New Results on Nuclear Fission
-
Data and Interpretation

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http://www.gsi.de/charms/

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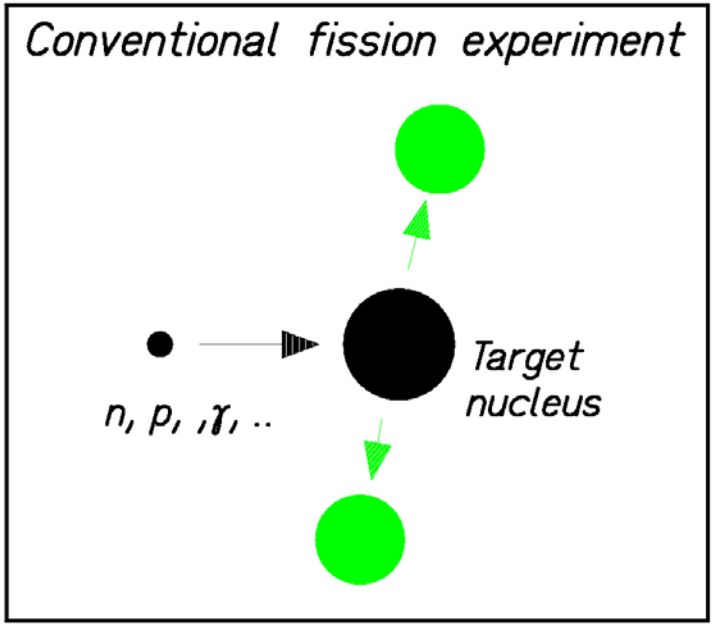
Overview

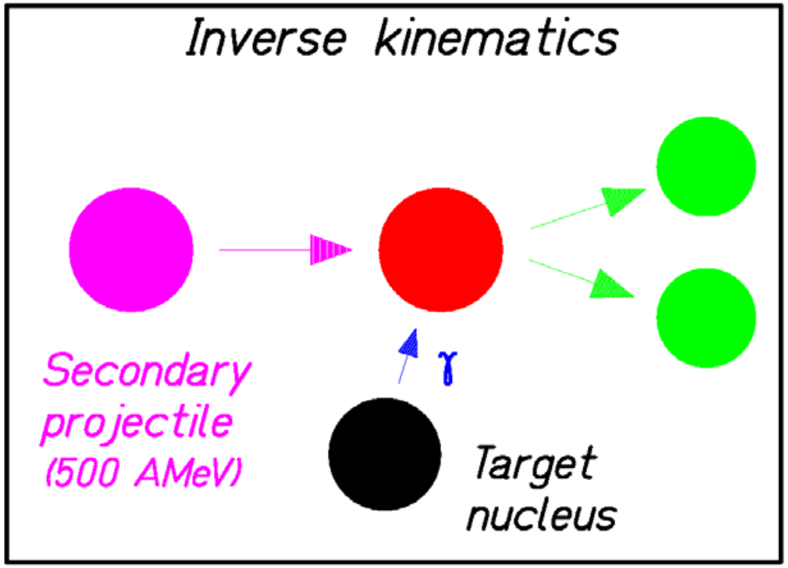
- **Experiments**
  - Inverse-kinematics approach
  - Results
- **Interpretation**
  - Semi-empirical approach to multimodal fission
  - The nuclear-reaction code ABRABLA07

Experiments

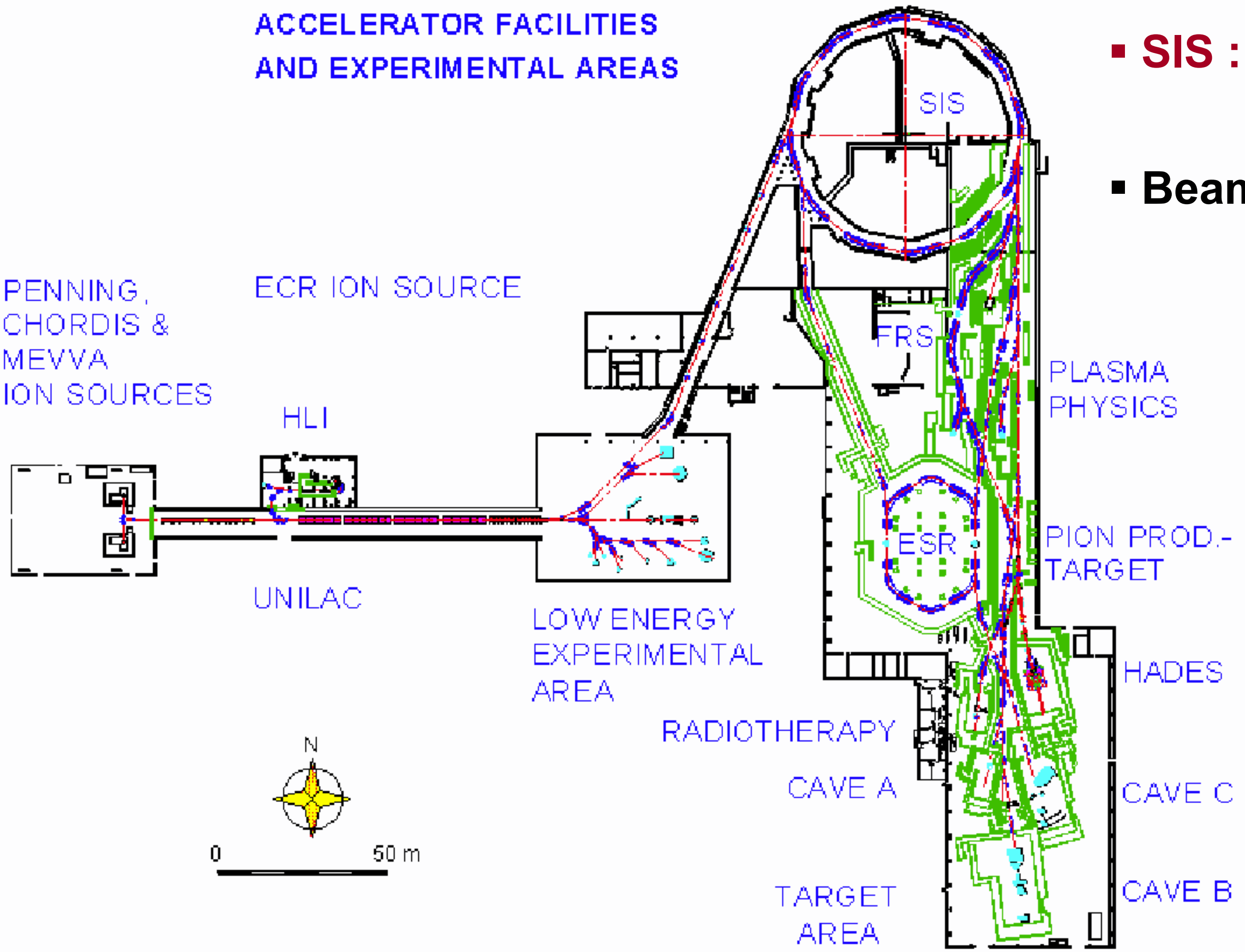
<u>Our approach → inverse kinematics</u>:

Investigating fission of projectiles instead of target nuclei.



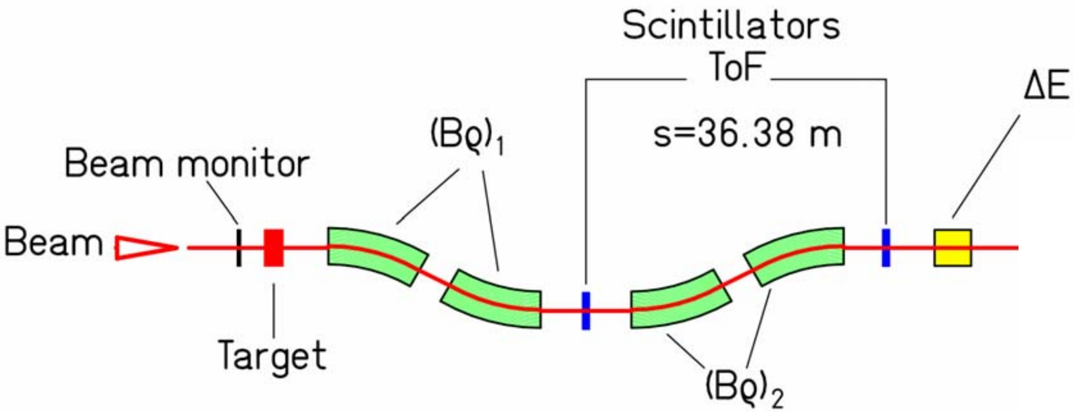


Heavy-ion beams from GSI accelerator facility

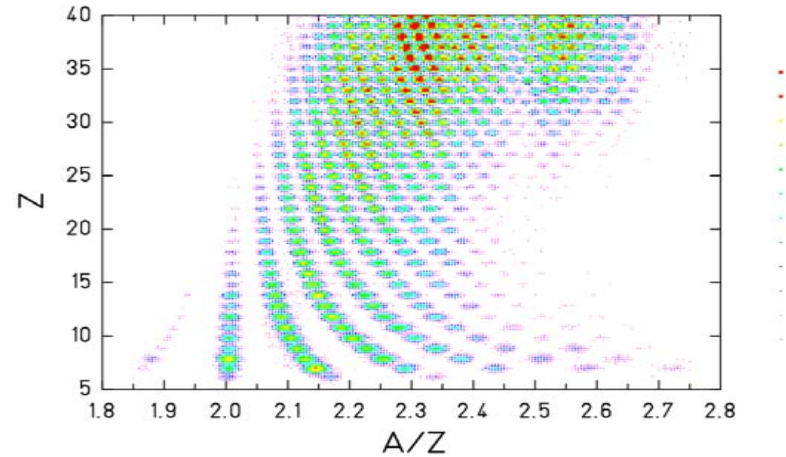


- **UNILAC : Up to 20 *A* MeV**
- **SIS : 50 – 2000 *A* MeV, up to 10^{11} particles/spill**
- **Beams of all stable nuclides up to ^{238}U**

Identification with magnetic spectrometer (FRS)



Nuclide identification
(^{238}U + p, M. V. Ricciardi)



Acceptance:

Θ^{max} = 15 mrad

$\Delta p/p$ = ± 1.5 %

Detection within 200 ns after production!

