# SPY: a microscopic statistical scission-point model to predict fission fragment distributions

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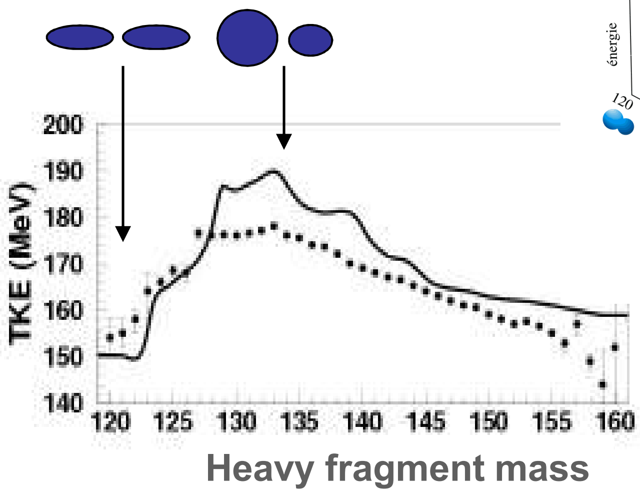
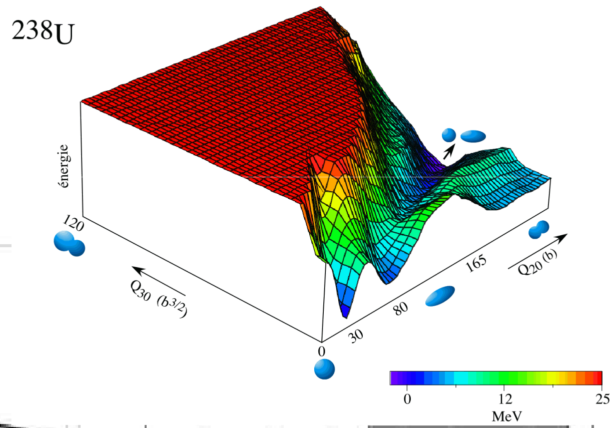
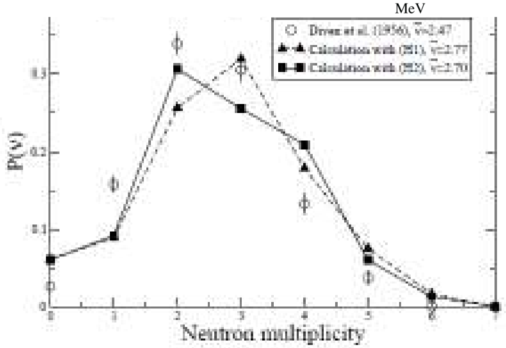
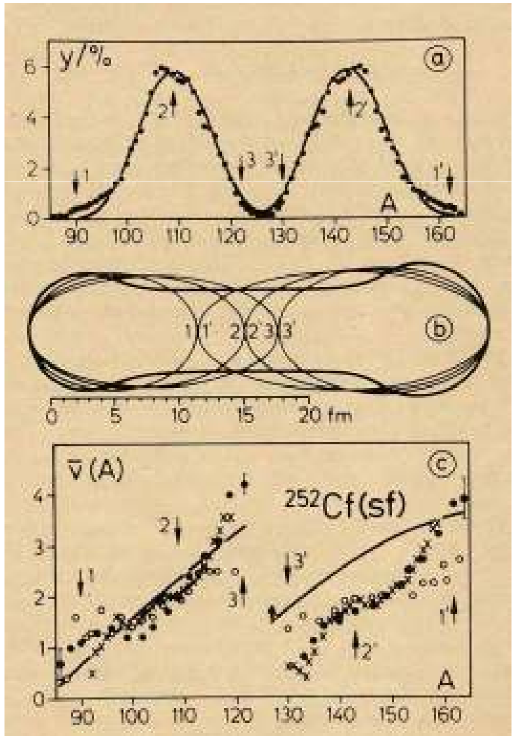
# Fission: an old reaction over towards new challenges

- The fission process is the most complete nuclear physics laboratory
  - Internal nuclear structure (shell effects, pairing,…)
  - Nuclear deformations
  - Dynamics (coupling between collective modes and internal excitation)
- A lot of data and models to interpret them but still…



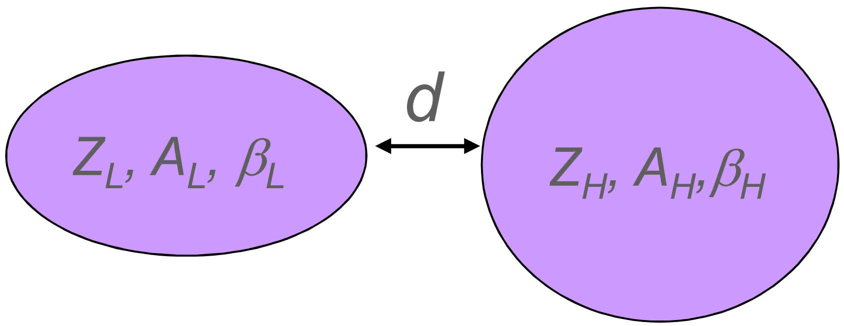



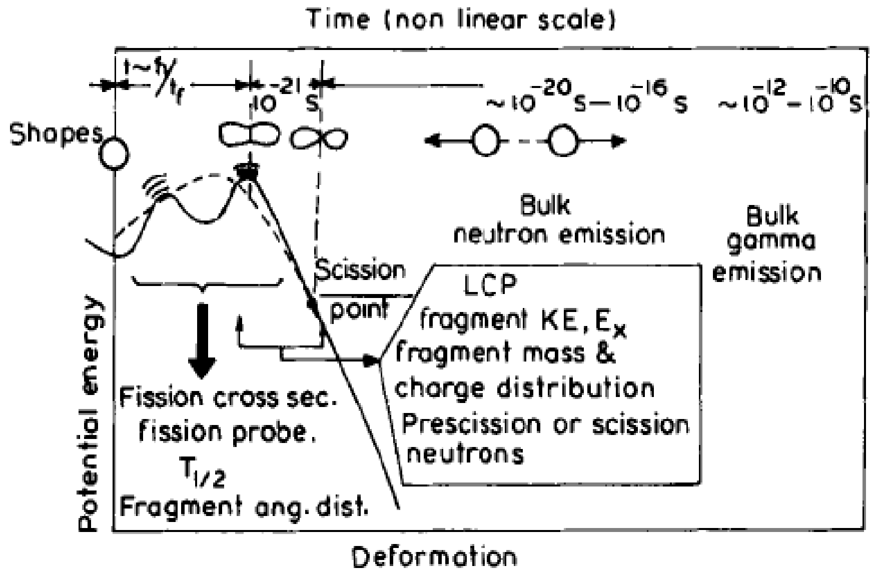



# The scission-point model

- First proposed by Wilkins (*Wilkins et al, Phys. Rev. C 14 (1976) 5)*
- Static approach:
  - Fission process is slow
  - A statistical «quasi»-equilibrium is reached at scission
  - The main fragment characteristics are freezed at this point!
  - Dynamics is not explicitly treated
  - The scission configuration is defined by two ellipsoids with an inter-surface distance d

