Peculiar quantal and statistical effects in nuclear fission

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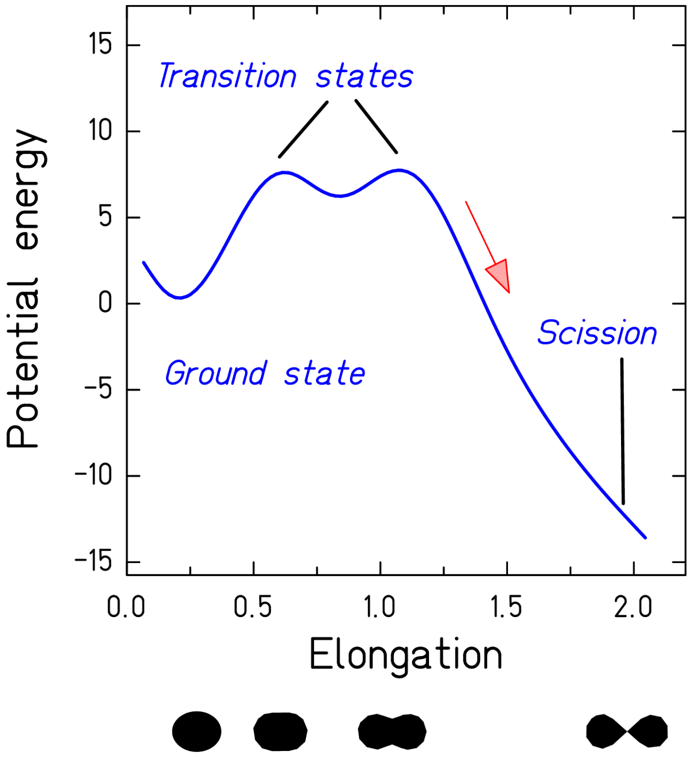
Some orientation

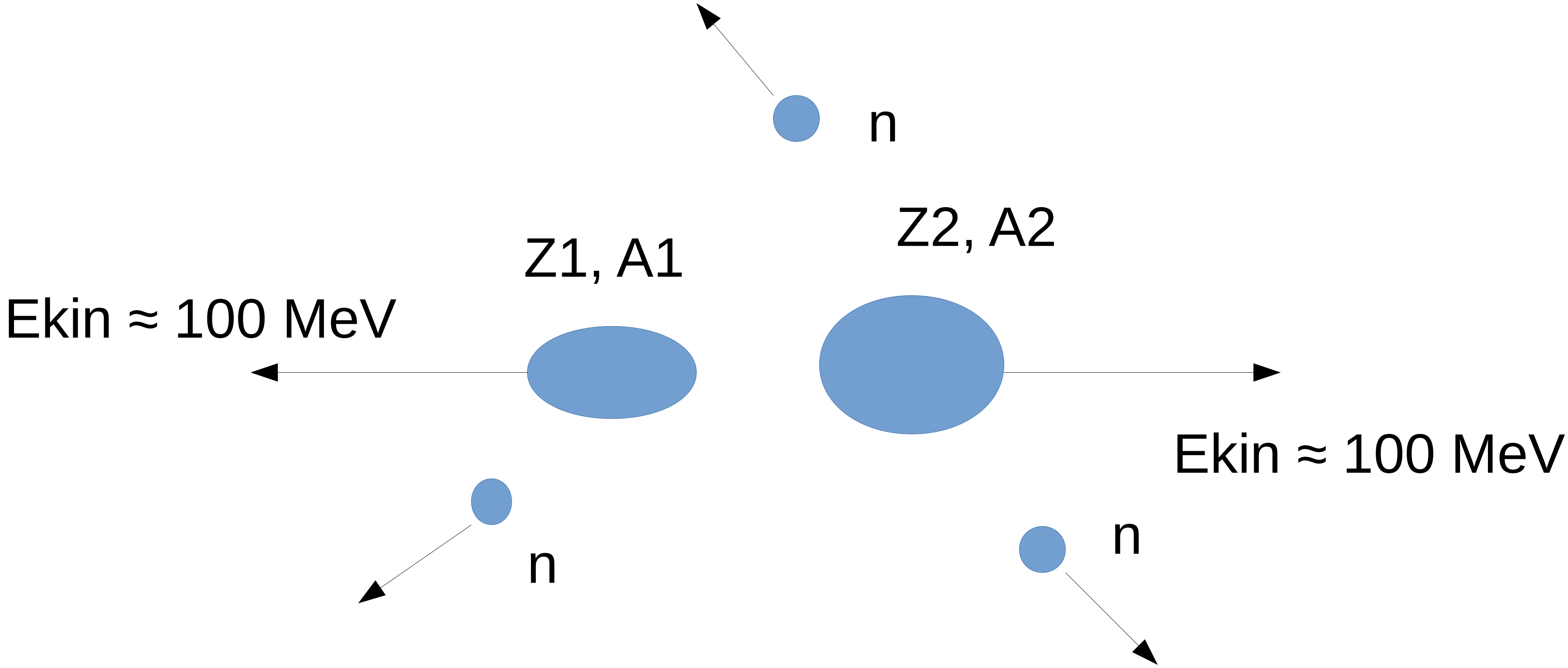
This talk is not specific about nuclear fission, but the fission process provides specific conditions for the observation of the peculiar effects, I will speak about.

