Striking observations in low-energy fission and what they tell us

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Program INT 13-3
Quantitative Large Amplitude Shape Dynamics: fission and heavy-ion fusion
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by the ERINDA (http://www.erinda.org/) projects of the European Union.

Traditional knowledge

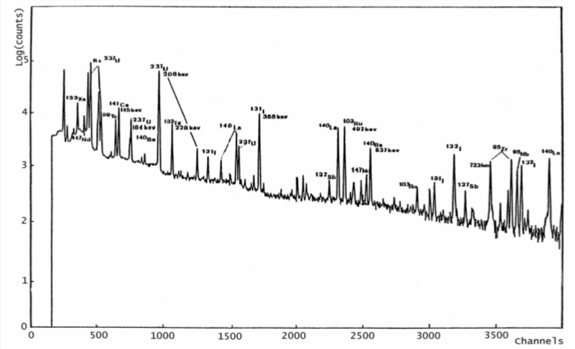
Recent experimental progress

Specific results and interpretation

Conclusion and outlook

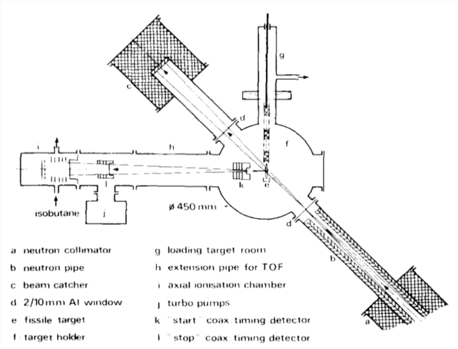
Conventional experimental techniques

Off-line gamma spectroscopy



No short-lived fragments,
uncertainties from spectroscopic data.

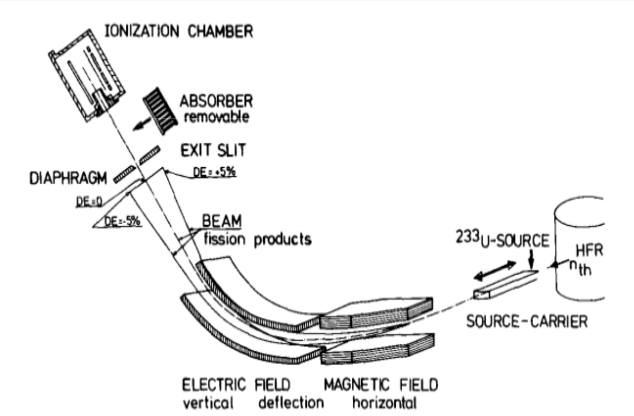
Double ToF – double Energy



Cosi
Fan
Tutte

Pre- and post-neutron masses,
limited resolution.

Spectrograph LOHENGRIN



A of all fragments,
Z of light fragments
for thermal-neutron-induced fission.

Position of the heavy fragment

229Th

233U

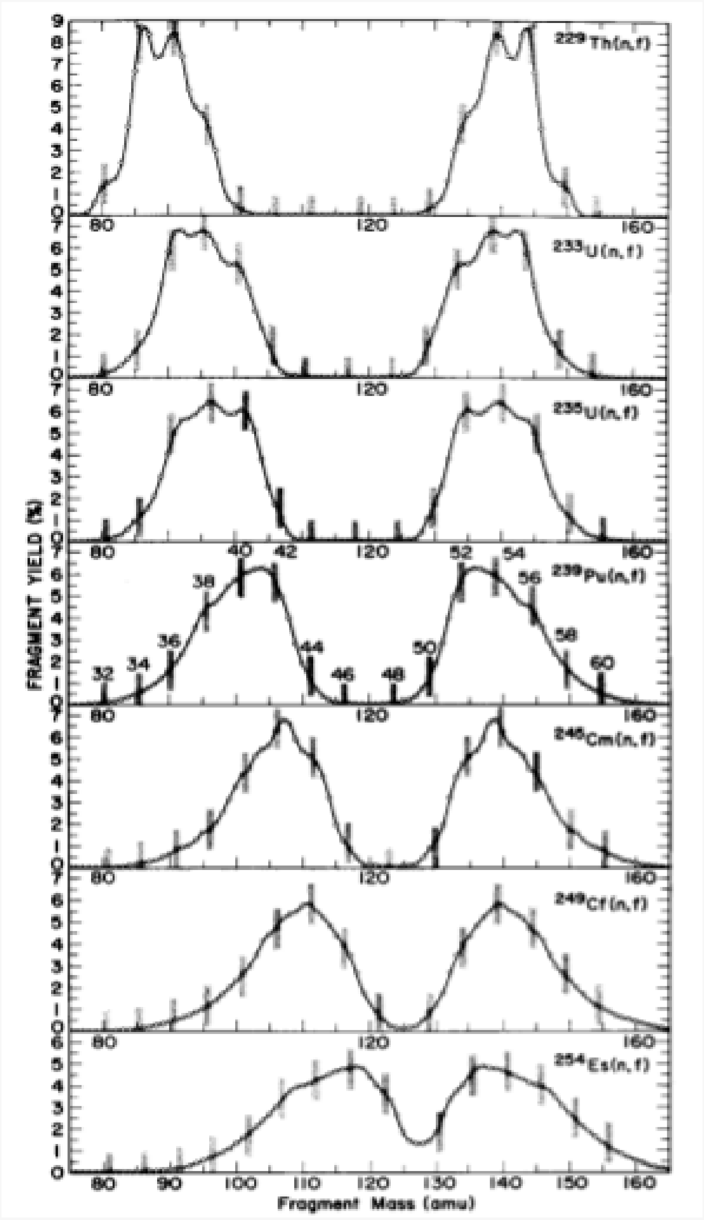
235U

239Pu

245Cm

249Cf

254Es

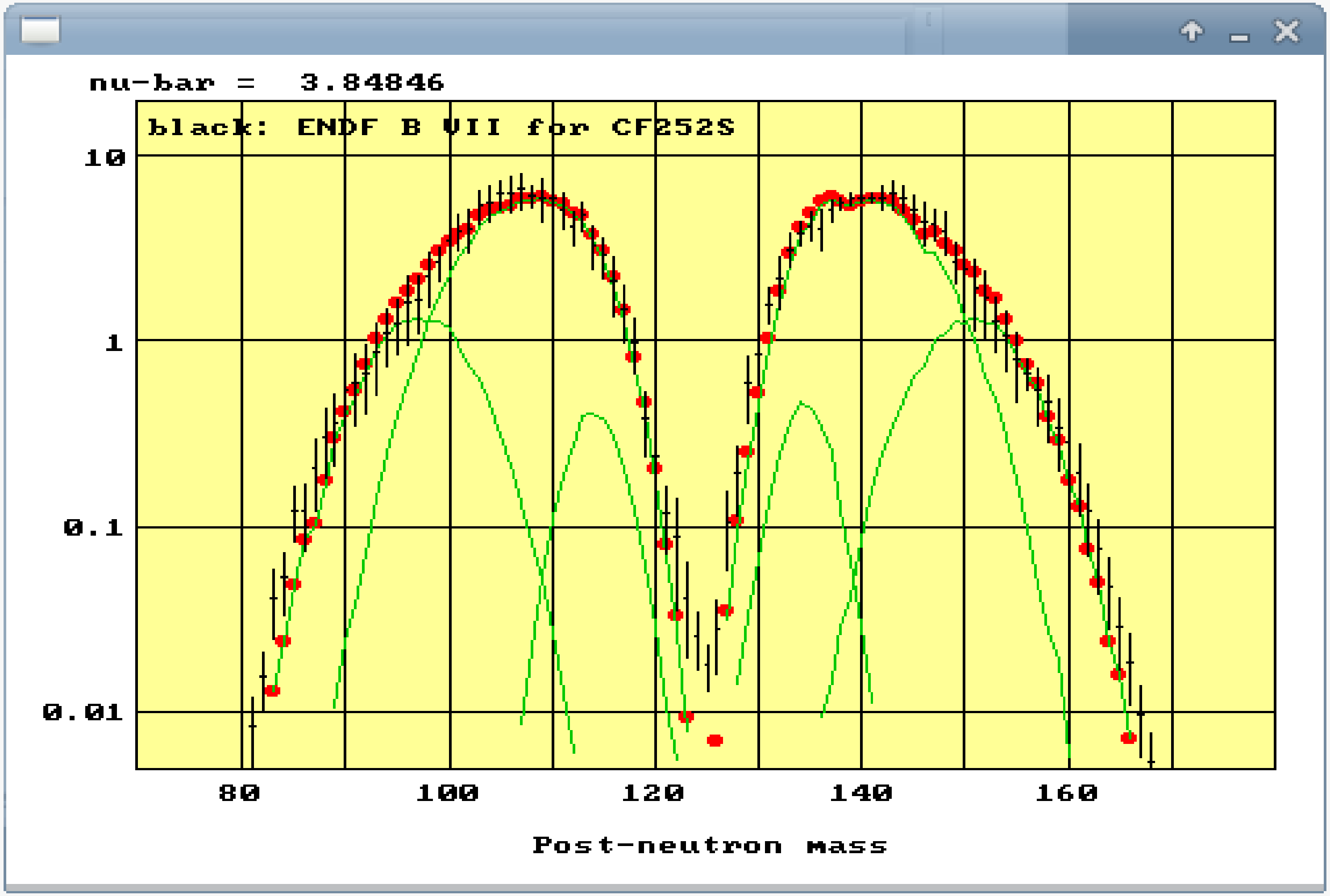


Unik et al., 1973

Fission-fragment mass distribution from Z=90 to Z=99.

The position of the heavy fragment is constant at A ≈ 140.

Fission modes



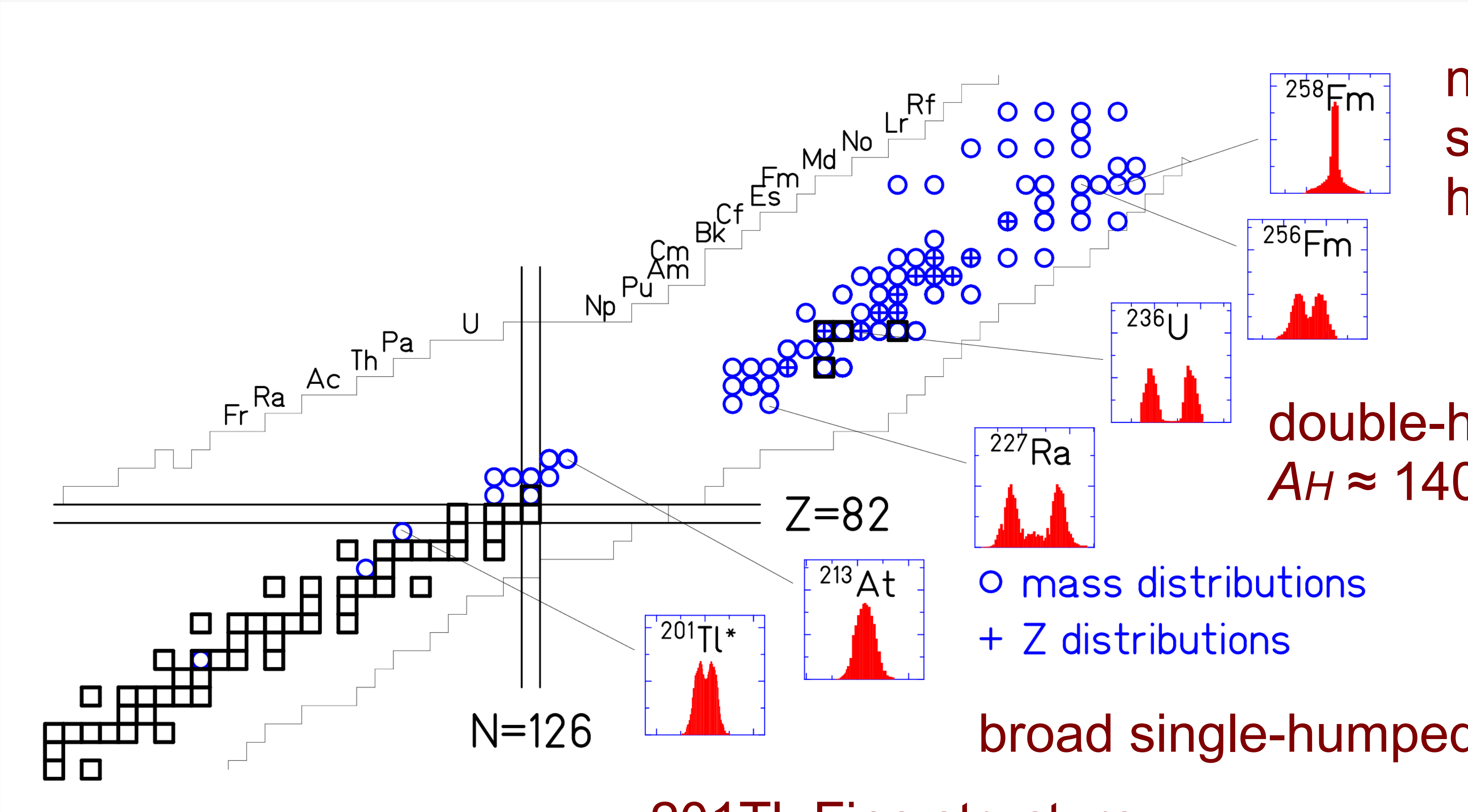
Mass distribution of

252Cf(s,f)

Fission-fragment distributions (A or A-TKE) can be described as the sum of fission modes, associated to valleys in the potential-energy surface.

GEF calculation (www.khs-erzhausen.de).

