DE LA RECHERCHE À L'INDUSTRIE

cea den

Energy dependence of Delayed-Neutron Data

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DEN/CAD/DER/SPRC/LEPh

Aix*Marseille université

WONDER 2018

October 9th, 2018

OUTLINE:

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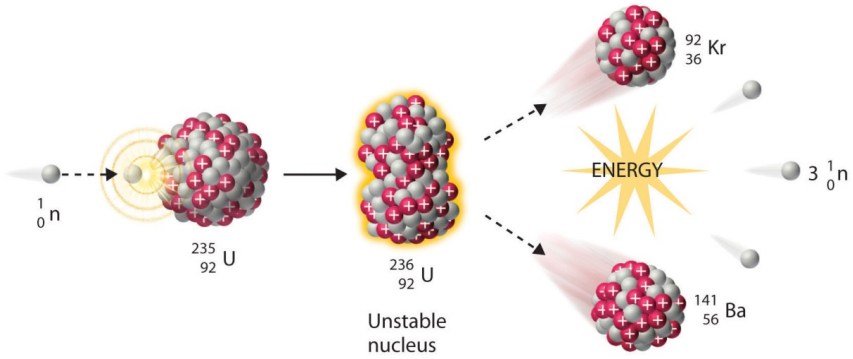
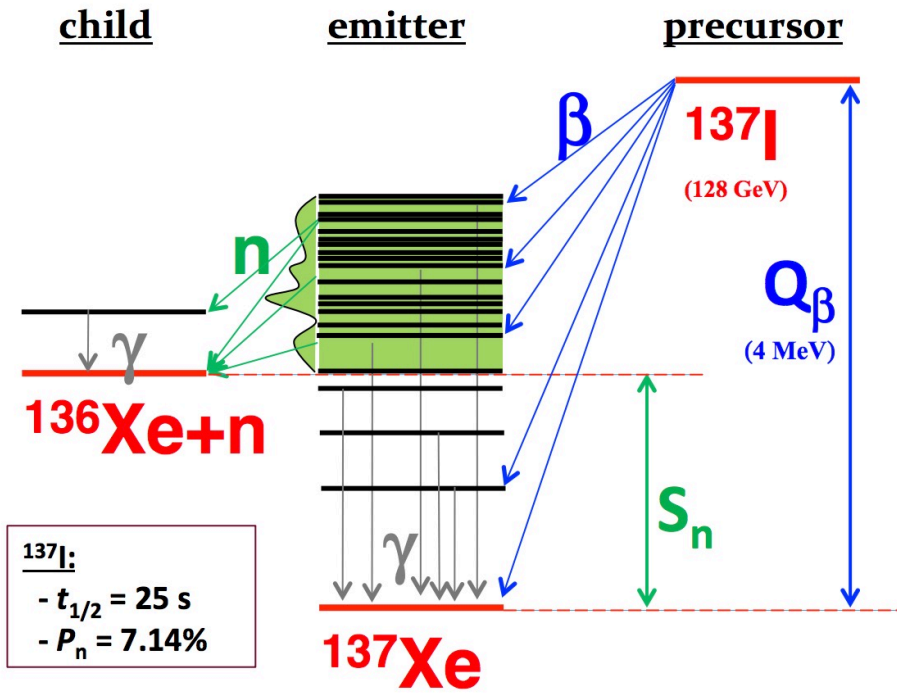
- Context
- State of the art
- Alternative method
- Results: ν_d
- Results: a_i, $\langle T_{1/2} \rangle$
- Conclusions
- Open questions

Context
Physics of Delayed Neutrons



Delayed neutrons are emitted by β^- - decay of fission fragments

The neutron emission (from the ***emitter***) is almost instantaneous. The delay in the appearence of the **delayed neutron** is therefore linked to the half-life of the ***precursor***!



$$\rho = \frac{\Lambda}{T} + \beta_{eff} \sum_i \frac{a_i}{1 + \lambda_I T} \approx \beta_{eff} \frac{\overline{T_{1/2}}}{T}$$

$$\beta_{eff} = \frac{\sum_k \int_0^\infty \Phi^+(E')\, \chi_{d,k}(E') dE' \int_0^\infty \nu_{d,k}(E) \Sigma_{f,k}(E) dE}{\sum_k \int_0^\infty \Phi^+(E')\, \chi_{t,k}(E') dE' \int_0^\infty \nu_{t,k}(E) \Sigma_{f,k}(E) dE}$$

$$\overline{T_{1/2}} = \sum_i \frac{a_i}{\lambda_i}$$

Quantities of interest:

- Average DN yield $\nu_{d,k}(E)$
- DN group kinetic parameters $a_i\,(E)\ \lambda_i$
- DN specra $\chi_{d,k}(E')$

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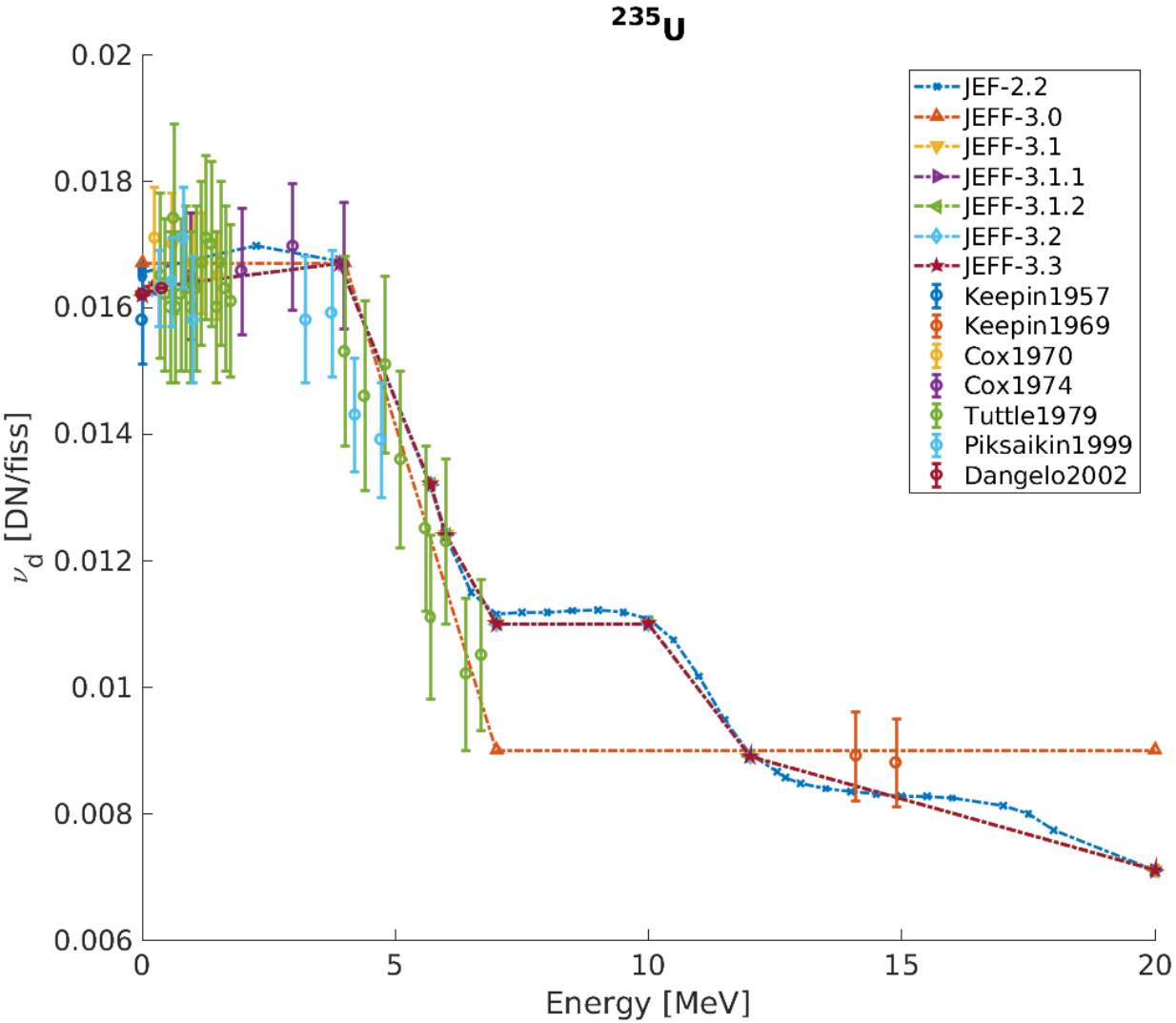
State of the art
JEFF evaluated library



State of the art
from JEF-2 …

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JEF2        LIBRARY, DUMMY TAPE HEADER
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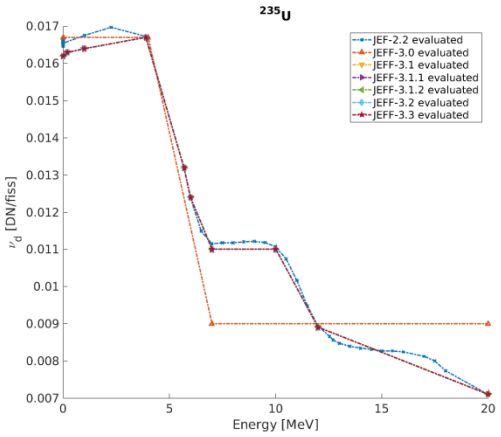


