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

S. Panebianco[1], N. Dubray[2], H. Goutte[1], S. Heinrich[2], S. Hilaire[2], J.-F. Lemaître, J.-L. Sida[1]*

[1]CEA Centre de Saclay, Irfu, 91191 Gif-sur-Yvette, France
[2]CEA, DAM, DIF, 91297 Arpajon, France
** Former member of the laboratory*

WONDER 2012
Aix-en-Provence, 25-28 September 2012

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

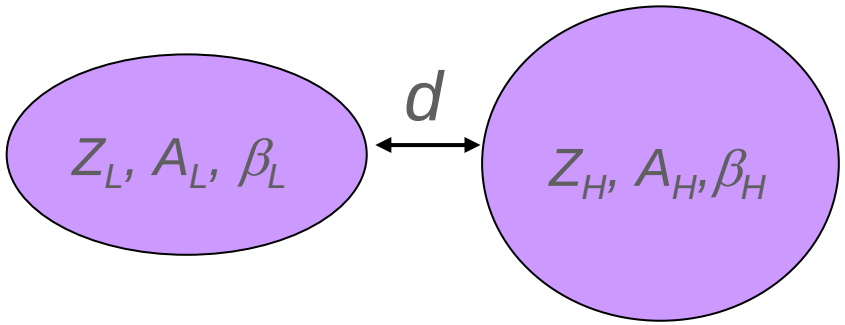
S. Panebianco[1], N. Dubray[2], H. Goutte[1], S. Heinrich[2], S. Hilaire[2], J.-F. Lemaître, J.-L. Sida[1]*

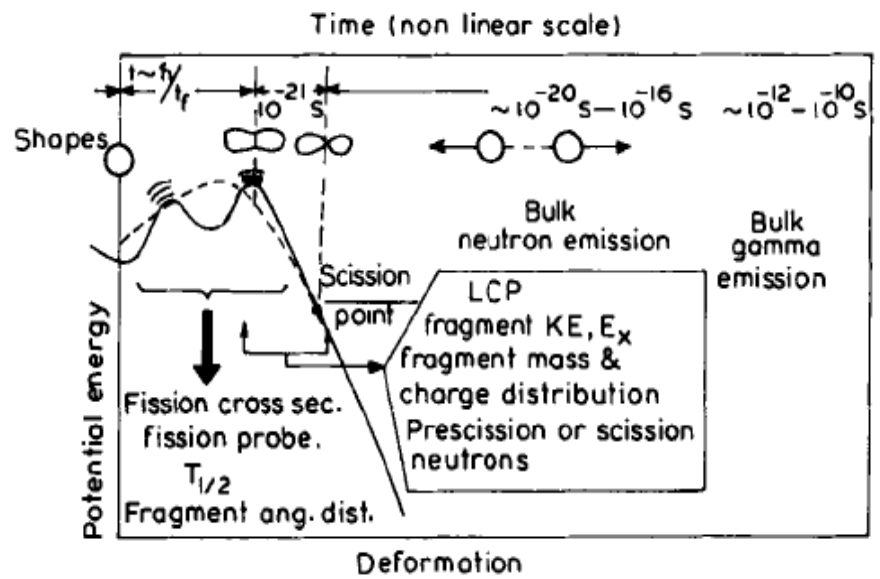
[1]CEA Centre de Saclay, Irfu, 91191 Gif-sur-Yvette, France
[2]CEA, DAM, DIF, 91297 Arpajon, France
** Former member of the laboratory*

WONDER 2012
Aix-en-Provence, 25-28 September 2012

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

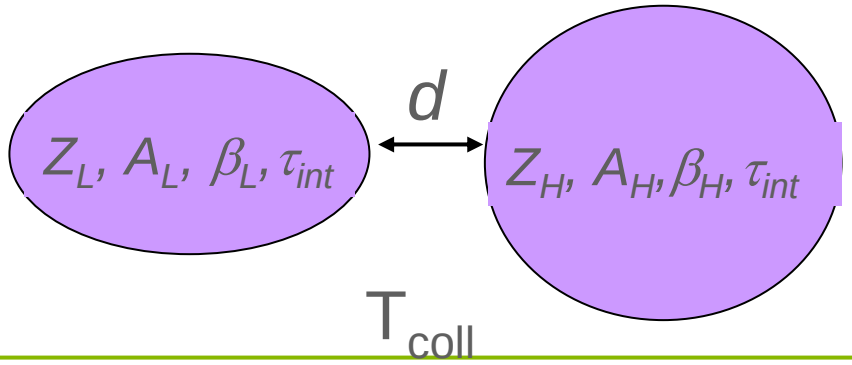




The scission-point model

- 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 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 (avail. @ Amedee database)
  - No dependence on intrinsic temperature
  - Available energy is calculated as:

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

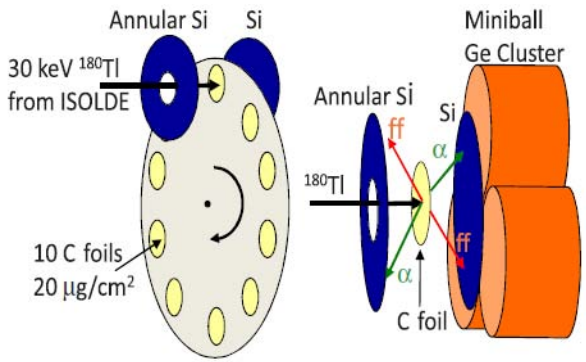
$$V(Z_{1,2},N_{1,2},\beta_{1,2},d) = \Sigma V_{HFB}^{1,2}(Z^{1,2},N^{1,2},\beta^{1,2}) + V_{coul}(Z_{1,2},N_{1,2},\beta_{1,2},d) + V_{nucl}(Z_{1,2},N_{1,2},\beta_{1,2},d)$$

  - Coulomb interaction based on Cohen Swiatecki formalism

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

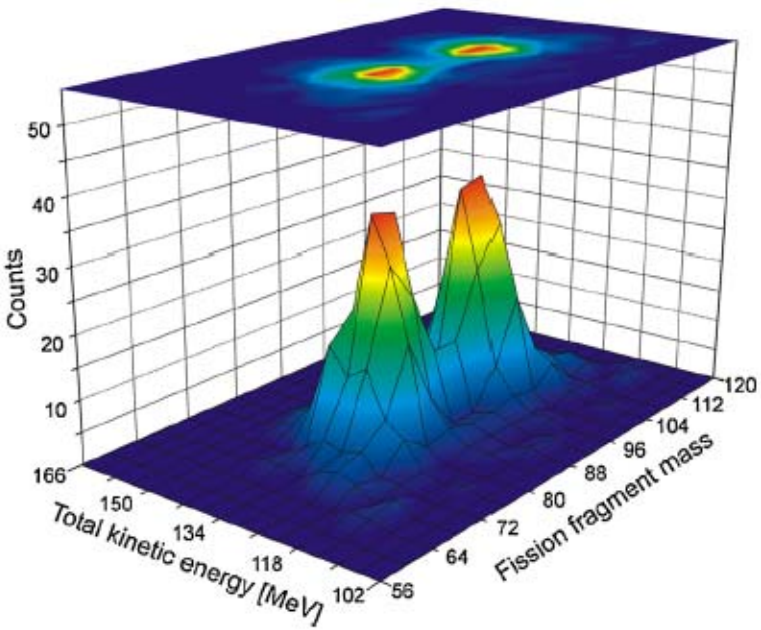
    Blocki et al, Annals of Physics 105 (1977) 427

SPY into the Hg fission 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 (2011) 252502

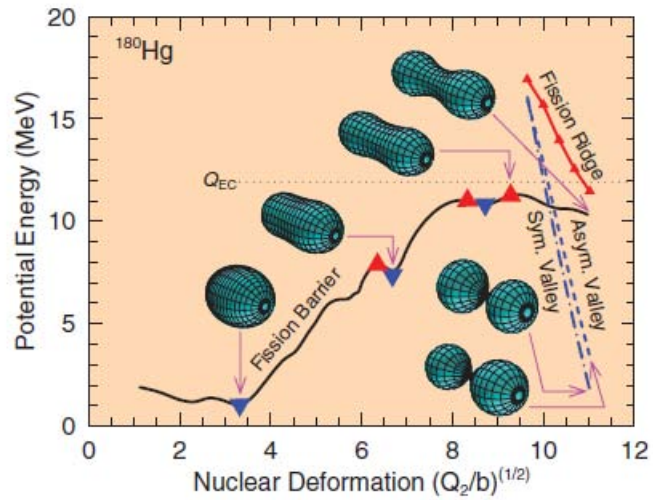
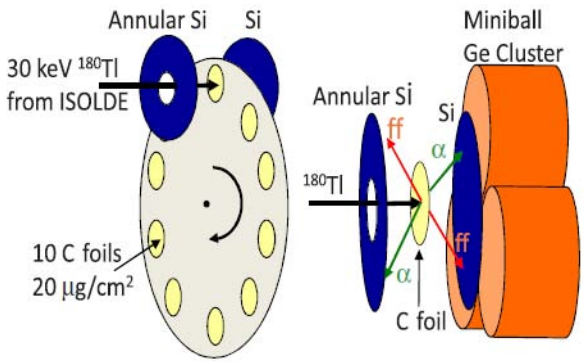


FIG. 4. (Color online) Minima, saddles, major valleys, and ridges in the 5D potential-energy surface of ^{180}Hg (see text). At the last plotted point on the fission barrier, $(Q_2/\mathrm{b})^{(1/2)} \approx 11$, the asymmetry of the shape is $A_H/A_L = 108/72$.

