Fission-fragment and neutron data traced back to the macroscopic and microscopic properties of the fissioning systems

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Work performed during a short-term visit in the frame of the EFNUDAT project

Modelling of nuclear fission

Level 1: Microscopic properties of the nuclear system.

Nucleon-nucleon interaction
Nuclear potential, residual interactions
Time-dependent evolution of wave functions ...

Level 2: Intermediate properties of the nuclear system.

Potential-energy surface on the fission path
Level densities (T=const.), **Dynamical memory (early freeze-out)**
Coupling between different degrees of freedom (friction),
Separability principle (mac.-mic.), **Energy sorting**,

Level 3: Observable quantities

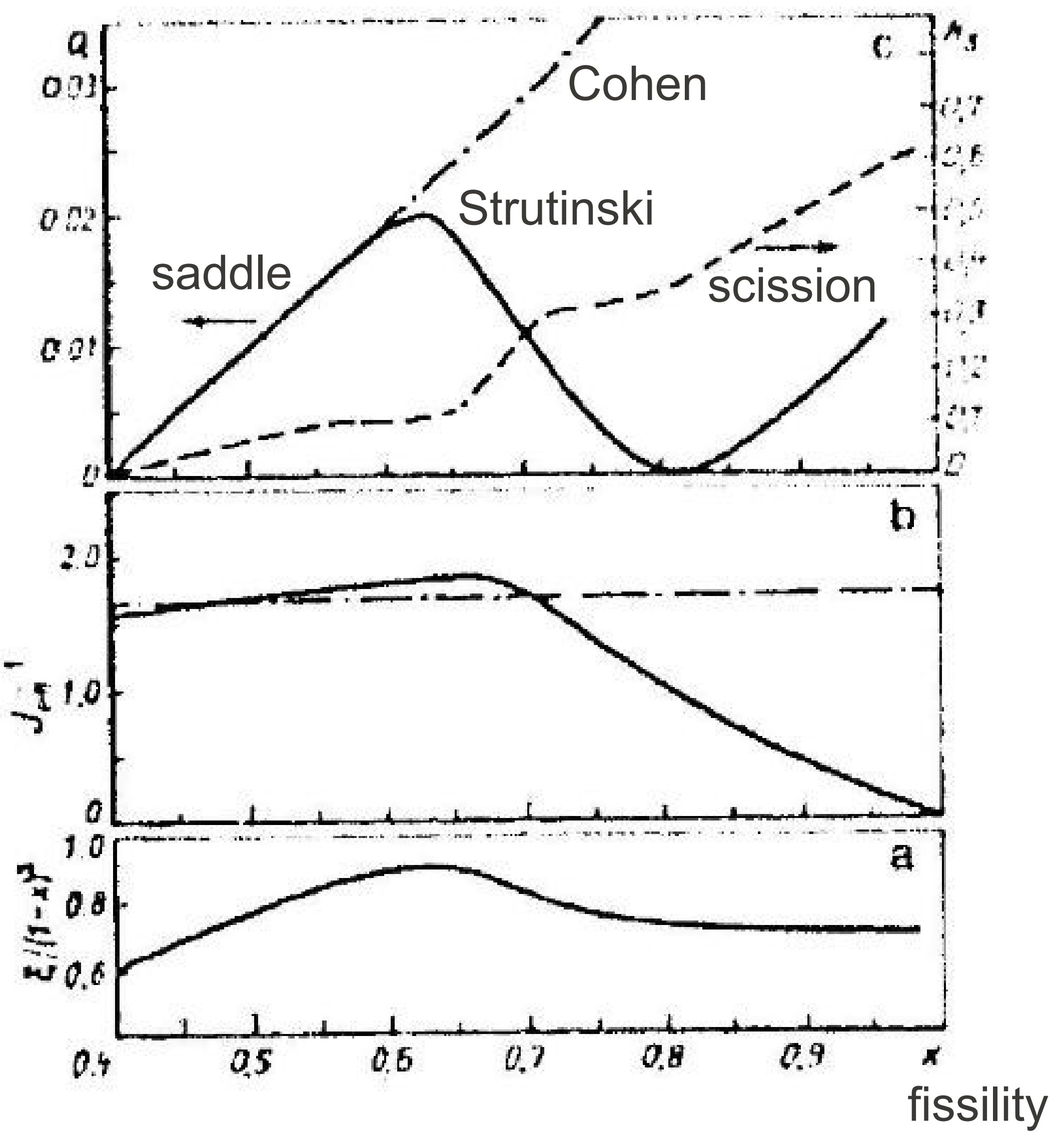
Mass distributions; nuclide yields
Neutron multiplicities and energies
Fragment kinetic energies ...

The problems: (i) Models based on Level 1 are not yet precise enough.
(ii) Empirical models on Level 3 have low predictive power.

Our concept: Deduce properties of Level 2 from experiment.
Our aim: High precision and good predictive power.

GEF code just released: www.cenbg.in2p3.fr/GEF

Systematics of the liquid-drop potential



Itkis et al., 1988

Stiffness of the potential with respect to mass asymmetry.

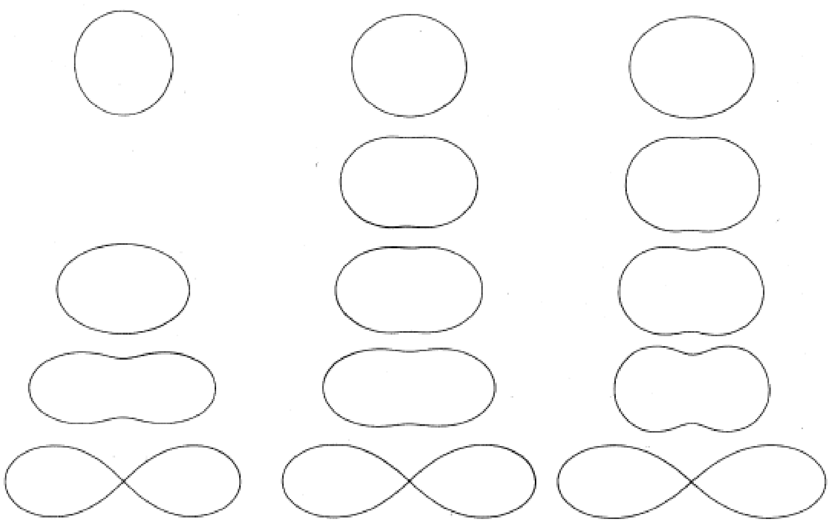
Related to the width of the mass distribution:

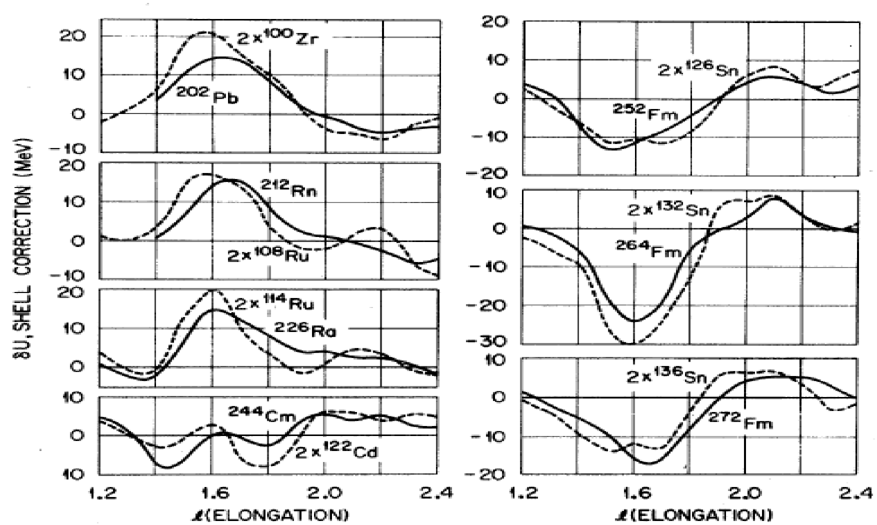
$$\sigma_A \propto \frac{T}{d^2 V / dA^2}$$

Momentum of inertia

Fission barrier

Shell effects:
Shells beyond outer saddle resemble shells in separate fragments



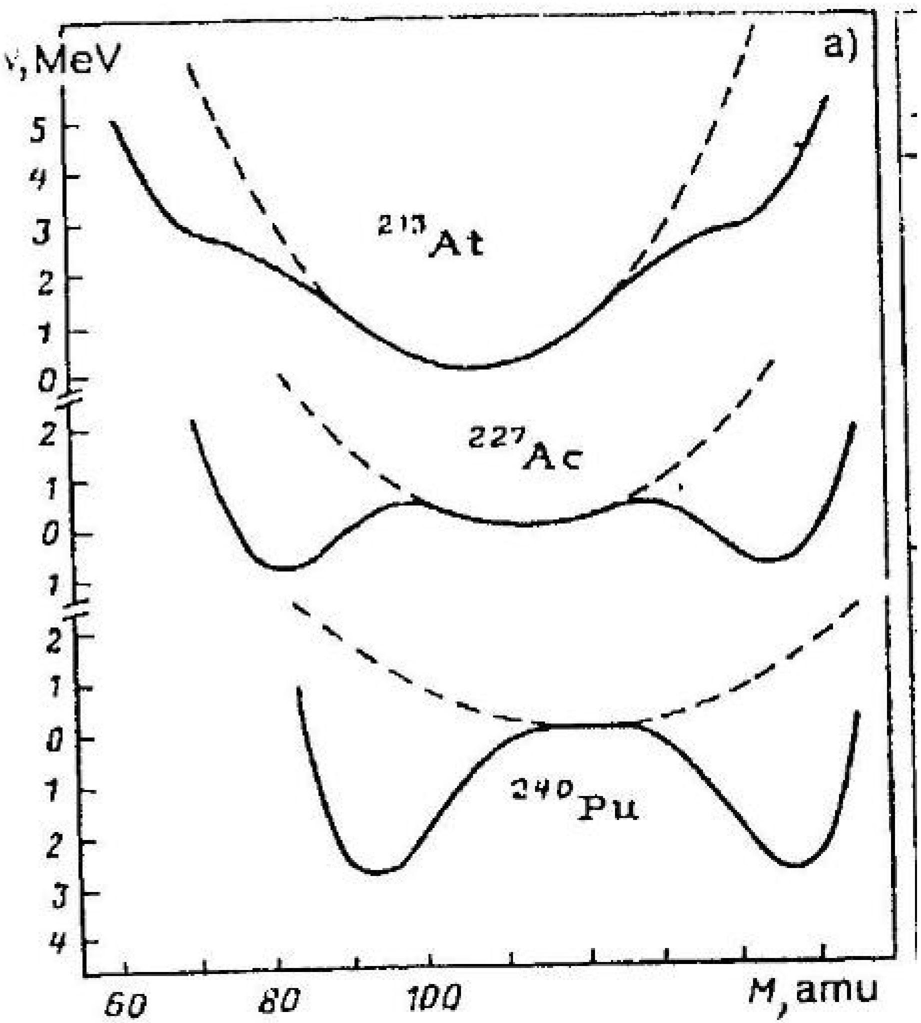


Shape evolution from CN to scission

Mosel and Schmitt, 1971

Comparison:
Two-centre shell model
with
shells in separate fragments
(midway between saddle and scission)

Macroscopic-microscopic approach: Competition between symmetric and asymmetric fission

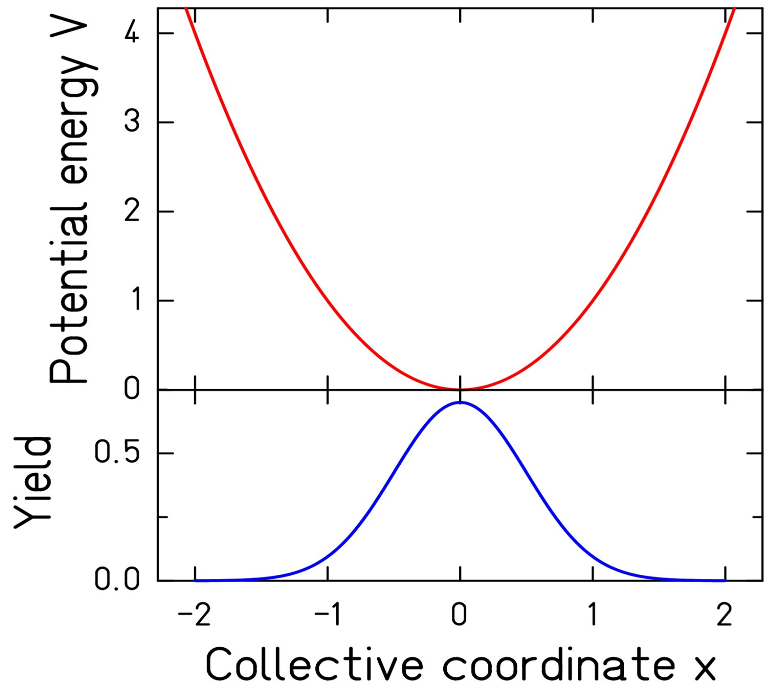


Itkis et al., 1988

Liquid drop favours symmetric fission, shells win, if they are close to symmetry.

Even if shells are the same for the same fragments, the mass distribution varies from one CN to another due to the interplay of macroscopic and microscopic potential.

Distributions in collective variables



Schematic:

Yield:

$Y \sim \exp((E^* - V_0)/T_{coll})$

Width:

$\sigma \sim \sqrt{T_{coll}/(d^2V/dx^2)}$

Potential:

Quadratic expansion around the potential-energy minimum

Mass asymmetry (each fission channel)

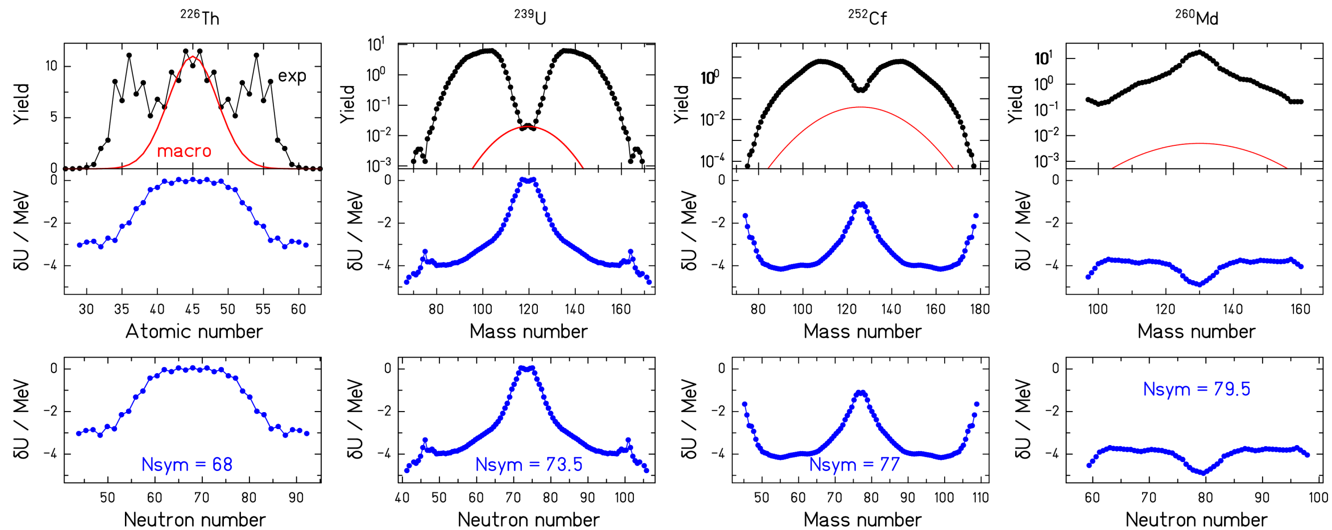
Charge polarization (*N*/*Z*) for given mass split

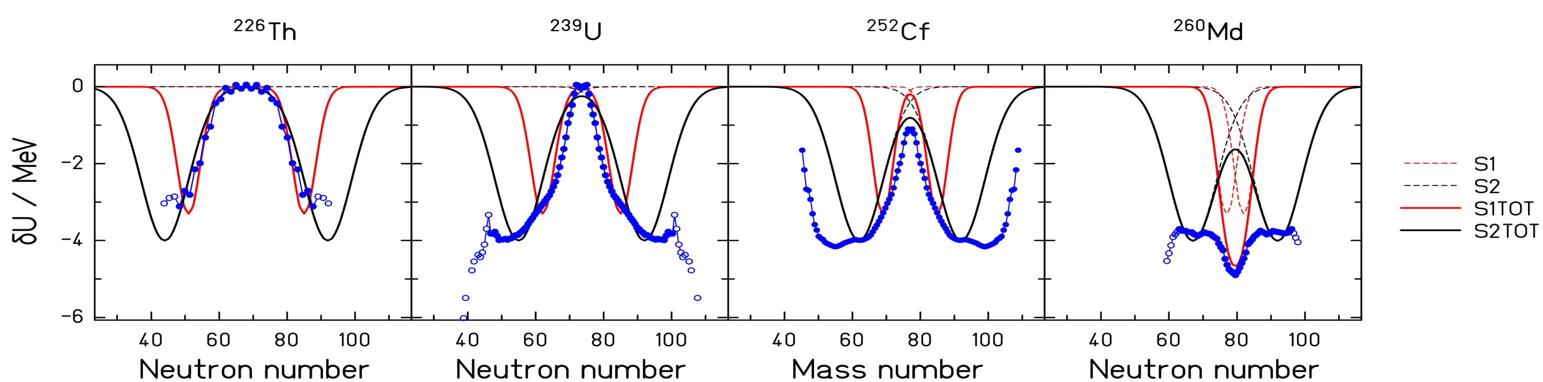
Deformation, ...