What we have to know about fission



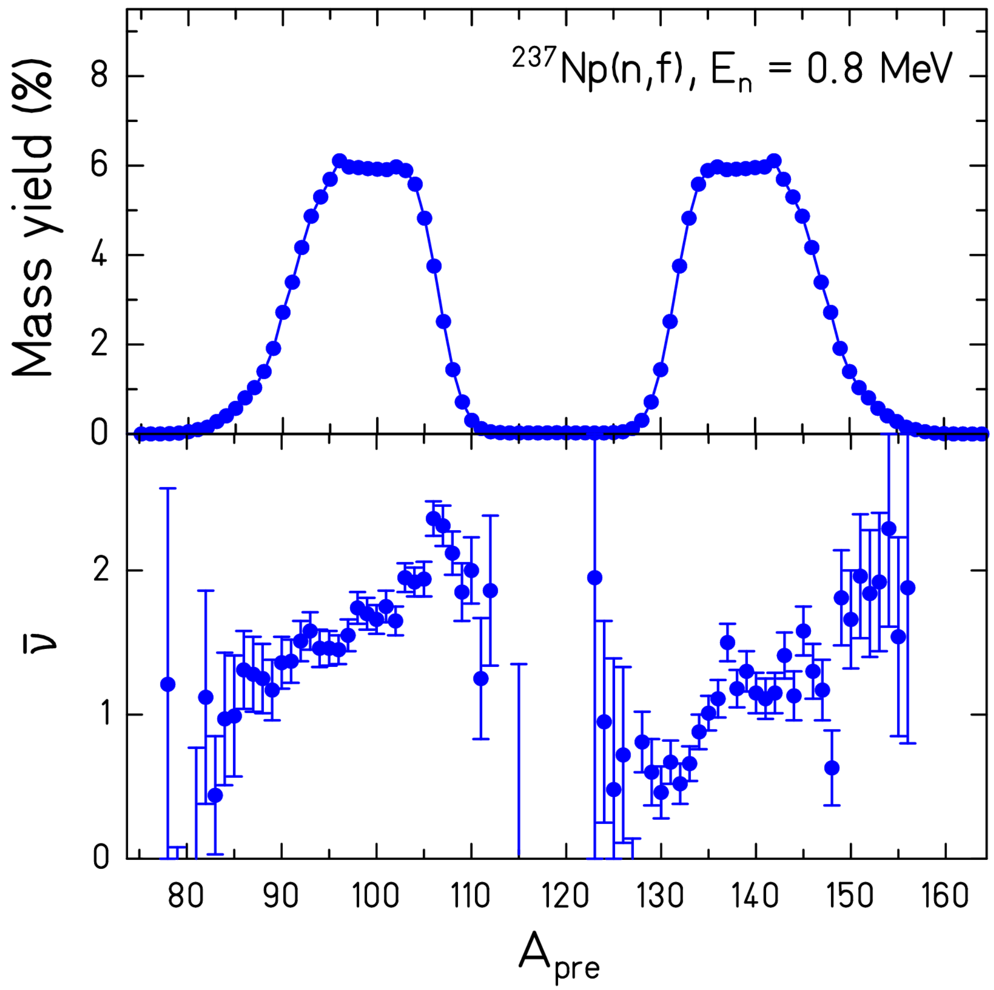
- In the fission process, a heavy nucleus escapes from the minimum in its metastable compact (ground) state and evolves to a di-nuclear system (2 nascent fragments connected by a neck), before it fissions.
- The velocities of the nascent fragments before scission are low (much lower than the Fermi velocity).

What can be observed?

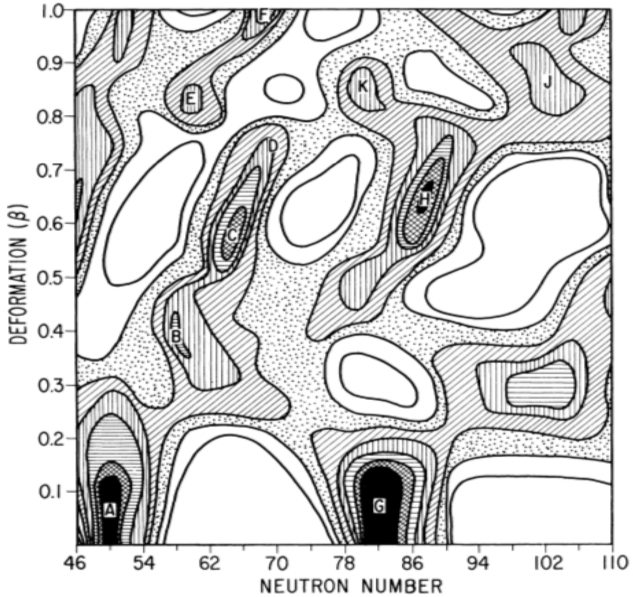


- Fission-fragments (Z,A,Ekin),
- Neutrons emitted from the fragments (number, energies)
- Gammas emitted from the fragments (number, energies)

Nu-bar over Apre



Saw-tooth behaviour is understood (deformation energy due to shell effects near scission):