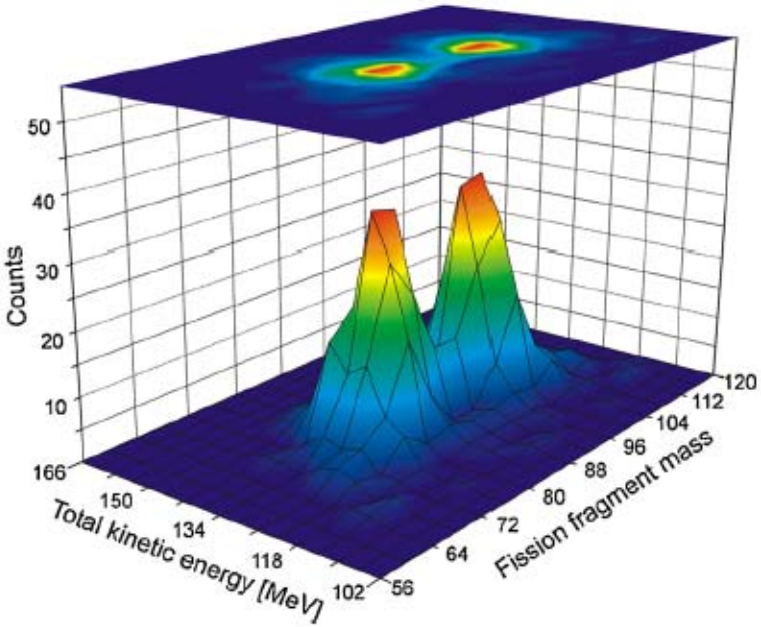
Möller et al., PRC 85 (2012) 024306

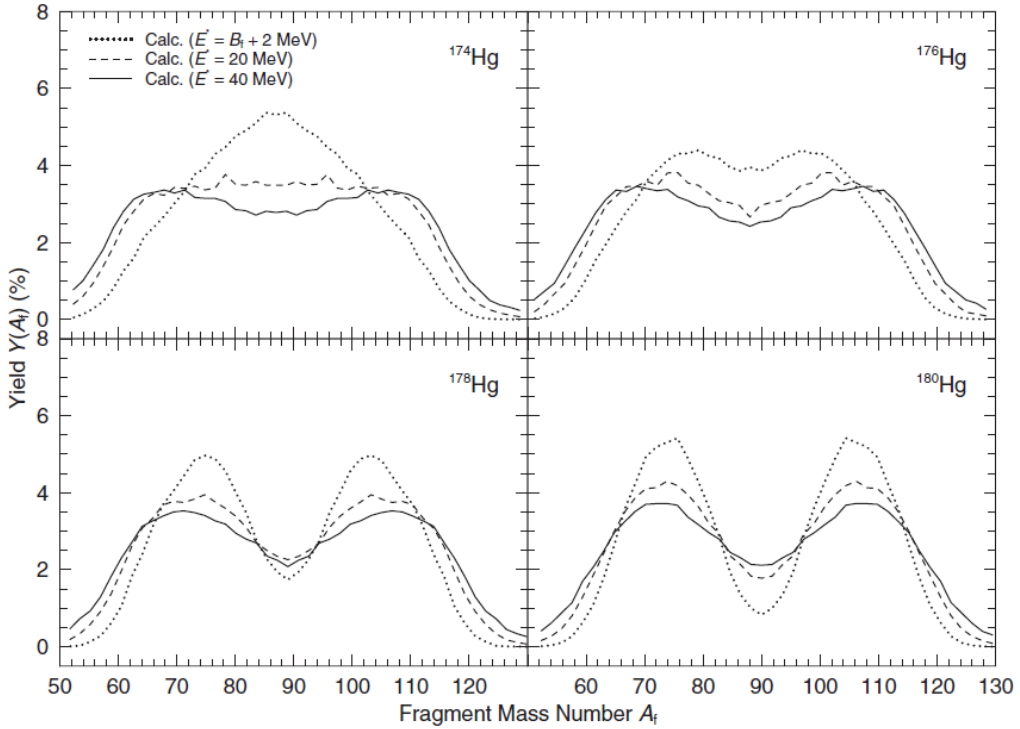
SPY into the Hg fission debate…



β-delayed fission of ^{180}Tl

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



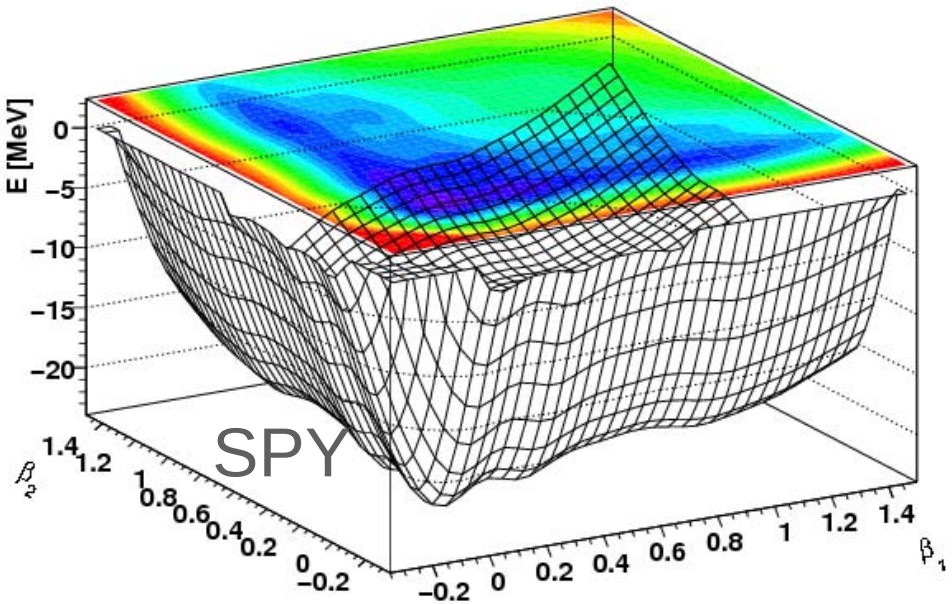


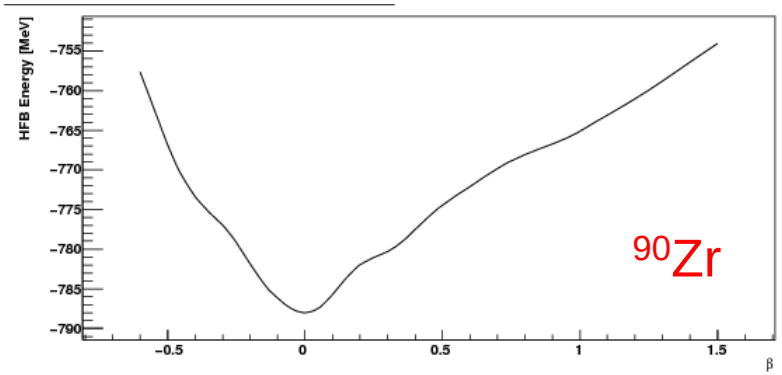
Andreyev et al., PRL 105 (2011) 252502

Möller et al., PRC 85 (2012) 024306

Available energy at scission: symmetric fragmentation

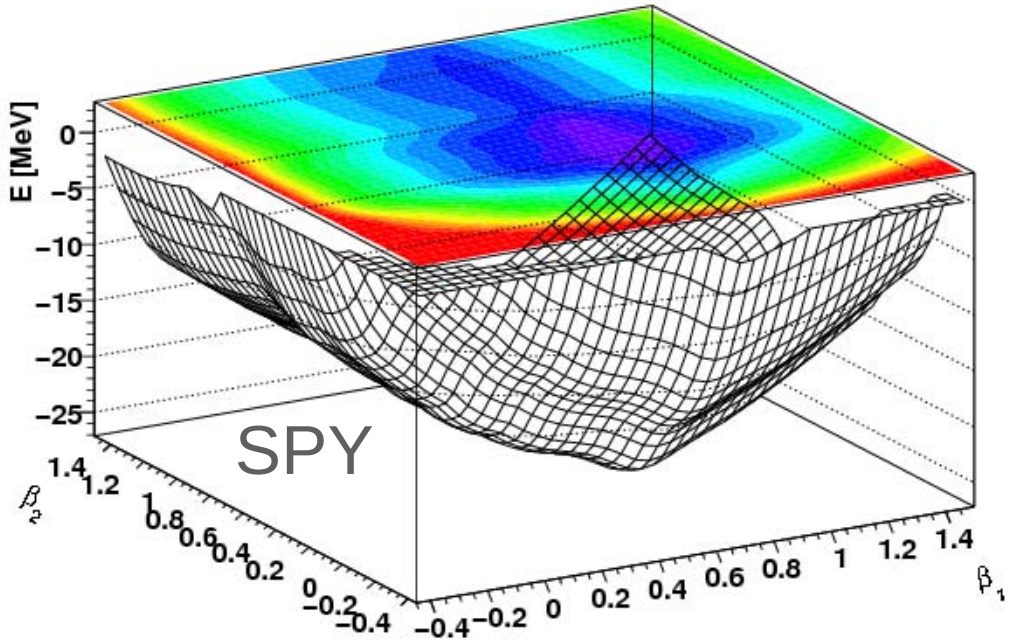
^{180}Hg fission @ E*=10MeV

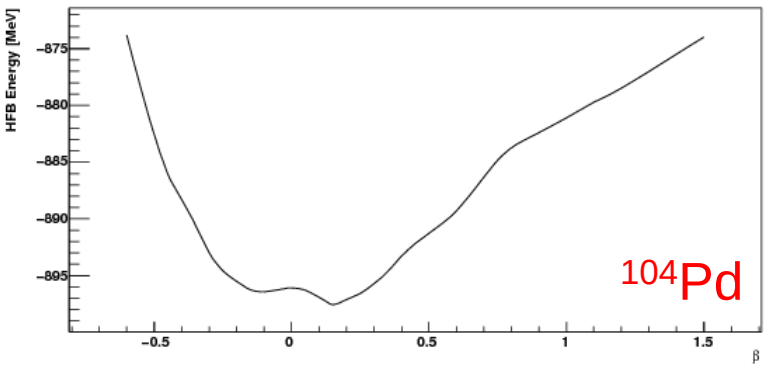


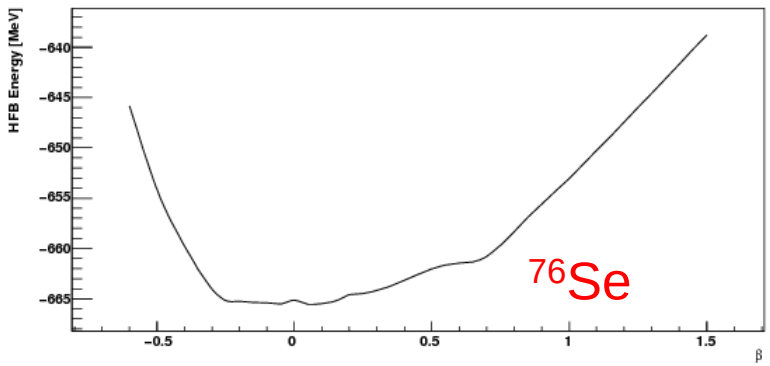


Available energy at scission: asymmetric fragmentation