Global results of conventional experiments



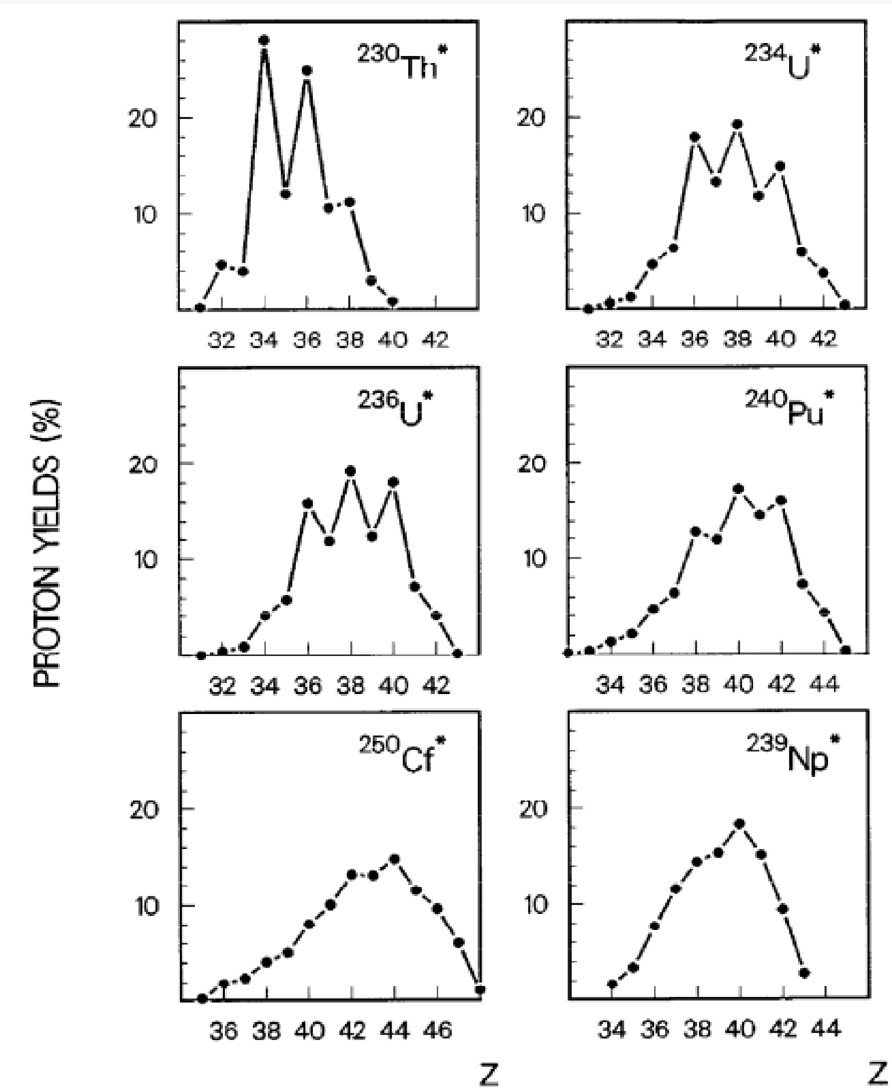
narrow single-humped

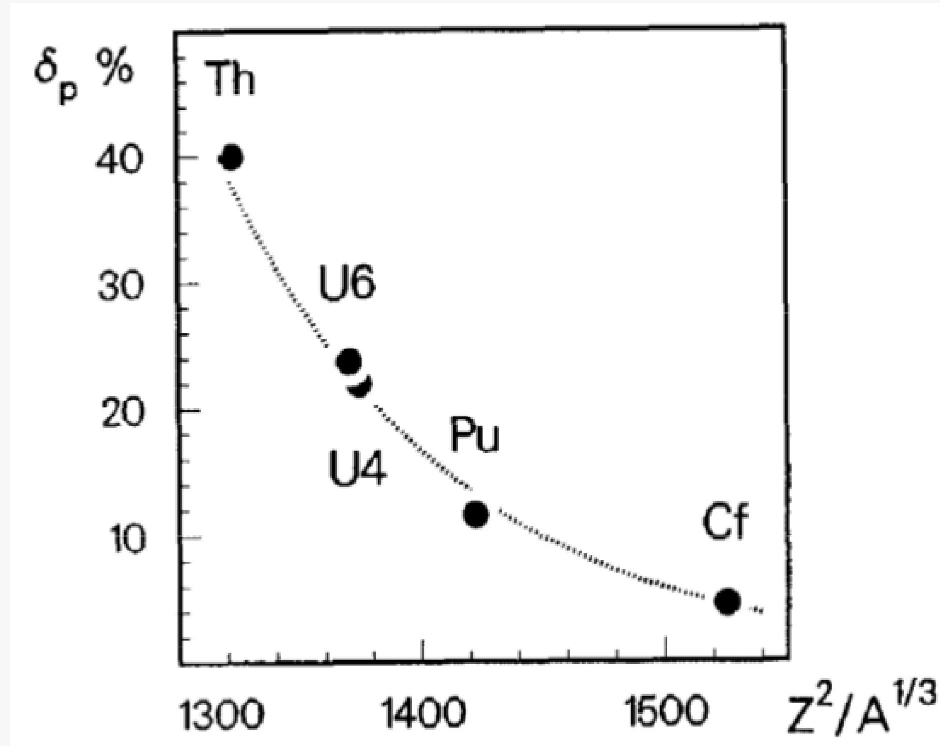
double-humped
$A_H \approx 140$

broad single-humped

201Tl: Fine structure
even at
E* = 7 MeV
above Bf! (Itkis et al., 1985-1991)

Global even-odd effect in fission-fragment Z distributions

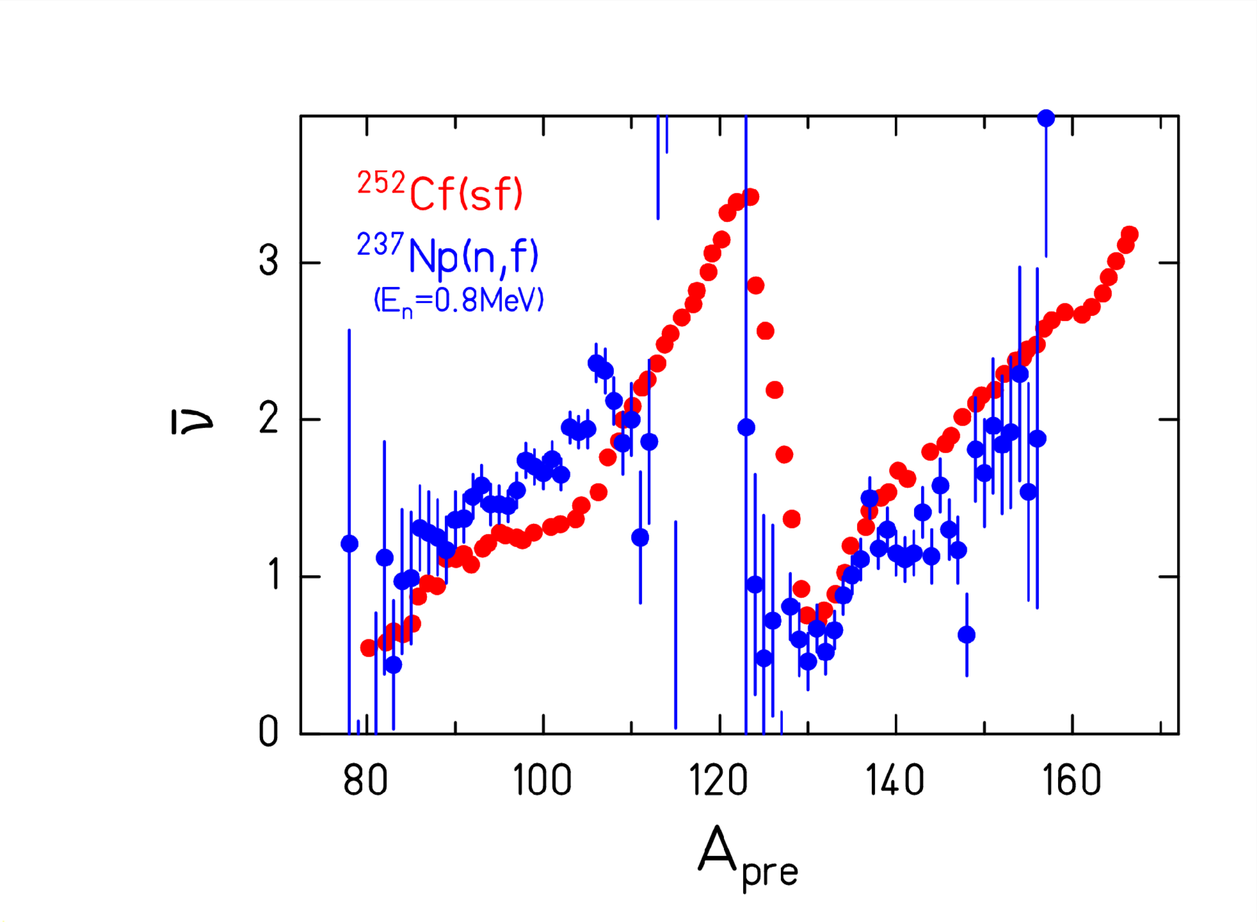




Bocquet, Brissot, NPA 502 (1989) 213c

Systematic variation of even-odd effect with the Coulomb parameter.

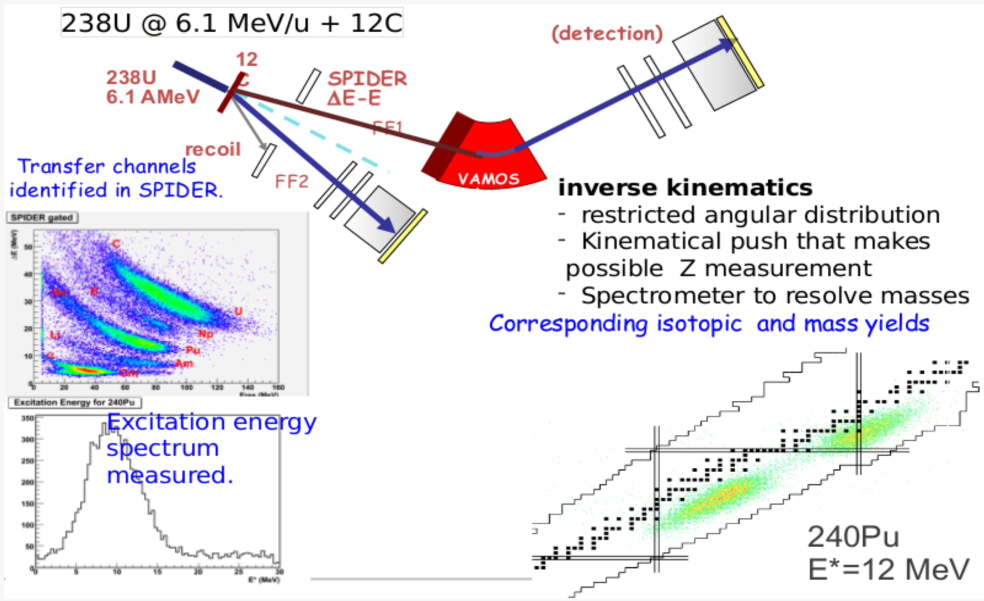
Prompt-neutron multiplicities

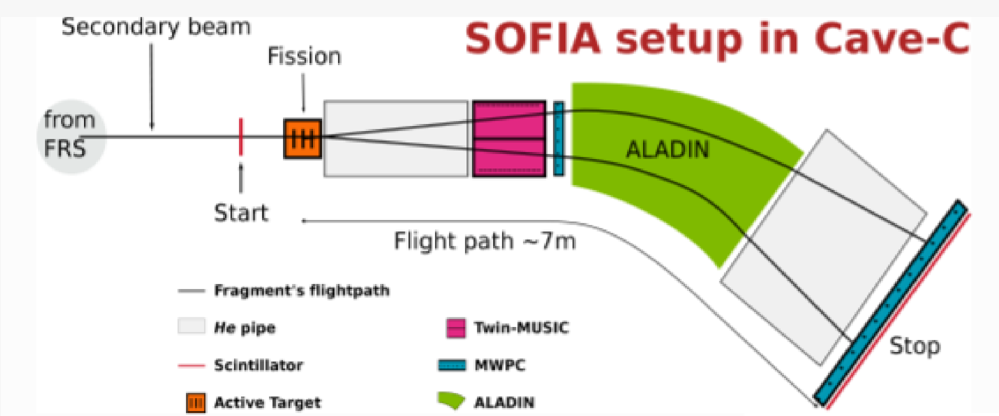


Zeynalov et al., 2012 / Naqvi et al., PRC 34 (1986) 218

Sawtooth behaviour in the actinides

Recent experimental progress 1
Extended choice of fissioning systems





Beta-delayed fission
A. Andreyev et al.

Transfer-induced fission
K. Nishio et al.

←
Transfer-induced fission
(GANIL, F. Farget et al.)

←
Electromagnetic-induced fission
(GSI, J. Taieb et al.)

Recent experimental progress 2

Unambiguous identification of Z and A in experiments in inverse kinematics

Relativistic heavy beams (~1 A GeV):

Projectile fragments from fragmentation reactions
(A <= Aproj)
@ GSI Darmstadt, Germany

Fast heavy beams (> 6 A MeV):

Transfer reactions, fusion reactions
(A in some distance to the projectiles, also A > Aproj)
@ GANIL Caen, France