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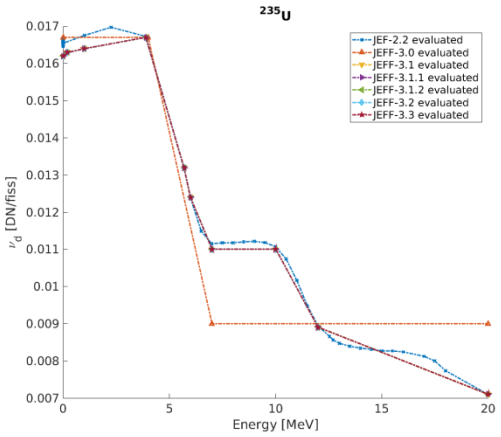
MF=1
MT=452 NU.  SYSTEMATICS. (REF. 5)
MT=458 ENERGY OF FISSION.  SYSTEMATICS OF SHER (REF. 6)
```

→ No info about MT=455

In producing the JEF-2.2 evaluations for ^{235}U and ^{239}Pu Fort and Long (1989) calculated the energy dependence using the theoretical model of Lendel *et al* (1986).

A. D'angelo and J. Rowlands Conclusions concerning the delayed neutron data for the major actinides (2002)

State of the art
… to JEFF-3.1.2



JEF2 LIBRARY, DUMMY TAPE HEADER

JEFF-3.0 file header. Release April 2002

JEFF-3.1 General Purpose Neutron File, May 2005.

JEFF-3.1.1 general purpose neutron file update release Jan. 2009

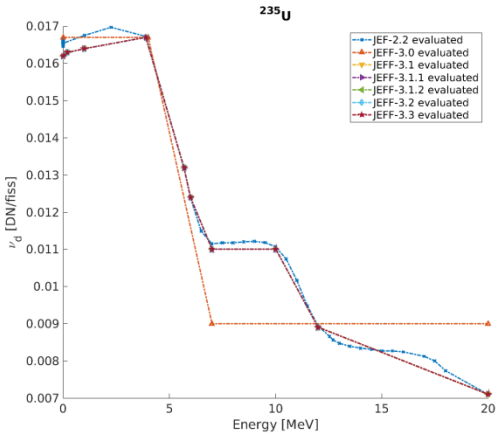
JEFF-3.1.2 general purpose neutron file update released Oct.2011

MF=1
MT=452 NU. SYSTEMATICS. (REF. 5)
MT=458 ENERGY OF FISSION. SYSTEMATICS OF SHER (REF. 6)

File 1 Descriptive and Nubar Information
MT=455 Delayed neutron yields from England [EN89] ★

★ [En89] T.R. England et al, Los Alamos National Laboratory reports: LA-11151-MS(88)
LA-11534T(89)
LAUR-88-4118 to be published in Nucl.Sci.Eng. (1989)

State of the art
Recursive reference



JEF2 LIBRARY, DUMMY TAPE HEADER

JEFF-3.0 file header. Release April 2002

JEFF-3.1 General Purpose Neutron File, May 2005.

JEFF-3.1.1 general purpose neutron file update release Jan. 2009

JEFF-3.1.2 general purpose neutron file update released Oct.2011

JEFF-3.2 Release - Neutron File March 2014

JEFF-3.3 Incident Neutron File