- Mass yields from GEF,
- nu-bar from Naqvi et al., PRC 34 (1986) 218

Neutron shells on N-beta plain from Wilkins et al., PRC 14 (1976) 1832

Even-odd staggering in Z

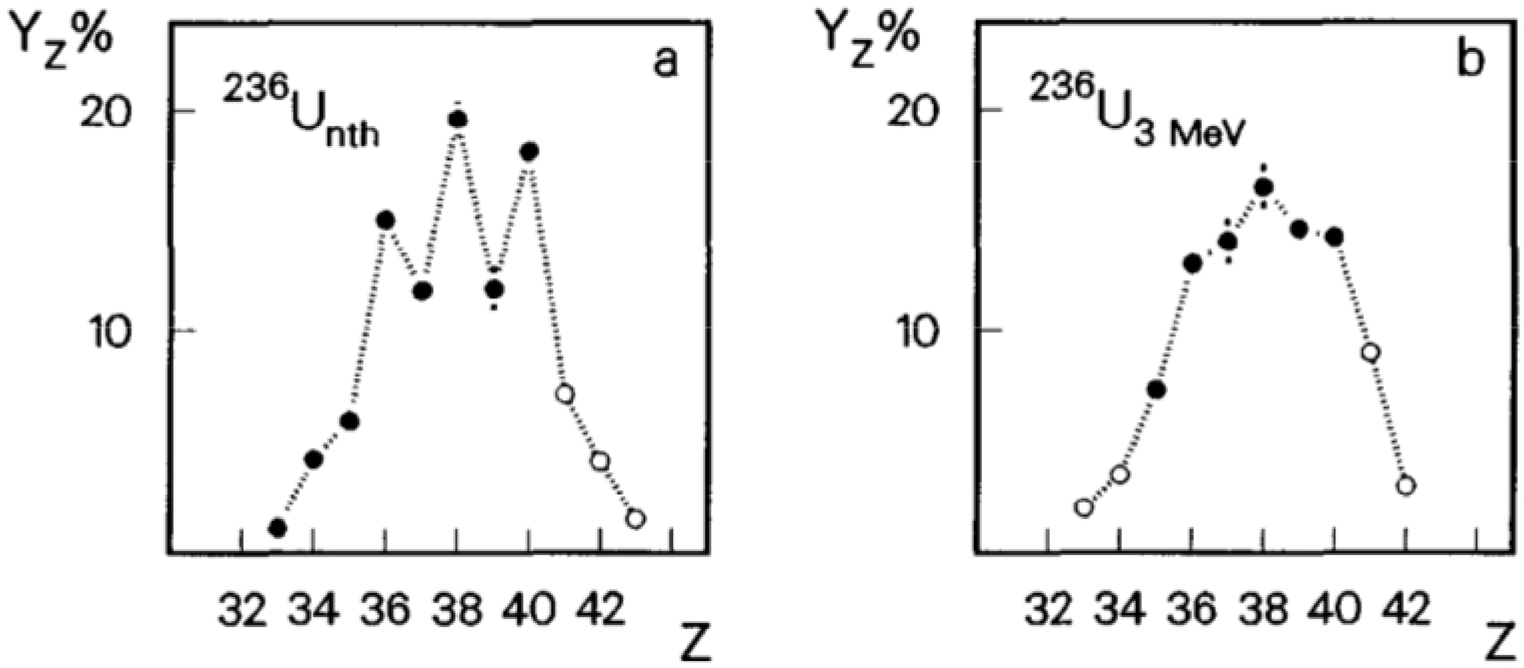
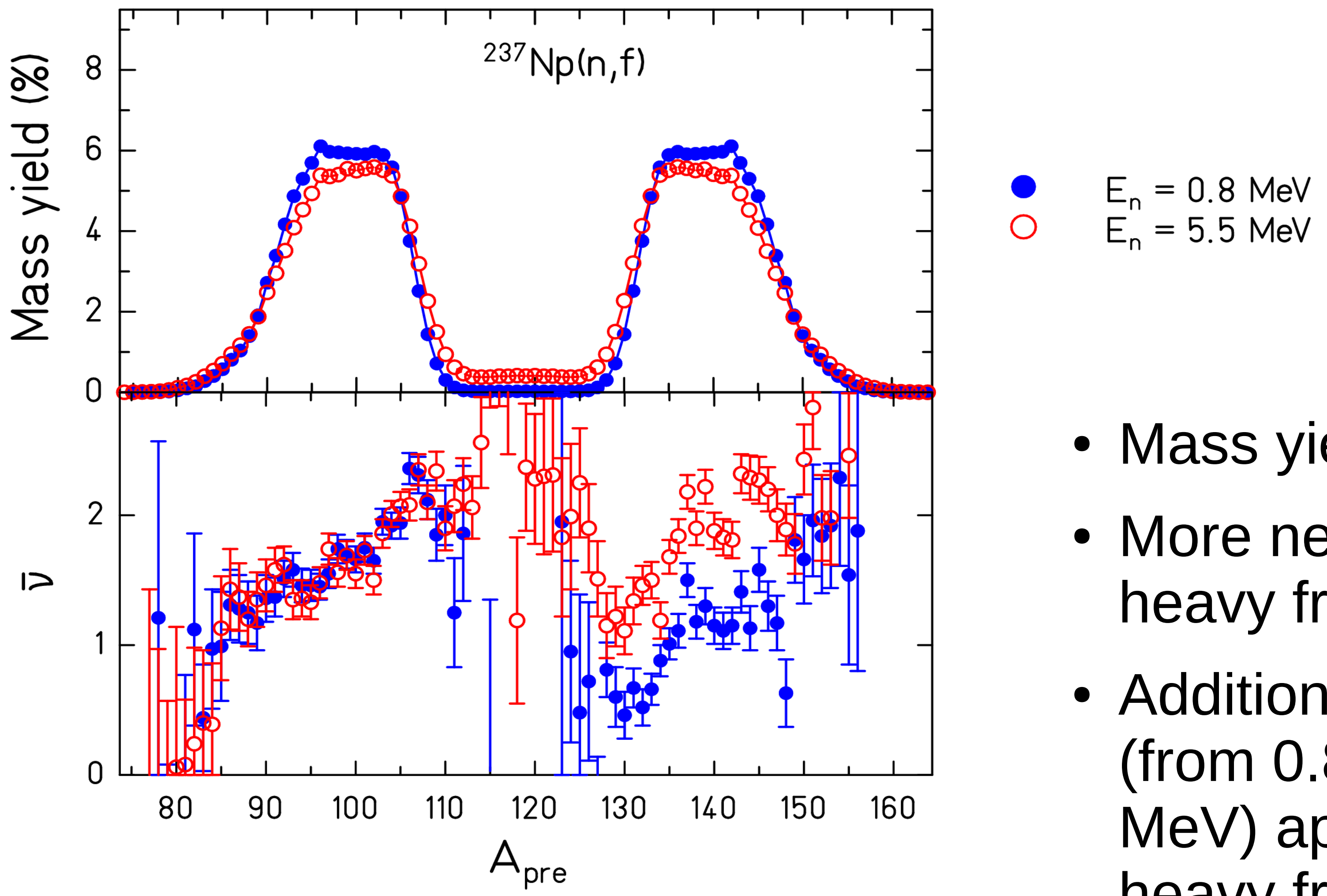


Figure from Bocquet et al.,
Nucl. Phys. A 502 (1989) 213

Neighbouring system: 235U(nth,f)

Shows that excitation energy at scission is low (in the range of pairing correlations, < 10 MeV).

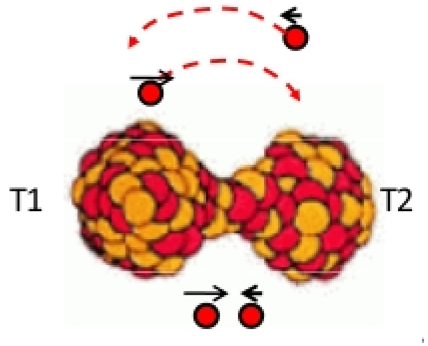
Nu-bar over Apre



- Mass yields are similar.
- More neutrons from the heavy fragment.
- Additional initial energy (from 0.80 to 5.55 MeV) appears in the heavy fragment, only!
- Why?