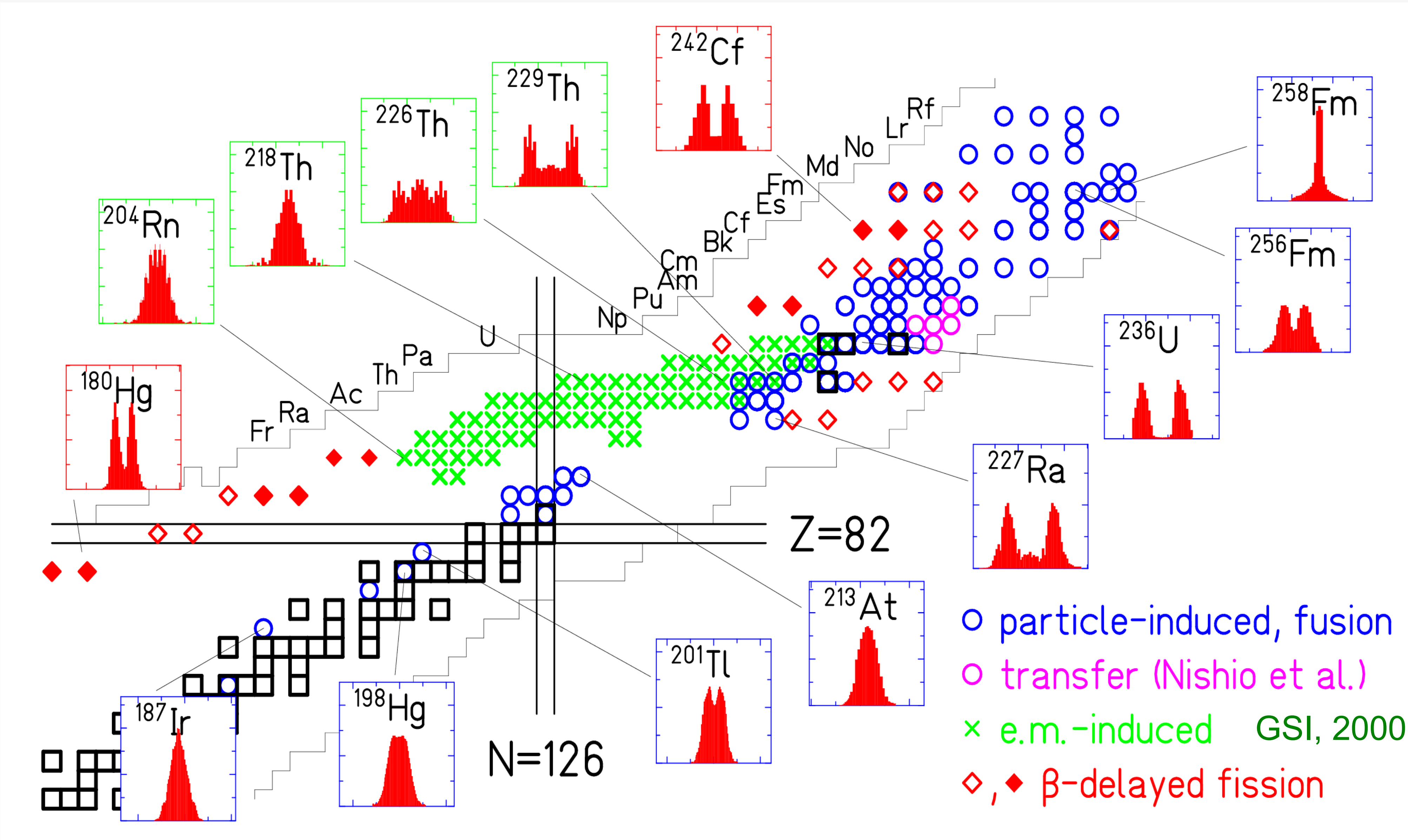
Specific results and interpretation

1. Fission-fragment mass distributions

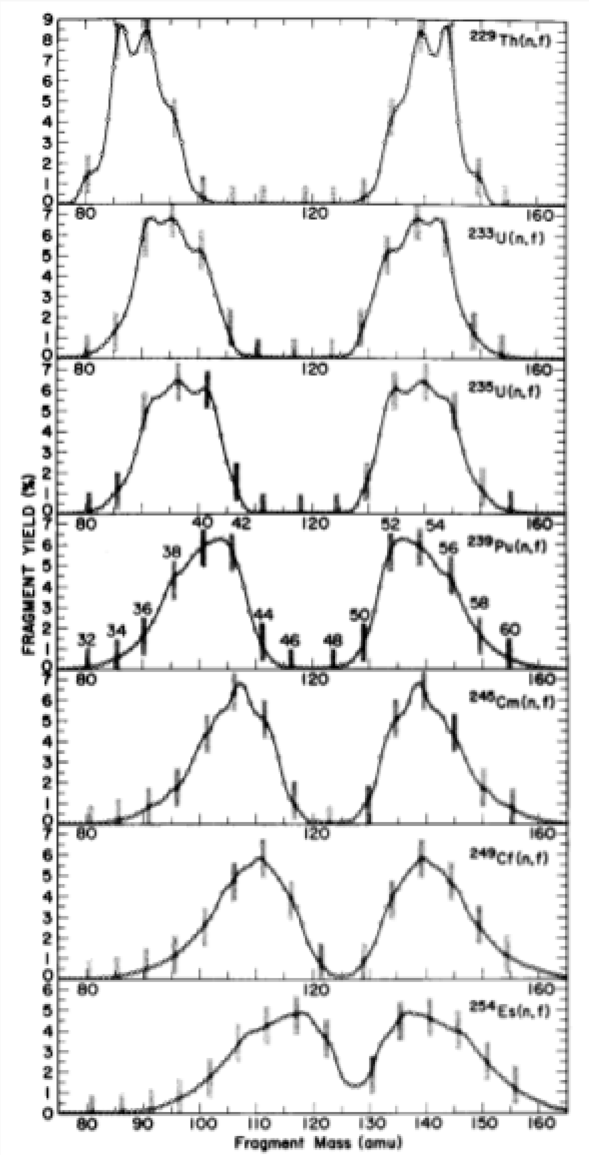
2. Energetics

3. Charge polarization / evaporation

Extended systematics of fission-fragment distributions

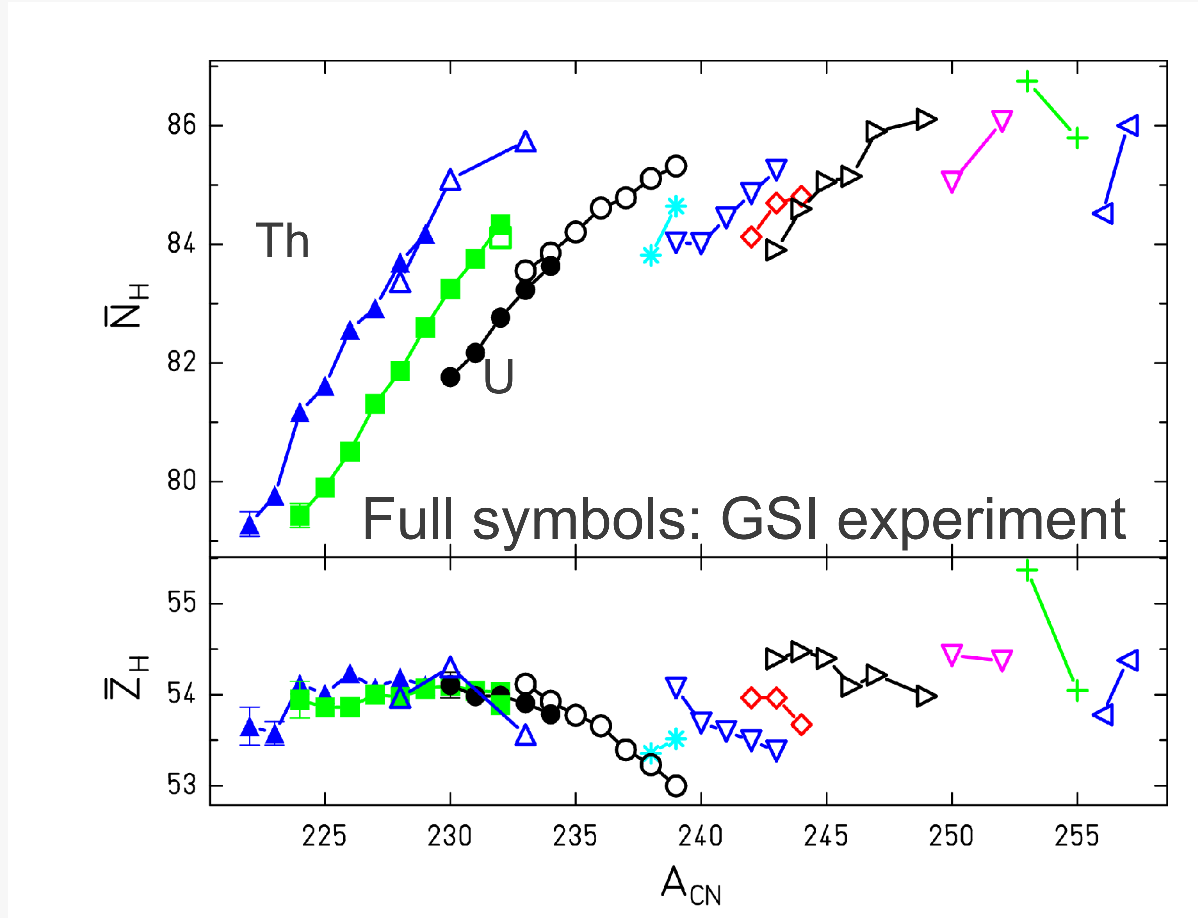


Position of heavy fragment for the actinides



Unik et al., 1973

<A> ≈ 140

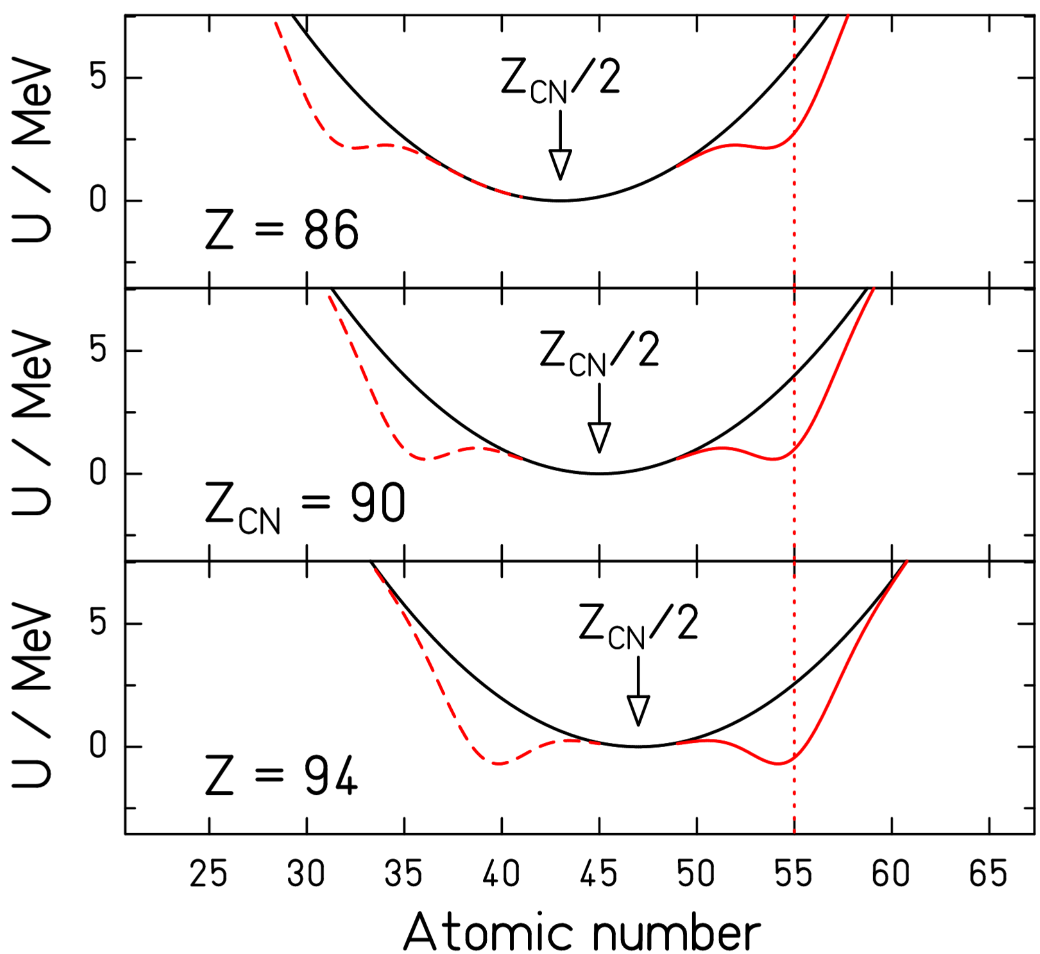


Böckstiegel et al., NPA 802 (2008) 12

Position is constant at *Z* ≈ 54 and varies strongly in *A* and *N*.

→ **General systematics of PES.**

Competition of mac. and mic. effects



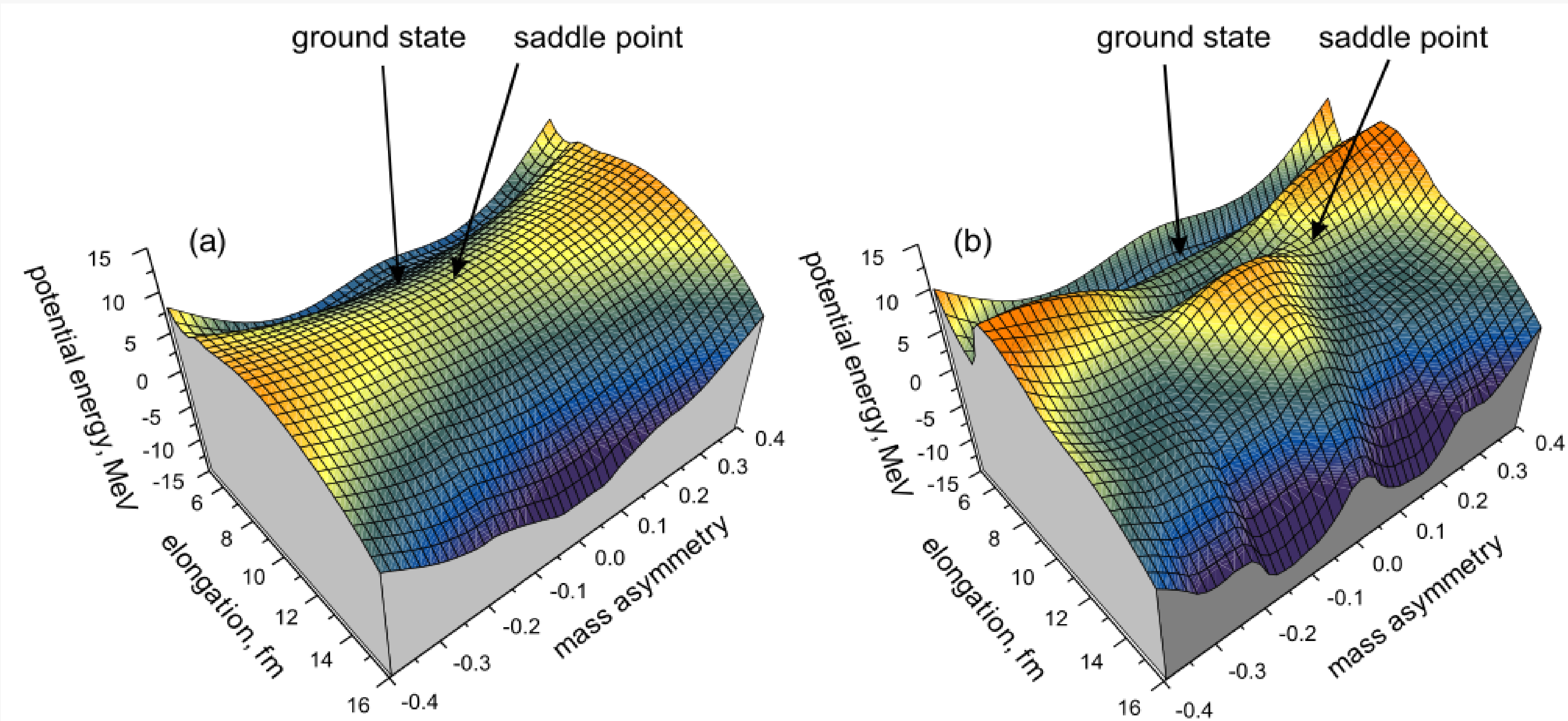
Asymmetric component is caused by shell effect in heavy fragment.

Explains transition from single-humped to double-humped distributions around A=226.