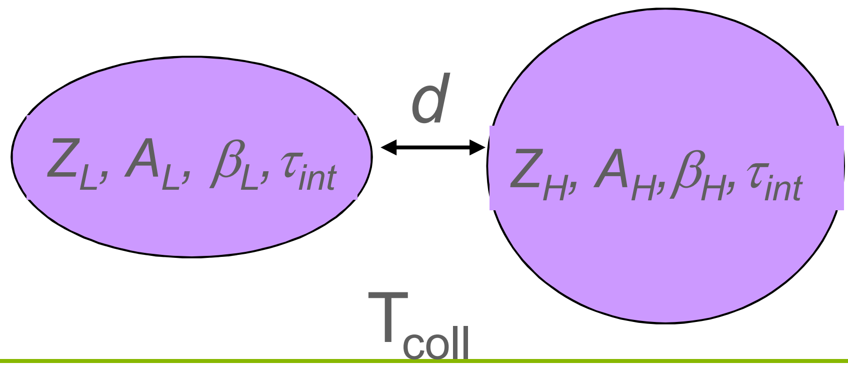


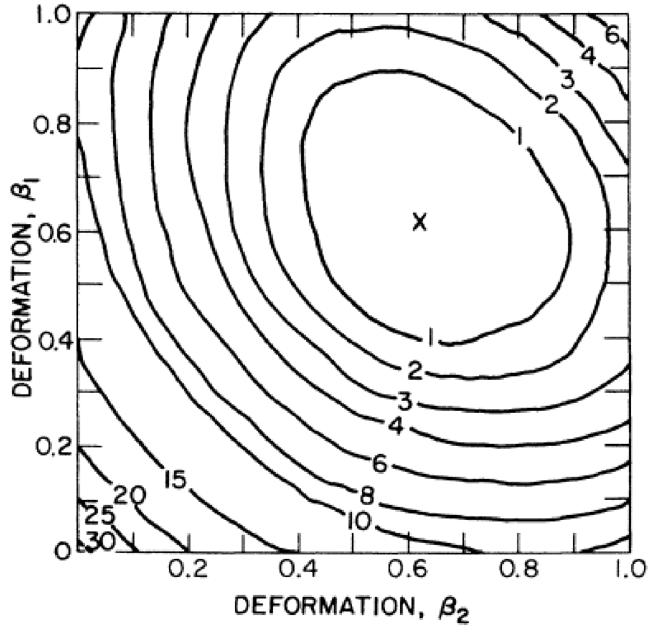
# The scission-point model

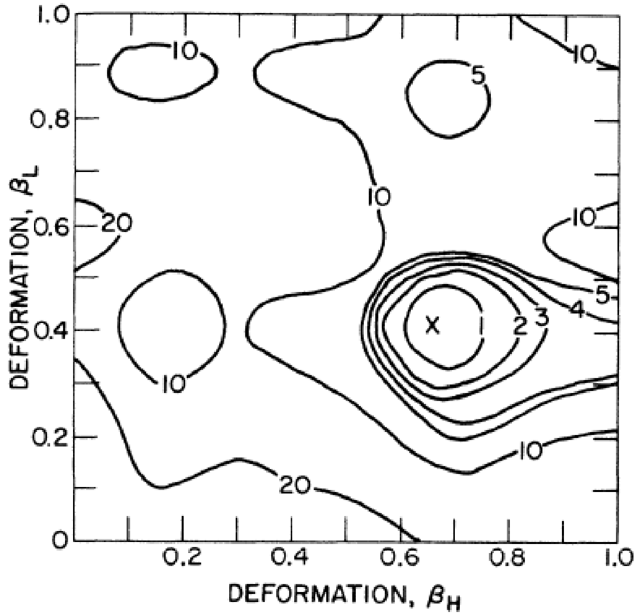
- First proposed by Wilkins (*Wilkins et al, Phys. Rev. C 14 (1976) 5)*
- Static approach
- Based on an energy balance at scission
- Main limitations:
  - Collective and intrinsic temperature parameters (+ d!) fitted on data
  - Energy potentials are relative to the scission point
  - Only prolate deformations
  - Individual energies are not microscopic (liquid drop + Strutinski + pairing)

$$V(Z_{1,2},N_{1,2},\beta_{1,2},d,\tau_{1,2}) = \Sigma V_{LD}^{1,2}(Z^{1,2},N^{1,2},\beta^{1,2})+\Sigma V_{Str.}^{1,2}(Z^{1,2},N^{1,2},\beta^{1,2},\tau_{1,2}) + V_{coul}(Z_{1,2},N_{1,2},\beta_{1,2},d) +V_{nucl}(Z_{1,2},N_{1,2},\beta_{1,2},d)$$

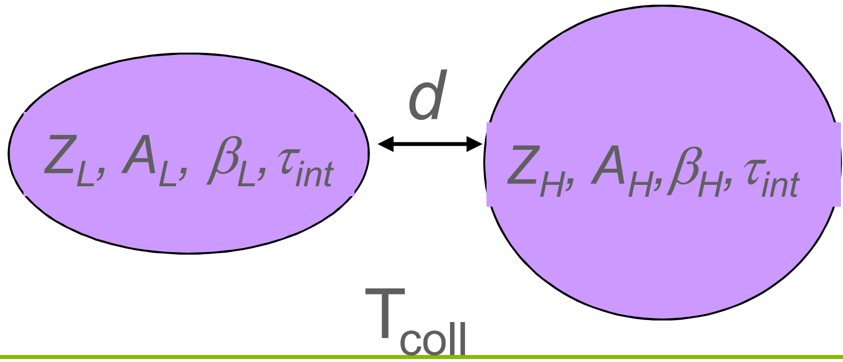


# The scission-point model: Wilkins




$$V(Z_{1,2},N_{1,2},\beta_{1,2},d,\tau_{1,2}) = \Sigma V_{LD}{}^{1,2}(Z^{1,2},N^{1,2},\beta^{1,2}) + \Sigma V_{Str.}{}^{1,2}(Z^{1,2},N^{1,2},\beta^{1,2},\tau_{1,2}) + V_{coul}(Z_{1,2},N_{1,2},\beta_{1,2},d) + V_{nucl}(Z_{1,2},N_{1,2},\beta_{1,2},d)$$



# The SPY model

- A revised version of Wilkins model was developed by S. Heinrich (PhD thesis, 2006) and J.-L. Sida
- Main core of SPY (Scission Point model for fission fragment Yields)
- Based on microscopic ingredients
  - Individual microscopic energies based on HFB calculation with the Gogny D1S interaction (S. Hilaire, avail. @ Amedee database)
  - No dependence on intrinsic temperature
  - Available energy is calculated as:

$$A = E_{tot} - V$$

$$V(Z_{1,2},N_{1,2},\beta_{1,2},d) = \Sigma V_{HFB}^{1,2}(Z^{1,2},N^{1,2},\beta^{1,2}) + V_{coul}(Z_{1,2},N_{1,2},\beta_{1,2},d) + V_{nucl}(Z_{1,2},N_{1,2},\beta_{1,2},d)$$

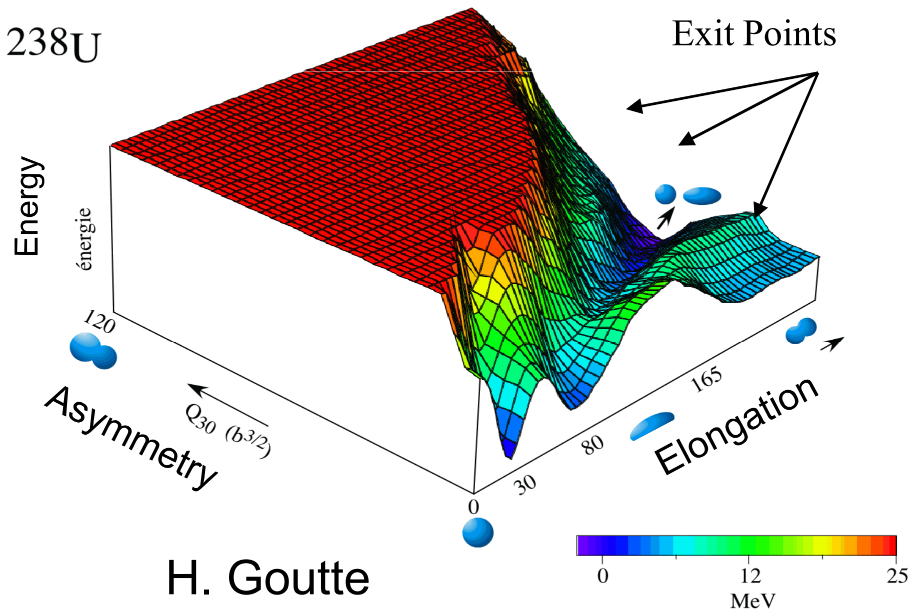
  - Coulomb interaction based on Cohen Swiatecki formalism