- Mass yields from GEF,
- nu-bar from Naqvi et al., PRC 34 (1986) 218

1. attempt to understand: Independent-particle picture + thermal equilibrium



Two nascent fragments in contact, before scission.

- Fermi-gas level density:
  $\rho = \exp(2\ \mathrm{sqrt}(a\ E))$
  $T = \mathrm{sqrt}(E/a)$
  $a = A/8$ (or $A/10$)
- Thermal equilibrium: $T1 = T2$
  $E = T^2\ A/8$
  $E1 / E2 = A1 / A2$
- → In conflict with data.

What about residual interactions in nuclei?

- Signatures of residual interactions:
  - Even-odd staggering in binding energies
    (from pairing correlations).
    Increase of the nuclear binding energy.
  - Wigner (congruence) energy, kink in masses at N=Z
    (from proton-neutron interactions).
    Increase of the nuclear binding energy, when neutrons and protons occupy the same orbits.
- Both effects change during fission.
  - Even-odd staggering ~ 1/sqrt(A) (increases by $\sqrt{2}$)
  - Wigner energy ~ ? - |N-Z|/A (doubles)
- Independent-particle picture is not realistic.
  - How do residual interactions influence the level density?

Experimental level densities

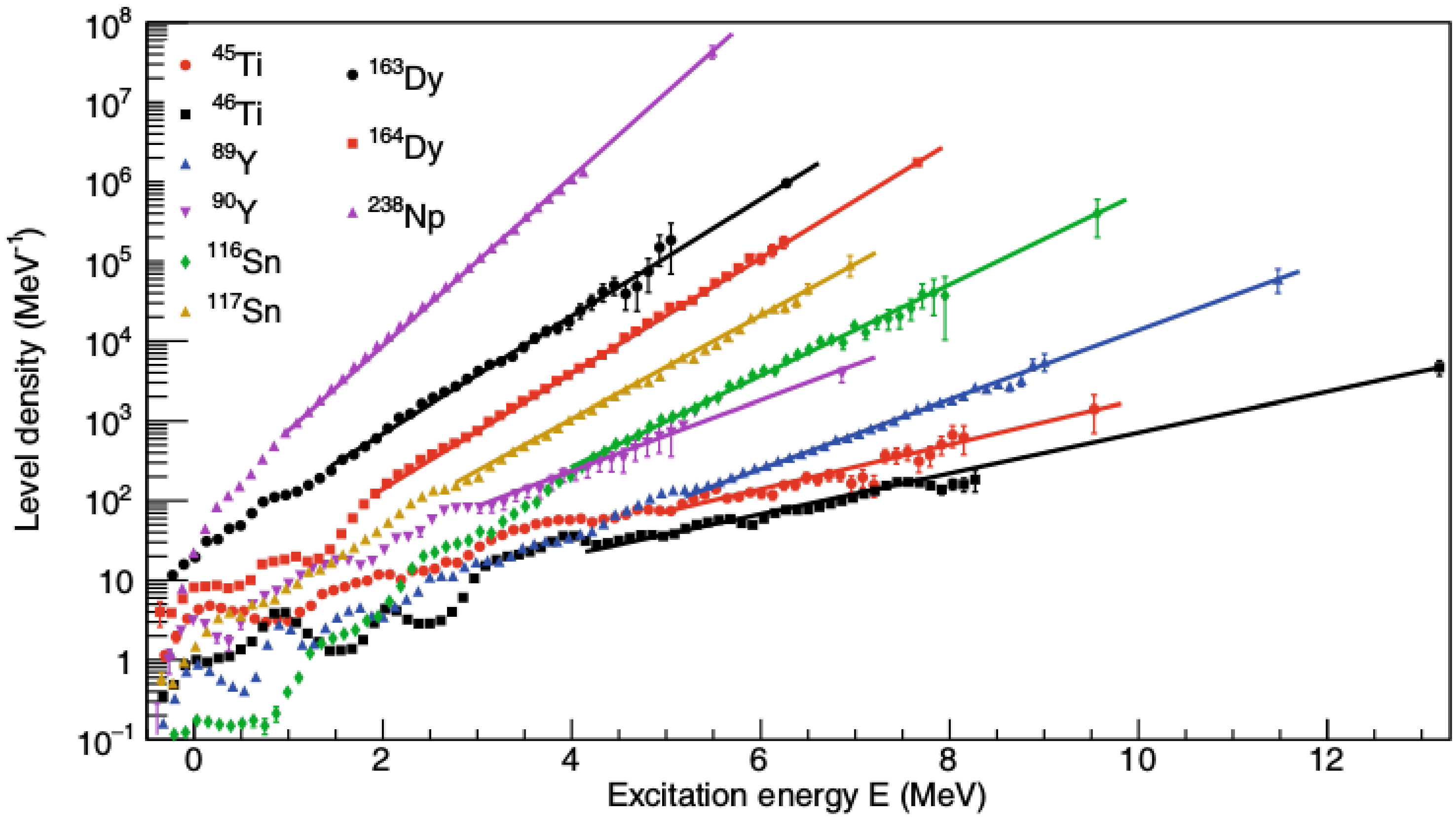
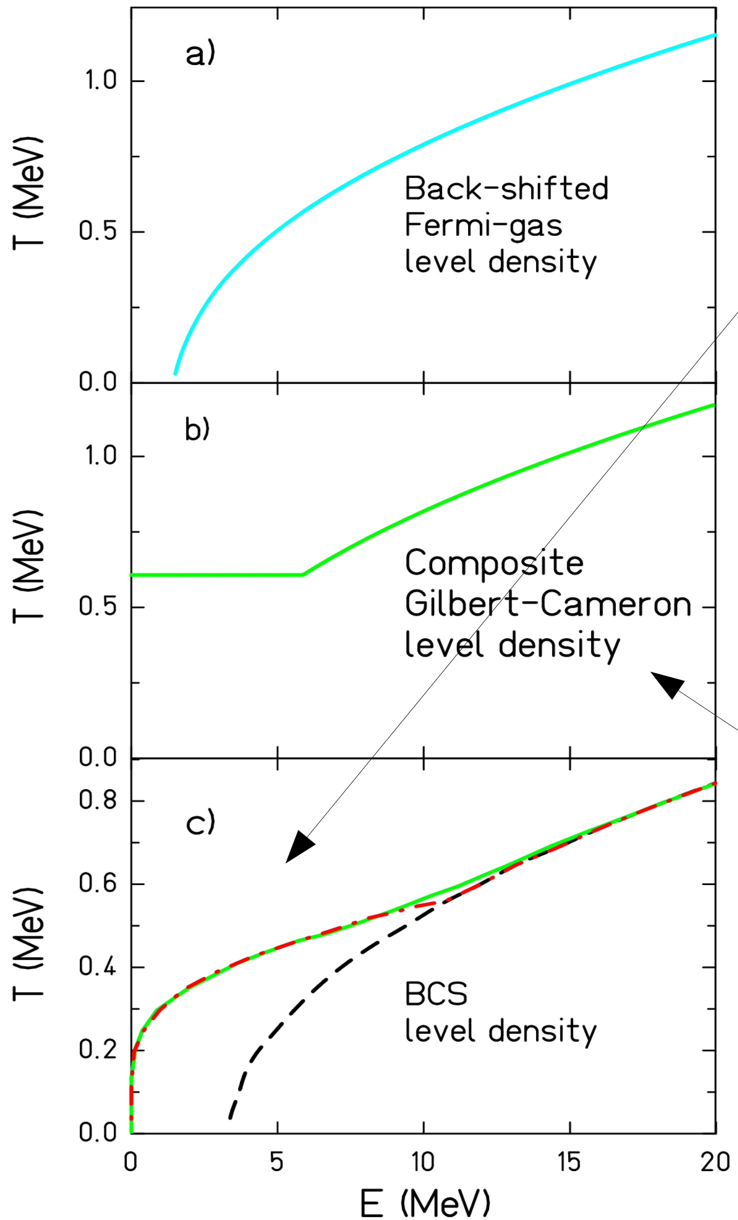


