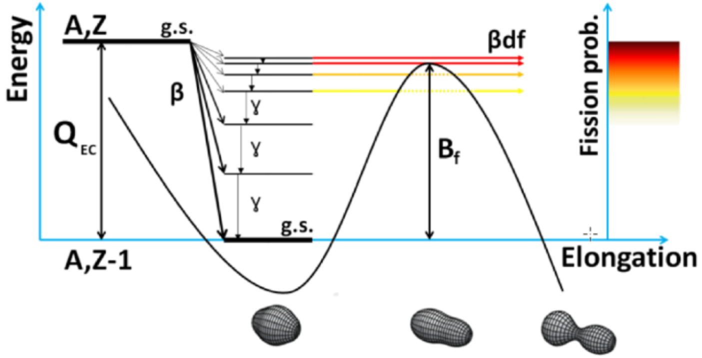
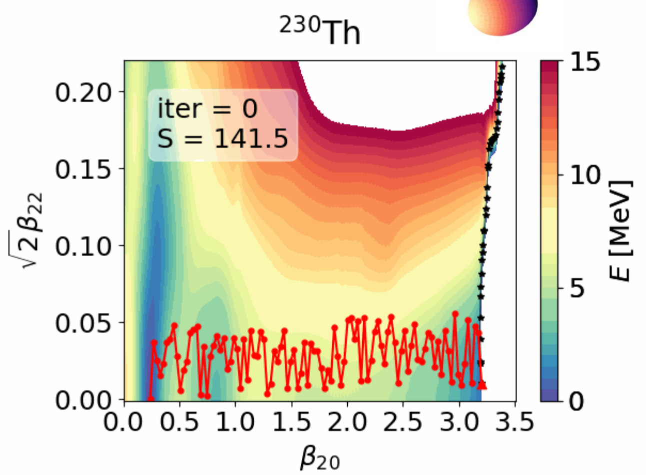
Silvia Bara

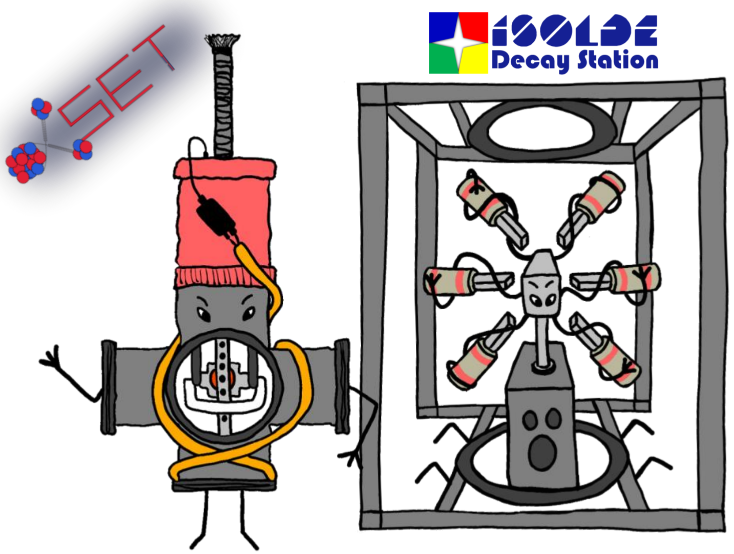
Beta-delayed fission of neutron-rich actinides