Yield:

Statistical model applied: Gaussian distribution

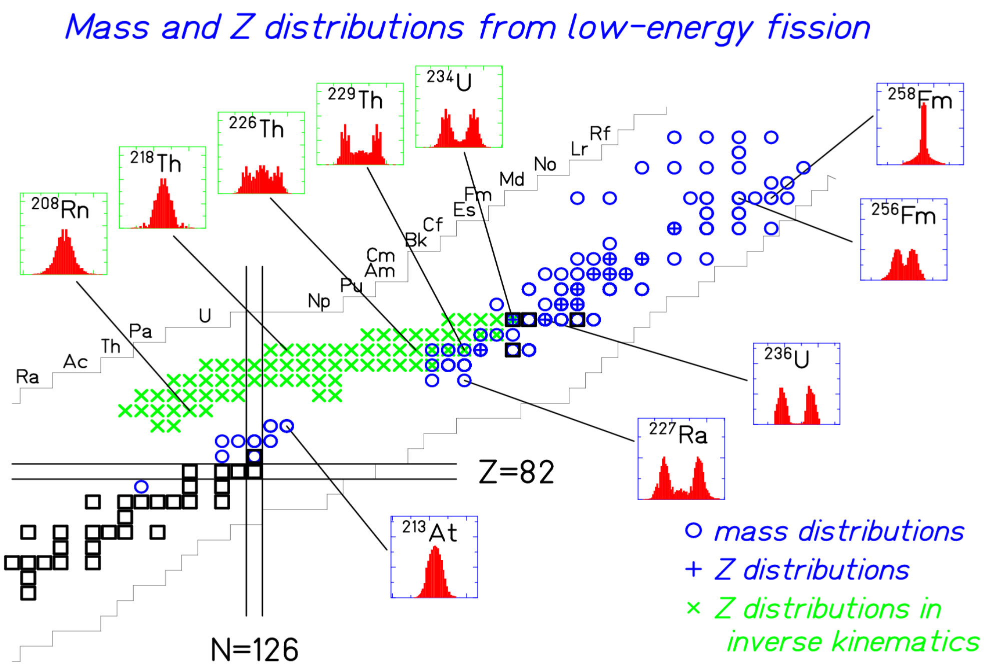
The separability principle

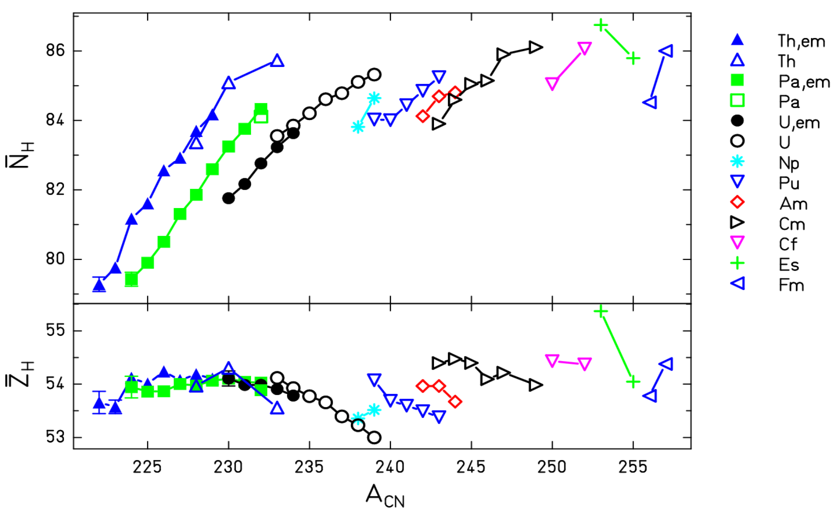




Application of the macroscopic-microscopic approach to fission:
Macroscopic potential: Property of the compound nucleus
Shell effects: Properties of nascent fragments (from outer saddle to scission)
-> The separability principle seems to work.
226Th to 260Md are described with the same shells.

Fine tuning of the parameters:
Asymmetric fission: The position of the heavy fragment



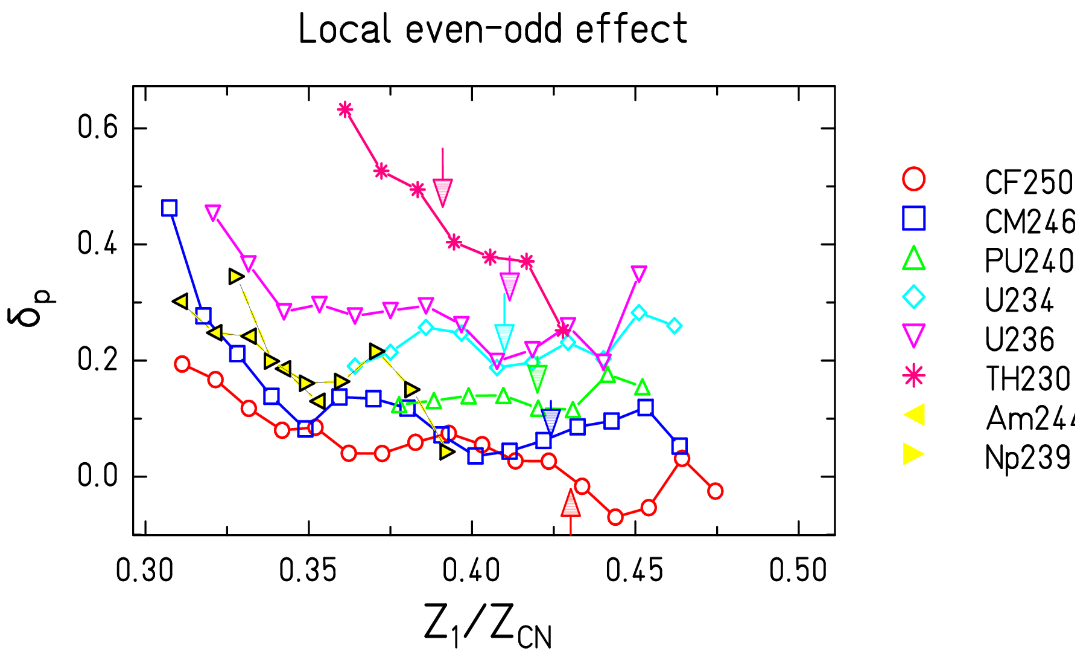


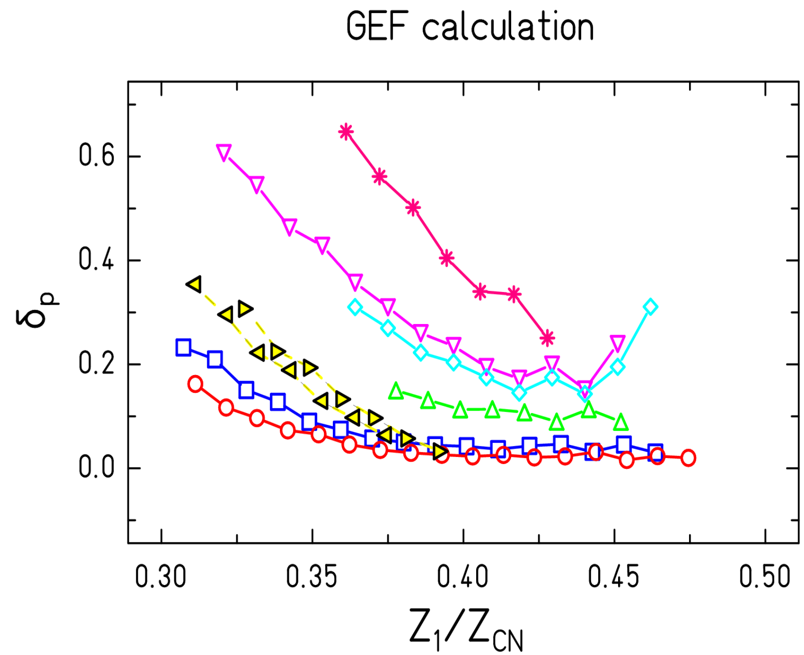
Since 1970s:
Mean position of the heavy fragment at A=140

New finding on a finer scale:
Mean position of heavy fragment at Z=54
(Böckstiegel et al., NPA 802 (2008) 12)

Even-odd effect by energy sorting

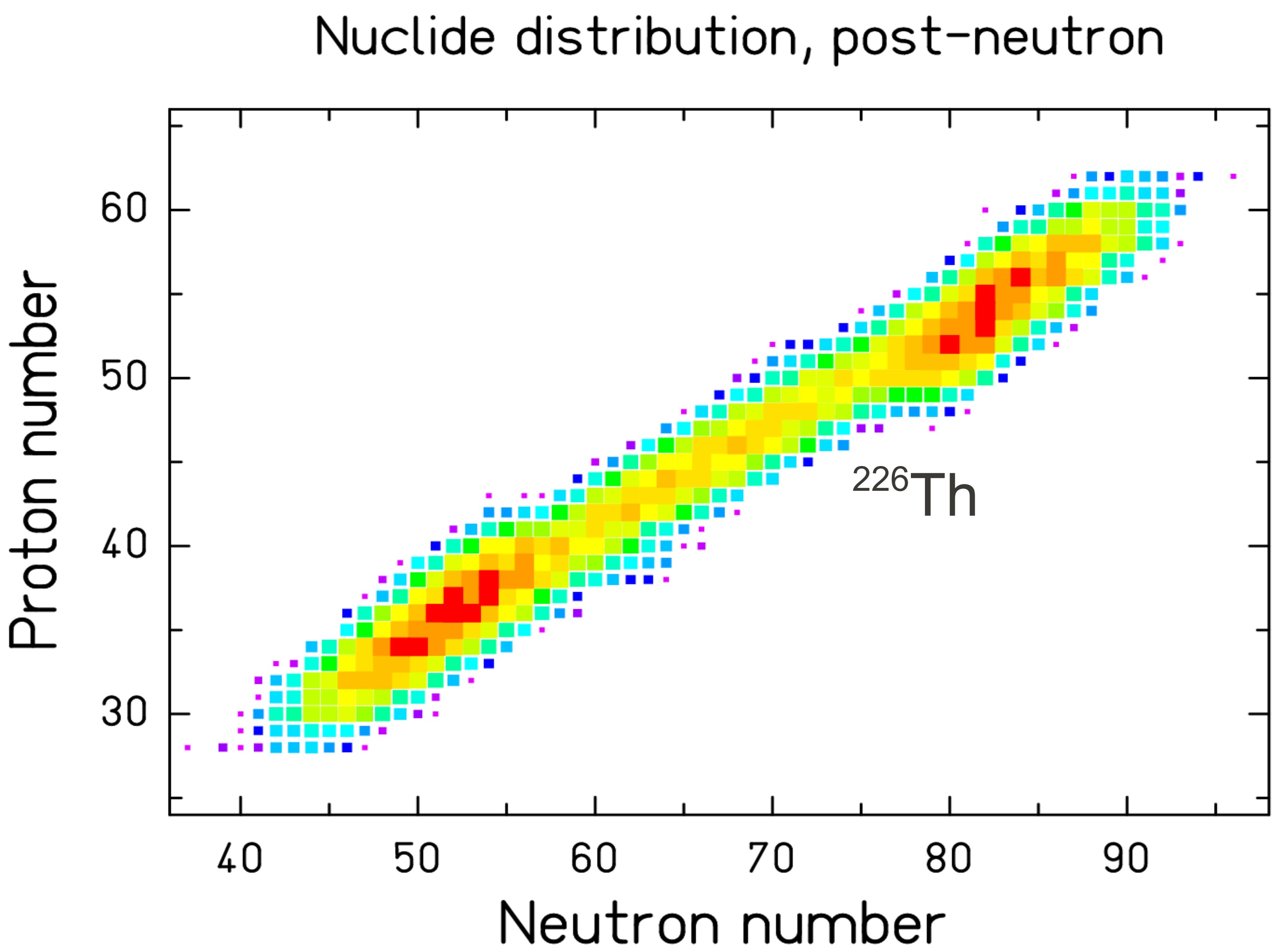
Experimental systematics on (nth,f)
(→ F. Rejmund)





At symmetry: small even-odd effect for even-Z systems
zero even-odd effect for odd-Z systems
-> Probability of completely paired configuration at scission
At large asymmetry: strong increase of even-odd effect
-> Consequence of energy sorting (-> B. Jurado)

Nuclide distribution



Parameters of the model

Many quantities determined from theory or previous work.
(e.g. energy release from saddle to scission (Asghar and Hasse),
macroscopic potential surface (Cohen)
level densities (v. Egidy), ...)

<u>S1 fission channel:</u>

Mean position in heavy fragment: **<Z> = 52.5**
Potential depth: **-4.8 MeV**
Potential curvature: **0.3 units**

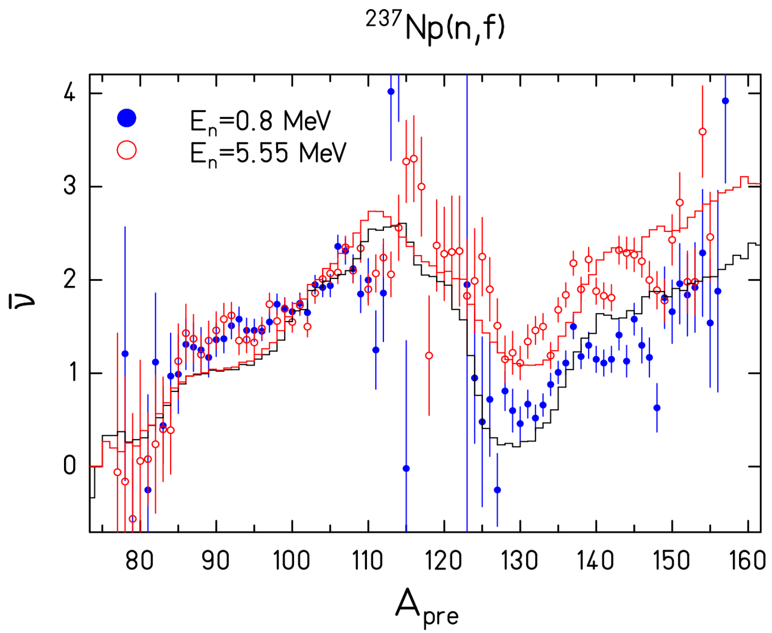
<u>S2 fission channel:</u>

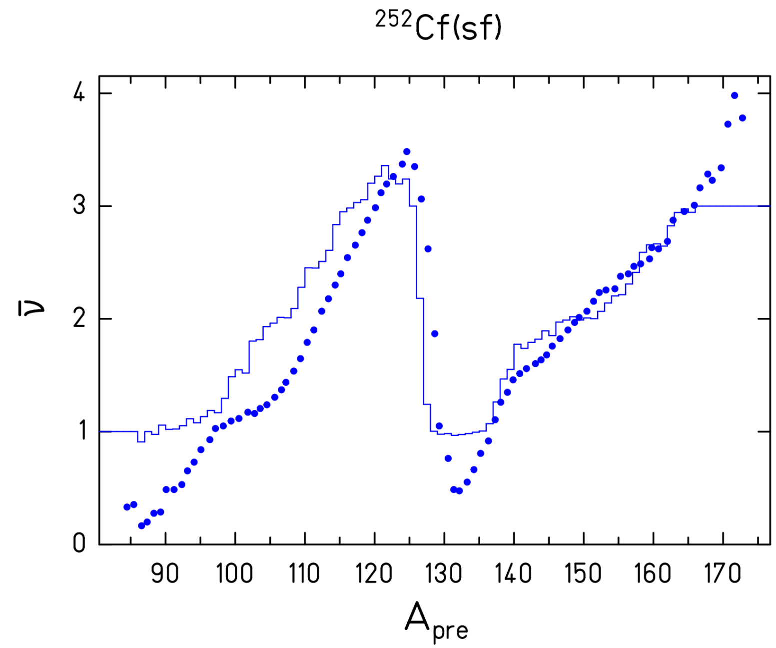
Mean position in heavy fragment: **<Z> = 55**
Potential depth: **-4.0 MeV**
Potential curvature: **0.1 units**

Saddle-scission energy dissipated into normal modes: **20%**
Saddle-scission energy dissipated into intrinsic excitations: **50%**
Threshold for asymm.-driven even-odd effect: **0.035 units** in $(T_2 - T_1)/E^*$
Neck distance: **1 fm**
Enhancement factor for charge polarization: **1.5 (!)**

(… plus a few other parameters.)