Qualitative idea of M. Itkis et al. Z. Phys. A 320 (1985) 433

Potential energy landscape

2-dim. calculation by A. Karpov, JPG 35 (2008) 035104



liquid-drop potential

With shell effects

Property of the CN

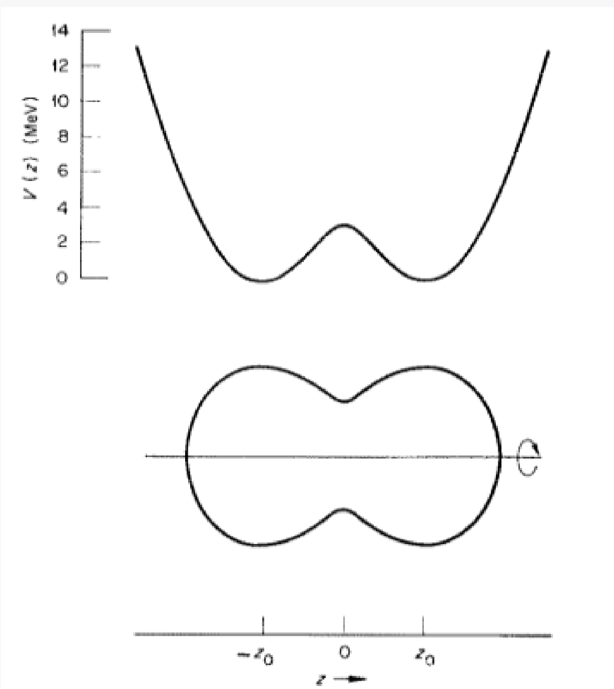
Shells behind outer saddle:
Property of the nascent fragments

→ **Separability principle**

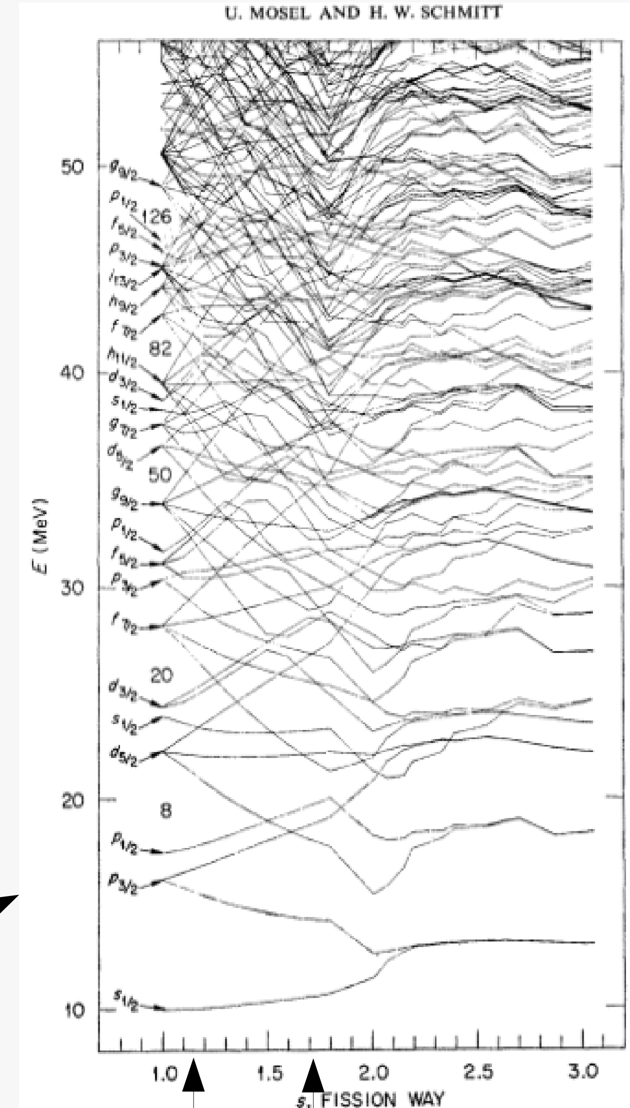
Shells

Two-centre shell model developed by:
Holzer, Mosel, Greiner (Nucl. Phys. A138 (1969) 241)

Continuous treatment from ground state to separated fragments.



U. Mosel, H. W. Schmitt
Nucl. Phys. A
165 (1971) 73



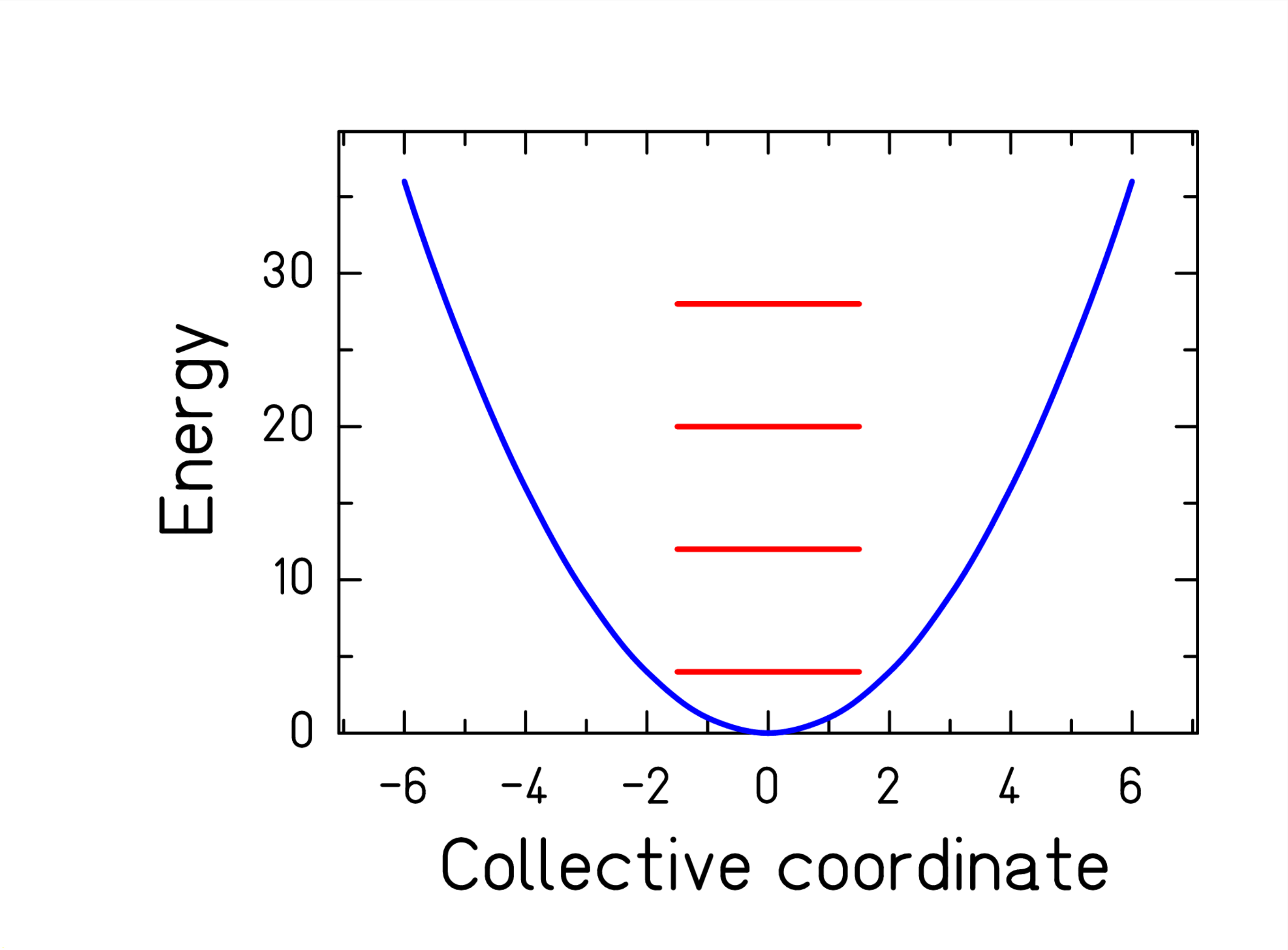
Single-particle levels
in a di-nuclear potential

Ground state

Outer saddle

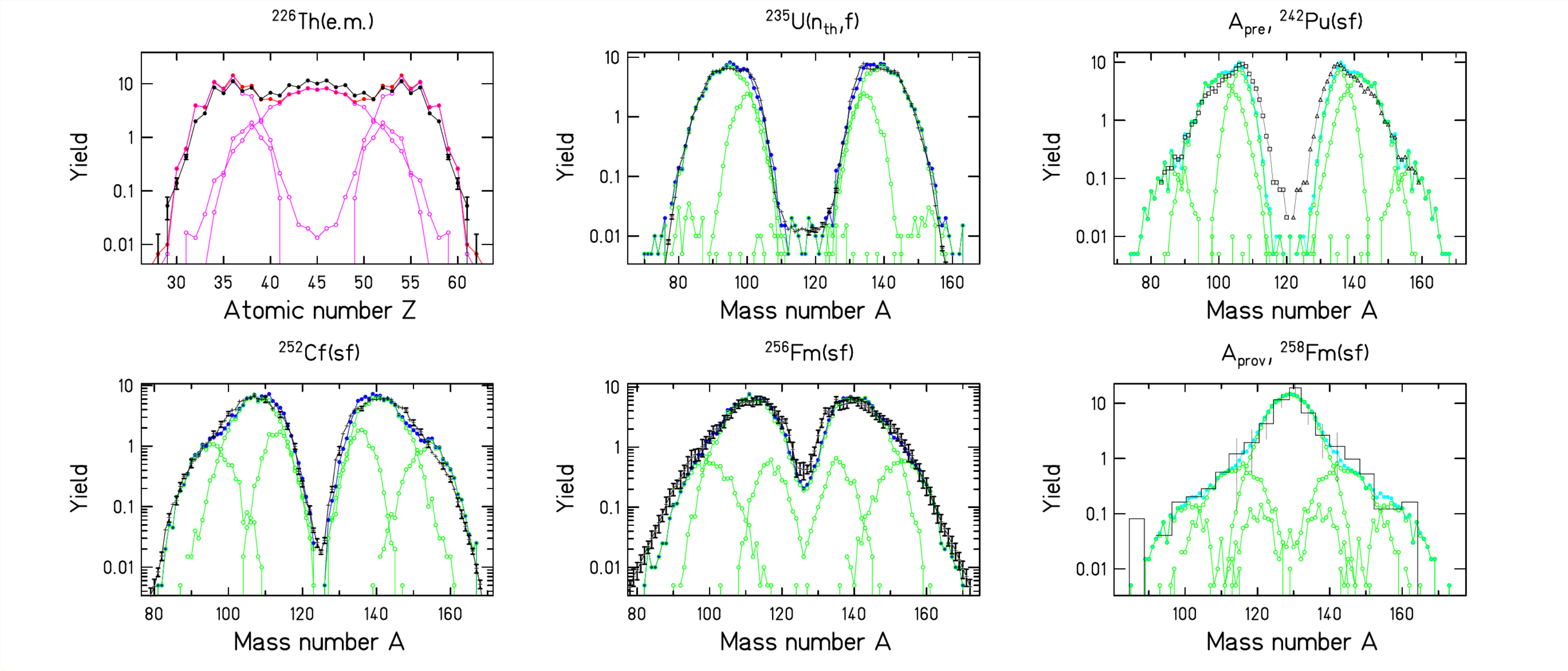
Early manifestation of fragment shells.

Quantum oscillators of normal modes



<u>Assumption:</u> Properties and populations of oscillator states (mass asymmetry, *N/Z* ratio etc.) in the nuclear heat bath determine the distributions of observables.

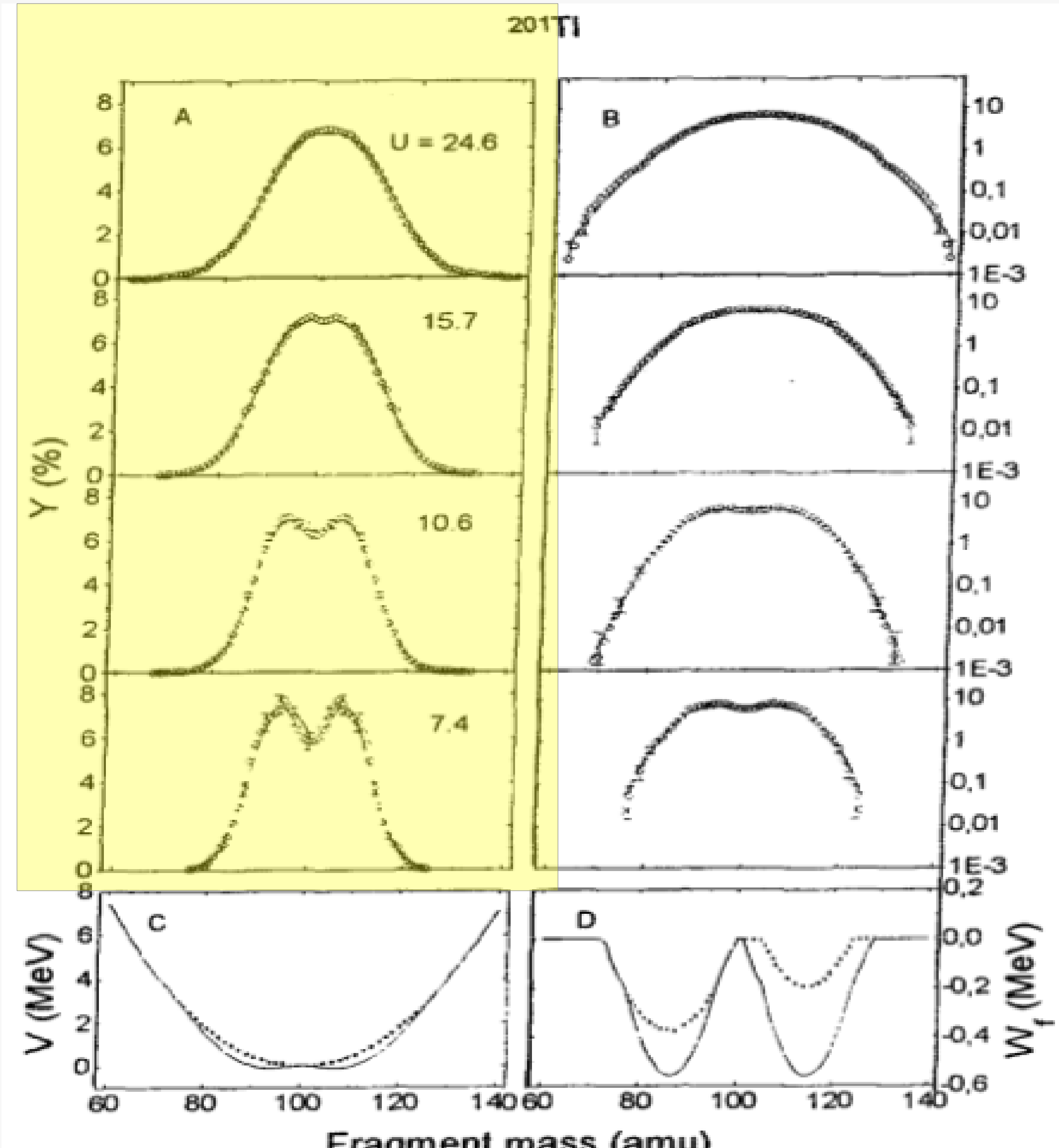
Hidden simplicity of fission !



Variety of mass (*Z*) distributions very well described with the same fragment shells (*Z*≈51, *Z*≈55, *Z*≈59, *Z*≈42)!
(All distributions obtained with the same parameter set: position, depth and width of shells.)

GEF code: www.khs-erzhausen.de or www.cenbg.in2p3.fr/GEF

Thermal washing out of shell effects



Low fission probability: **First-chance fission dominates** in 201Tl.

Direct information on thermal washing out of shell effects in fission-fragment mass distributions (PES).