Introduction

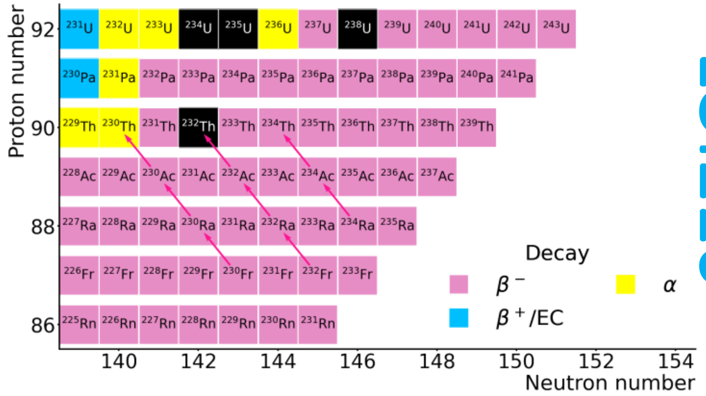


βDF with PyNeb

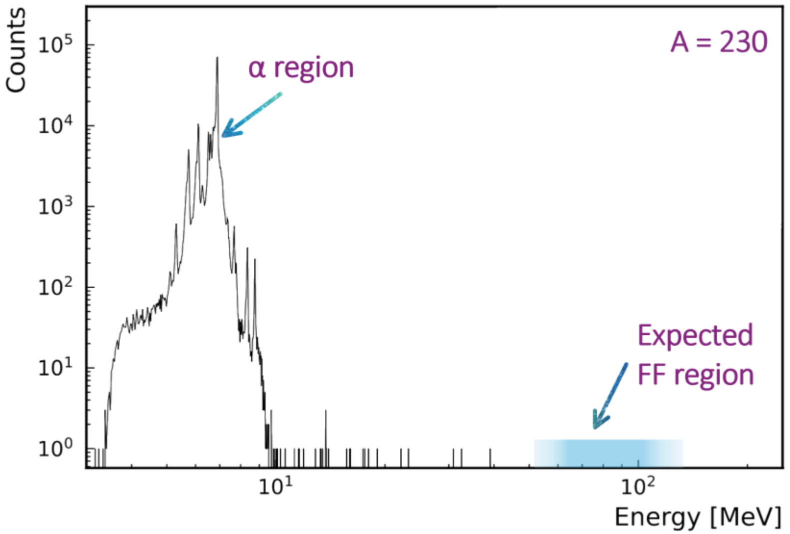




LOI216



Results

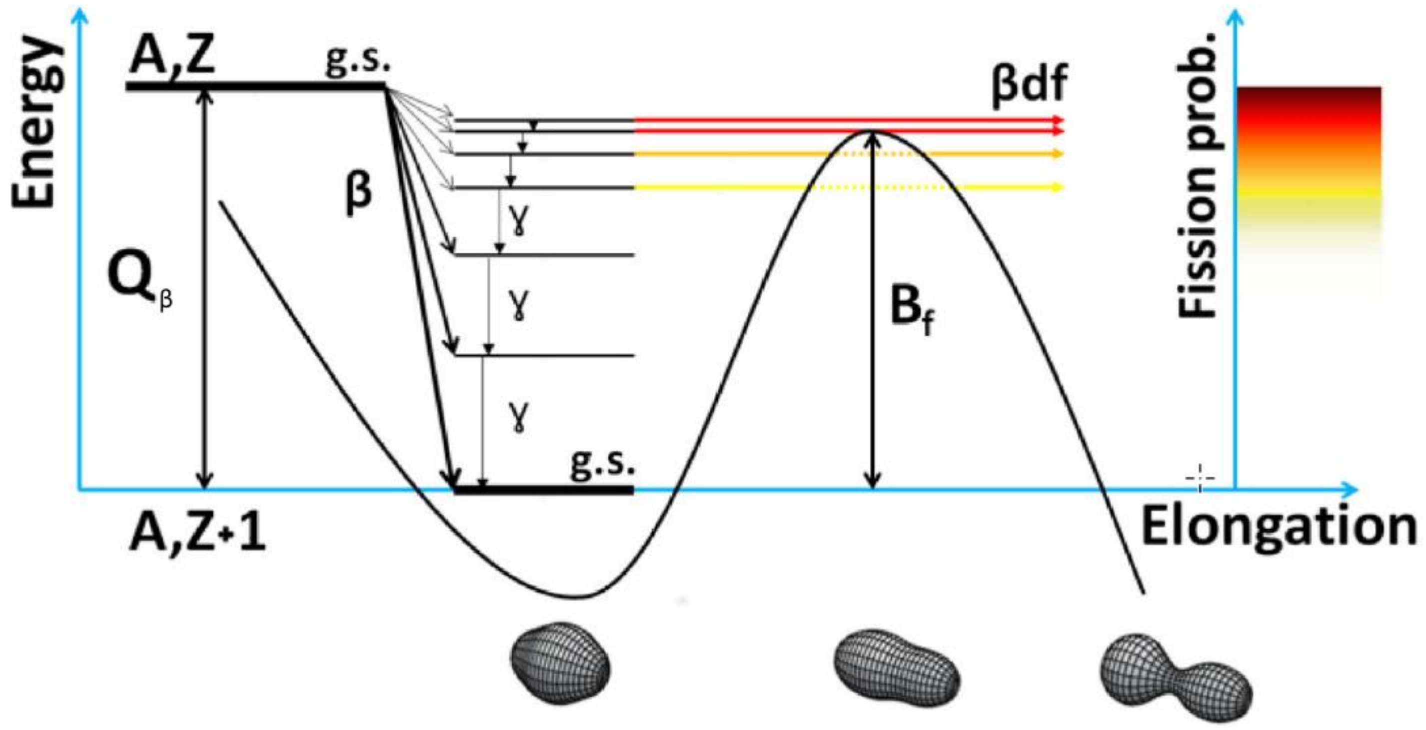


β-delayed fission

- Two-step process:
  1. β-decay
  2. fission

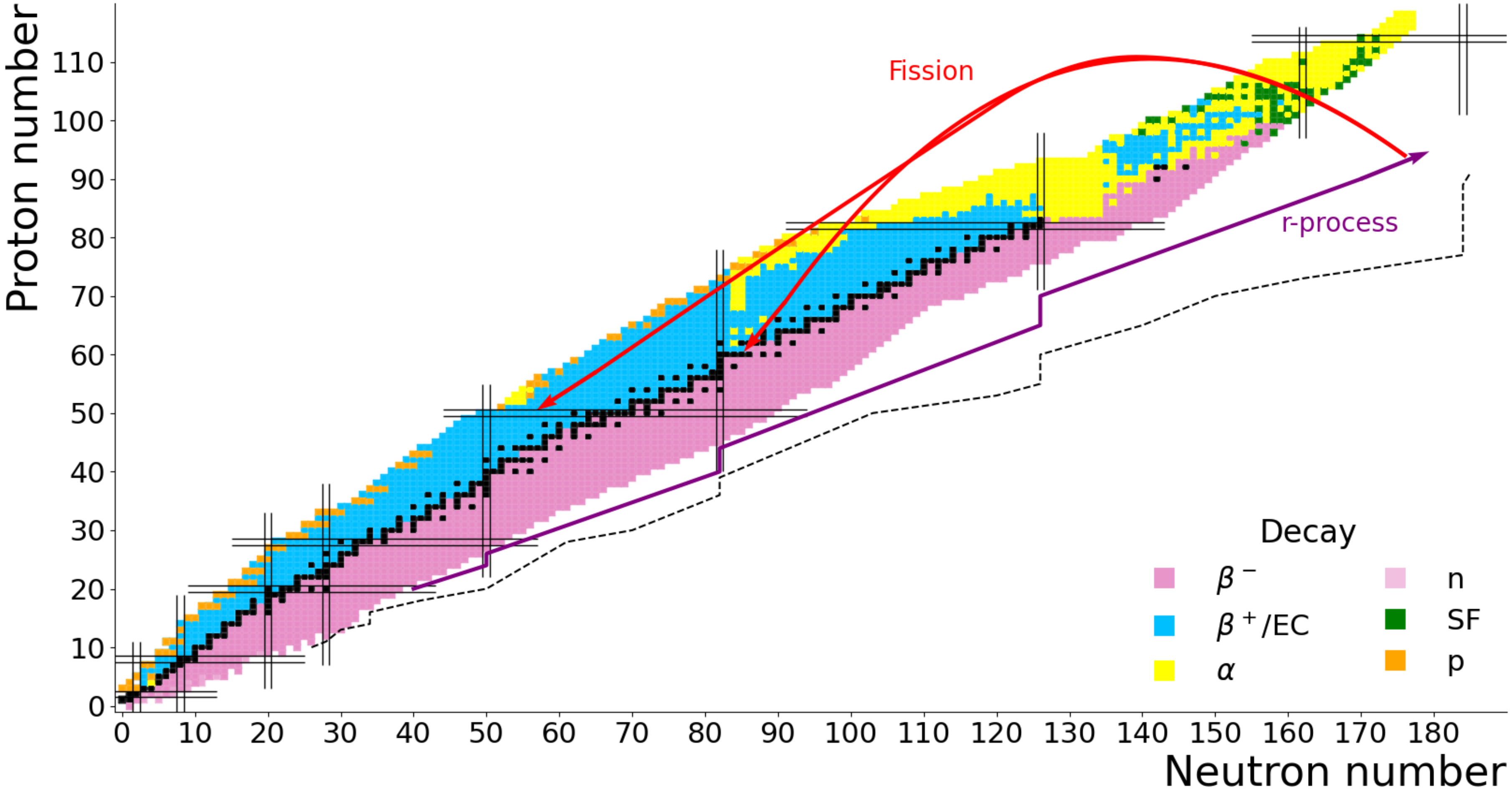
- Probability of βDF

$$P_{\beta DF} = \frac{N_{\beta DF}}{N_{\beta}}$$



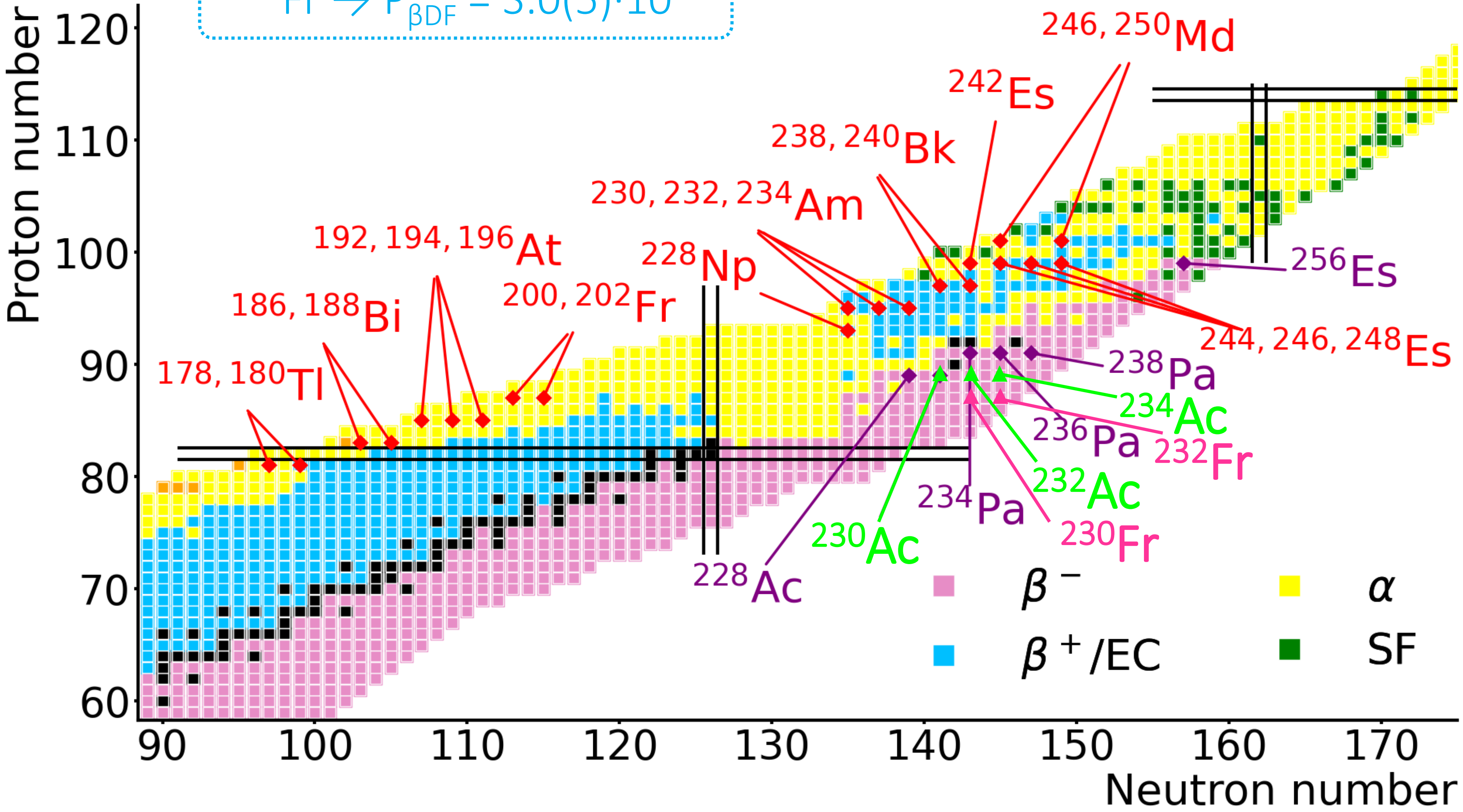
Motivations

- **r-process** → $P_{\beta DF}$ and fission fragments mass distribution



Previous studies

$^{202}Fr \rightarrow P_{\beta DF} = 3.0(5)\cdot 10^{-4}$



- Belov et al. and Gangrsky et al. (1976, 1978)[1,2]
  - $^{236}Pa \rightarrow P_{\beta DF} \sim 10^{-9} - 10^{-10}$
  - $^{238}Pa \rightarrow P_{\beta DF} \sim 10^{-7} - 10^{-8}$
- Baas-May et al. (1985)[3]
  - $^{238}Pa \rightarrow P_{\beta DF} < 10^{-8}$
- Shuanggui et al. (2001)[4]
  - $^{230}Ac \rightarrow P_{\beta DF} \sim 10^{-8}$
- Yanbing et al. (2006)[5]
  - $^{228}Ac \rightarrow P_{\beta DF} \sim 10^{-12}$

[1] G. Belov *et al.*, Report JINR P15-9795 (1976).
[2] Y. P. Gangrsky *et al.,* Yad. Fiz. 27, 894 (1978); Soy. J. Nucl. Phys. 27, 475 (1978).
[3] A. Baas-May *et al.,* Z. Phys. A 322, 457-462 (1985).
[4] Y. Shuanggui *et al.*, Eur. Phy. J. A 10, 1-3 (2001).
[5] X. Yanbing *et al.*, Phys. Rev. C 74, 047303 (2006).

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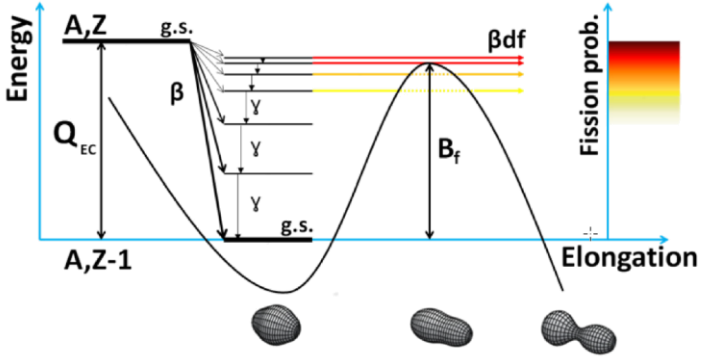
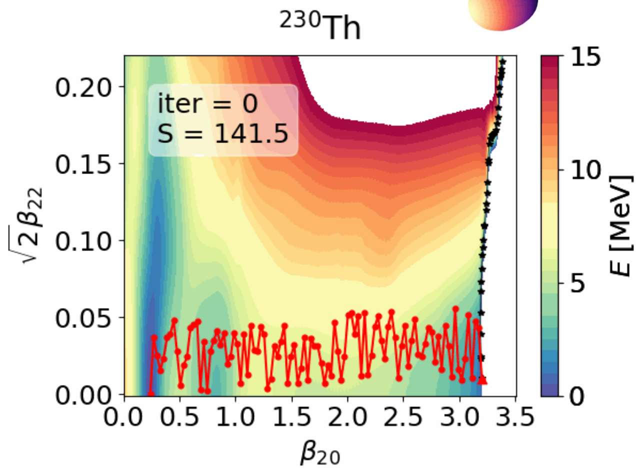
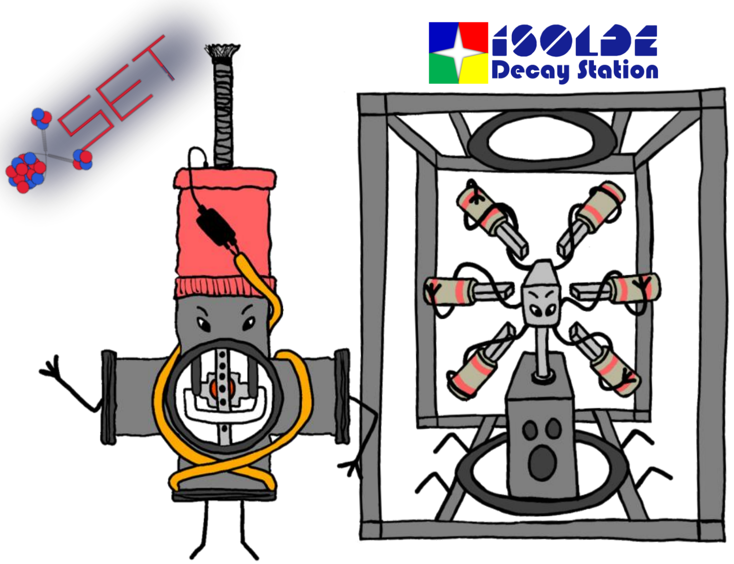
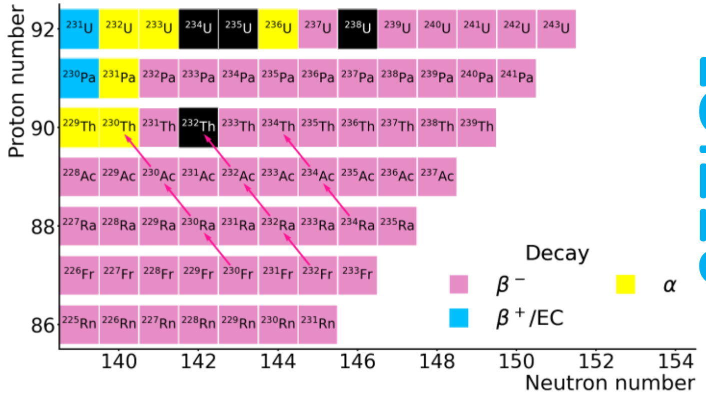