ToF ⇨ $\beta\gamma$

x_1, x_2 ⇨ $B\rho$

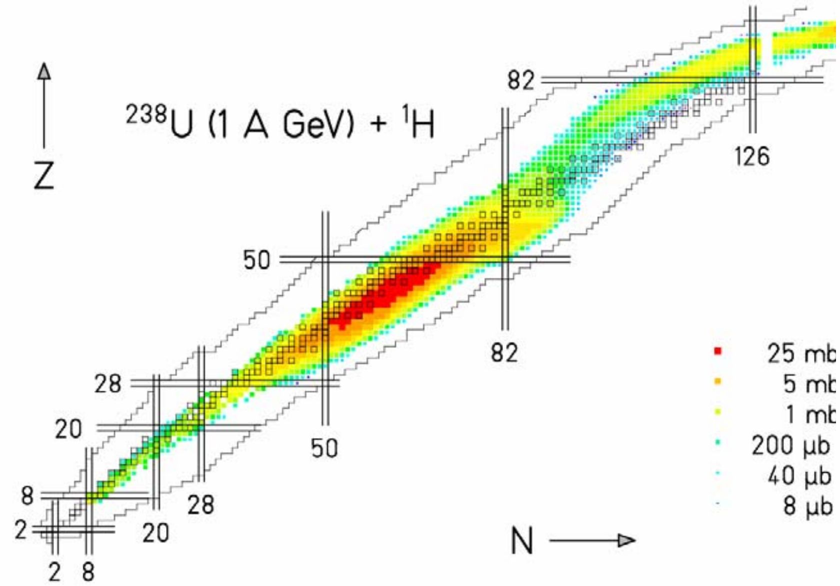
ΔE ⇨ Z

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

Resolution:

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

Nuclide production in fragmentation of ^{238}U



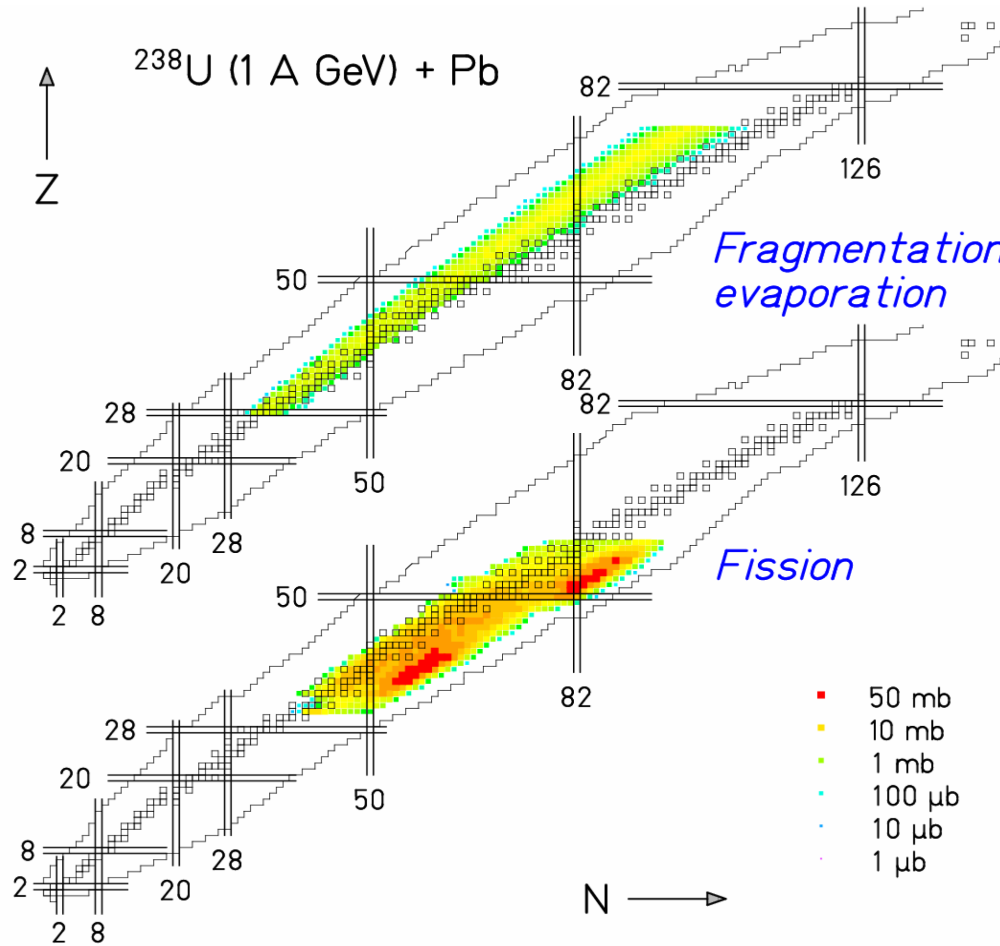
Complete coverage

J. Taieb et al., NPA 724 (2003) 413

M. Bernas et al., NPA 725 (2003) 213

M. V. Ricciardi et al., PRC 73 (2006) 014607

M. Bernas et al., NPA 765 (2006) 197



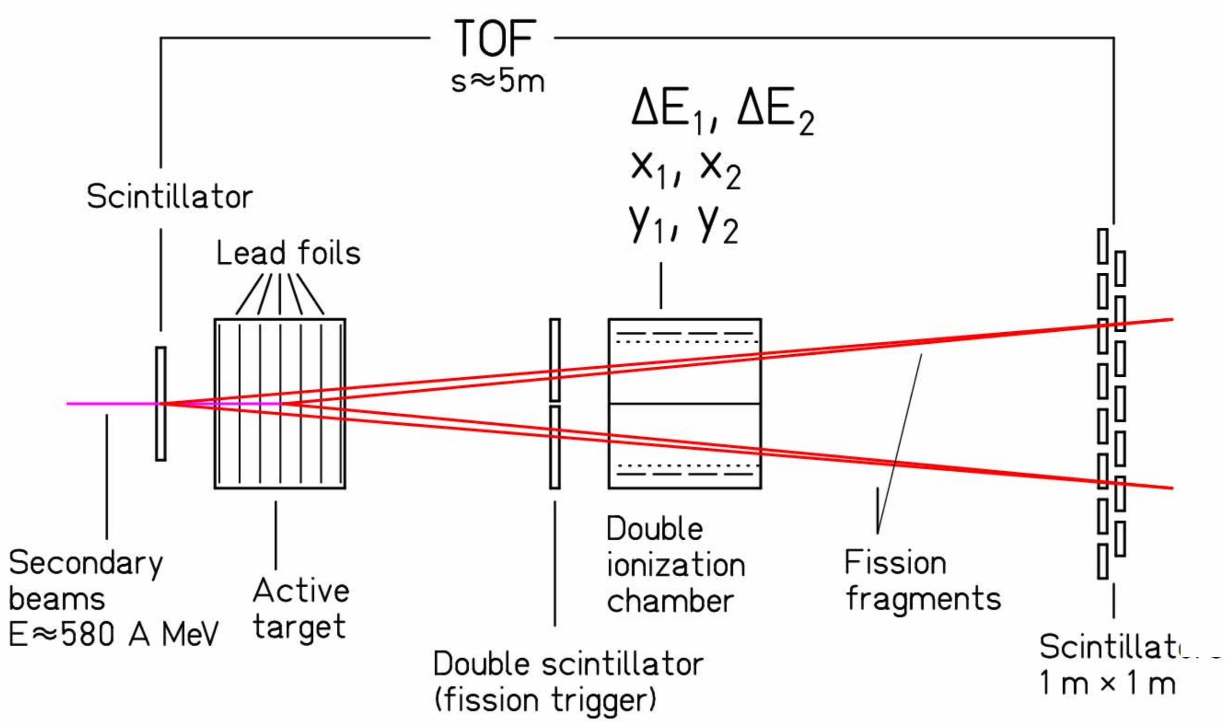
Only fission region covered

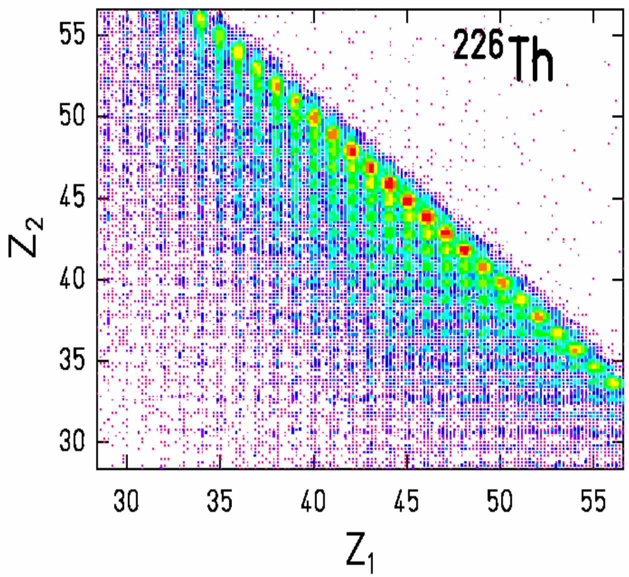
T. Enqvist et al., NPA 658 (1999) 47

Valuable information on the production of neutron-rich isotopes

Detection of both fission fragments in-flight

Set-up for fission experiments with secondary beams



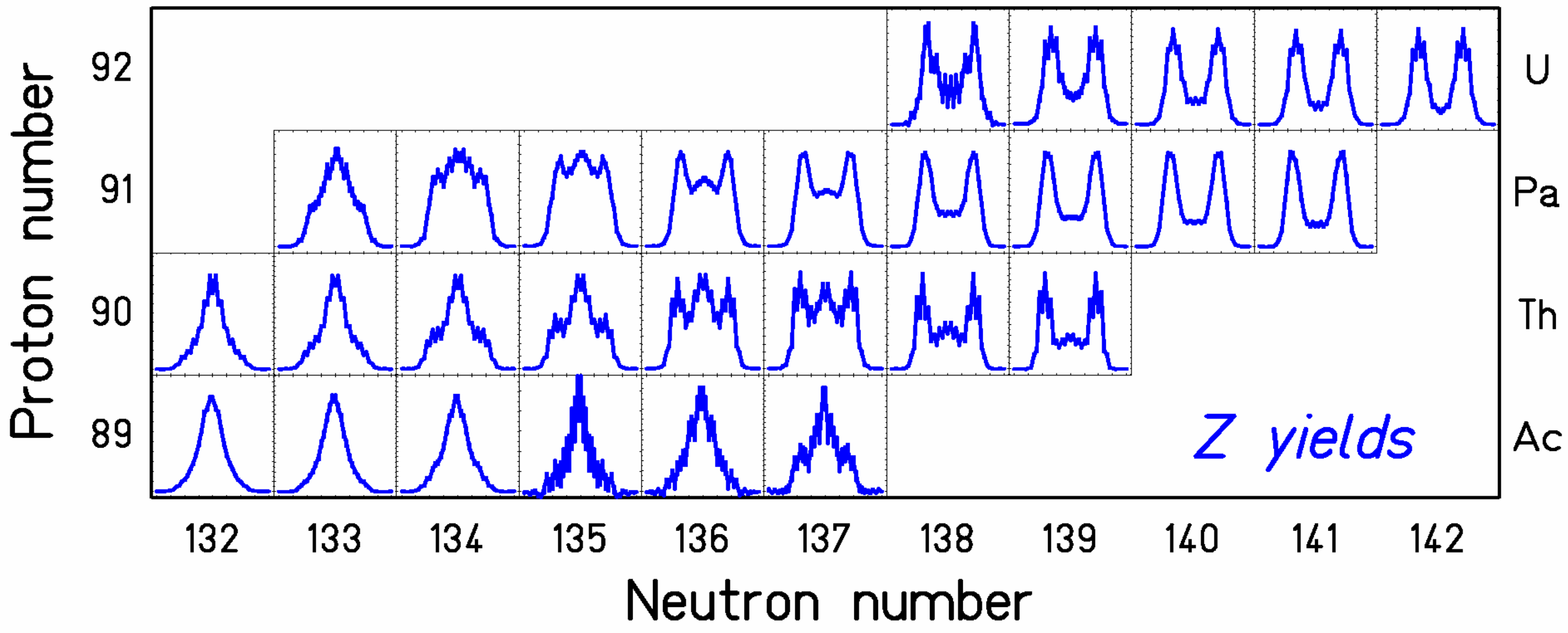


Determination of Z_1 and Z_2

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

Multi-modal fission around ^{226}Th

Experimental survey at GSI by use of secondary beams
Coulomb fission from GDR ($E^* \approx 11$ MeV)



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

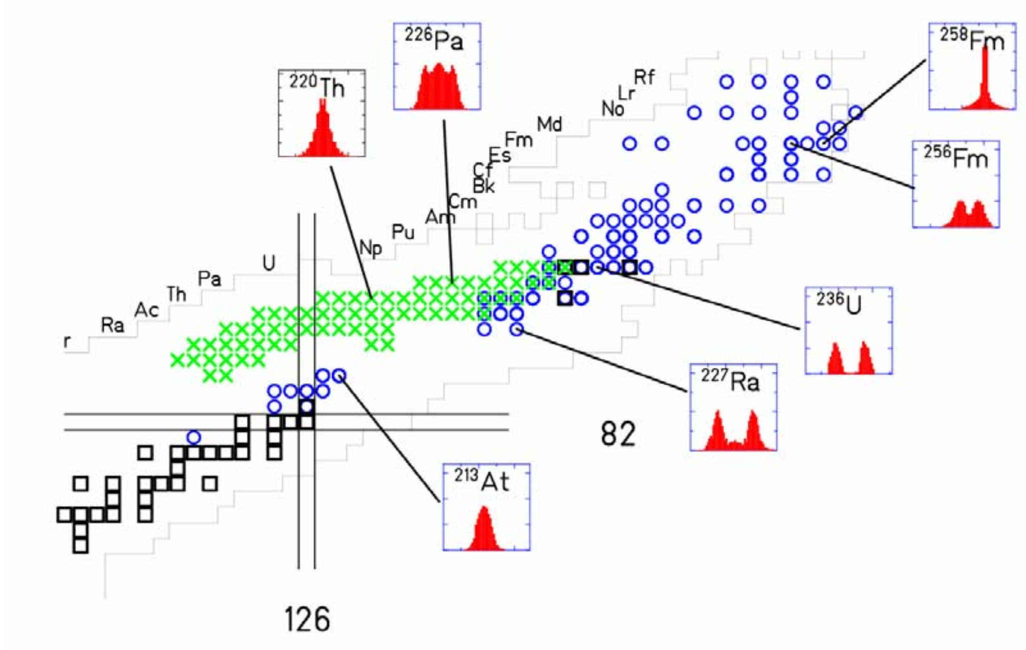
Experimental information – low-energy fission

• Particle-induced fission of long-lived targets and spontaneous fission

Available information:

- *A*(*E**) in most cases

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



• EM fission of secondary beams at GSI

Available information:

- *Z* distributions at energy of GDR ($E^* \approx 11$ MeV)

Interpretation

Statistical approach

exploiting the separation of

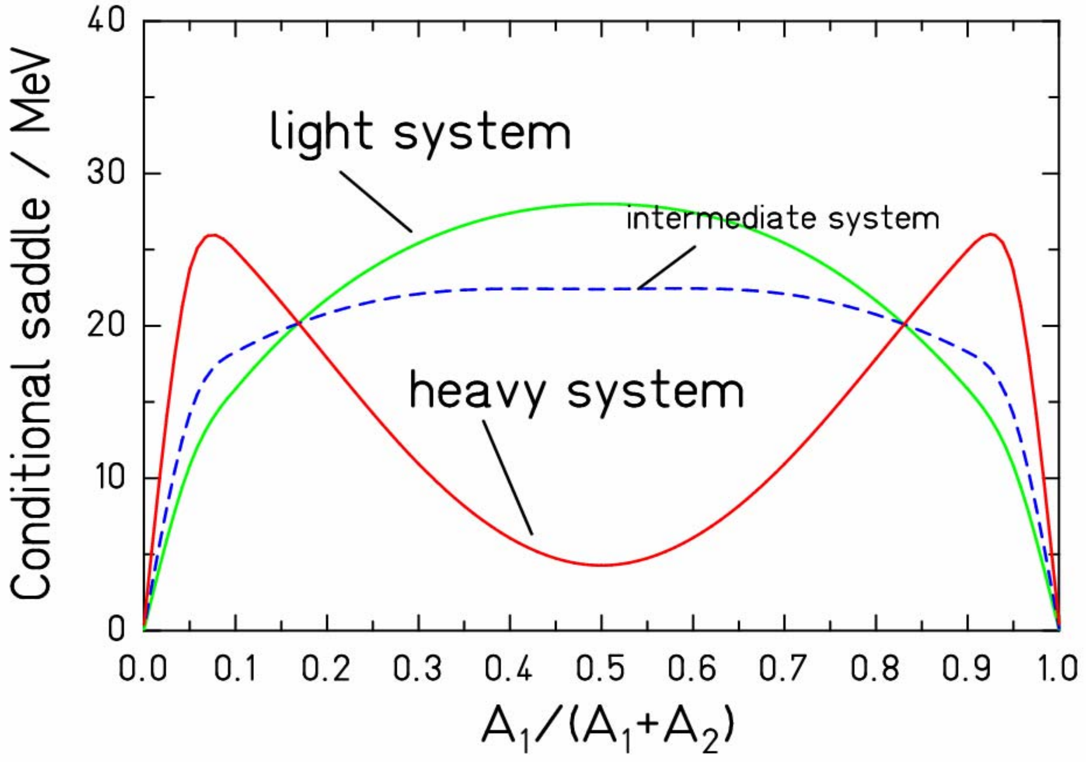
compound nucleus and fragment properties

on the fission path.

(Basic concept: Yields proportional to available states on the fission path, *somewhere between saddle and scission*. Contrast to statistical scission-point model of Wilkins et al. PRC 14 (1976) 1832).