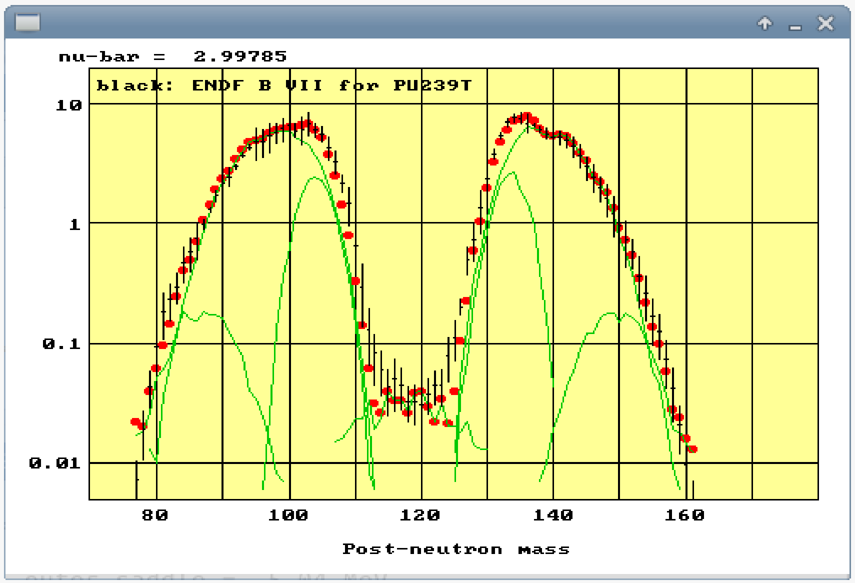
U = energy above Bf

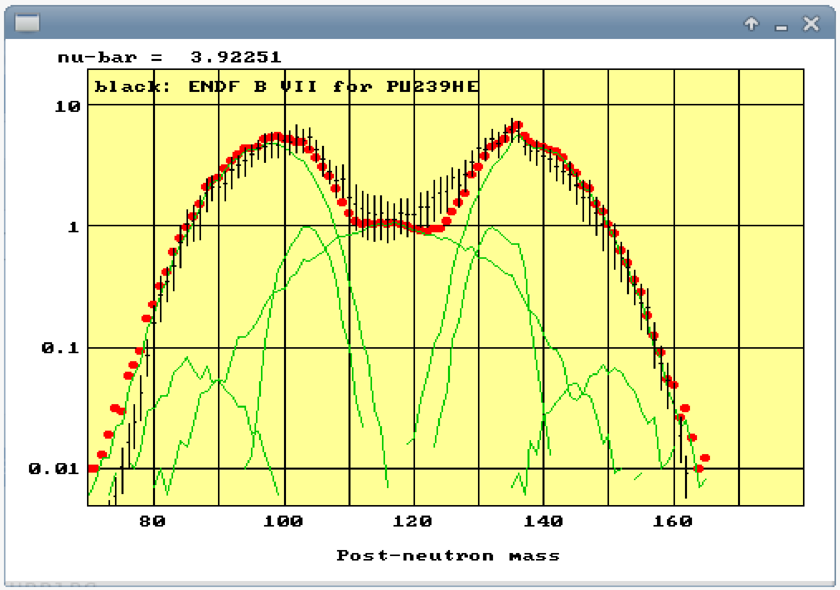
M. Itkis et al., SJNP 41 (1985) 544

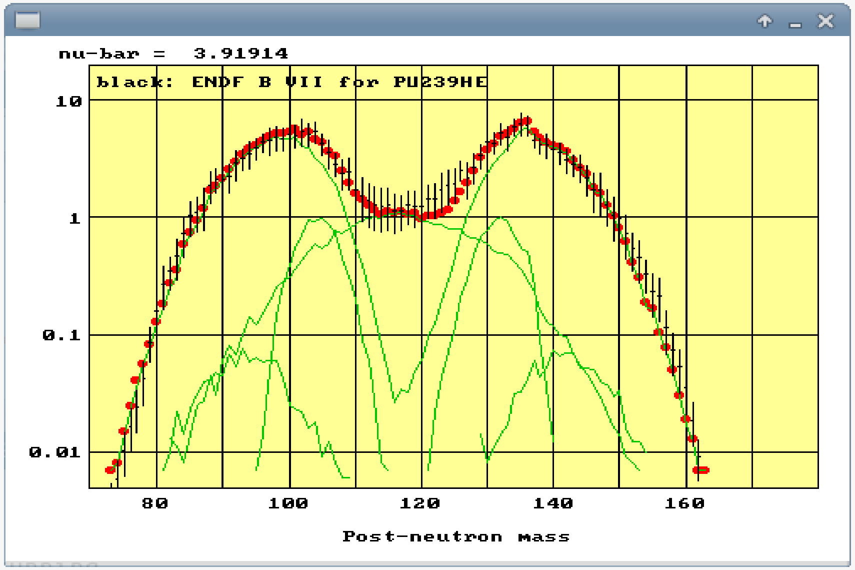
Thermal shift of fission channels

En = thermal

En = 14 MeV







Increasing influence of
macroscopic potential with E*:
Shift towards symmetry →

Calculations with the GEF code
www.khs-erzhausen,de

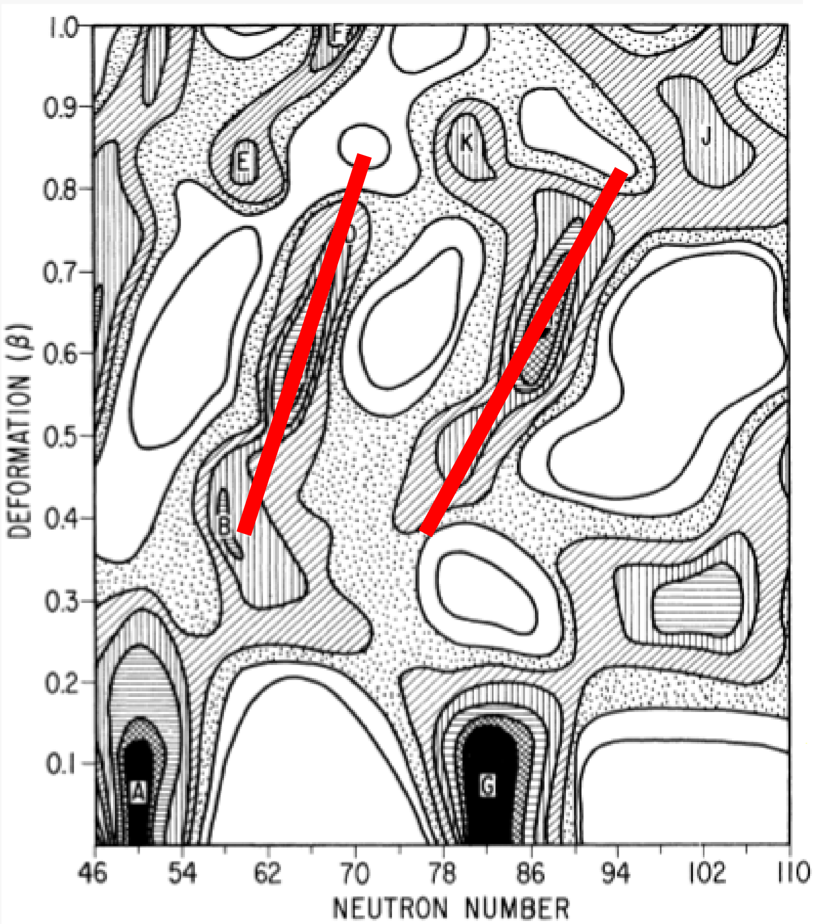
Specific results and interpretation

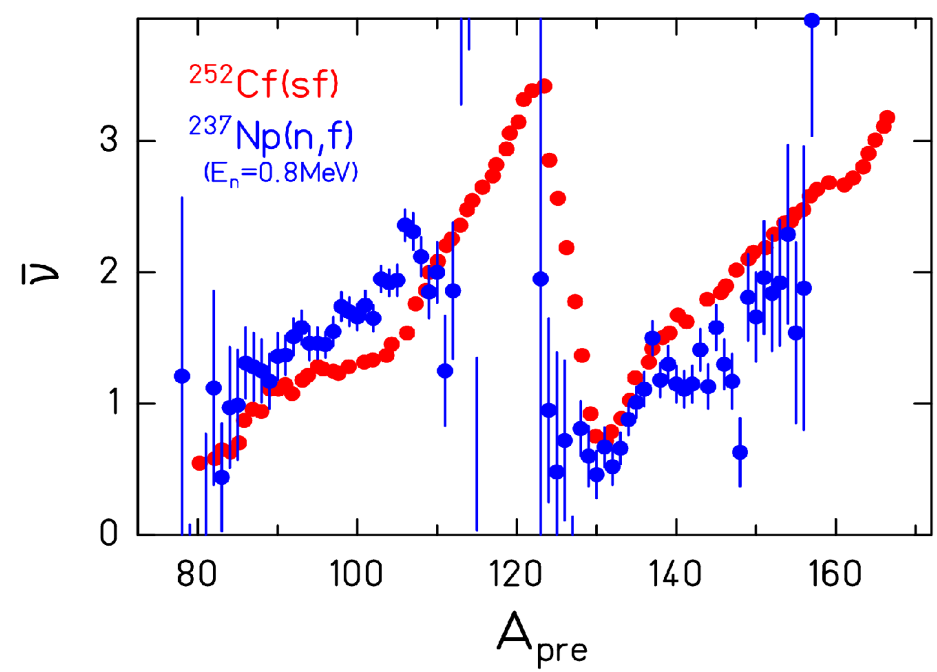
1. Fission-fragment mass distributions

2. **Energetics**

3. Charge polarization / evaporation

Fragment deformation → prompt neutrons





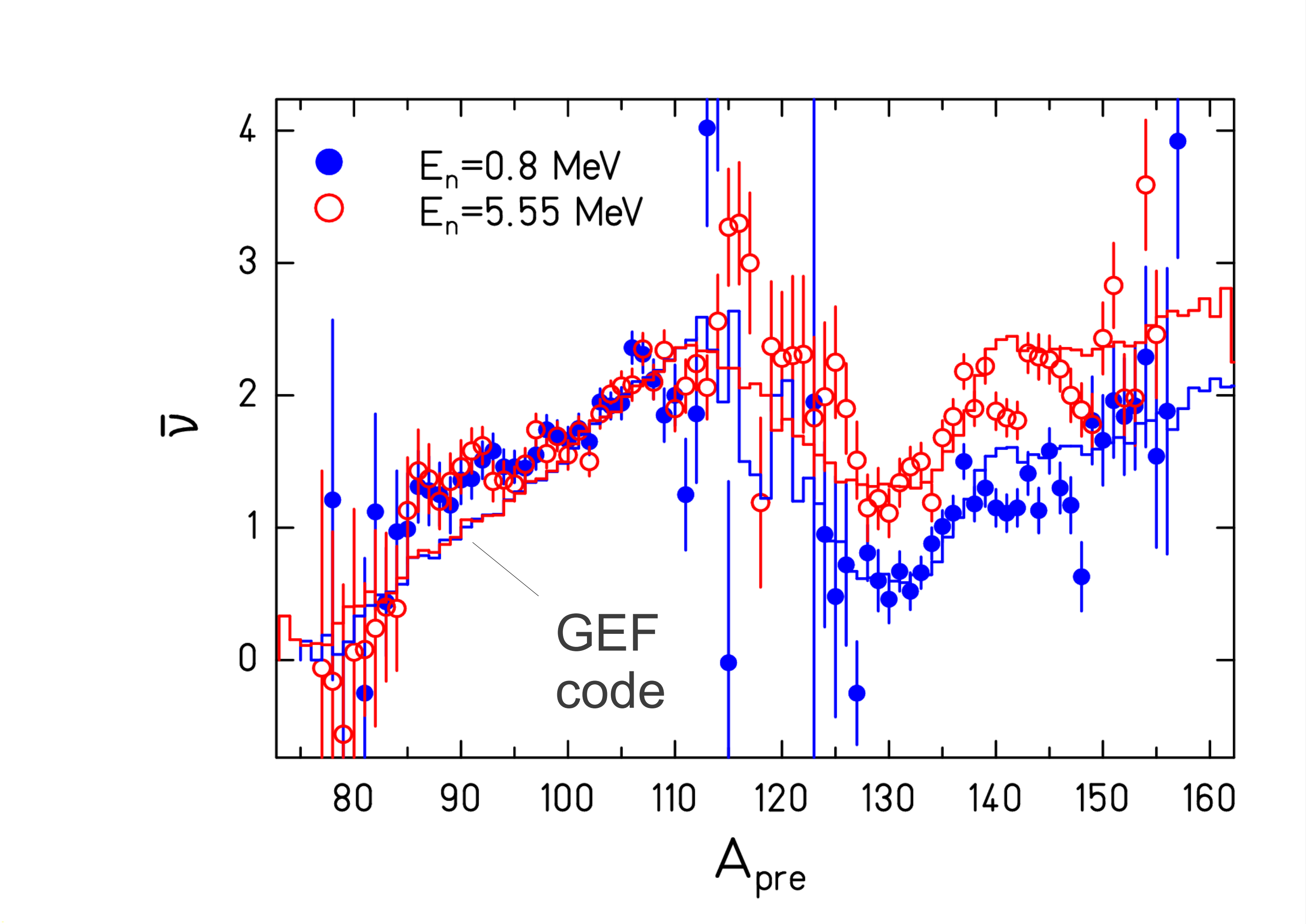
Naqvi et al, 1986 / Zeynalova et al., 2012

Wilkins et al., Phys. Rev. C 14 (1976) 1832

General systematics of deformed shells:
Correlation particle number ↔ deformation
(Additional influence of mac. potential.)

Saw-tooth behaviour reflects fragment deformation at scission.