Prompt neutron emission

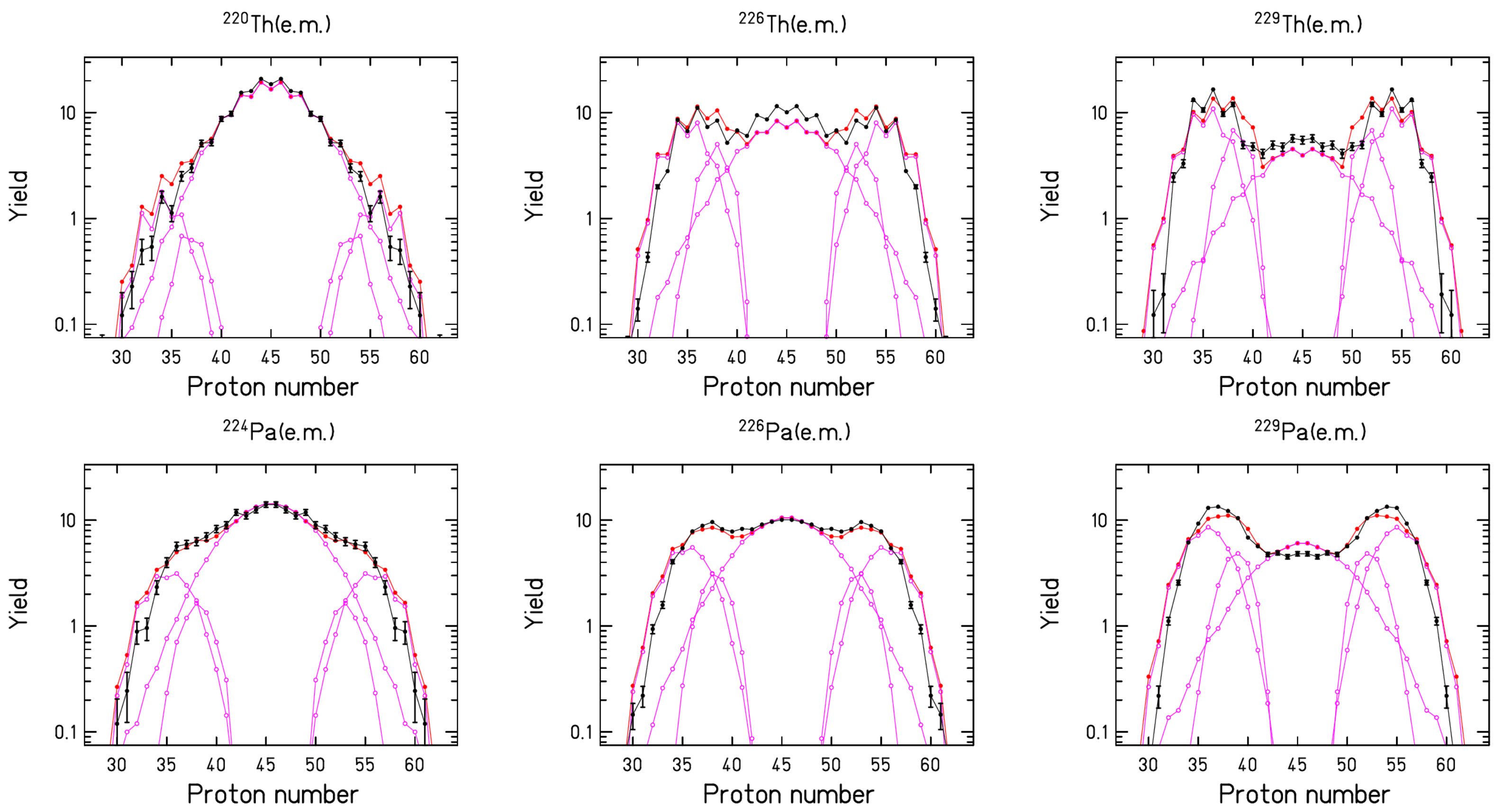




Contributions from different components at scission:

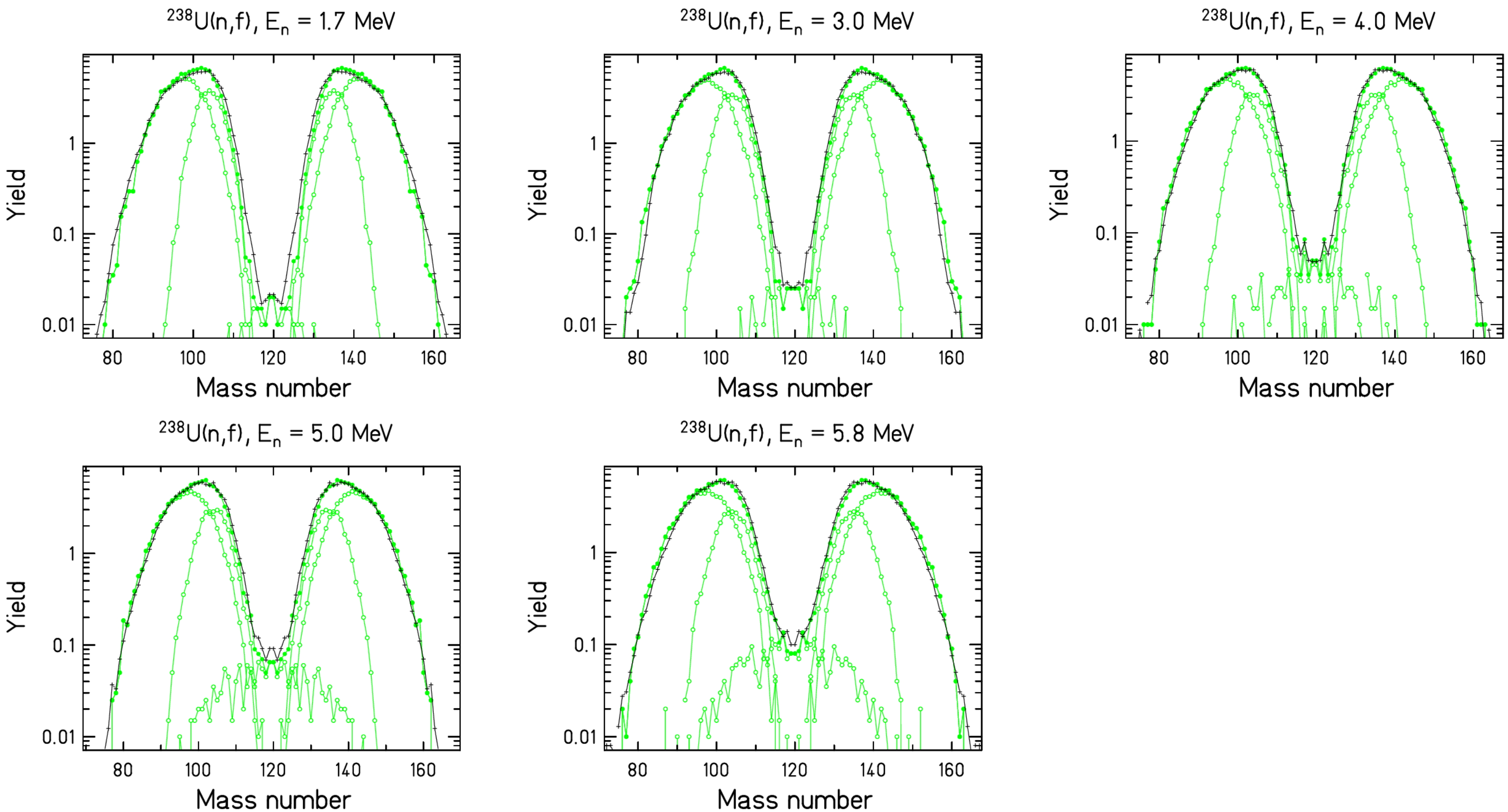
Intrinsic excitation energy (-> energy sorting)
Collective excitations (-> about equal parts)
Deformation (-> structural effects, responsible for the saw-tooth shape)

Transition from symmetric to asymmetric fission around A = 226



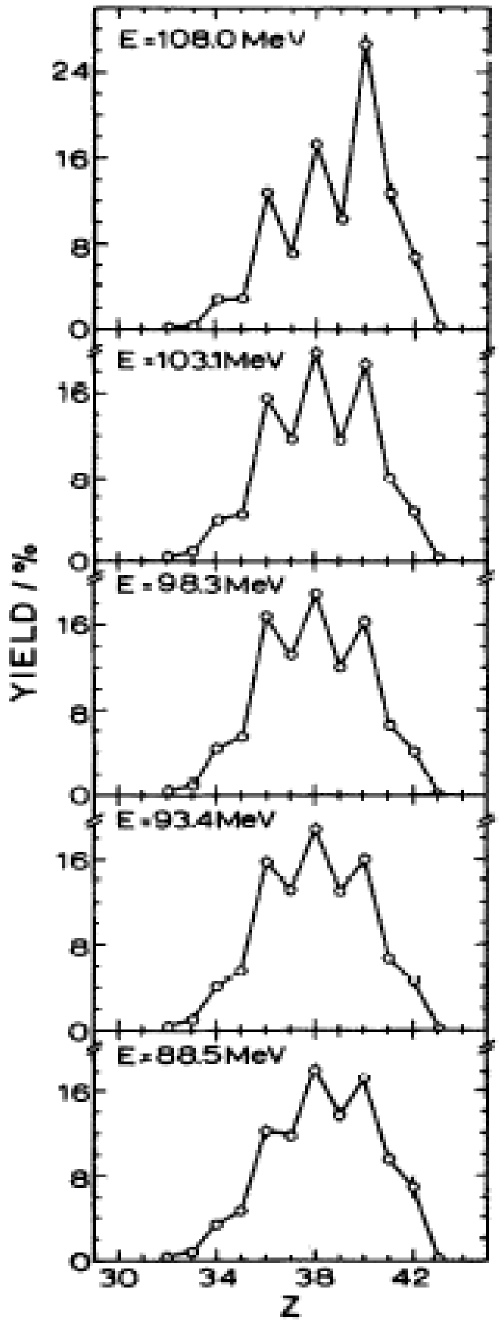
Data: Electromagnetic-induced fission, GSI experiment 2000.

$^{238}U(n,f)$, E_n from 1.7 Mev to 5.8 MeV

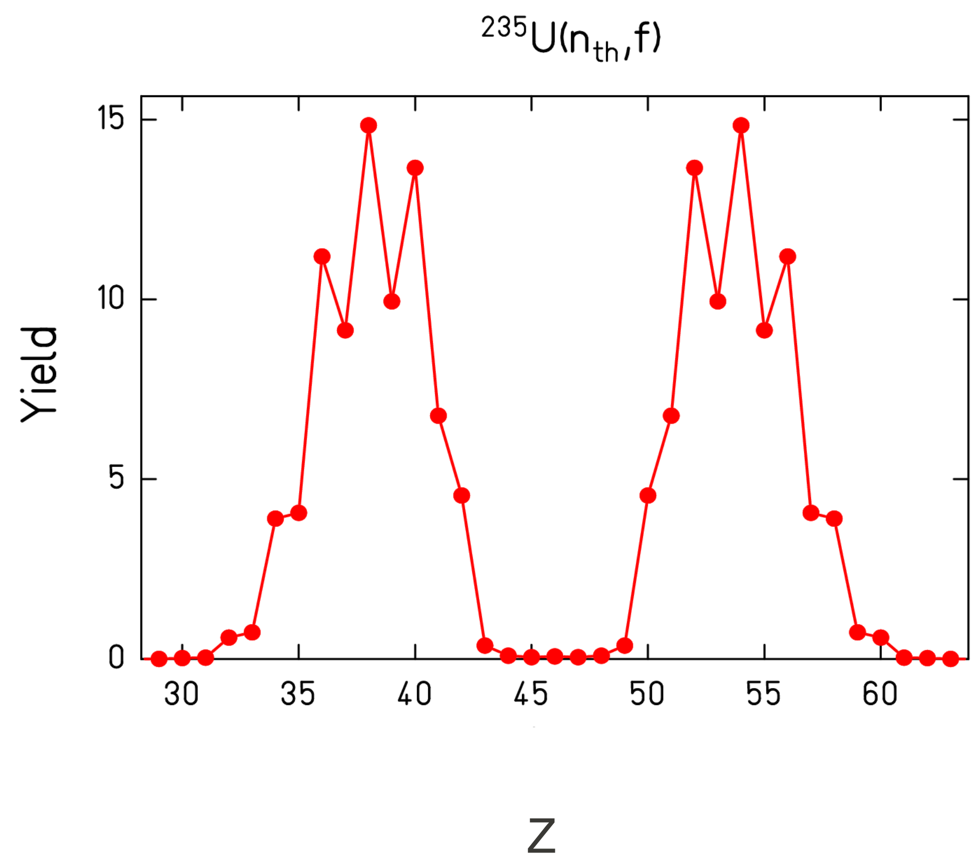


Data: Vives et al.

$^{235}U(n_{th},f)$ – Z yields

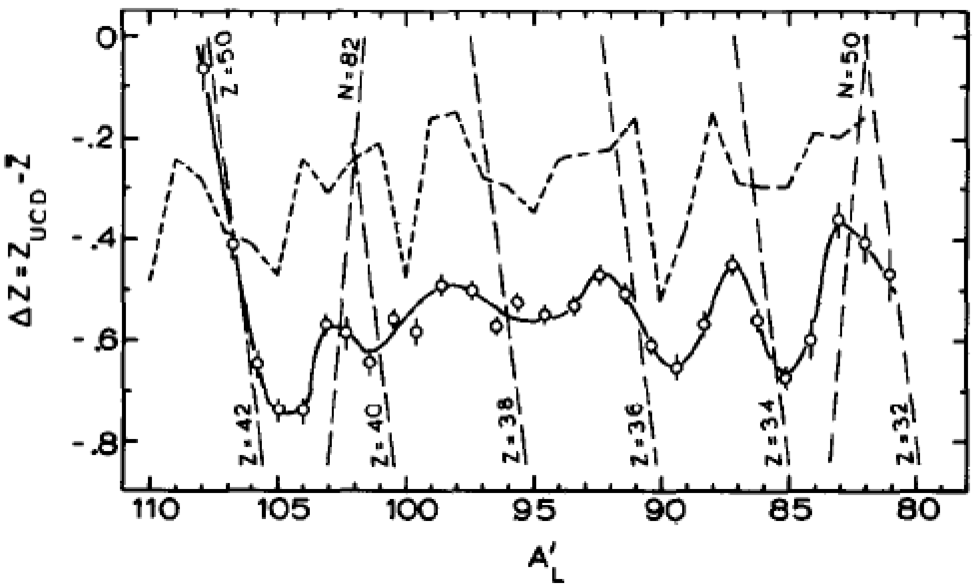


Data (Lang et al.)