βDF with PyNEB

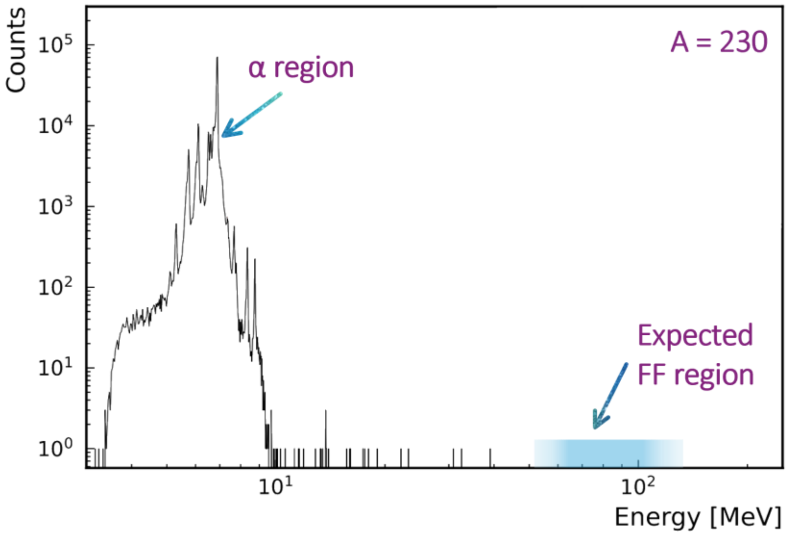




LOI216

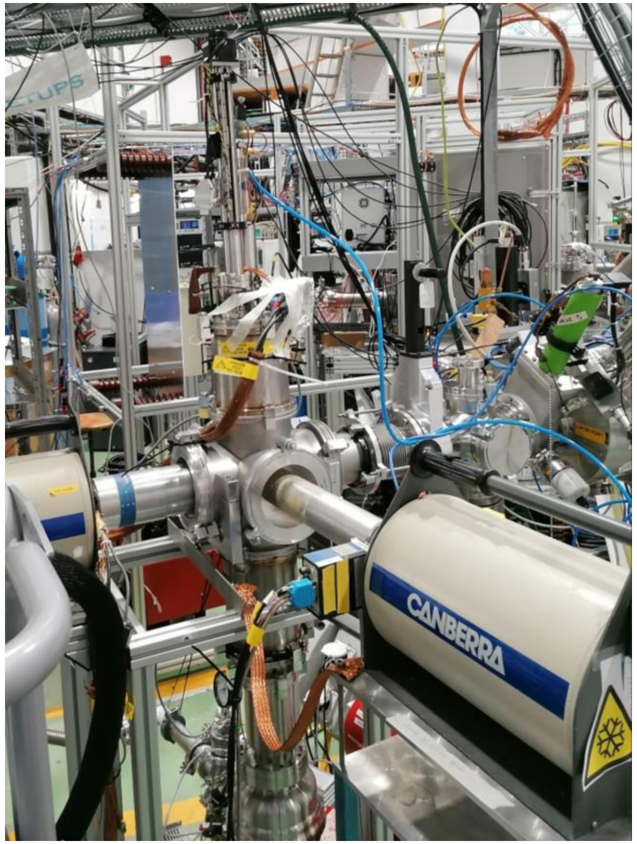


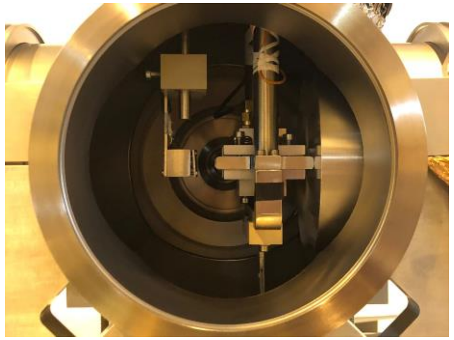
Results

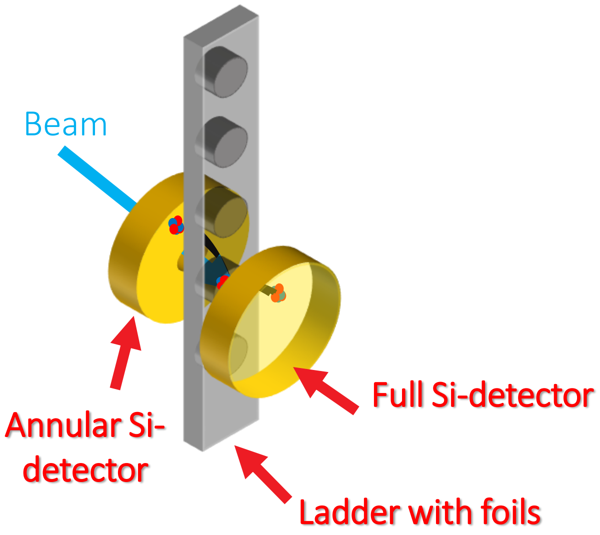


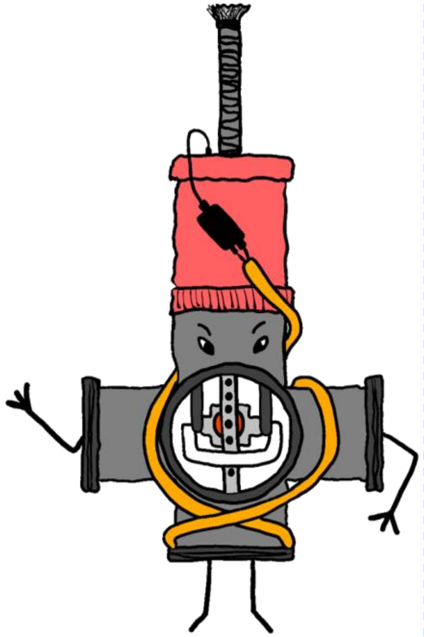
SET

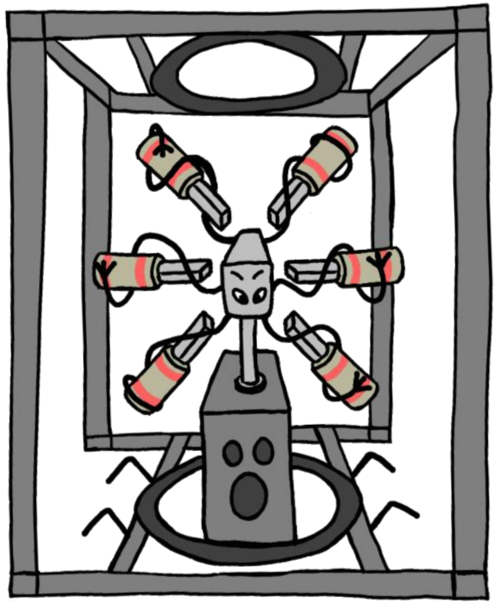
ISOLDE Decay Station



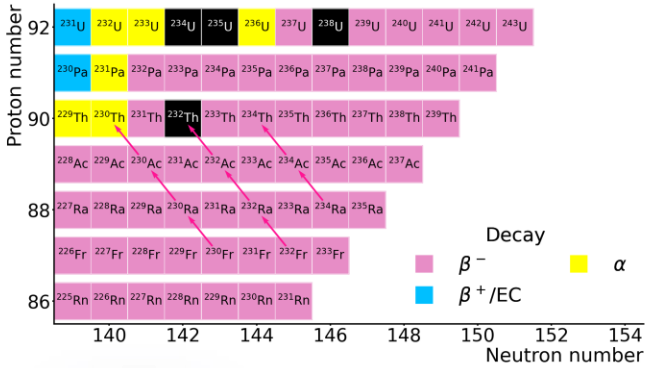








LOI216: βDF of ^{230,232,234}Ac



^{230}Ra $\xrightarrow{\beta^-}$ ^{230}Ac $\xrightarrow{\beta^-}$ ^{230}Th ⇒ Implantation of ~ 2 h + decay

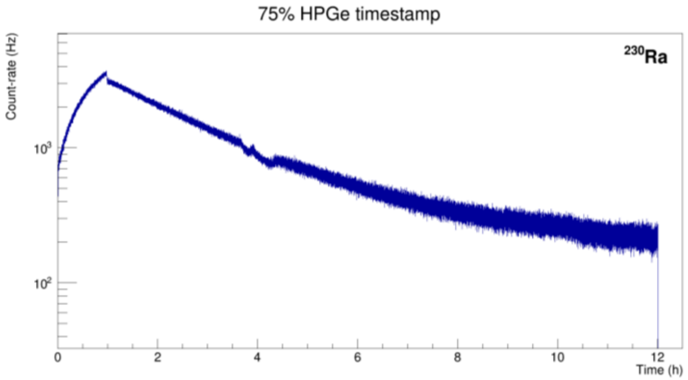
$T_{1/2}$ = 93 min, $T_{1/2}$ = 122 s, $T_{1/2} = 7.54 \cdot 10^4$ y

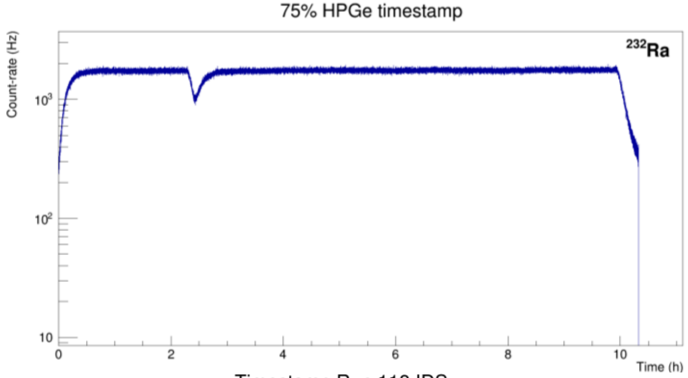
^{232}Ra $\xrightarrow{\beta^-}$ ^{232}Ac $\xrightarrow{\beta^-}$ ^{232}Th ⇒ Continuous implantation

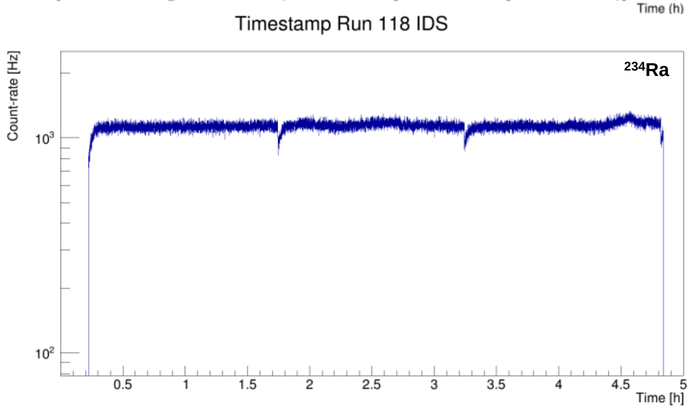
$T_{1/2}$ = 4.2 min, $T_{1/2}$ = 119 s, $T_{1/2} = 1.405 \cdot 10^{10}$ y

^{234}Ra $\xrightarrow{\beta^-}$ ^{234}Ac $\xrightarrow{\beta^-}$ ^{234}Th ⇒ Continuous implantation

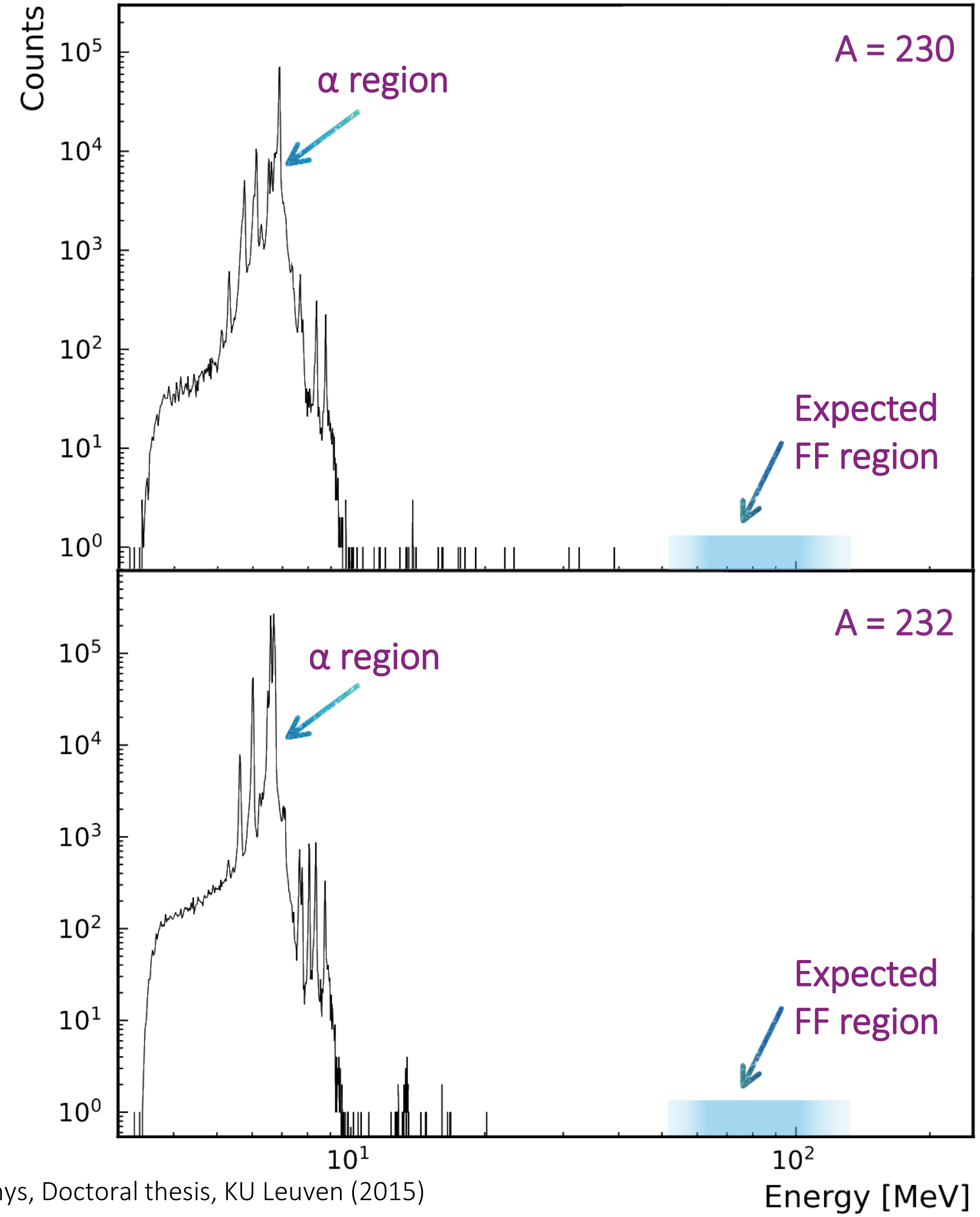
$T_{1/2}$ = 30 s, $T_{1/2}$ = 40 s, $T_{1/2}$ = 24.1 d