Figure from Guttormsen et al., Eur. Phys. J. A 51 (2015) 170

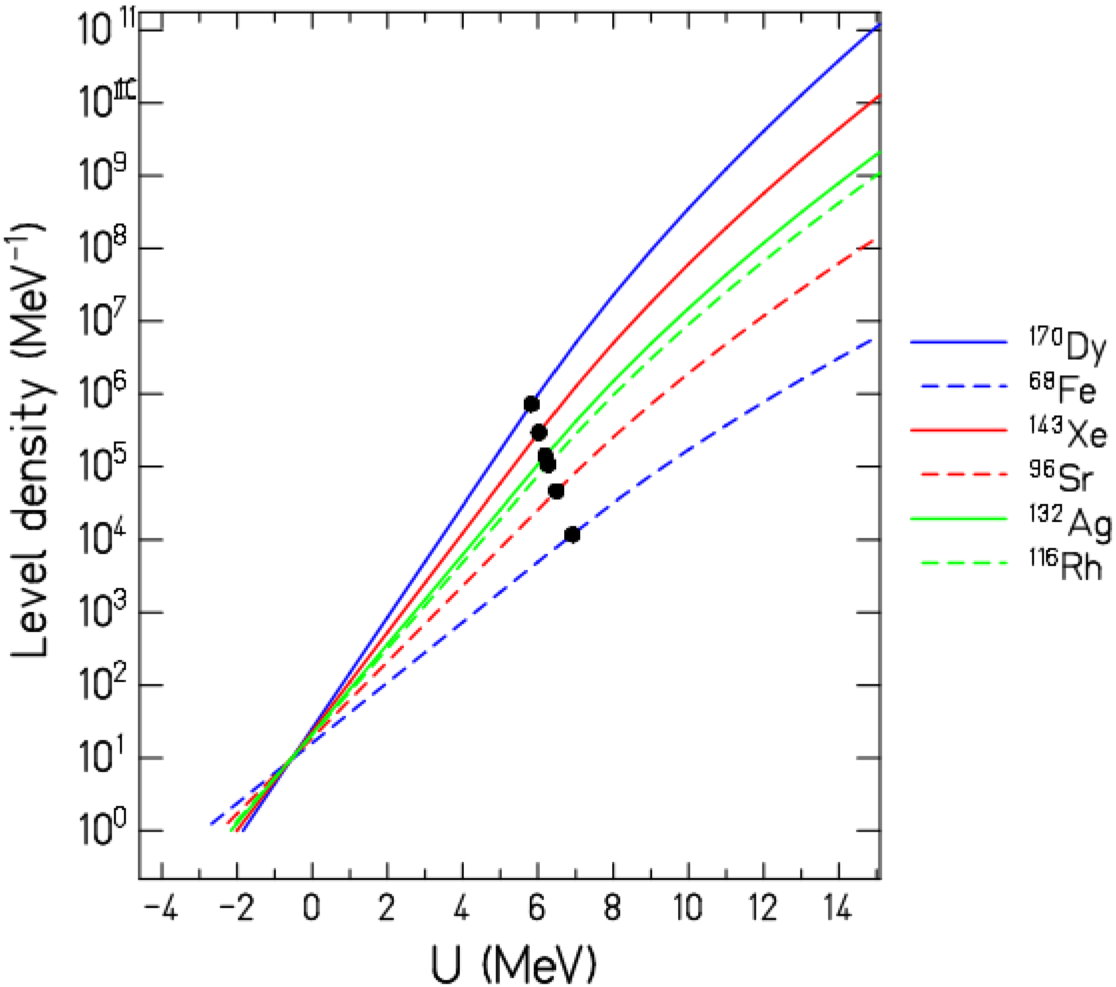
- Constant inverse logarithmic slope (temperature) up to ≈ 10 MeV.
- $T \sim A^{-2/3}$ plus some additional influence of shell effects.
- Origin: Phase transition from superfluid to Fermi gas.

What does theory say?



- BCS calculation (Moretto 1972) (and others) shows the tendency to a constant temperature below the critical pairing energy.
- Moretto et al. (J. Phys. Conf. S. 580 (2015) 012048) obtains T = const., also with BCS, like Gilbert Cameron.
- How behave level densities from microscopic models?

