Fully microscopic scission-point model to predict fission fragment observables : SPY model

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Energy production applications

nuclear power reactors

nuclear waste recycling

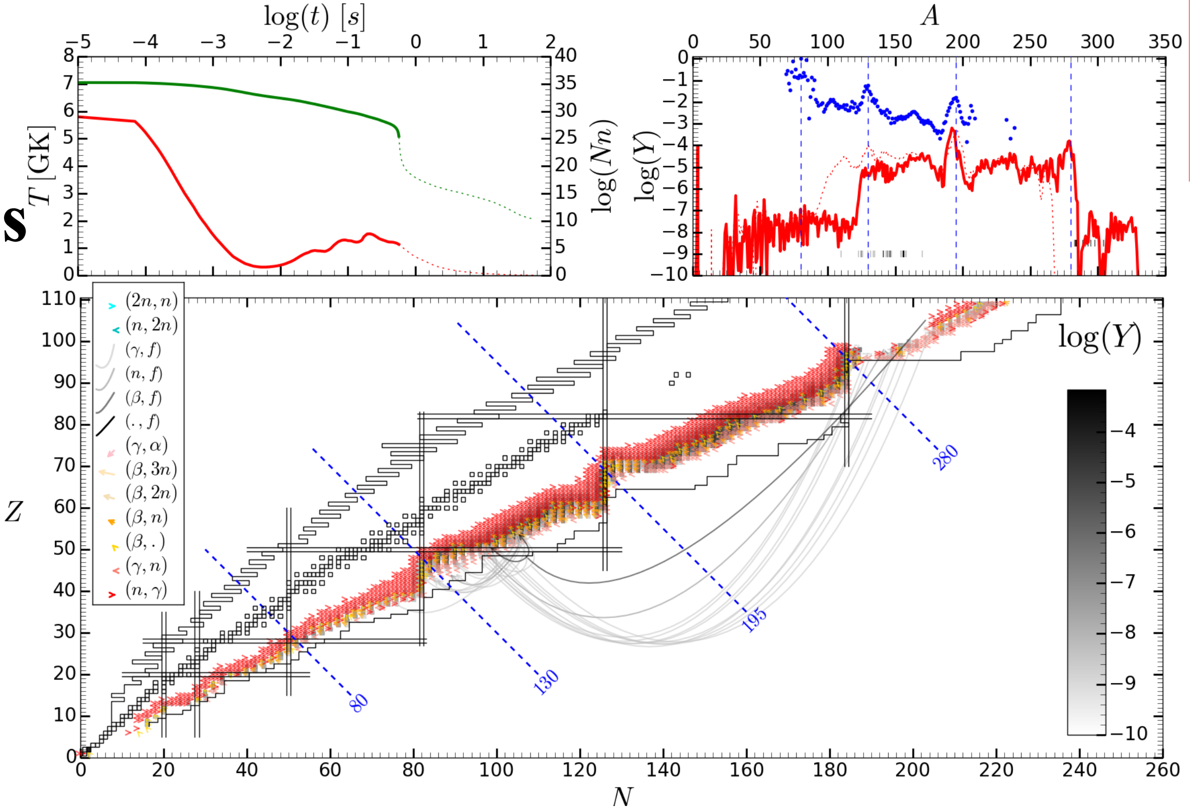
Astrophysics (NS ejecta)

rapid neutron-capture process

Nuclear physics

static & dynamic properties

neutron rich nuclei production



*** Fission process**

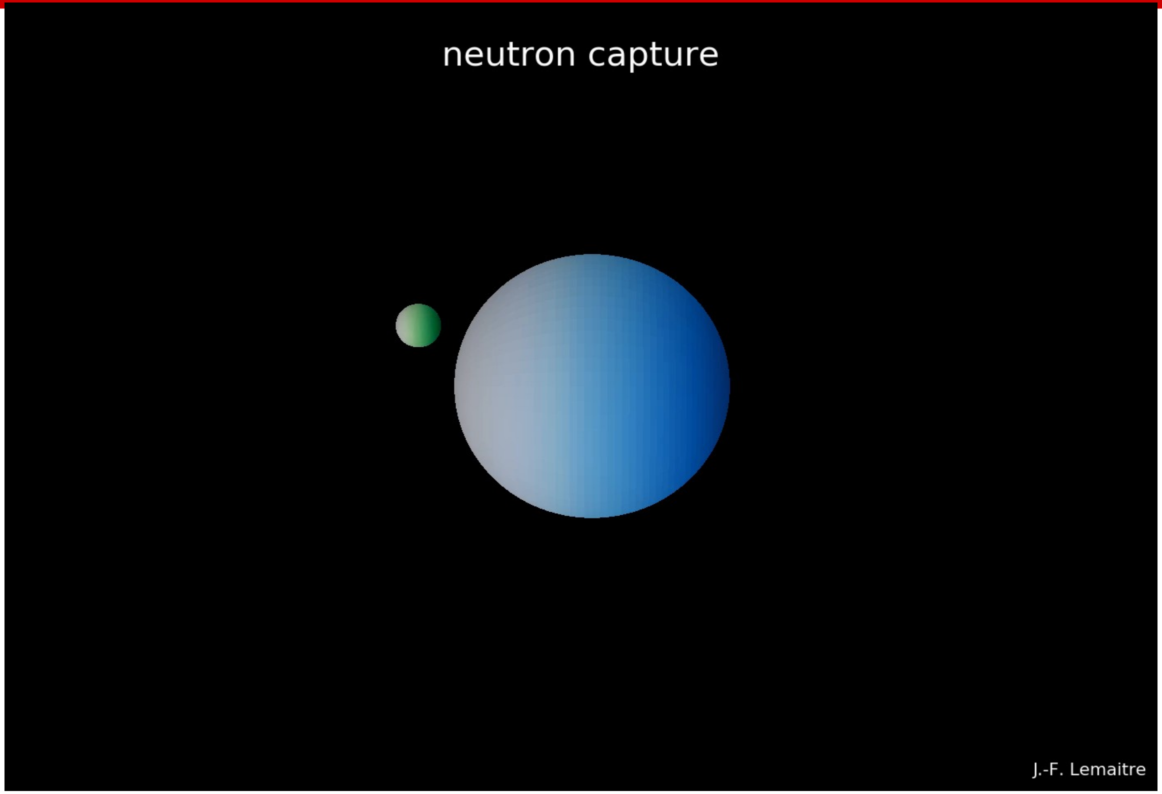
*** SPY model**

*** Results**

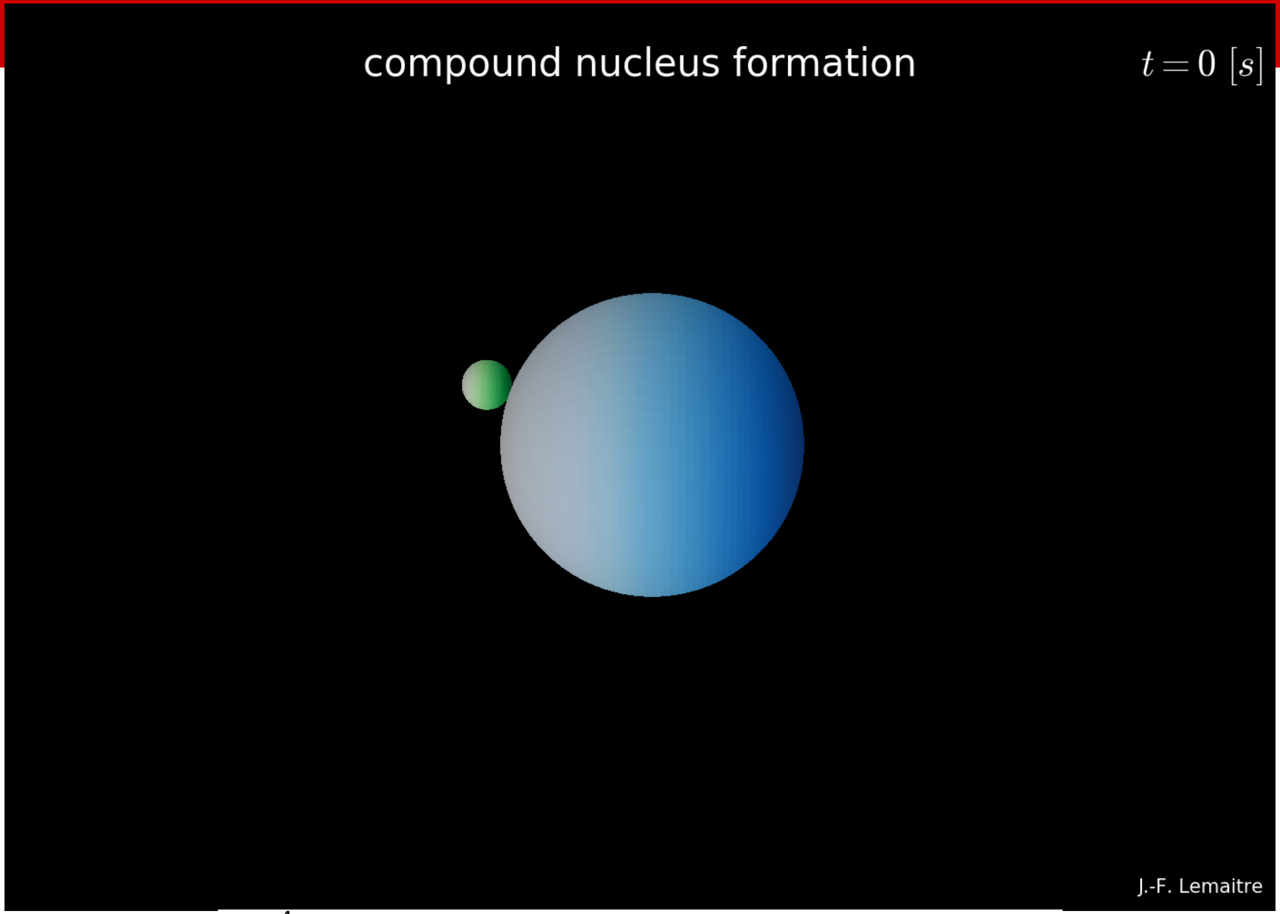
*** Pu240**

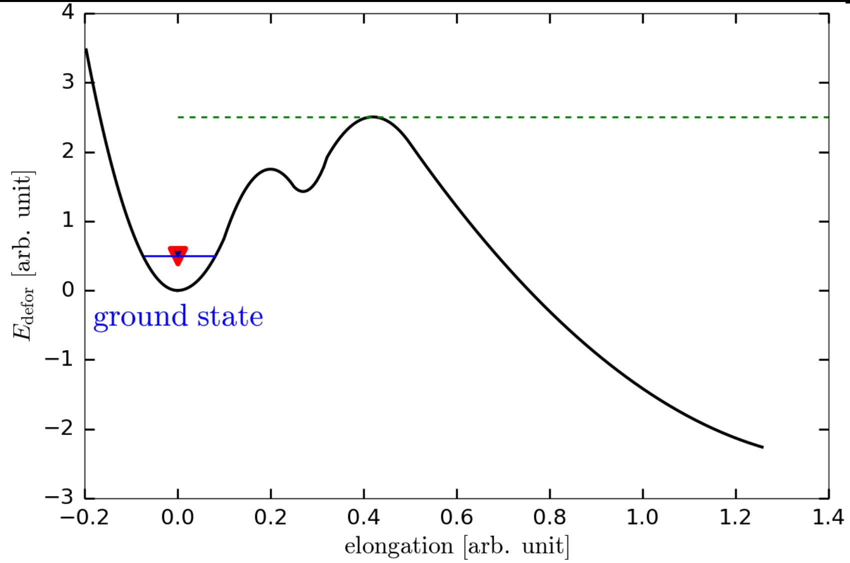
*** Systematic**

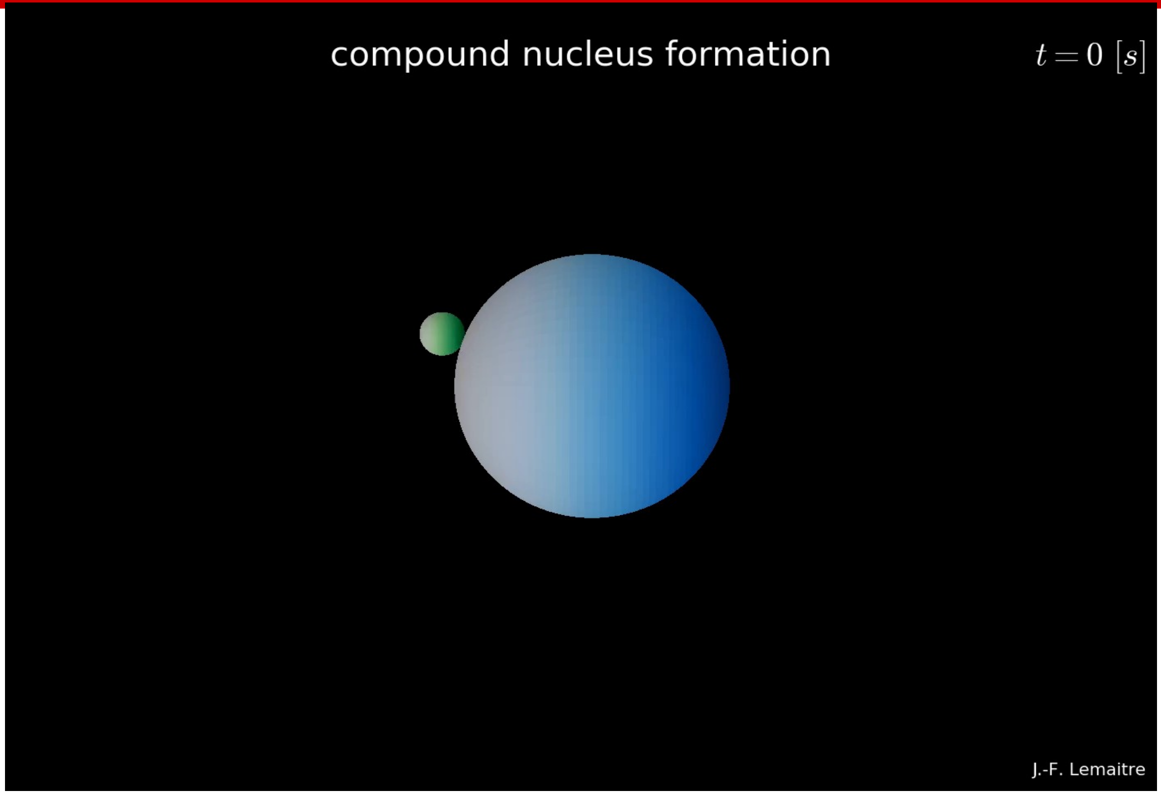
Fission process

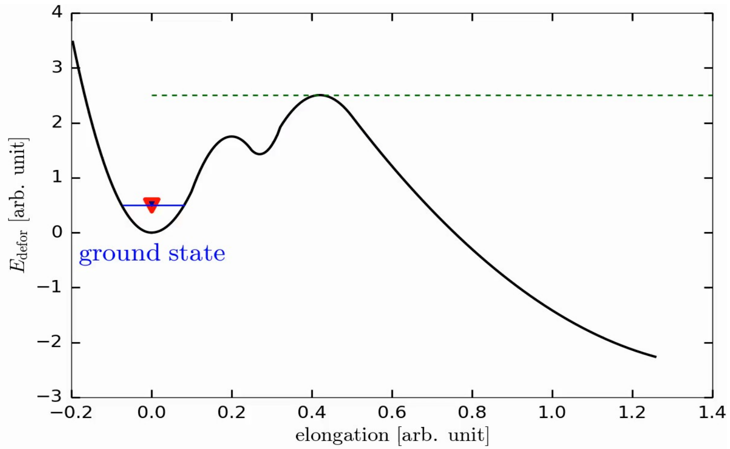


Fission process

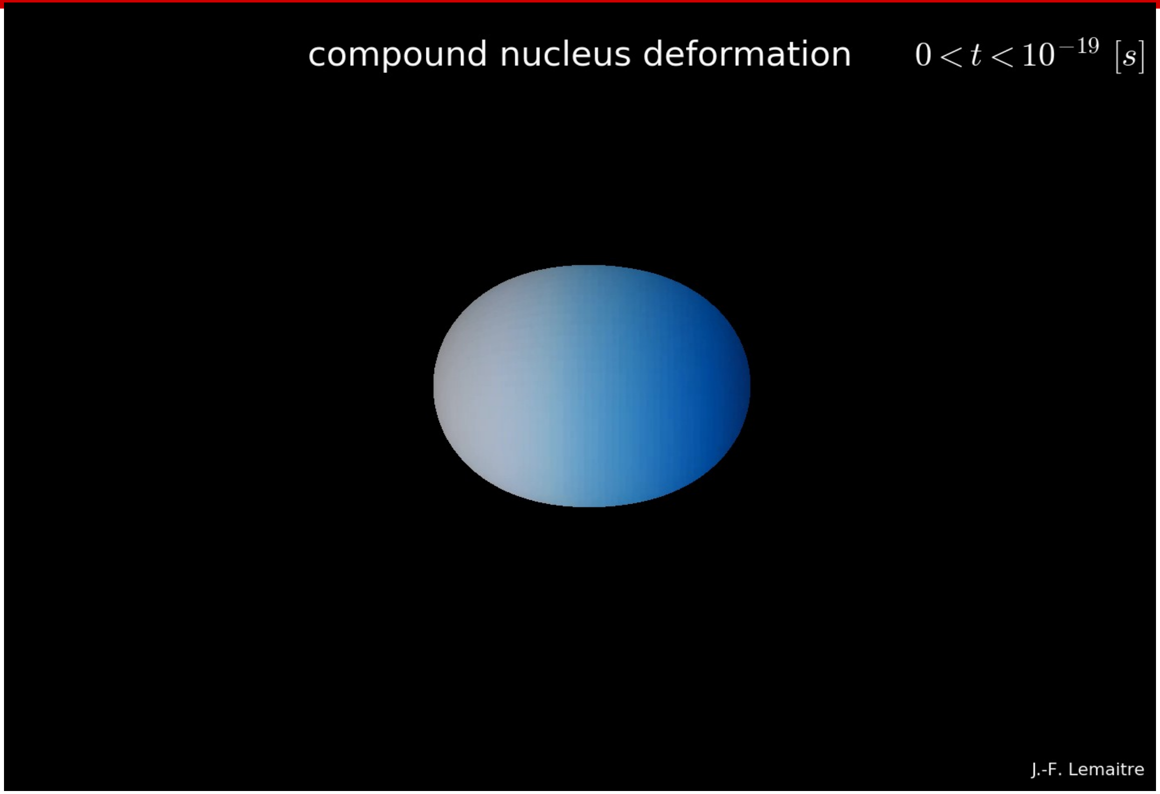


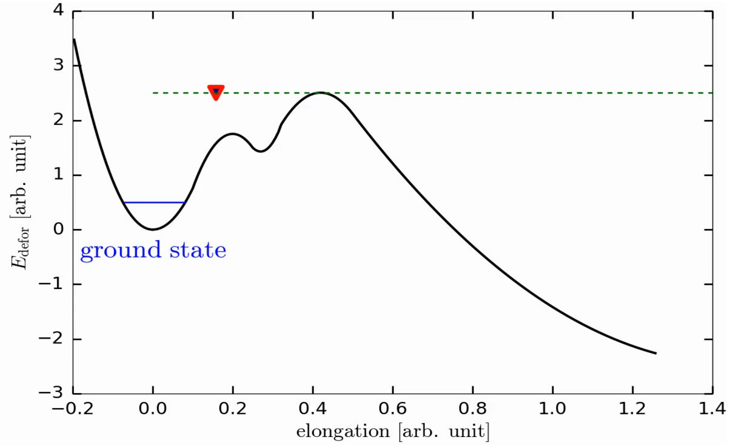



compound nucleus formation
$t = 0$ [s]
J.-F. Lemaitre

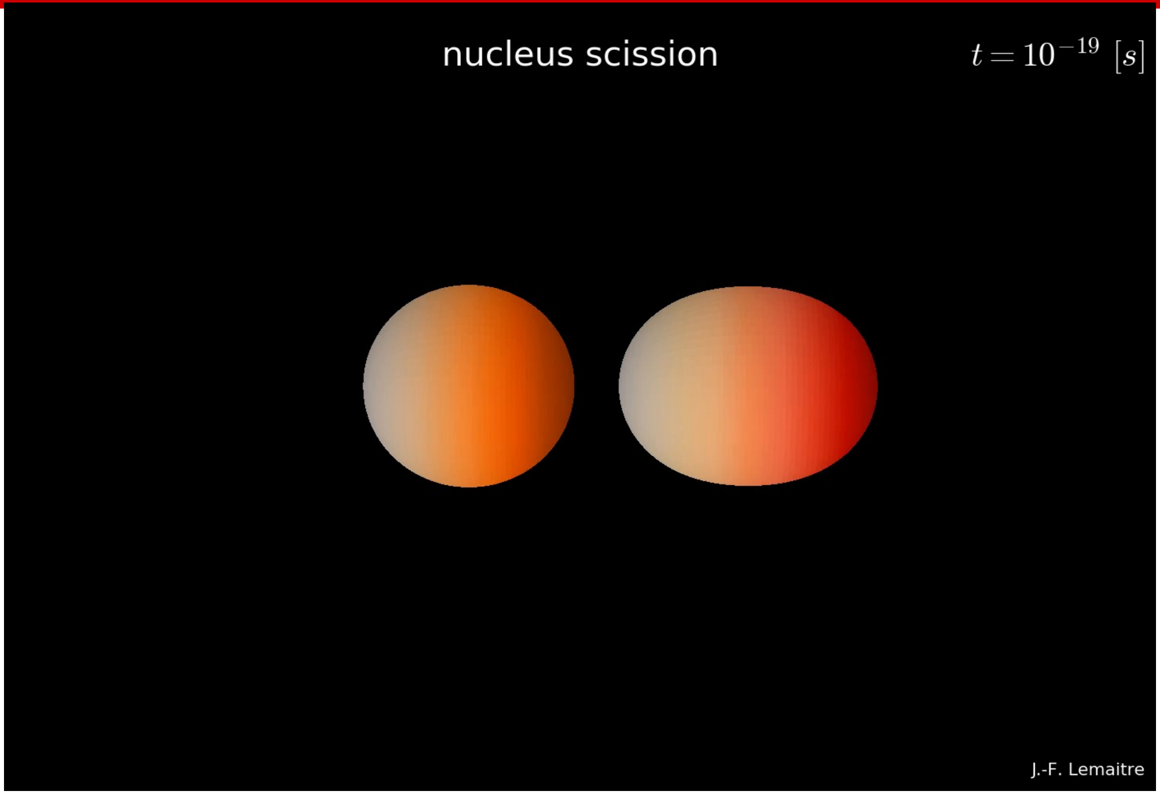

ground state
$E_{\rm defor}$ [arb. unit]
elongation [arb. unit]
4
3
2
1
0
−1
−2
−3
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Fission process