^{180}Hg fission @ E*=10MeV

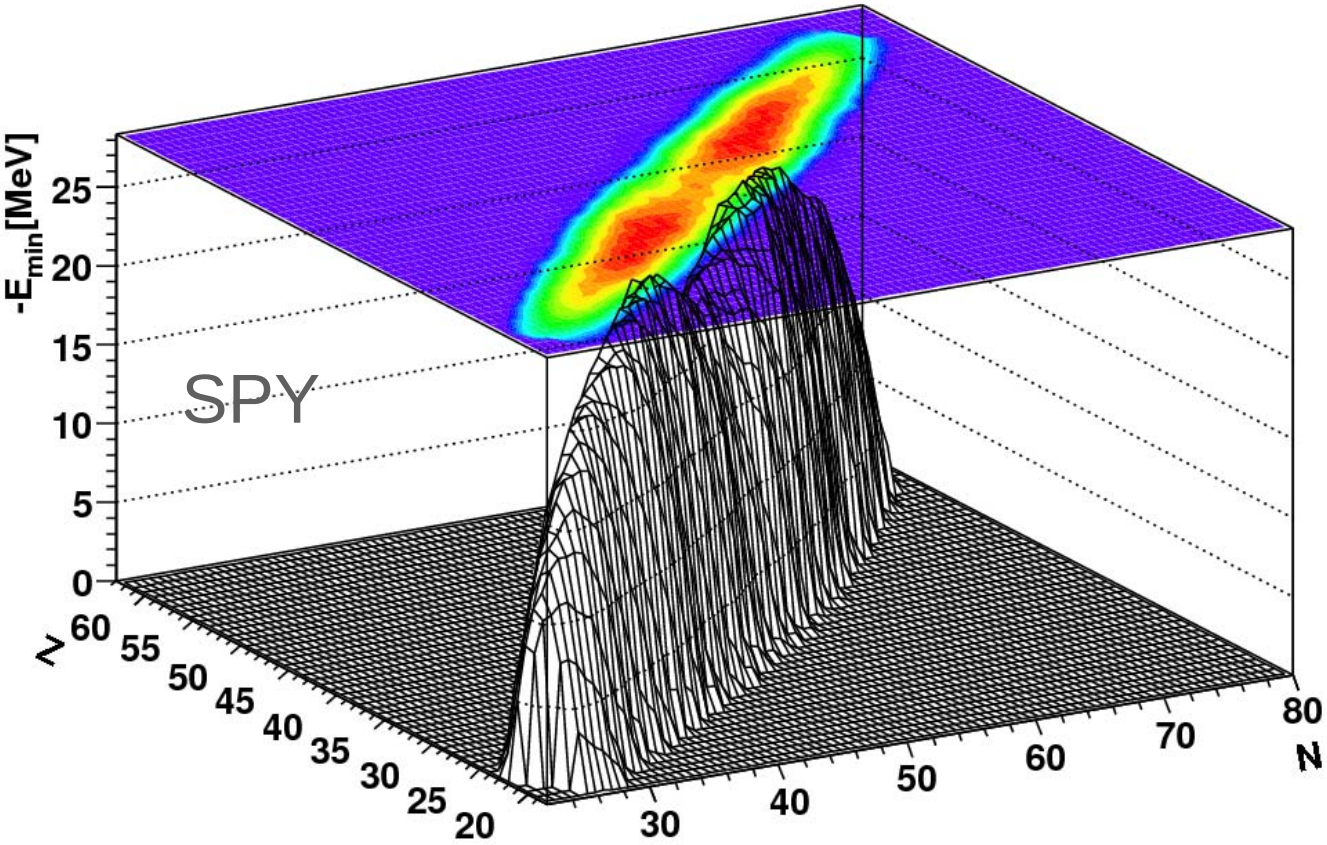






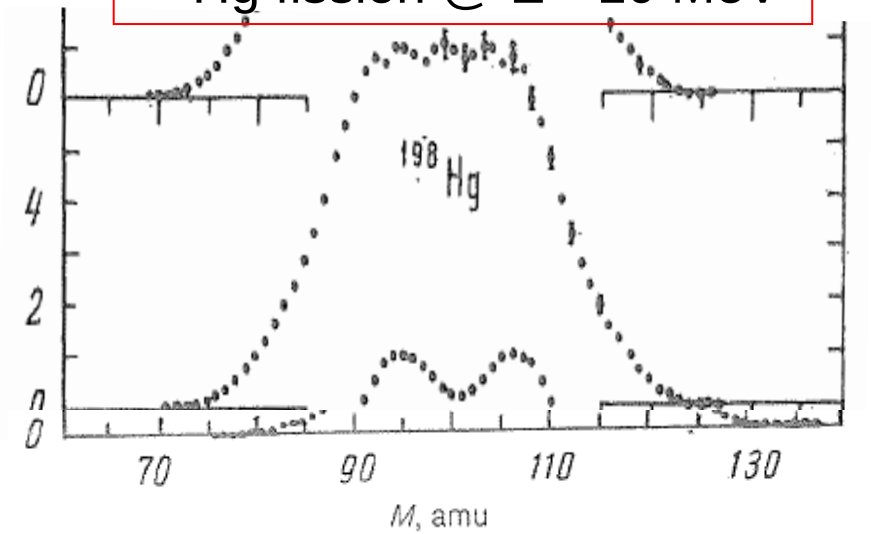
Available energy at scission

^{180}Hg fission @ E*=10MeV



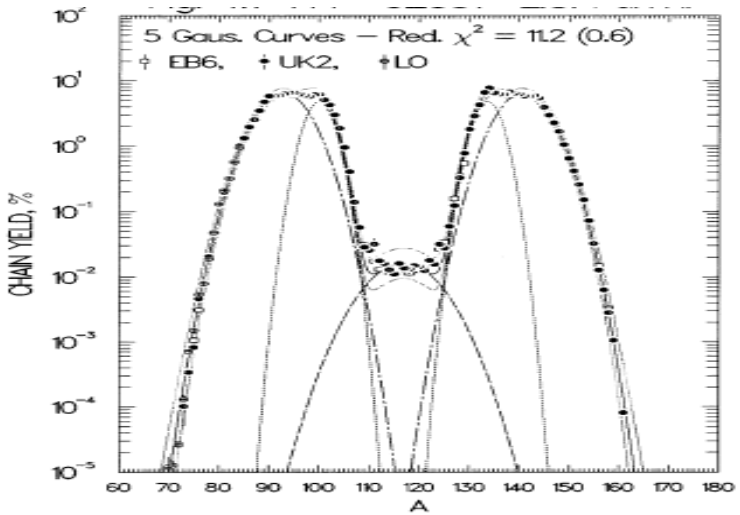
Two reference cases

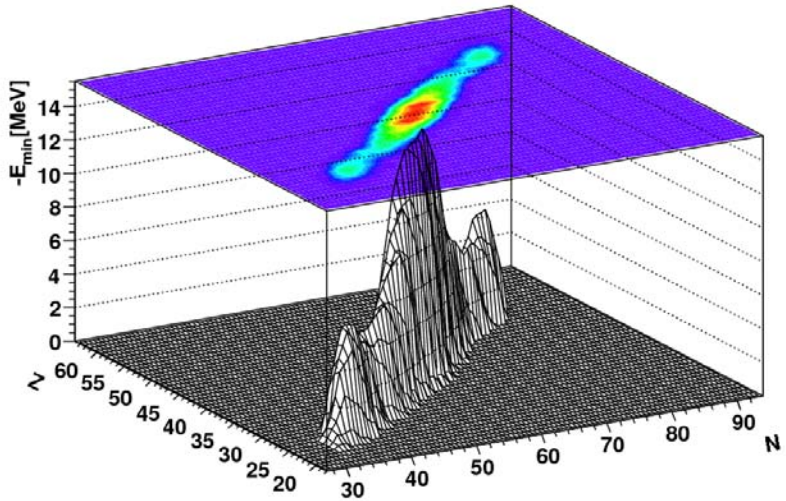
^{198}Hg fission @ E*=10 MeV



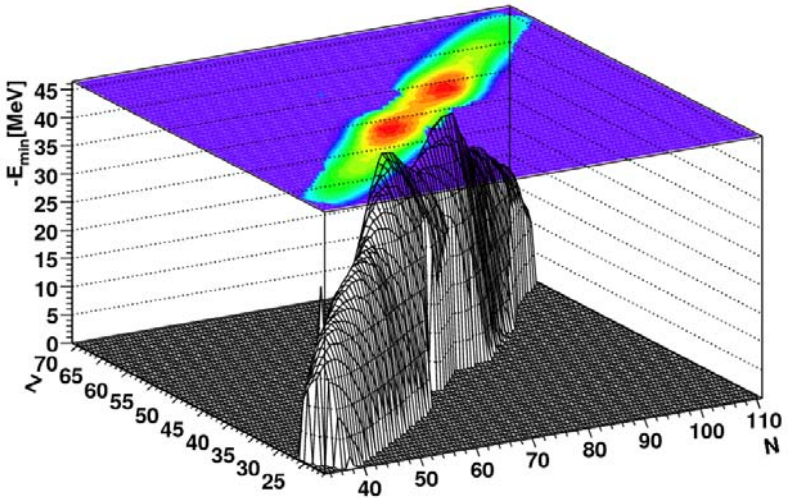
Itkis et al., Yad. Fiz. 53 (1991) 1225

^{236}U fission @ E*=8 MeV





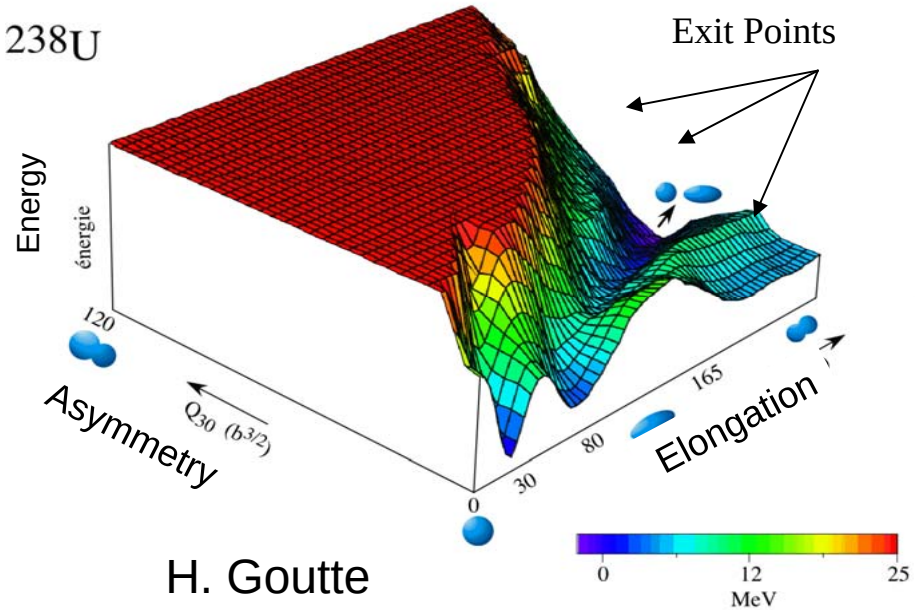
SPY



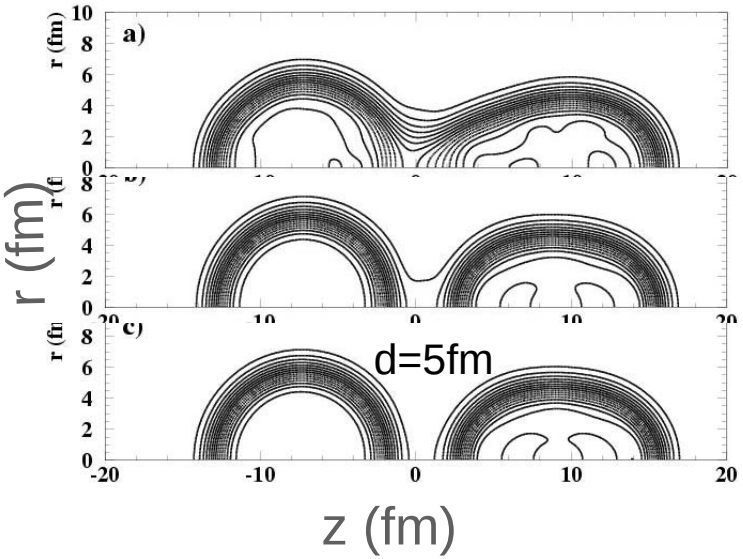
On the scission point definition

- 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

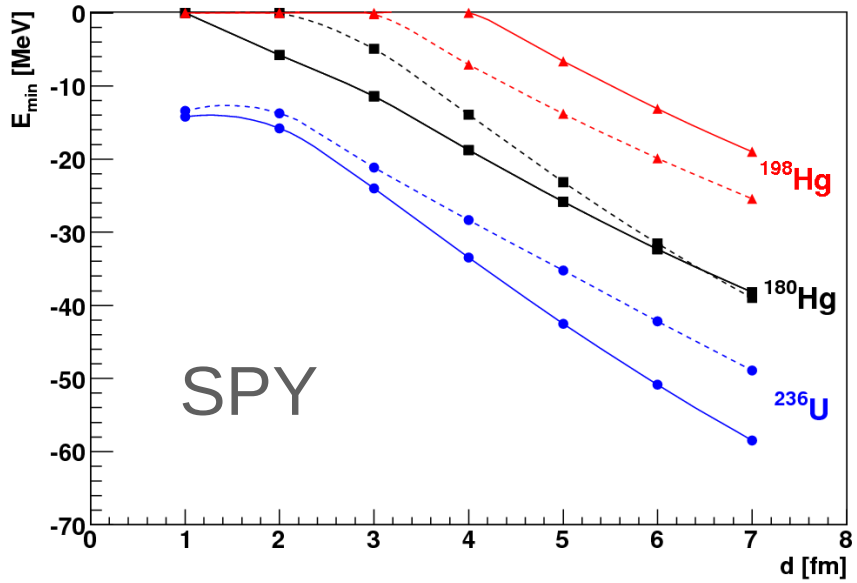
Nucleon density at the neck $\rho < 0.01$ fm^3