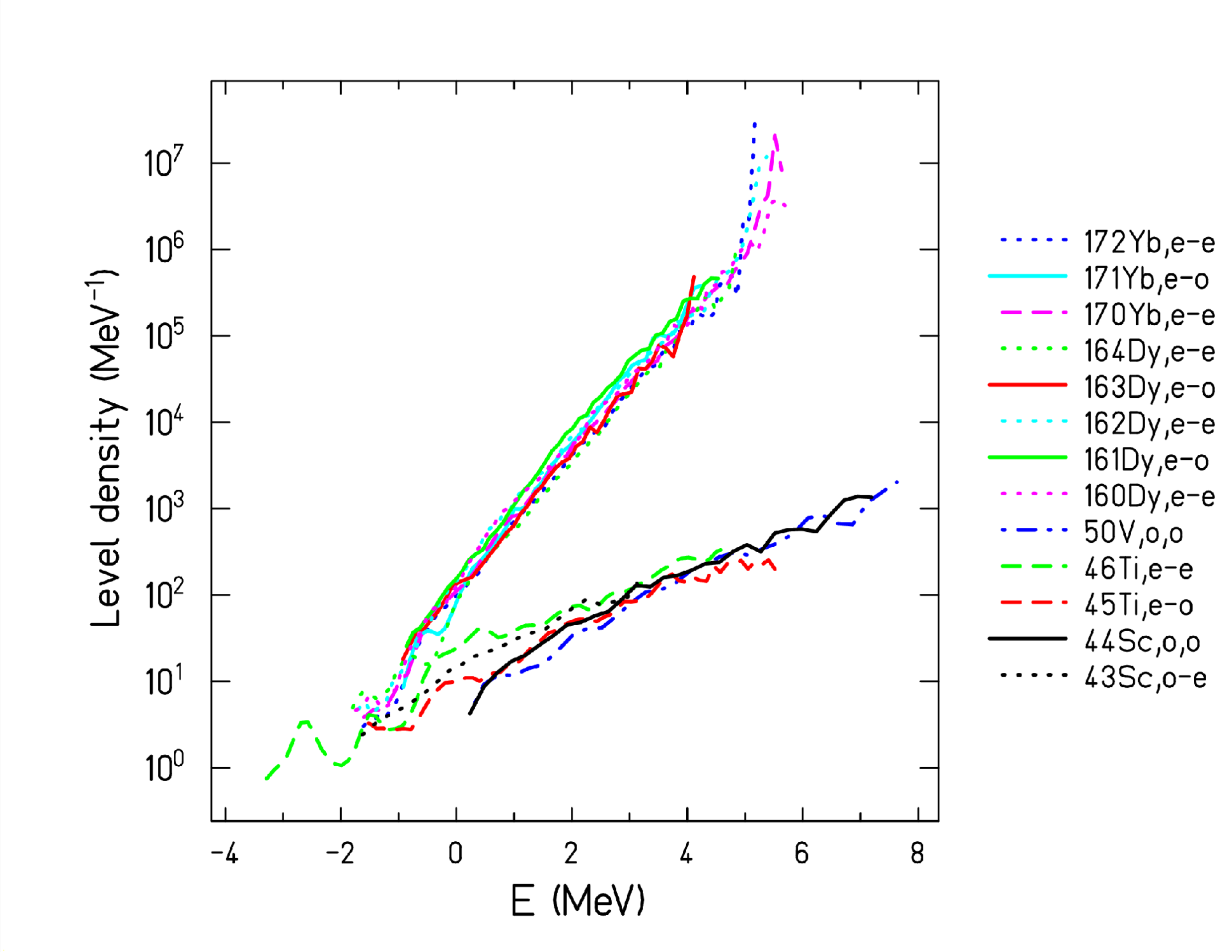
Prompt-neutron yields

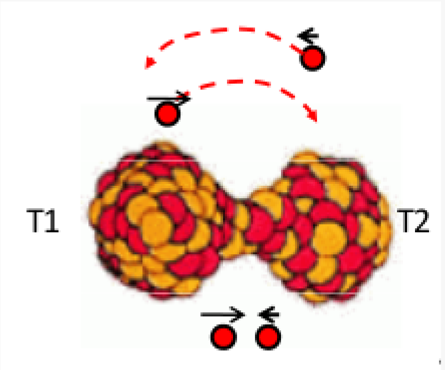


Experiment: Naqvi et al., 1986

All additional energy of the neutron ends up in the heavy fragment.

New results on level densities suggests energy sorting in fission





Nascent fragments:

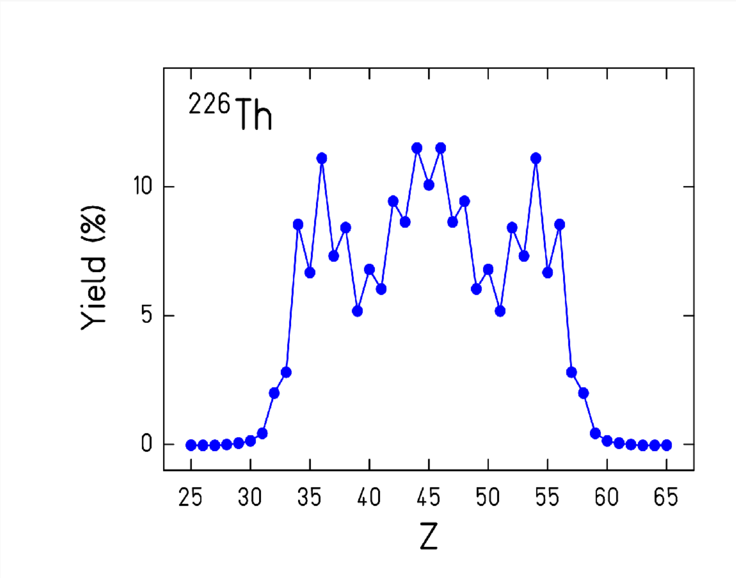
Two thermostats in contact.
→ Energy sorting

Guttormsen et al. 2012

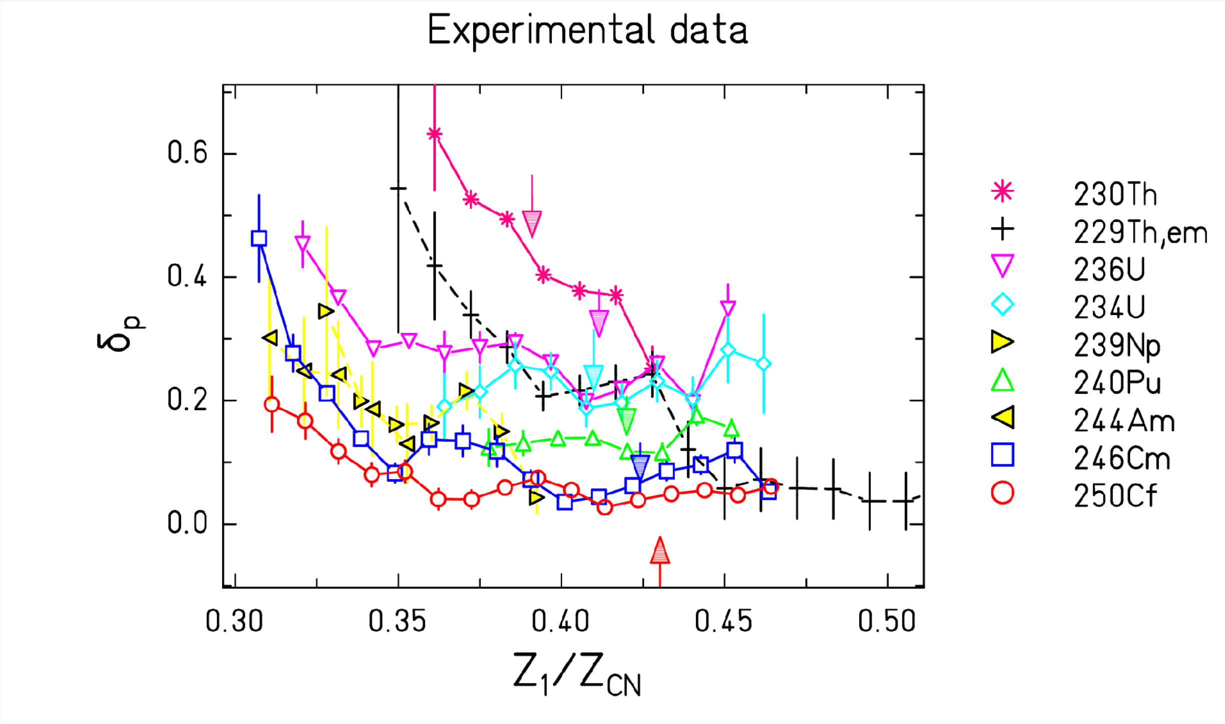
Schmidt, Jurado,
PRL 104 (2010) 212501

Constant nuclear temperature at low E*.

Influence of asymmetry on even-odd effect



Schmidt et al., 2000



Caamano et al., 2011

GSI-experiment:
Z distribution measured over the whole range.

Systematics:
Even-odd effect strongly enhanced in asymmetric splits.
→ **even-even light fragments = end products of energy sorting**

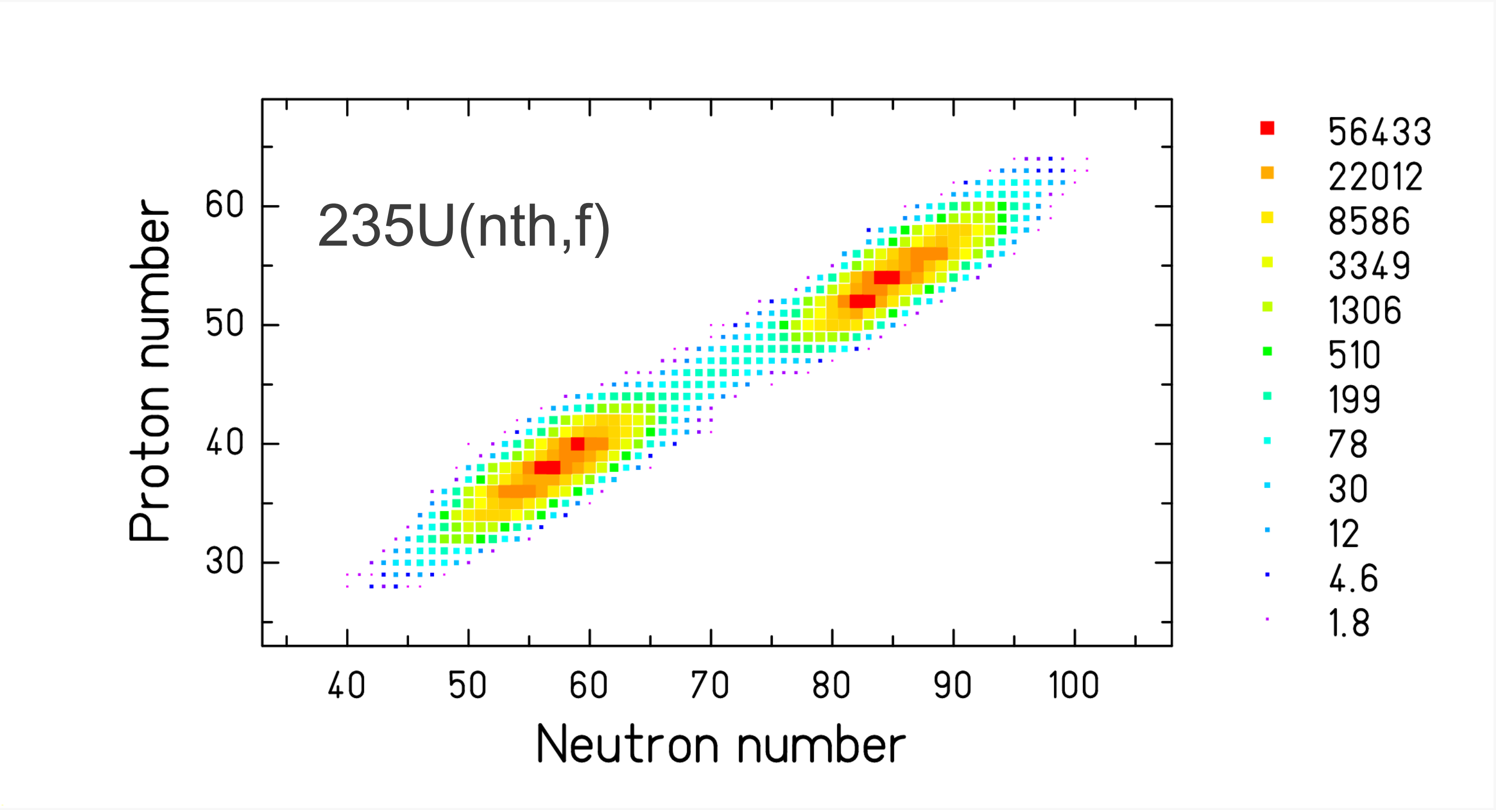
Specific results and interpretation

1. Fission-fragment mass distributions

2. Energetics

3. Charge polarization / evaporation

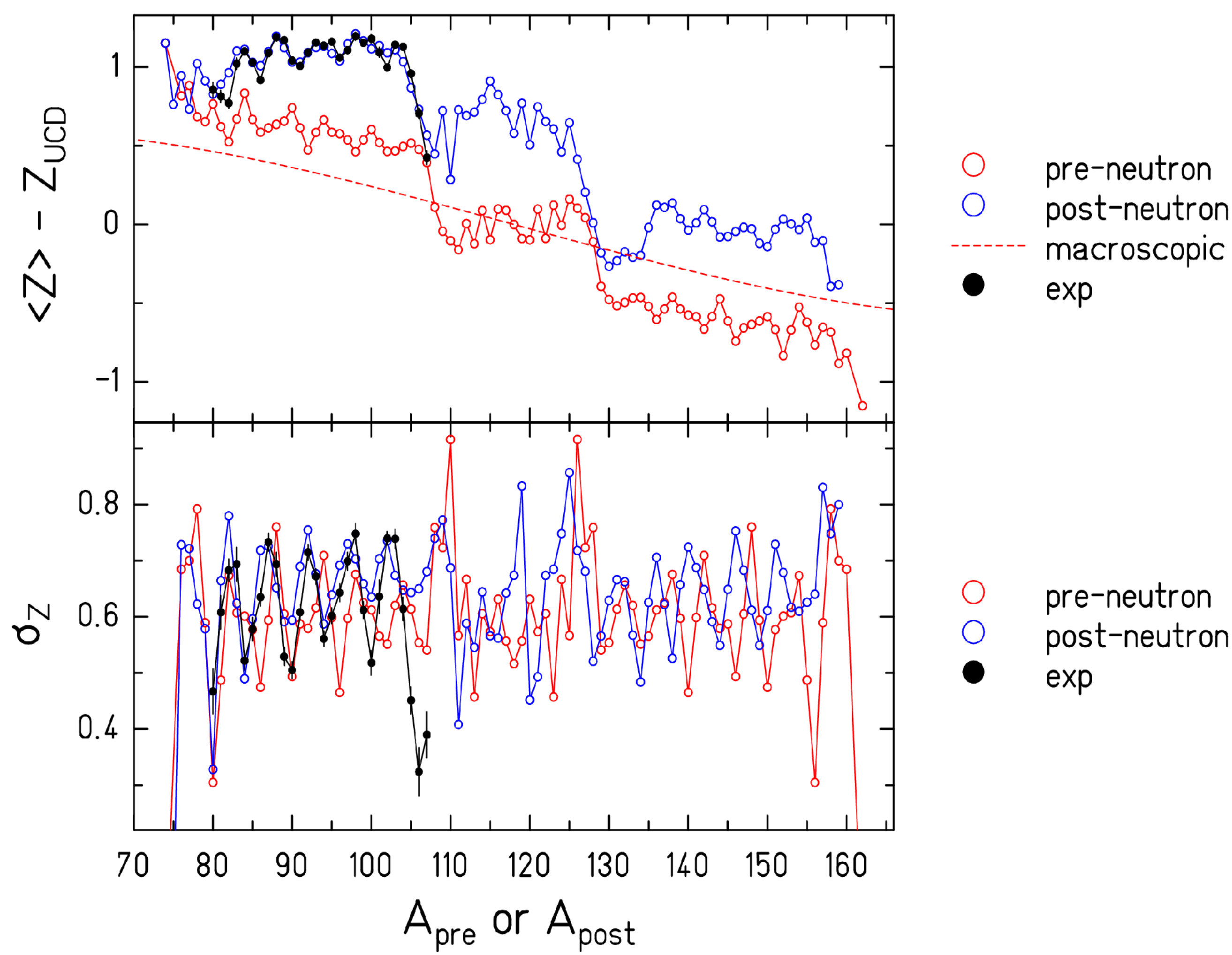
Nuclide distribution



GEF calculation

More than 500 nuclides produced.
Deviation from UCD: shift and fluctuations.