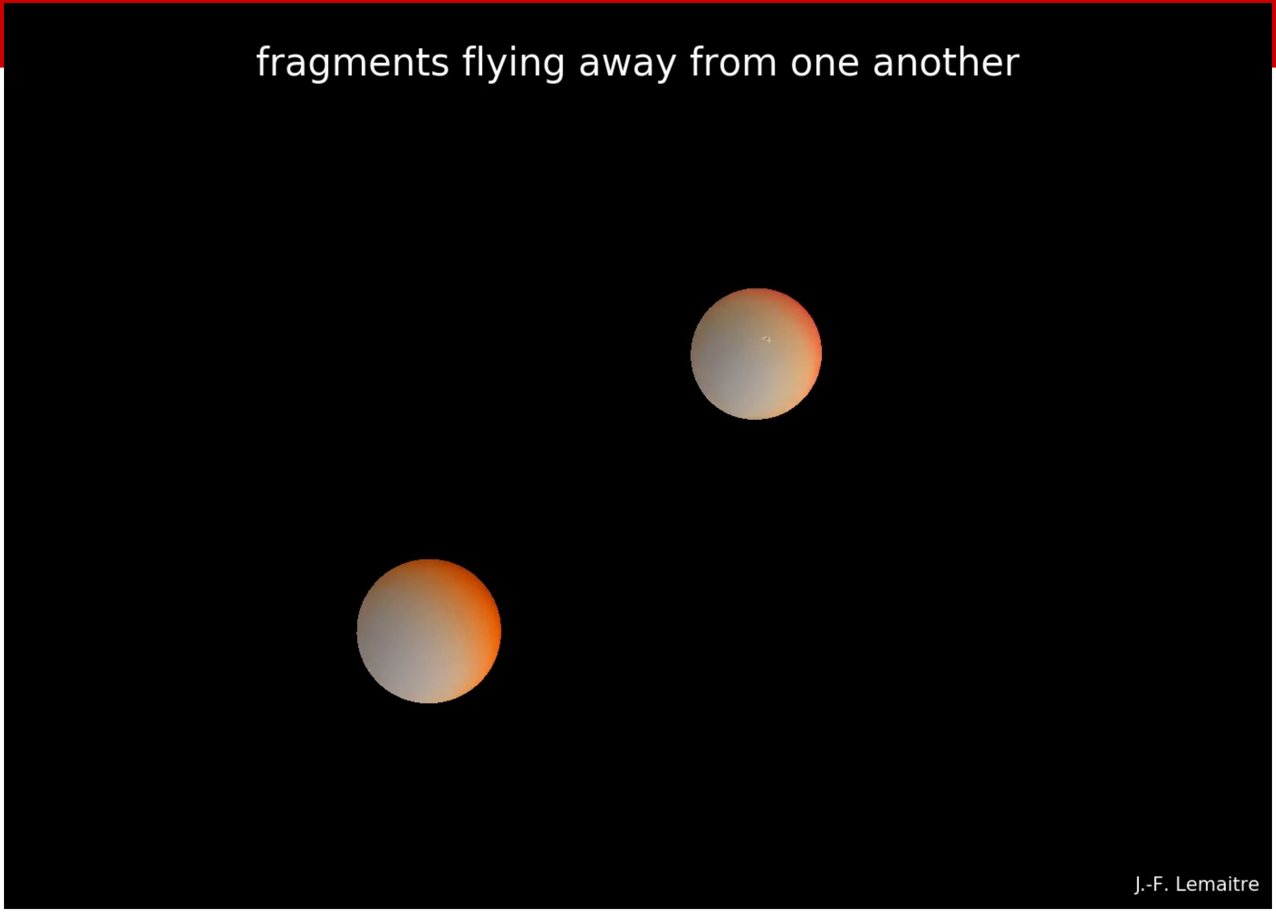




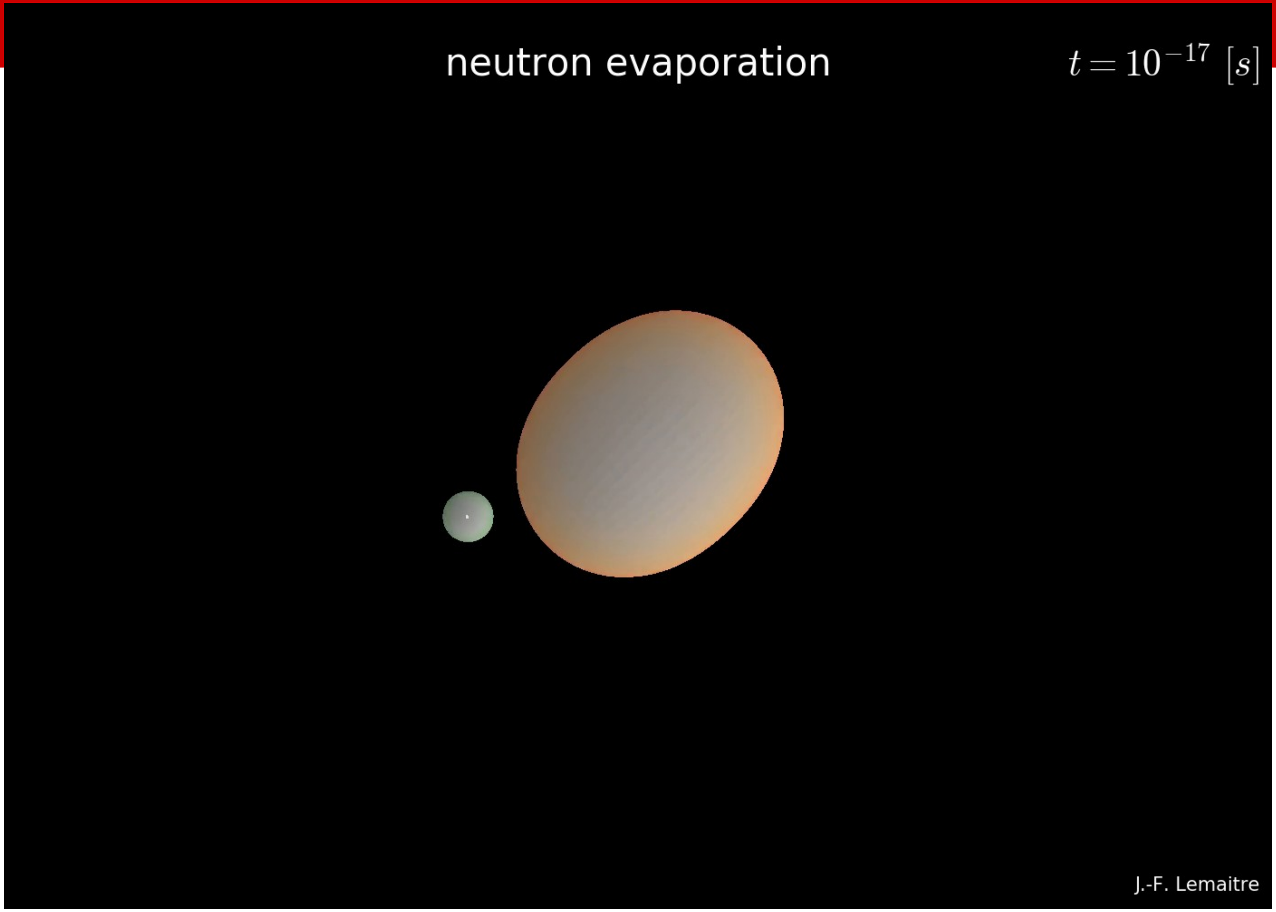
Fission process



Fission process

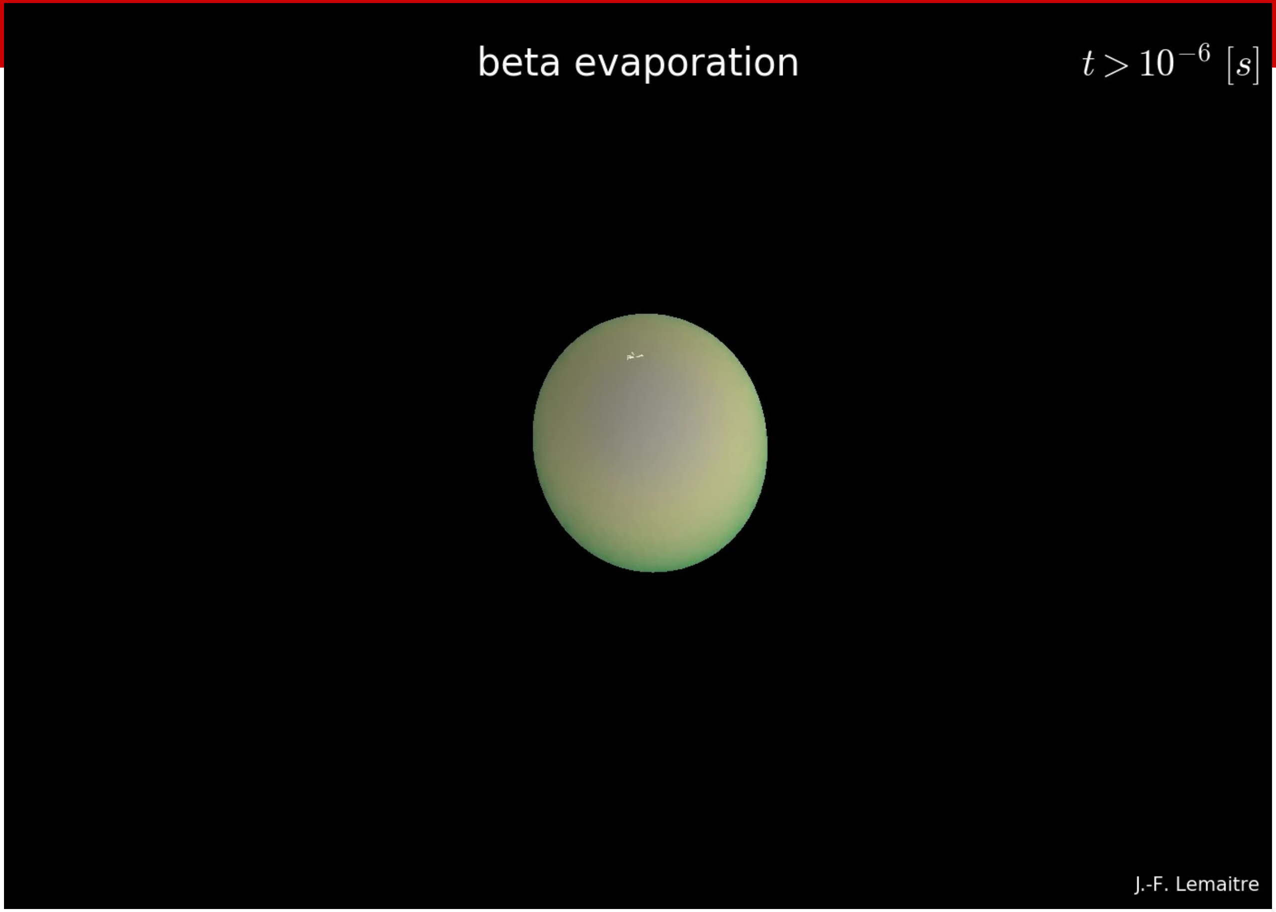


Fission process



Fission process

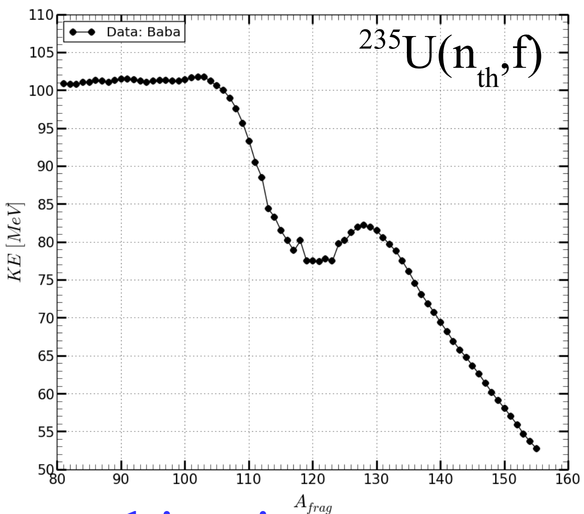
Fission process



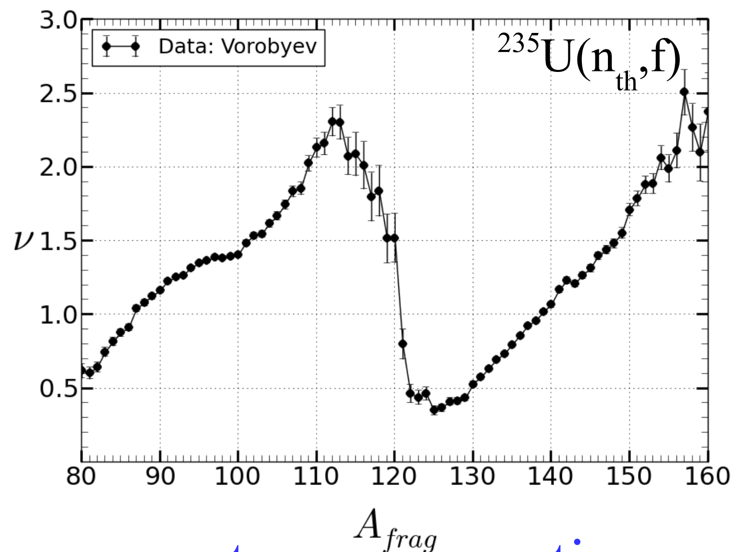
SPY model
presentation

What is the role of the nuclear structure of fission fragments during the fission process ?

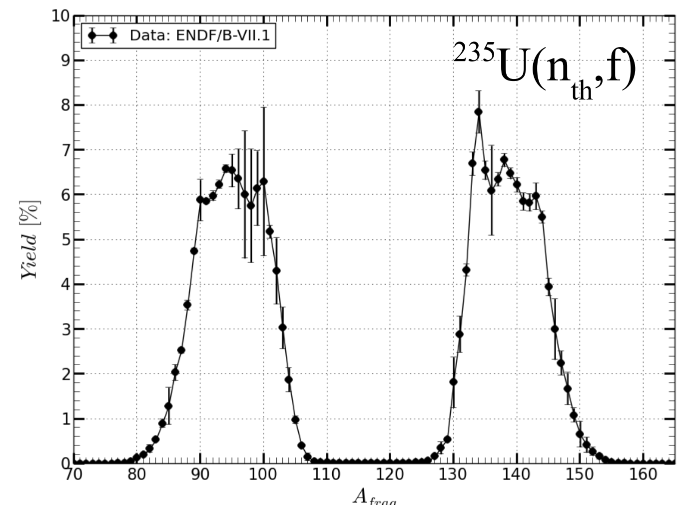
Can experimental data be understood/reproduced considering <u>only the nuclear structure of the fission fragments</u> ?



kinetic energy

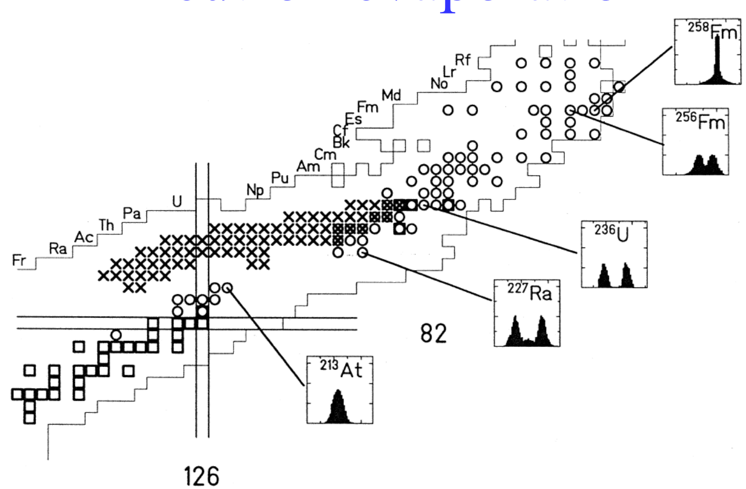


neutron evaporation



yields

symmetric/asymmetric fission

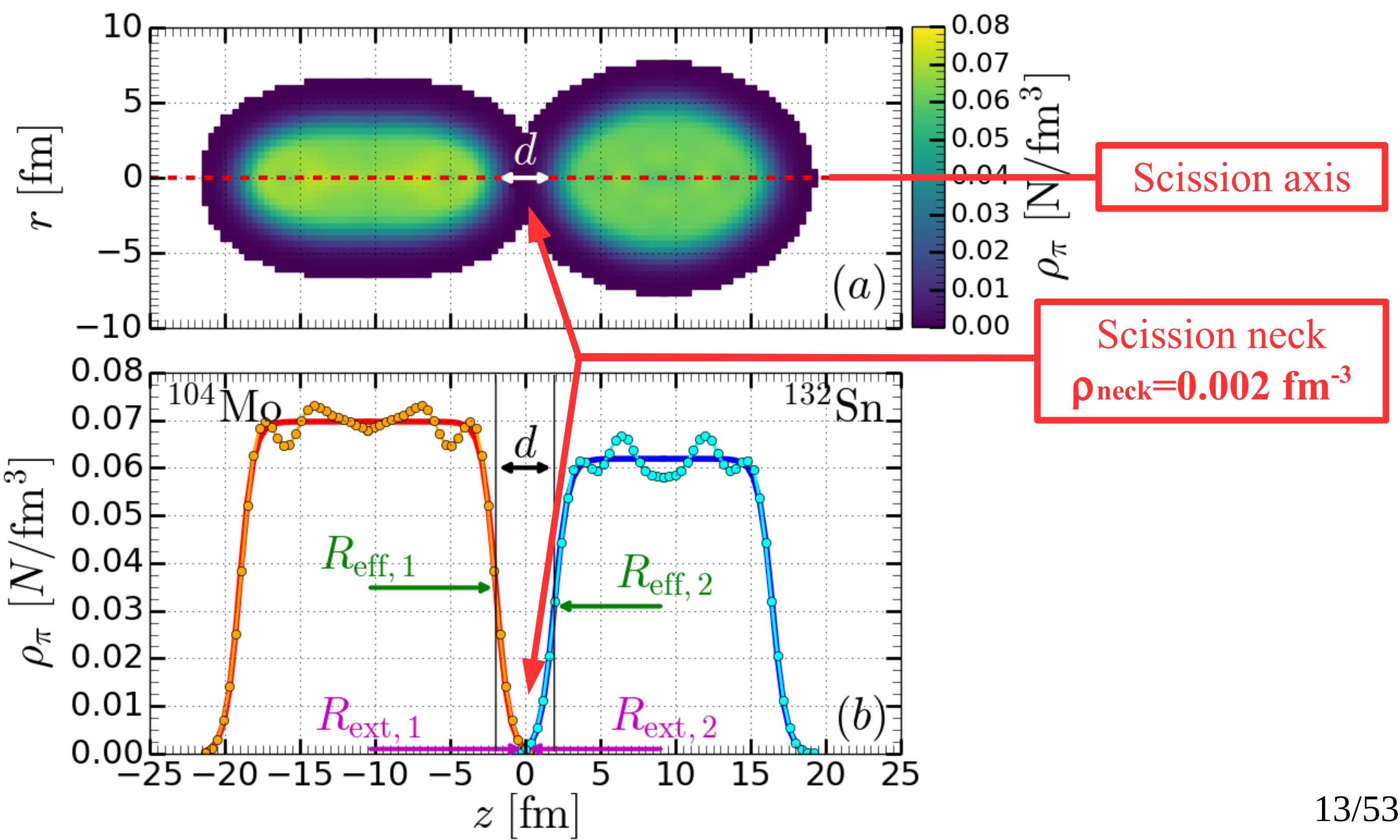


SPY model
a scission point model

Hypo. to determine the frag. properties : fission process (CN→ frag.) ≈ scission line
Scission configuration : defined by the proton density at scission neck between 2 frag.
Fragments are at rest (no prescission kinetic energy)
Fragments are axially symmetric
Inputs : frag. E_{ind}, spl & proton density from HFB calculations (Gogny or Skyrme)

Proton density distribution
$^{104}Mo_{(\beta=1.2)}+^{132}Sn_{(\beta=0.4)}$

Proton density along scission axis



SPY model
a statistical model

→ **ONLY based on fission fragments & <u>first-chance fission</u>**

→ Evolution (quasi static) between saddle point to scission point is neglected

→ Isolated fragments

→ Well defined fragments characteristics (Z, N, β)

→ Fragmentation probability ∝ number of available states

↳ Fragments observables

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Two quantities are needed to compute physical quantities

- available energy for each fragmentation of the system : AE
- the number of available states for each fragmentation of the system : AS

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Two quantities are needed to compute physical quantities

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- the number of available states for each fragmentation of the system : AS

$^{235}U(n_{th},f)$: ~500 fragmentations

1 fragmentation → 57 x 57 deformations

↥ Ecoul : the most time-consuming numerically computed

↳ AE ≈ 20 MeV → 20 AS/fragmentation

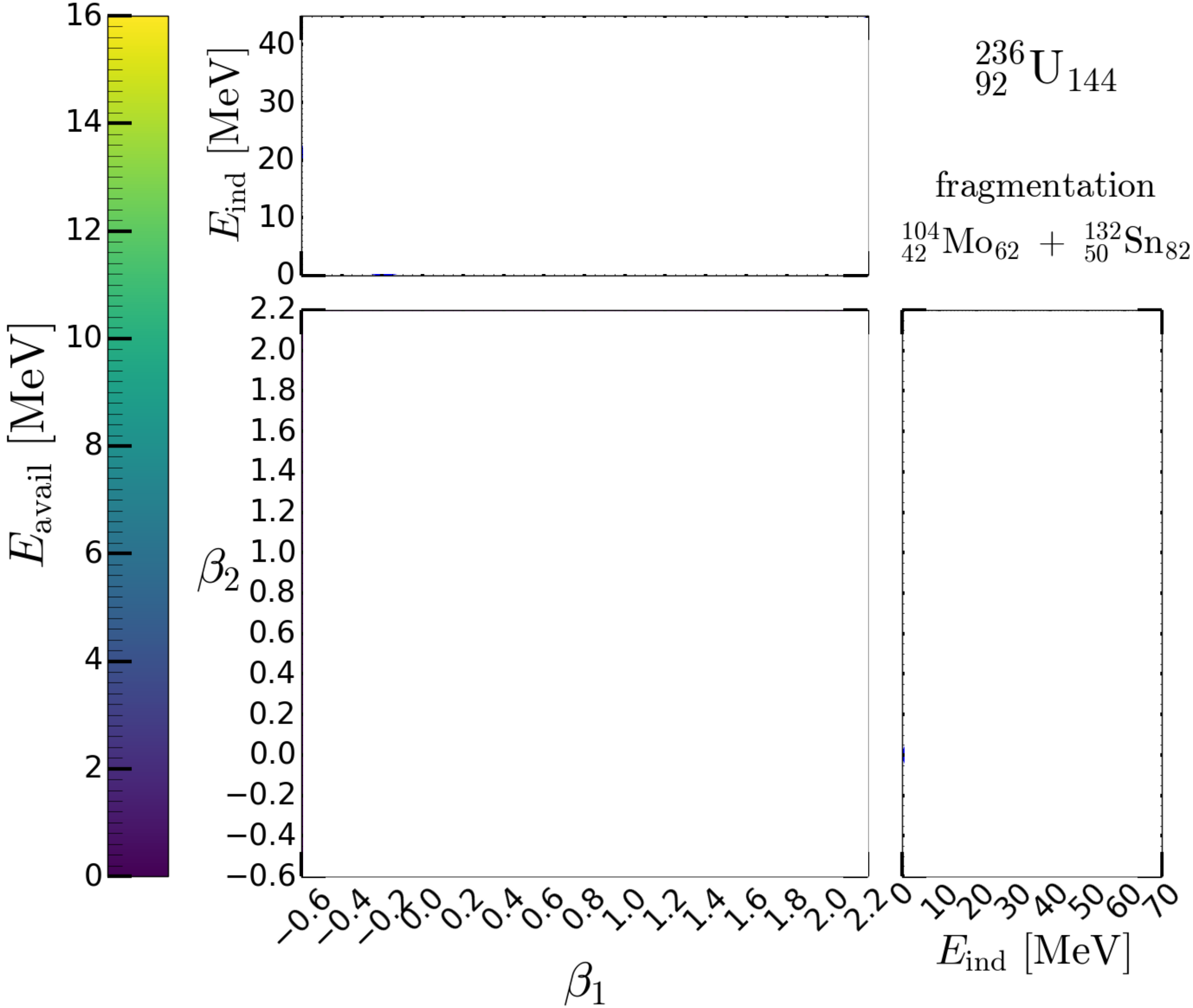
→ 1,6 million AE

→ 32 million AS

SPY model

available energy & available states

$$AE = \left| E_{\text{ind}\,1} + E_{\text{ind}\,2} + E_{\text{coul}} + E_{\text{nucl}} - E_{\text{CN}} \right|$$