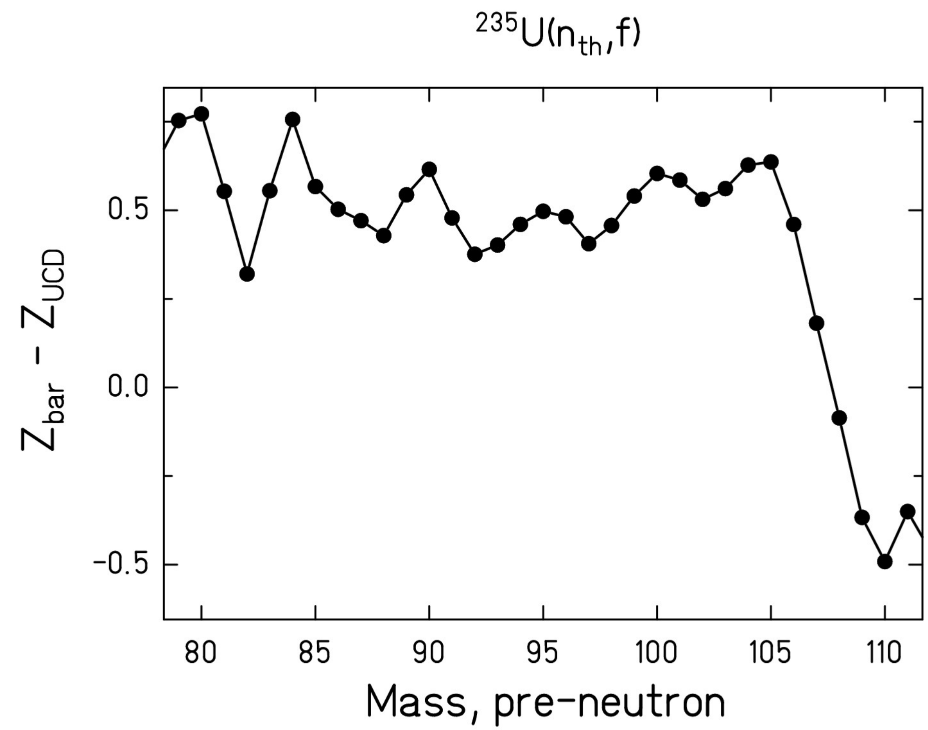


GEF code

Charge polarization - $^{235}U(n_{th},f)$

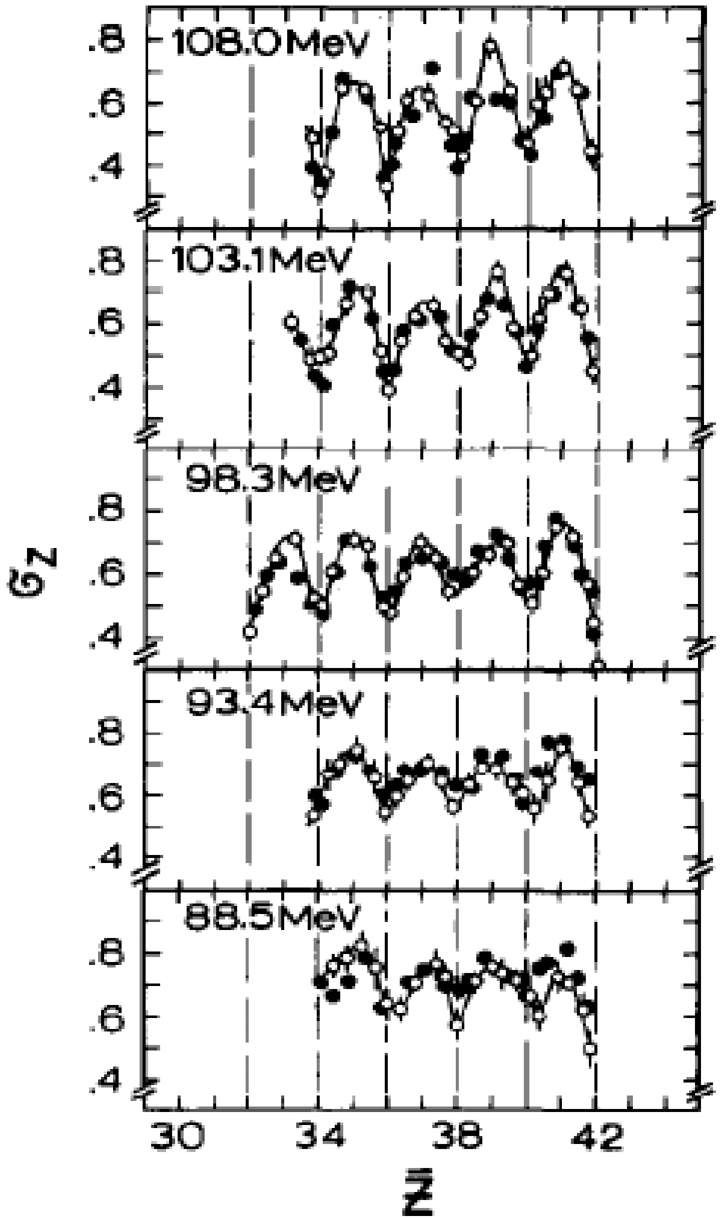


Data (Lang et al.)

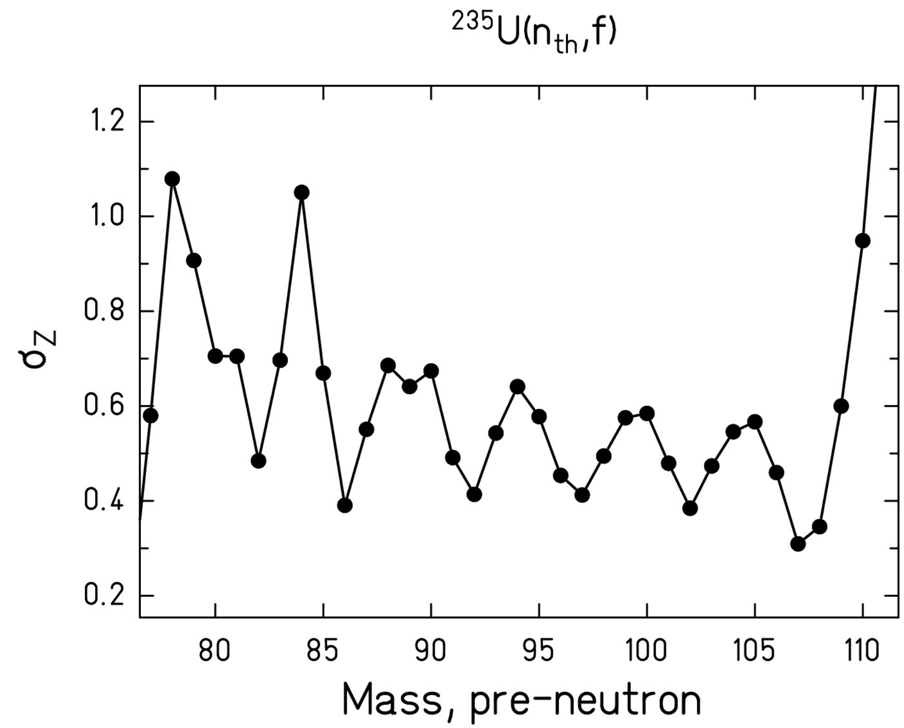


GEF code

Width of isobaric charge distributions - $^{235}U(n_{th},f)$

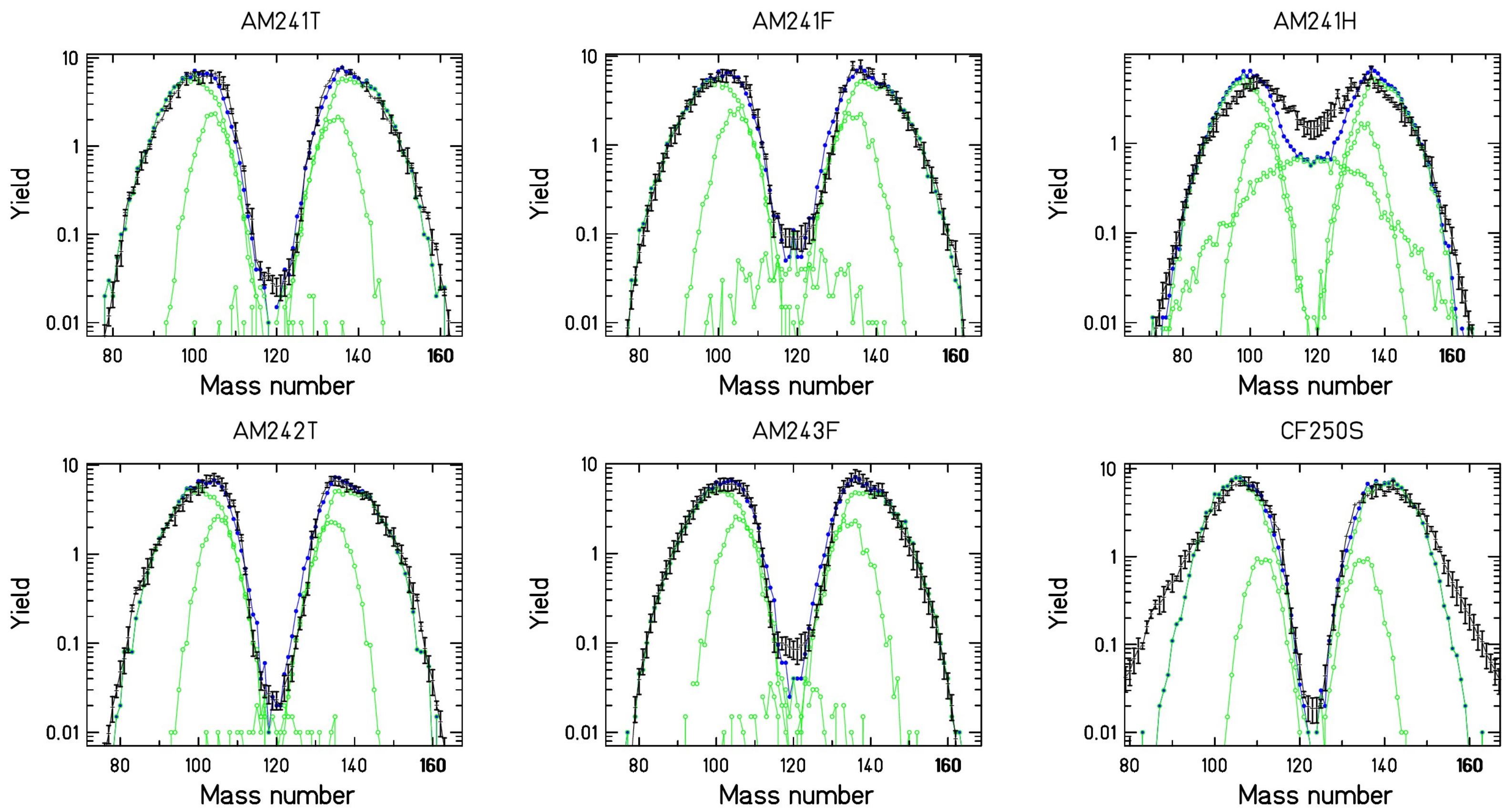


Data (Lang et al.)