    *Cohen and Swiatecki, Annals of Physics 19 (1962) 67*
  - Nuclear interaction based on the Blocki proximity potential

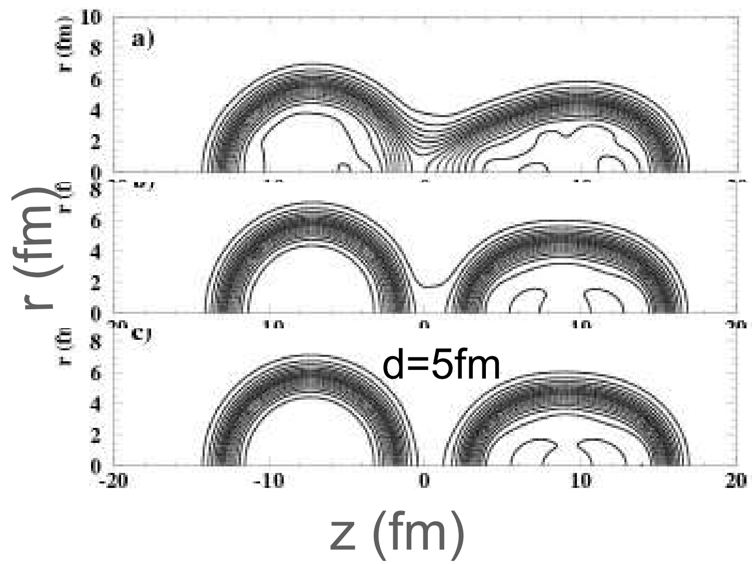
    *Blocki et al, Annals of Physics 105 (1977) 427*

# On the scission point definition

- The SPY model is parameter free
- The distance d is fixed at 5 fm
- The distance is chosen on the exit points selection criteria used on Bruyères microscopic fission calculations

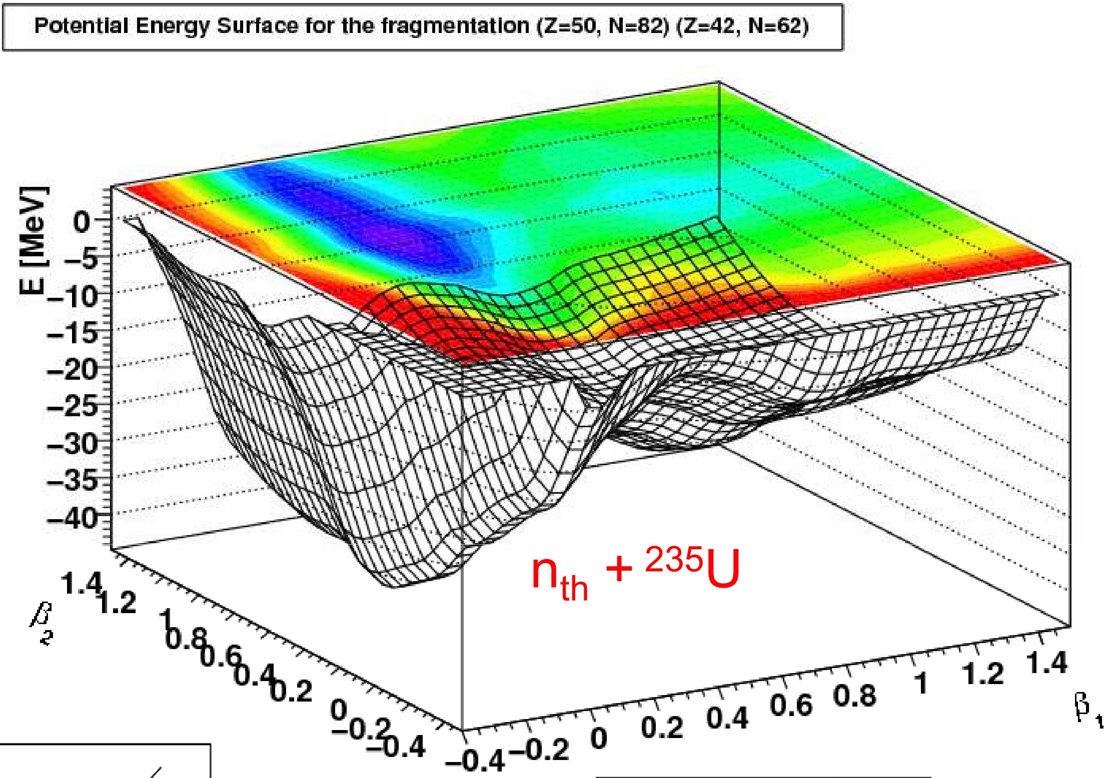


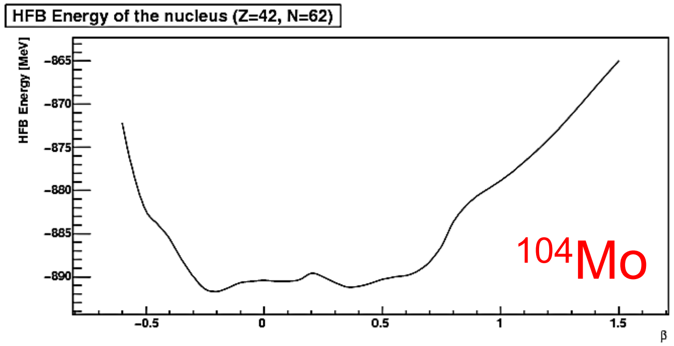

Nucleon density at the neck $\rho < 0.01$ fm$^3$
Total binding energy drop (≈ 15 MeV)
Hexadecupolar moment drop (≈ 1/3)