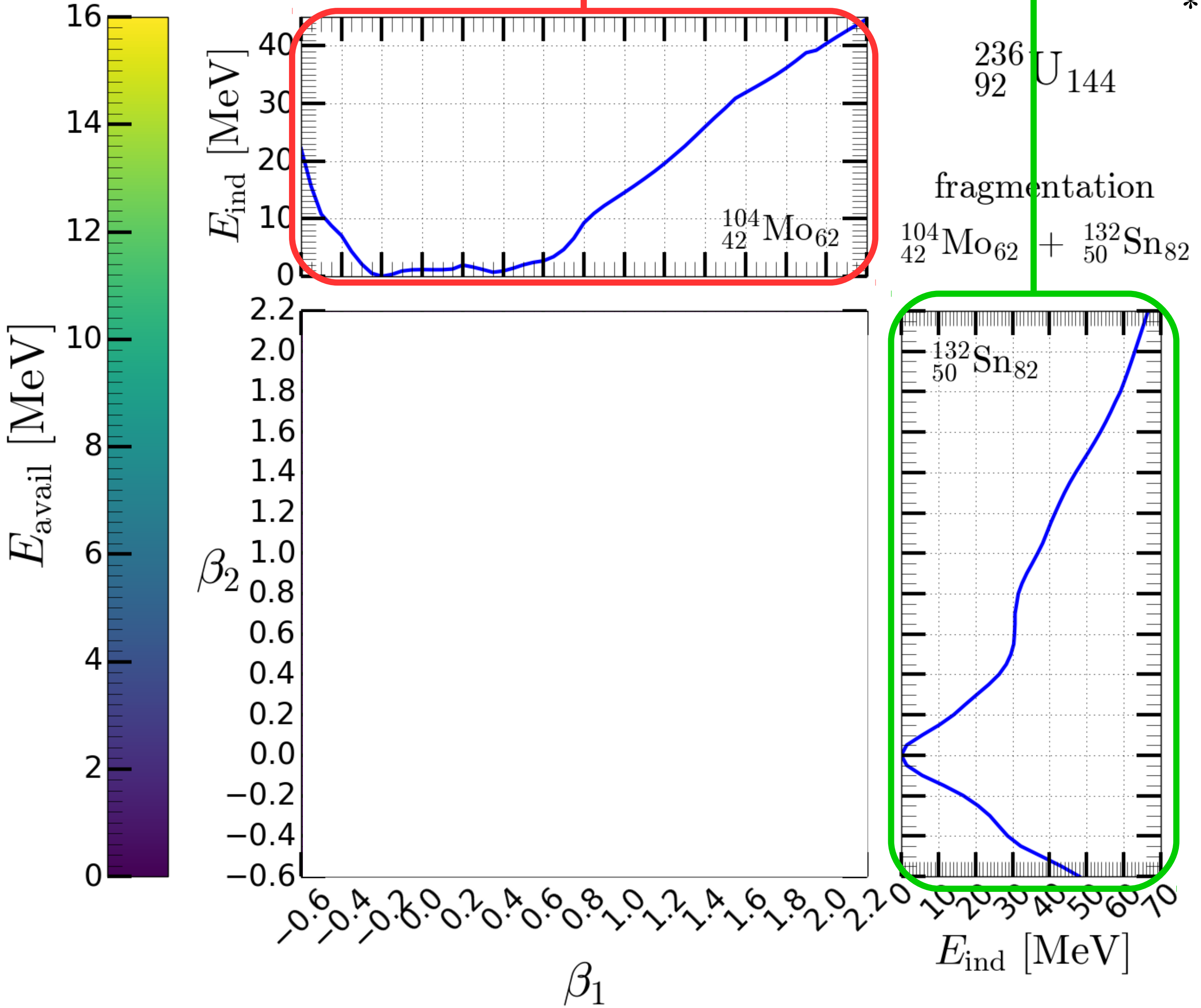


SPY model

available energy & available states

$$AE = \left| E_{ind\,1} + E_{ind\,2} + E_{coul} + E_{nucl} - E_{CN} \right|$$

* Individual energies :
  HFB with eff. N-N int.
  Gogny or Skyrme



SPY model

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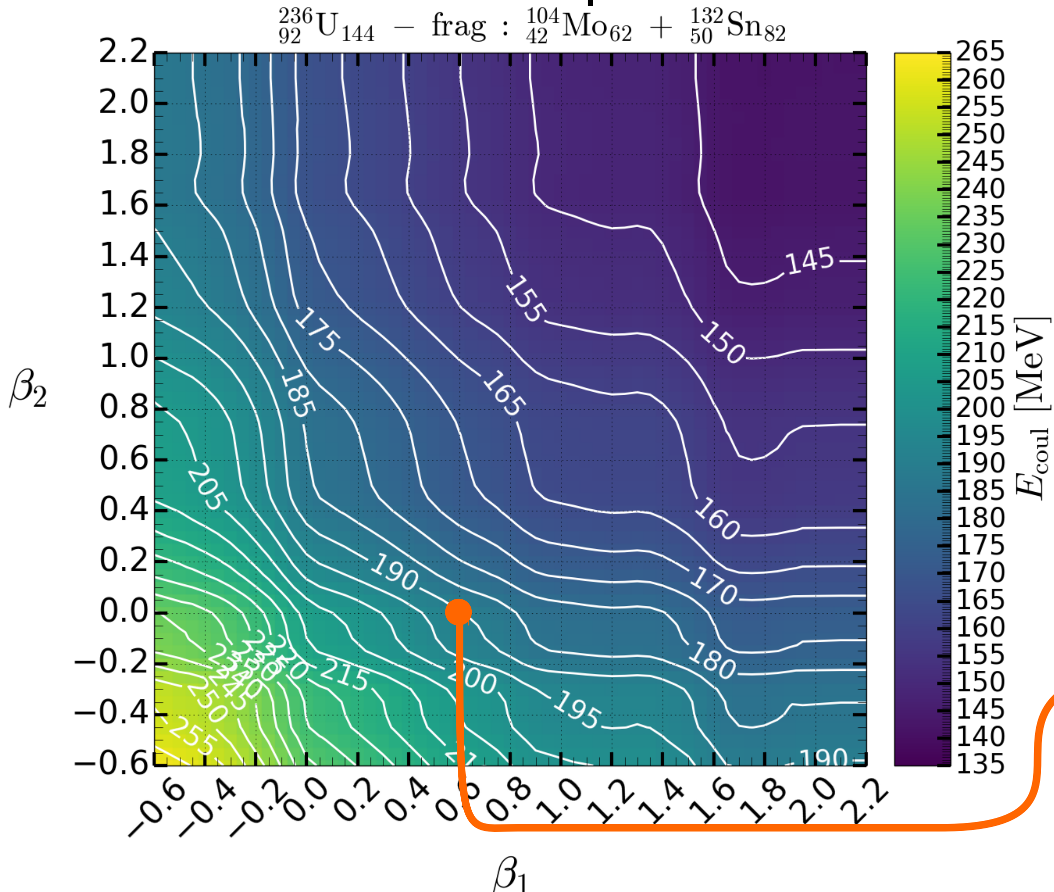
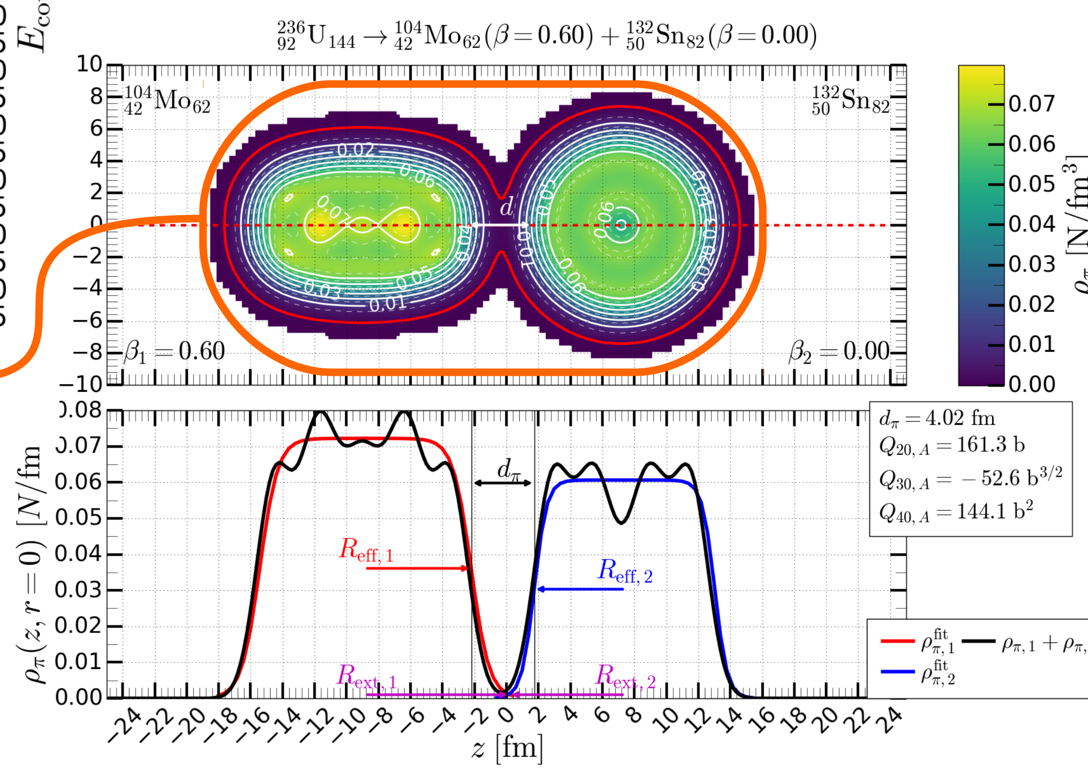
$$AE = \left| E_{ind\,1} + E_{ind\,2} + E_{coul} + E_{nucl} - E_{CN} \right|$$



* Individual energies :
HFB with eff. N-N int.
Gogny or Skyrme

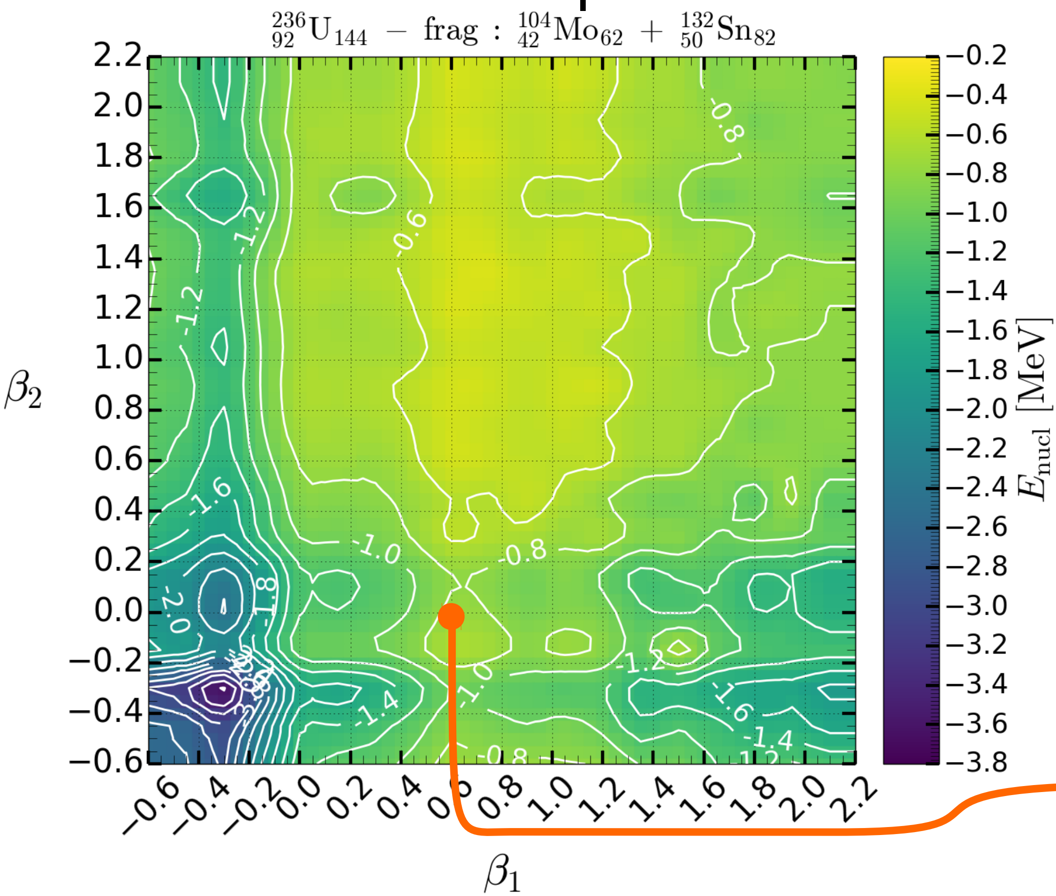
* Coulomb repulsion energy :
numerically computed
using HFB proton density



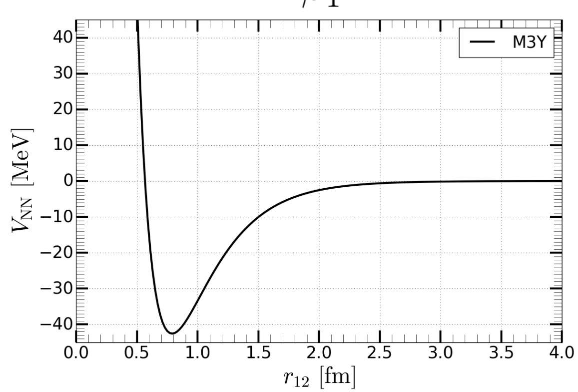
SPY model

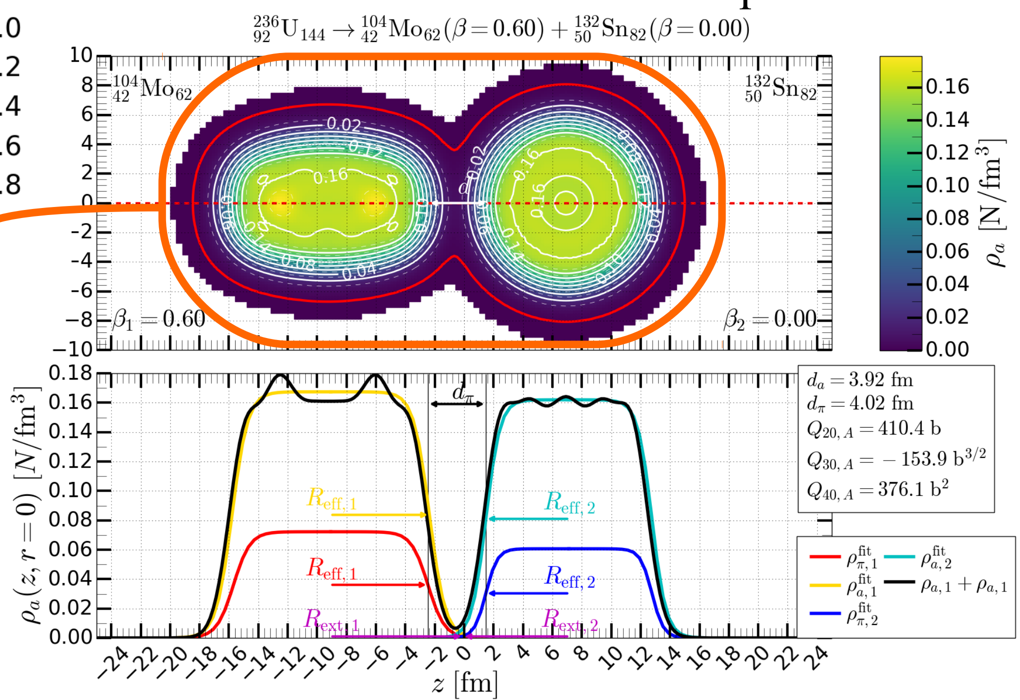
available energy & available states

$$AE = \left| E_{ind\,1} + E_{ind\,2} + E_{coul} + E_{nucl} - E_{CN} \right|$$



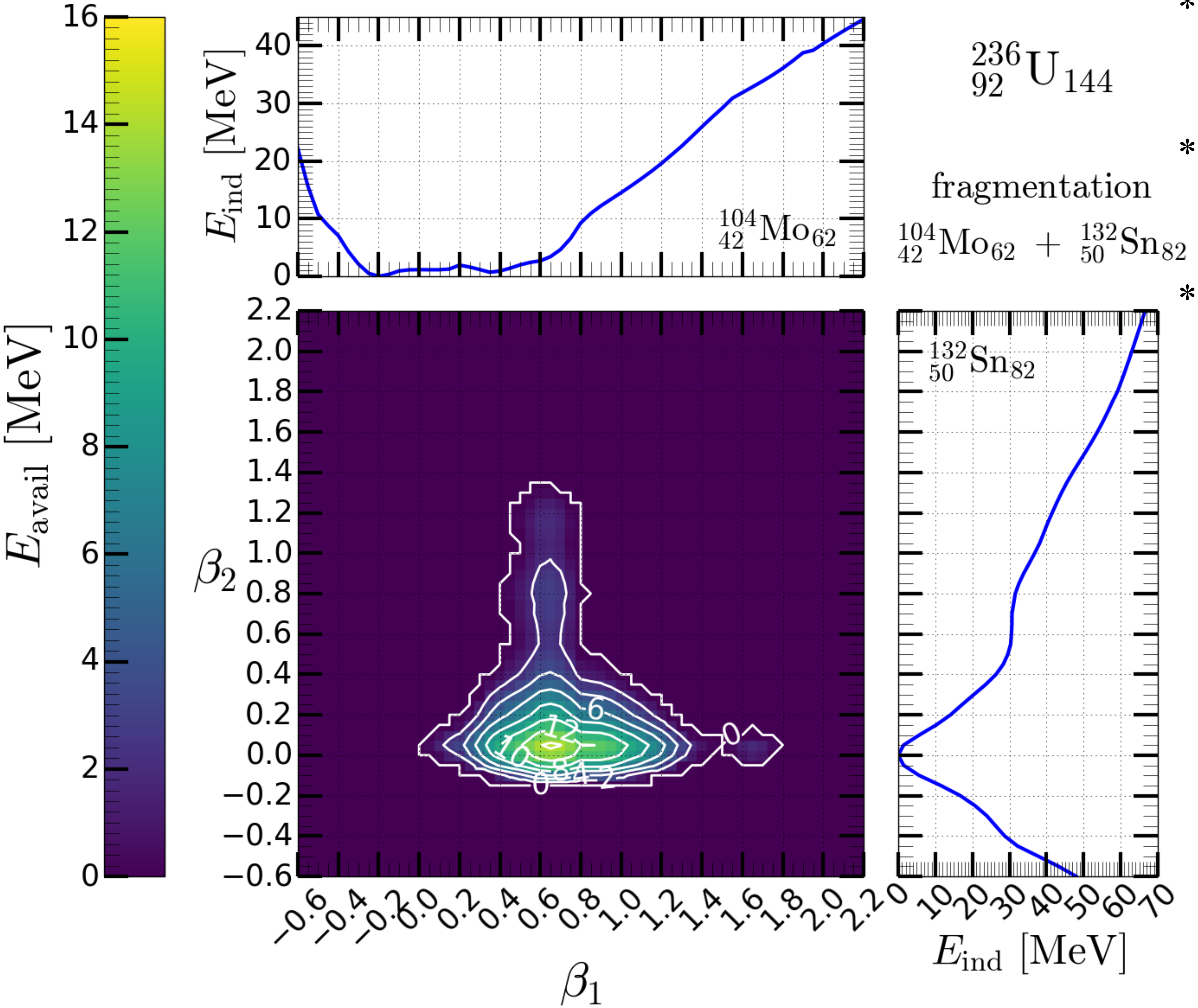
- * Individual energies :
  HFB with eff. N-N int.
  Gogny or Skyrme
- * Coulomb repulsion energy :
  numerically computed
  using HFB proton density
- * Nuclear attraction energy :
  numerically computed
  using HFB nucleon density
  or Blocki prox. Pot.