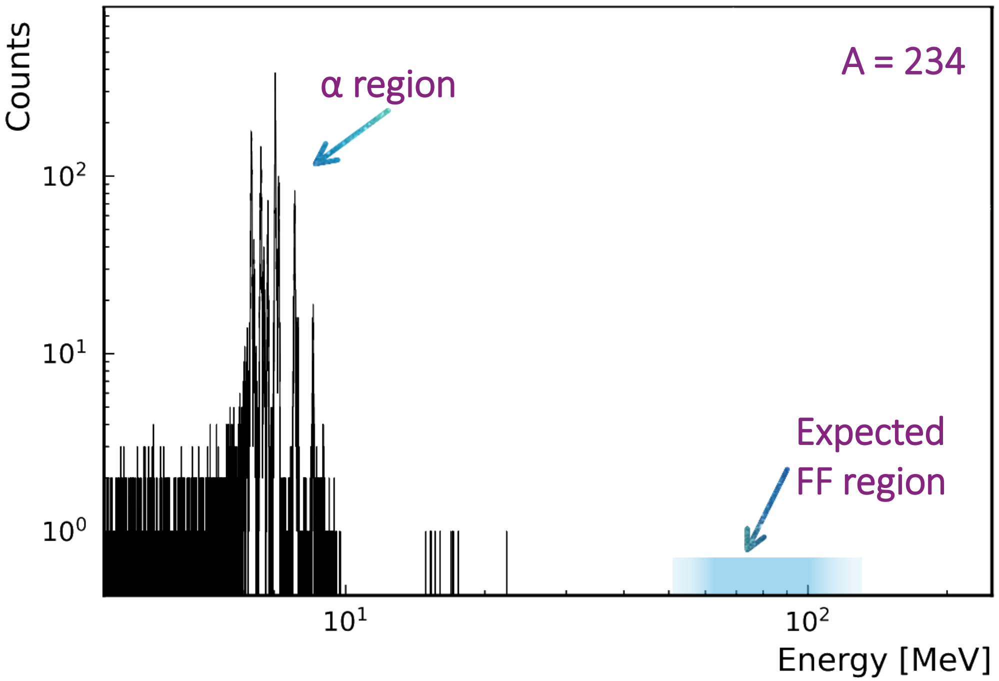






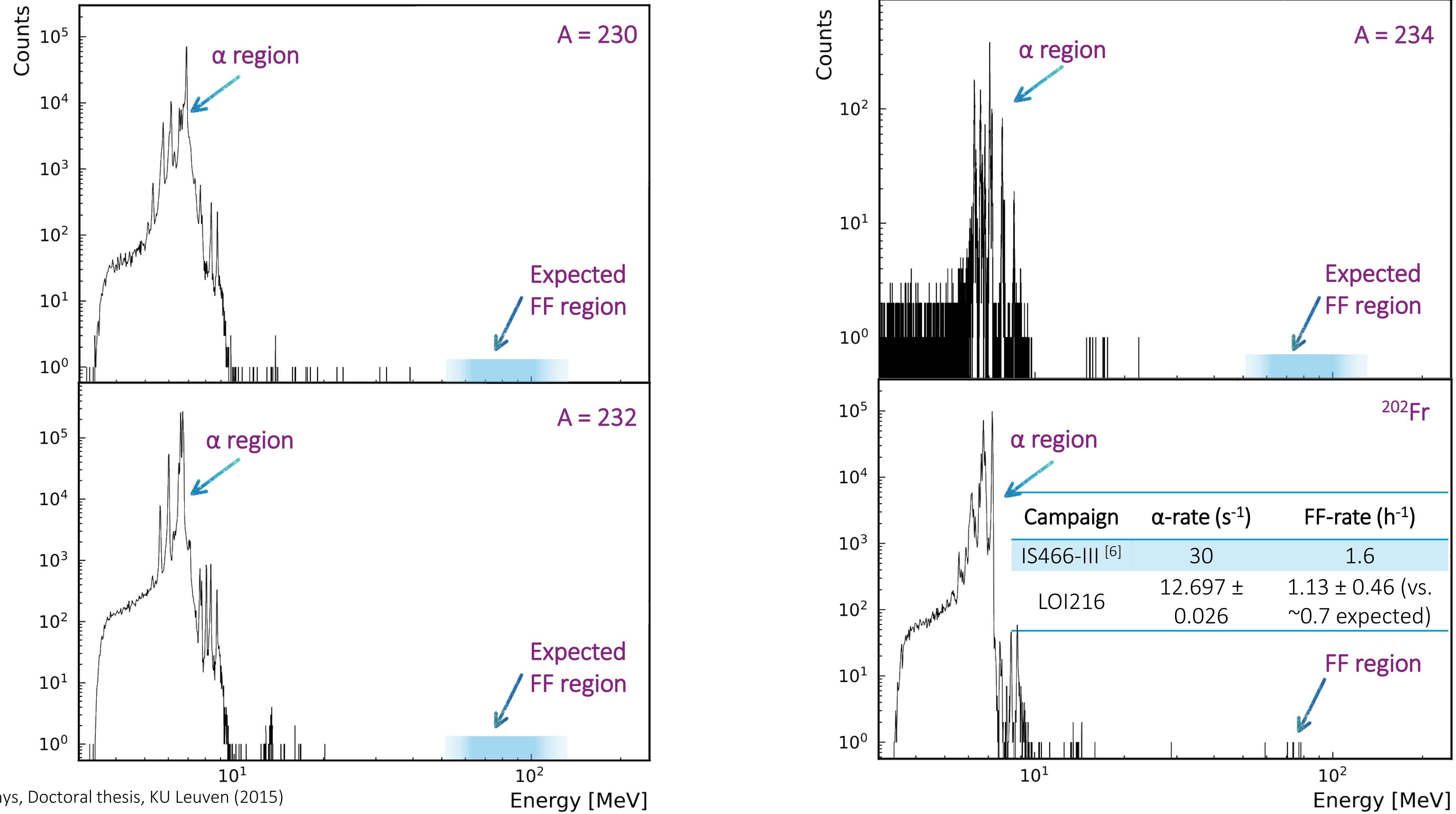
LOI216: βDF of ^{230,232,234}Ac





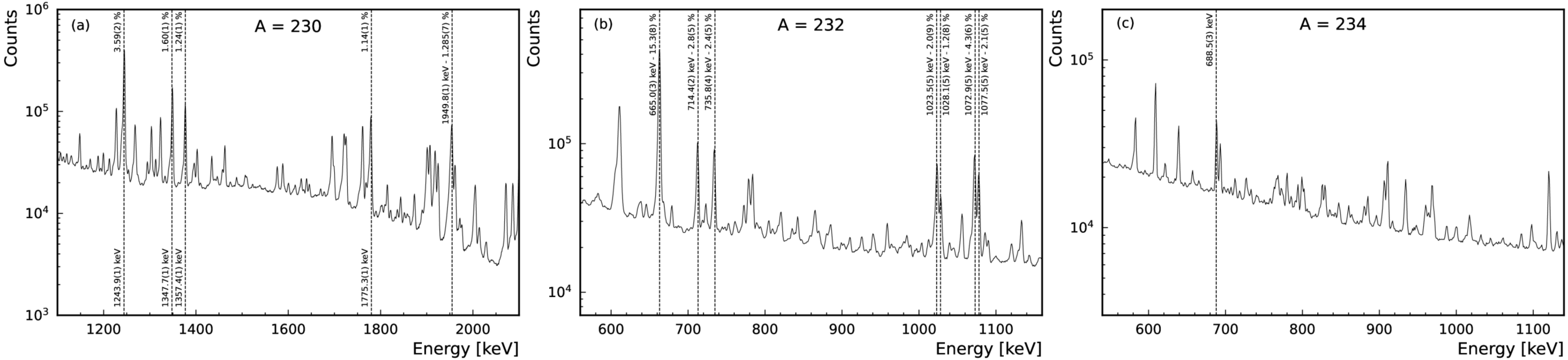
[6] L. Ghys, Doctoral thesis, KU Leuven (2015)

LOI216: βDF of $^{230,232,234}Ac$



Campaign	α-rate (s^{-1})	FF-rate (h^{-1})
IS466-III [6]	30	1.6
LOI216	12.697 ± 0.026	1.13 ± 0.46 (vs. ~0.7 expected)

[6] L. Ghys, Doctoral thesis, KU Leuven (2015)



$$P_{\beta DF} = \frac{1.84^{*}}{\frac{N_\gamma}{I_\gamma \cdot \varepsilon_\gamma} \cdot \varepsilon_{FF}}$$

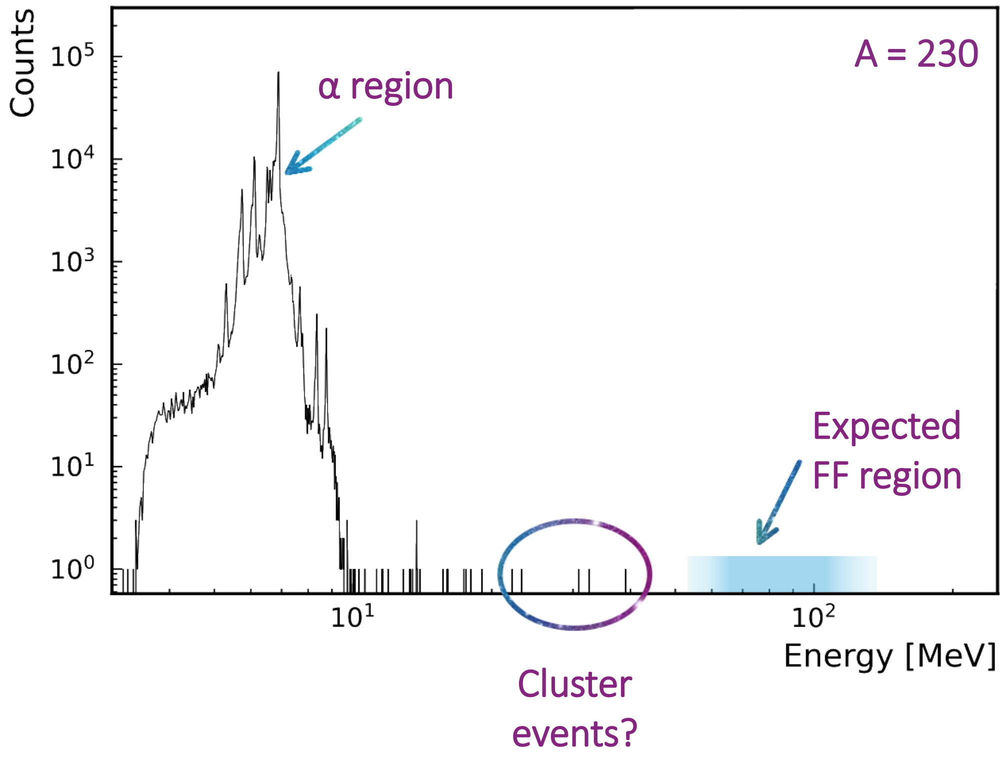
$$T_{1/2p,\beta DF} = \frac{T_{1/2}}{P_{\beta DF}}$$

* 1.84 is the upper limit of Poisson's distribution of 0 observed events with a confidence level of 84% [8]

Isotope	N_β	$P_{\beta DF}$			$T_{1/2p,\,\beta DF}$
		Lit.		This work [**]	
^{230}Fr	$1.4(1)\cdot10^{8}$	$< 3\cdot10^{-6}$	[7]	$< 3.3\cdot10^{-8}$	$> 5.8\cdot10^{8}$
^{232}Fr	$4.3(10)\cdot10^{7}$	$< 2\cdot10^{-6}$	[7]	$< 1.3\cdot10^{-7}$	$> 4.2\cdot10^{7}$
^{230}Ac	$1.02(4)\cdot10^{10}$	$1.19(40)\cdot10^{-8}$	[4]	$< 4.3\cdot10^{-10}$	$> 2.8\cdot10^{11}$
^{232}Ac	$1.50(8)\cdot10^{9}$	$< 10^{-6}$	[7]	$< 2.7\cdot10^{-9}$	$> 4.4\cdot10^{10}$
^{234}Ac	$8.4(29)\cdot10^{6}$	/		$< 4.9\cdot10^{-6}$	$> 9.0\cdot10^{6}$

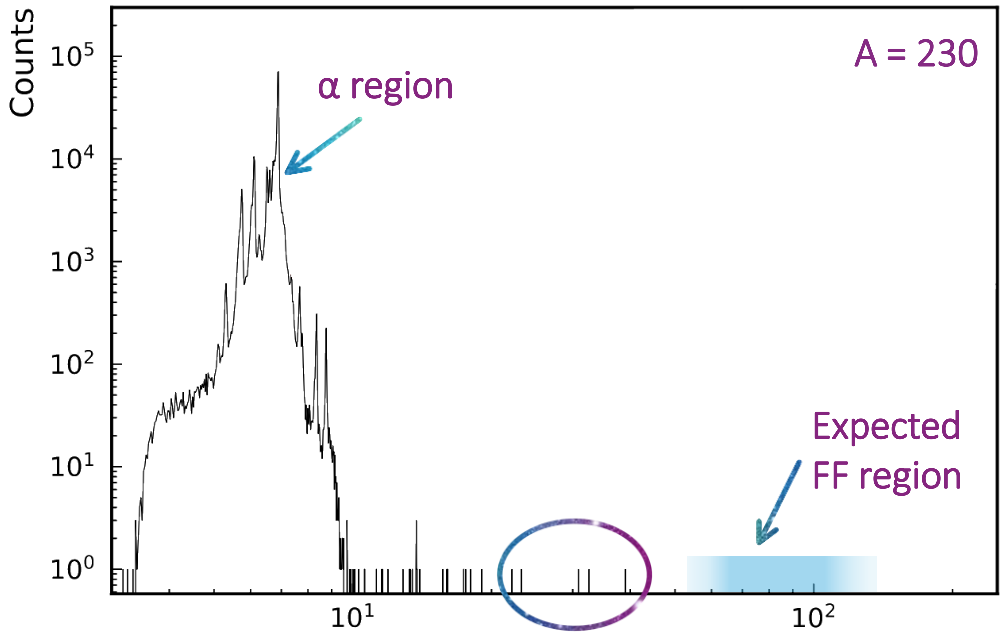
[4] Y. Shuanggui *et al.*, Eur. Phy. J. A 10, 1-3 (2001).
[7] K. A. Mezilev *et al.*, Zeitschrift für Physik A Atomic Nuclei 337, 109 (1990).
[8] K.-H. Schmidt et al., Z. Phys. A – Atoms and Nuclei 316, 19-26 (1984).
[**] S. Bara *et al.*, Phys. Rev. C, submitted (2025)