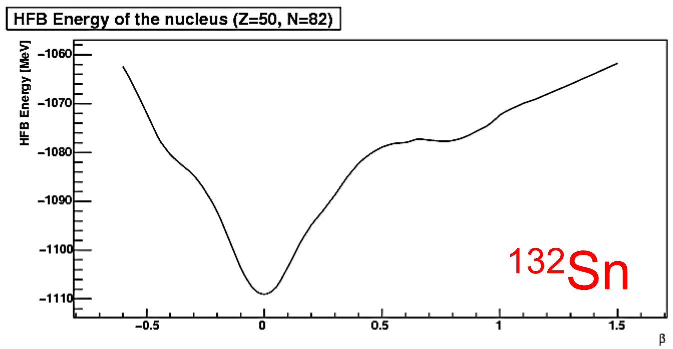


# Available energy at scission: asymmetric fragmentation

Driven by the double shell effect of spherical $^{132}Sn$

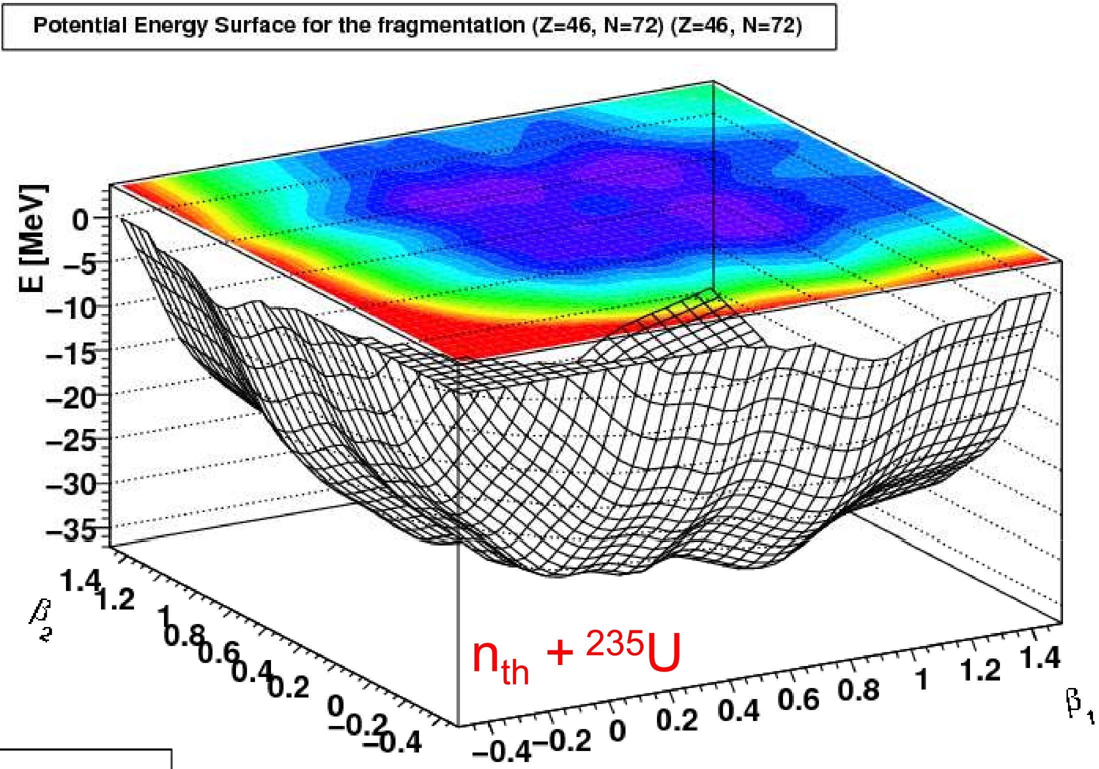


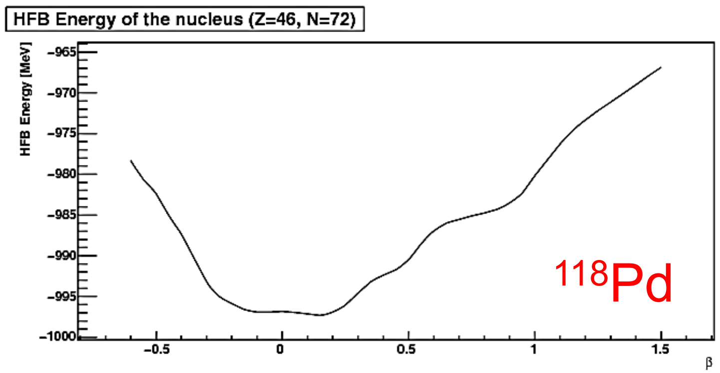



# Available energy at scission: symmetric fragmentation

Quite large deformations available for soft nuclei



# The statistical treatment

- The probability of a given fragmentation is linked to the phase space available at scission
- The phase space is defined by the number of available states of each fragment, i.e. the intrinsic level/state density
- The energy partition at scission is supposed to be equiprobable between each state available to the system (microcanonical system)
- Therefore the phase space is defined as:

$$\pi(N_l, N_h, Z_l, Z_h, \beta_l, \beta_h, A) = \int_{\varepsilon=0}^{\varepsilon=A} \rho_l(\beta_l, \varepsilon)\ \rho_h(\beta_h, A-\varepsilon)\quad d\varepsilon$$

- The relative probability of a given fragment pair is:

$$P(N_l, N_h, Z_l, Z_h) = \int_0^{\beta_{max}} \int_0^{\beta_{max}} \pi(\ldots, \beta_l, \beta_h, A)\, d\beta_l\, d\beta_h$$

# The level density ingredient

- Very delicate point of the model…
- In this approach the level densities are a natural counterbalance to a stronger stabilization of spherical deformations and even-even nuclei, which leads to unphysical fragment mass distributions
- For the time being, a Fermi gas approach has been tested
- The CTM effective level density is parameterized as:

*Koning et al., Nucl. Phys. A 810 (2008) 13*

$$\rho_F(E) = \frac{1}{\sqrt{2\pi}\,\sigma}\frac{\sqrt{\pi}}{12}\frac{e^{2\sqrt{aE}}}{a^{1/4}E^{5/4}}$$

with $a = \alpha A + \beta A^{2/3}$ , $\alpha = 0.0692559, \beta = 0.282769$

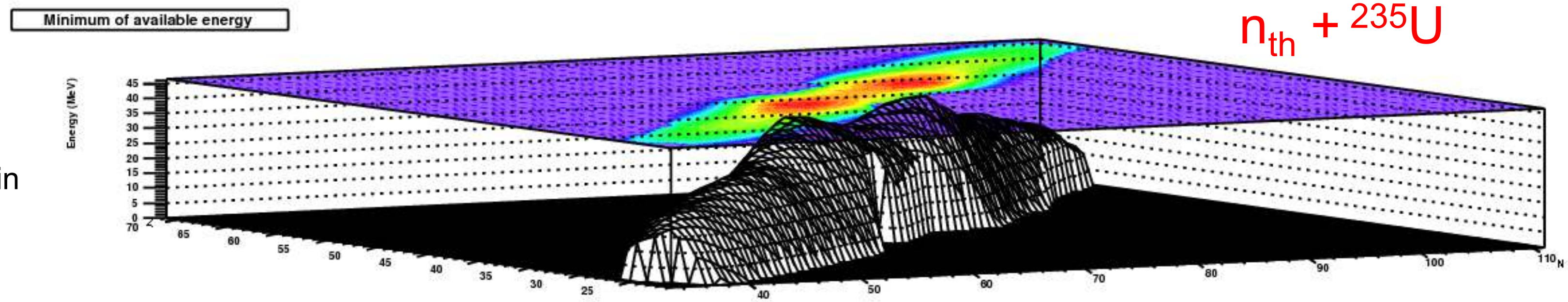
and $\sigma = I_0 a\sqrt{E/a}$

- A microscopic calculation of level densities is actually performed (at zero temperature) in the framework of HFB formalism by S. Hilaire
- Very time consuming since the we need the energy evolution at each deformation for some hundreds of nuclei

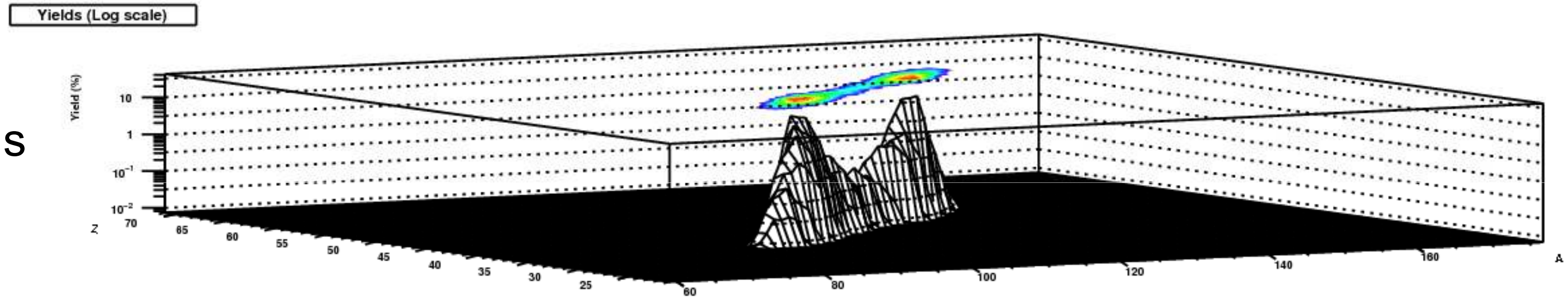
# From the available energy to the yield