SPY model
available energy & available states

$$AE = \left| E_{ind\,1} + E_{ind\,2} + E_{coul} + E_{nucl} - E_{CN} \right|$$



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  HFB with eff. N-N int.
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  numerically computed
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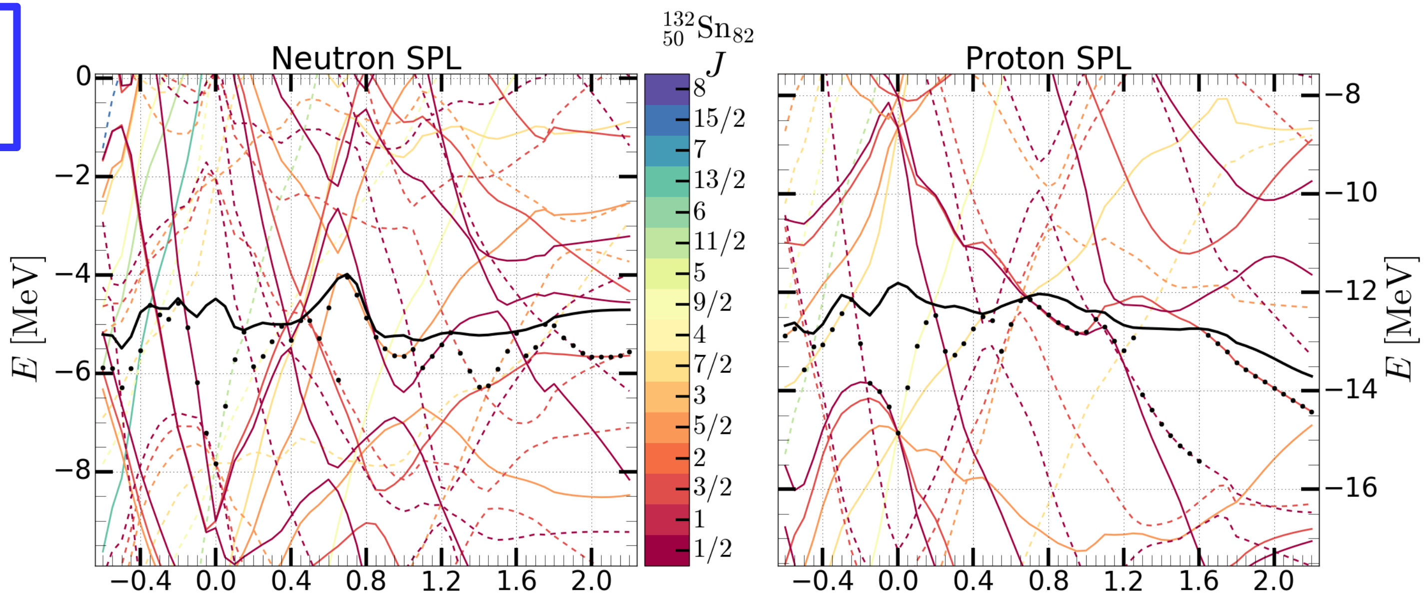
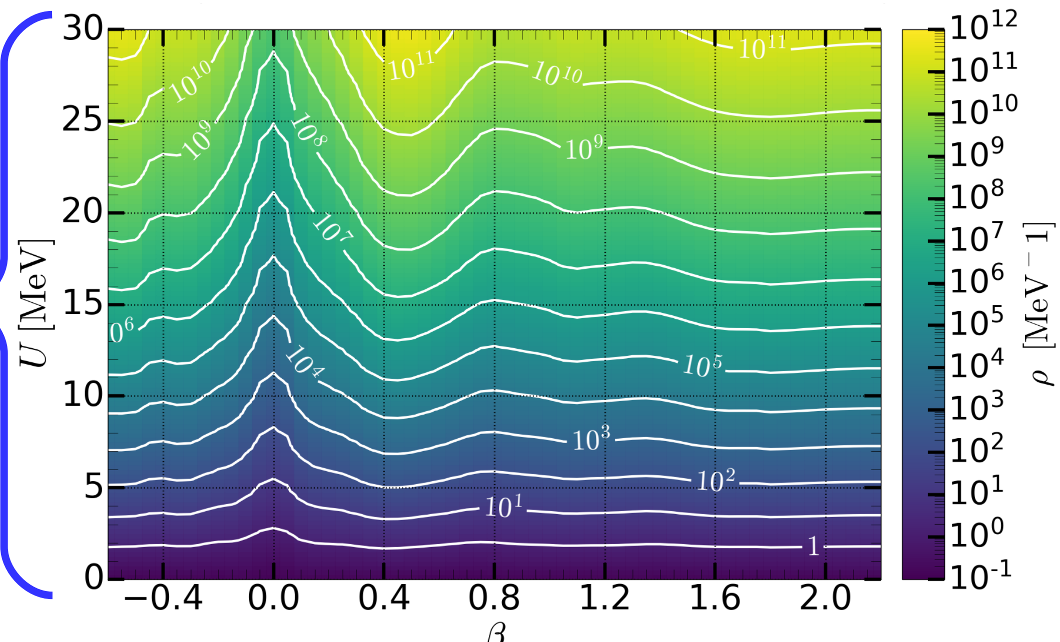
SPY model
available energy & available states

$$AS = \rho_1(x\,AE)\,\rho_2((1-x)\,AE)\,\delta E^2$$

HFB single particle levels



statistical description of NSD : BCS theory

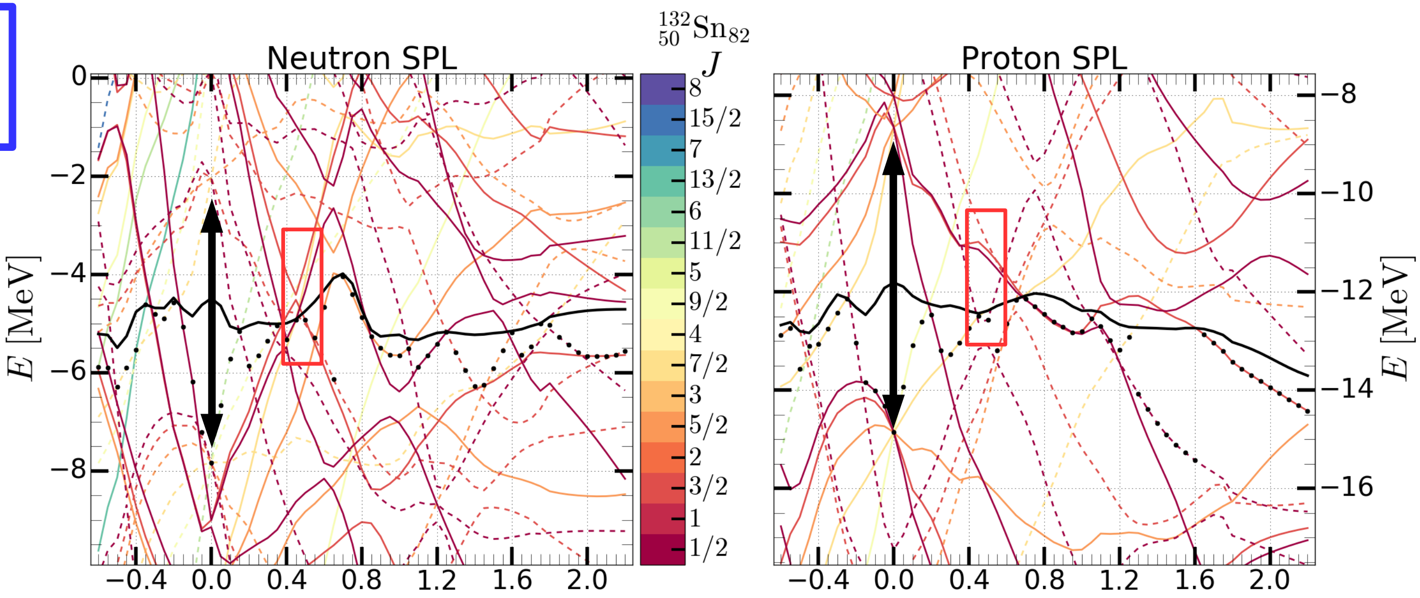


SPY model

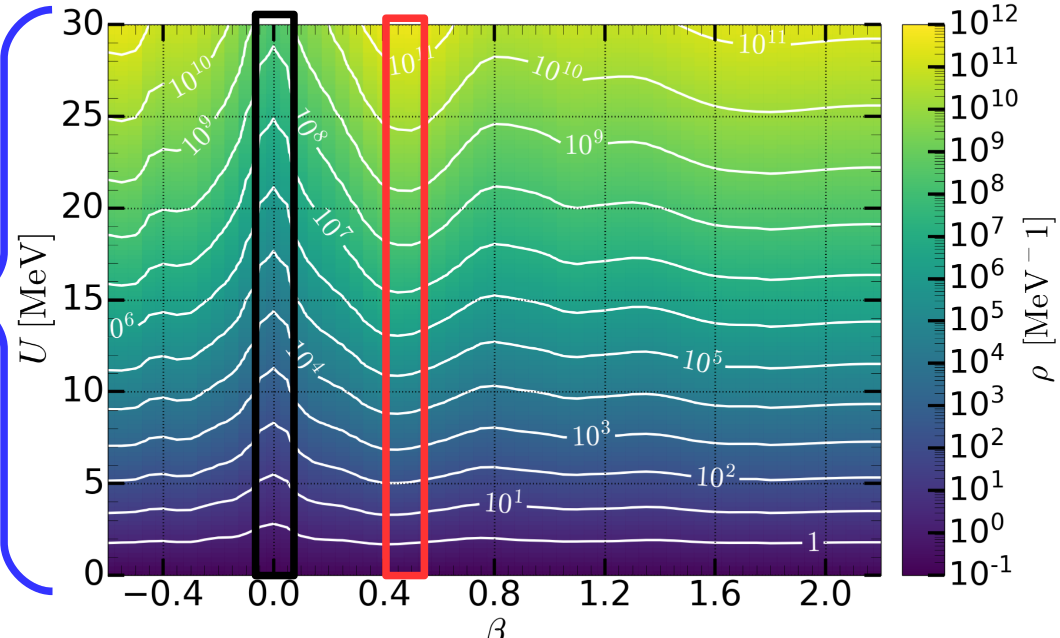
available energy & available states

$$AS = \rho_1(x\,AE)\,\rho_2((1-x)\,AE)\,\delta E^2$$

HFB single particle levels



statistical description of NSD : BCS theory

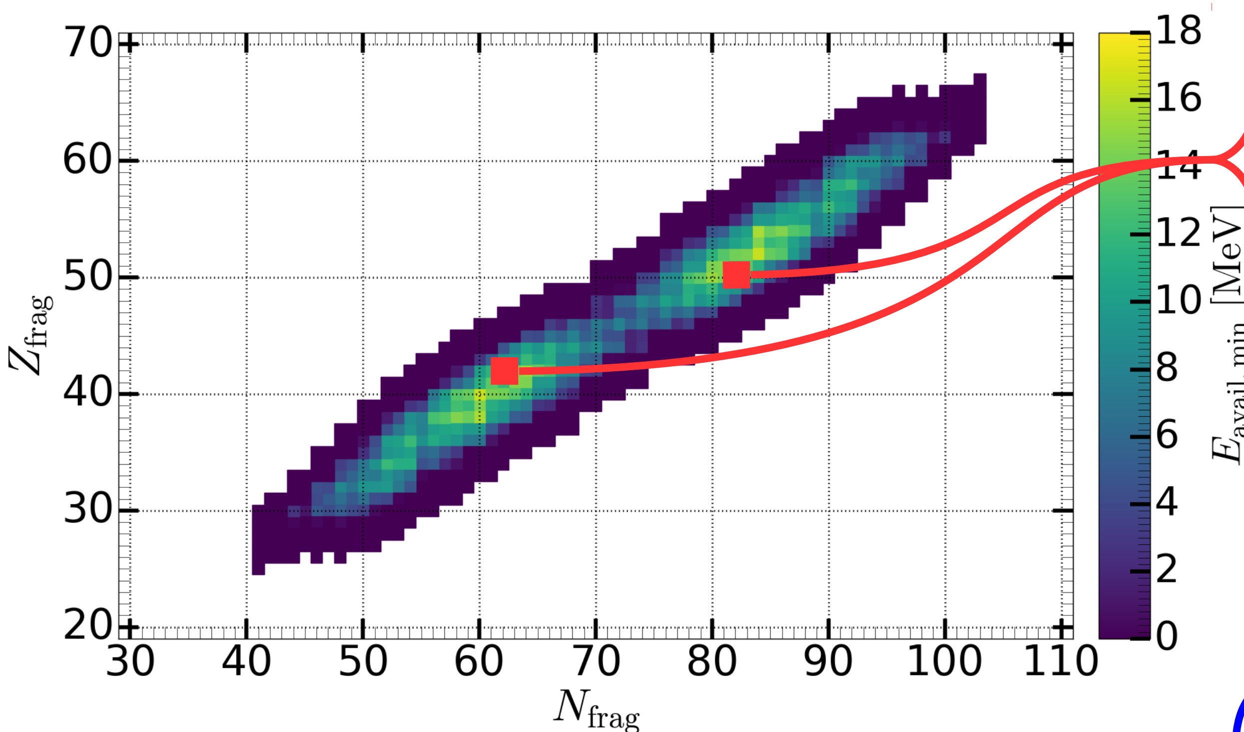


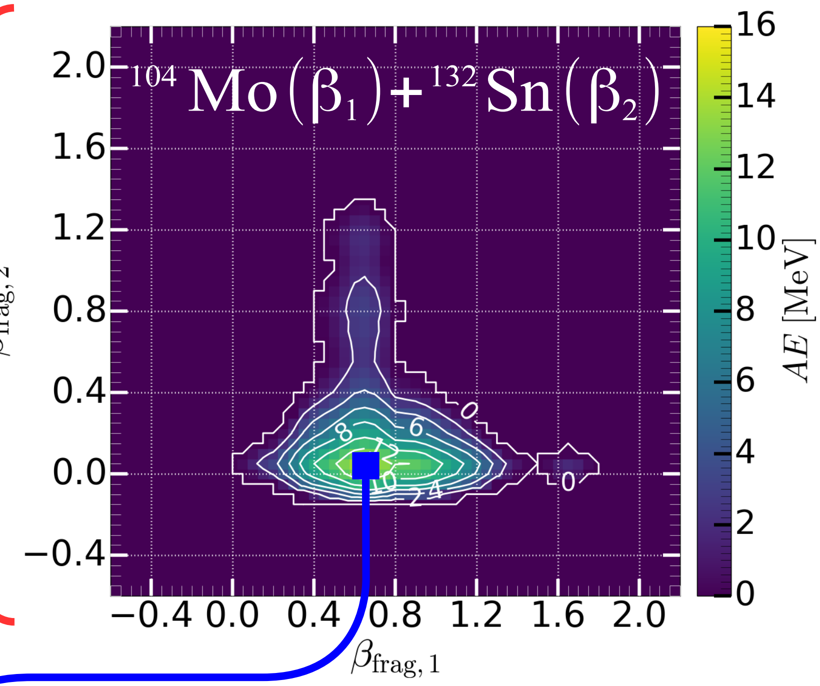
double shell closure

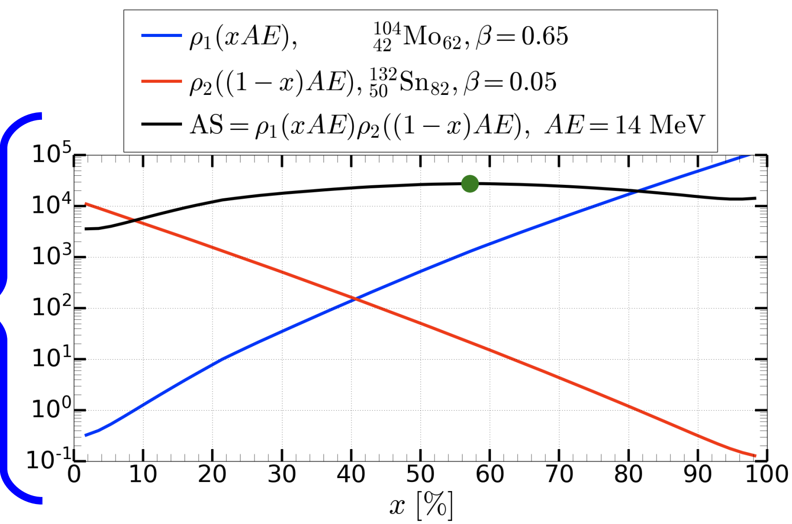
open shell

SPY model

available energy & available states







All deformation couples (β_1,β_2)

All energy shares

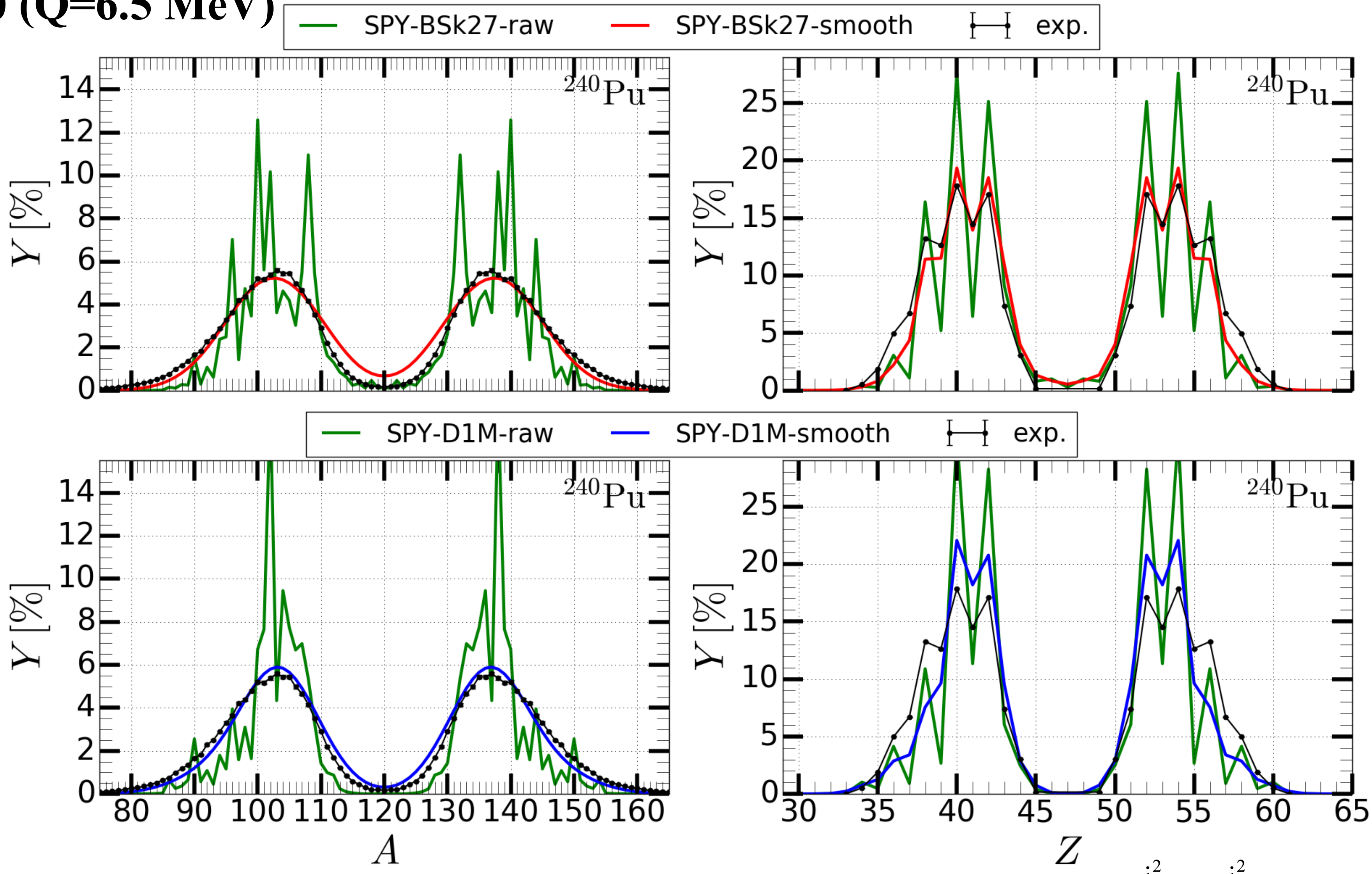
Probability of a given fragmentation

$$Y(Z_1,N_1,Z_2,N_2)=\iint_{\beta_1,\beta_2}\int_0^1 \rho_1(x\,\overbrace{AE}^{AE(\beta_1,\beta_2)},\beta_1)\,\rho_2((1-x)AE,\beta_2)\,\delta E^2\,dx\;d\beta_1\,d\beta_2$$

SPY model

raw yields VS smoothed yields

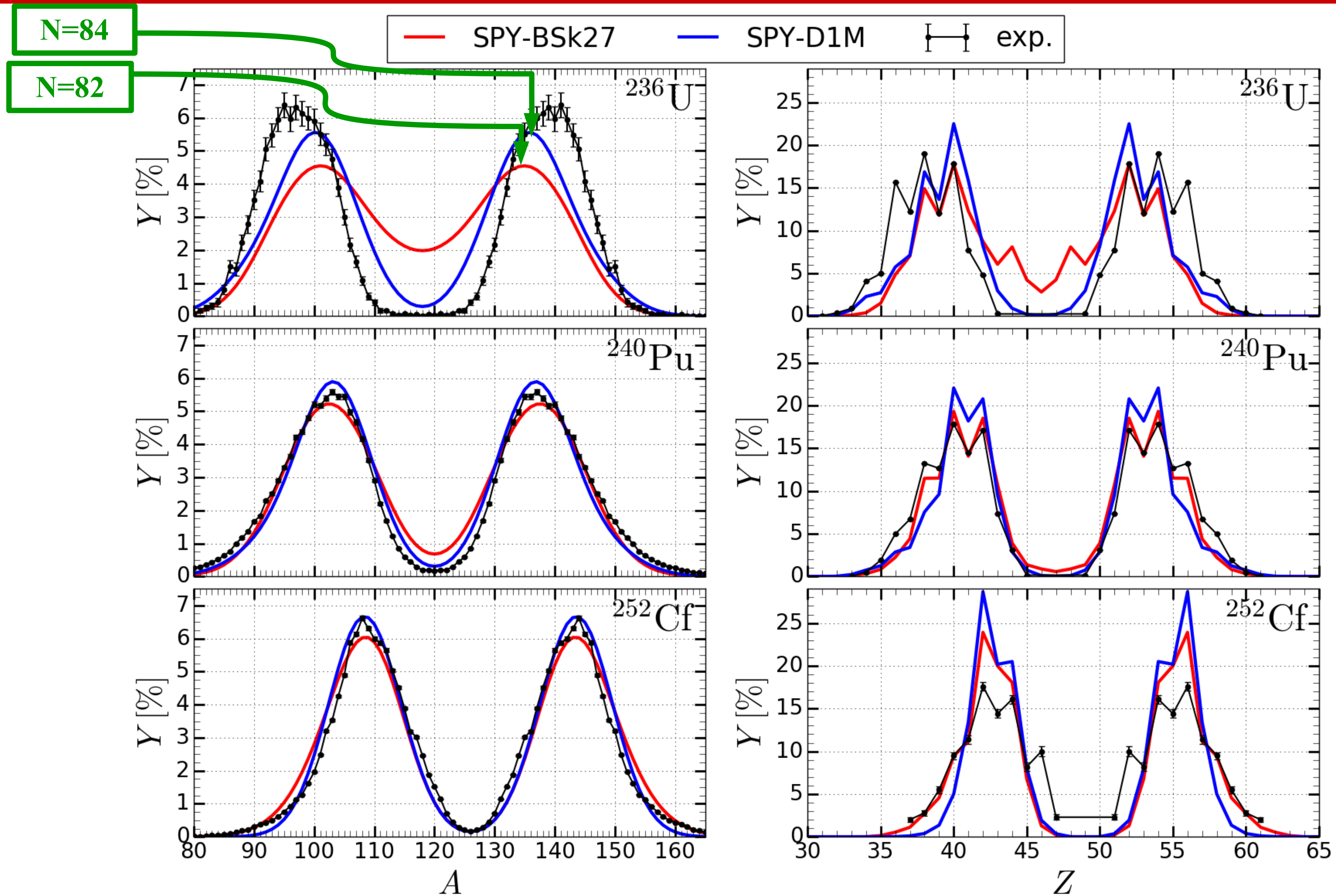
Pu240 (Q=6.5 MeV)



$$Y_{smooth}(Z,N)=\sum_{i=-4}^{4}\sum_{j=-15}^{15} Y_{raw}(Z+i,N+j)\,C_z\,C_n\,e^{-\frac{i^2}{2\sigma_z^2}-\frac{j^2}{2\sigma_n^2}}$$