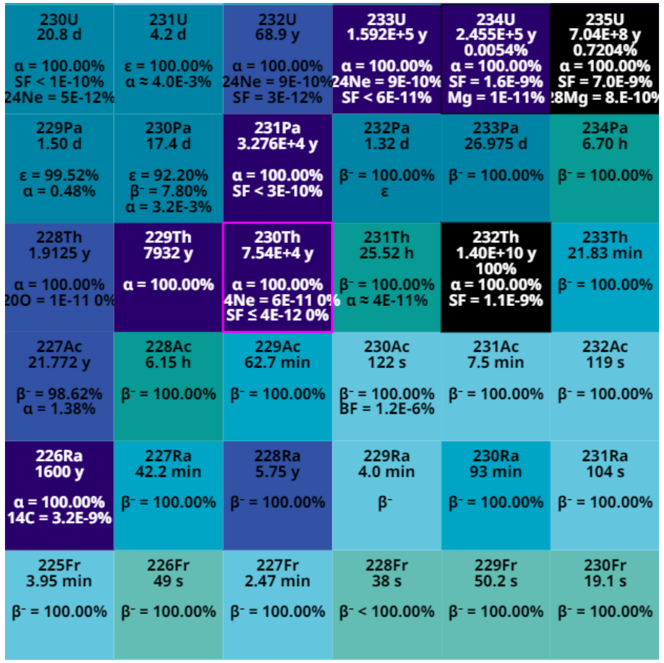
LOI216: βDF of ^{230,232,234}Ac



230U 20.8 d α = 100.00% SF < 1E-10% 24Ne = 5E-12%	231U 4.2 d ε = 100.00% α ≈ 4.0E-3%	232U 68.9 y α = 100.00% 24Ne = 9E-10% SF = 3E-12%	233U 1.592E+5 y α = 100.00% 24Ne = 9E-10% SF < 6E-11%	234U 2.455E+5 y 0.0054% α = 100.00% SF = 1.6E-9% Mg = 1E-11%	235U 7.04E+8 y 0.7204% α = 100.00% SF = 7.0E-9% 8Mg = 8.E-10
229Pa 1.50 d ε = 99.52% α = 0.48%	230Pa 17.4 d ε = 92.20% β^- = 7.80% α = 3.2E-3%	231Pa 3.276E+4 y α = 100.00% SF < 3E-10%	232Pa 1.32 d β^- = 100.00% ε	233Pa 26.975 d β^- = 100.00%	234Pa 6.70 h β^- = 100.00%
228Th 1.9125 y α = 100.00% 20O = 1E-11 0%	229Th 7932 y α = 100.00%	230Th 7.54E+4 y α = 100.00% 4Ne = 6E-11 0% SF ≤ 4E-12 0%	231Th 25.52 h β^- = 100.00% α ≈ 4E-11%	232Th 1.40E+10 y 100% α = 100.00% SF = 1.1E-9%	233Th 21.83 min β^- = 100.00%
227Ac 21.772 y β^- = 98.62% α = 1.38%	228Ac 6.15 h β^- = 100.00%	229Ac 62.7 min β^- = 100.00%	230Ac 122 s β^- = 100.00% BF = 1.2E-6%	231Ac 7.5 min β^- = 100.00%	232Ac 119 s β^- = 100.00%
226Ra 1600 y α = 100.00% 14C = 3.2E-9%	227Ra 42.2 min β^- = 100.00%	228Ra 5.75 y β^- = 100.00%	229Ra 4.0 min β^-	230Ra 93 min β^- = 100.00%	231Ra 104 s β^- = 100.00%
225Fr 3.95 min β^- = 100.00%	226Fr 49 s β^- = 100.00%	227Fr 2.47 min β^- = 100.00%	228Fr 38 s β^- < 100.00%	229Fr 50.2 s β^- = 100.00%	230Fr 19.1 s β^- = 100.00%

LOI216: βDF of $^{230,232,234}Ac$





- BR ≈ $4.1(4)\cdot 10^{-11}$
- Cluster: ^{22}O from ^{230}Ra

Tentative!

Work of Natalia Thomas

Silvia Bara

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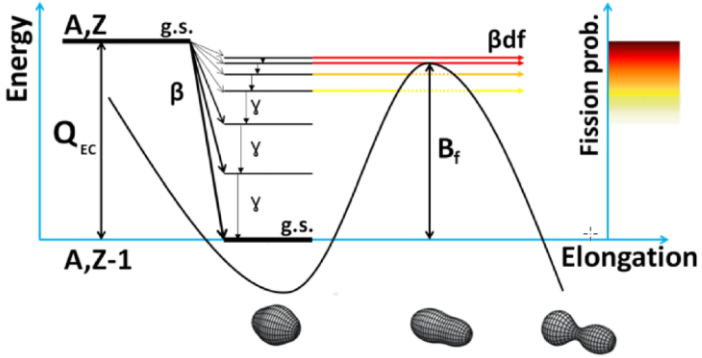
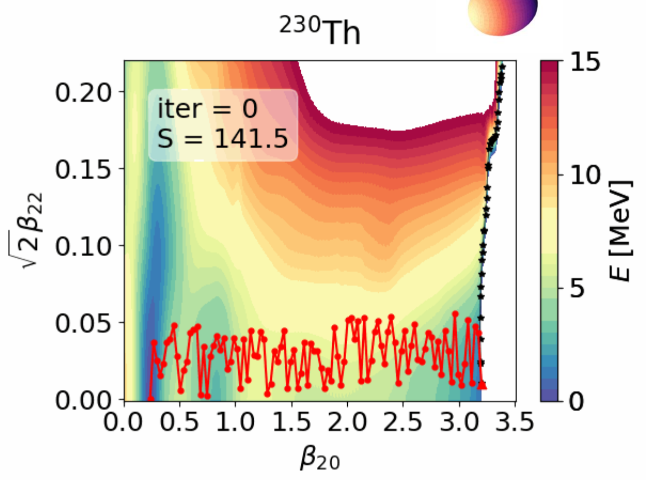
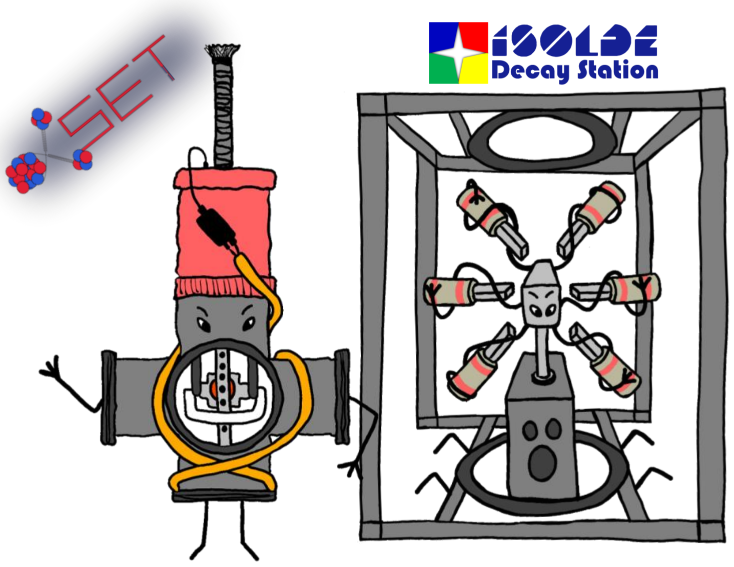
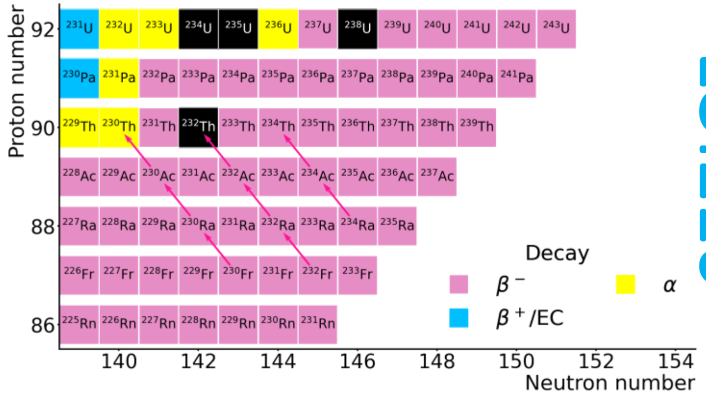