Total binding energy drop ($\approx$ 15 MeV)
Hexadecupolar moment drop ($\approx$ 1/3)

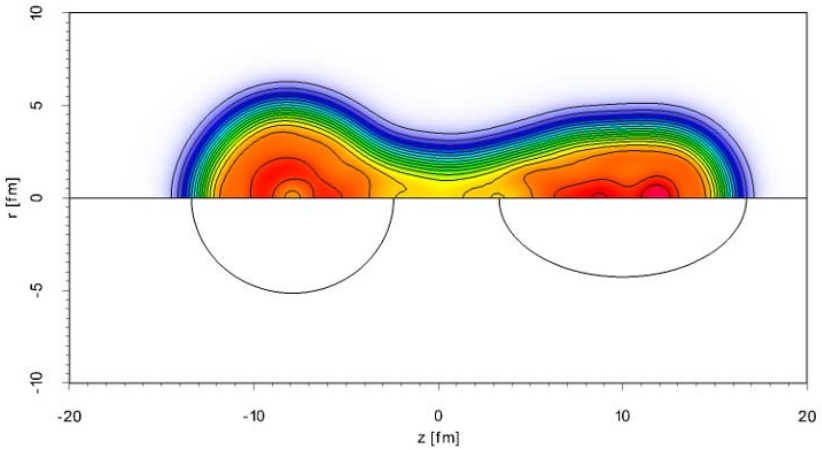


H. Goutte



On the choice of the scission distance





Self-consistent HFB of ^{180}Hg: most probable configuration (q_{20}=256.12b ; q_{30}=33.28b$^{3/2}$)

d = 5.7 fm

N. Dubray

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

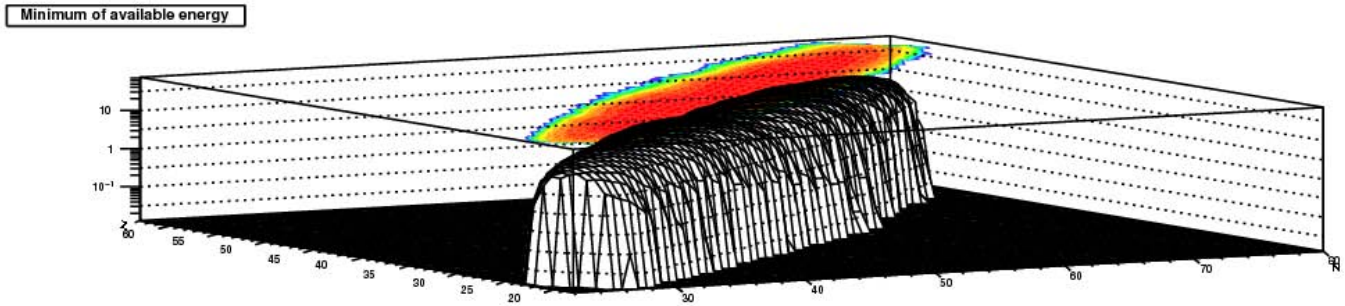
and $\sigma = I_0 a\sqrt{E/a}$

- A microscopic calculation of level densities has been recently performed (at zero temperature) in the framework of HFB formalism
- Very time consuming since the we need the energy evolution at each deformation for some 1500 nuclei