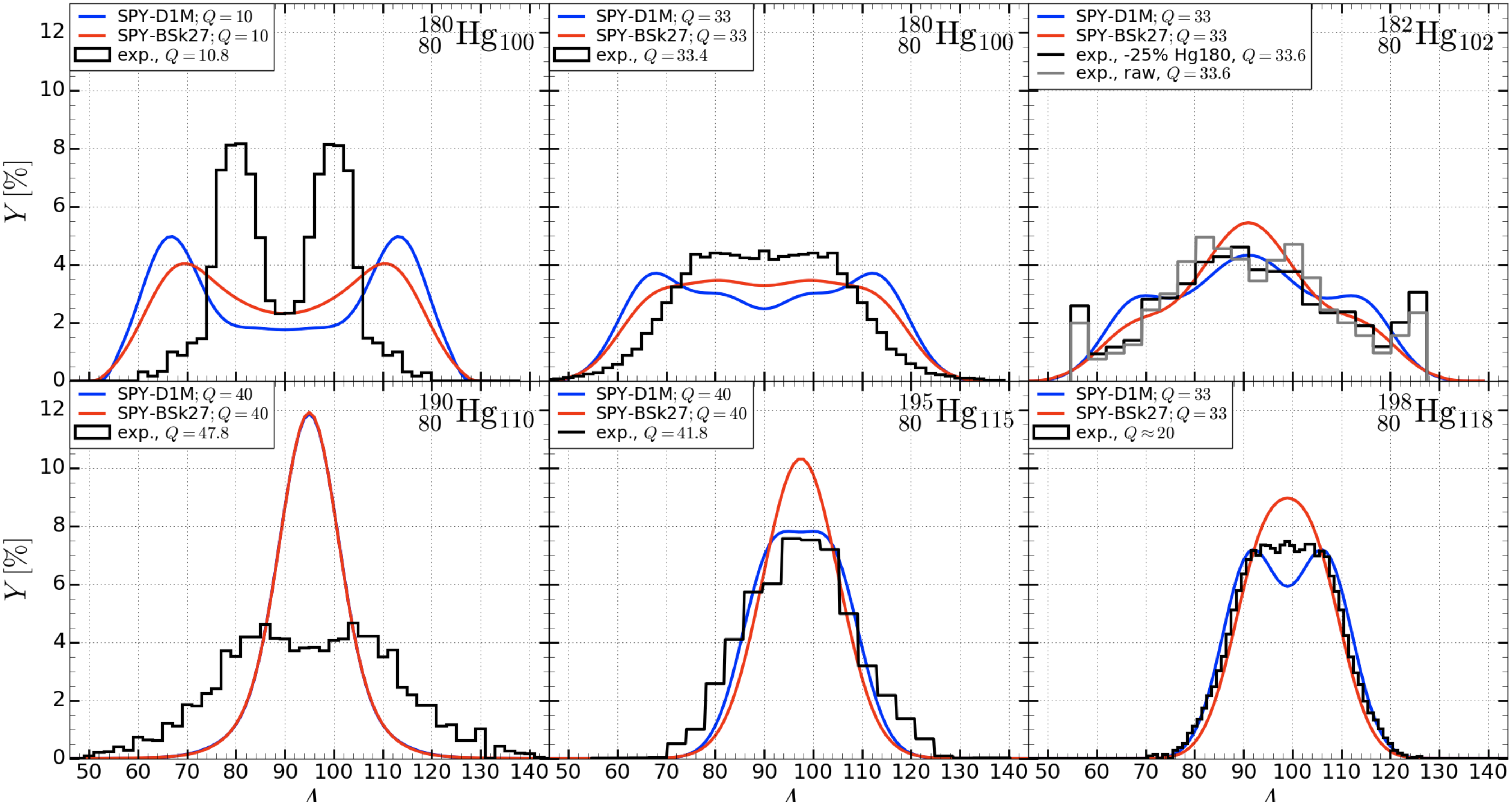
$\sigma_n=5$ and $\sigma_z=0.65$

Results
Fission of U236, Pu240 & Cf252



Exp data : U236 → C. Romano et al, PRC81, 014607 (2010) // W. Lang et al, NPA345, 34 (1980)
Pu240 → C. Tsuchiya et al , J. Nucl. Sci. Technol. 37, 941 (2000) // C. Schmitt et al, NPA430, 21 (1984)
Cf252 → Sh. Zeynalov et al, J. Korean Phy. Soc. 59, 1396 (2011) // G. Mariolopoulos et al, NPA361, 213 (1981)

Results
Fission of Hg isotopes



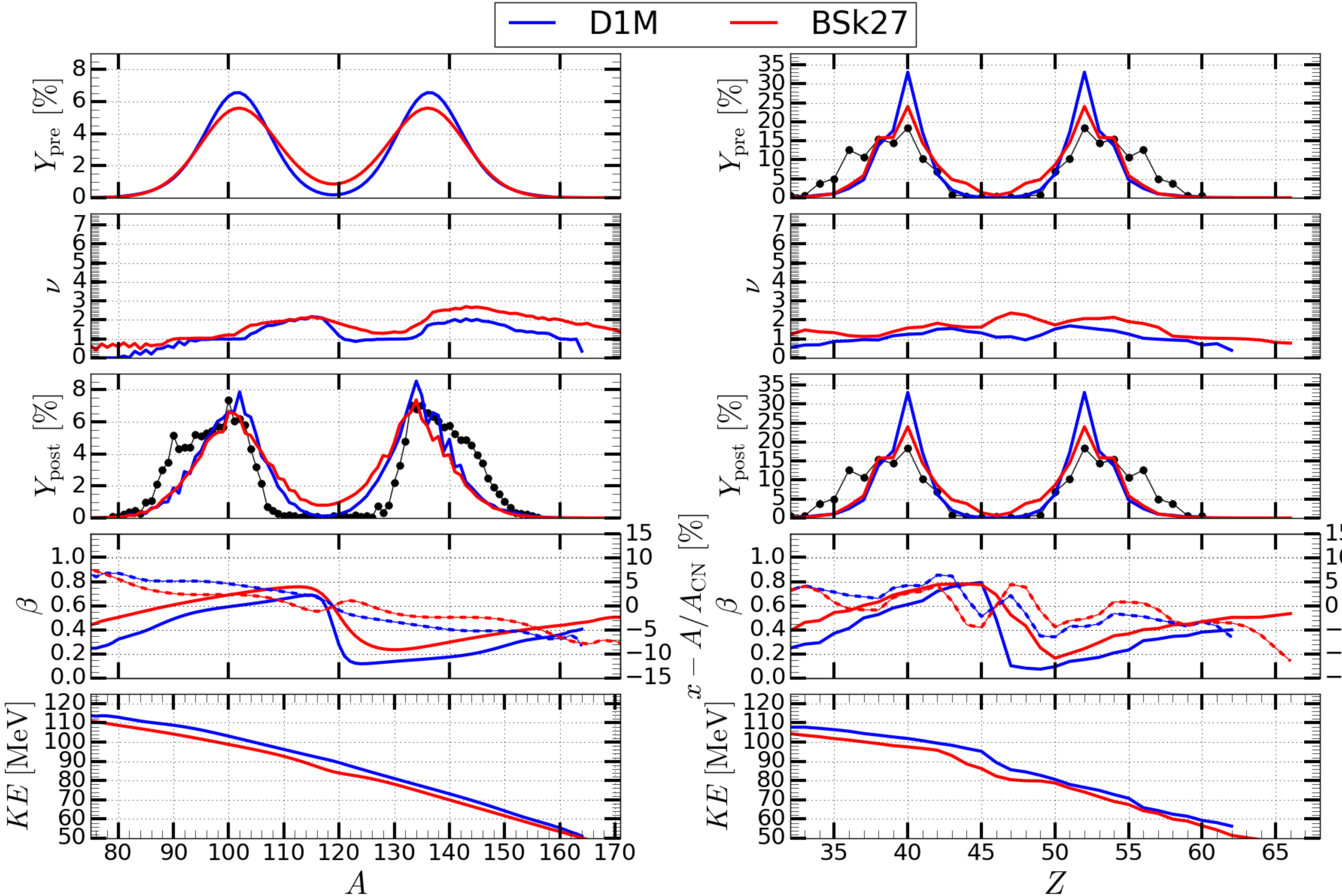
ρ_{neck} = 0.001 fm^{-3}, half of the reference value

for ^{180}Hg, TKE$_{D1M}$=129.5 MeV, TKE$_{BSk27}$=127.2 MeV, TKE$_{exp}$=134.6 MeV

Hg180 : low TKE due to peak location (around shell closure Z_H=50), too asymetric

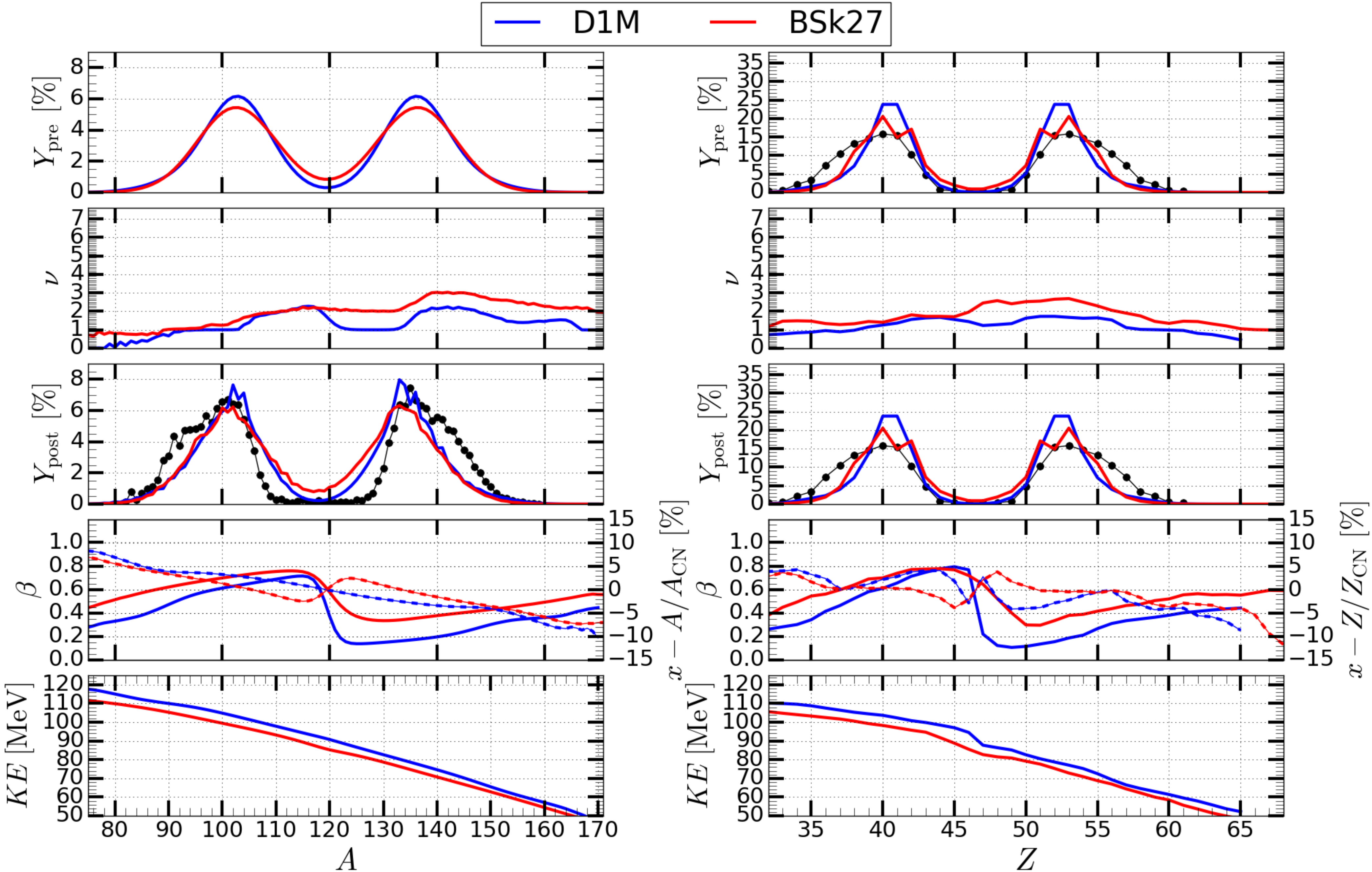
Results

Fission of U238 – Q=7.4 MeV



Exp. data : D. Ramos et al, PRC97, 054612 (2018)

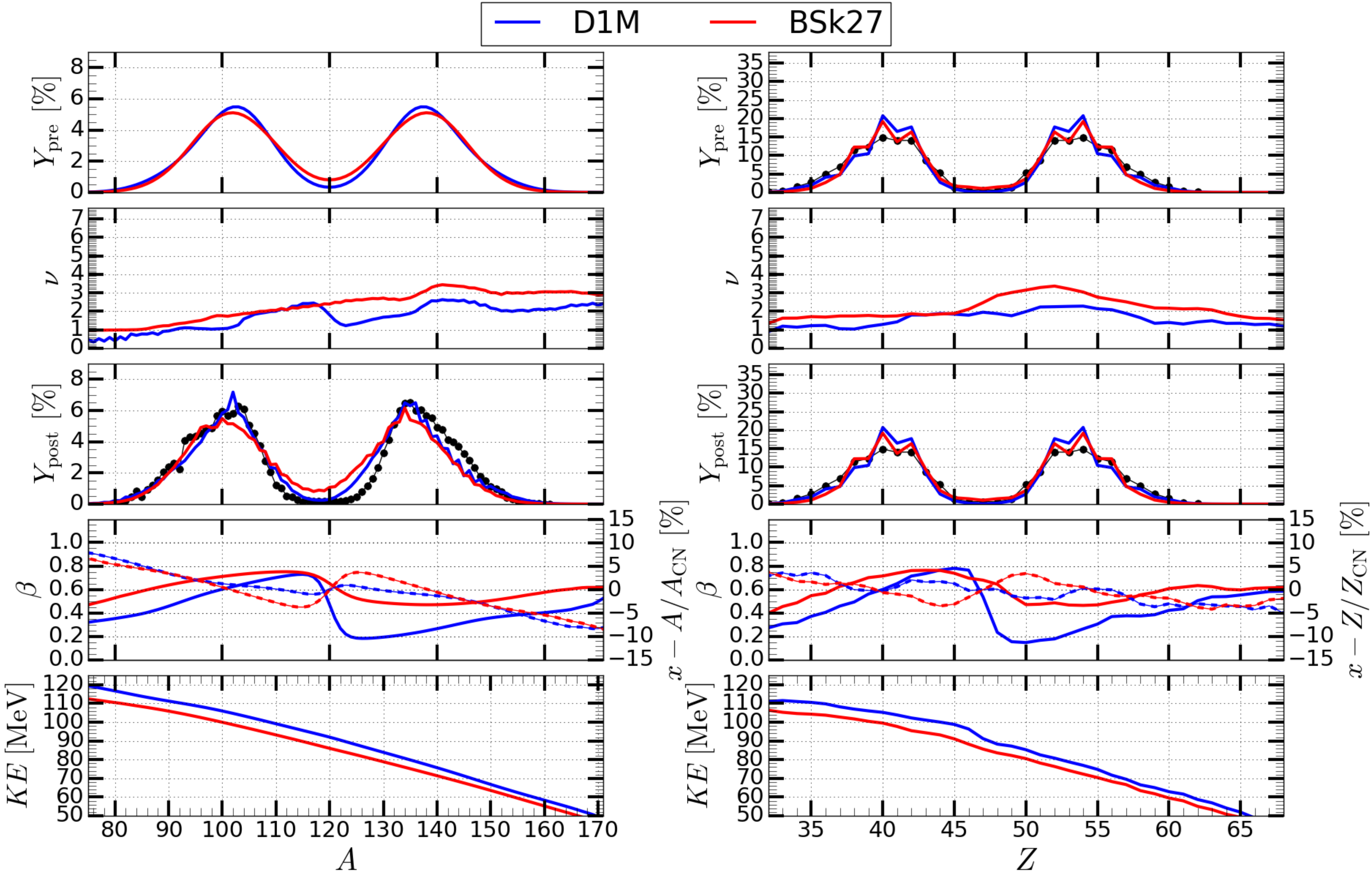
Results
Fission of Np239 – Q=7.5 MeV



Exp. data : D. Ramos et al, PRC97, 054612 (2018)

Results

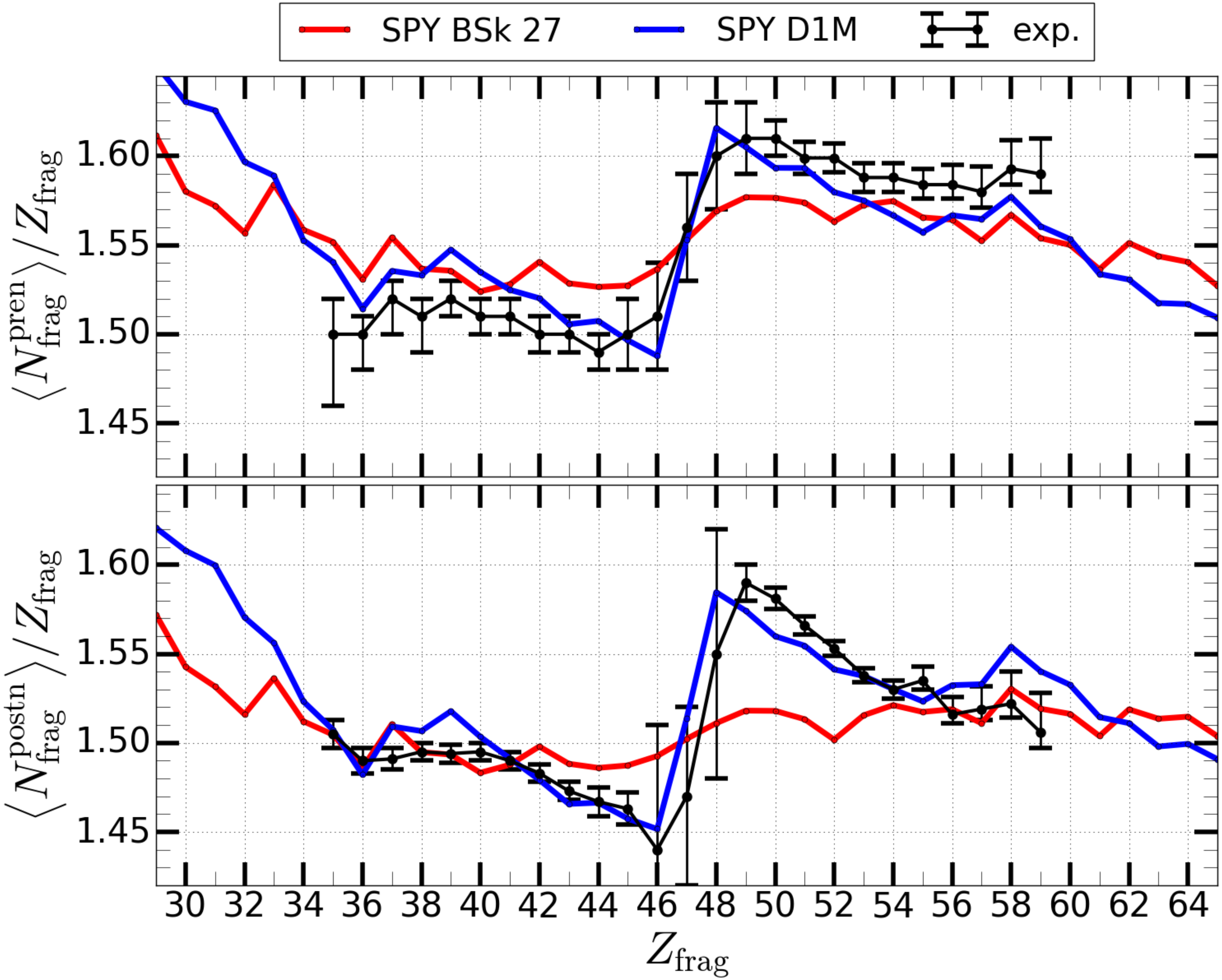
Fission of Pu240 – Q=10.7 MeV



Exp. data : D. Ramos et al, PRC97, 054612 (2018)

Pu240

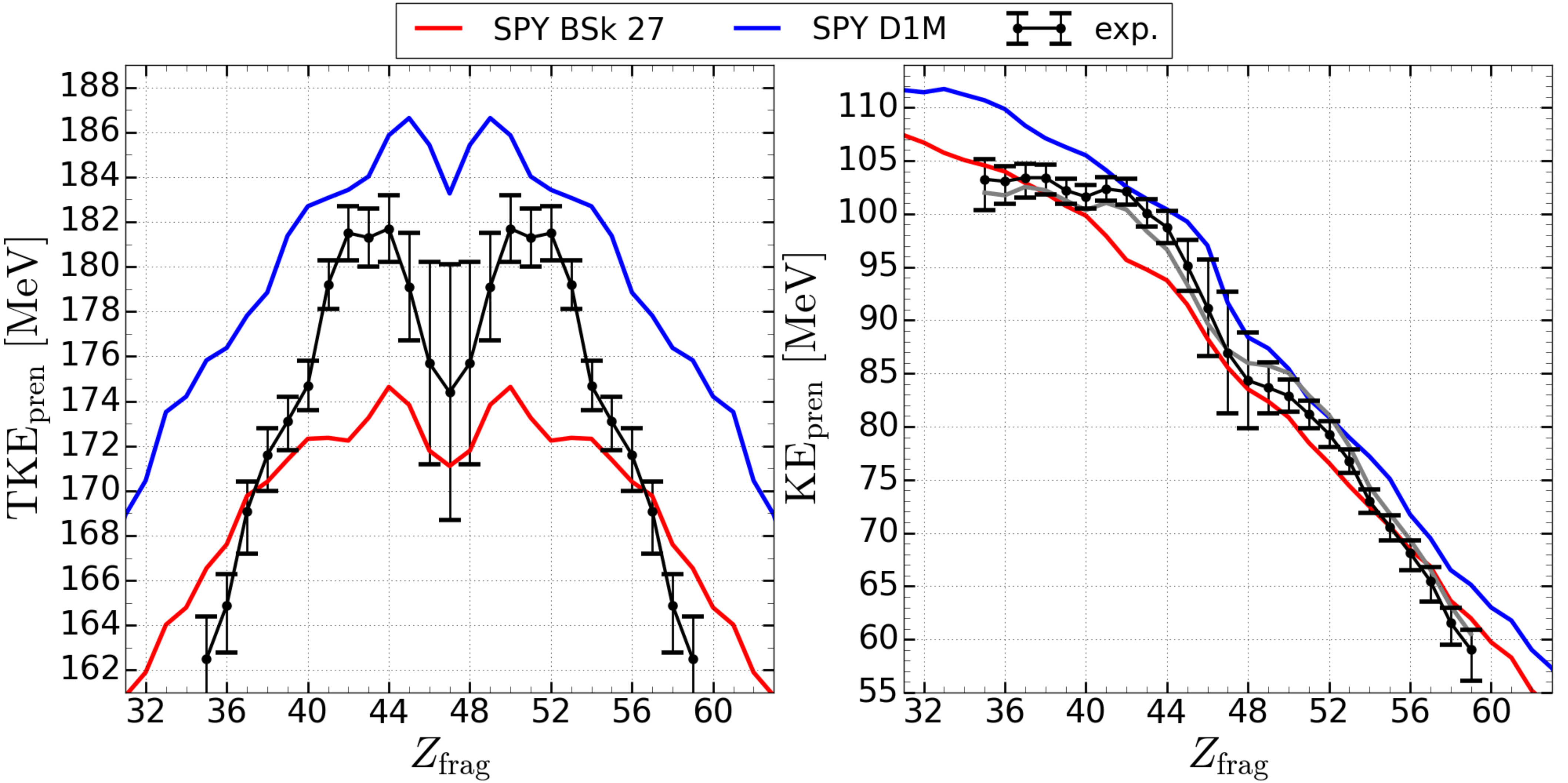
<N>/Z - Q=9 MeV



Exp. data : M. Caamano et al, PRC92, 034606 (2015)