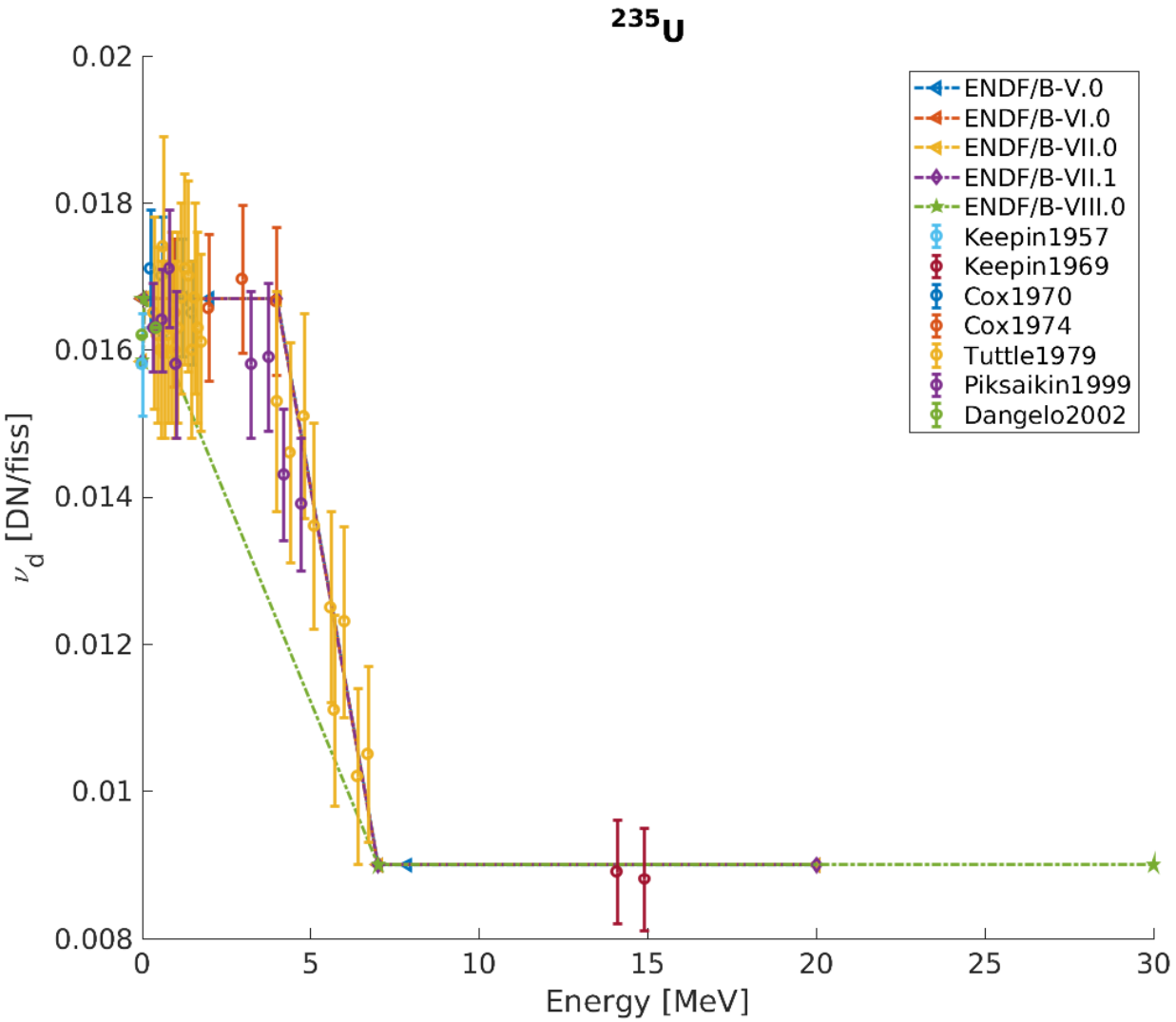
MF=1
MT=452 NU. SYSTEMATICS. (REF. 5)
MT=458 ENERGY OF FISSION. SYSTEMATICS OF SHER (REF. 6)

File 1 Descriptive and Nubar Information
MT=455 Delayed neutron yields from England [EN89]

MF=1 General Information
MT=455 Delayed Neutron Yields : JEFF-3.1

MF 1 MT 452,455: restoring delayed neutron data from JEFF-311
total is modifed accordinly (CEA/DEN)

State of the art
ENDF/B evaluated library



State of the art
Need for a change

Can't we do better than recycling over and over again the same data?

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• Results: ν_d

• Results: a_i, $\langle T_{1/2} \rangle$

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Alternative method
Summation calculations

There is another way to compute macroscopic quantities:

Summation Calculations

Average DN yield

$$\nu_d = \sum_i^N CY_i \cdot P_{n,i} \cdot x_i$$

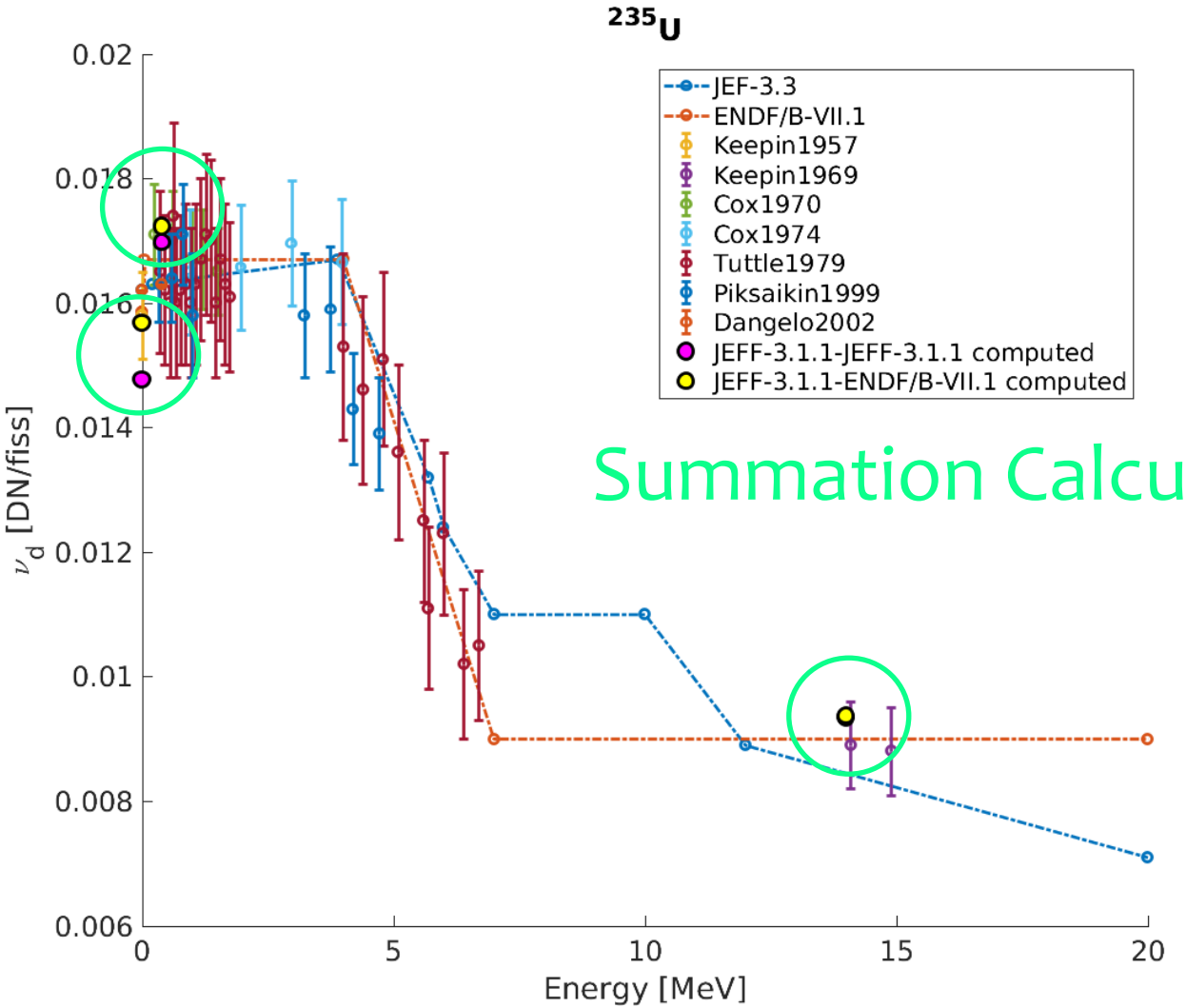
Kinetic Parameters

$$\frac{n_d(t)}{n_d(t_\infty)} - \sum_{i=1}^{8} \left(1 - \sum_{\substack{j=1 \\ j \neq i}}^{8} a_j \right) \left(1 - e^{-\lambda_i t_{irr}}\right) e^{-\lambda_i (t - t_{irr})} = 0$$

Mean precursors' half-life

$$\overline{T_{1/2}} = \frac{\sum_i^8 a_i \cdot T_{1/2,i}}{\sum_i^8 a_i}$$

Alternative method
Summation calculations – 3 points only



Use GEF to compute JEFF

The idea is to apply the GEF energy dependence to JEFF

$$FY_{JEFF}(E) = \frac{FY_{GEF}(E)}{FY_{GEF}(E_{ref})} FY_{JEFF}(E_{ref})$$

Fissioning System	E_{ref}
235U, 239Pu	0,0253 eV