Macroscopic features

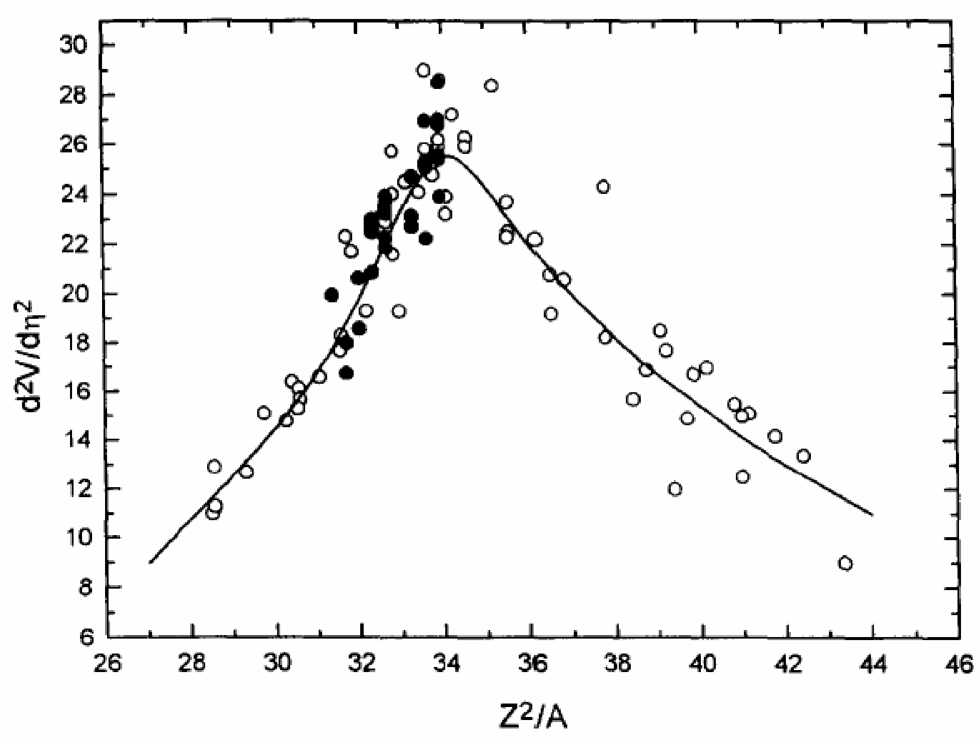
Macroscopic potential on the fission path for heavy systems is ≈ parabolic as a function of mass asymmetry (schematic).



Statistical model → Mass distribution ($Y(A) \sim e^{E^*-U}$) is Gaussian.

Macroscopic potential - experimental systematics

Experiment: In cases when shell effects can be disregarded (high E*), the fission-fragment mass distribution of heavy systems is Gaussian.



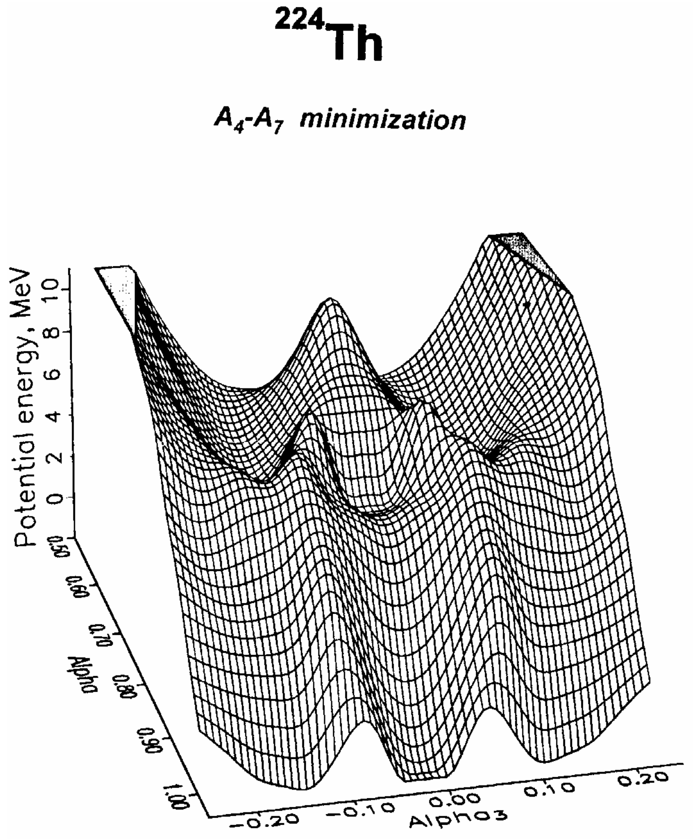
Second derivative of potential in mass asymmetry deduced from width of fission-fragment mass distributions.

$$\sigma_A^2 \sim T/(d^2V/d\eta^2)$$

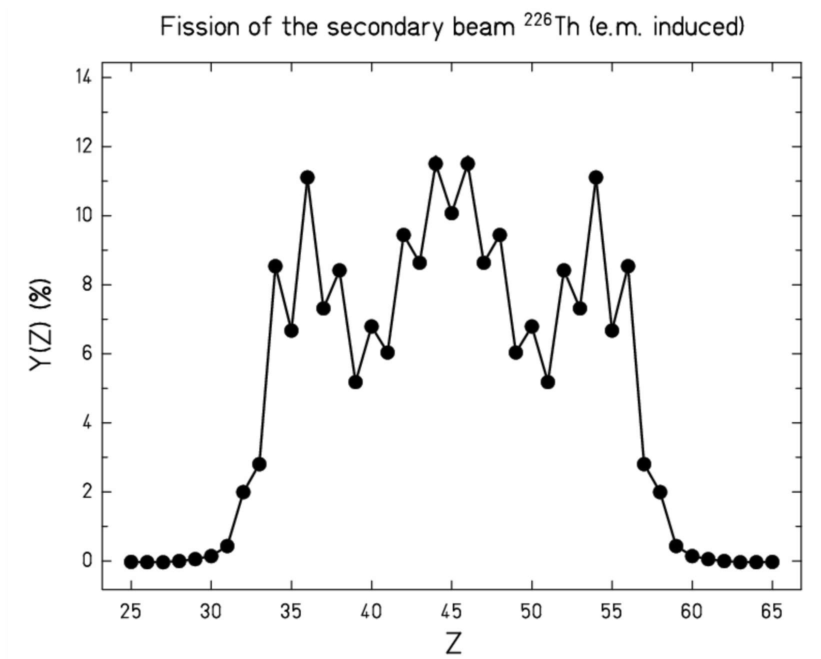
← Mulgin et al. NPA 640 (1998) 375

Width of mass distribution is empirically well established. (M. G. Itkis, A.Ya. Rusanov et al., Sov. J. Part. Nucl. 19 (1988) 301 and Phys. At. Nucl. 60 (1997) 773)

Microscopic features



Potential-energy landscape (Pashkevich)



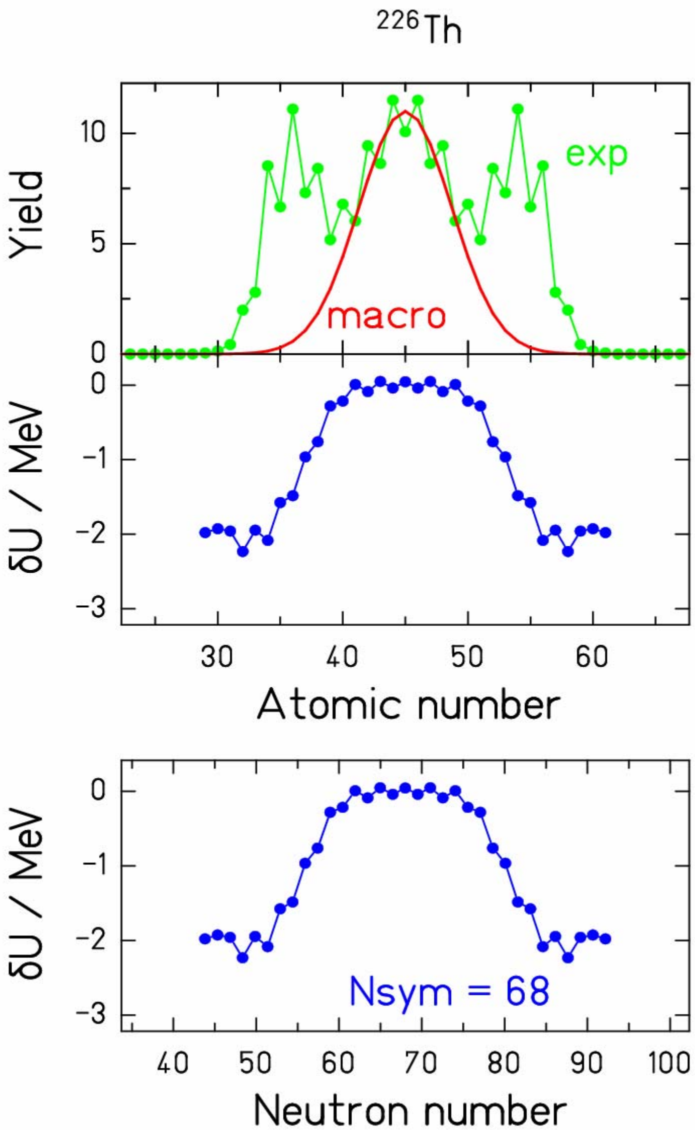
Measured element yields

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

Extension of the statistical model to multimodal fission:

Yields of fission channels ~ number of states in the fission valleys

Microscopic potential of ^{226}Th deduced from Z distribution



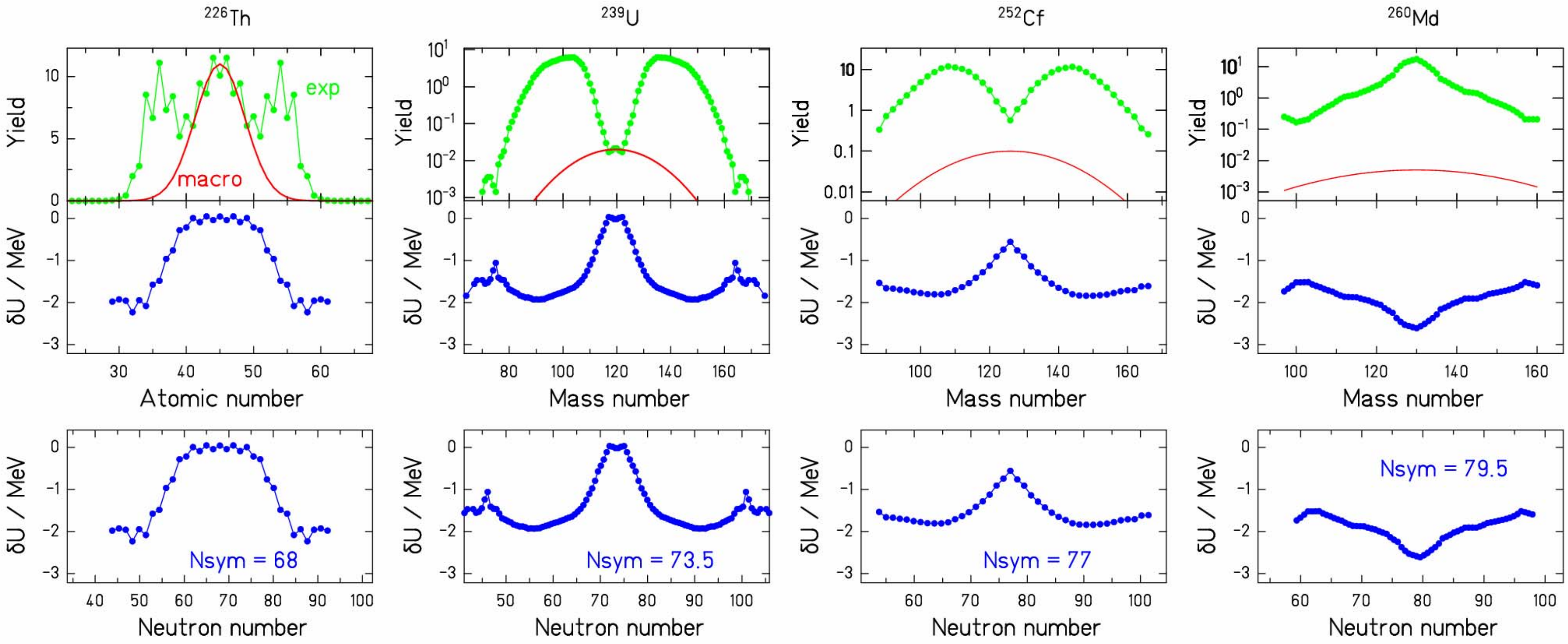
Input:
- experimental yields and
- „macroscopic“ yields

$$\frac{Y_{\mathrm{exp}}}{Y_{\mathrm{macro}}} = \exp\left(-\frac{\delta U}{T_{eff}}\right)$$

Result:
- Shell-correction energy *δU*

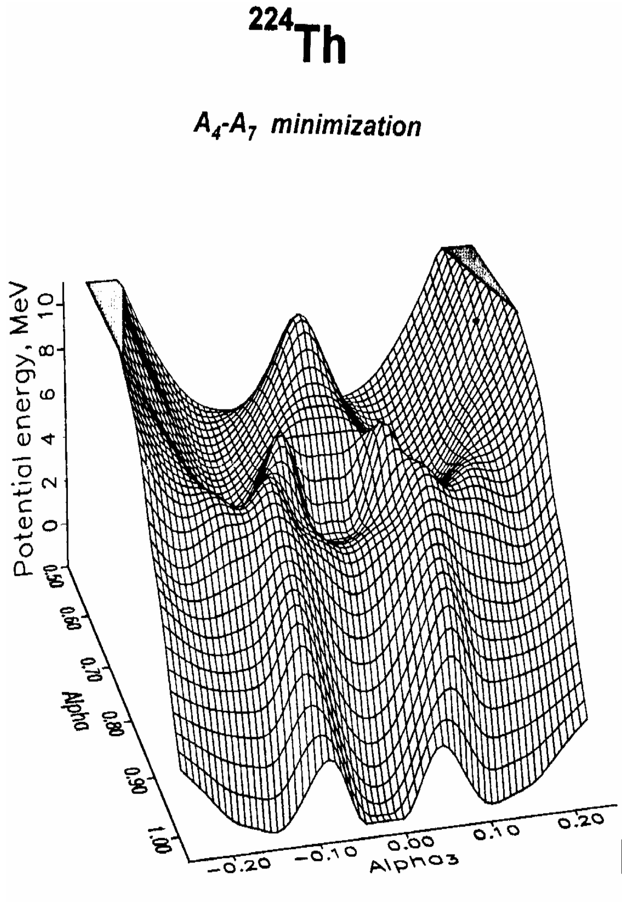
Idea introduced by Itkis et al., Sov. J. Nucl. Phys. 43 (1986) 719

Microscopic potential of other systems



Shape of microscopic potential varies drastically.

Preformation hypothesis



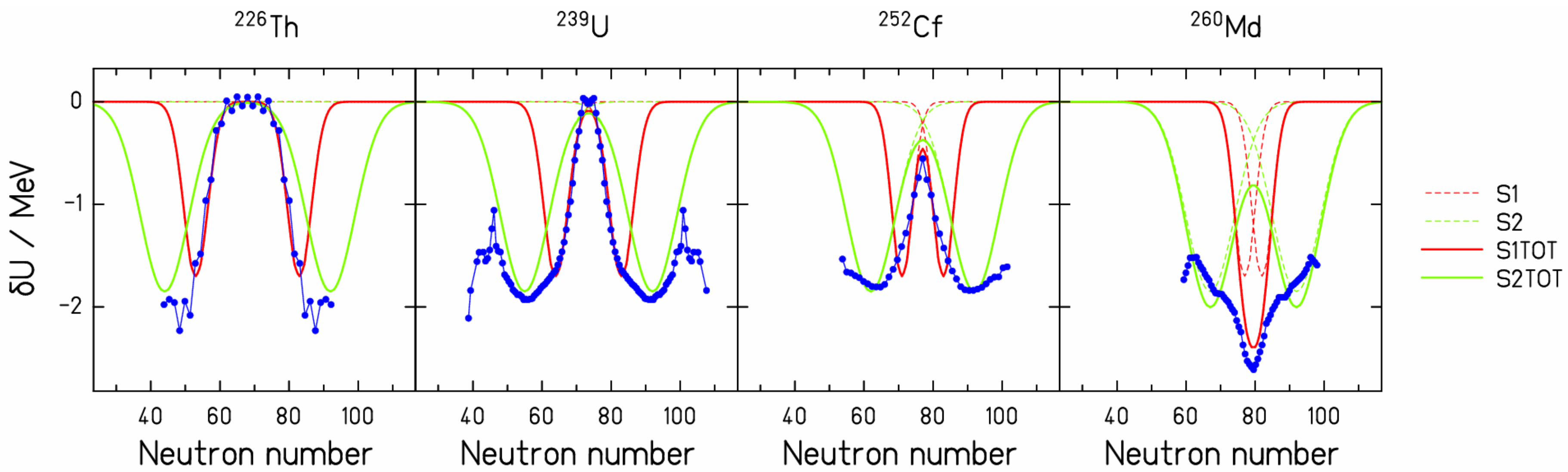
U. Mosel and H. W. Schmitt, NPA 165 (1971) 73:

"By analyzing the single-particle states along the fission path .. we have established the fact that the influence of fragment shells reaches far into the PES. The preformation of the fragments is almost completed already at a point where the nuclear shape is necked in only to 40 %."

Potential-energy surface of ^{224}Th calculated by Pashkevich.

Conclusion:
Shells on the fission path are a function of *N* and *Z* of the fragments!