Pu240

TKE & KE pren - Q=9 MeV

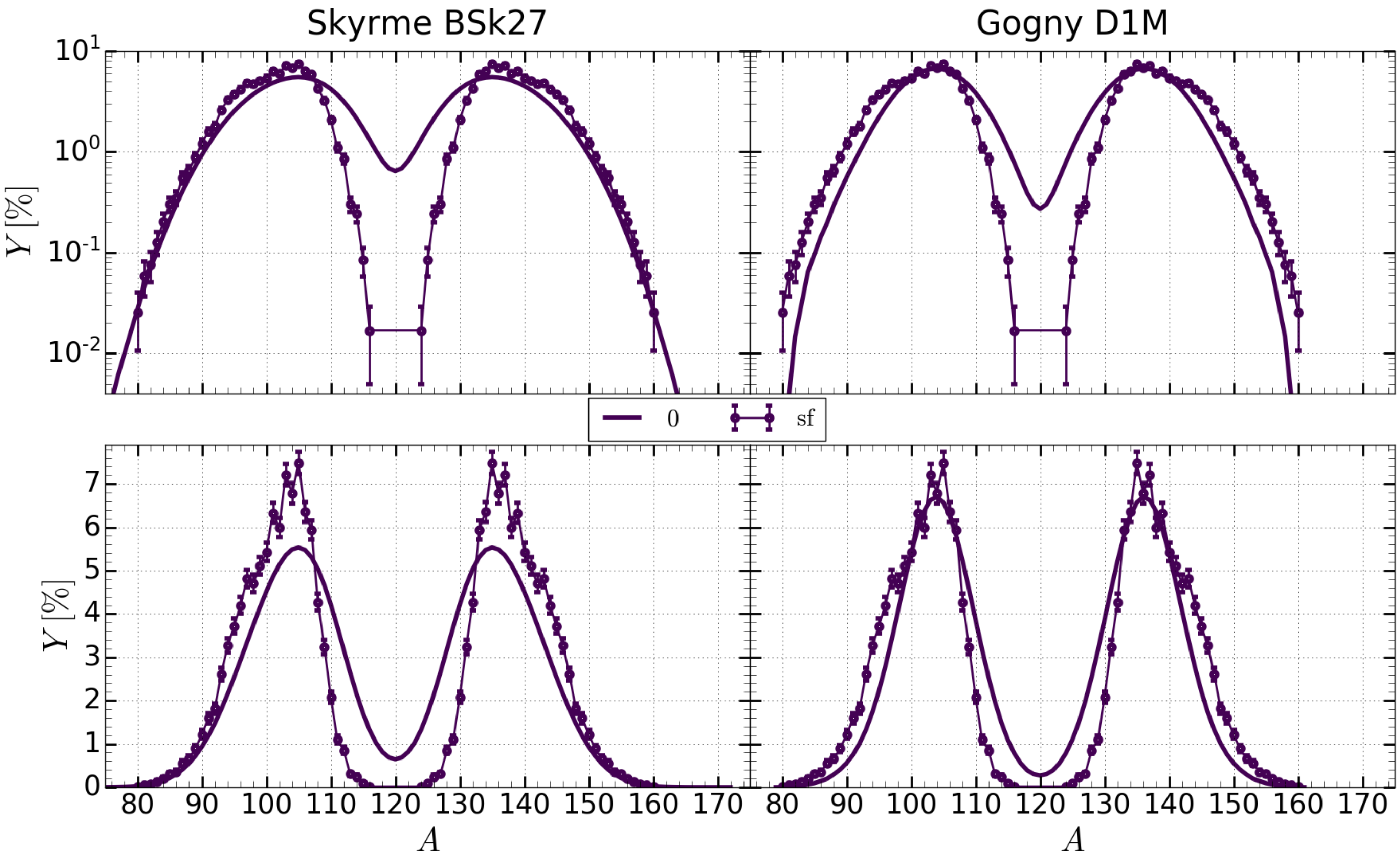


In gray, exp. TKE + Z_{UCD}

In black, exp.TKE + exp. <N>/Z

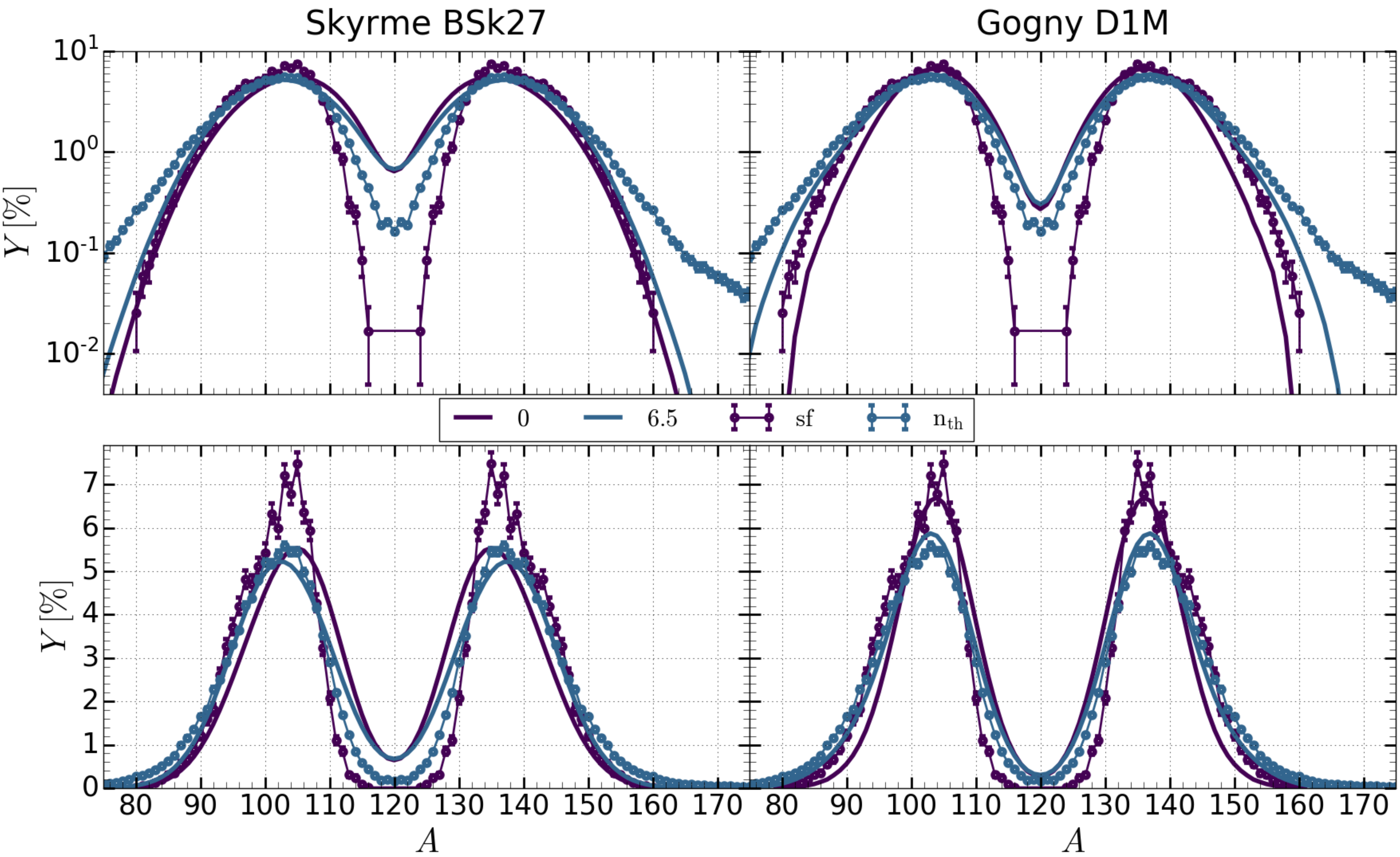
Exp. data : M. Caamano et al, PRC92, 034606 (2015)

Pu240
Q=0 MeV

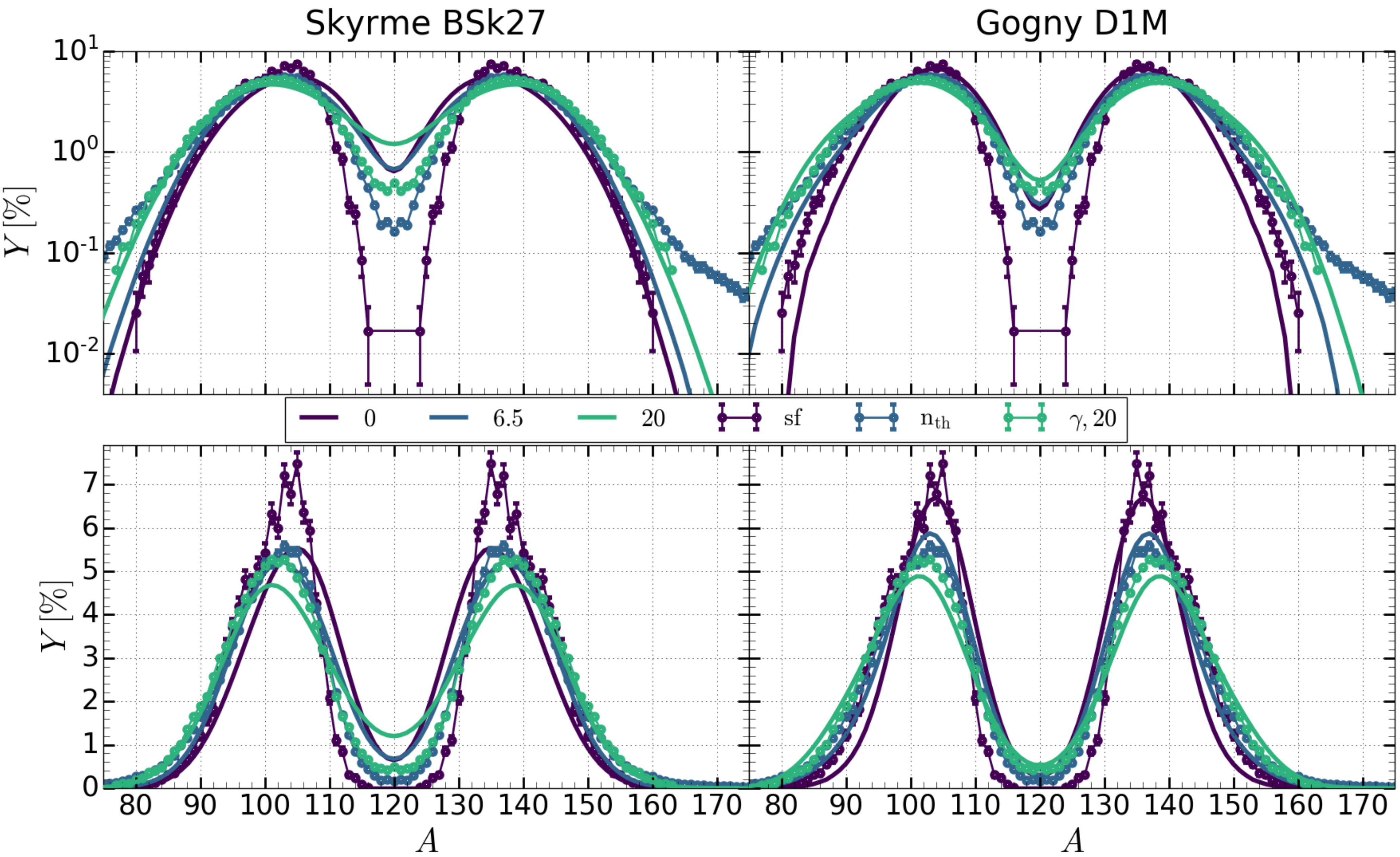


Skyrme BSk27
Gogny D1M
Y [%]
10^{1}
10^{0}
10^{-1}
10^{-2}
0
sf
7
6
5
4
3
2
1
0
80 90 100 110 120 130 140 150 160 170
A

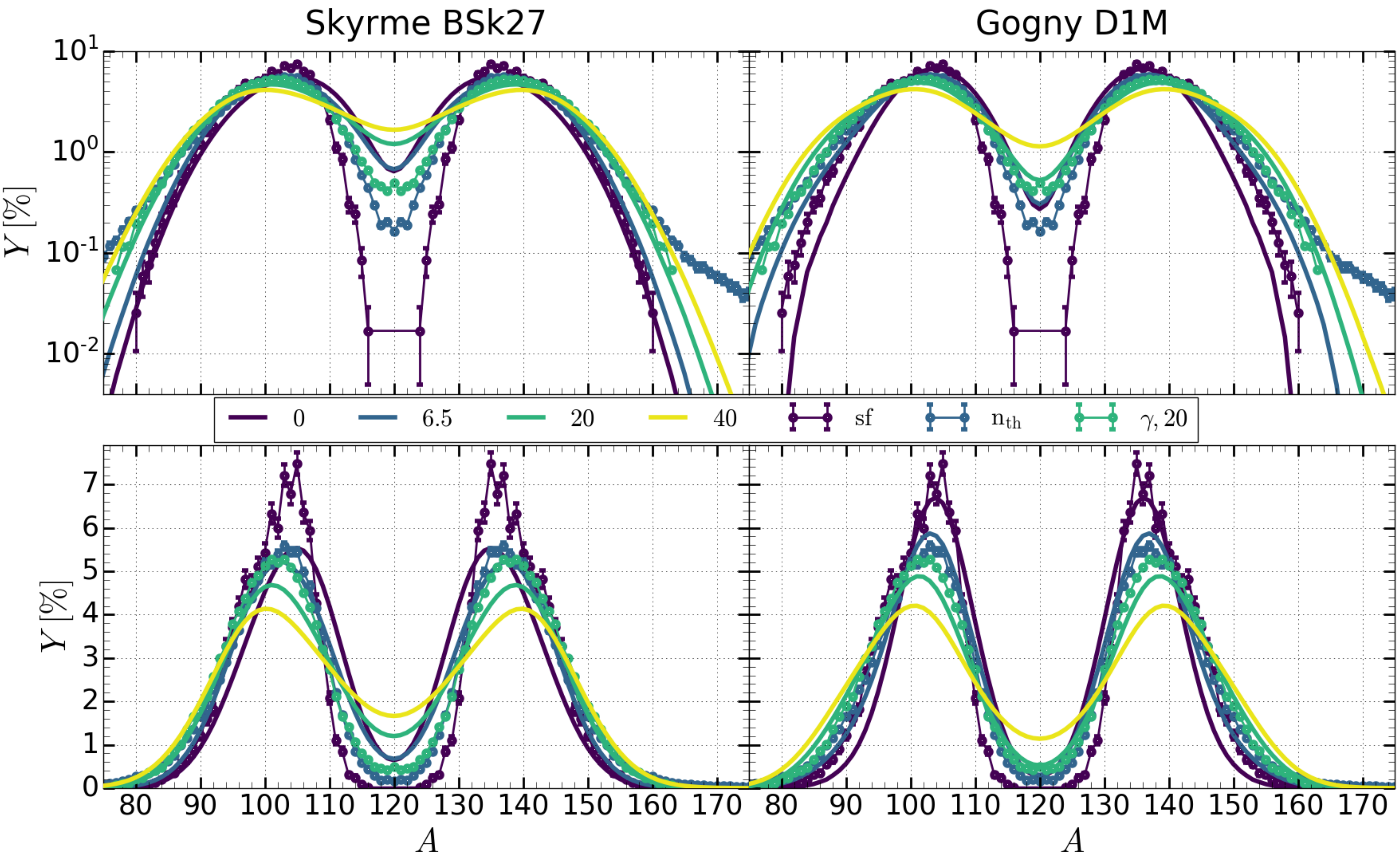
Pu240
Q=0/6.5 MeV



Pu240
Q=0/6.5/20 MeV

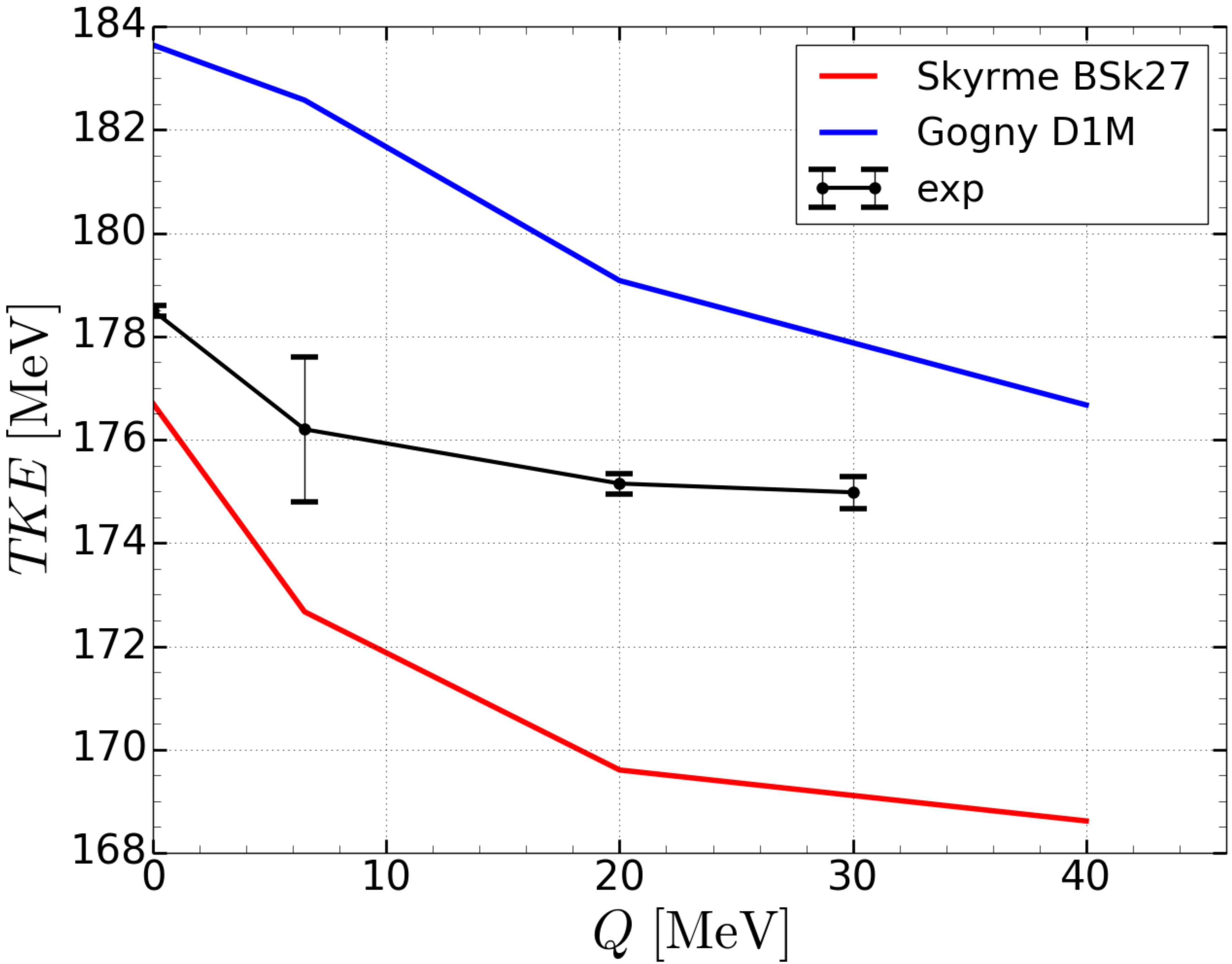


Pu240
Q=0/6.5/20/40 MeV

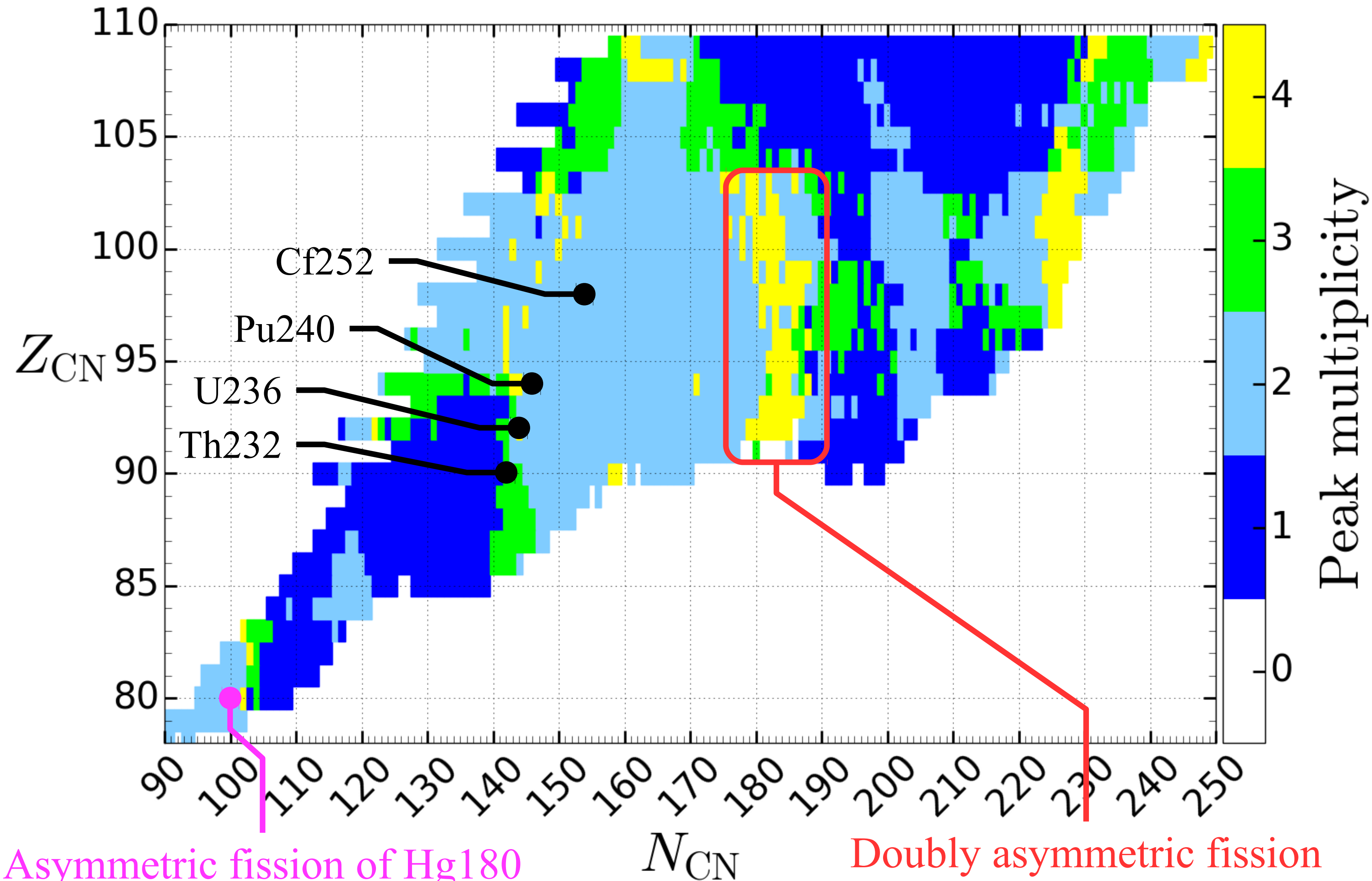


Pu240

Q=0/6.5/20/40 MeV



Systematic
Peak multiplicity

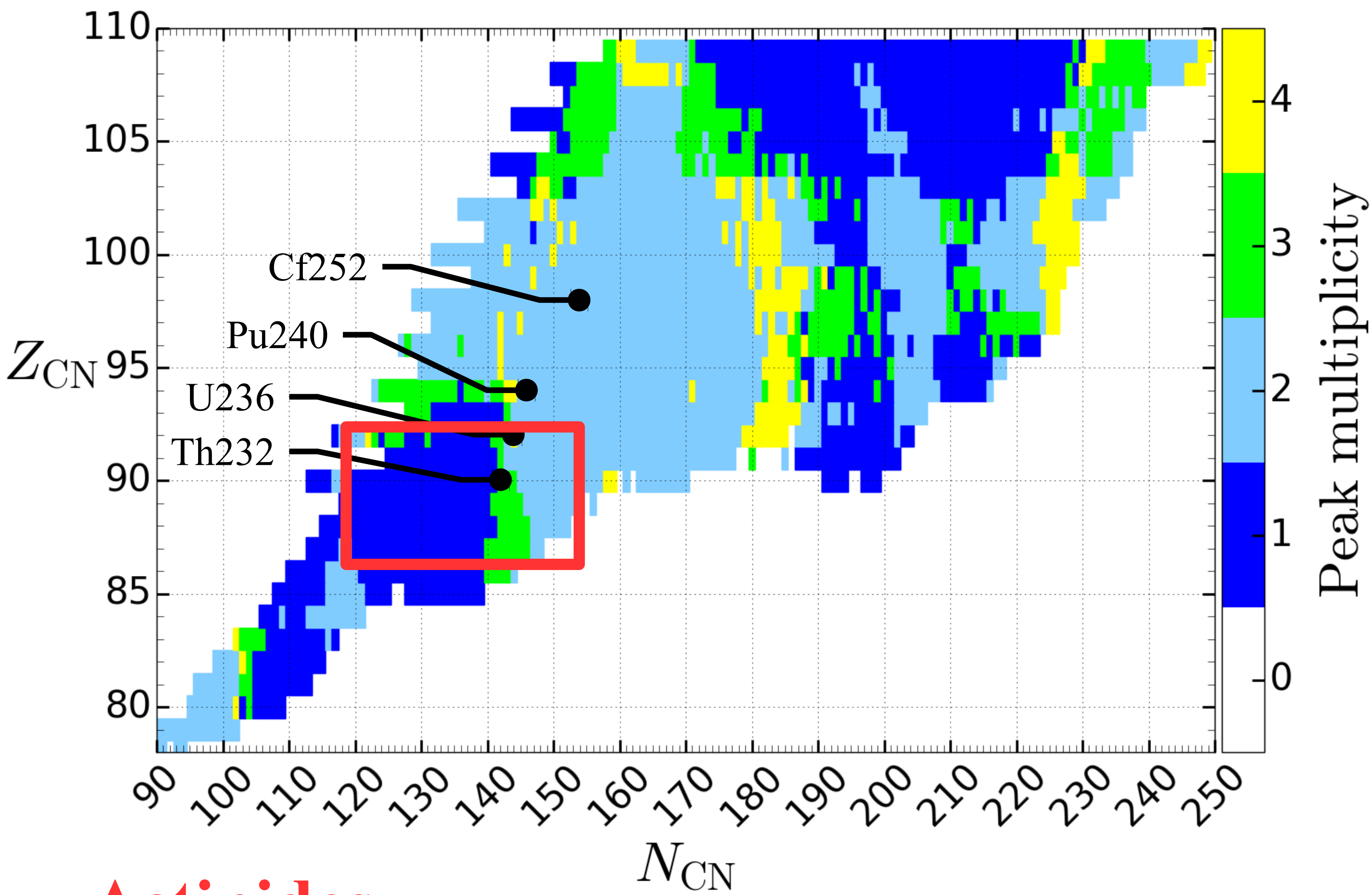


Asymmetric fission of Hg180
(S. Panebianco et al, Phys. Rev. C 86, 064601 (2012))