βDF with PyNeb

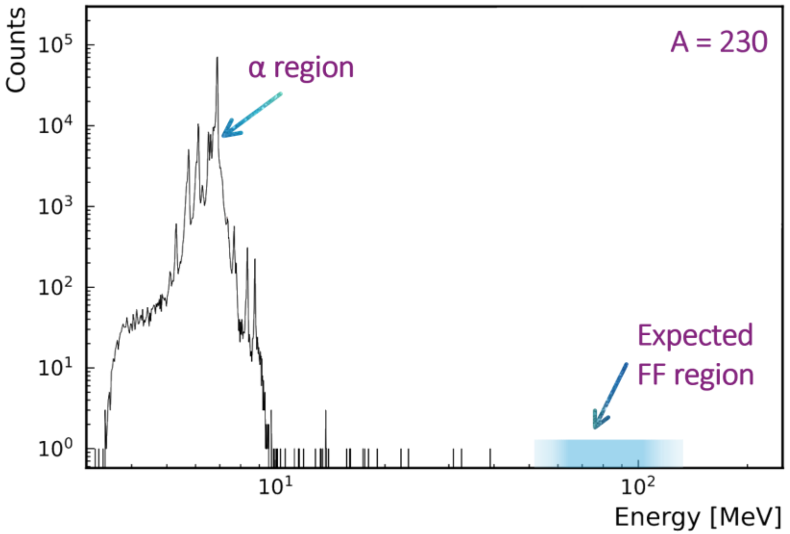






LOI216

Results

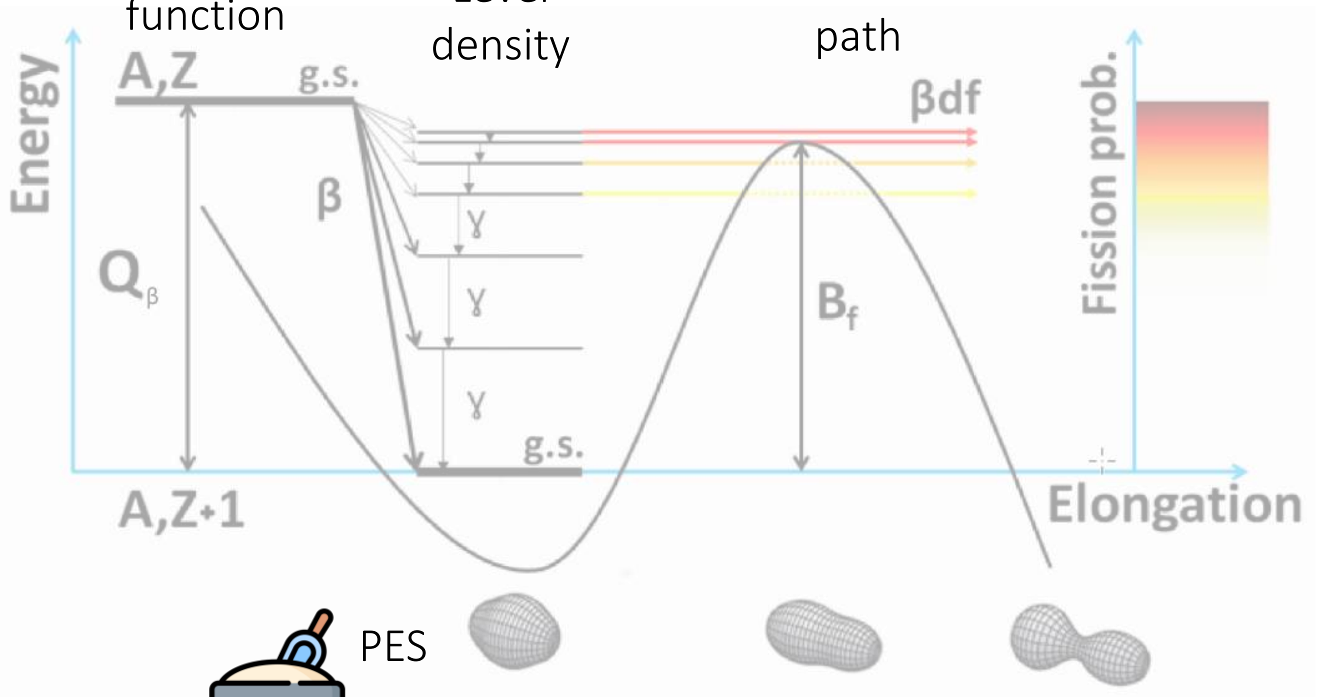


The recipe

β-strength function

Level density

Fission path



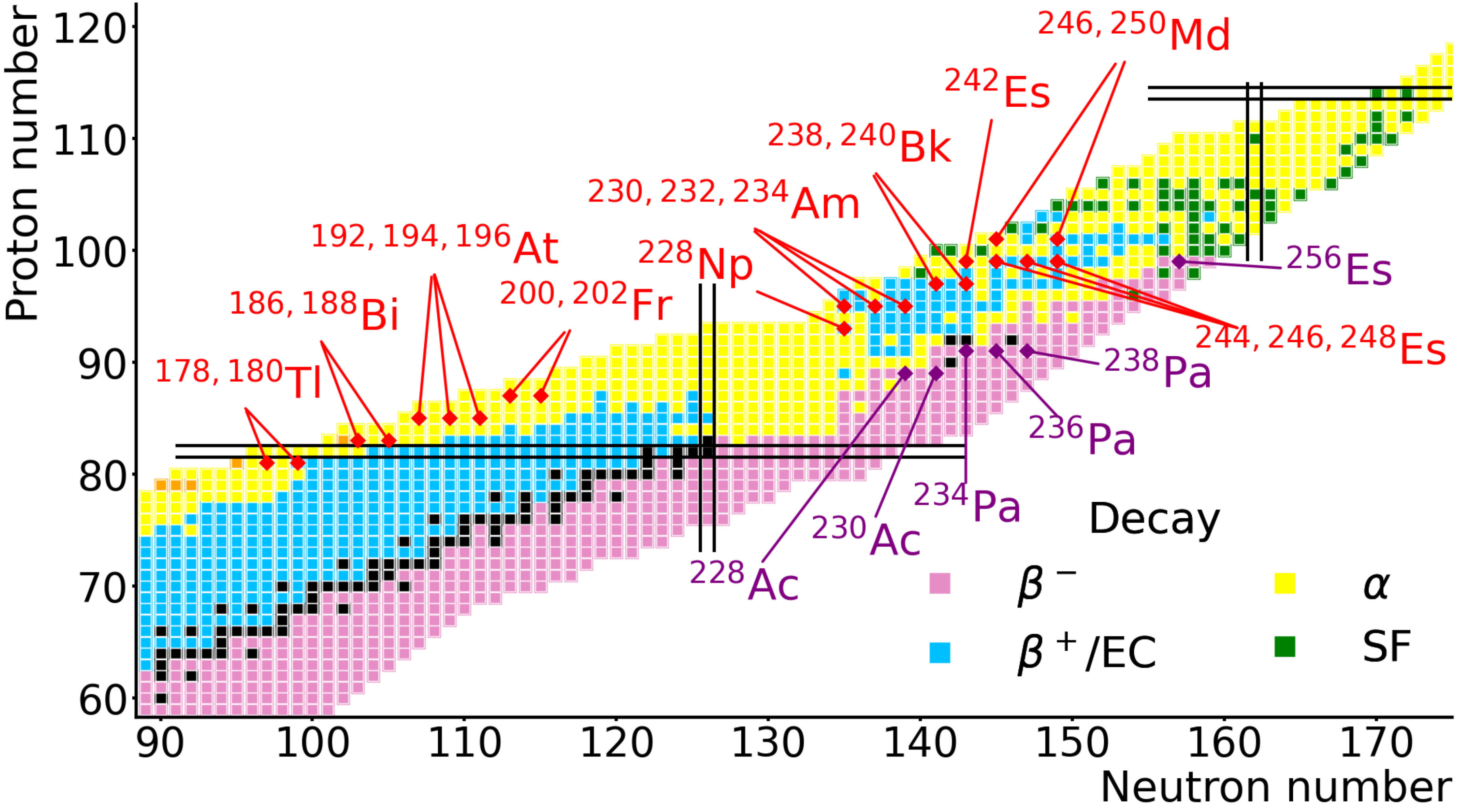
PES

TALYS

$P_{\beta DF}$

The recipe

$P_{\beta DF}$

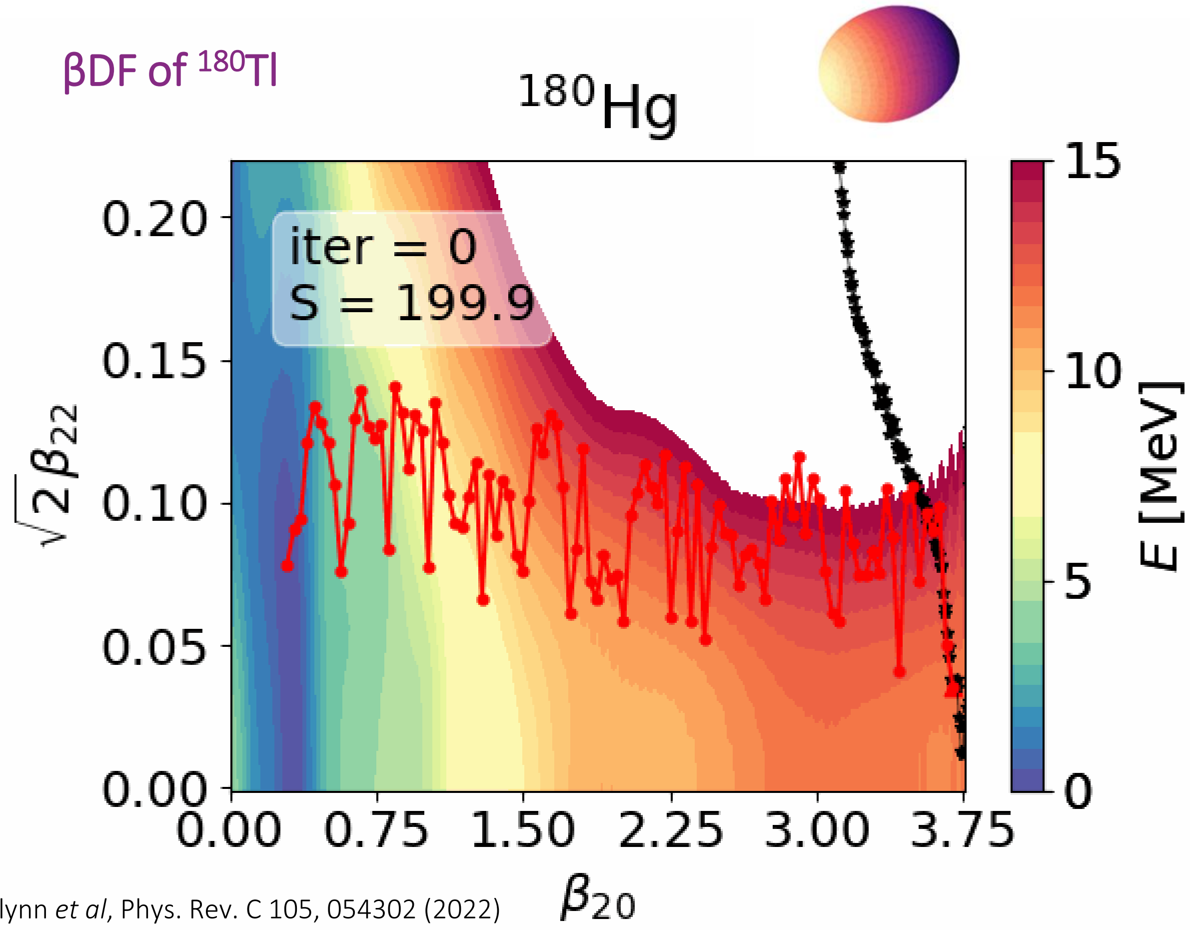


Fission path with PyNEB

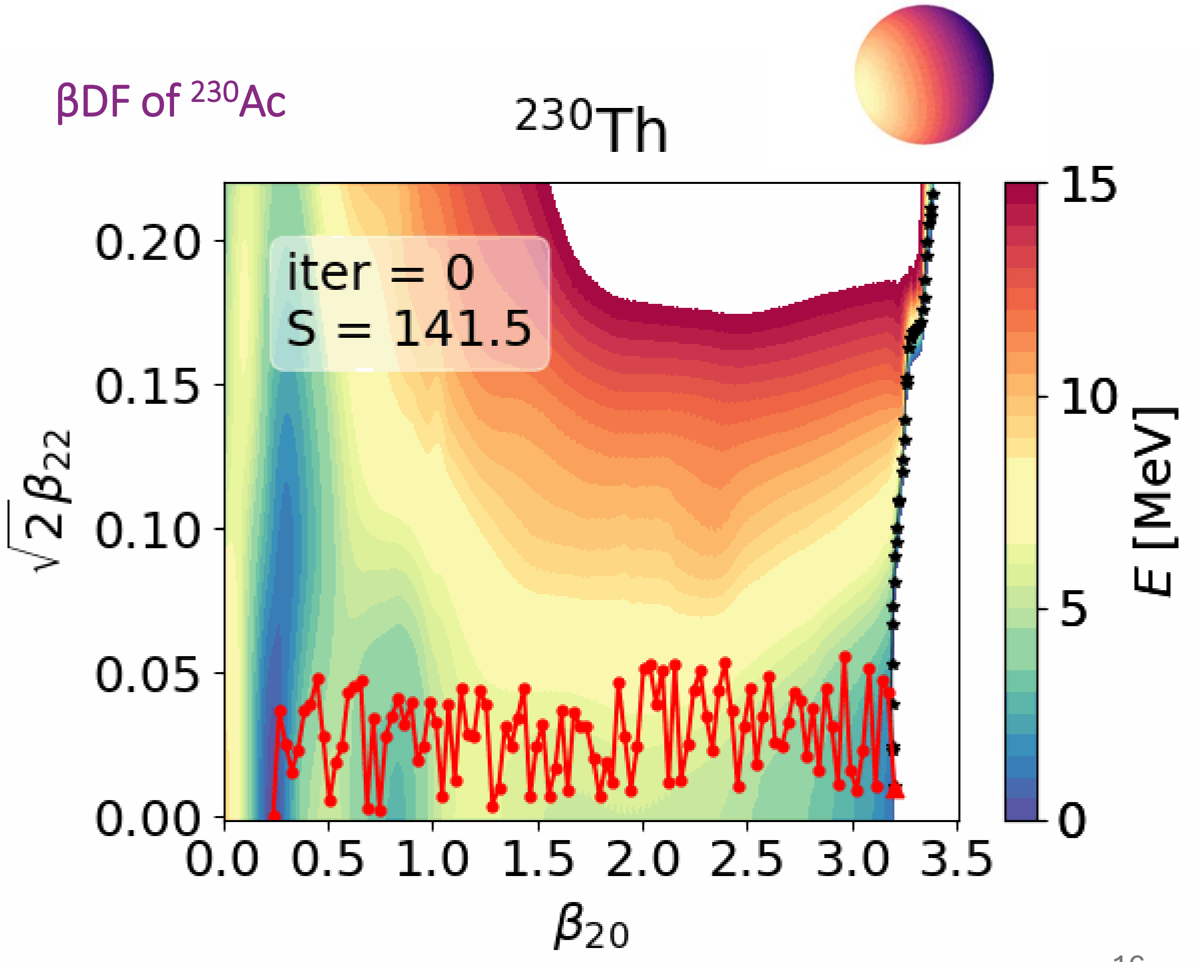
Python **N**udged **E**lastic **B**and, **PyNEB**, on PES calculated with **BSkG3**.