Test case: fission channels from ^{226}Th to ^{260}Md

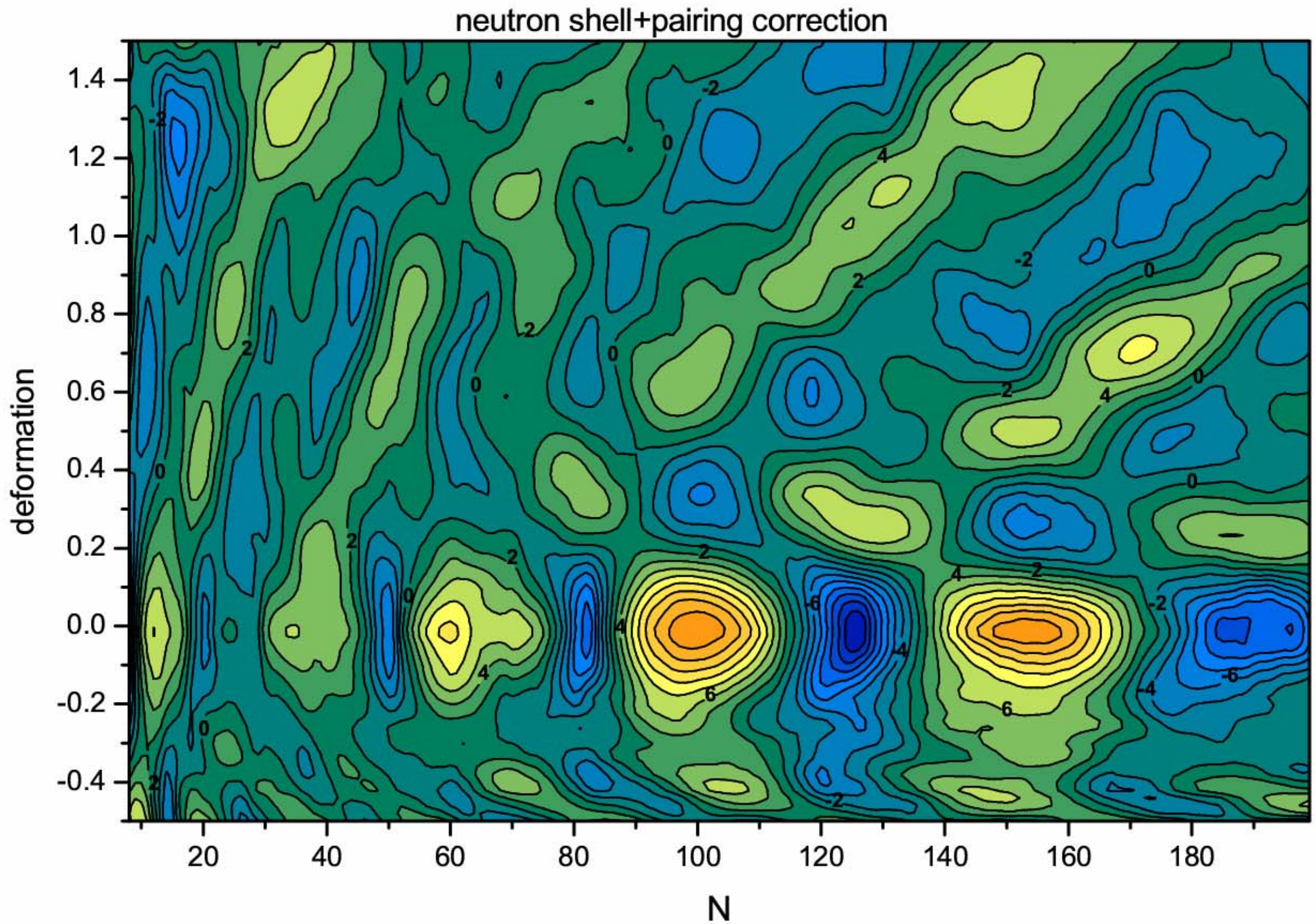


Simplified illustration:

Schematic decomposition of microscopic structure by N = 82 (Standard 1) and N ≈ 92 (Standard 2) shells, only. (Same shell parameters for all cases.)

Global features of microscopic structure are reproduced.

Shells of fragments

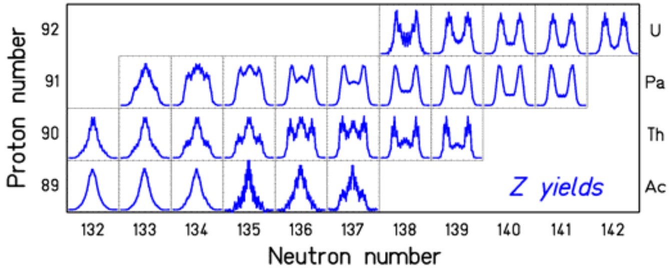


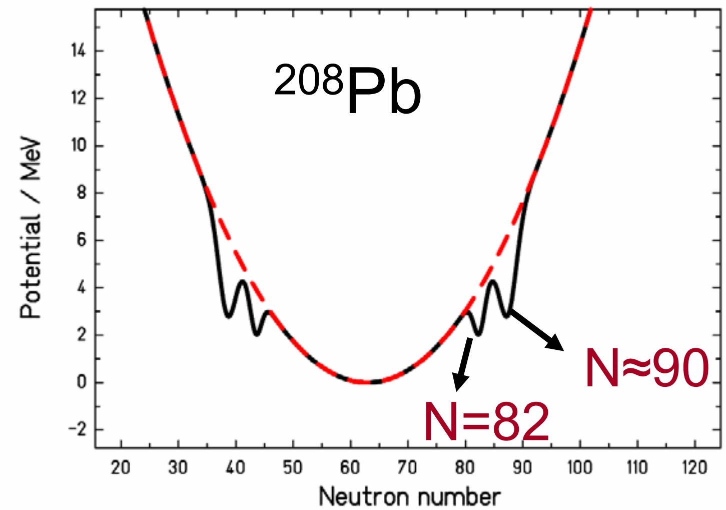
Two-centre shell-model calculation by A. Karpov, 2007 (private communication)

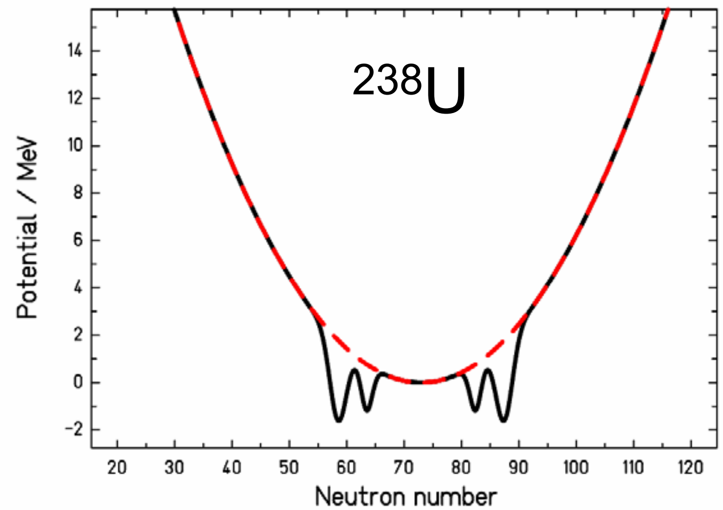
Test case: multi-modal fission around ^{226}Th

- 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*
(deduced from data)