Doubly asymmetric fission
→ production of r-process elements A~165
(S. Goriely et al, Phys. Rev. Lett. 111, 242502 (2013))

SPY-BSk27 * Q=8 MeV * ρ_{neck}=0.002 fm^{-3}

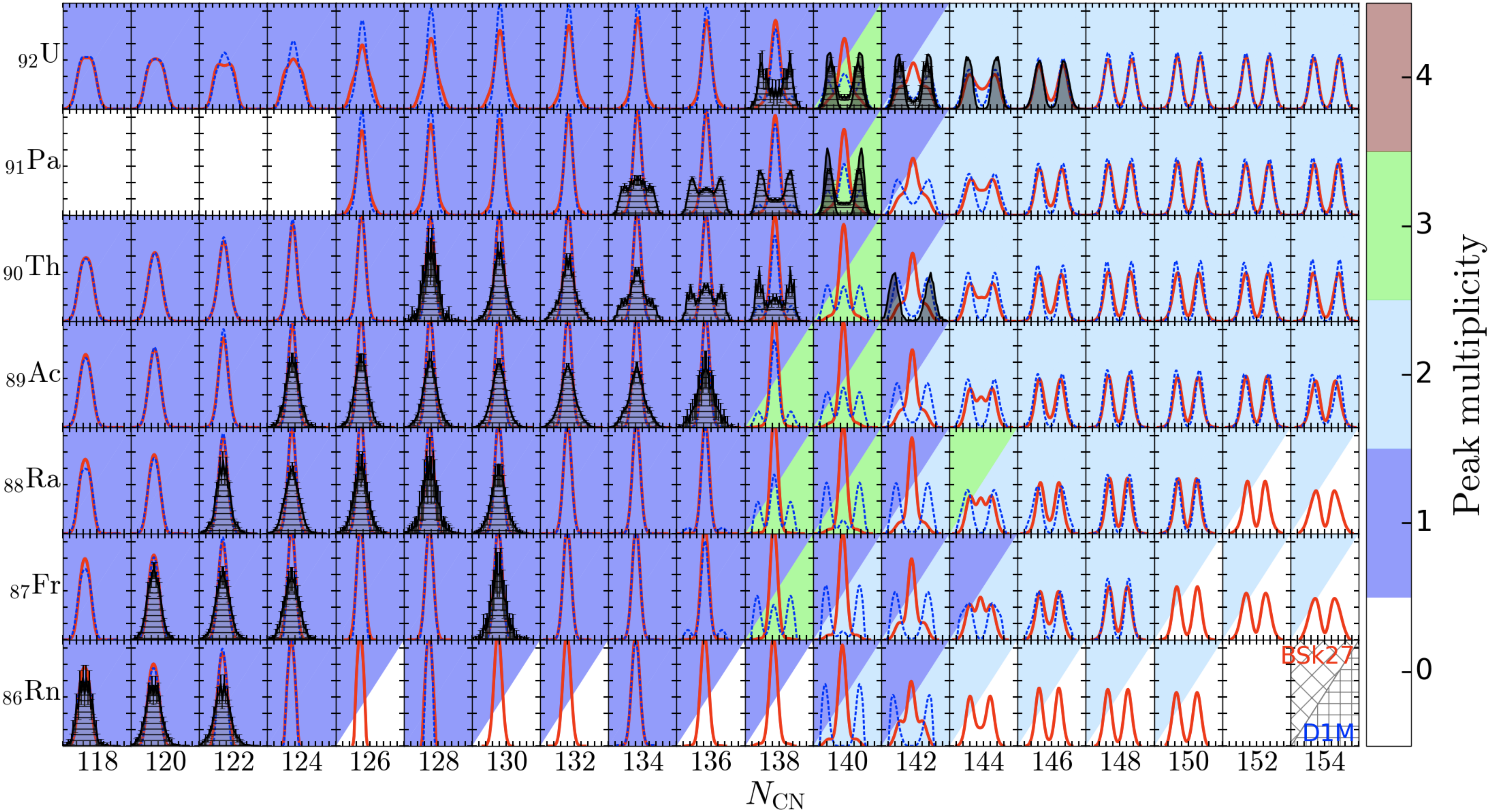
Systematic
Peak multiplicity



« Actinides »

Systematic, BSk27+D1M

nuclei : Rn → U, Q=10 MeV, ρ_{neck}=0.002 fm^{-3}



Disparity of the location of sym/asym fission for Fr, Rn (6 neutrons)
Transition sym/asym occurs for a too neutron rich isotope wrt exp. data
Exp. Data, curve with a striped filling : Coulex induced fission, E* around 11 MeV (GDR) (NPA655 p221(2000))
Q$_{EC}$ transition sym/asym of U at low E* (< E$_{barr}$ + 2 MeV) ? transition sym/asym location for Z<90

Conclusions & outlooks

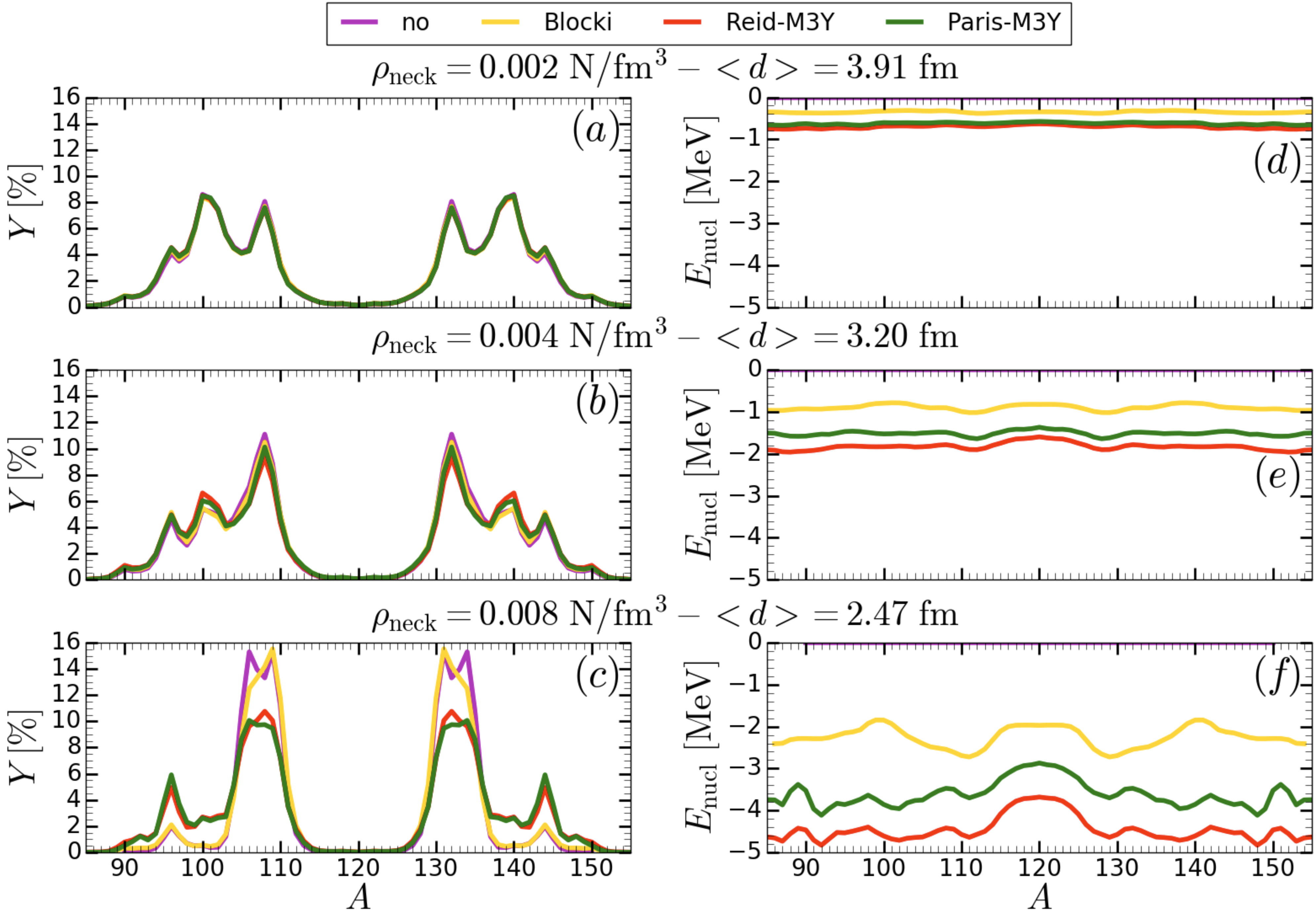
Conclusions

- Scission point, static frag., statistical (microcanonical description)
- Definition of the scission point based on realistic proton distribution
- All ingredients are calculated coherently in the same microscopic framework (Skyrme BSk27 eff. N-N interaction ; J.-F. Lemaître et al, Phys Rev C 99, 034612 (2019))
- Applied to the r-process, doubly asymm. fission (S. Goriely et al, Phys. Rev. Lett. 111, 242502 (2013))

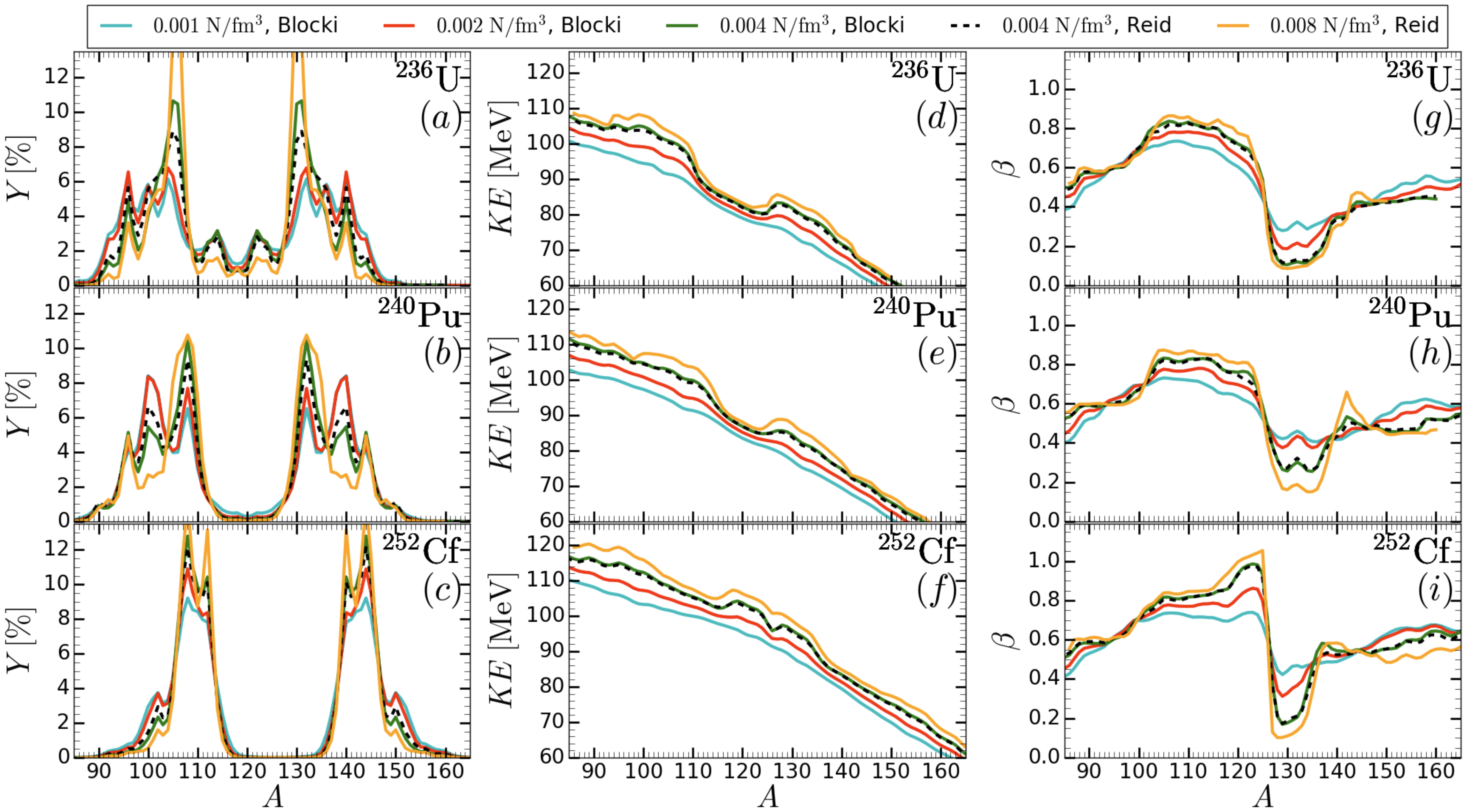
Outlooks

* Improve the description of the kinetic energy
* Improve the neutron evaporation
* Improve Y evolution with Q
* Octupole deformations
* Explore the odd-even effects in observables
* States densities including pairing gap (Δ) fluctuations
* New version with Gogny-D1M eff. N-N interaction → link with PES

Impact of E_{nucl} & and ρ_{neck} on Pu240

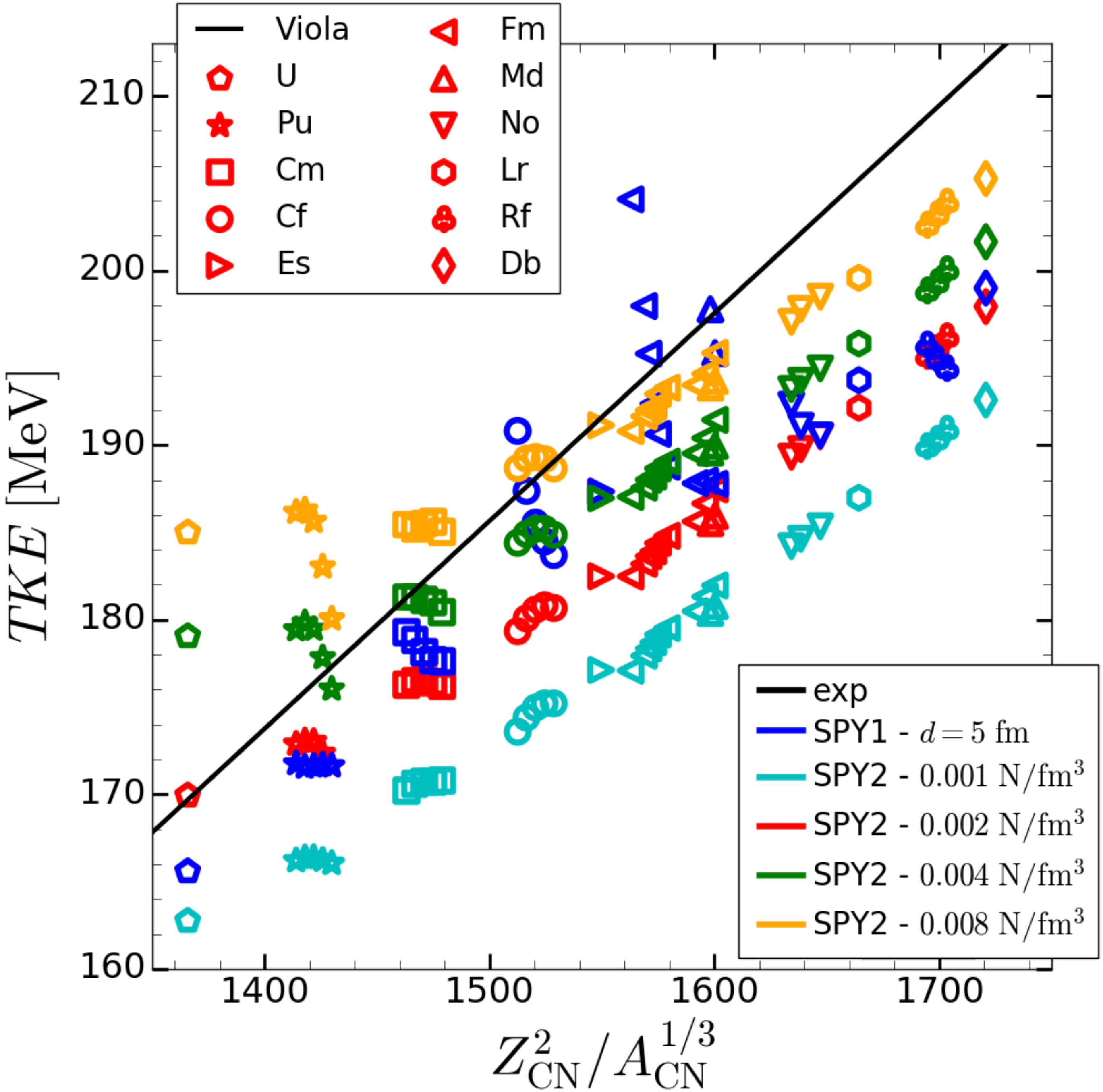


Impact of ρ_{neck} on yields



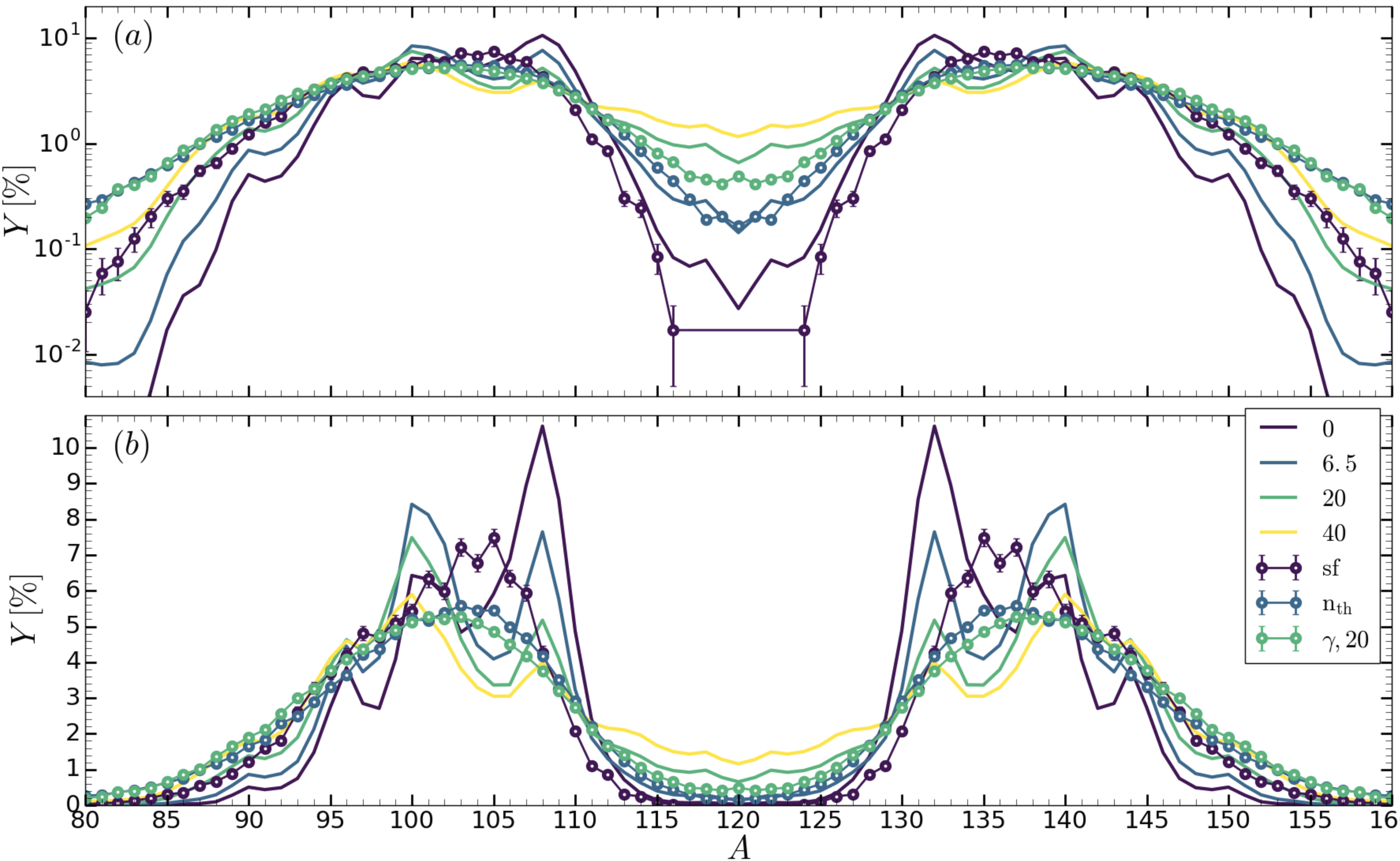
Impact of ρ_{neck} on TKE

BSk 27
Q=8MeV



Fission of Pu240 – Q=0/6.5/20/40 MeV with BSk27

$\sigma_z = \sigma_n = 0.65$



BCS equations to compute NSD

particle number equation :

$$N_q = \sum_k 1 - \frac{\varepsilon_q^k - \lambda_q}{E_q^k} \tanh\left(\frac{E_q^k}{2T}\right) \text{ with } N_q = Z \text{ or } N$$

gap equation :

$$\frac{2}{G_q} = \sum_k \frac{1}{E_q^k} \tanh\left(\frac{E_q^k}{2T}\right) \text{ with } G_q \text{ the pairing strength}$$

where :

