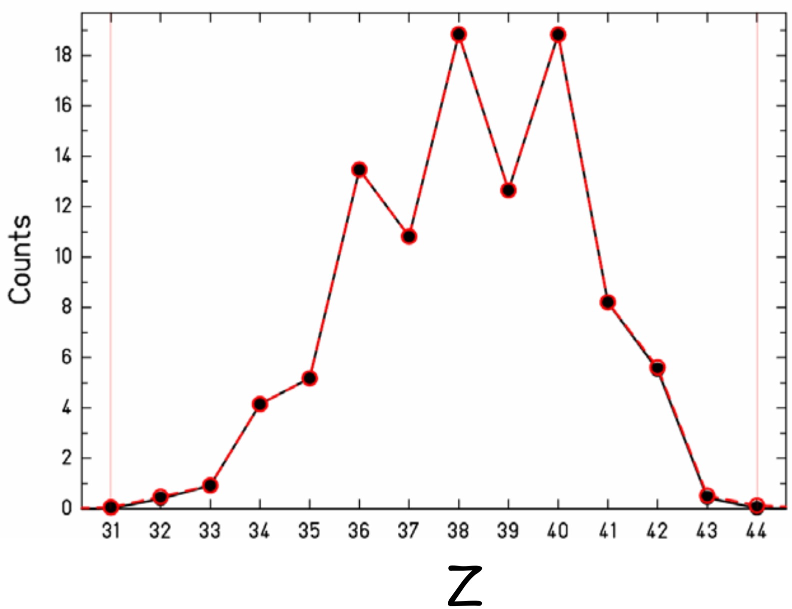
Comparison with data

n_{th} + ^{235}U (Lang et al.)