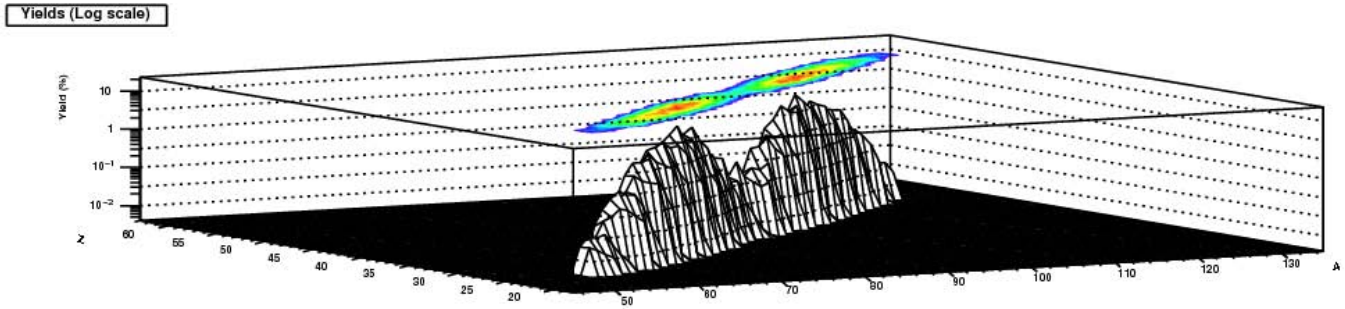
From the available energy to the yield

^{180}Hg fission @ E*=10MeV

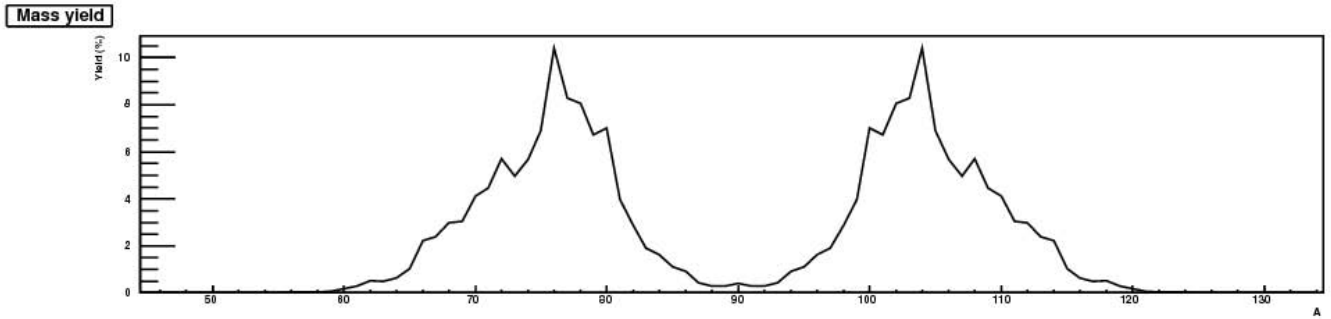
A_{min}



Yields



Mass yields



Conclusions and perspectives

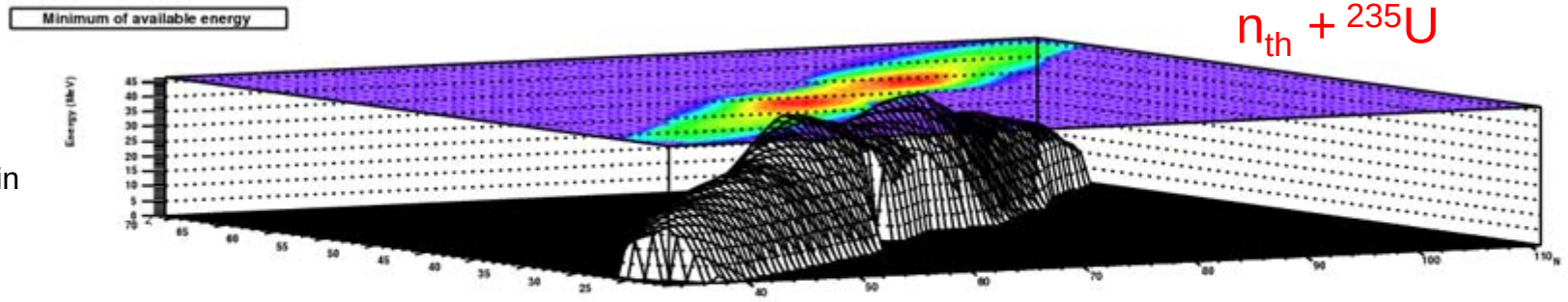
- **SPY: a scission-point model fully based on microscopic ingredients (beyond Wilkins)**
- Work in progress but first results are rather encouraging
- Able to **explain the mass asymmetry observed in ^{180}Hg** fission (paper just submitted for publication…)
- The lack of dynamics is visible (width of yields distributions… see B. Jurado talk!) and expected
- Ongoing and future developments (PhD thesis starting):
  - Take into account pre-scission energy into the balance (this can wash out the dependence on d)
  - Integration of the new D1M Gogny interaction
  - Integration of HFB calculation at finite temperature ($E^* \approx T^2$)
  - Microscopic level densities from HFB (intrinsic + collective)
  - Integration of full spin populations
  - Integration in THALYS
  - **...**