Proposed level-density description



Composite:

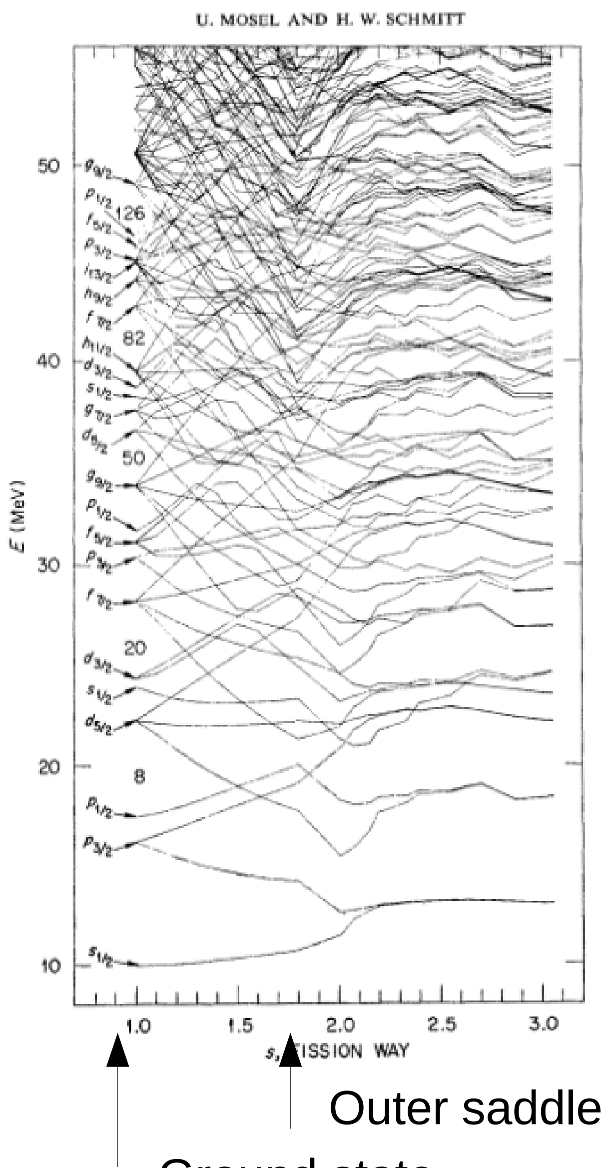
Const T. + Fermi gas

(matching energy higher than in Gilbert-Cameron formula)

$U = E^* - 2\,\Delta$

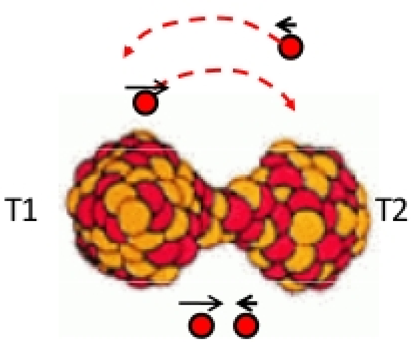
Jurado, Schmidt, J. Phys. G: Nucl. Part. Phys. 42 (2015) 055101

How much does the neck disturb the properties of the fragments?



- Single-particle energies in a di-nuclear potential (Mosel and Schmitt,
  NPA 165 (1971) 73).
- In necked-in shape, the single-particle levels resemble those in the separate fragments.
- Fragment properties are not much disturbed by the neck.
- Fragments have their individual temperatures well before scission.
- There is time for thermal equilibration.

Thermodynamical considerations

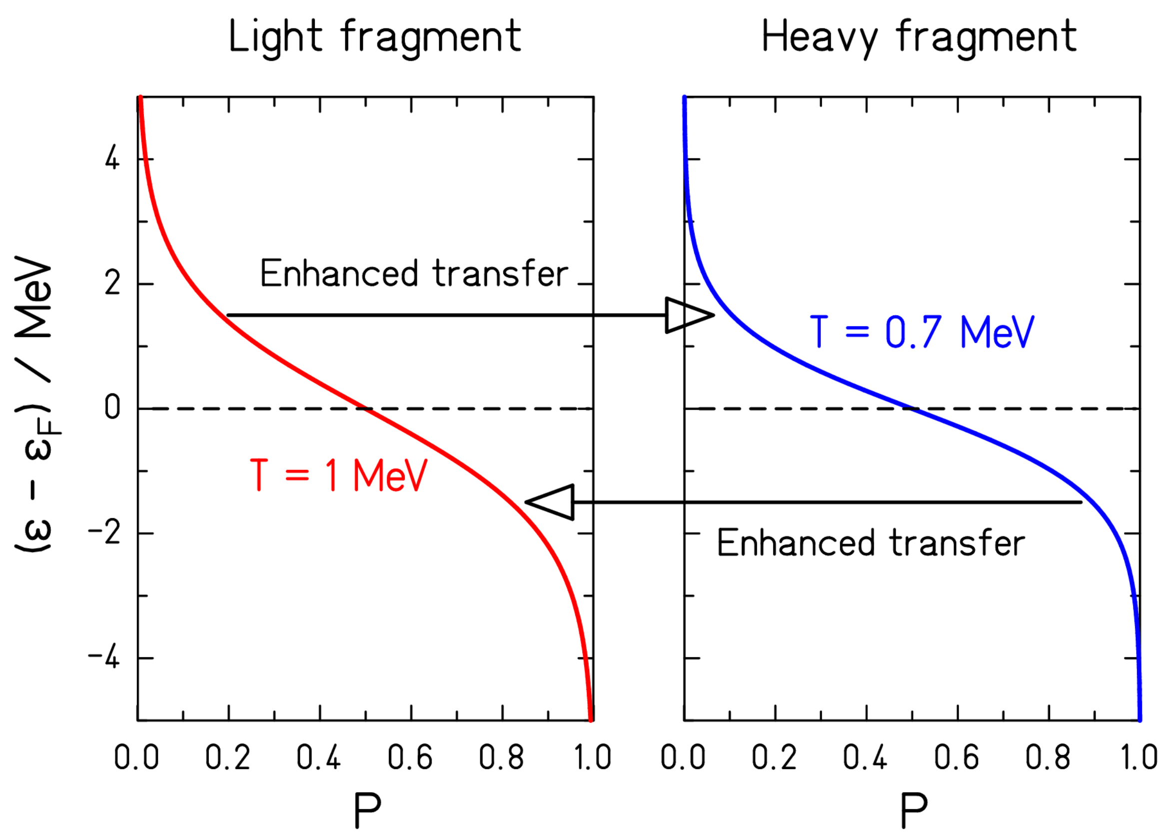


Peculiar system of coupled microscopic thermostates

- The two nascent fragments have the properties of thermostates (T=const) with eventually different temperatures ($T \sim A^{-2/3}$).
- The coupling by the neck leads to flow of thermal energy from the hotter (smaller) to the colder (heavier) fragment. (Process like in former ice creme machines!)
- Thermal equilibrium T1 = T2 cannot be reached. → Energy sorting.
- Consistent with the data.