Information on charge polarization



235U(nth,f)

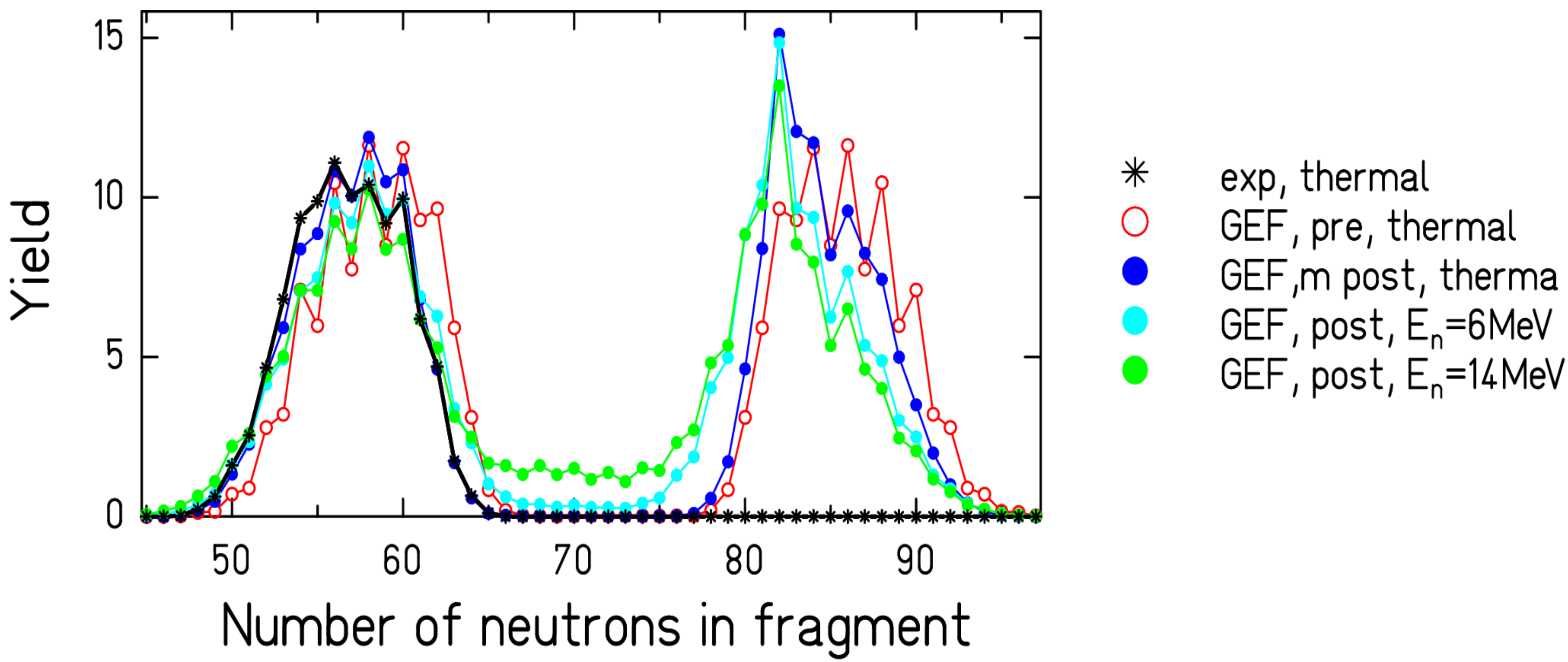
Moments of isobaric Z distributions. ←

Influence of macroscopic potential, shell effects and evaporation.

GEF code and experiment.

→ Full resolution in A and Z required!

Even-odd effect in ff neutron number

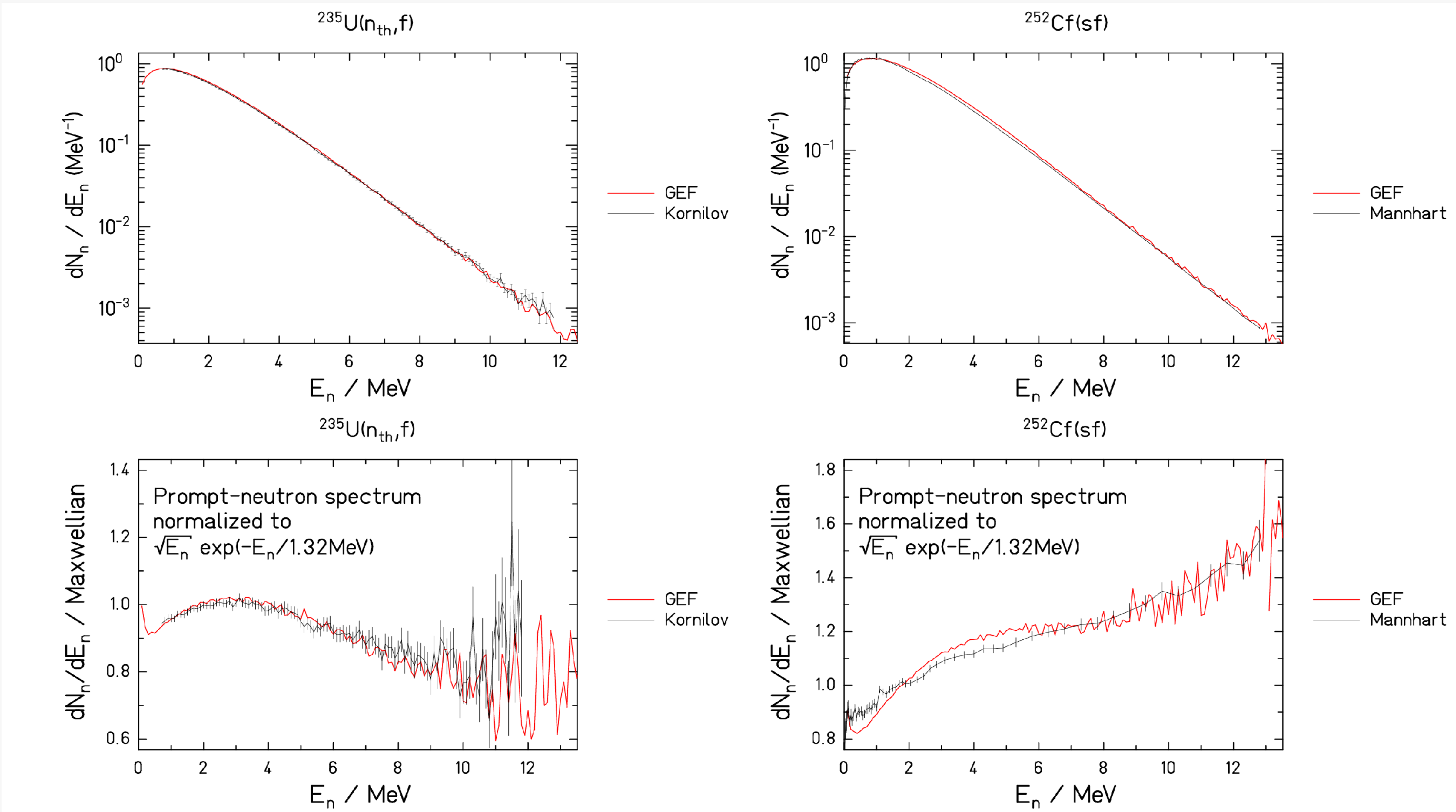


Even-odd effect in neutron number of fragments (post-neutron) is created by evaporation. (Does not depend on E*!)

Influence of pairing on binding energies and level densities.

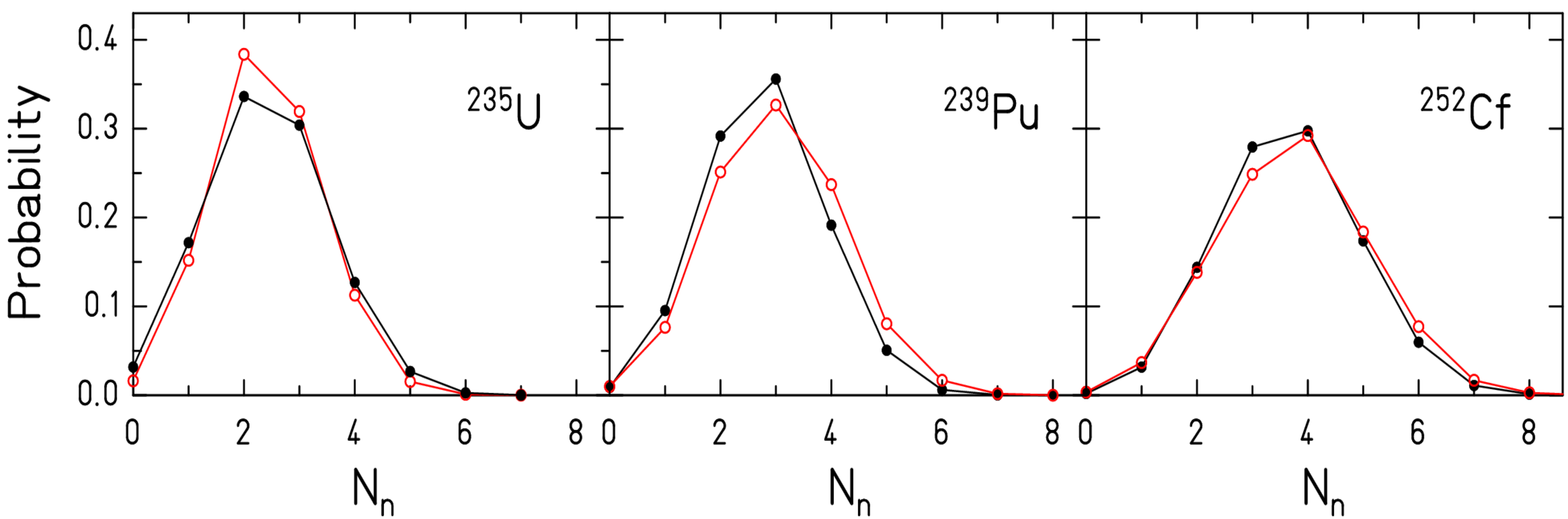
M. V. Ricciardi et al., Nucl. Phys. A 733 (2004) 299

Energy spectra of prompt neutrons



Clue: Modified composite Gilbert-Cameron nuclear level density.
(Increased condensation energy, collective enhancement)
K.-H. Schmidt, B. Jurado, Phys. Rev. C 86 (2012) 044322

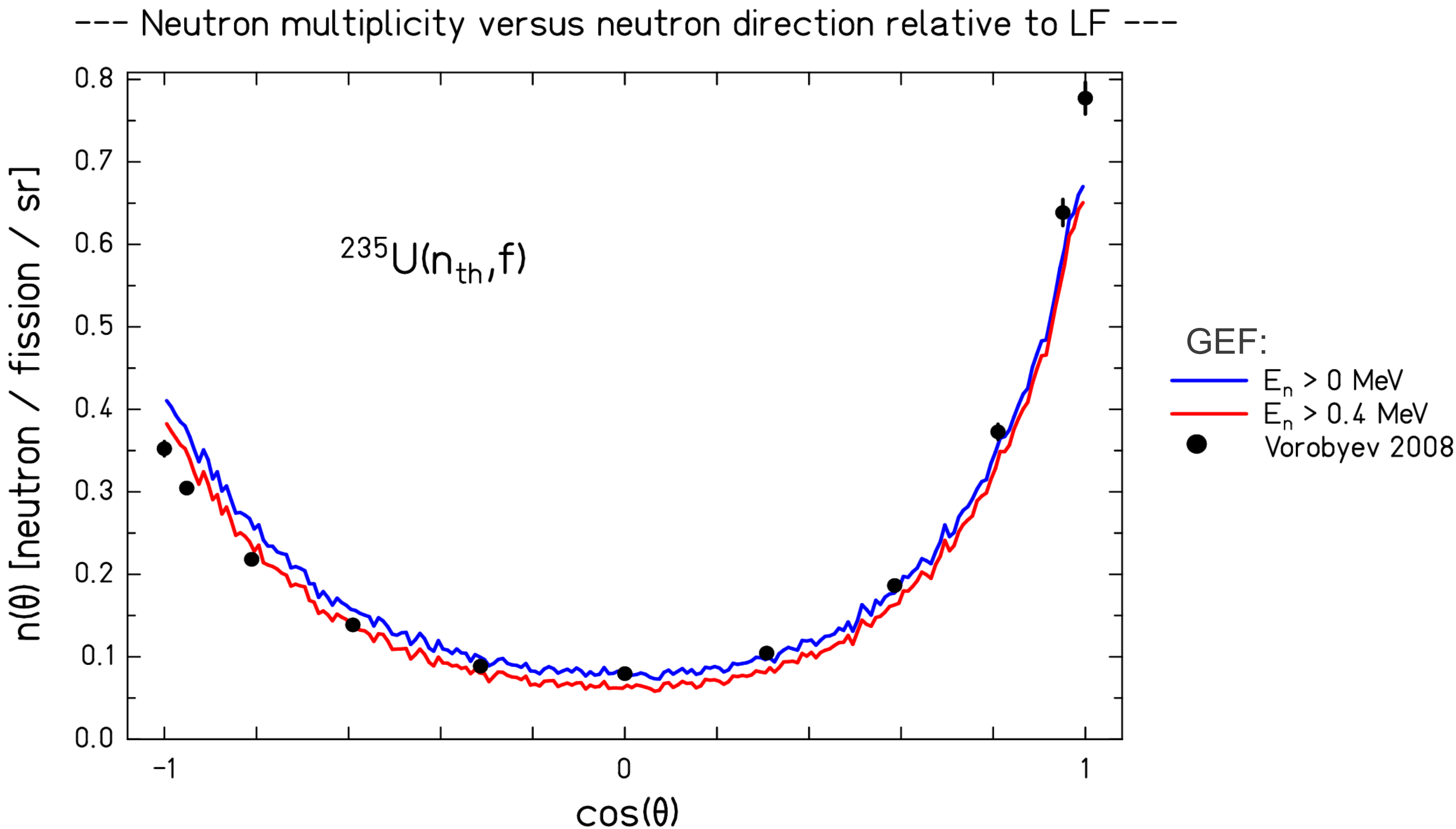
Multiplicities of prompt neutrons



--- experimental data
--- GEF code

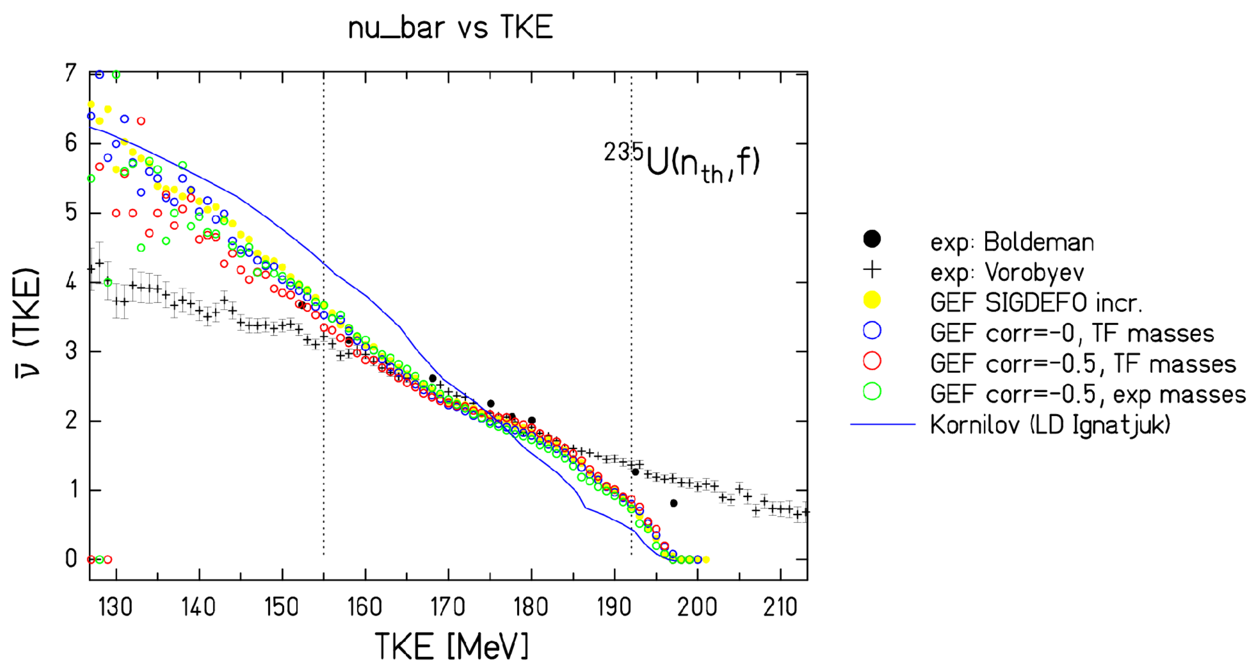
Multiplicity distribution mostly reflects the fluctuations in nuclear deformation at scission.