238U	400 keV

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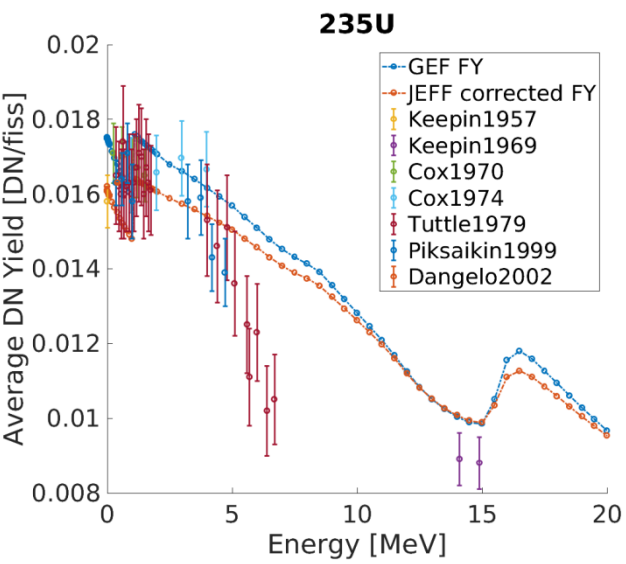
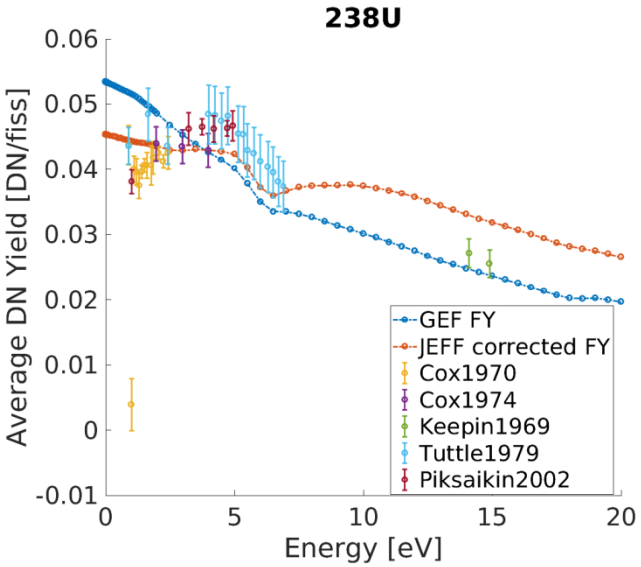
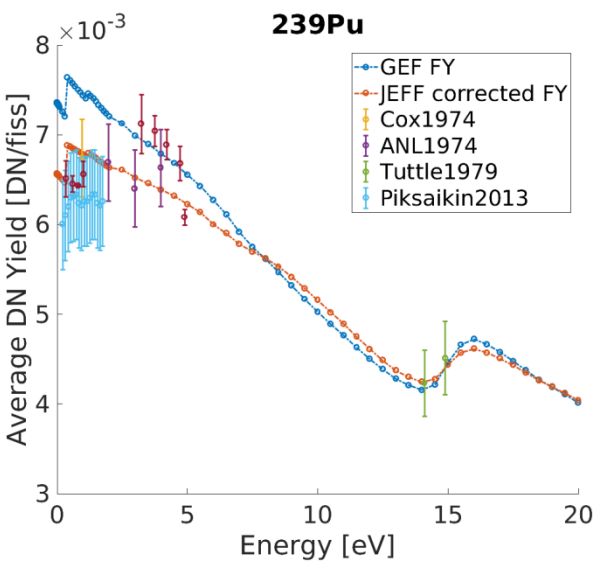
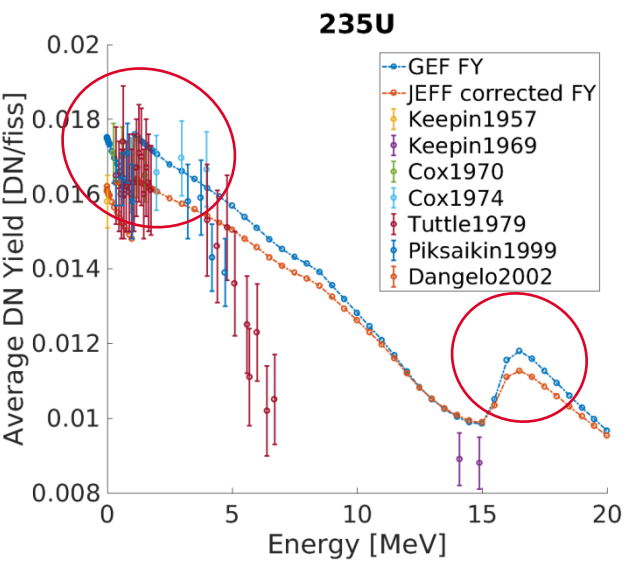
Results: ν_d
GEF-6.1 versus the « corrected » JEFF-3.1.1

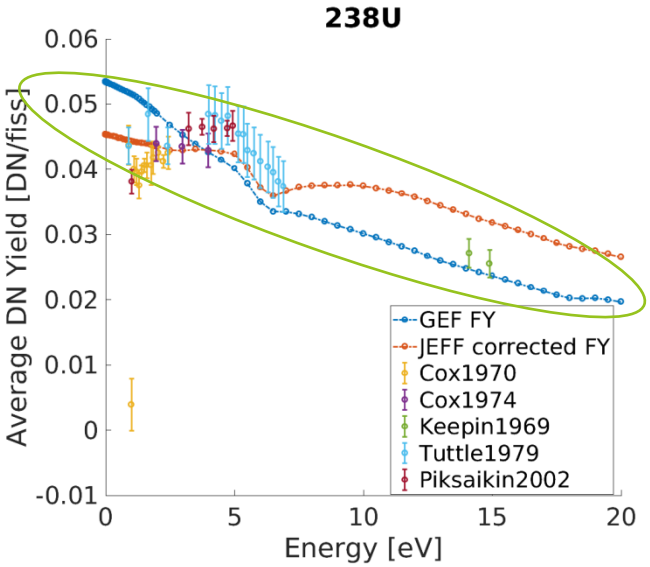


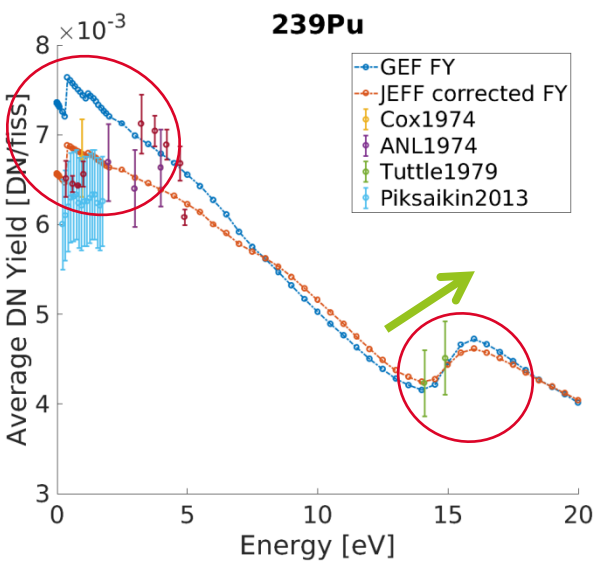




Results: ν_d
GEF-6.1 versus the « corrected » JEFF-3.1.1







Seems good: - 238U: step-like behavior
- 238U: visible second-chance fission effect
- 238U, 239Pu: agreement with experiments

Seems weird: - 235U, 239Pu: bump after 15 MeV
- 235U, 239Pu: uneven behavior below 4 MeV
- 235U: different slope

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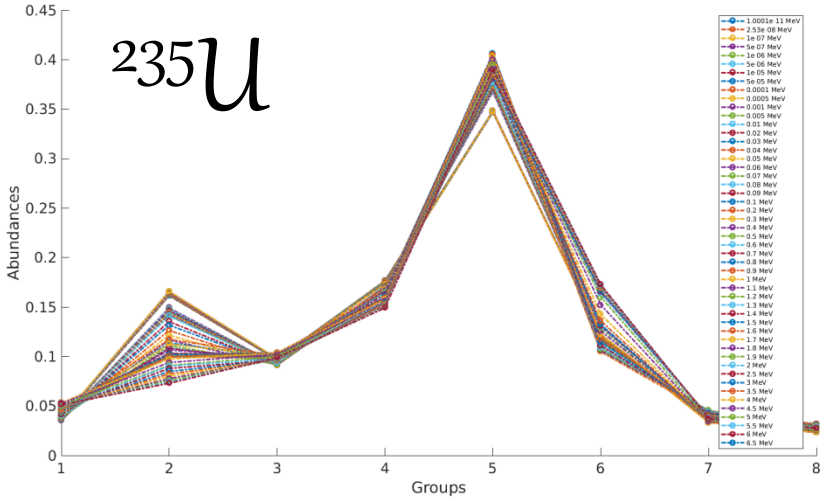
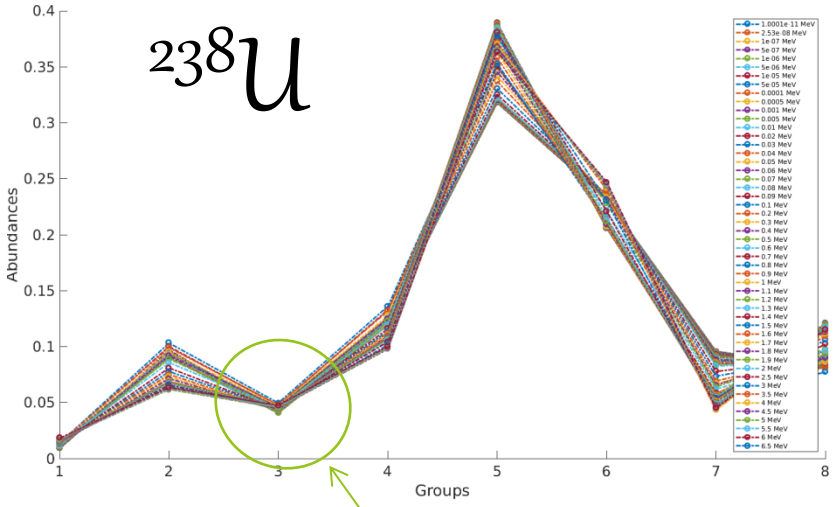
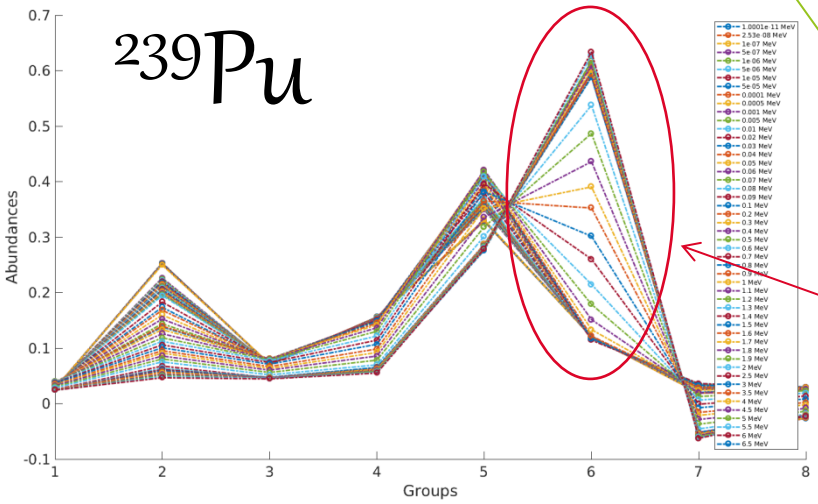
Results: a_i, $\langle T_{1/2} \rangle$
Abundances' sensitivity to an energy change





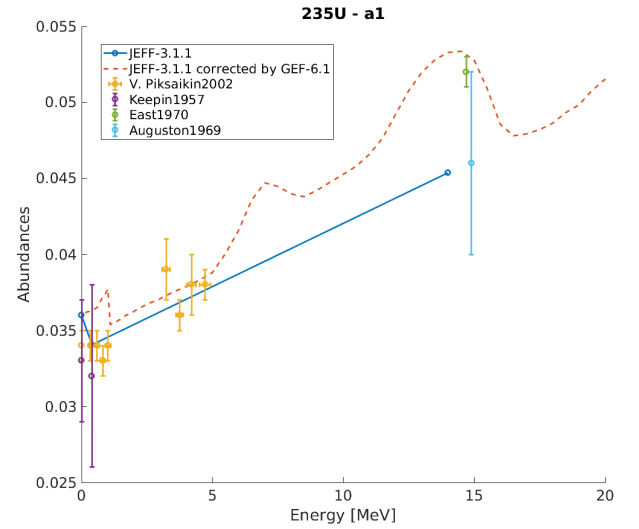


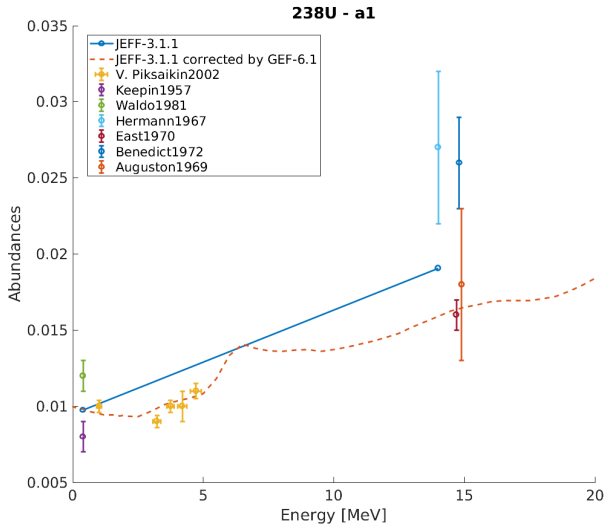
Unremarkably sensitive

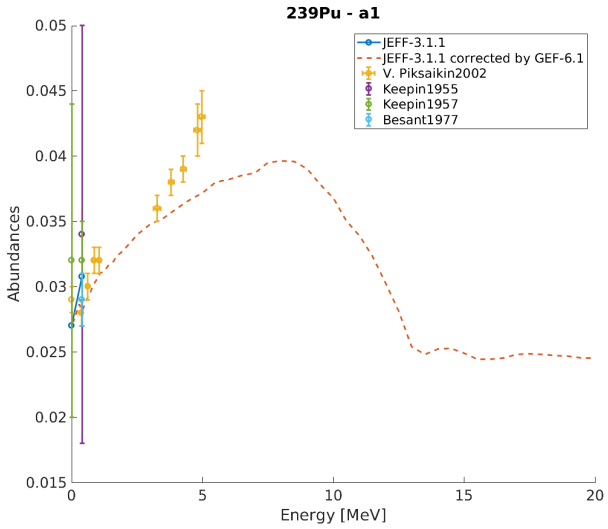
Extremely sensitive

HOW TO READ IT:
X-axis: Group number
Y-axis: Relative abundance
Lines: Energy

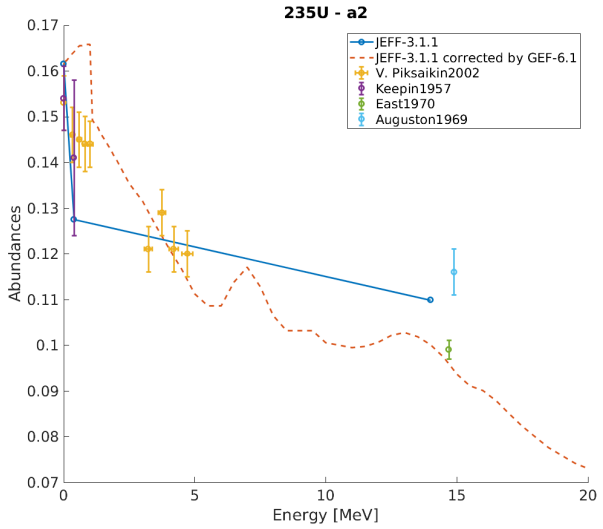
Results: a_i, $\langle T_{1/2} \rangle$
First abundance

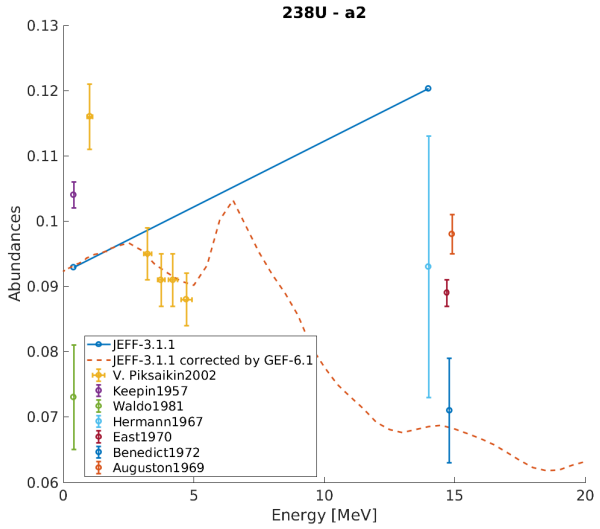


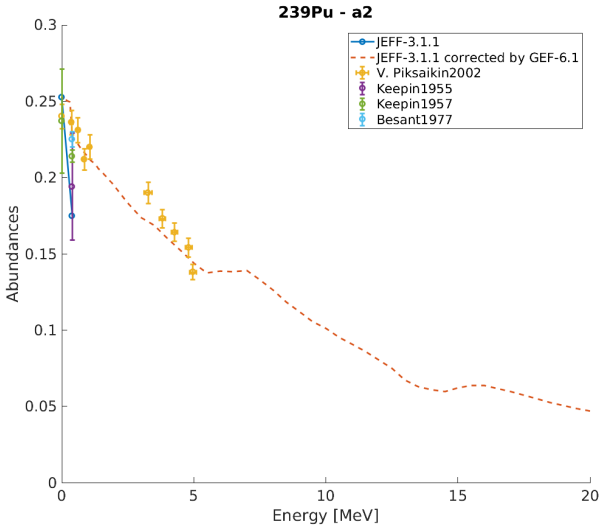




Results: a_i, $\langle T_{1/2} \rangle$
First abundance







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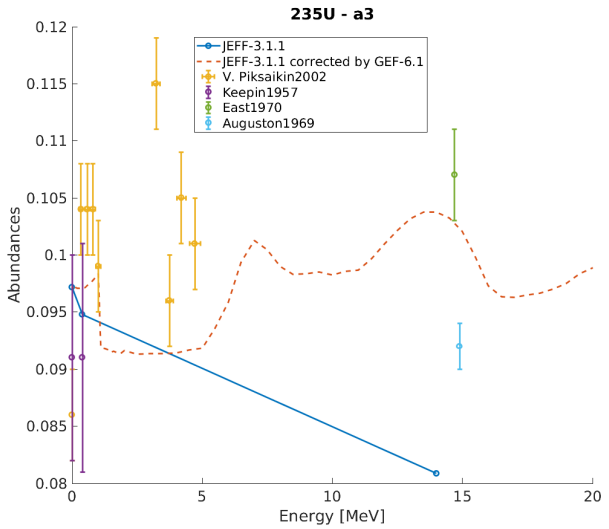