Backup slides

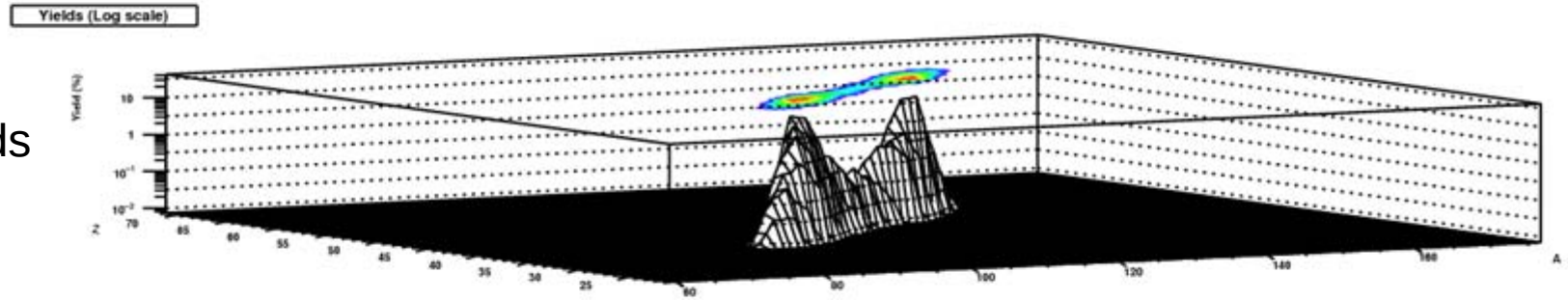
From the available energy to the yield

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

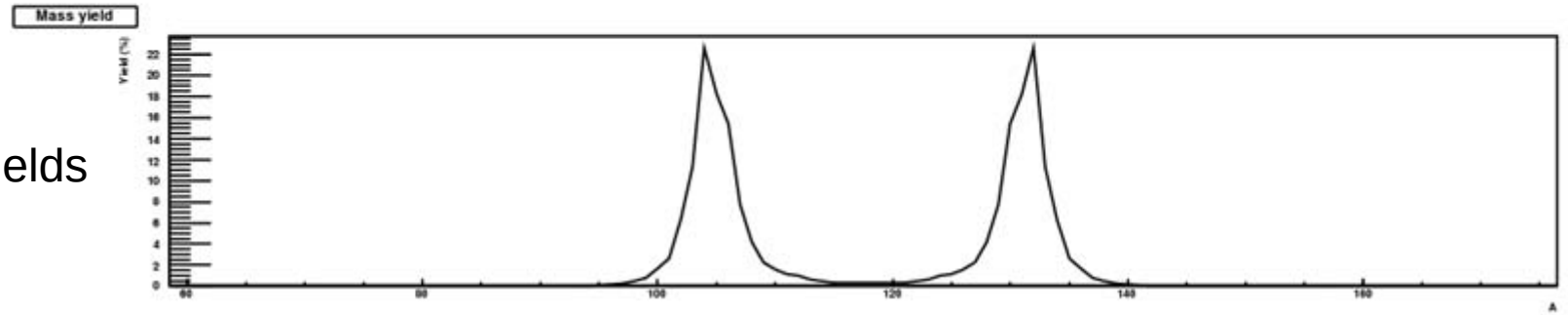
A_{min}



Yields

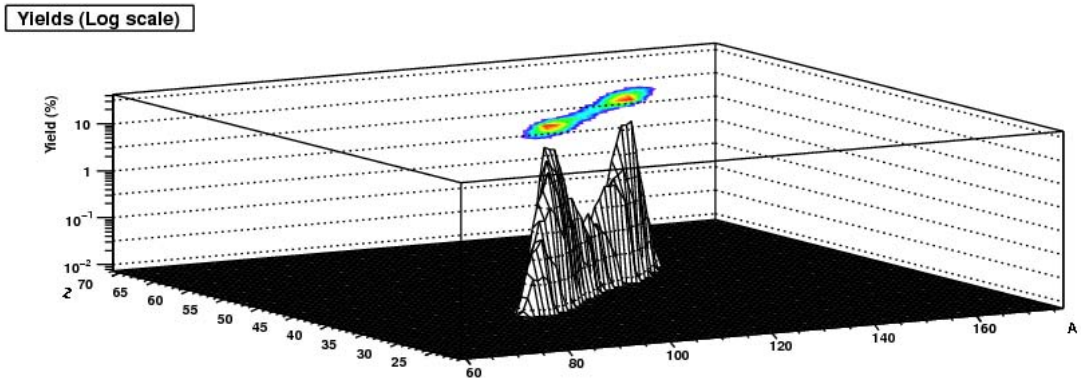


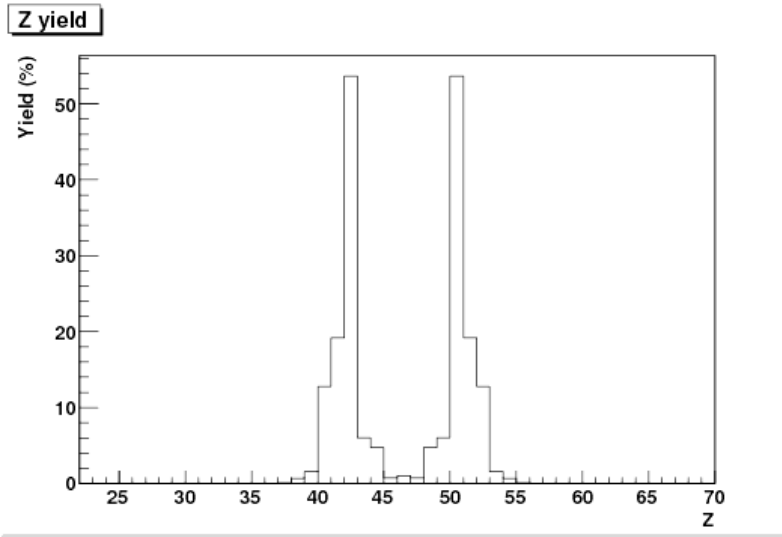
Mass yields

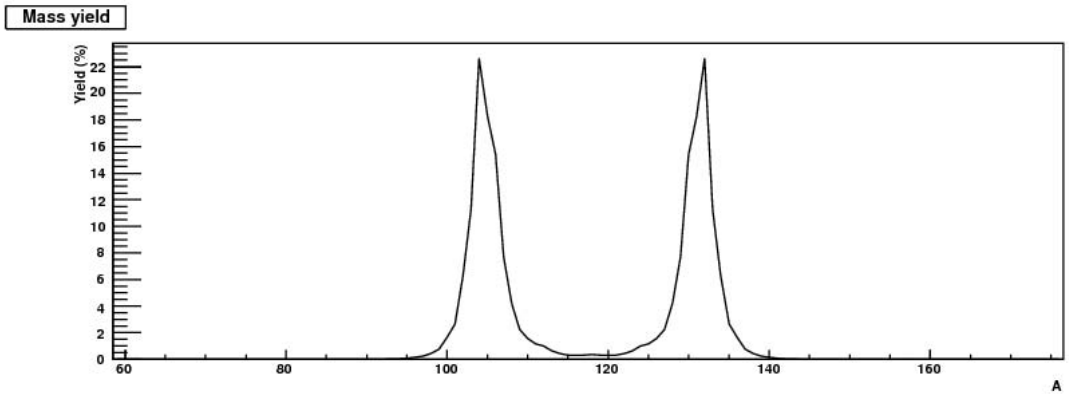


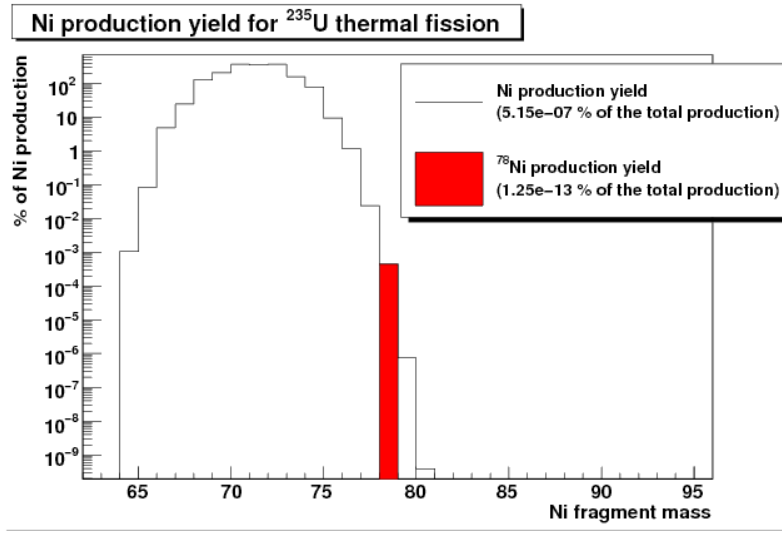
Observables: mass and charge yields

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

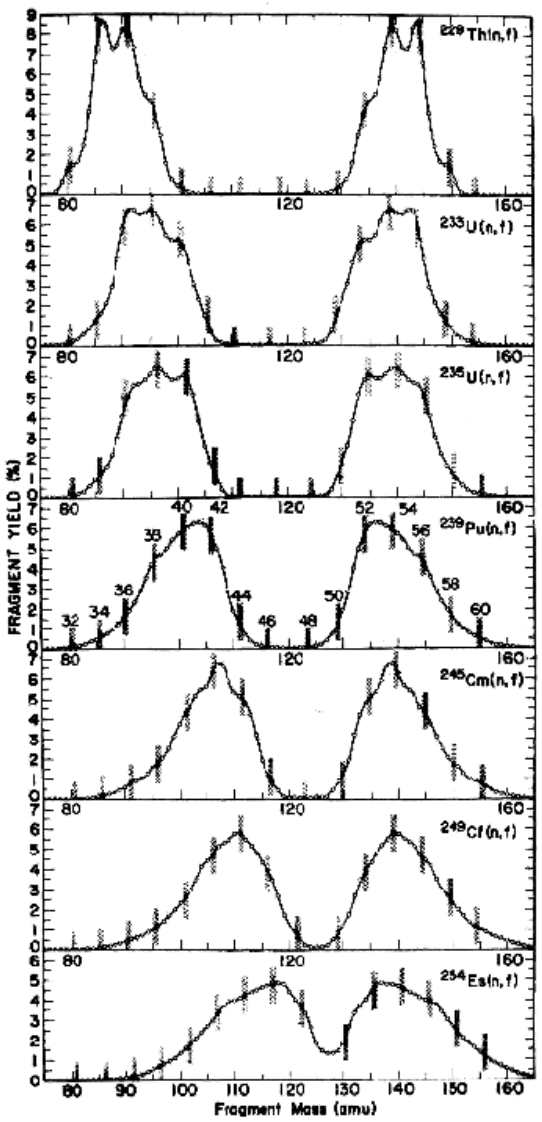








Systematics: mass yields for n-induced fission



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