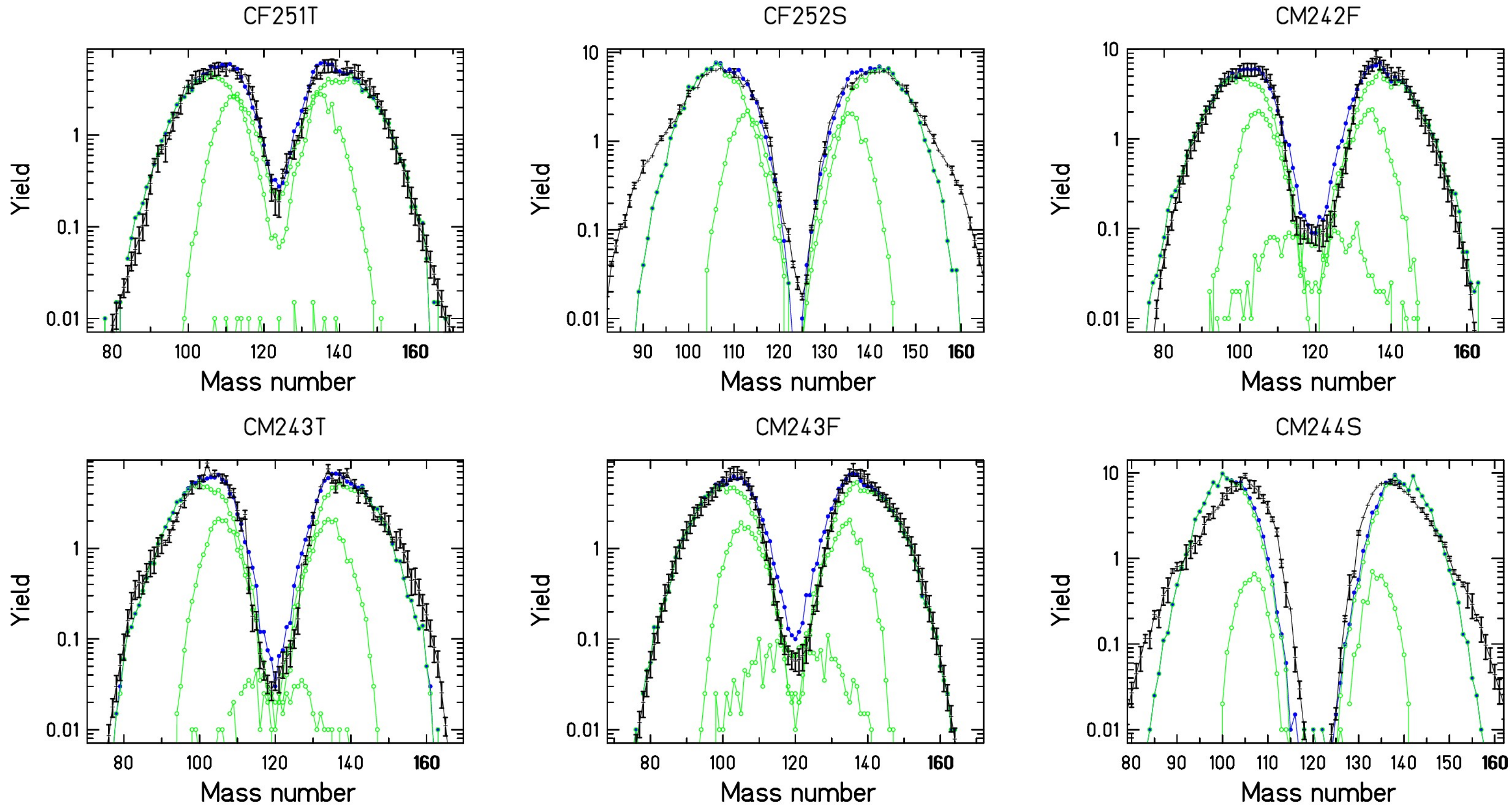
GEF code

Mass yields - comparison with England and Rider 1



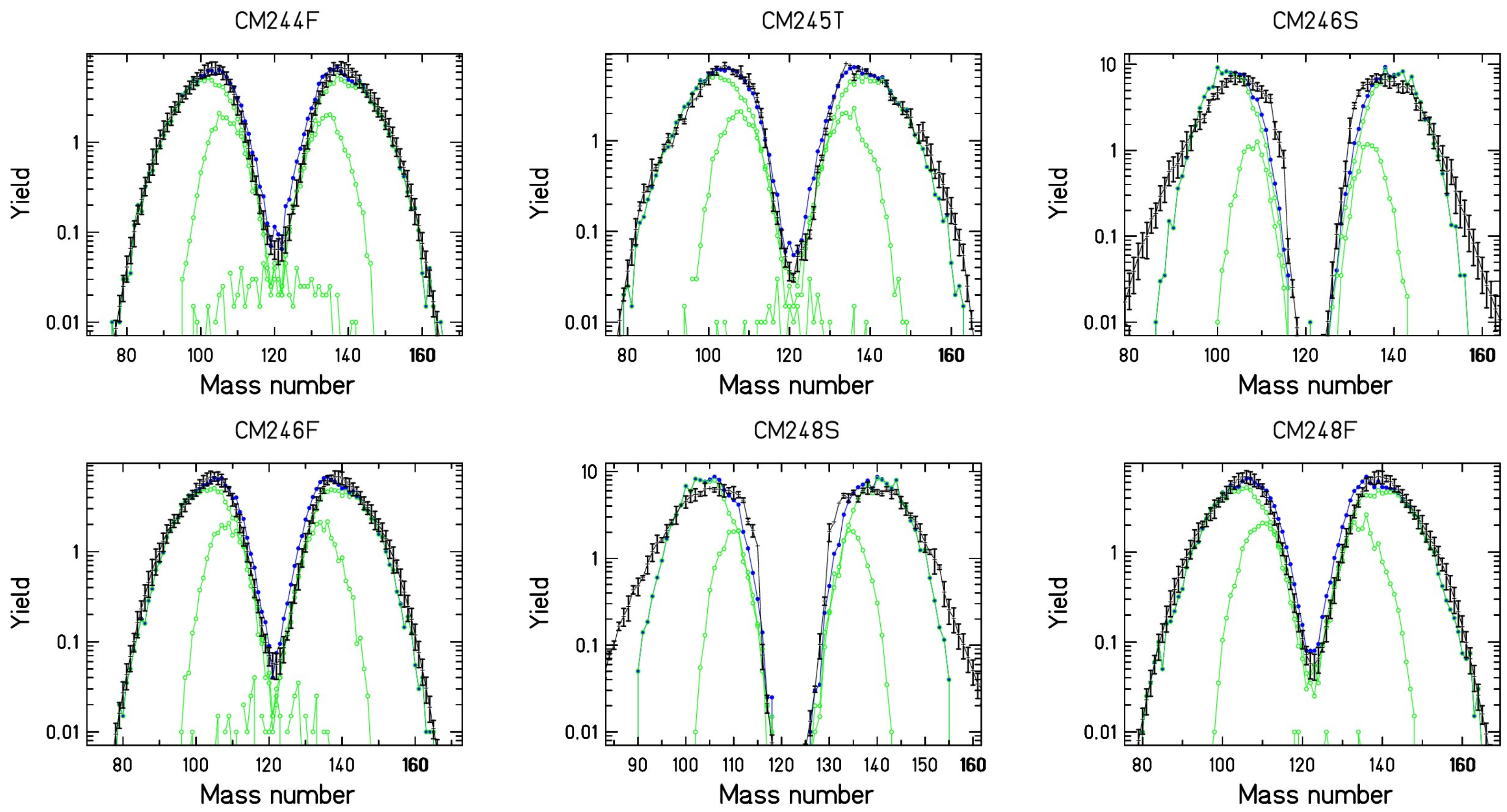
S : spontaneous fission, T: thermal, F: fast neutrons, H: 14 MeV neutrons

Mass yields - comparison with England and Rider 2



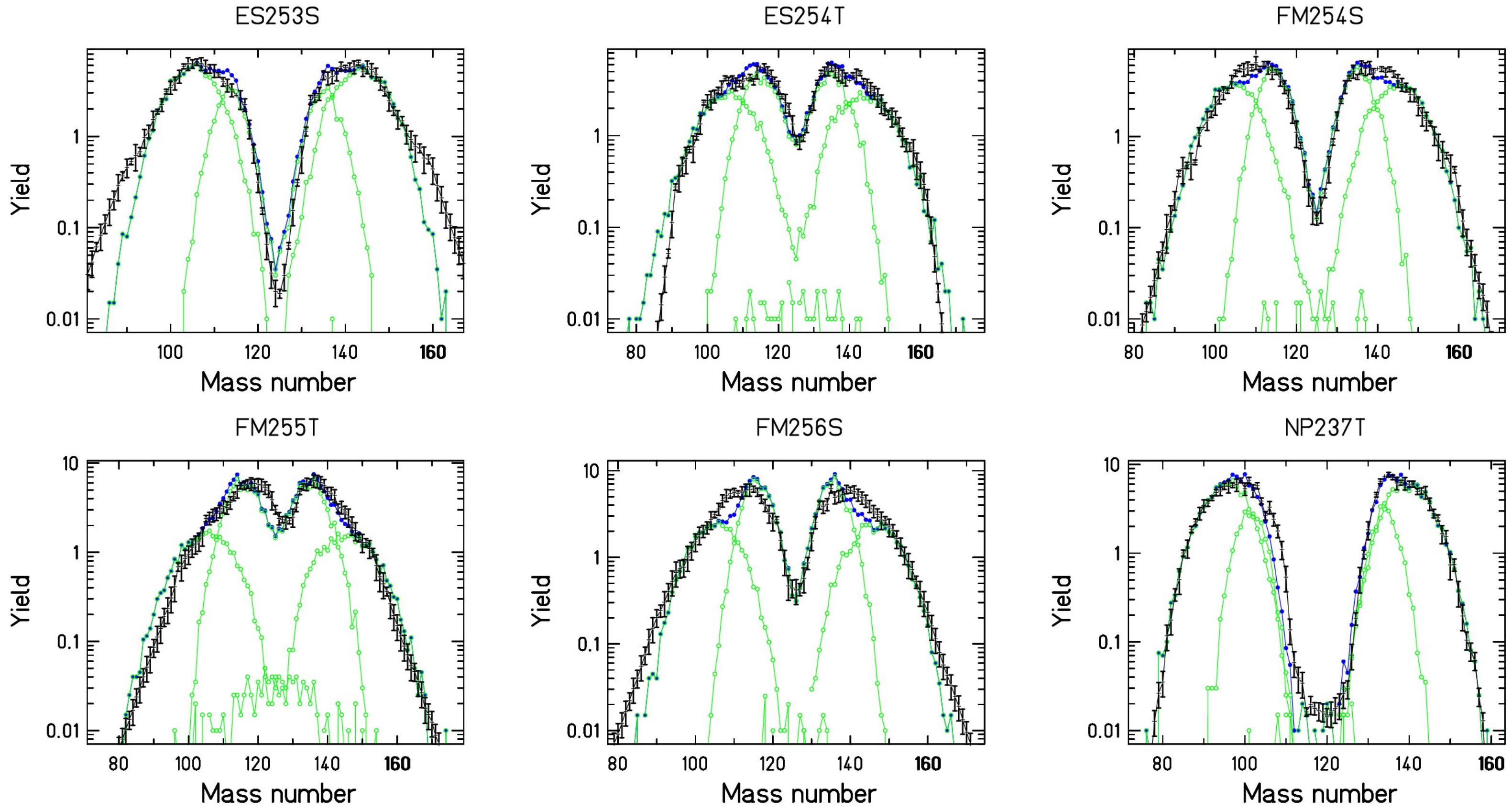
S : spontaneous fission, T: thermal, F: fast neutrons, H: 14 MeV neutrons

Mass yields - comparison with England and Rider 3



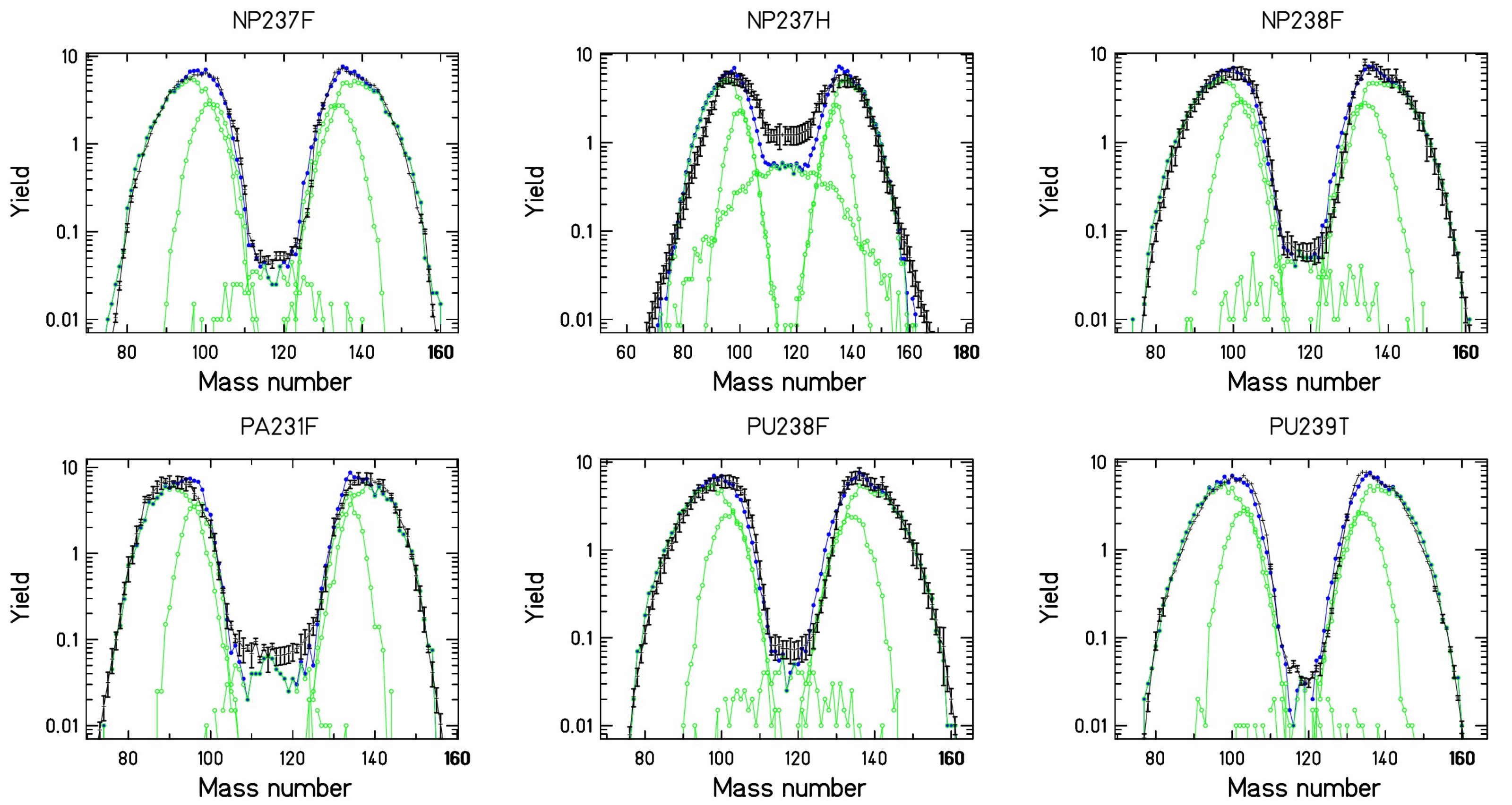
S : spontaneous fission, T: thermal, F: fast neutrons, H: 14 MeV neutrons

Mass yields - comparison with England and Rider 4



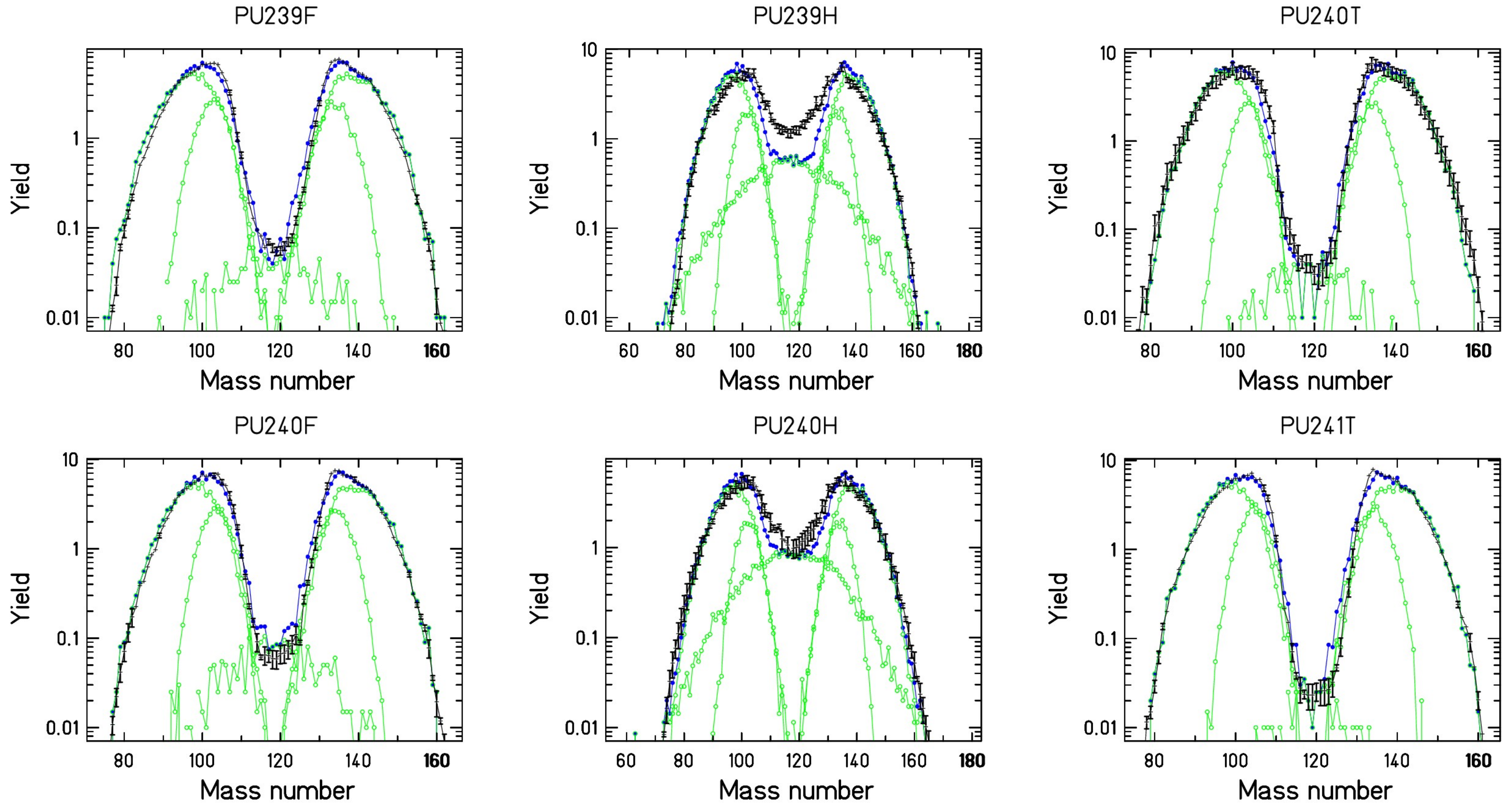
S : spontaneous fission, T: thermal, F: fast neutrons, H: 14 MeV neutrons

Mass yields - comparison with England and Rider 5



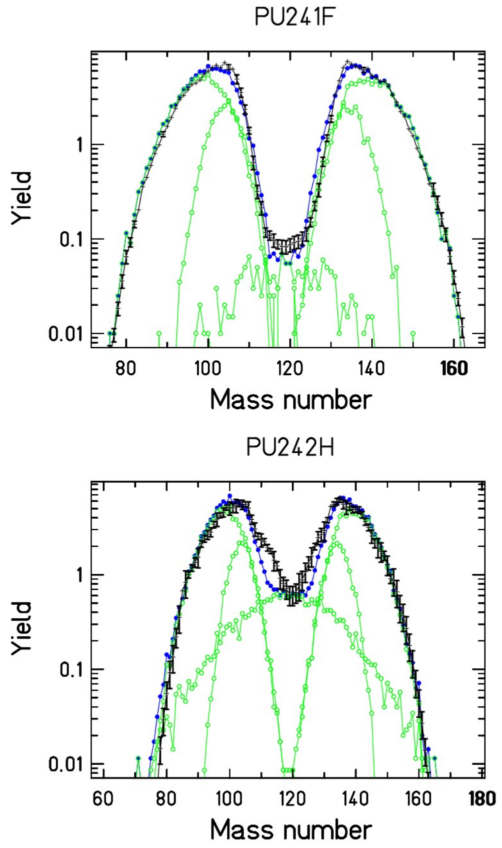
S : spontaneous fission, T: thermal, F: fast neutrons, H: 14 MeV neutrons