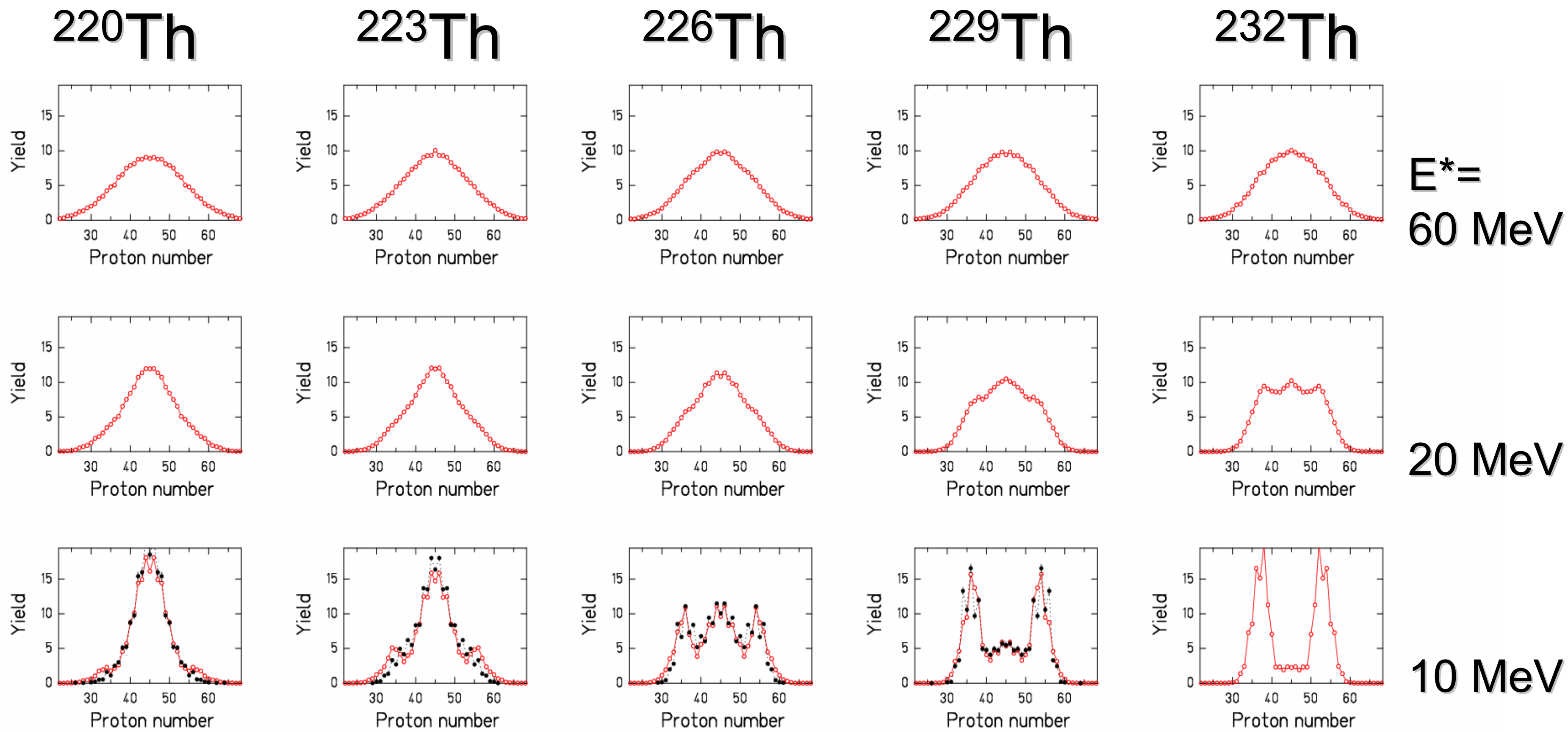






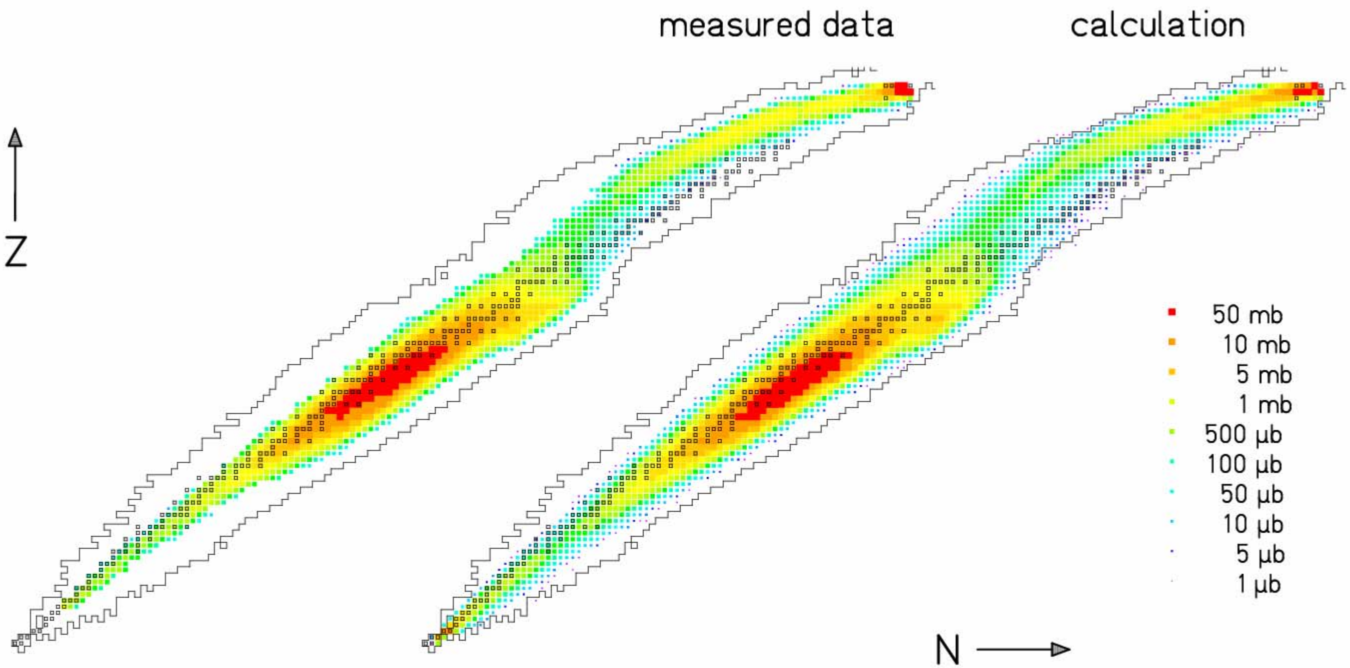
* Maruhn and Greiner, Z. Phys. 251 (1972) 431, PRL 32 (1974) 548; Pashkevich, NPA 477 (1988) 1;

Multimodal fission around ^{226}Th



Black: experimental data (GSI experiment)
Red: model calculations (N=82, Z=50, N=92 shells)

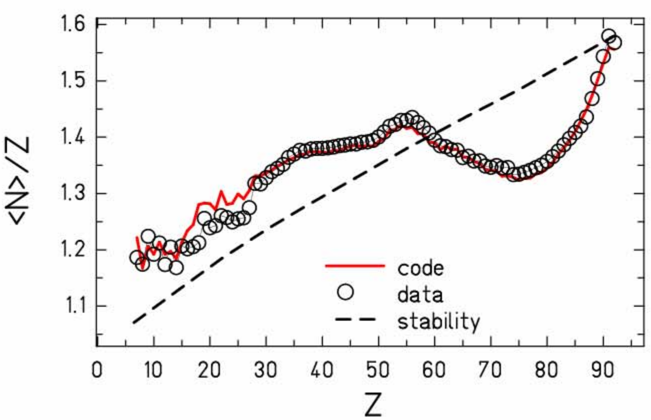
Comparison with ^{238}U (1 A GeV) + ^{1}H

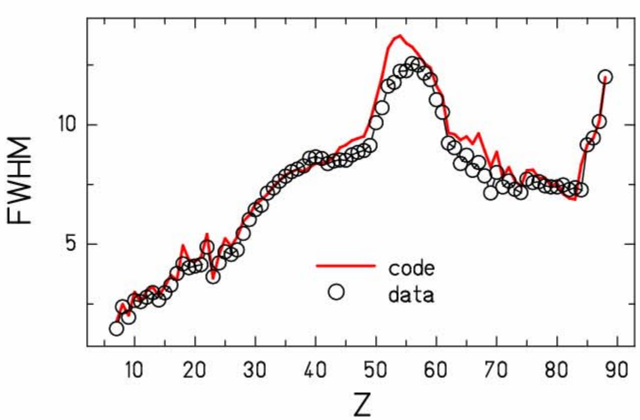


Full calculation with ABRABLA07 code (description of fission included)

Comparison of nuclide yields and moments.

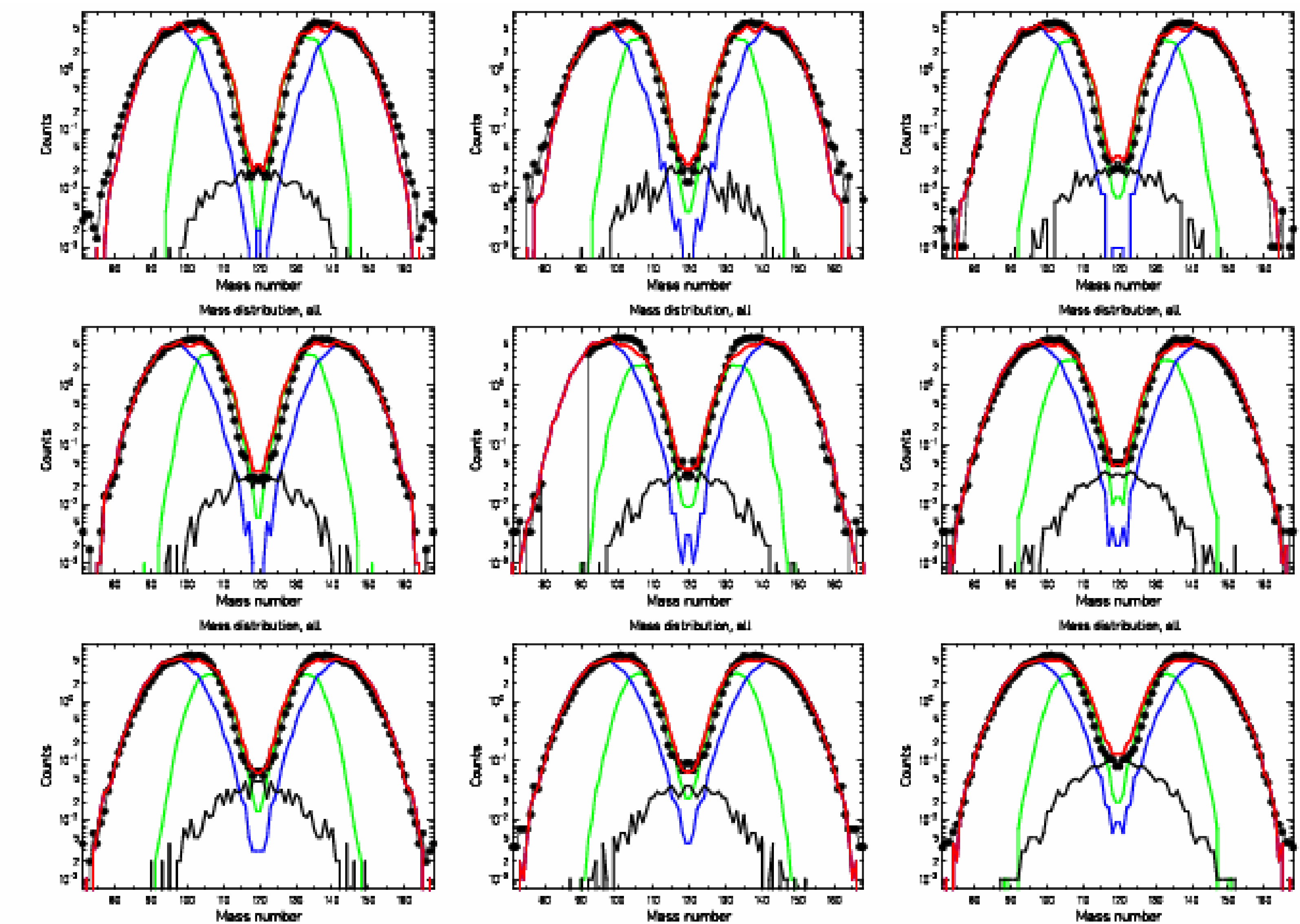
(M. V. Ricciardi et al., PRC 73 (2006) 014607)