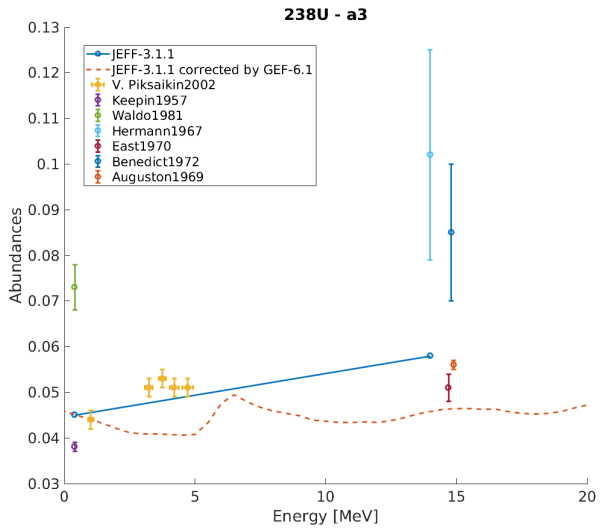

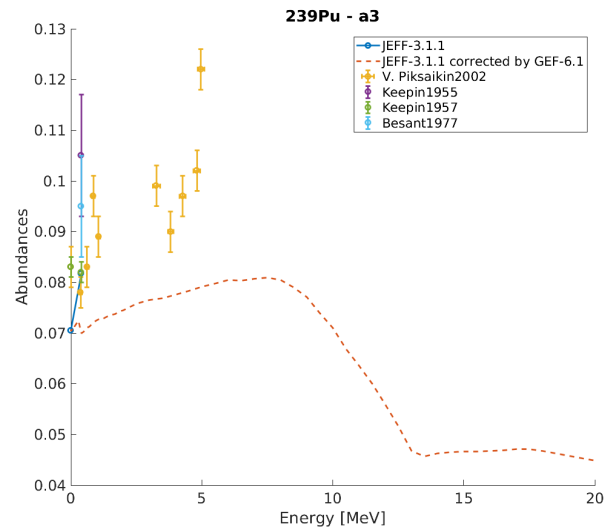

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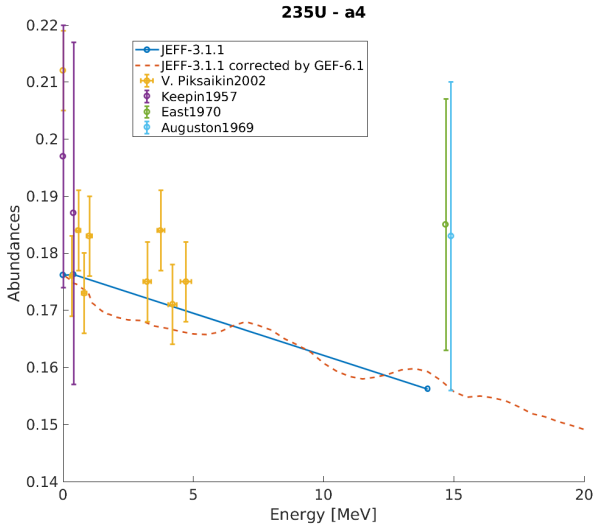

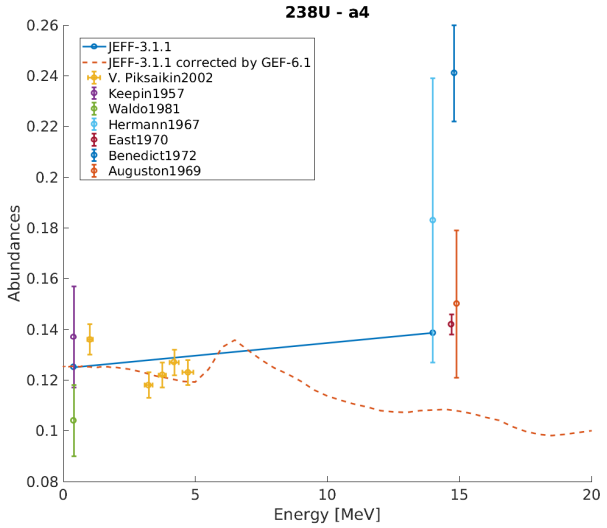

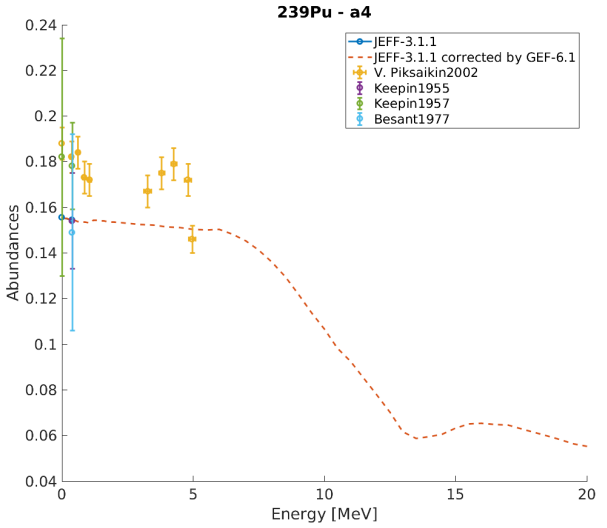

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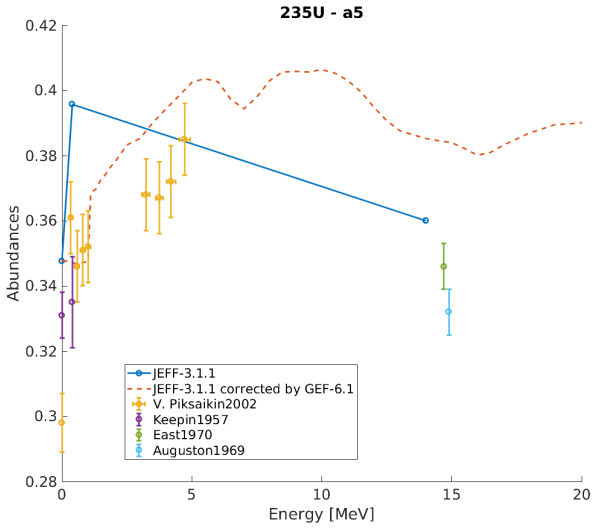

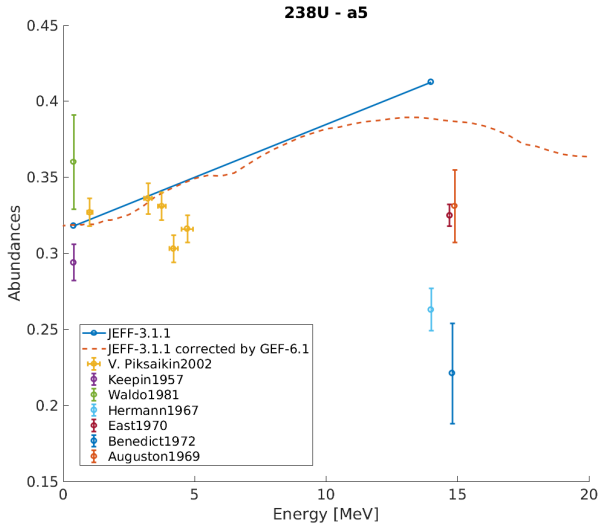

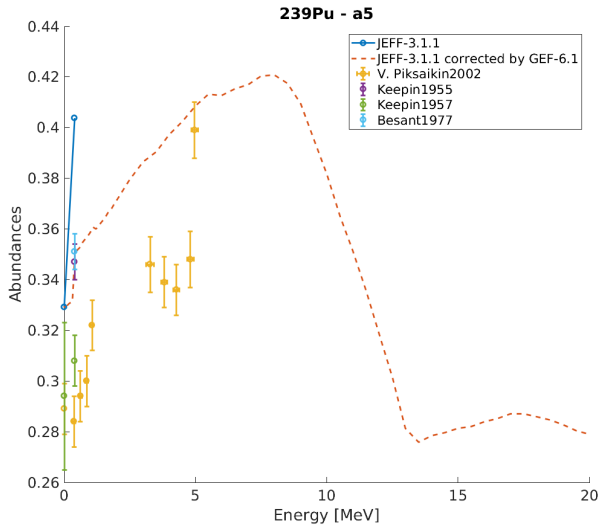

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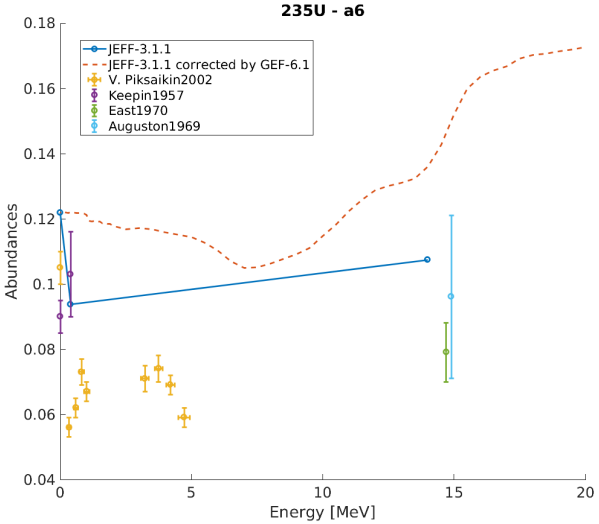

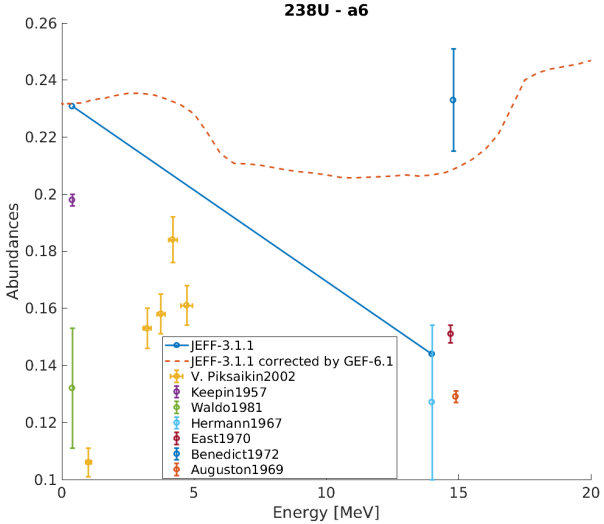

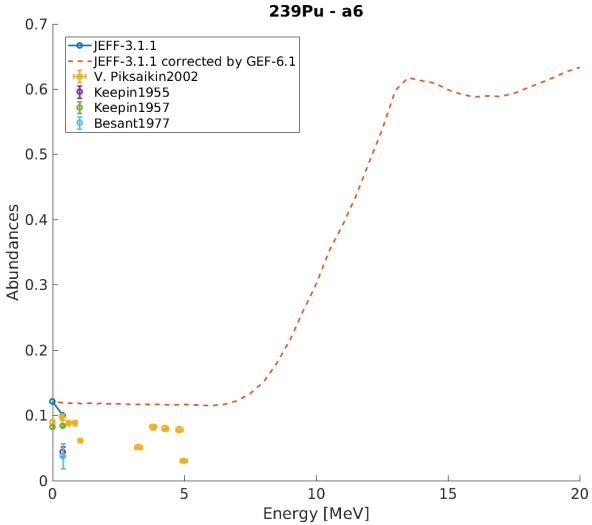

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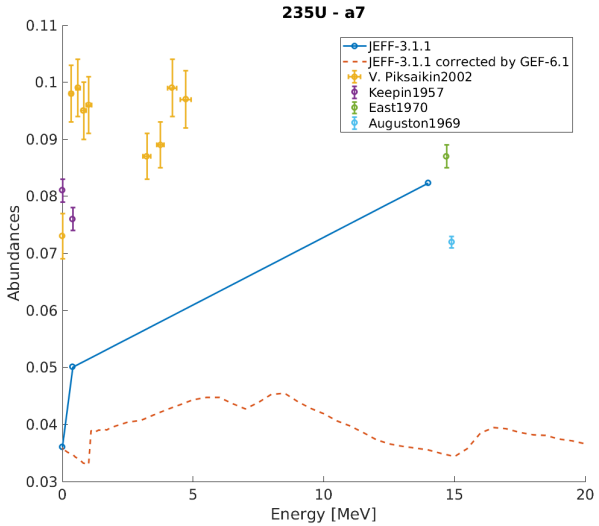

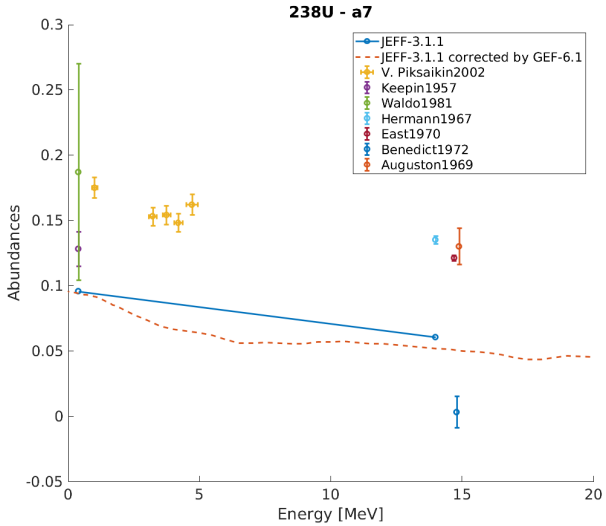

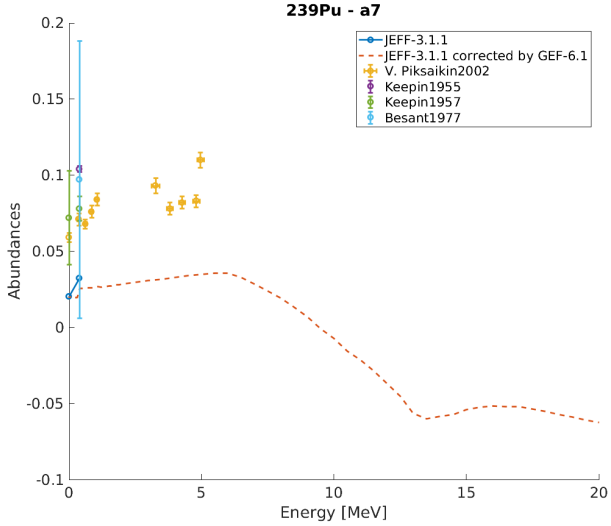

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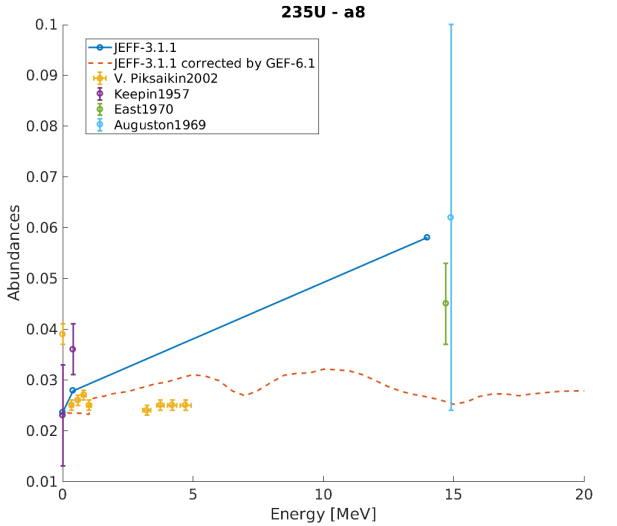
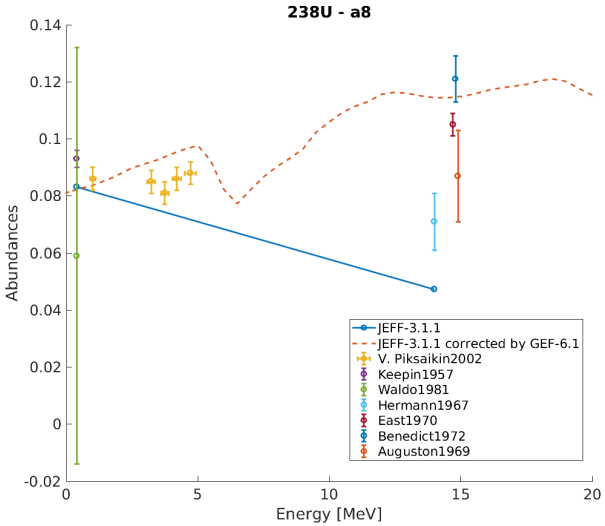
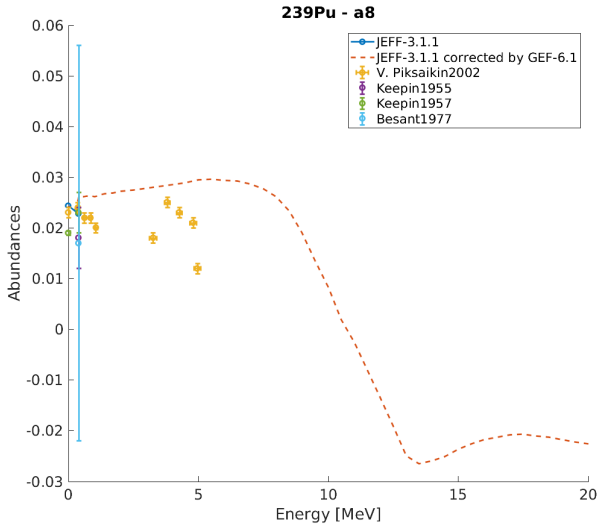
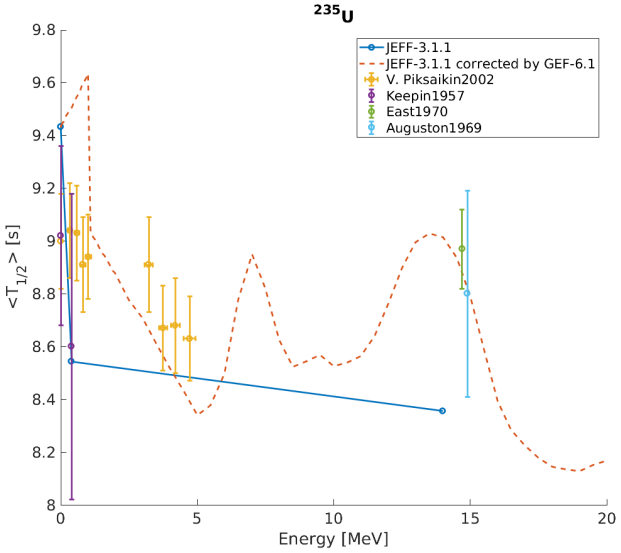
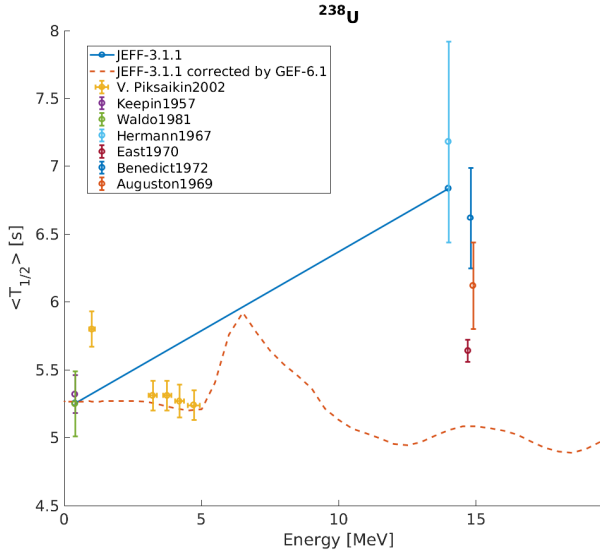






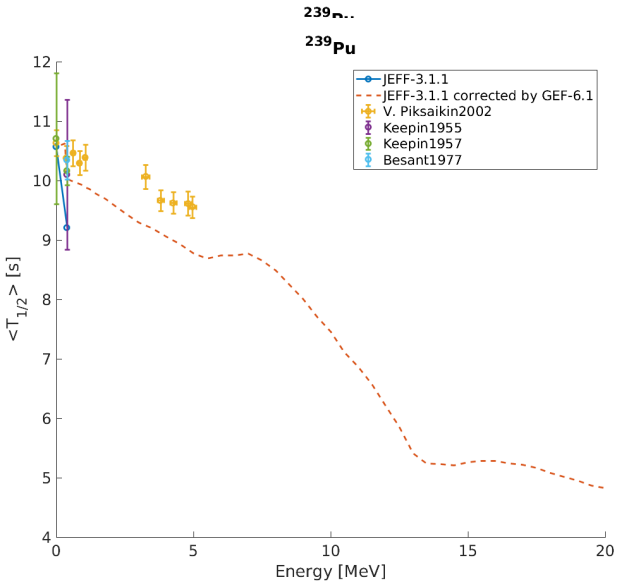
Results: a_i, $\langle T_{1/2} \rangle$
^{235}U – Mean precursors' half-life





For small reactivity insertions, the reactivity is proportional to the mean DN precursors' half-life ($\overline{T_{1/2}}$)

$$\rho \propto \beta_{eff} \cdot \frac{\overline{T_{1/2}}}{T}$$



V.M. Piksaikin et al. Energy Dependence of Relative Abundances and Periods of Delayed Neutrons from neutron-induced fission of 235U, 238U, 239Pu in 6- and 8-group model representation (2002)