Mass yields - comparison with England and Rider 6



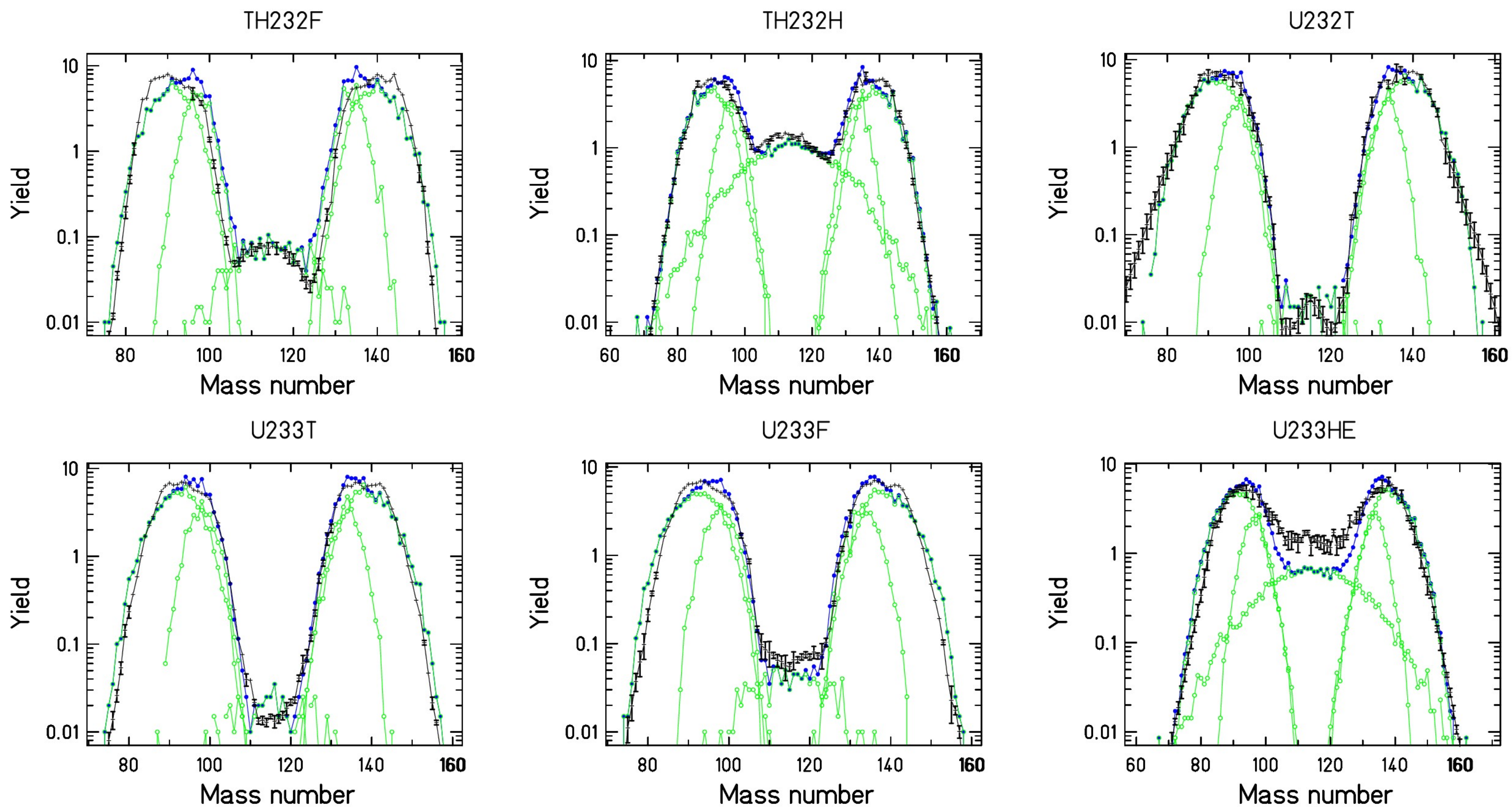
S : spontaneous fission, T: thermal, F: fast neutrons, H: 14 MeV neutrons

Mass yields - comparison with England and Rider 7



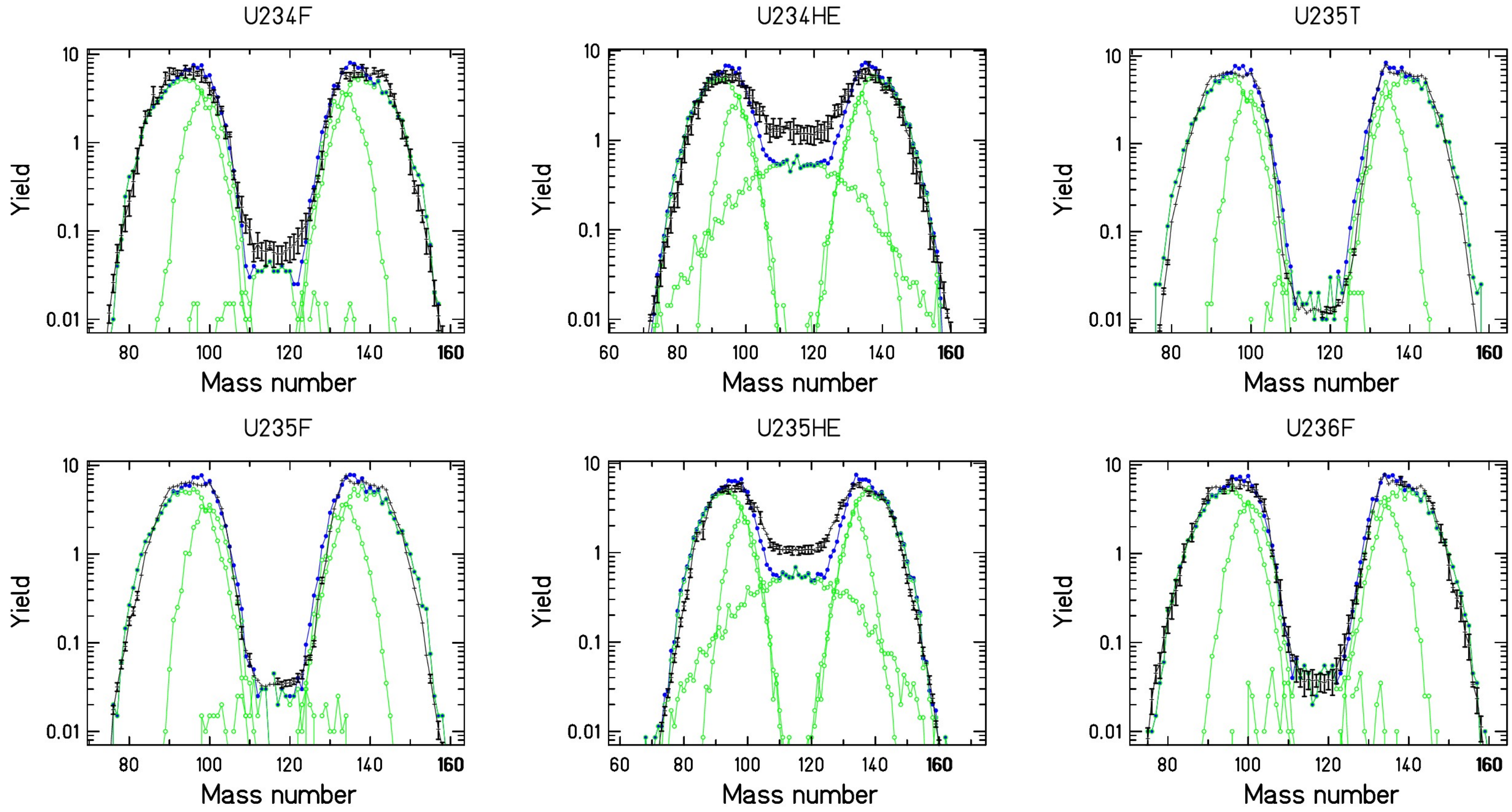
S : spontaneous fission, T: thermal, F: fast neutrons, H: 14 MeV neutrons

Mass yields - comparison with England and Rider 8



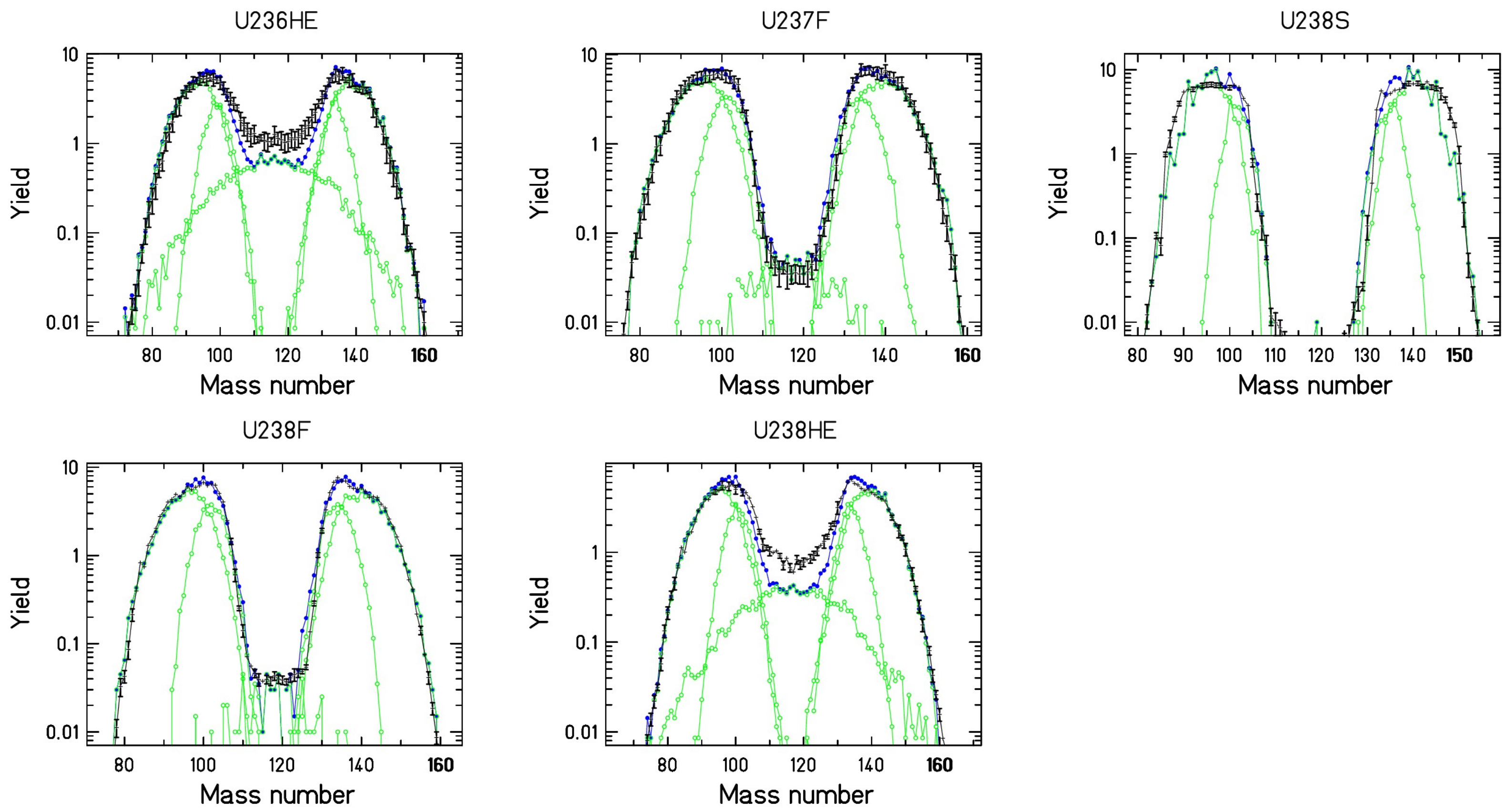
S : spontaneous fission, T: thermal, F: fast neutrons, H: 14 MeV neutrons

Mass yields - comparison with England and Rider 9



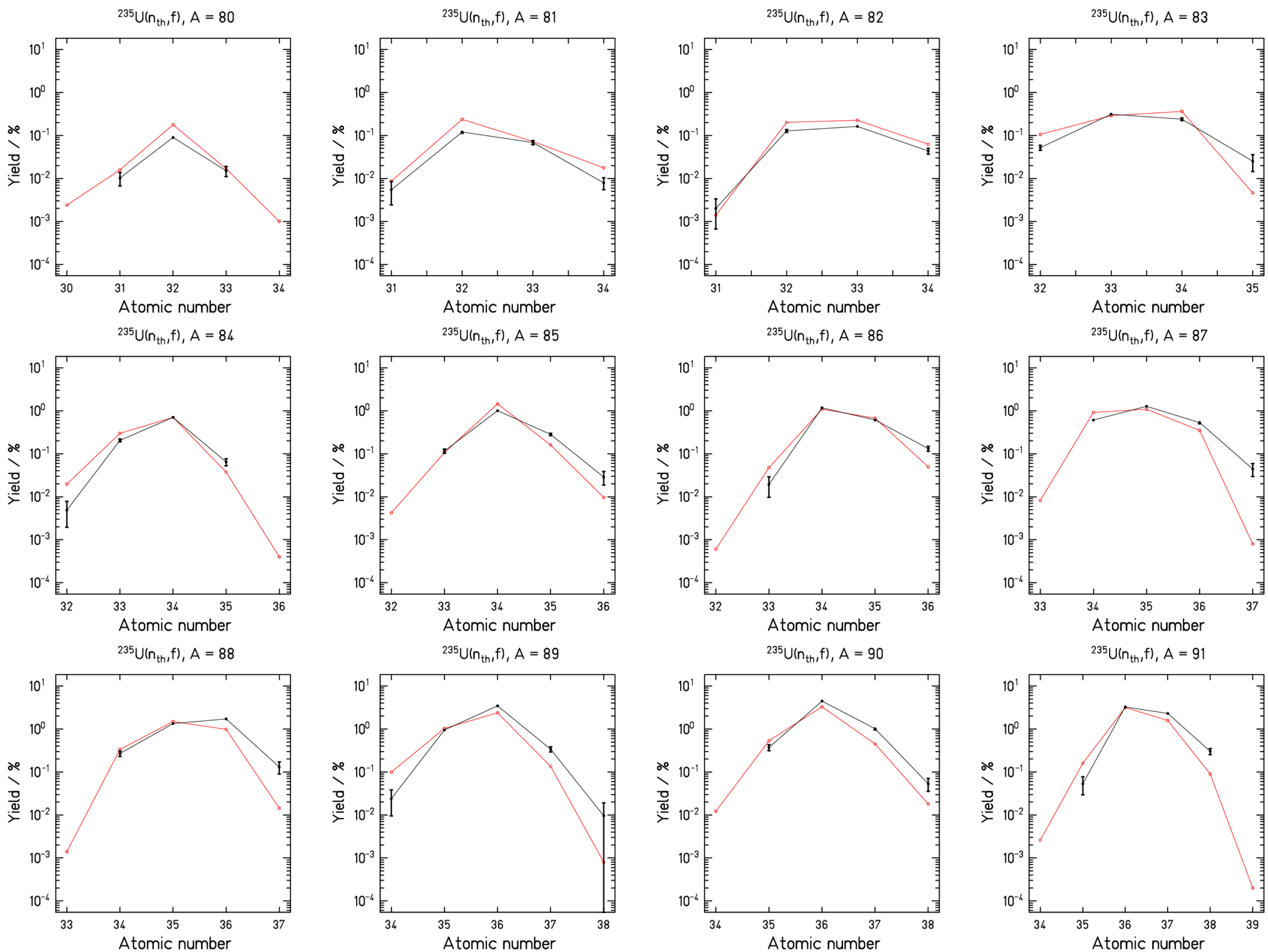
S : spontaneous fission, T: thermal, F: fast neutrons, H: 14 MeV neutrons