$n_{th} + {}^{235}U$

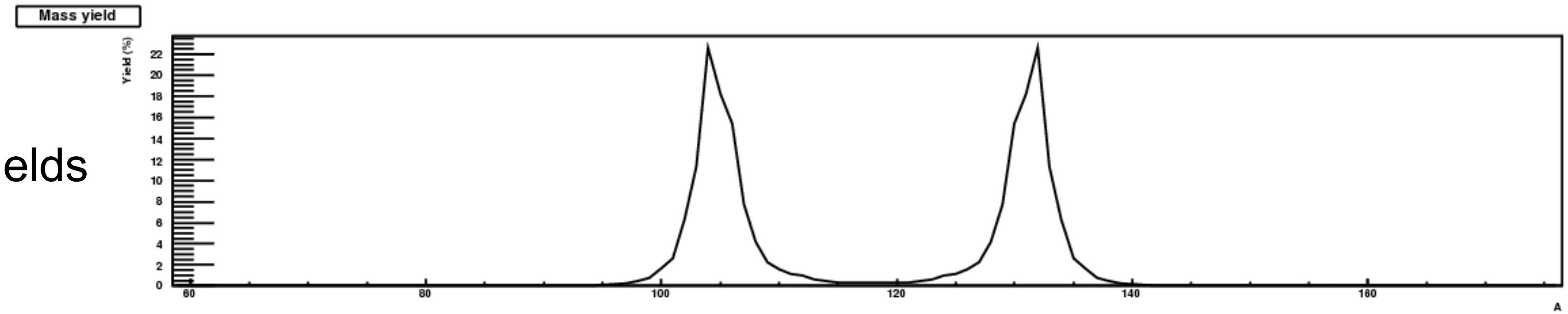
$A_{min}$




Yields

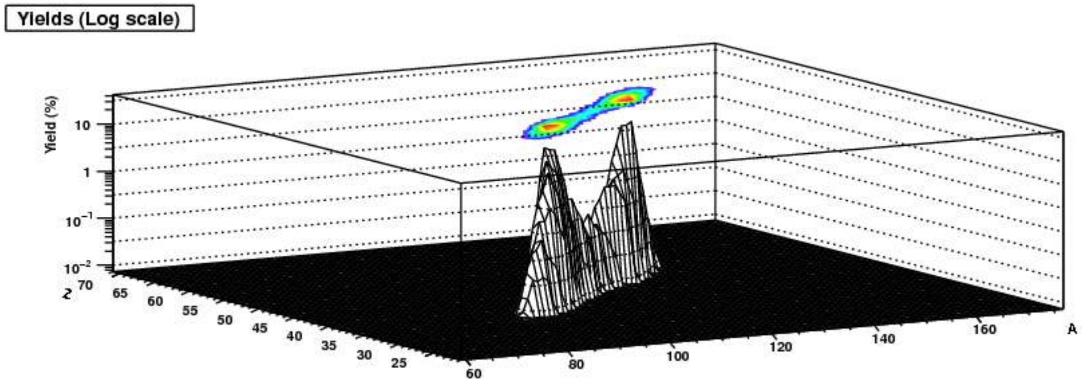


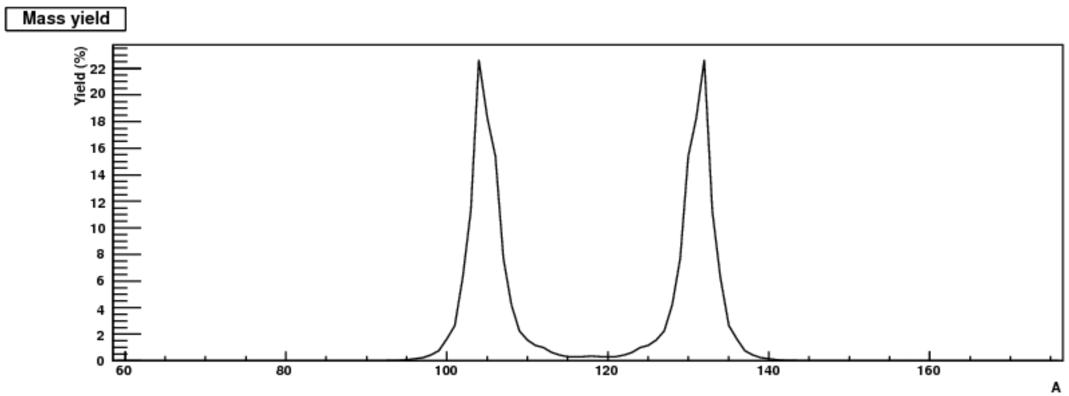

Mass yields

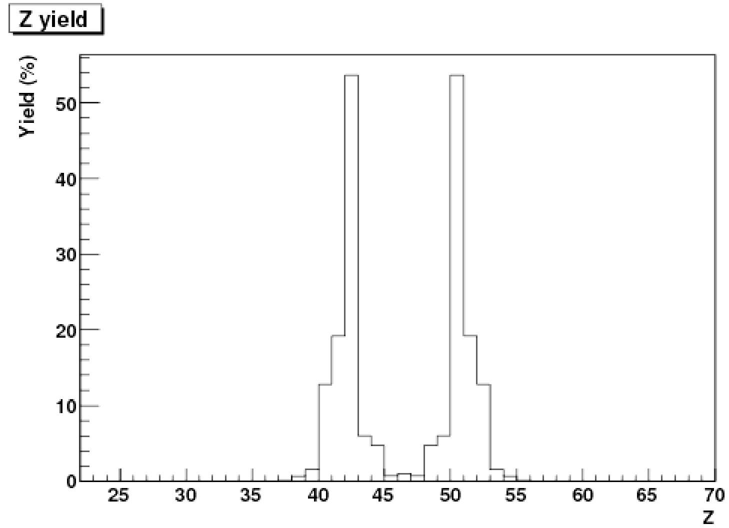


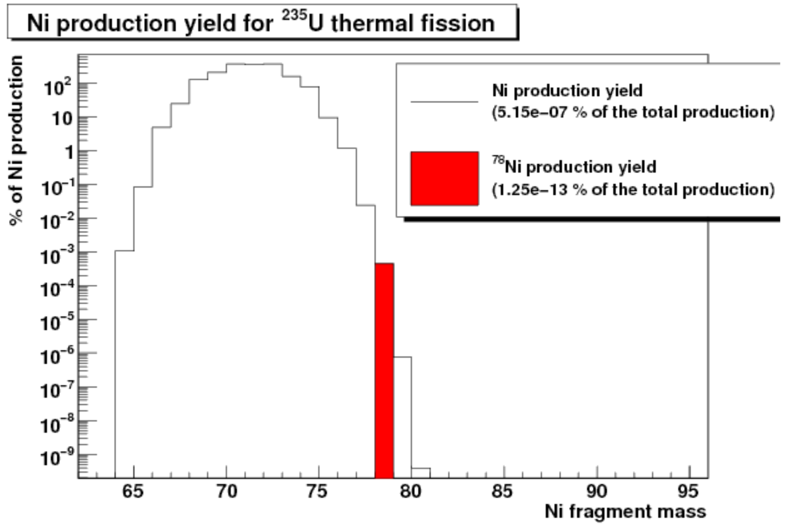
# Observables: mass  and charge yields

$n_{th} + {}^{235}U$

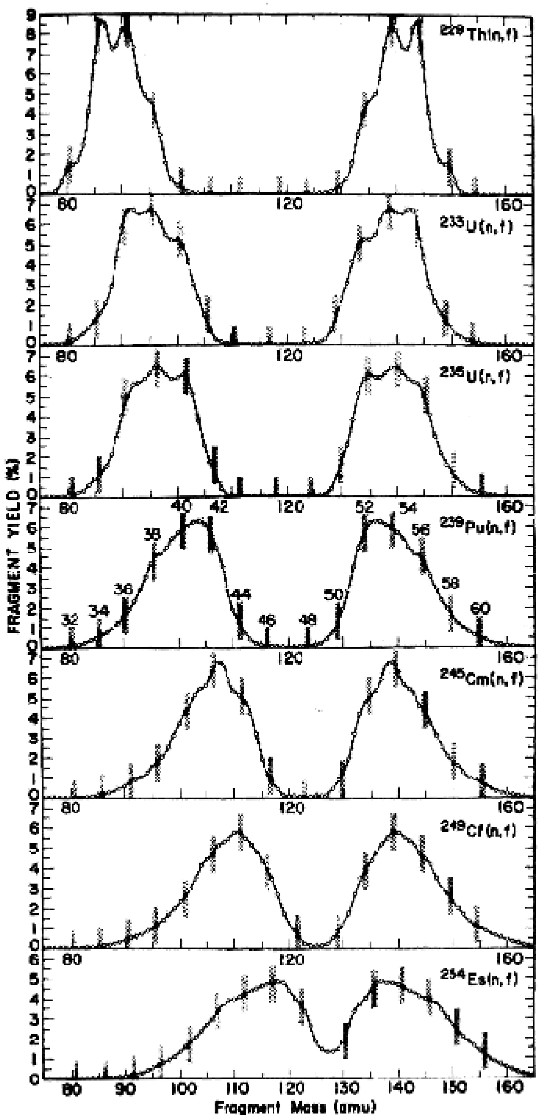