$E_q^k = \sqrt{\left(\varepsilon_q^k - \lambda_q\right)^2 + \Delta_q^2}$ the quasiparticle energy

ε_q^k : energy of the kth level of the SPL scheme

λ_q : chemical potential ; Δ_q : paring gap ; T : temperature

$$E_{tot}(T) = \sum_{q=n,p} \sum_k \left[1 - \frac{\varepsilon_q^k - \lambda_q}{E_q^k} \tanh\left(\frac{E_q^k}{2T}\right)\right] - \frac{\Delta_q^2}{G_q}$$

$$S(T) = 2 \sum_{q=n,p} \sum_k \ln\left(1 + e^{-E_q^k/T}\right) + \frac{E_q^k/T}{1 + e^{E_q^k/T}}$$

BCS equations to compute NSD

finally we have :

$$\frac{1}{\rho(U)} = (2\pi)^{3/2}\left[\frac{\sqrt{D(U)}}{e^{S(U)}} + \frac{1}{\omega_0(U)}\right]$$

with :

$$\omega_0(U) = \frac{\pi^2 e}{12}\frac{S(U)^2}{T\sqrt{S_n(U)S_z(U)}}e^{S_n(U)S_z(U)}$$ to avoid unphysical divergence

where

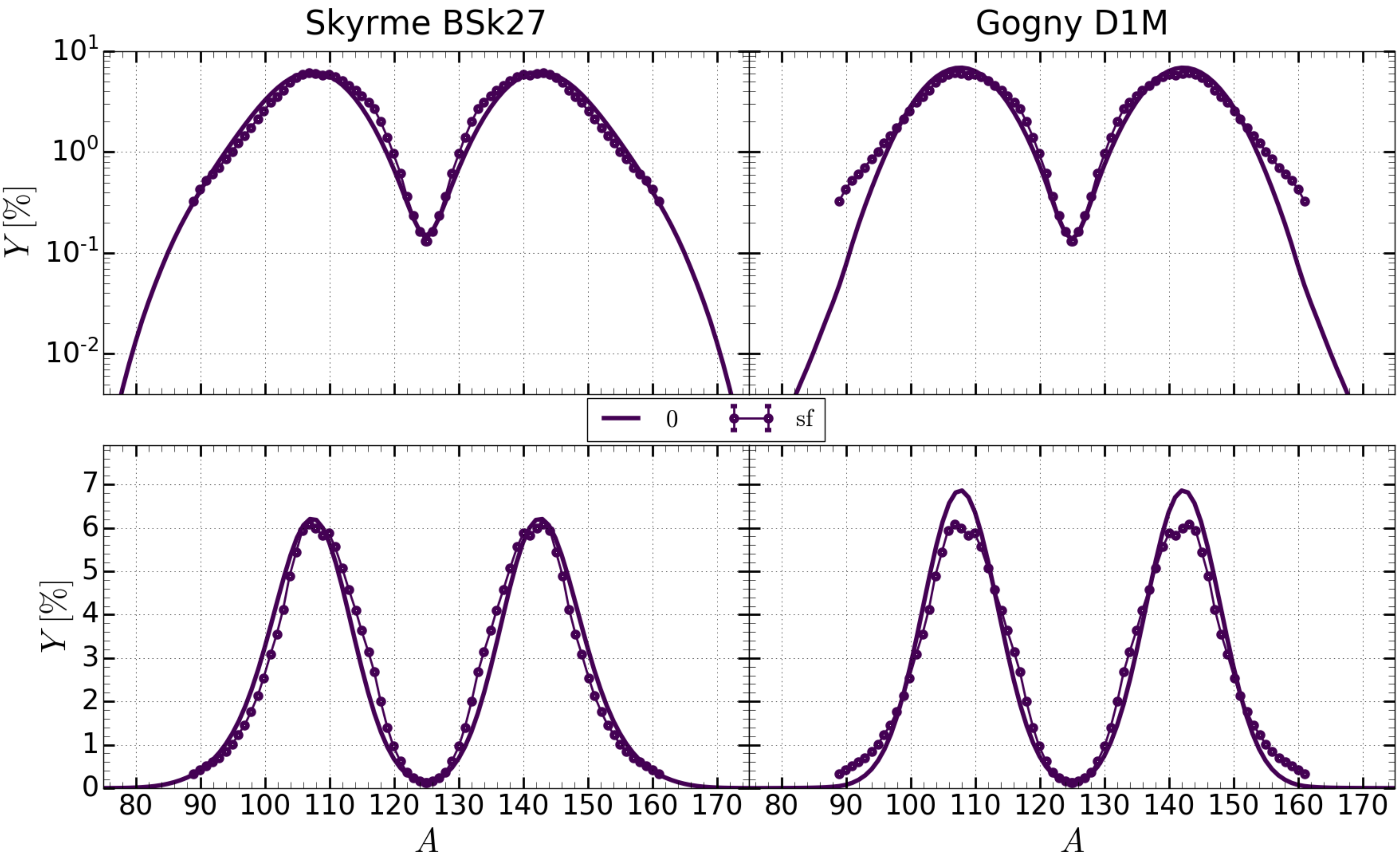
$$U = U(T) = E(T) - E(T=0)$$

$$S(U) = S_n(U) + S_z(U)$$

$D(U)$ is the determiant of the 2nd derivatives of Ξ

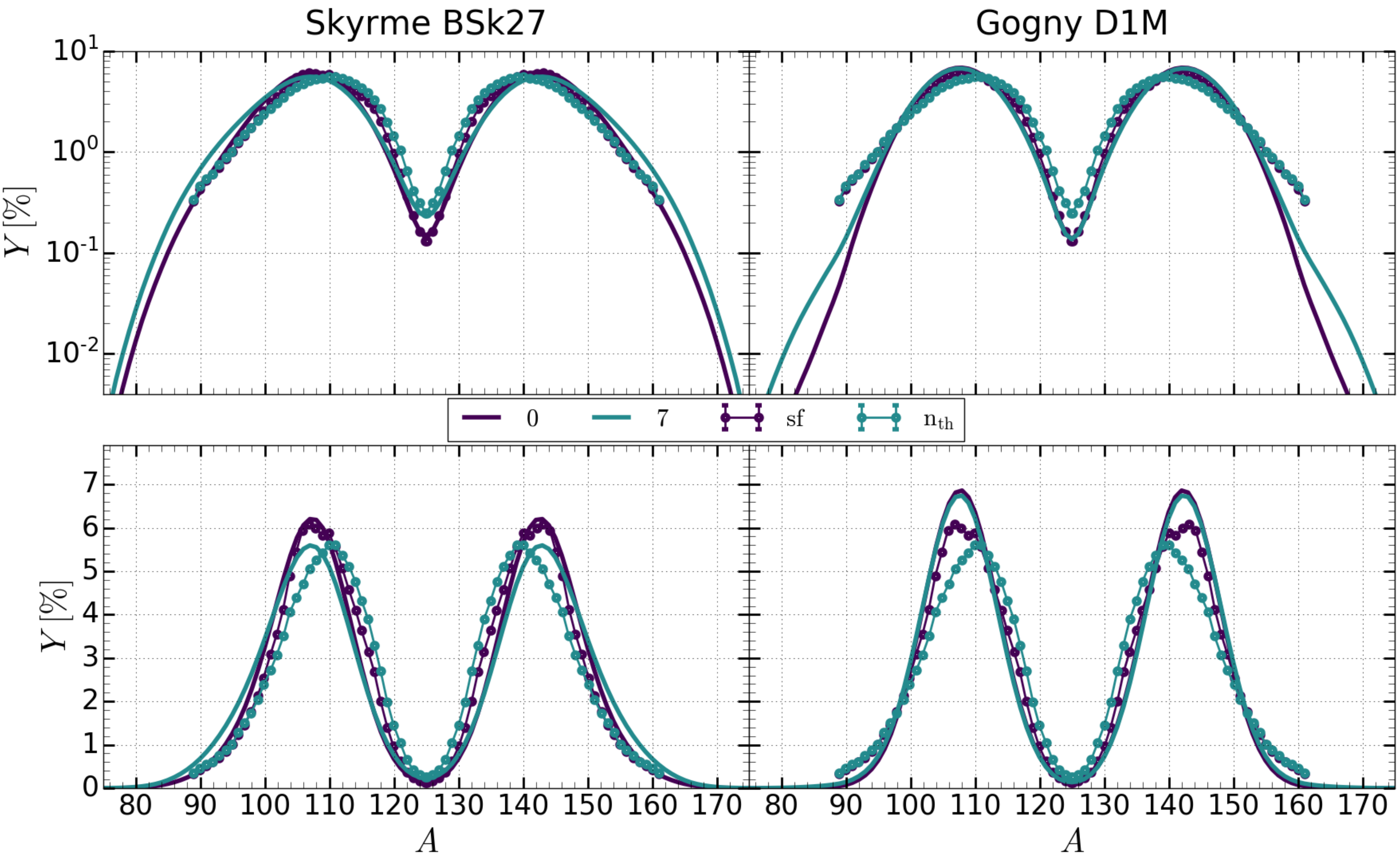
Cf250

Fission of Cf250 – Q=0/7/46 MeV



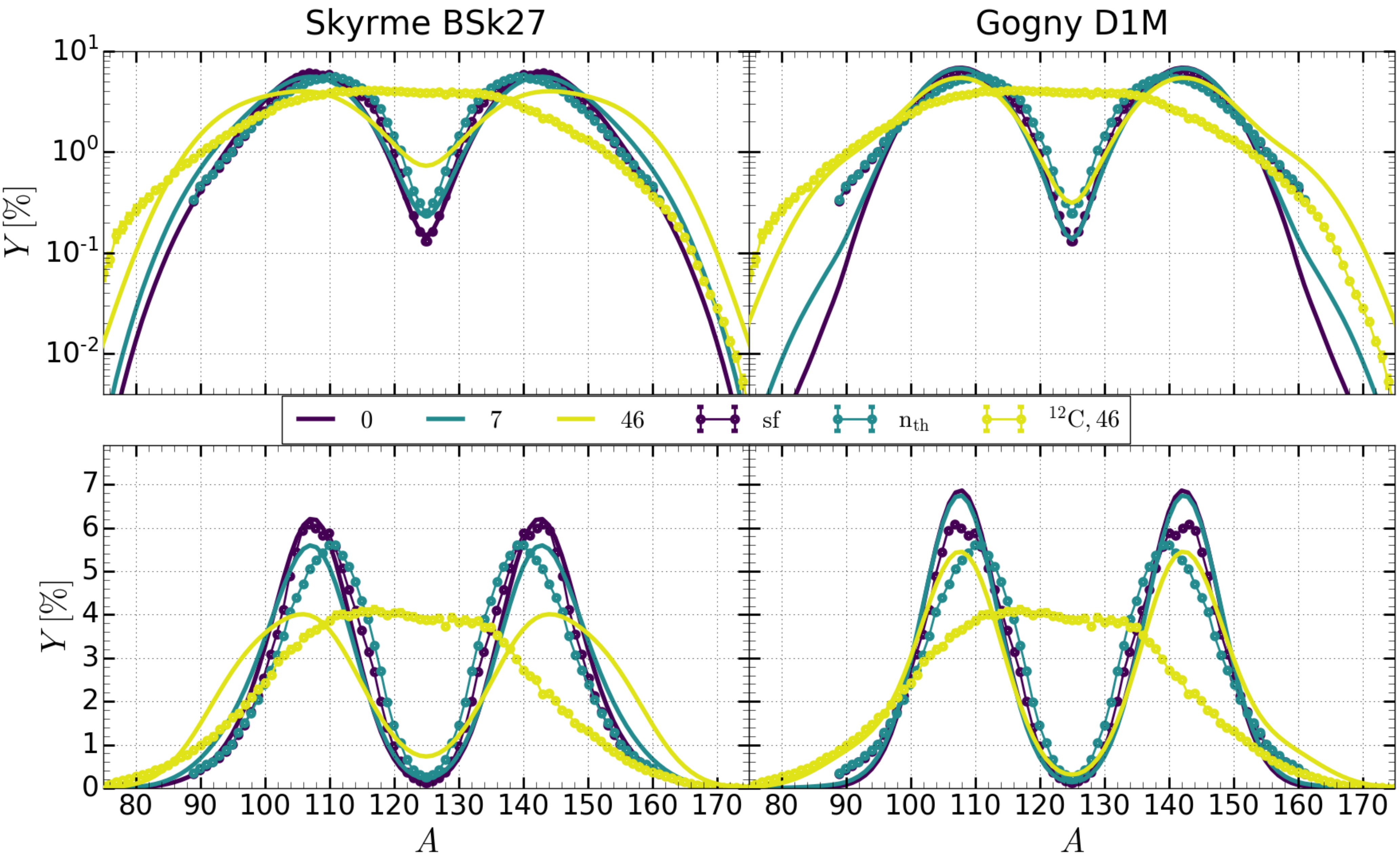
Cf250

Fission of Cf250 – Q=0/7/46 MeV



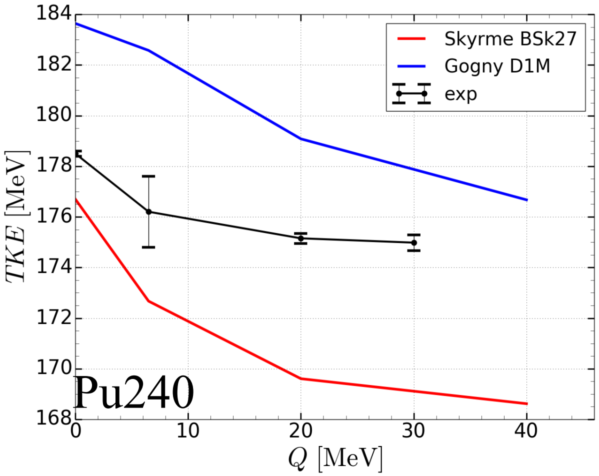
Cf250

Fission of Cf250 – Q=0/7/46 MeV



Pu240 VS Cf250
<TKE> evolution with Q

Pu240 : increase of the symm. part of the yields distribution with Q
<TKE> decreases, from sf to nif **-1 MeV** (D1M) & -4 MeV (BSk27)
Wagemans, ch8 : **-1.4 ± 0.1 MeV**



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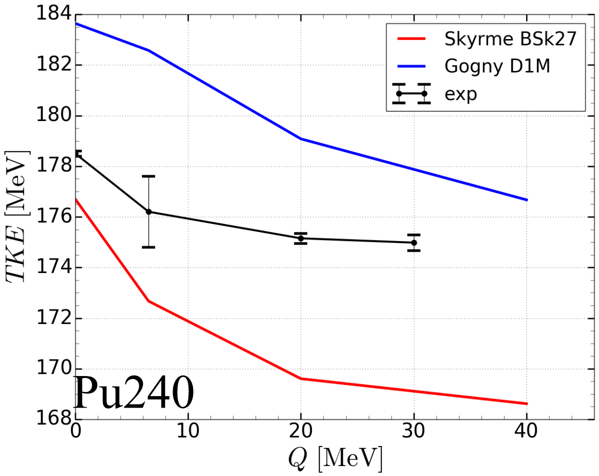
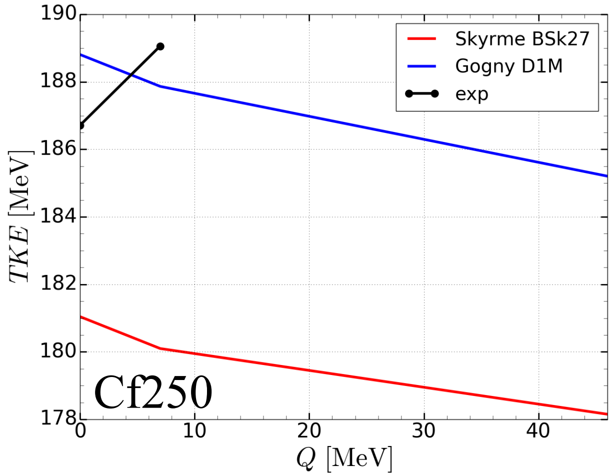
Cf250 : exp. : symm. & SPY : asymm.
<TKE> decreases, from sf to nif **-0.95 MeV** (D1M & BSk27)
Wagemans, ch8 : **<TKE> increase**





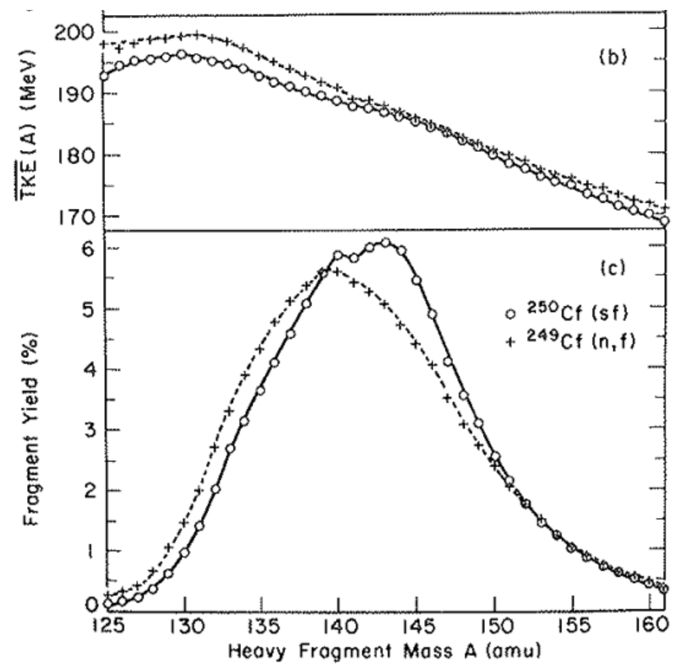


FIGURE 59. Spontaneous fission of ^{250}Cf (open points) and thermal neutron fission of ^{249}Cf(n,f) (crosses): preneutron mass yield (bottom), average total kinetic energy (middle), and rms width of total kinetic energy distribution (top) vs. heavy fragment mass. (From Unik, J. P., Gindler, J. E., Glendenin, L. E., Flynn, K. F., Gorski, A., and Sjoblom, R. K., in *Proc. Symp. Physics and Chemistry of Fission*, Vol. 2, IAEA, Vienna, 1974, 20. With permission.)

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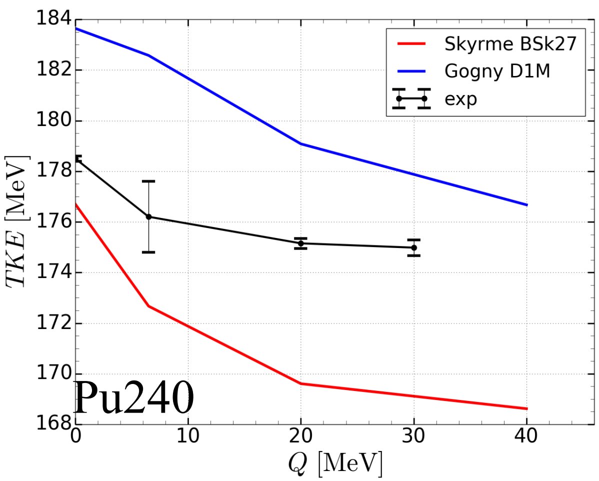

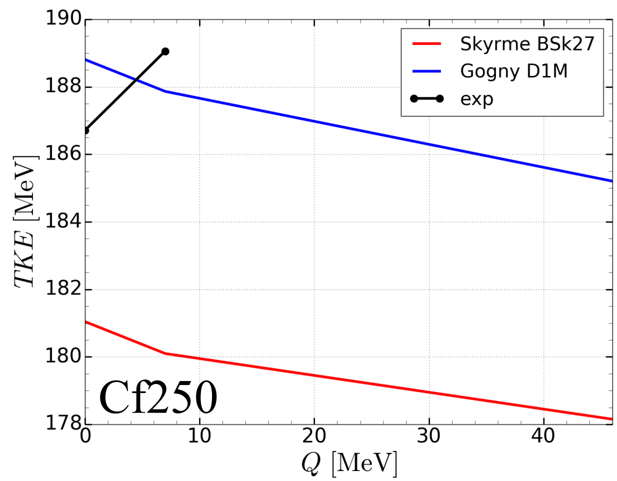

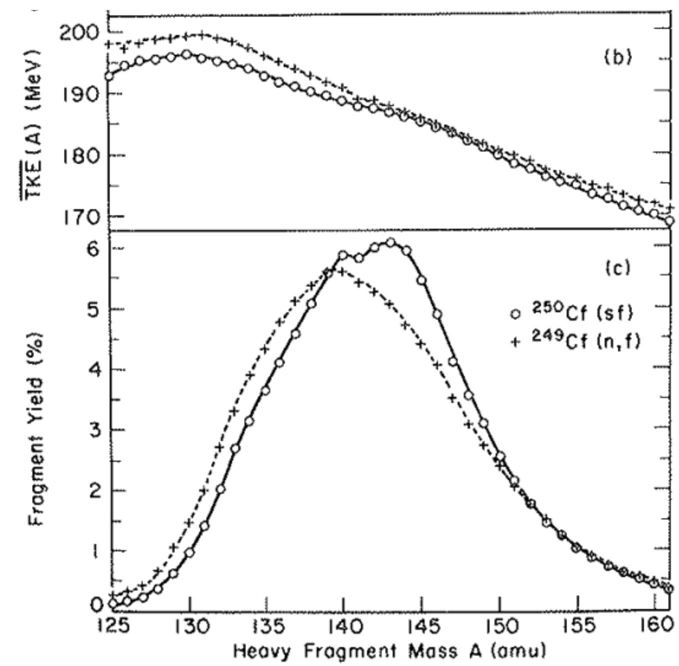

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* too strong structure effects ? → no shell closure in frag.
* state density evolution with E*
* $^{238}U(^{12}C,f) \neq {}^{249}Cf(n,f)$ or $^{250}Cf(\gamma,f)$
* Why <TKE> increases with Q for Cf250 case ? (multi-chance?)

Wagemans, ch8 'The interpretation of the above results [TKE evolution with Q] is not obvious. The change of sign in the average shift of KE release when moving from spontaneous to induced fission is, however, a strong indication that the question whether superfluidity in the nuclear system is preserved in the fission process is not at stake. [...]'

→ **Measure Y & <TKE> of Pu240 & Cf250 with Q ?**