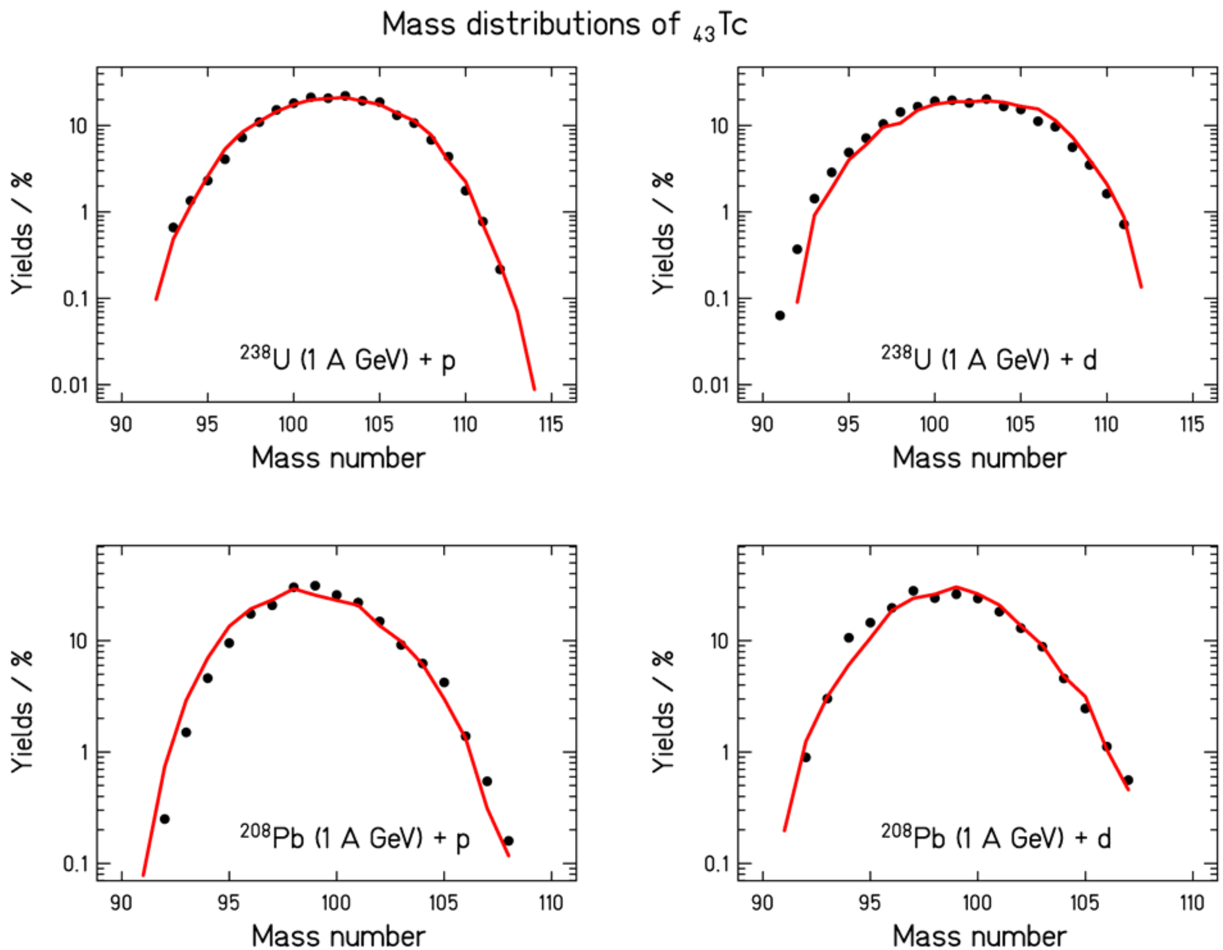
Mass distribution



Charge distribution



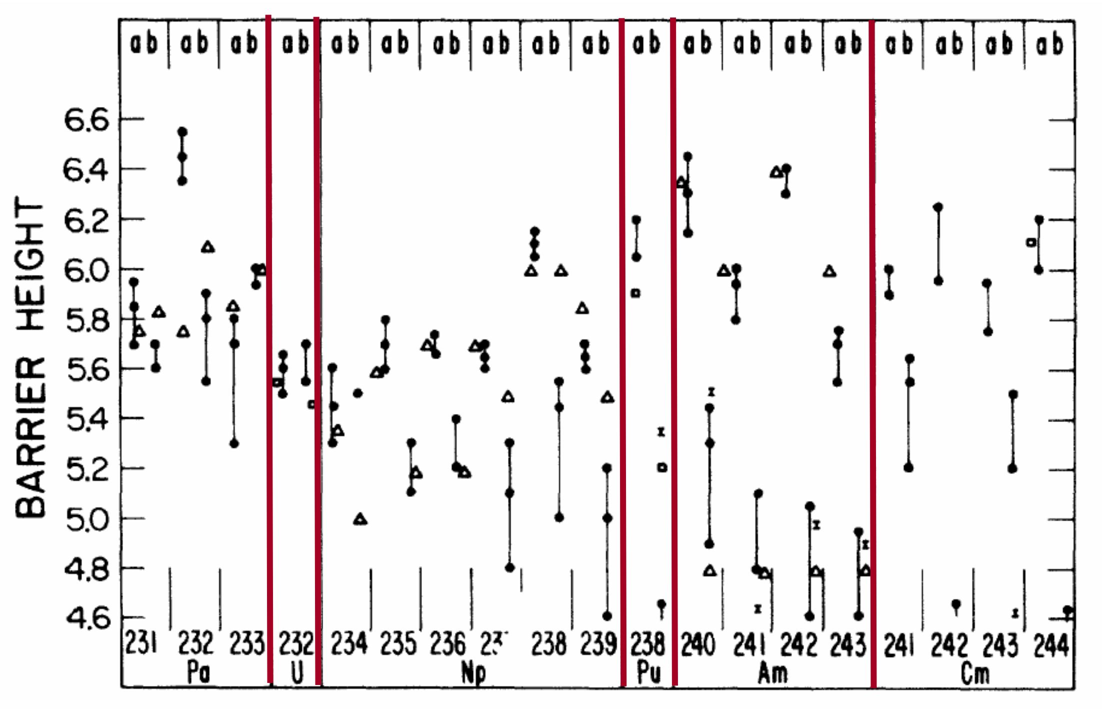
Comparison with data



Experiment - Difficulties

Extraction of barrier parameters:

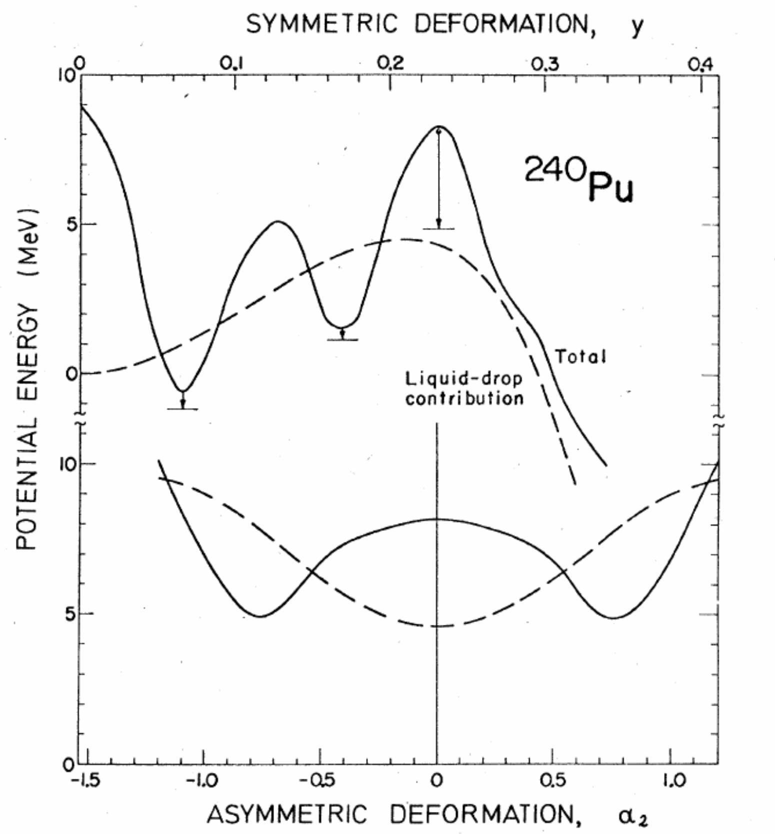
Requires assumptions on level densities.



Gavron et al., PRC13

Theoretical difficulties

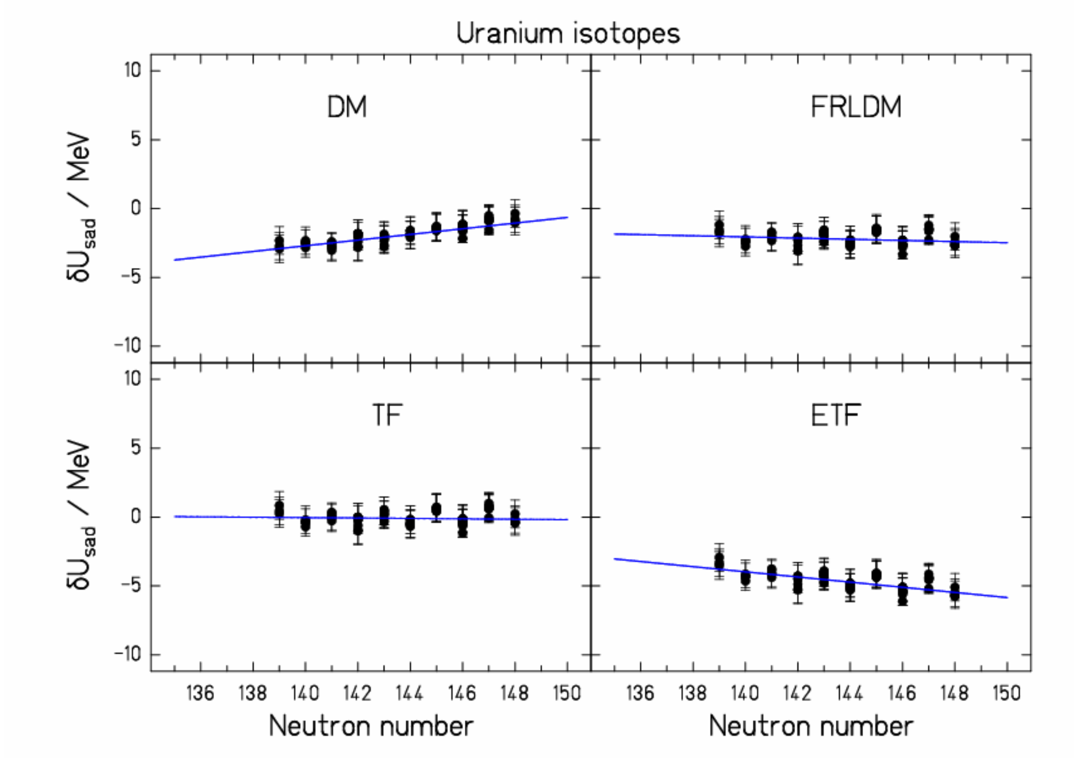
Dimensionality (Möller et al, PRL 92) and **symmetries** (Bjørnholm and Lynn, Rev. Mod. Phys. 52) of the considered deformation space are very important!