Mass yields - comparison with England and Rider 10

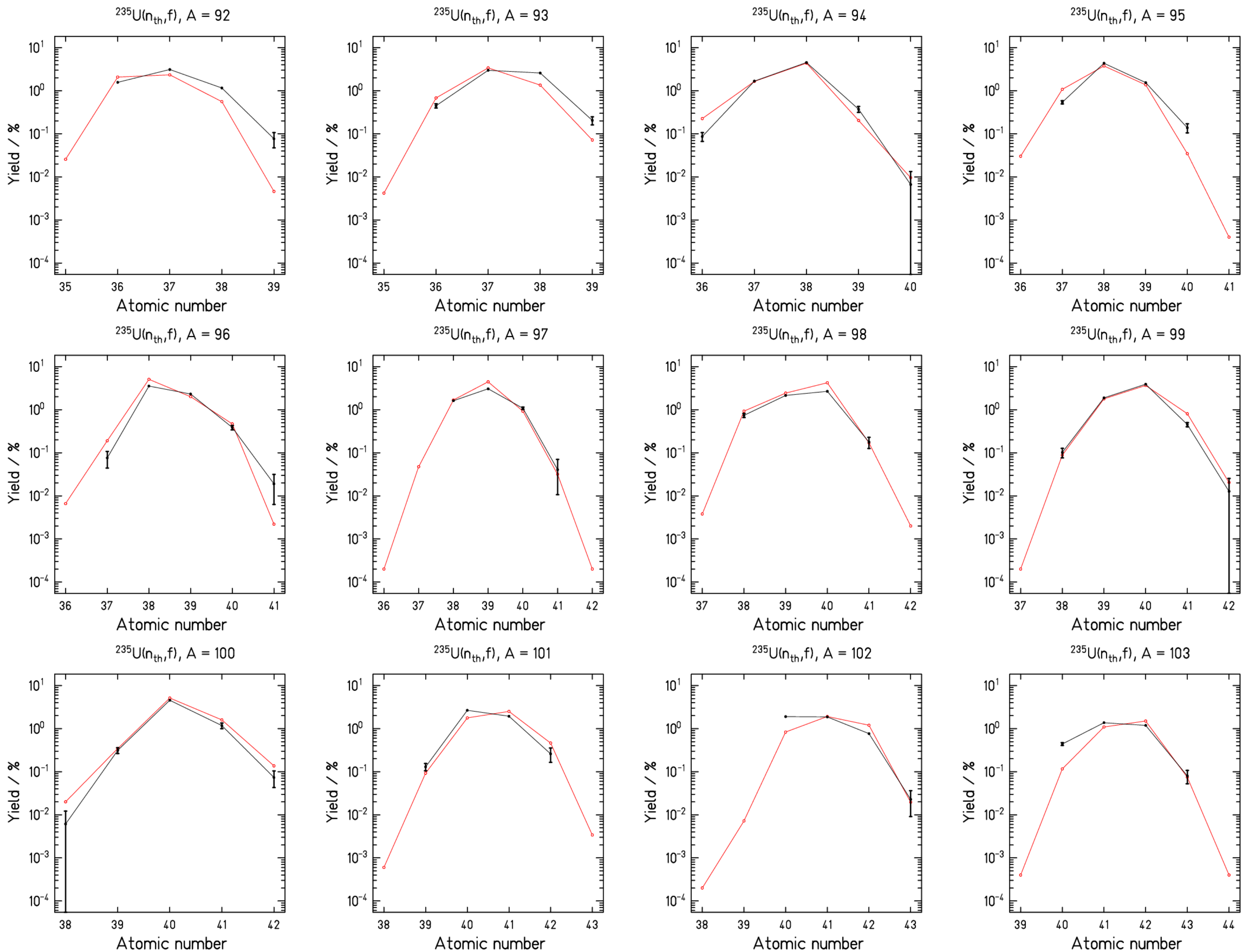


S : spontaneous fission, T: thermal, F: fast neutrons, H: 14 MeV neutrons

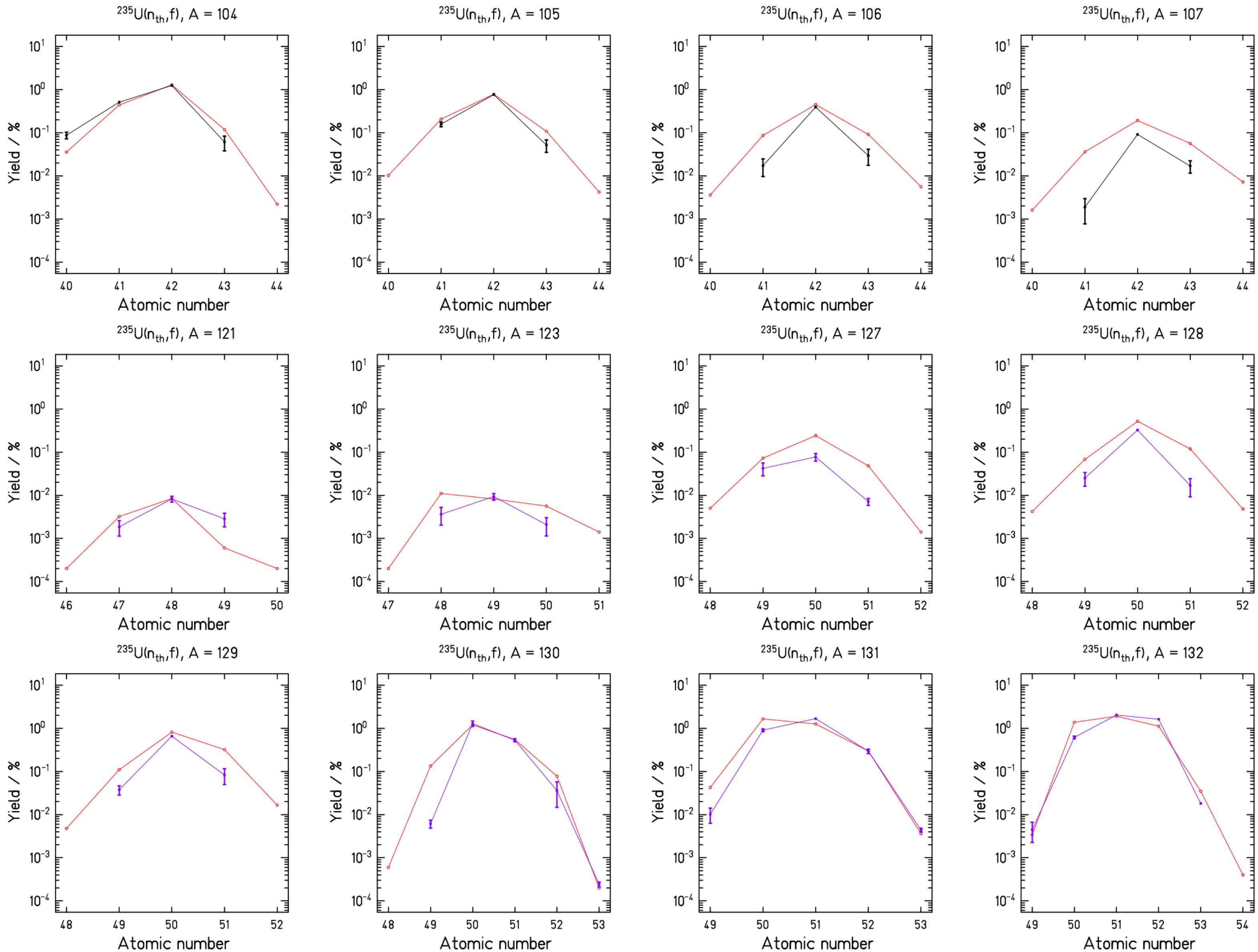
$^{235}U(n_{th},f)$ – nuclide yields - 1



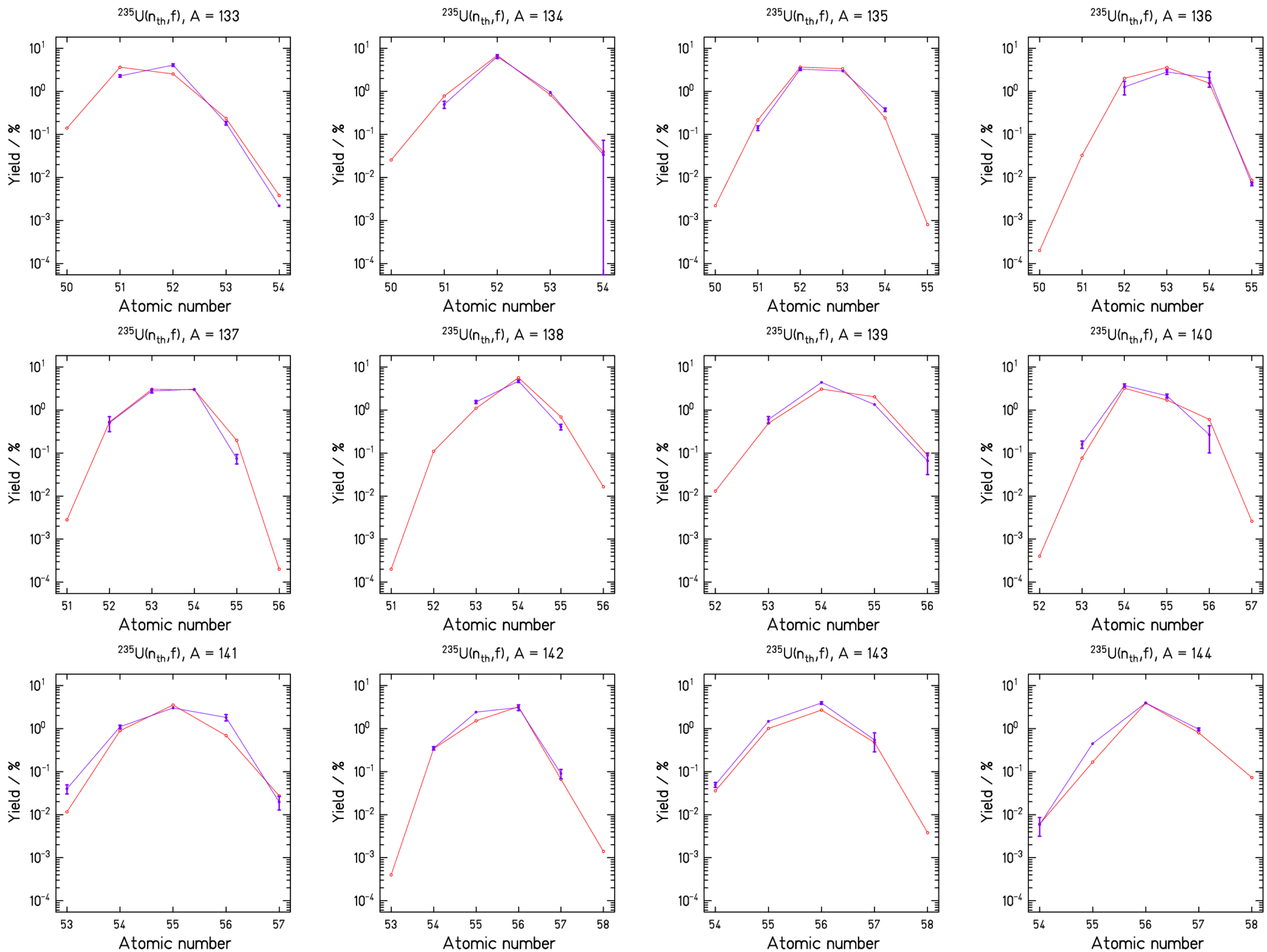
$^{235}U(n_{th},f)$ – nuclide yields - 2



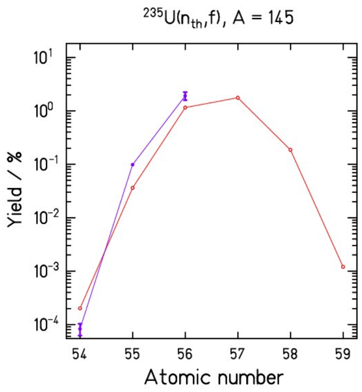
$^{235}U(n_{th},f)$ – nuclide yields - 3