Microscopic view on energy transfer

Single-particle occupation functions: (Fermi levels are equal: no net mass transfer.)



Transfer of nucleons through the neck transports energy (heat) due to the different occupation functions.

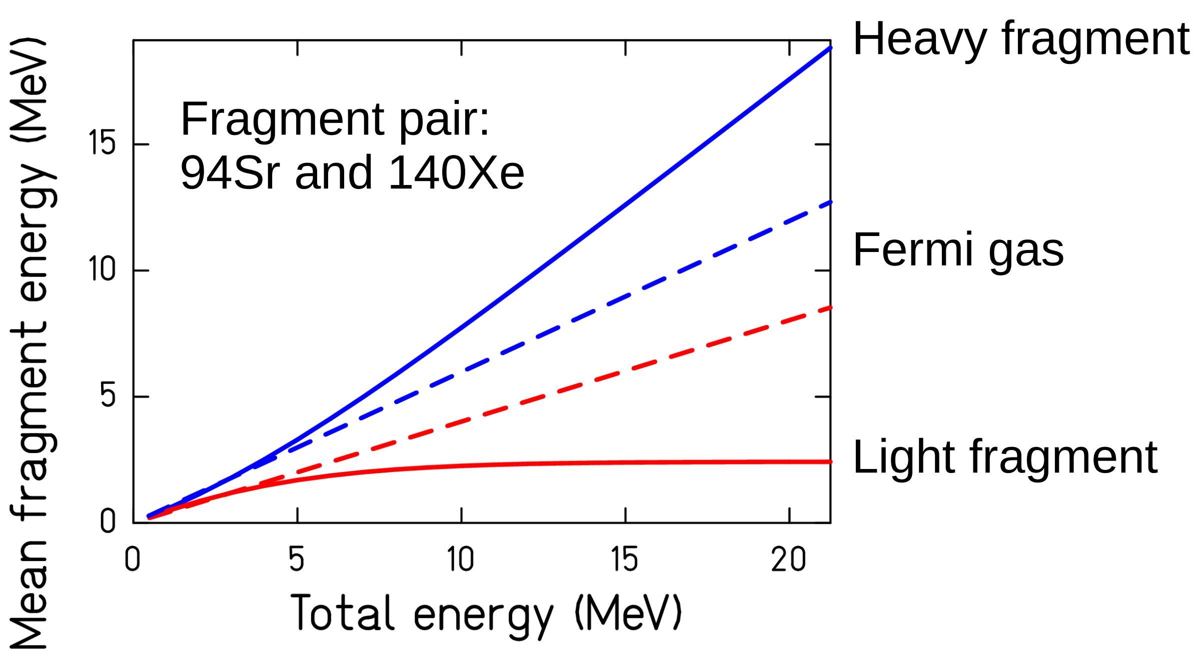
This mechanism is included in the Window Formula:
Window formula of one-body dissipation for zero relative velocity!
D. H. E. Gross NPA 240 (1975) 472

Final result: Statistical model

$$\frac{dN}{dE_1} \propto \rho_1(E_1) \cdot \rho_2(E_{tot} - E_1)$$

$$\rho_{\mathrm{CT}}(E) = \frac{1}{T} e^{(E-E_0)/T} \qquad \text{*)}$$

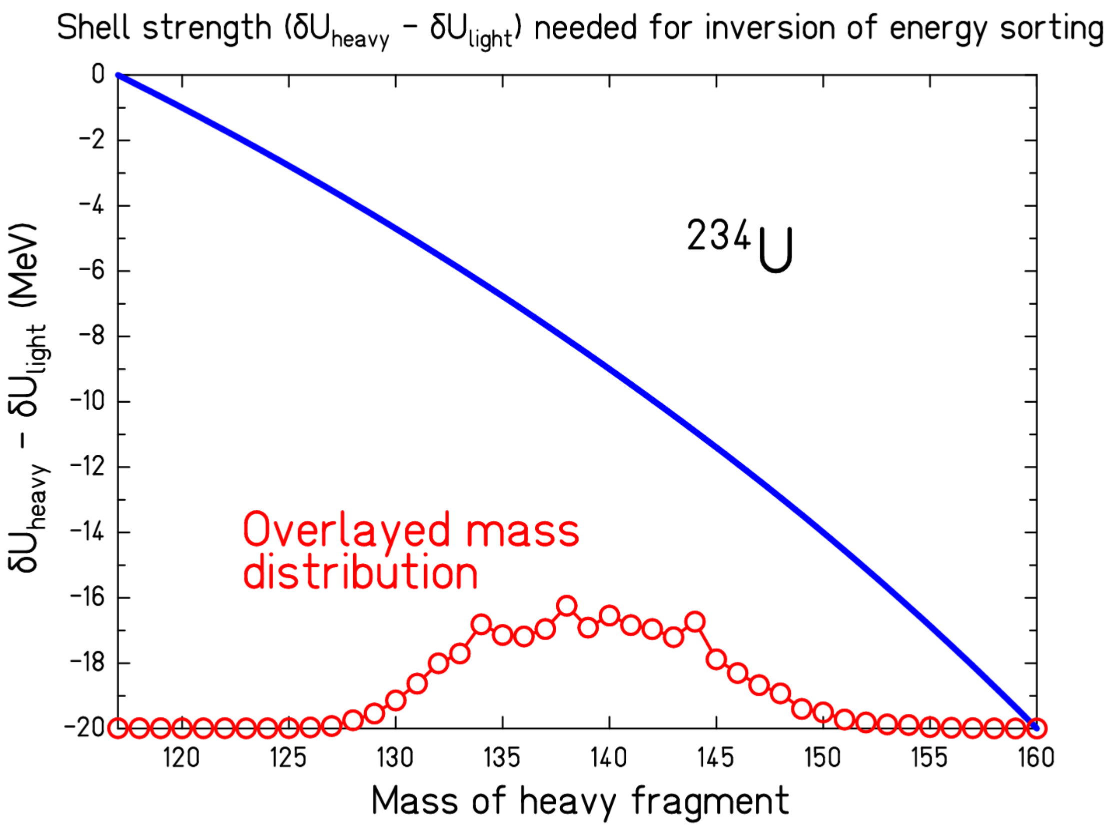
Division of energy determined by the number N of available states.