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

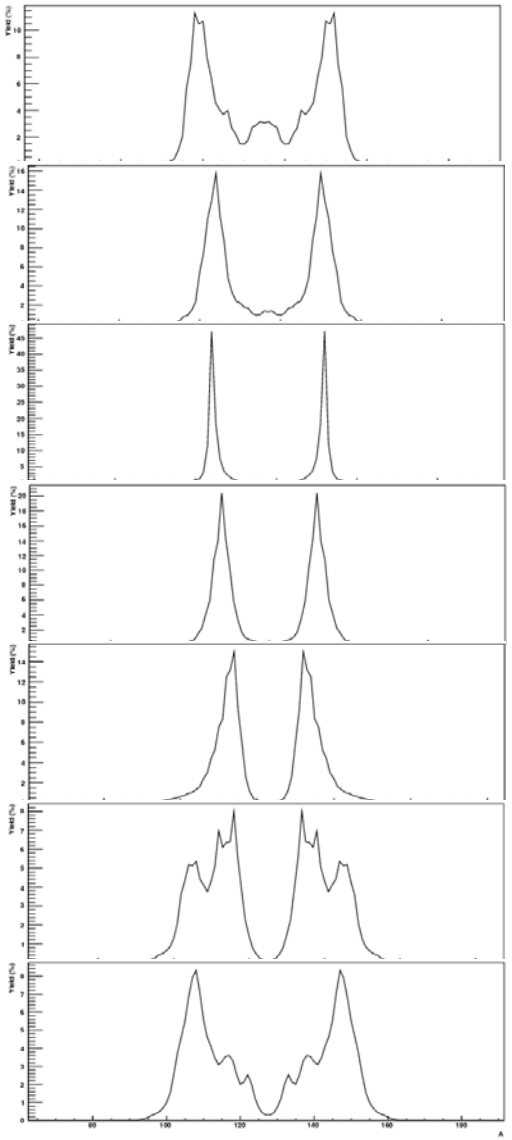
$n_{th} + {}^{235}U$

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

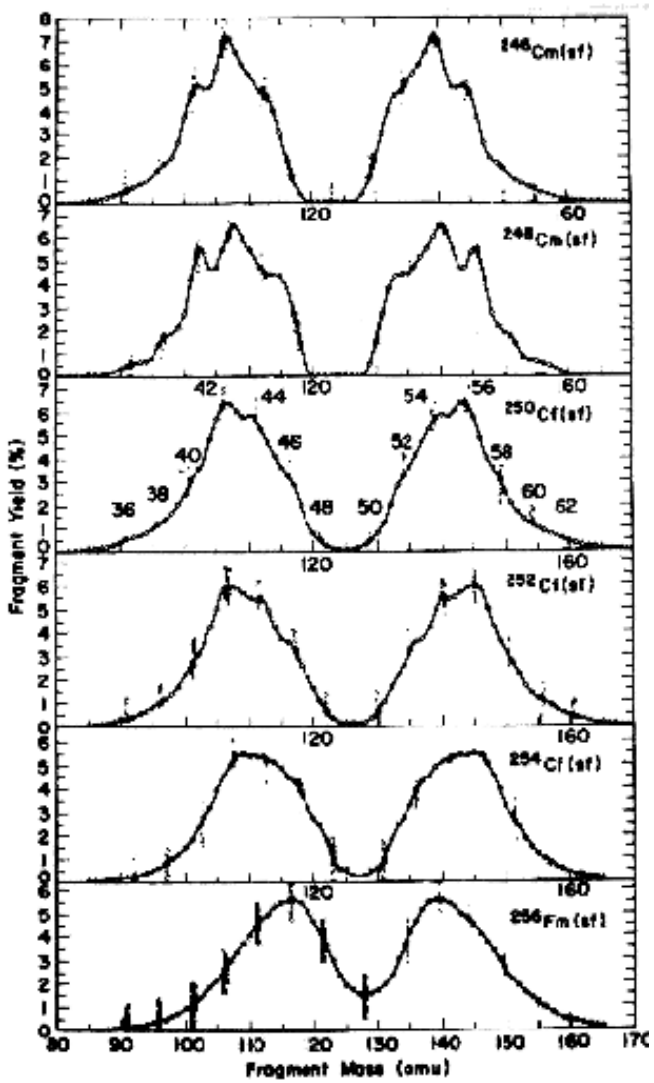
$n_{th} + {}^{245}Cm$

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

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



Systematics: mass yields for spontaneous fission



^{246}Cm(sf)

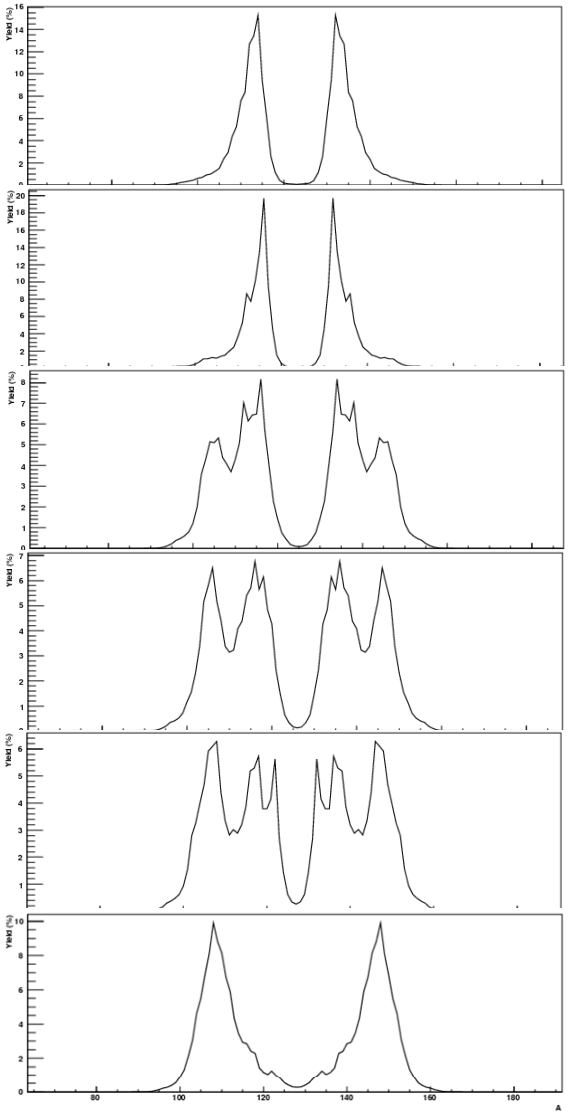
^{248}Cm(sf)

^{250}Cf(sf)

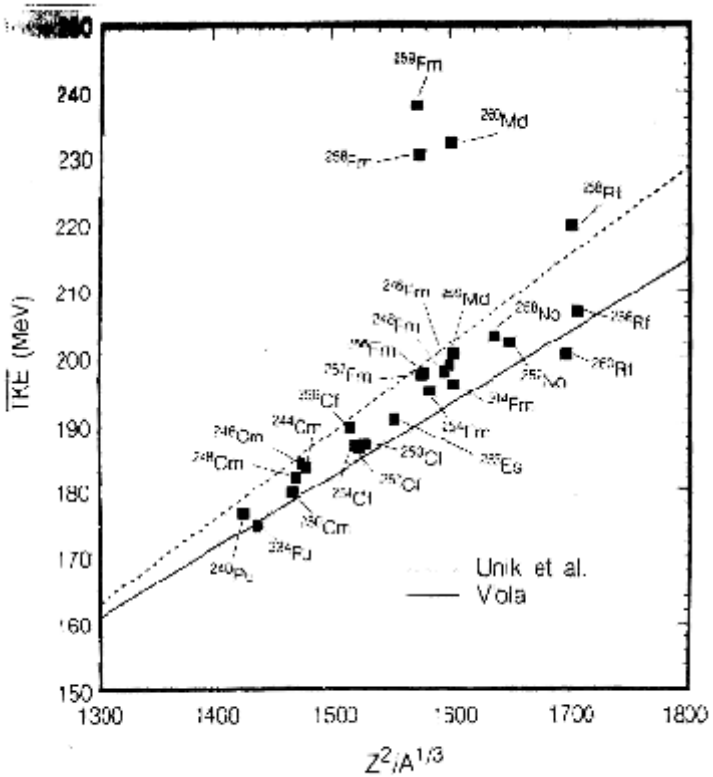
^{252}Cf(sf)

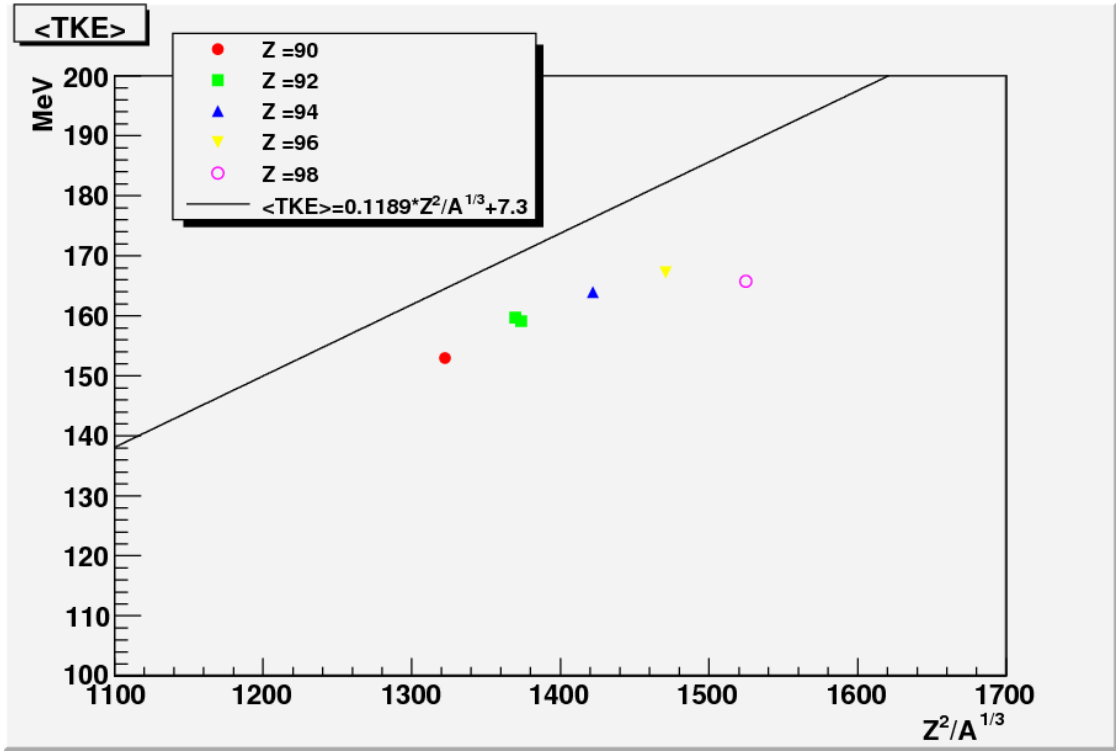
^{254}Cf(sf)