OUTLINE:

~ • Context

~ • State of the art

~ • Alternative method

~ • Results: ν_d

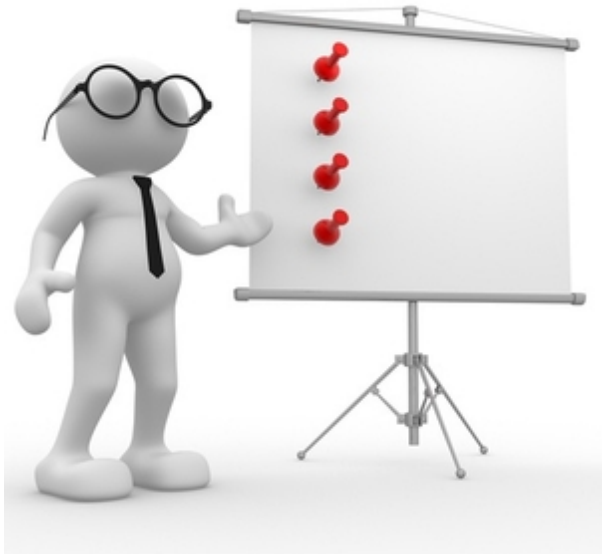
~ • Results: a_i, $\langle T_{1/2} \rangle$

~ • Conclusions

• Open questions

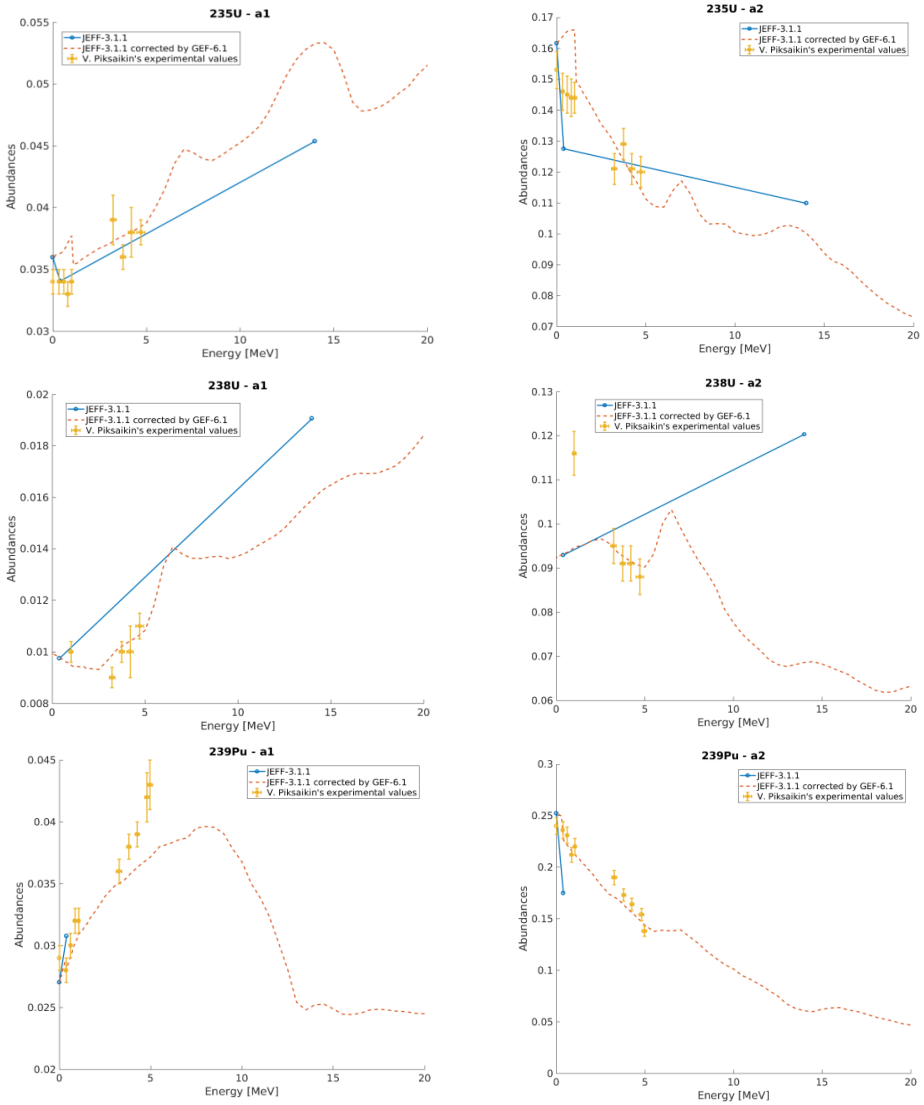
Conclusions

- DN data does not always has clear origins
- There is an evident need of a new evaluation
- The method seems promising for the estimation of $\langle T_{1/2} \rangle$



Conclusions

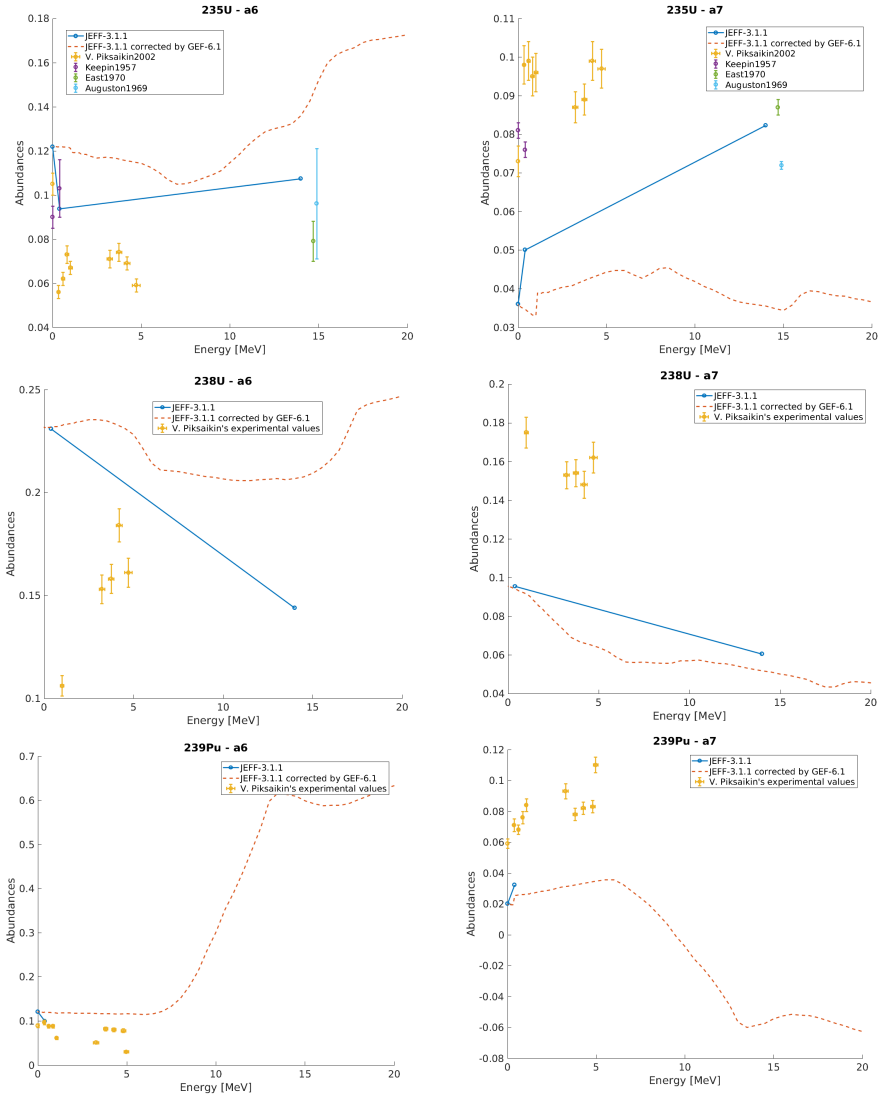
- Up to 5 MeV, the first two abundances are better estimated with the *corrected* JEFF-3.1.1 than with the original JEFF-3.1.1



Conclusions

- Up to 5 MeV, the first two abundances are better estimated with the *corrected* JEFF-3.1.1 than with the original JEFF-3.1.1

- The short-lived groups are very badly estimated by both calculations, which means that a considerable effort should be done for improving short-lived precursors' FY



OUTLINE:

~ • Context

~ • State of the art

~ • Alternative method

~ • Results: ν_d

~ • Results: a_i, $\langle T_{1/2} \rangle$

~ • Conclusions

~ • Open questions

Open questions

- How to compute the uncertainty in the modified FY?
- What else could we do for investigating/improving the energy dependence of delayed-neutron data?

Thank you!

Questions?

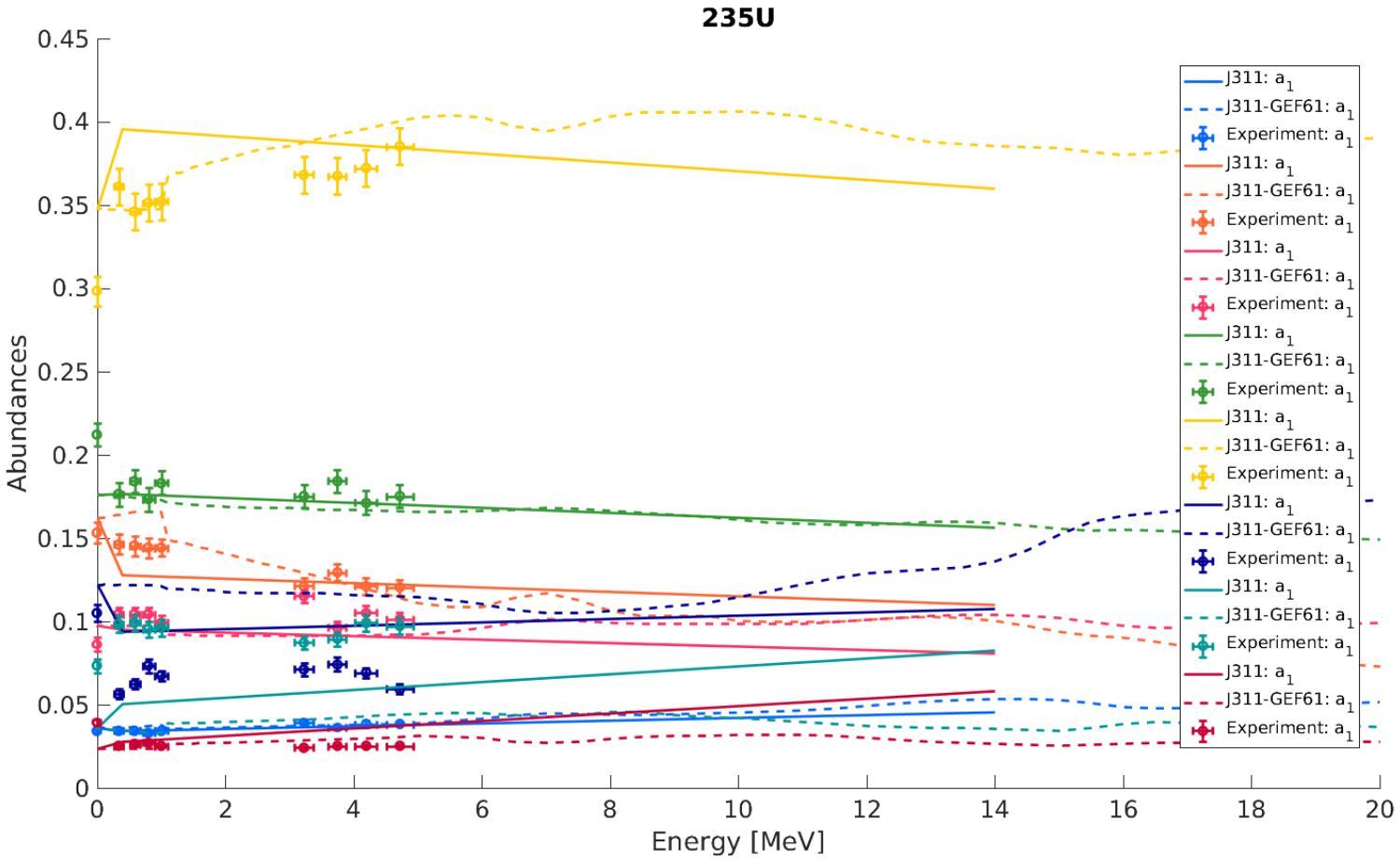
daniela.foligno@cea.fr

Back-up

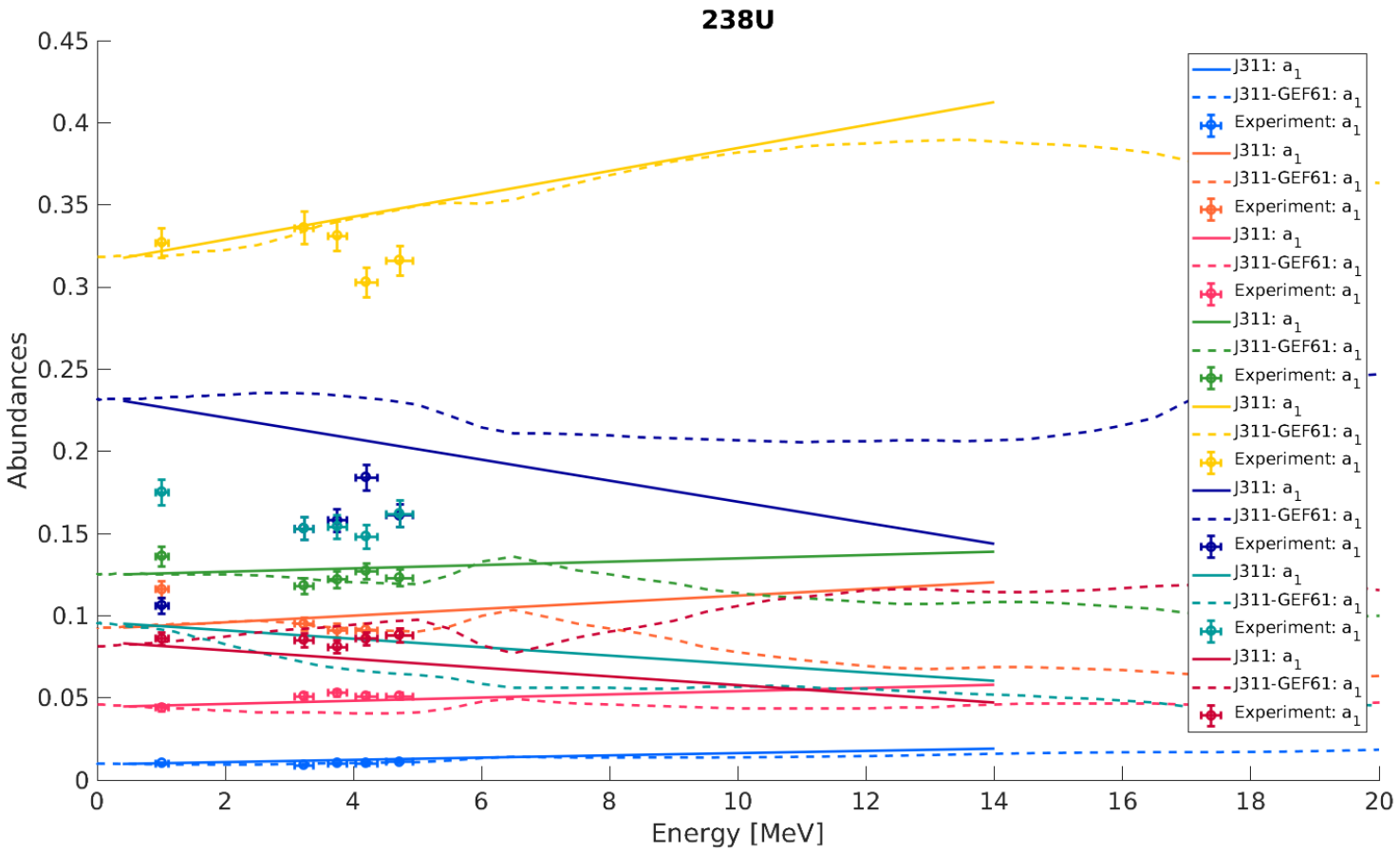
(Eq. 1) $$FY_{JEFF}(E) = \frac{FY_{GEF}(E)}{FY_{GEF}(E_{ref})} FY_{JEFF}(E_{ref})$$