# Systematics: mass yields for n-induced fission




$n_{th}$ + $^{229}$Th

$n_{th}$ + $^{233}$U

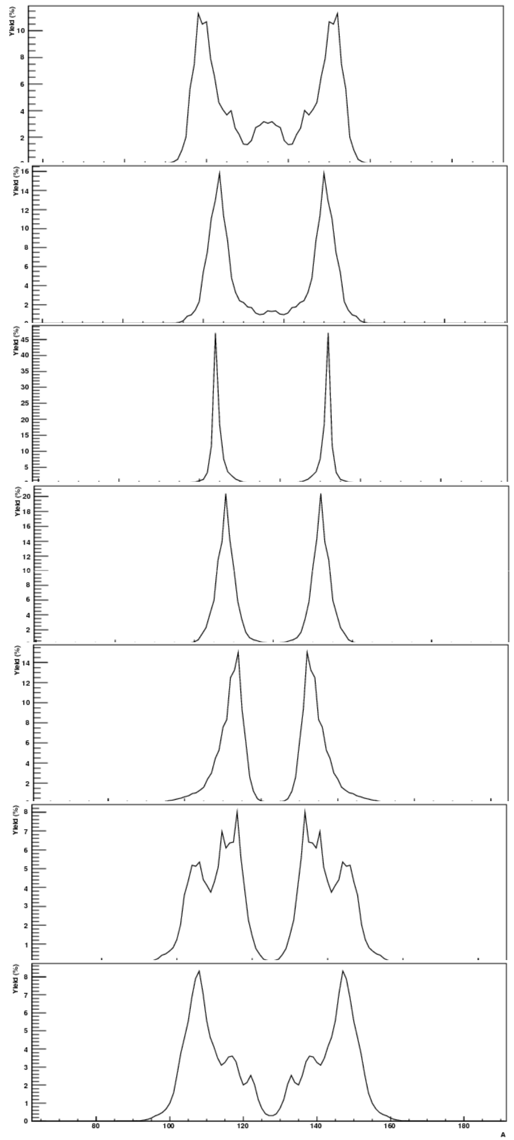
$n_{th}$ + $^{235}$U

$n_{th}$ + $^{239}$Pu

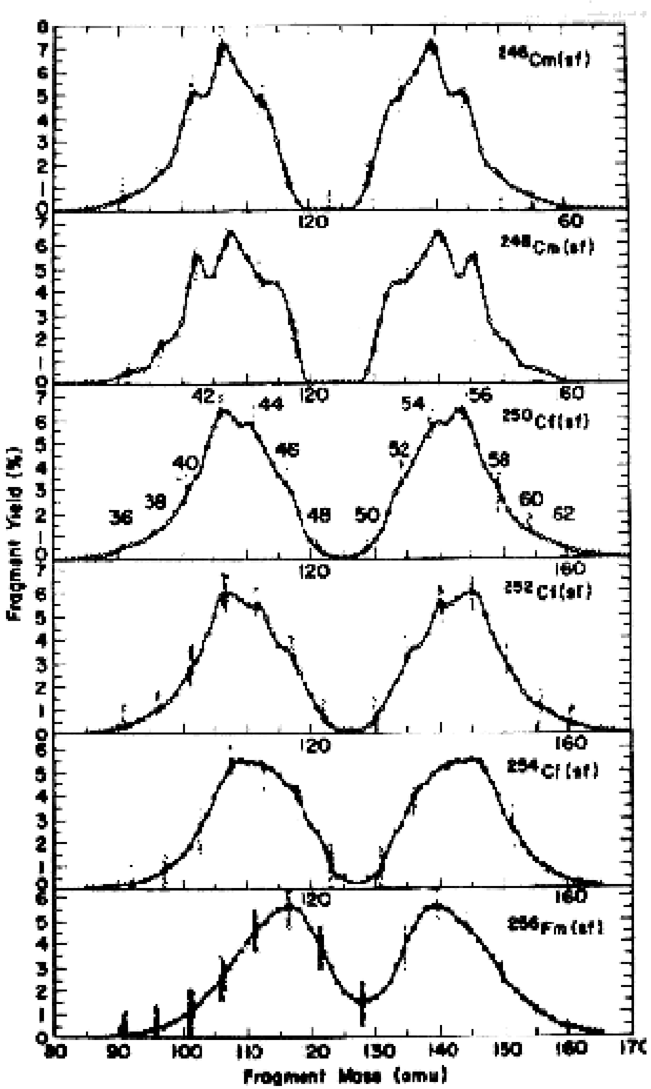
$n_{th}$ + $^{245}$Cm

$n_{th}$ + $^{249}$Cf

$n_{th}$ + $^{254}$Es



# Systematics: mass yields for spontaneous fission




$^{246}$Cm(sf)