^{256}Fm(sf)



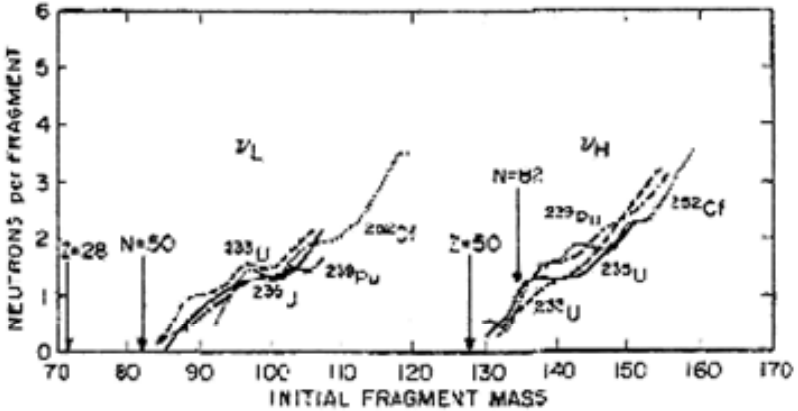
Systematics: mean TKE

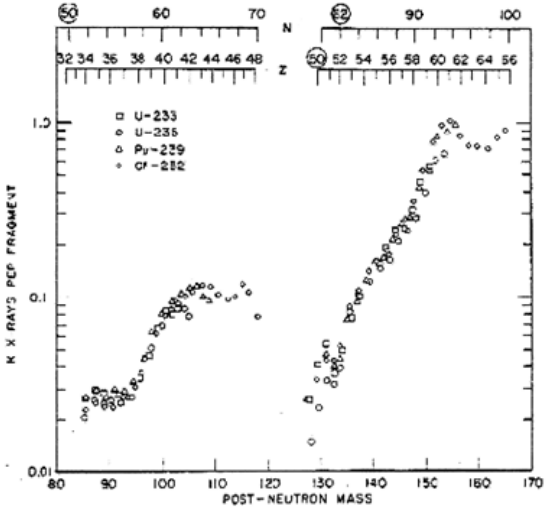


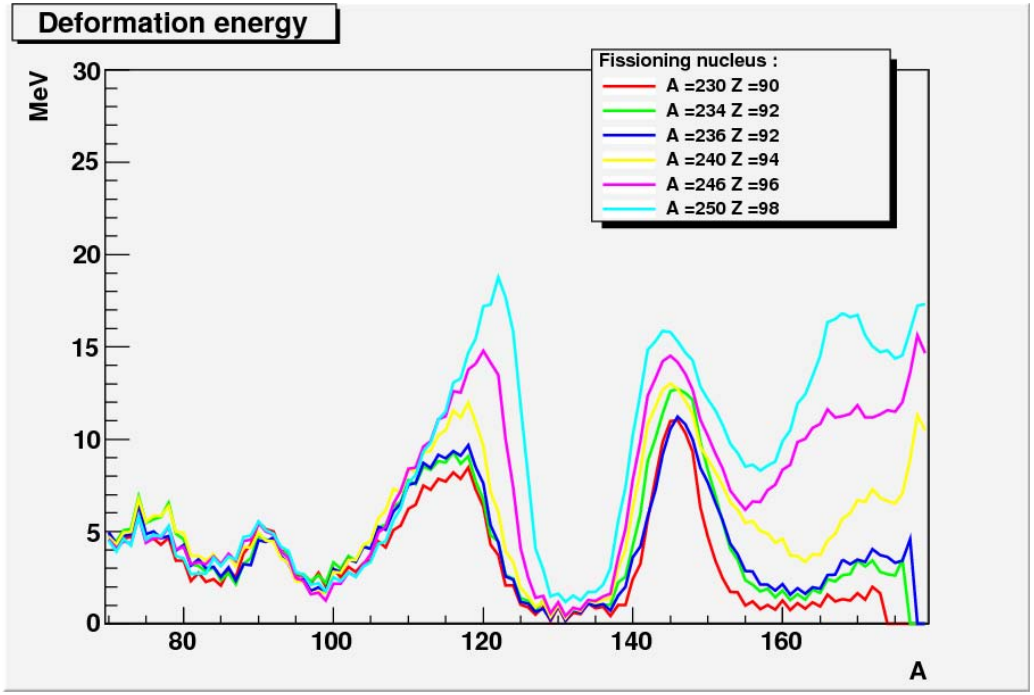


We miss around 10 MeV: prescission energy (d dependence), Coulomb?

Systematics: mean deformation energy



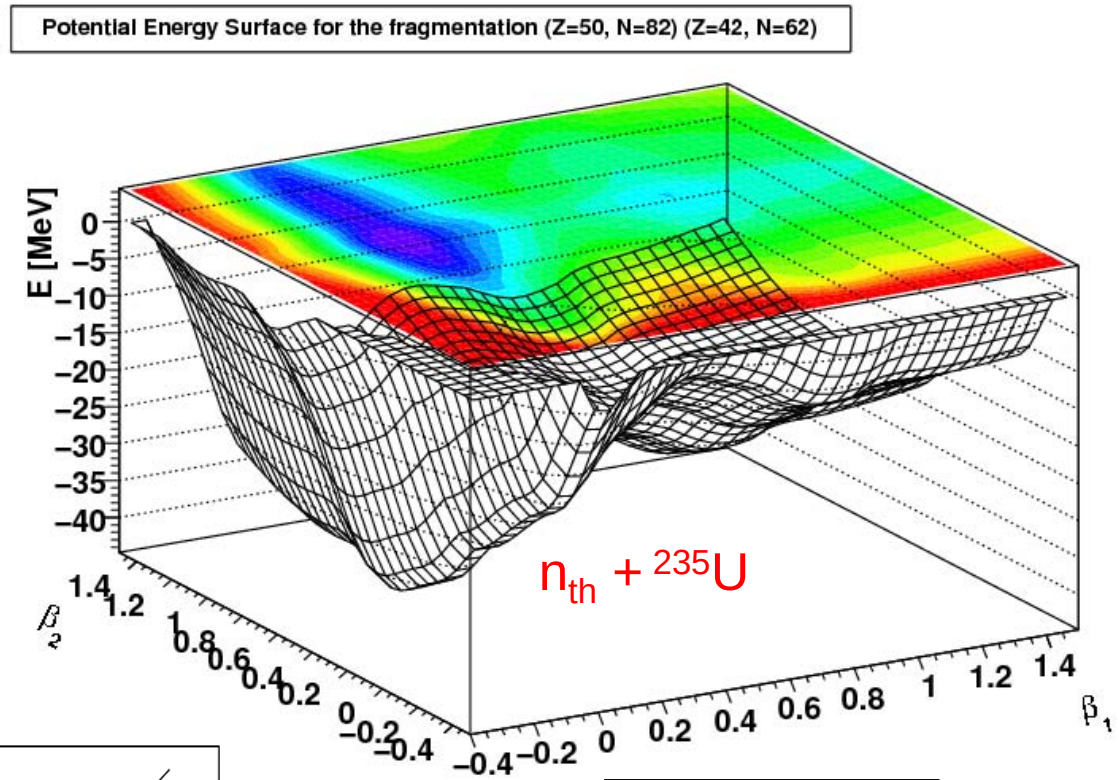


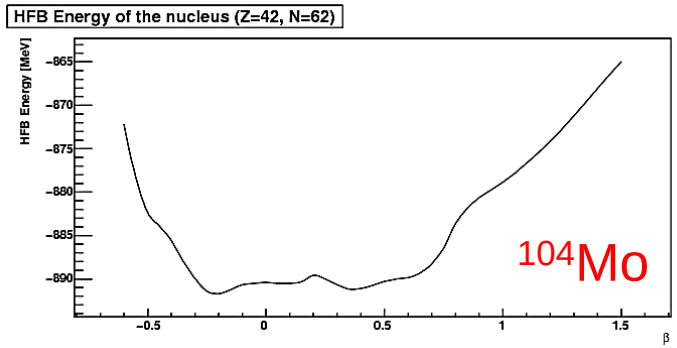


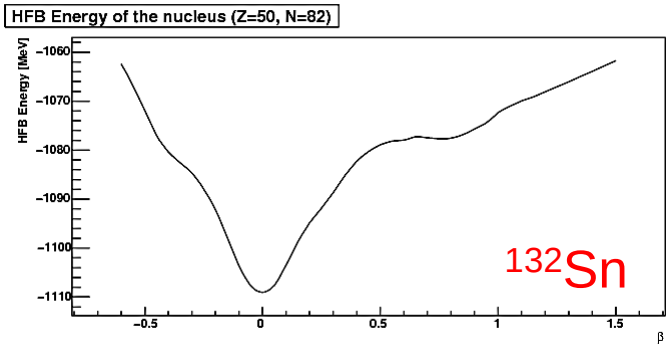
The deformation energy is somehow related to the number of emitted particles

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