(Eq. 2) $$FY_{JEFF}(E) = FY_{JEFF}(E_{ref})$$

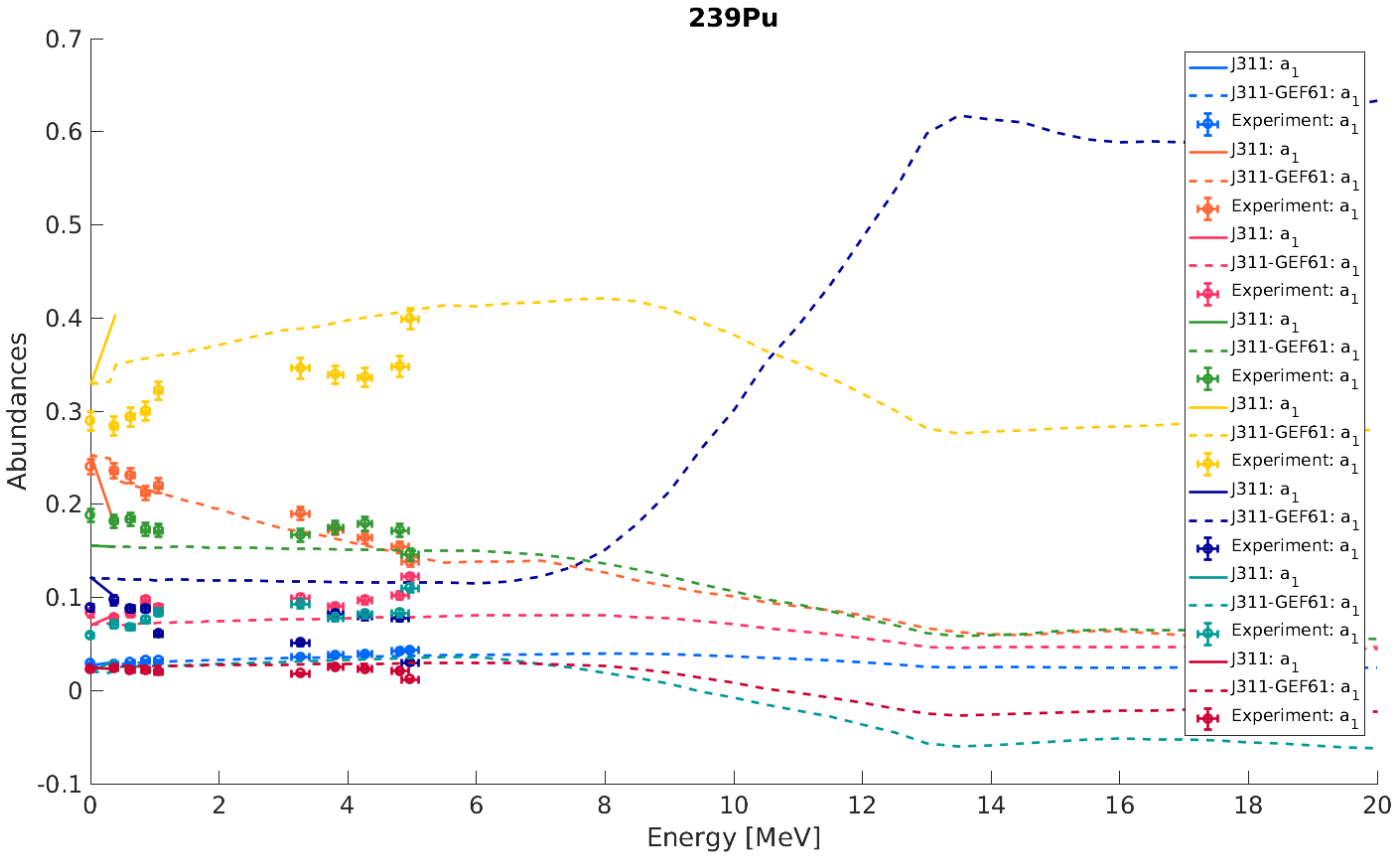
GEF(Eref)	GEF(E)	JEFF(E)
≠ 0	≠ 0	Eq. 1
≠ 0	= 0	Eq. 1
= 0	≠ 0	Eq. 2
missing		Eq. 2



V.M. Piksaikin et al. Energy Dependence of Relative Abundances and Periods of Delayed Neutrons from neutron-induced fission of 235U, 238U, 239Pu in 6- and 8-group model representation (2002)



V.M. Piksaikin et al. Energy Dependence of Relative Abundances and Periods of Delayed Neutrons from neutron-induced fission of 235U, 238U, 239Pu in 6- and 8-group model representation (2002)



V.M. Piksaikin et al. Energy Dependence of Relative Abundances and Periods of Delayed Neutrons from neutron-induced fission of 235U, 238U, 239Pu in 6- and 8-group model representation (2002)

Semi-empirical Lendel model

$$\nu_d(E) = Y_1(E) + \varphi(A_f, Z_f) \cdot \psi(E)$$

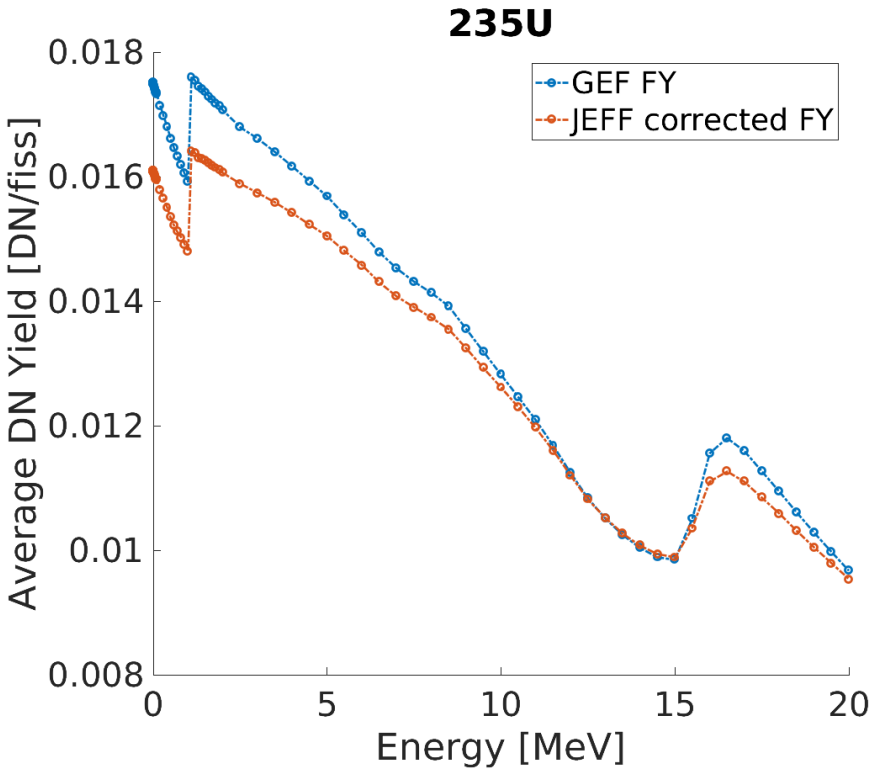
Direct macroscopic DN yield

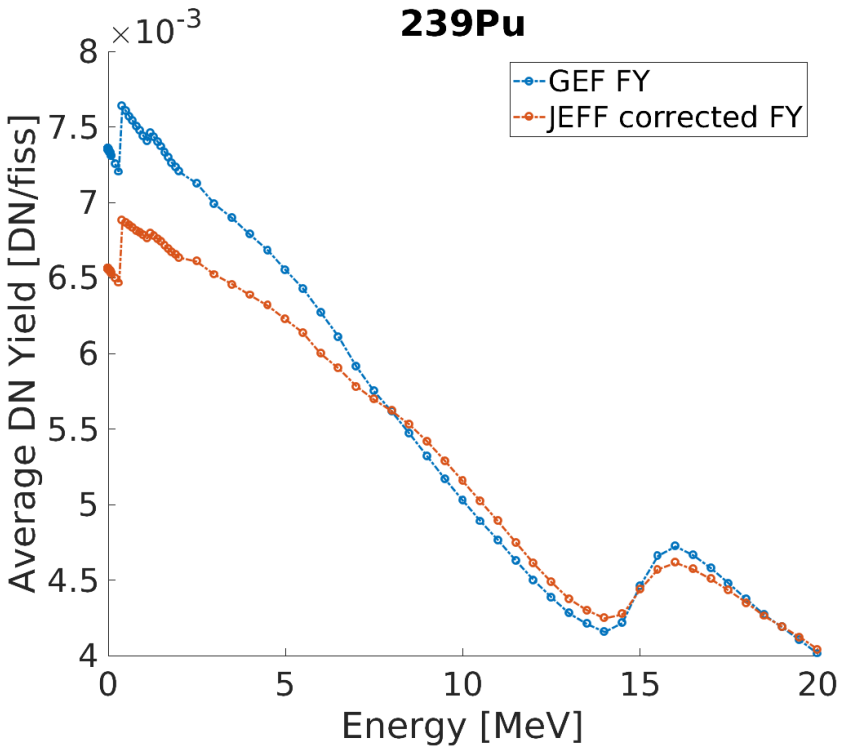
It describes the competition with prompt neutron emission

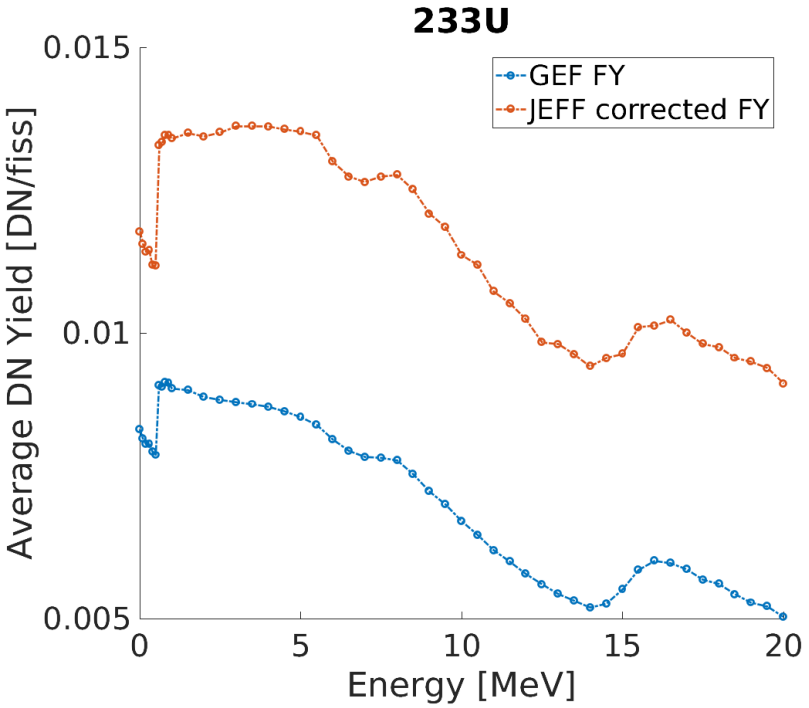
Correction

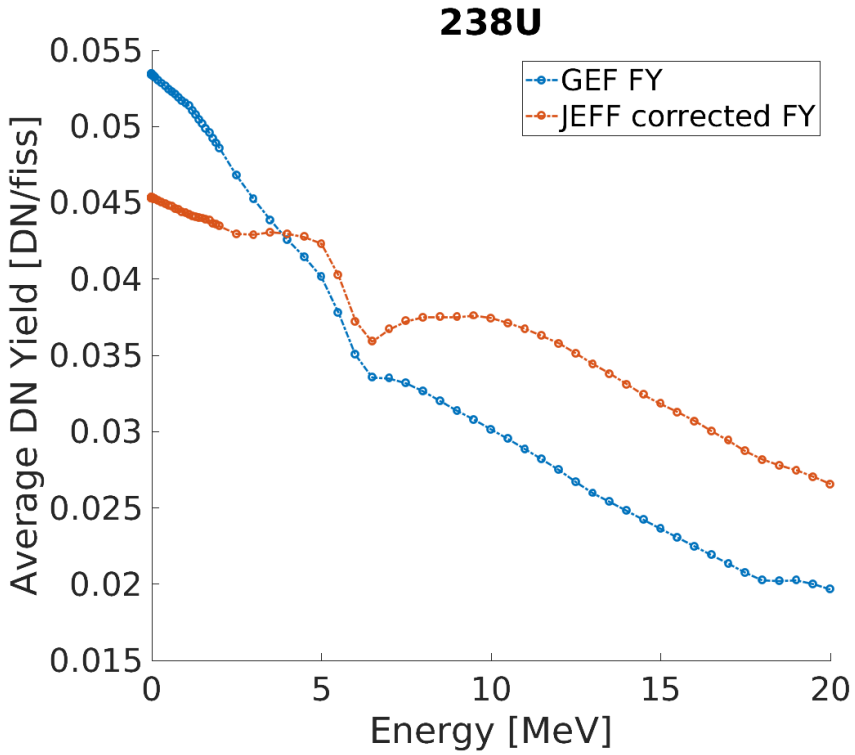
It takes into account the energy dependence of the odd-even effect in the first chance fissioning system

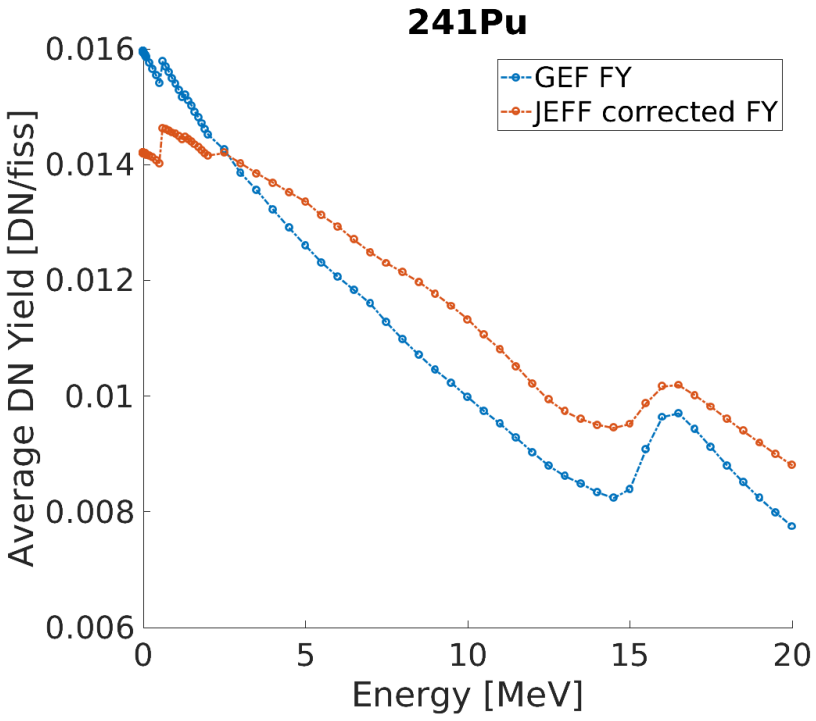
Title
GEF61

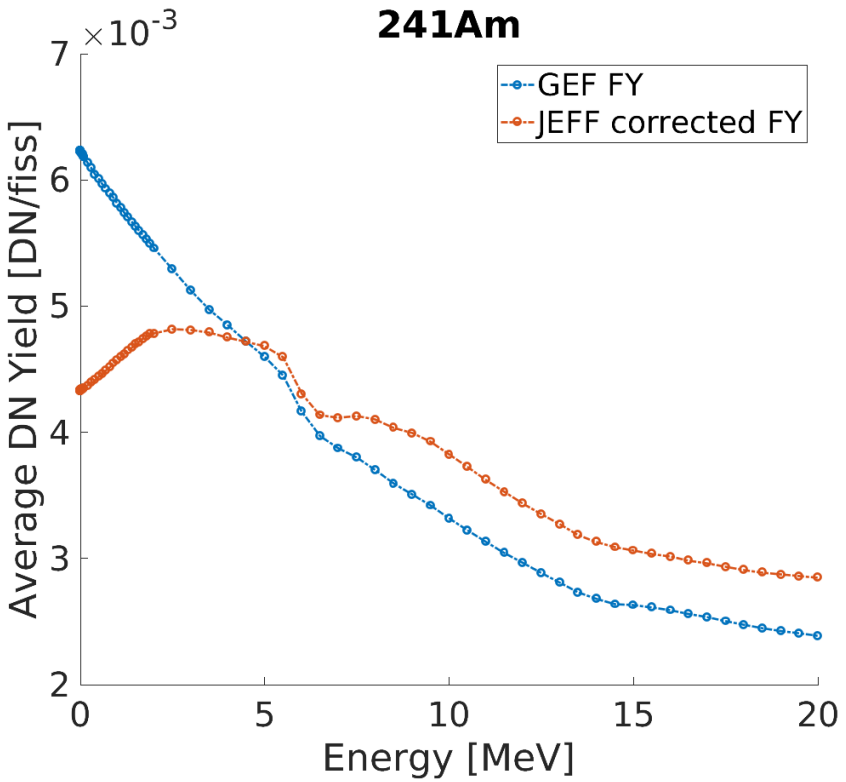

235U
GEF FY
JEFF corrected FY
Average DN Yield [DN/fiss]
Energy [MeV]
0.018
0.016
0.014
0.012
0.01
0.008
0
5
10
15
20

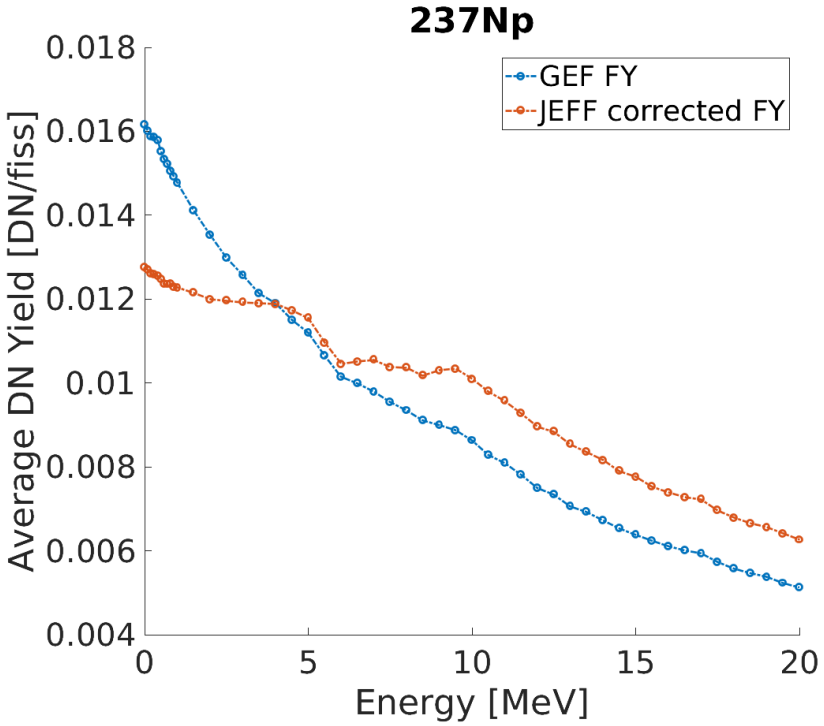

239Pu
×10^-3
GEF FY
JEFF corrected FY
Average DN Yield [DN/fiss]