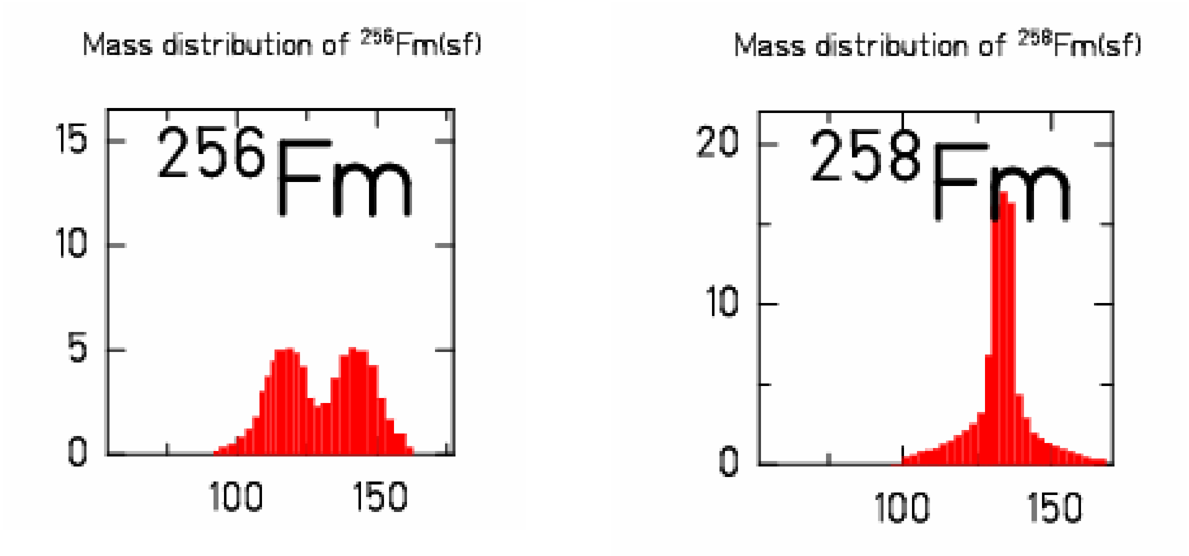
ABRABLA07: Monte-Carlo code, abrasion, multifragm. continuous emission of n, LCP, IMF, fission (transients, N_f,Z_f,TKE, evaporation pre, post)

Neutron-induced fission of ^{238}U for E_n = 1.2 to 5.8 MeV

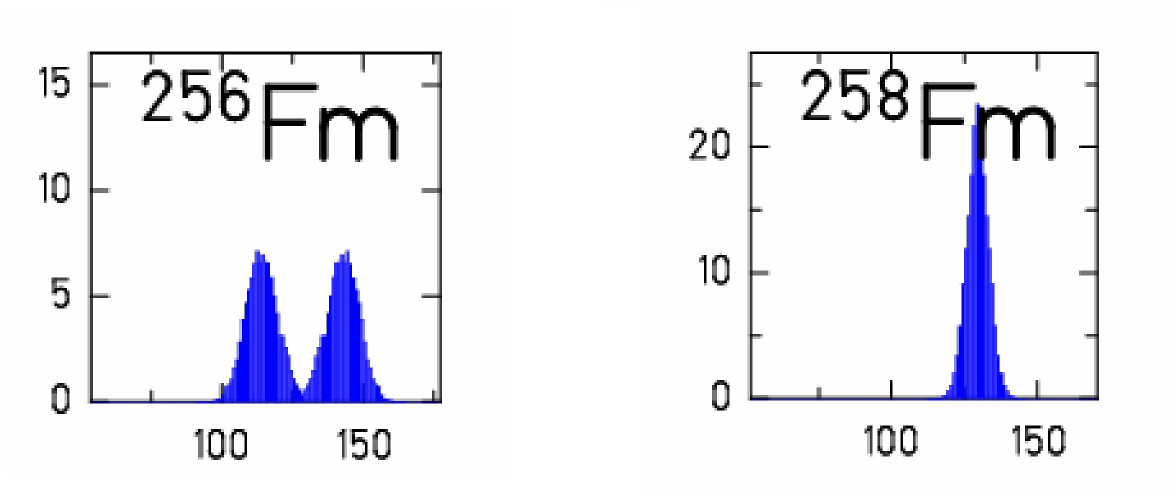


Data - F. Vives et al, Nucl. Phys. A662 (2000) 63; Lines – ABRABLA07 calculations

Comparison with data - spontaneous fission



Experiment



ABRABLA Calculations

(experimental resolution not included)

Conclusions

EXPERIMENT

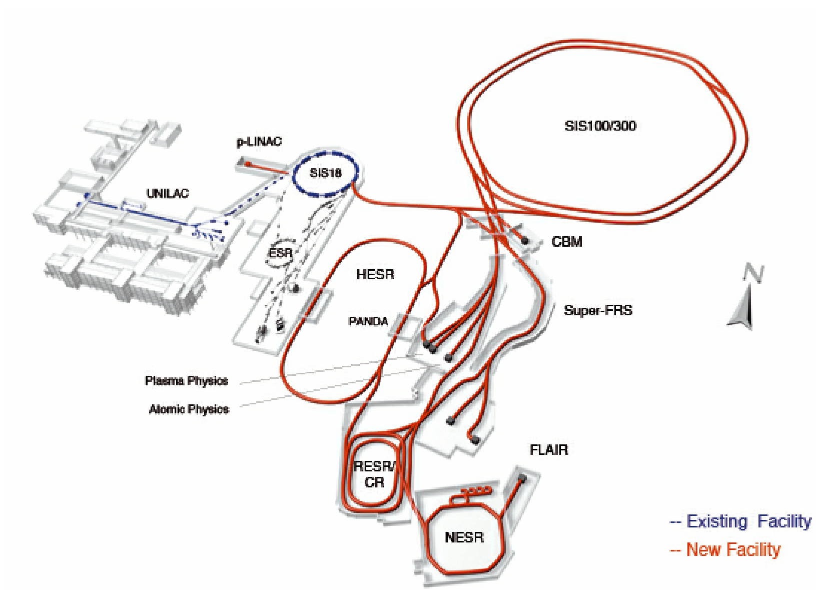
- Inverse kinematics opened a new door for studying nuclear fission
  - Detection of all residues prior to radioactive decay
  - Full identification in Z and A of all residues
  - Applicable to short-lived projectiles (secondary beams)

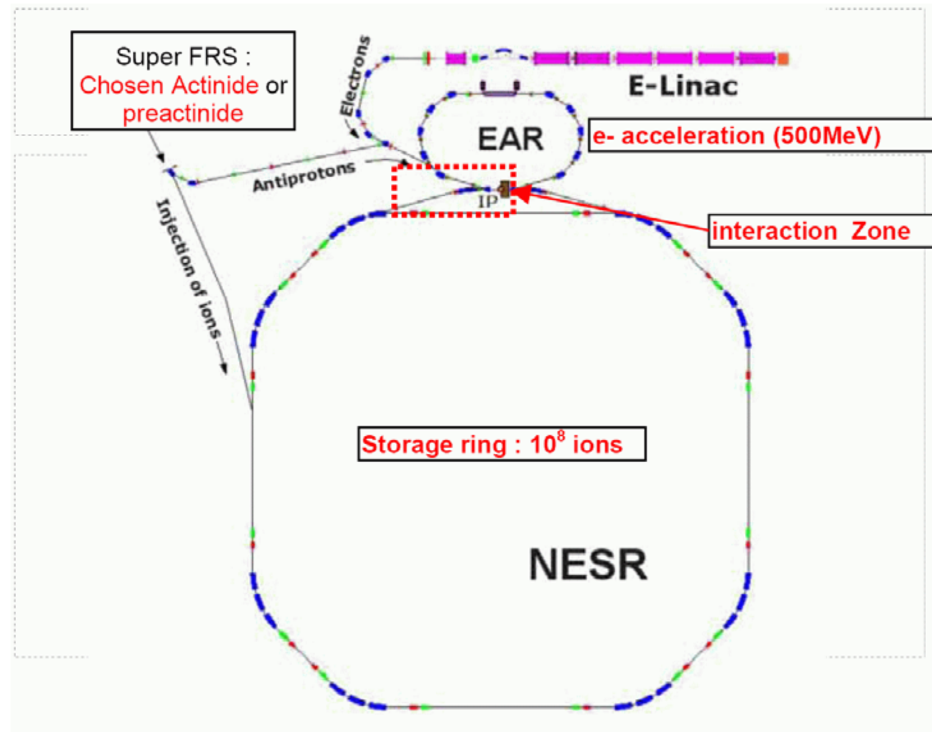
INTERPRETATION

- Power of the macro-microscopic approach in fission
  - Separation of macroscopic properties -> CN
    and microscopic properties -> fragment shells

- Development of a Monte-Carlo code for mass and charge division in fission (part of the ABRABLA07 abrasion-ablation code)
  - Statistical macroscopic-microscopic approach
    with schematic dynamical features and empirical potential.
  - Reproduces data on multimodal fission and
    allows for robust extrapolations (e.g. for astrophysics).

Future





Electron-ion collider ELISE of FAIR project of GSI, Darmstadt.

(Rare-isotope beams + tagged photons)

Aim: Precise fission data over large N/Z range.