- LAP = Least Action Path
- MEP = Minimum (least) Energy Path

βDF of ^{180}Tl



βDF of ^{230}Ac

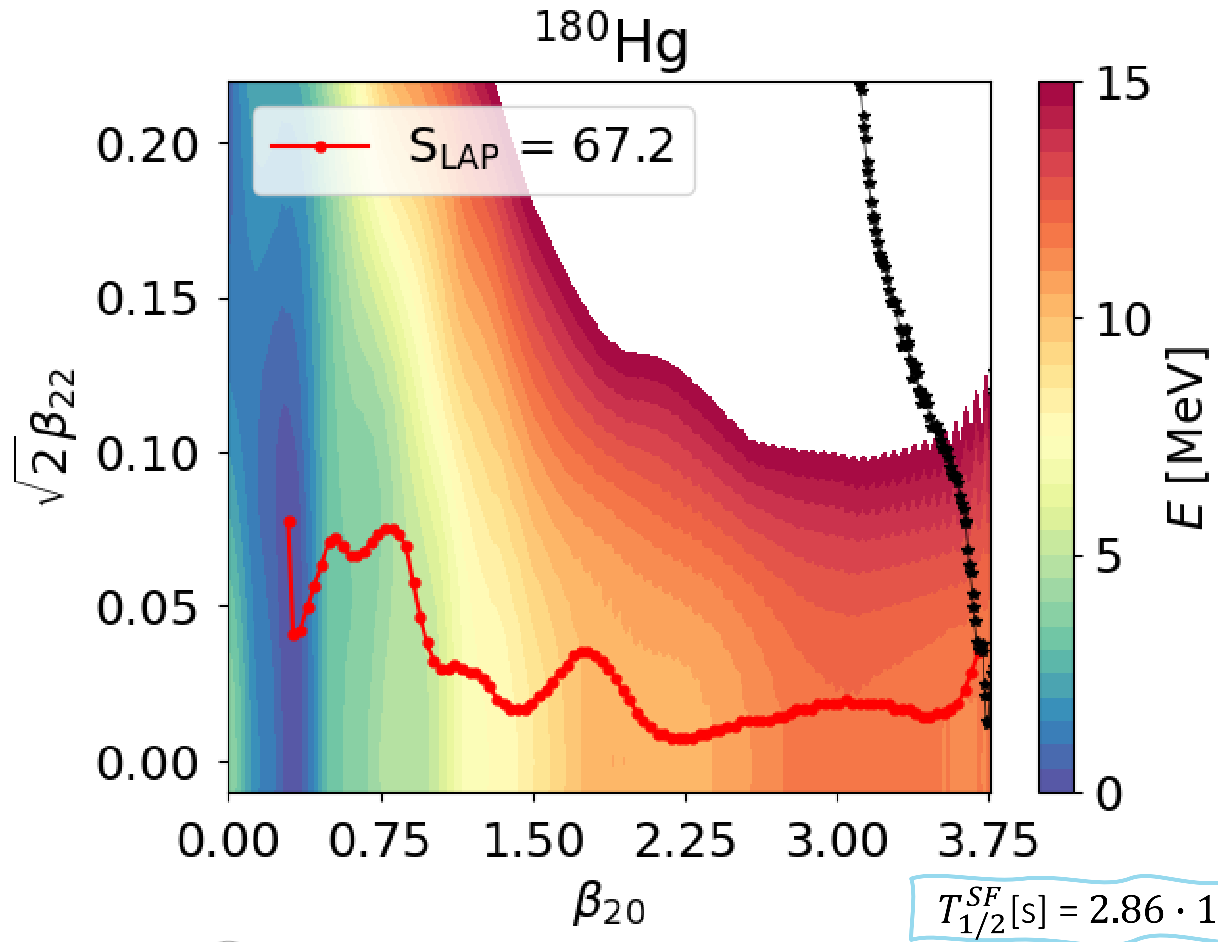


[9] E. Flynn *et al*, Phys. Rev. C 105, 054302 (2022)
[10] G. Grams *et al*, Eur. Phys. J. A 59, 270 (2023).

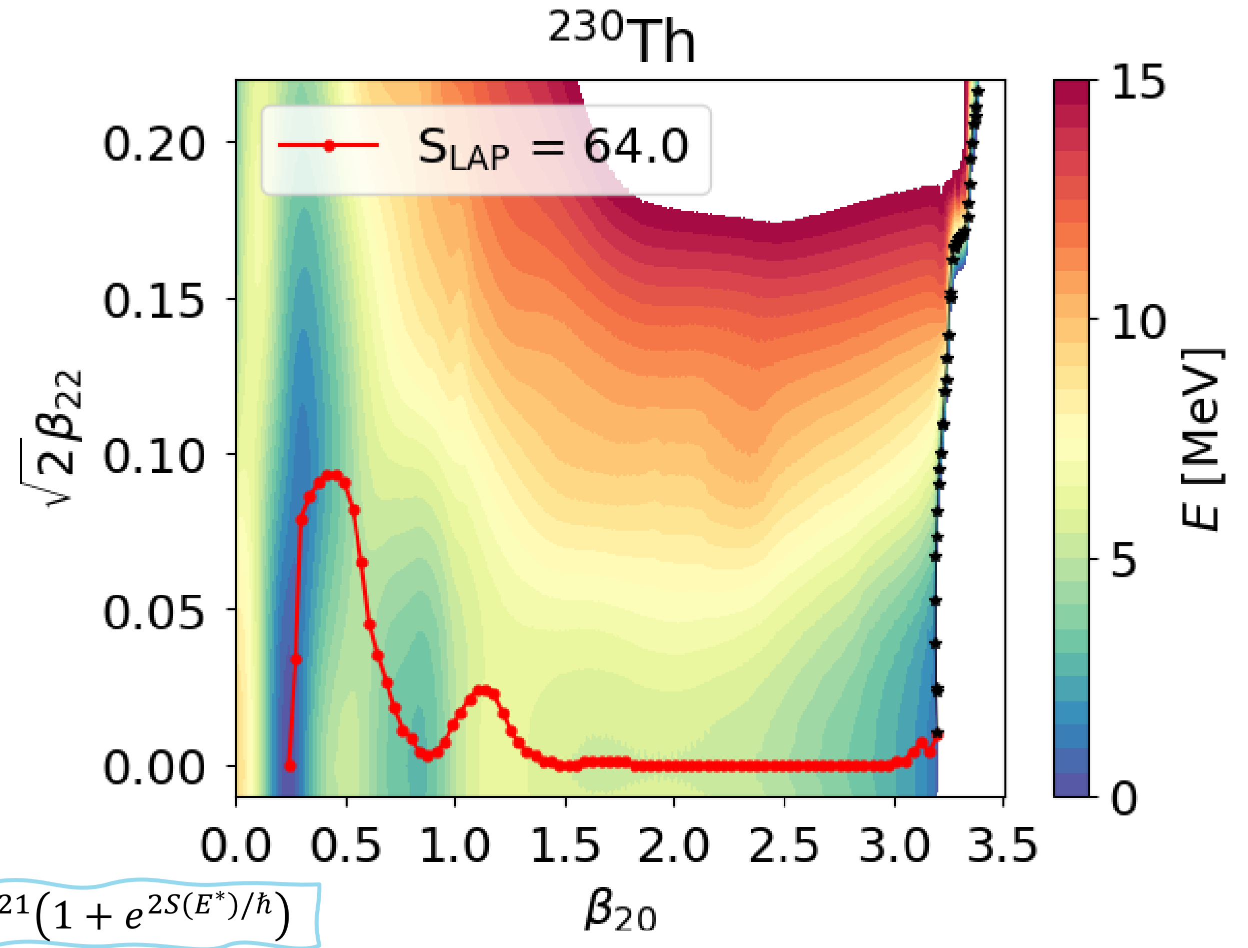
Shape plots thanks to W. Ryssens.

Fission path with PyNeb

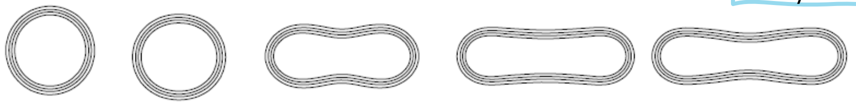
βDF of ^{180}Tl

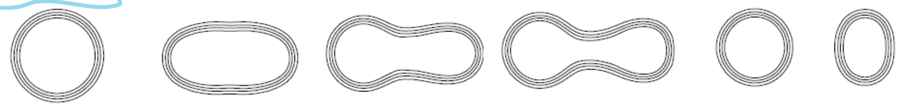


βDF of ^{230}Ac



$$T_{1/2}^{SF}[\mathrm{s}] = 2.86 \cdot 10^{-21}\left(1 + e^{2S(E^*)/\hbar}\right)$$

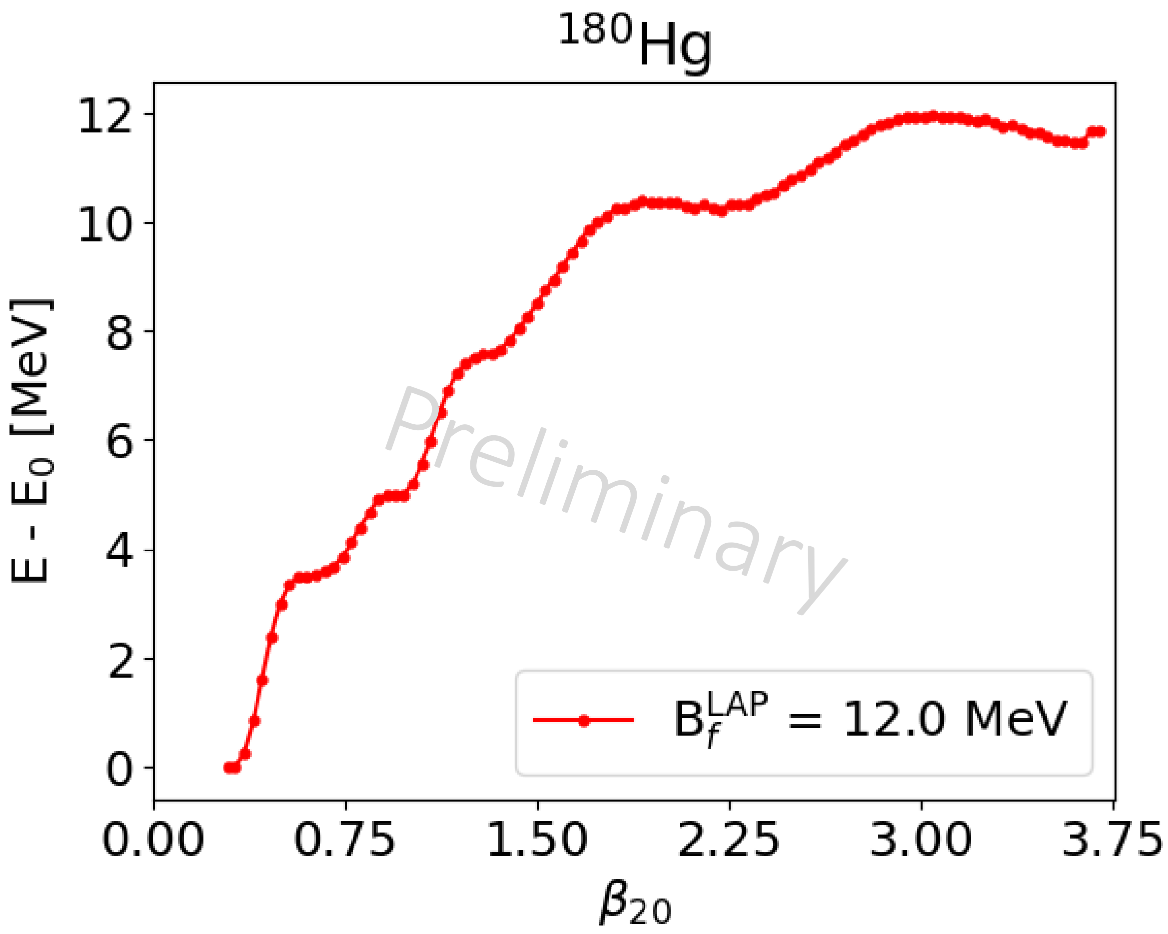


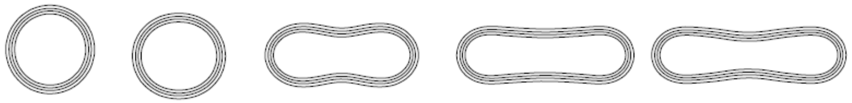


[9] E. Flynn *et al*, Phys. Rev. C 105, 054302 (2022)
[12] J. Lemaître *et al*, Phys. Rev. C 98, 024623 (2018)
Shape plots thanks to W. Ryssens.