Bjørnholm and Lynn, Rev. Mod. Phys. 52

Example for uranium

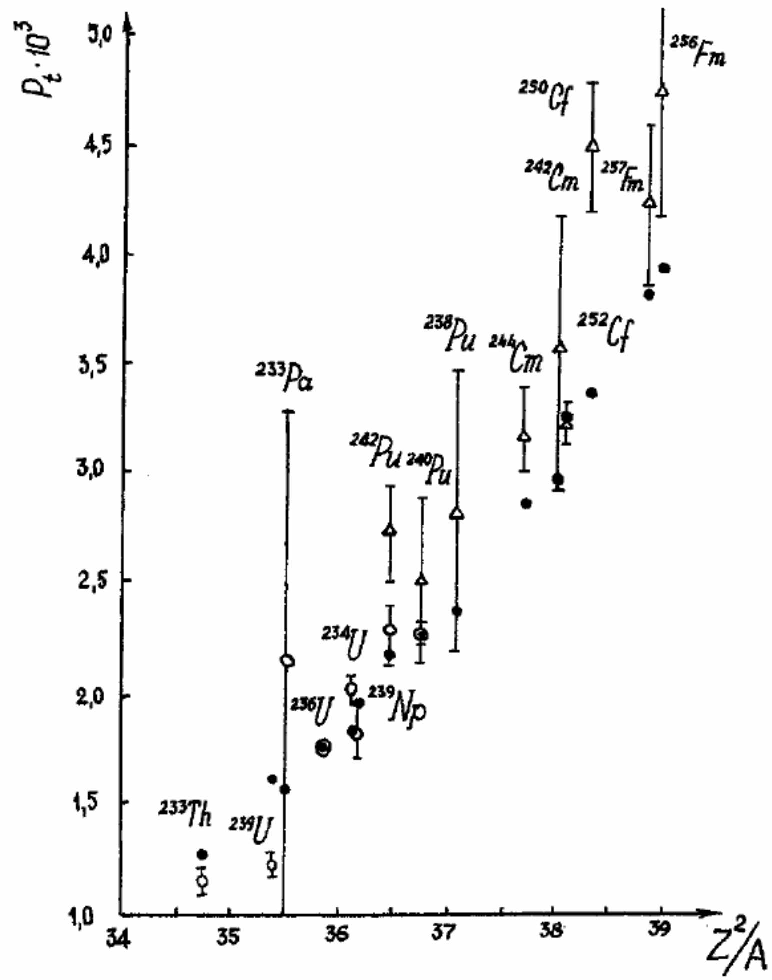
δU_{sad} as a function of a neutron number



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.