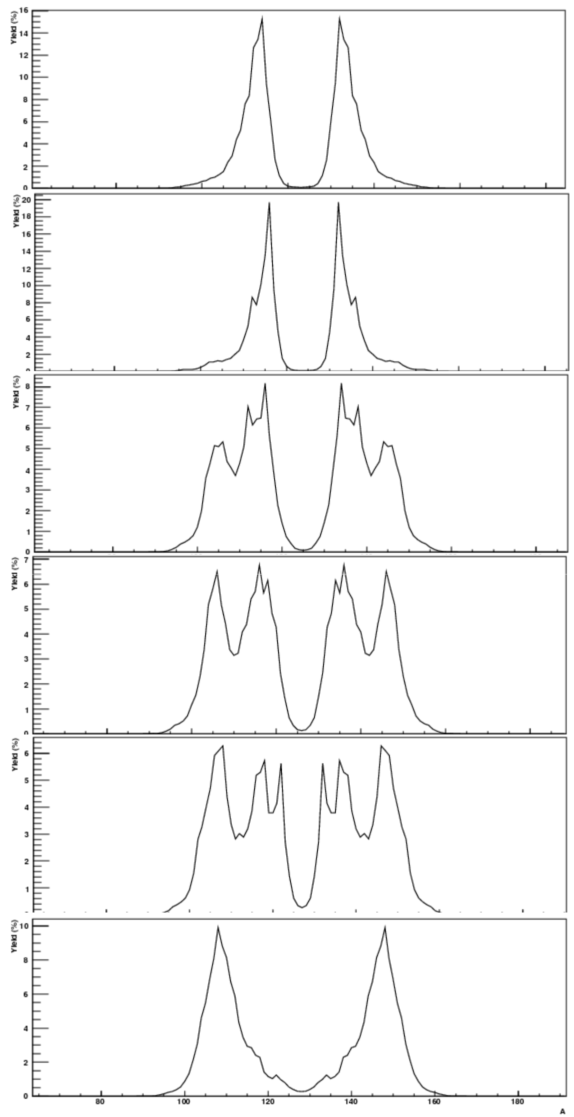
$^{248}$Cm(sf)

$^{250}$Cf(sf)

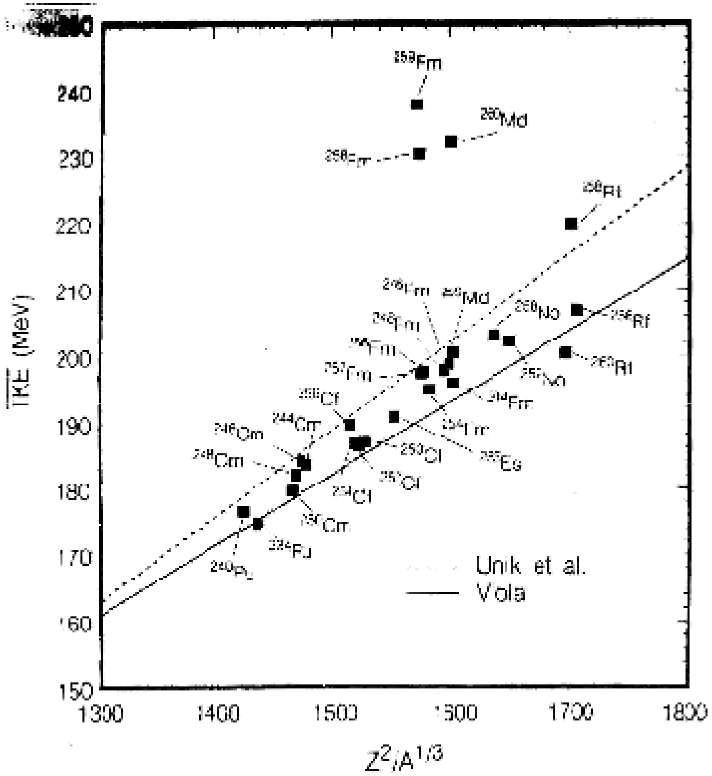
$^{252}$Cf(sf)

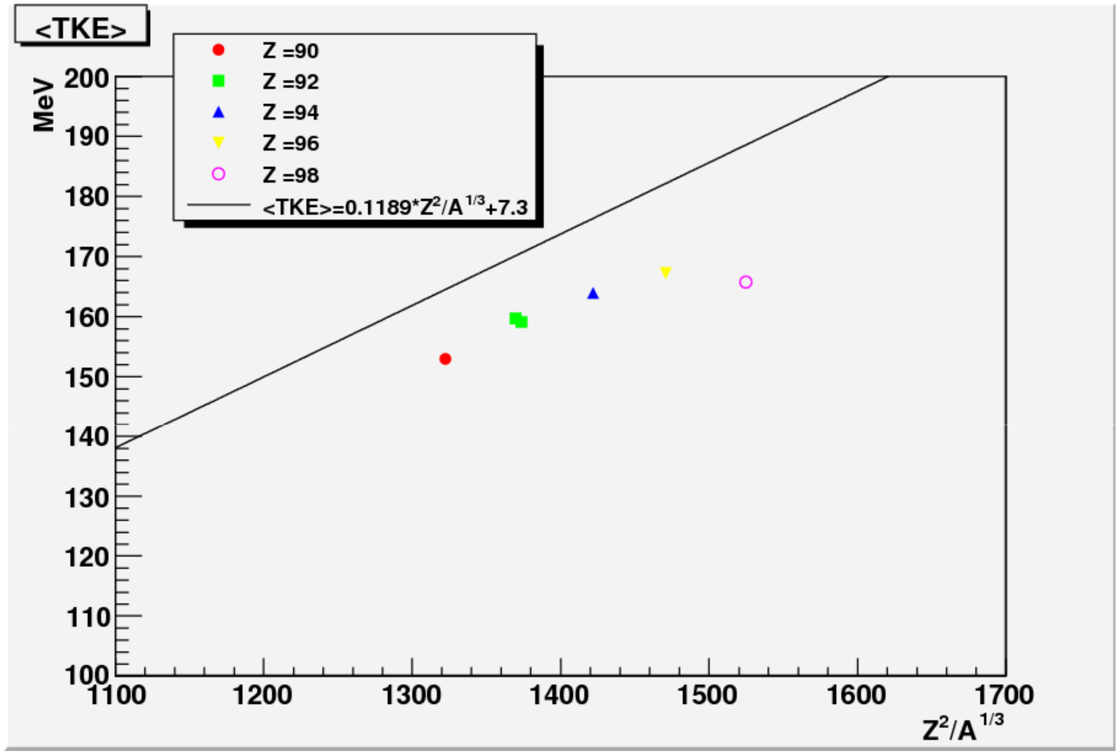
$^{254}$Cf(sf)

$^{256}$Fm(sf)