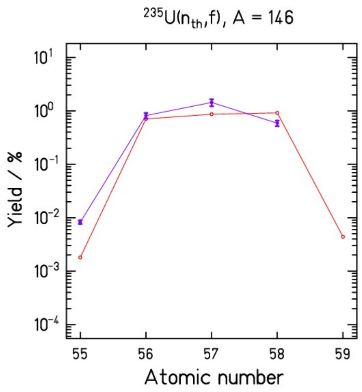


^{235}U(n_{th},f) – nuclide yields - 4

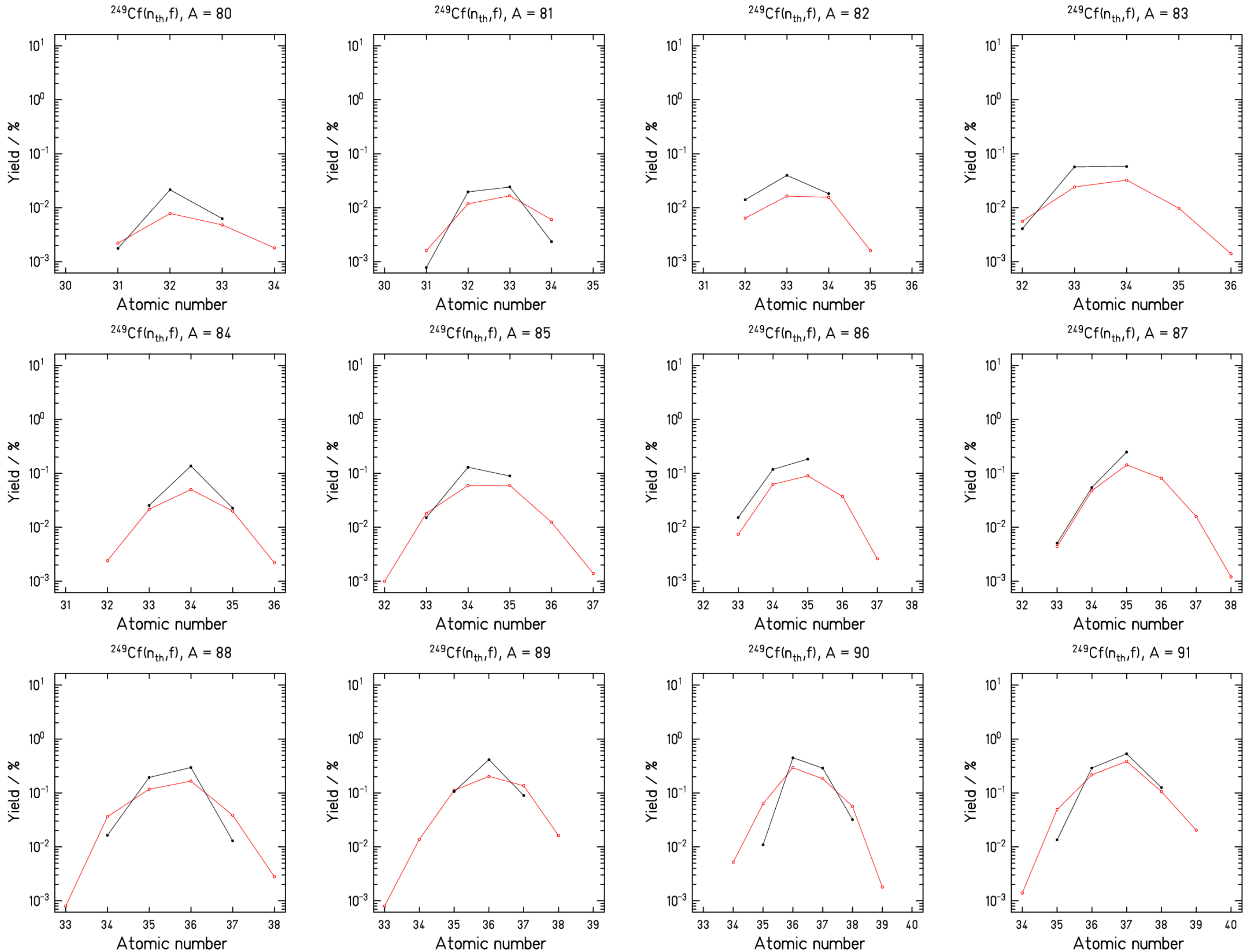


$^{235}U(n_{th},f)$ – nuclide yields - 5

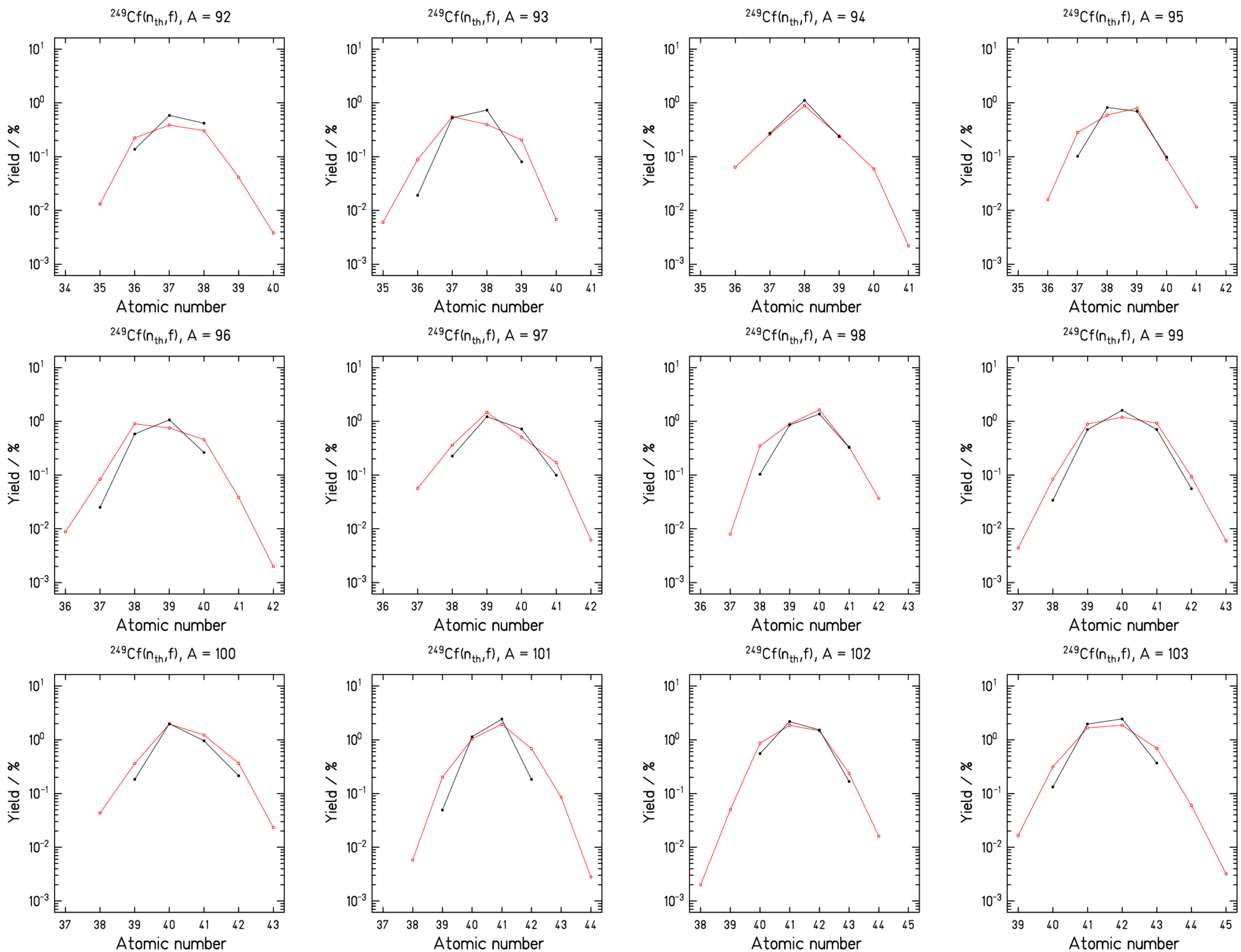




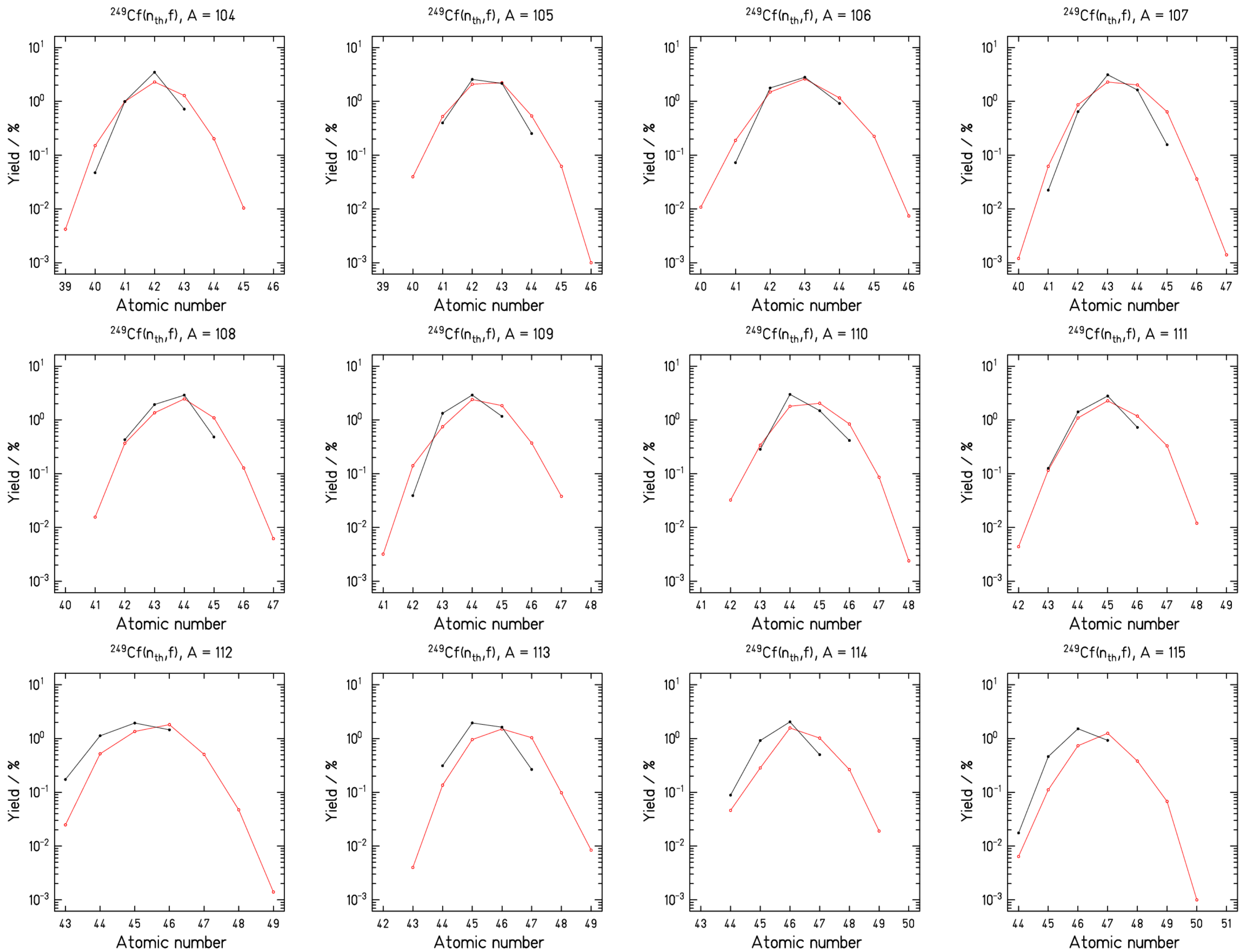
^{249}Cf(n$_{th}$,f) – nuclide yields - 1



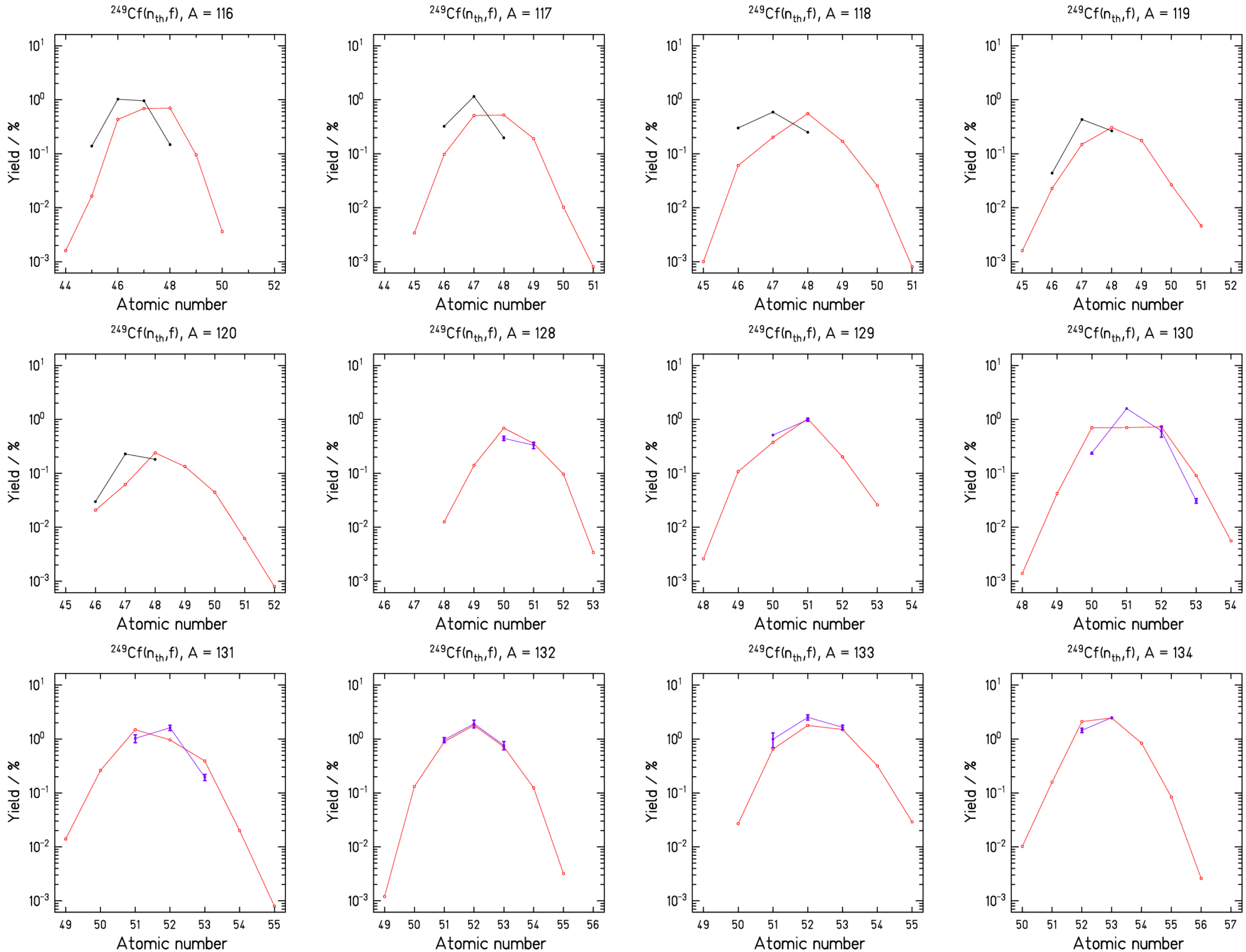
$^{249}Cf(n_{th},f)$ – nuclide yields - 2



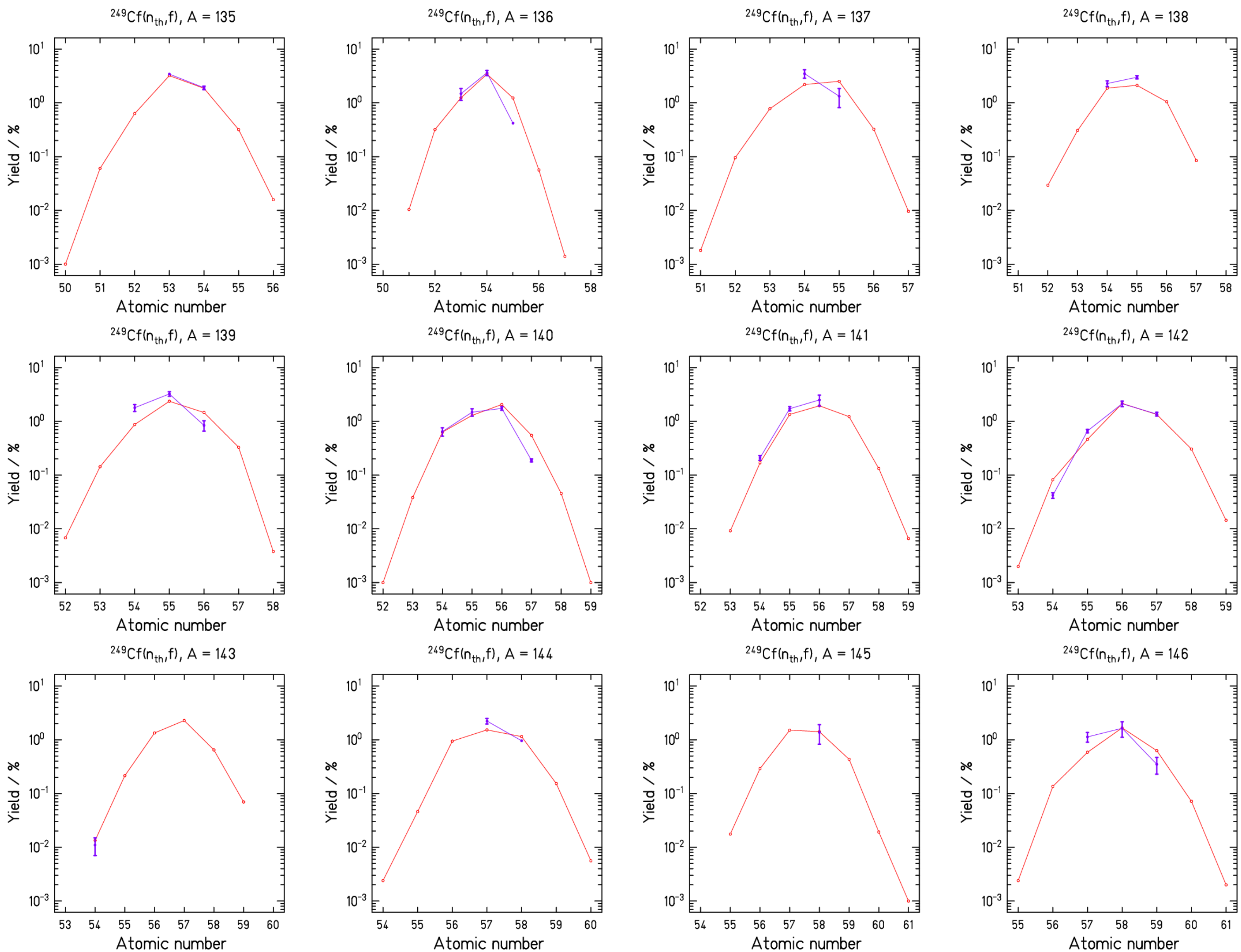
$^{249}Cf(n_{th},f)$ – nuclide yields - 3



$^{249}Cf(n_{th},f)$ – nuclide yields - 4



$^{249}Cf(n_{th},f)$ – nuclide yields - 5



Summary

Ingredients of the GEF code:

- Statistical population of states in the fission valleys at dynamical freeze-out.
- Separability principle governs interplay of macroscopic and microscopic effects.
- Three fission channels, constant positions in Z (heavy fragment).
- Empirical stiffness against mass asymmetry.
- Coupling of saddle-scission energy release to collective and intrinsic excitations.
- Energy sorting determines division of intrinsic energy between fragments.
- Final step of energy sorting creates asymmetry-associated even-odd effect.
- Statistical evaporation code with gamma competition.

Achievements:

- Consistent description from polonium to fermium with the same parameter set.
- From spontaneous fission to $E^* = 14$ MeV.
- Most parameters fixed from independent sources, only <20 free parameters.
- Very good reproduction of experiments and high predictive power.
- Combines some advantages of empirical and microscopical models.
- May be useful for nuclear technology.
- Particularities in superfluid regime (energy sorting; even-odd effect) discovered.
- New insight into dynamical times (energy transfer, proton exchange).

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