*) v.Egidy, Bucurescu PRC 80 (2009) 054310

Schmidt, Jurado, PRC 83 (2011) 061601

Influence of shell effects



Can shell effects invert the energy sorting?

Level density:

$$\rho_{\mathrm{CT}}(E) = \frac{1}{T} e^{(E-E_0)/T}$$

Influence of mass A and shell effect S:

$$T_k = A^{-2/3} / (0.0570 + 0.00193 S'_k)$$

(v.Egidy, Bucurescu, PRC 80 (2009) 054310)

Very strong shells (at scission!) are needed to invert the energy sorting, except very close to symmetry.

Practical importance

With increasing initial E*:

- Shift of isotopic distributions by prompt neutron emission only in the heavy fragment group!
- Light fragment yields stay essentially the same.

(Evidenced by still unpublished results of the SOFIA experiment by J. Taieb et al. at GSI.)

Behaviour at higher E*

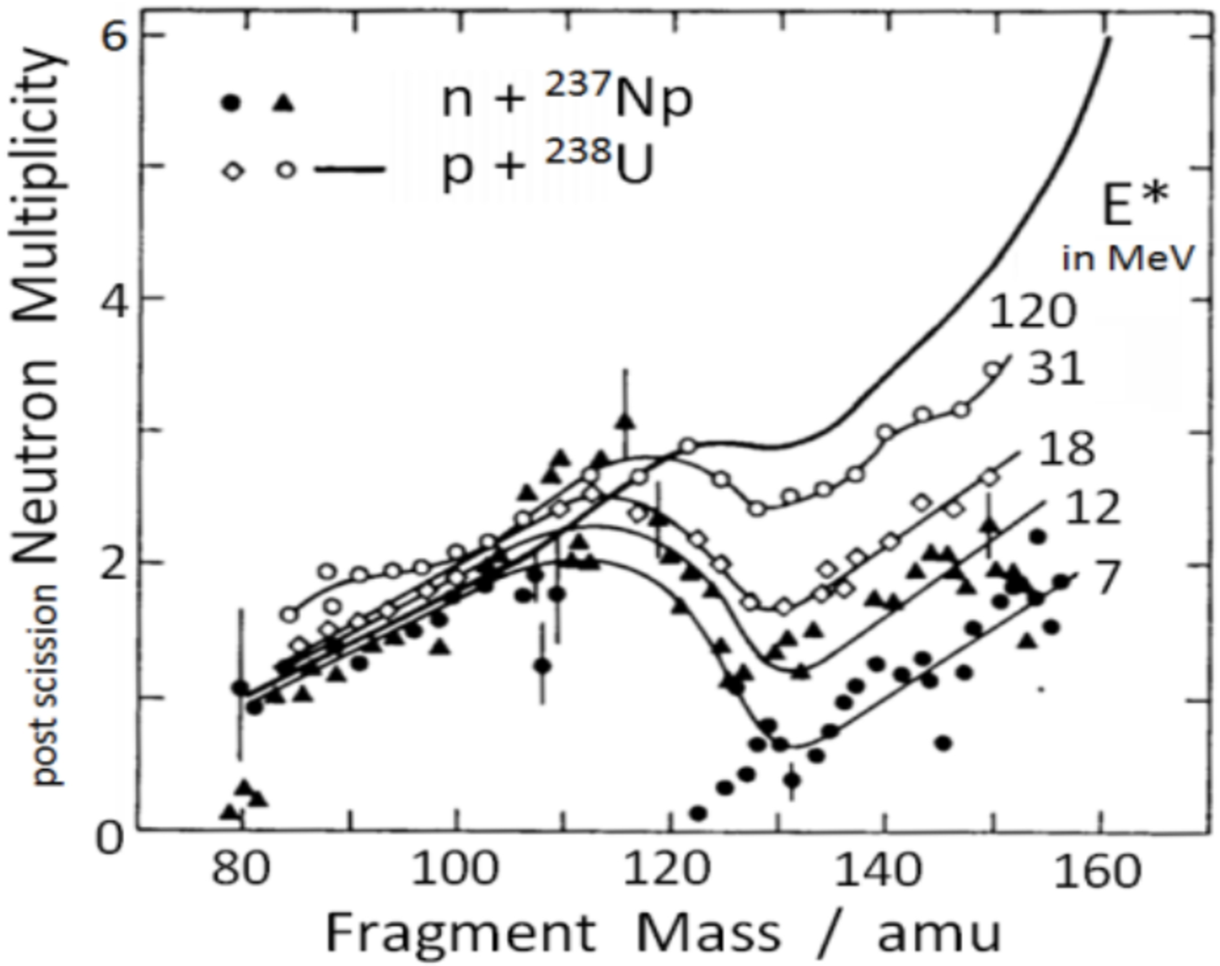
E* > Ecrit:

- Continuation of energy sorting!
- Influence of other residual interactions (phase transitions)? (Congruence energy?)

Complicated by

- Multi-chance fission

Challenge for theoretical understanding



Summary

- Measured level densities reveal constant nuclear temperatures in the pairing regime.
- The nascent fragments before scission form a very peculiar and rather unique system of microscopic thermostates with curious properties.
- Experimental data that remained unexplained for long are attributed to a process of energy sorting in fission (K.-H. Schmidt, B. Jurado, Phys. Rev. Lett. 104 (2010) 212501).
- The energy sorting is driven by entropy, Maxwell's demon is not in play.
- The phenomenon is implemented in the GEF model code (K.-H. Schmidt, B. Jurado, Ch. Amouroux, Ch. Schmitt, Nucl. Data Sheets 131 (2016) 107)
  www.khs-erzhausen.de