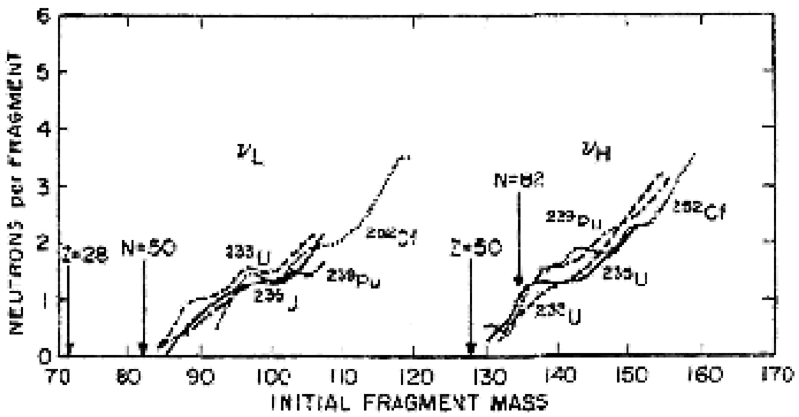
# Systematics: mean TKE

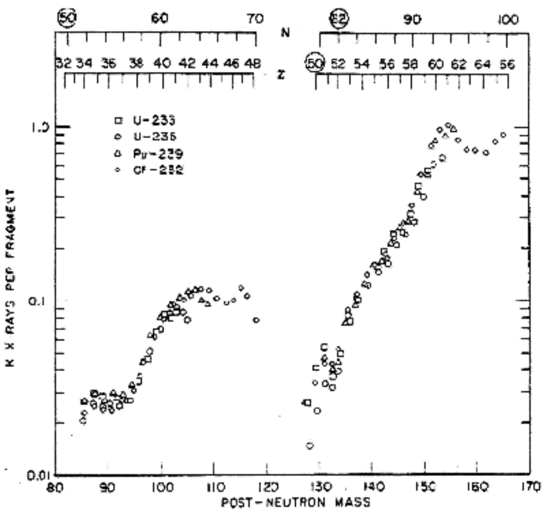


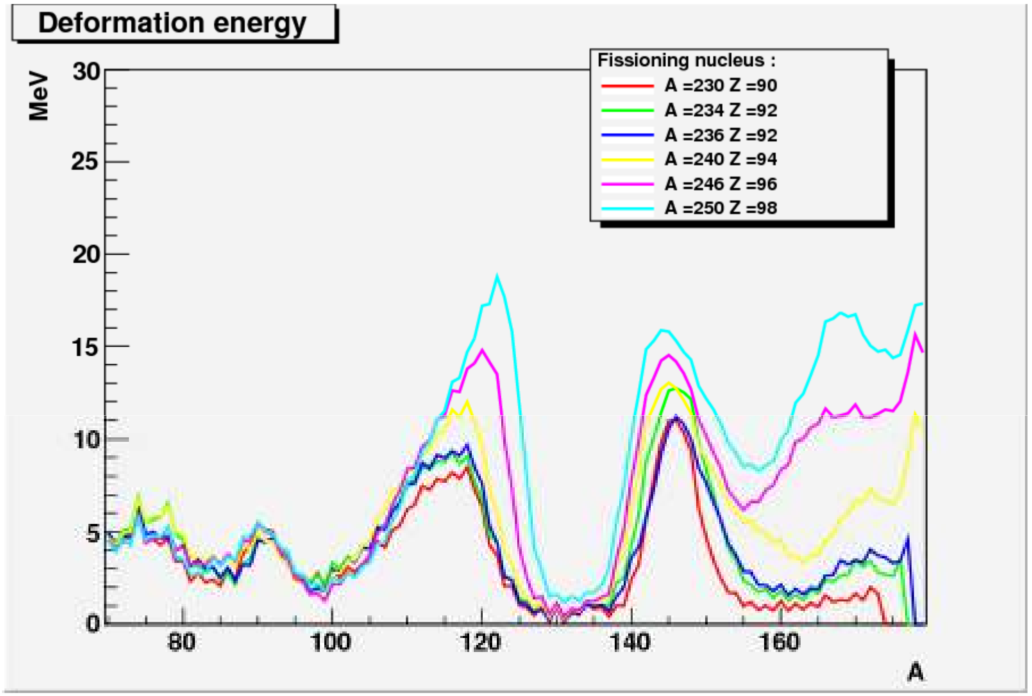




We miss around 10 MeV: prescission energy (d dependence), Coulomb?

# Systematics: mean deformation energy

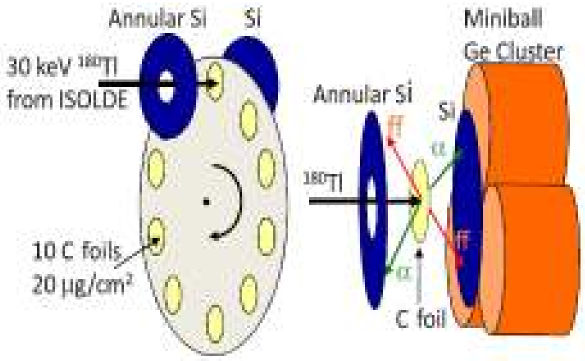


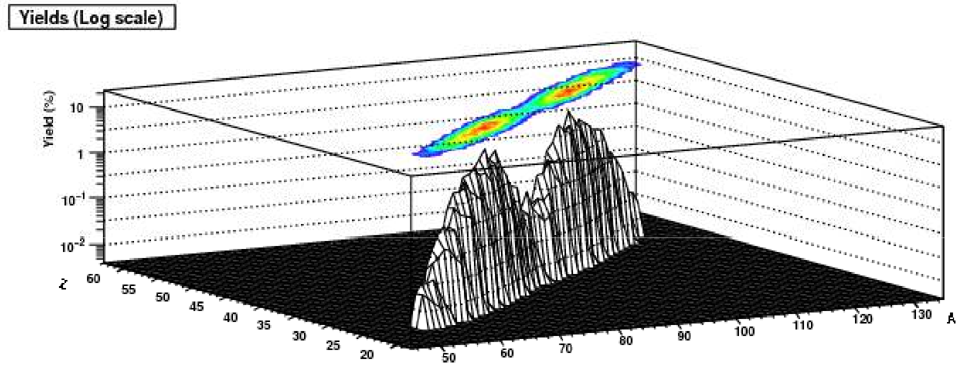

The deformation energy is somehow related to the number of emitted particles

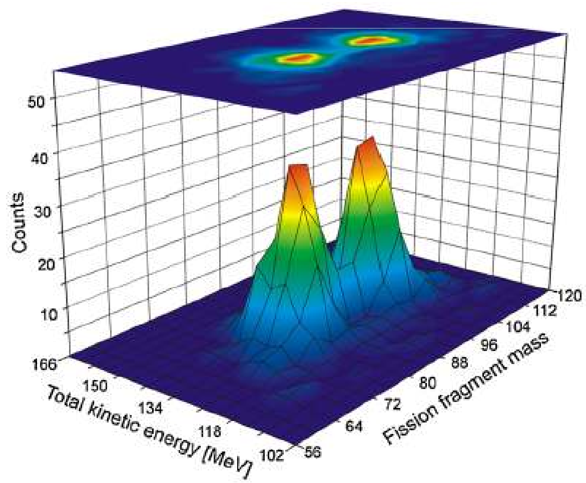
# SPY can already participate to a hot debate…

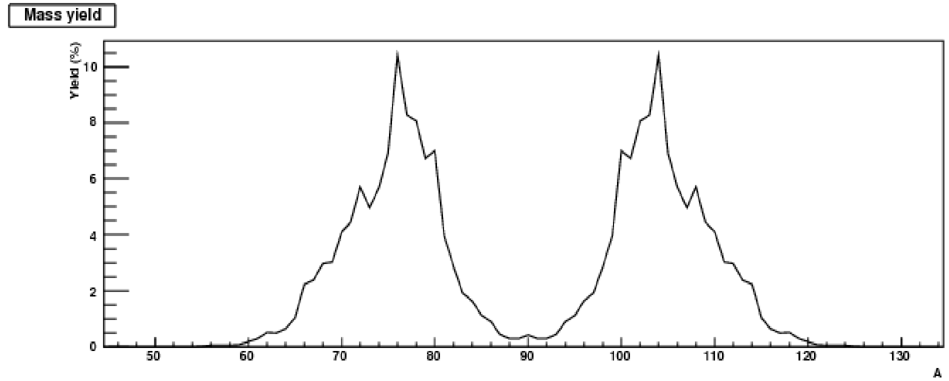



**β-delayed fission of $^{180}$Tl**

Surprising asymmetric yields of $^{180}$Hg fission fully attributed to the nuclear structure of the fissioning nucleus




*Andreyev et al., PRL 105 (2010) 252502*

# Conclusions and perspectives

- We are developing a statistical scission-point model fully based on microscopic ingredients
- Work in progress but first results are encouraging
- The lack of dynamics is visible (width of yields distributions)
- More work needed on:
  - Coulomb interaction calculation
  - Take into account pre-scission energy into the balance (this can wash out the dependence on d)
  - **Level density calculations (for "quasi" beginners…)**
    - **What is the best parametrization?**
    - **How to parameterize the beta dependence?**
    - **Is the E dependence really smooth (like Fermi gas)?**
    - **Microscopic level densities are a useless effort (besides the coherence of the microscopic approach)?**
    - **Is the spin/parity dependence well under control?**
  - Integration of HFB calculation at finite temperature ($E^* \approx T^2$)
  - Integration of full spin populations to calculate isomeric yields
  - …