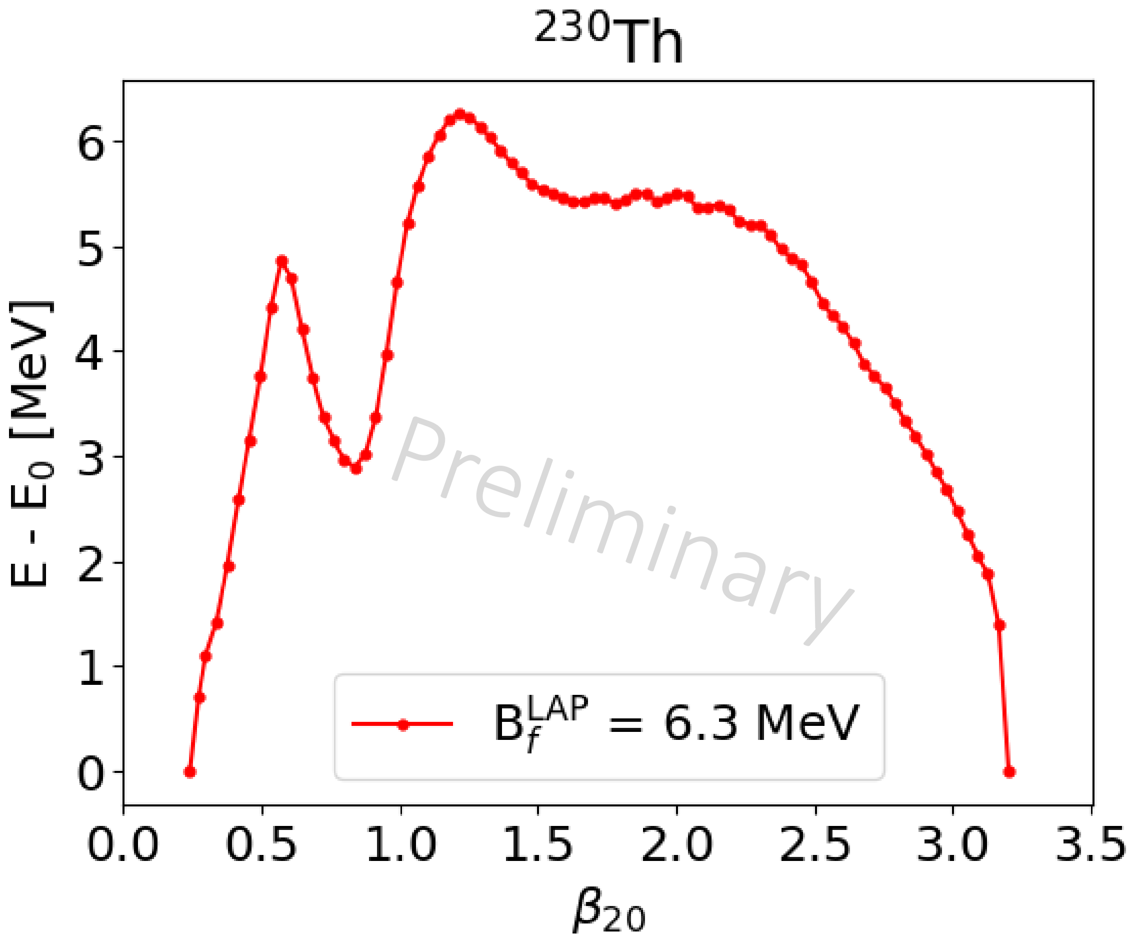
Fission path with PyNeb

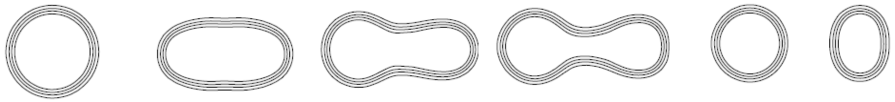
βDF of ^{180}Tl





βDF of ^{230}Ac

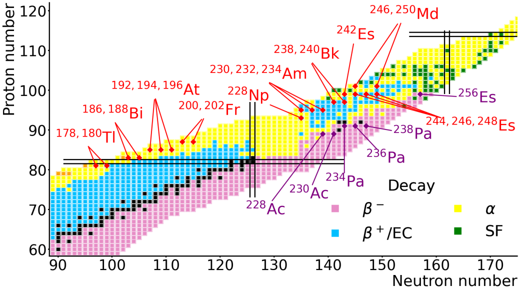


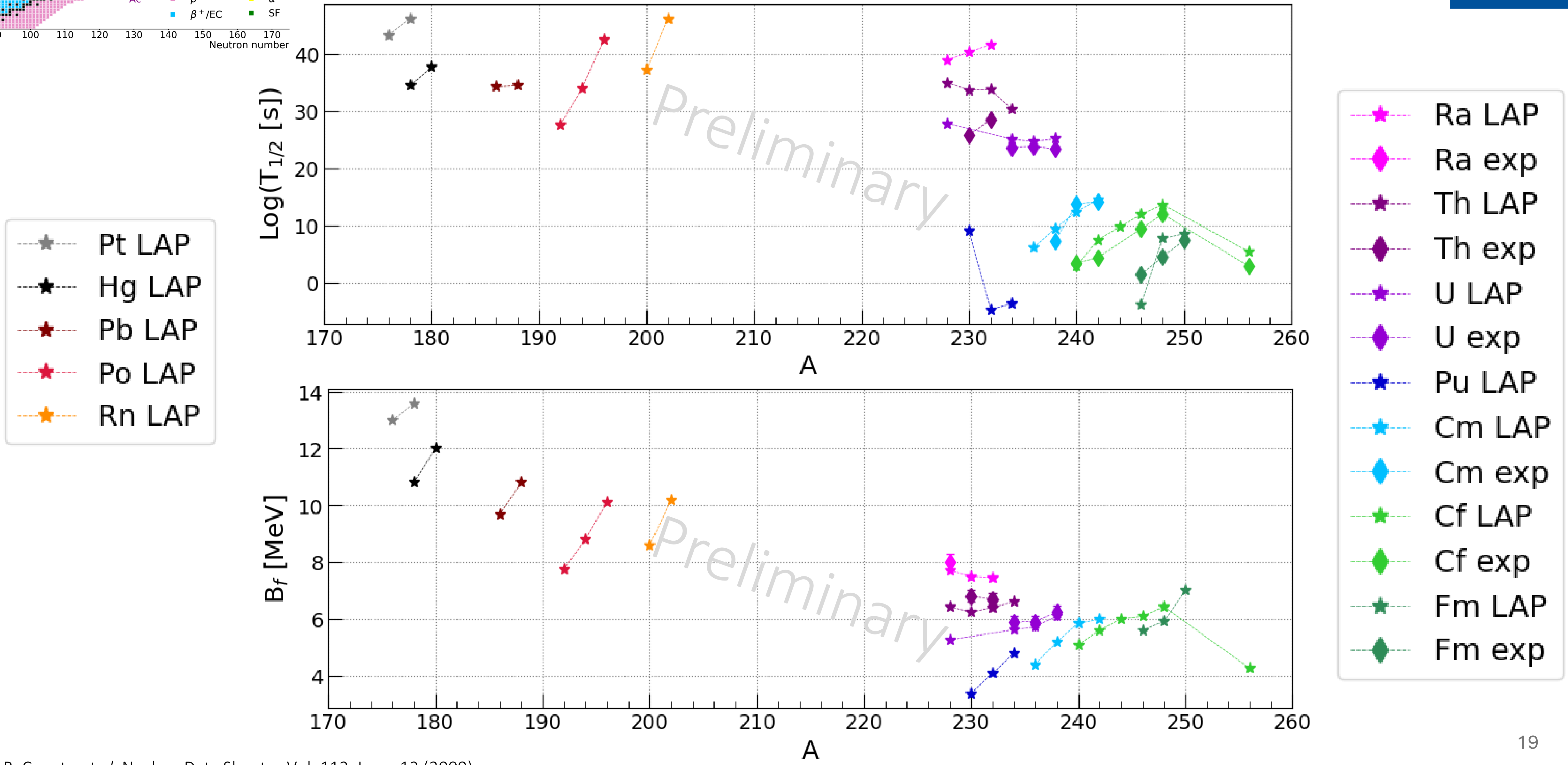


[9] E. Flynn *et al*, Phys. Rev. C 105, 054302 (2022)
Shape plots thanks to W. Ryssens.

Fission path with pyNeb

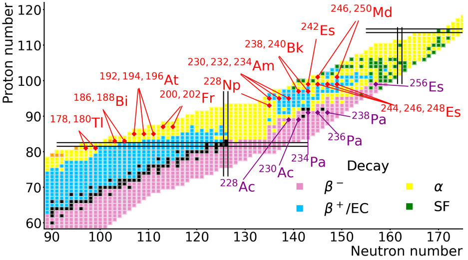
ULB

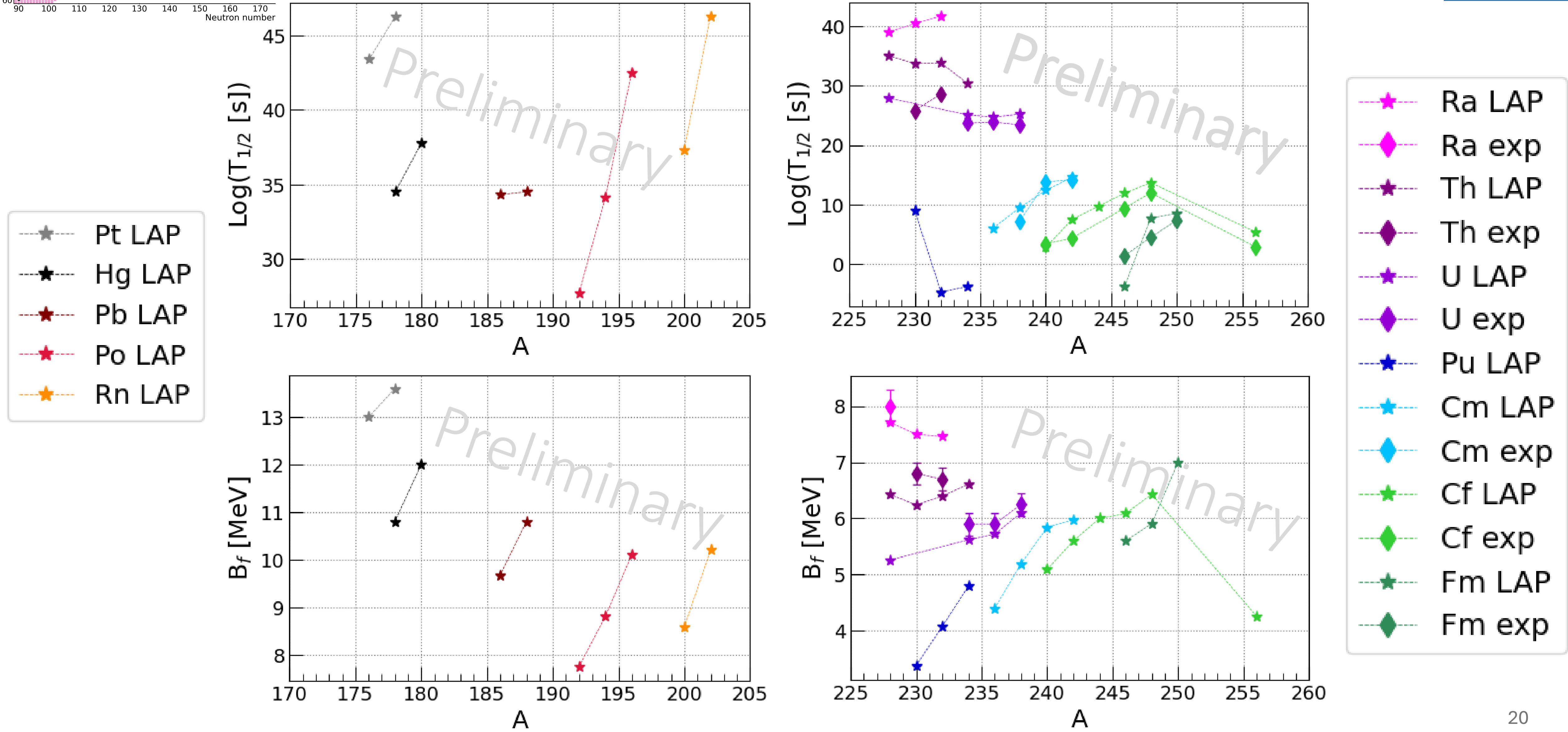




[13] R. Capote *et al*, Nuclear Data Sheets., Vol. 112, Issue 12 (2009)

Fission path with PyNeb





[13] R. Capote *et al*, Nuclear Data Sheets., Vol. 112, Issue 12 (2009)

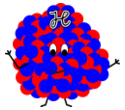
Conclusions & Outlook

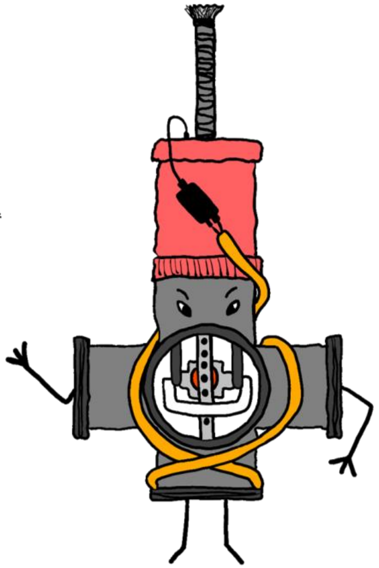
Conclusions

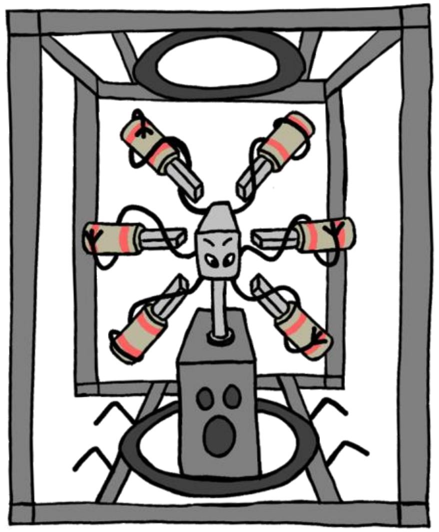
- Determination of new upper limits for the βDF probabilities of $^{230,232,234}Ac$ and $^{230,232}Fr$ with particular focus on the ^{230}Ac one that turned out to be two orders of magnitude lower than the value in literature.
- Observation of events that might hint at cluster emission at mass A = 230.
- Development of a theoretical procedure to calculate βDF probabilities.

Outlook

- Calculate βDF probabilities for previously studied cases and compare with experimental results.







Thank you for the attention

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