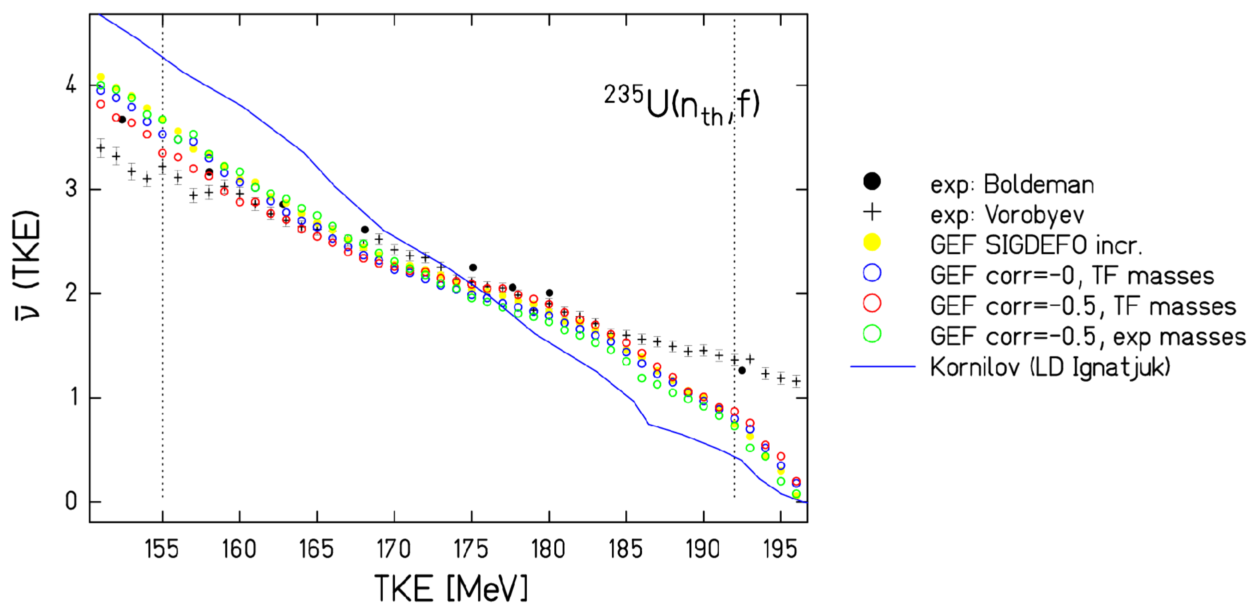
Correlations: nu-bar - angle



Searching for signatures of scission neutrons ...

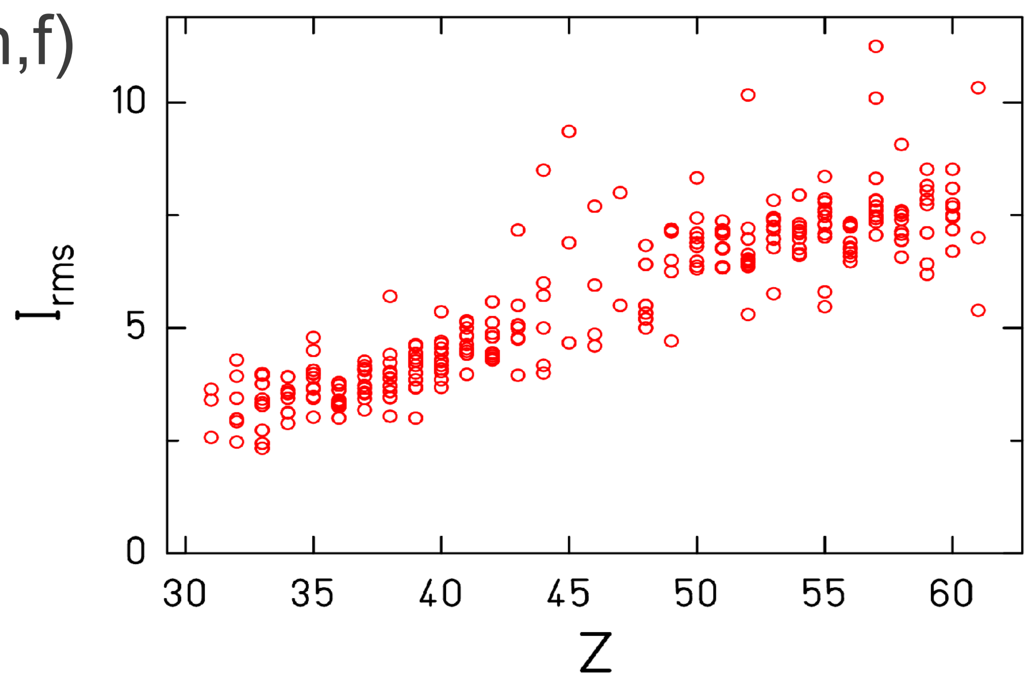
Correlations: nu-bar - TKE





Fragment angular momentum

235U(nth,f)



GEF calculations

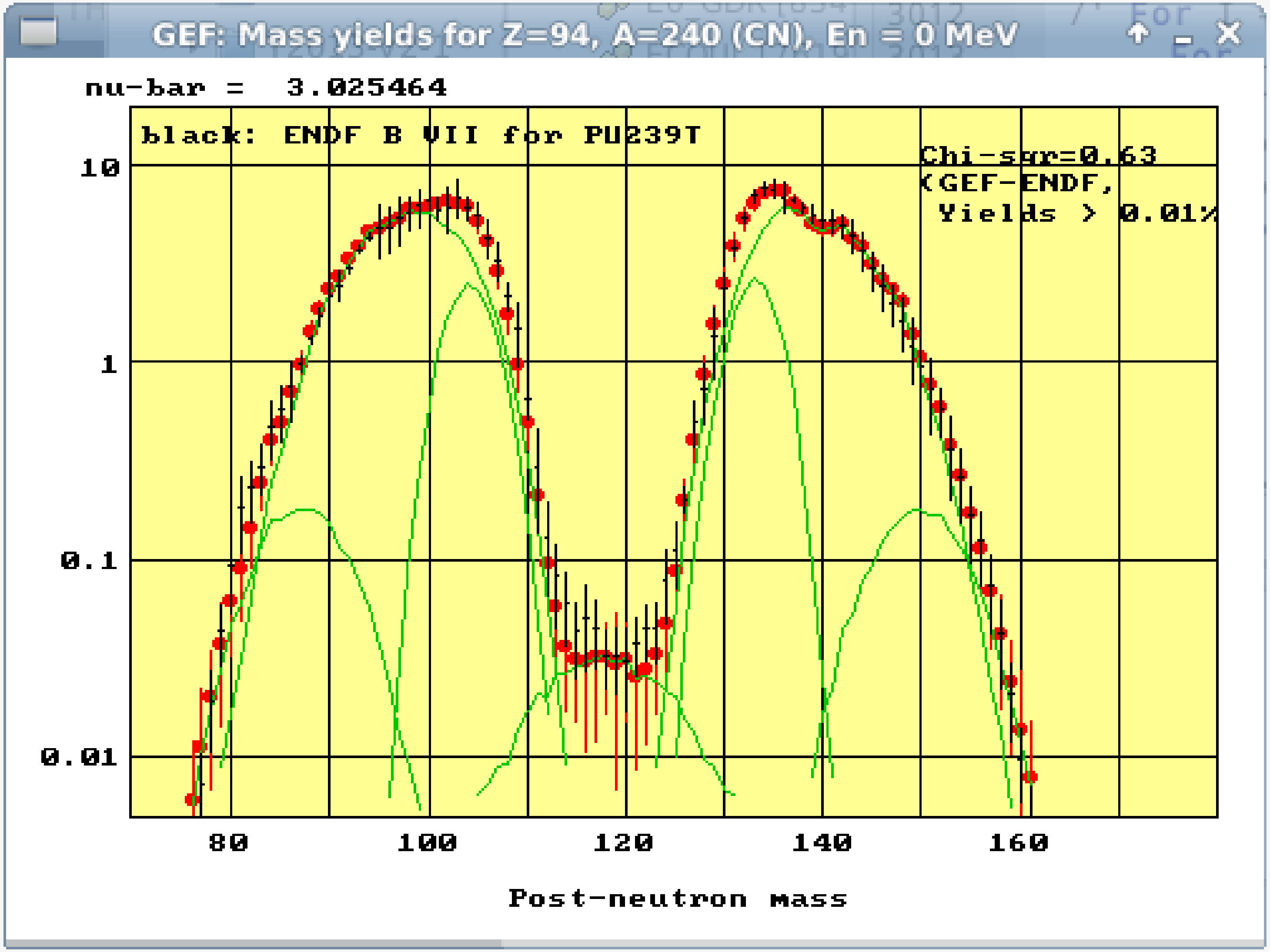
in good agreement with measured isomeric ratios

Theory: “Pumping” from q.m. uncertainty of orbital angular momentum (Kadmensky) + I of unpaired nucleons.

Fragment angular momentum

- stores collective energy at scission (less TKE)
- feeds contributions of rotational transitions to prompt gamma spectrum

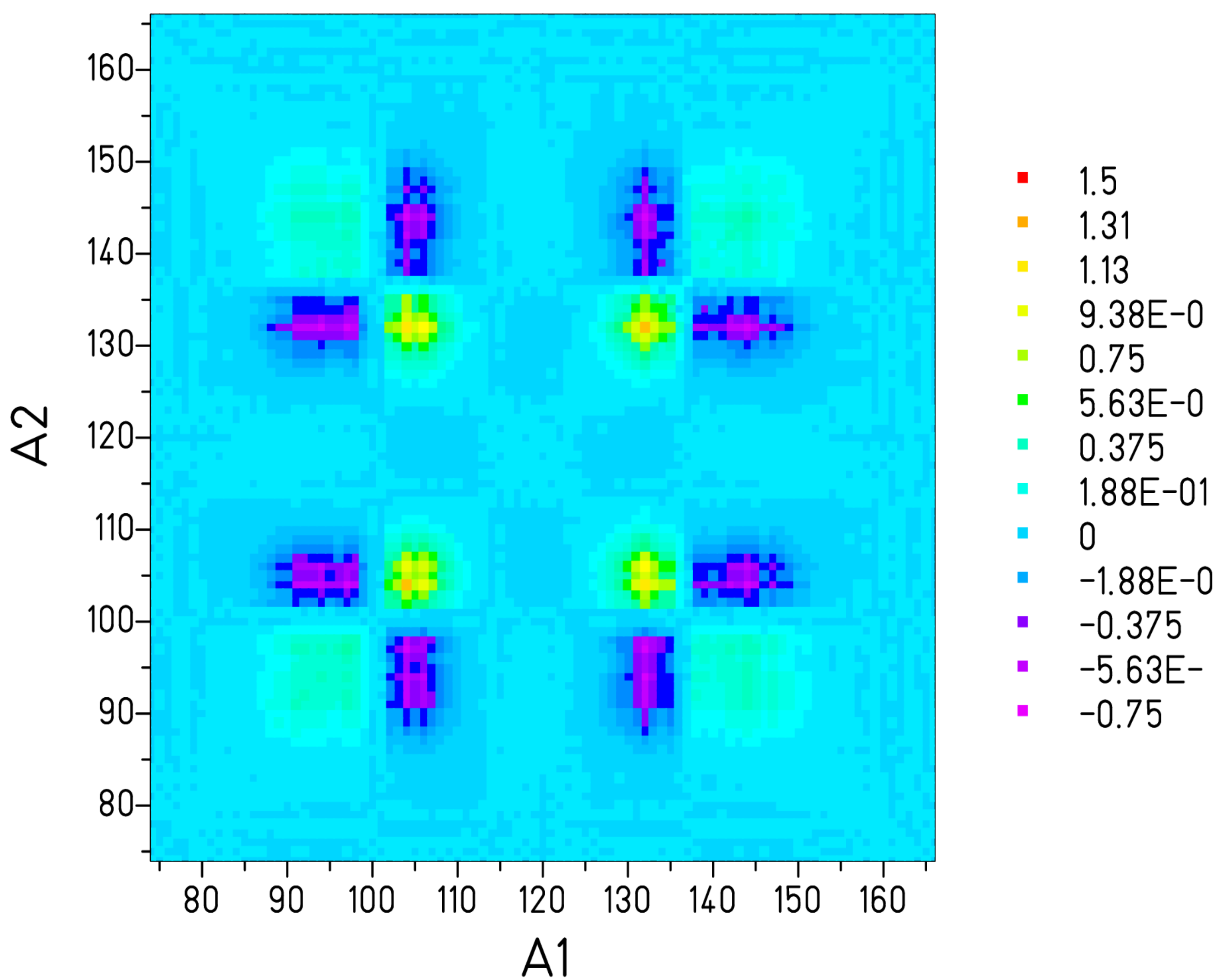
Uncertainties of the model



Mass yields from GEF with estimated uncertainties.

GEF calculations with perturbed parameters.

Covariance matrix



240Pu(nth,f)

Post-neutron masses.

Covariances defined by the model dependences.

A tool for improving evaluations.

Conclusion and outlook

- Fission is a large-amplitude shape evolution with a tremendous variety of final configurations.
- Fission experiments need to specify these configurations by as many observables with an as good resolution as possible.
- Inverse kinematics is a major clue for the revival of fission studies (→ variety of systems, isotopic resolution). Extending the data base considerably.
- A global view on experimental results reveals a surprising simplicity and systematics.
- Fission is governed to a great extent by general laws of quantum and statistical mechanics.

Further info: JEF/DOC 1423 (from www.khs-erzhausen.de)