Energy [MeV]
8
7.5
7
6.5
6
5.5
5
4.5
4
0
5
10
15
20

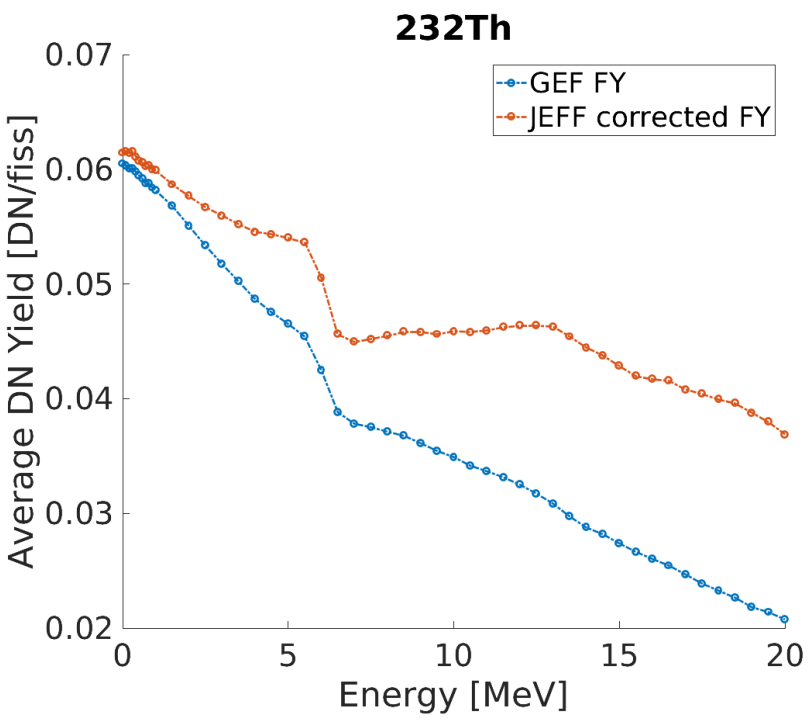

233U
GEF FY
JEFF corrected FY
Average DN Yield [DN/fiss]
Energy [MeV]
0.015
0.01
0.005
0
5
10
15
20


238U
GEF FY
JEFF corrected FY
Average DN Yield [DN/fiss]
Energy [MeV]
0.055
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0
5
10
15
20


241Pu
GEF FY
JEFF corrected FY
Average DN Yield [DN/fiss]
Energy [MeV]
0.016
0.014
0.012
0.01
0.008
0.006
0
5
10
15
20


241Am
×10-3
GEF FY
JEFF corrected FY
Average DN Yield [DN/fiss]
Energy [MeV]
7
6
5
4
3
2
0
5
10
15
20


237Np
GEF FY
JEFF corrected FY
Average DN Yield [DN/fiss]
Energy [MeV]
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0
5
10
15
20


232Th
GEF FY
JEFF corrected FY
Average DN Yield [DN/fiss]
Energy [MeV]
0.07
0.06
0.05
0.04
0.03
0.02
0
5
10
15
20

New Bateman Solver
Complete system of differential equations

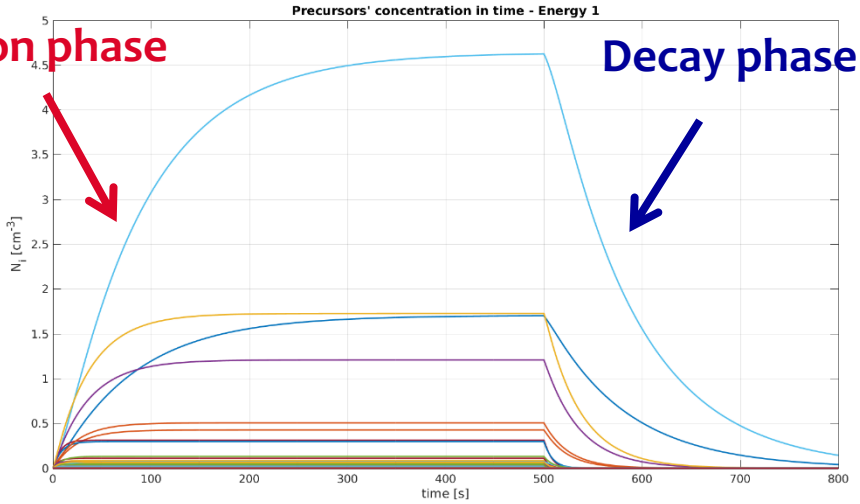
Delayed-neutron activity [DN/s]

$$n_d(t) = \sum_{i=1}^{n} x_i N_i(t) P_{n,i}$$

$$\begin{cases} \dfrac{dN_1(t)}{dt} = -\lambda_1 N_1(t) + S_1 \\ \dfrac{dN_2(t)}{dt} = -\lambda_2 N_2(t) + S_2 + \lambda_1 BR_{2\to1} N_1(t) \\ \vdots \\ \dfrac{dN_i(t)}{dt} = -\lambda_i N_i(t) + S_i + \lambda_{i-1} BR_{(i-1)\to i} N_{i-1}(t) \\ \vdots \\ \dfrac{dN_n(t)}{dt} = -\lambda_n N_n(t) + S_n + \lambda_{n-1} BR_{(n-1)\to n} N_{n-1}(t) \end{cases}$$

New Bateman Solver
Analytical solution

Individual precursor build-up and decay



$$N_n(t) = \sum_{i=1}^{i=n} \left[\left(\prod_{j=i}^{j=n-1} \lambda_j \cdot P_{j\to(j+1)} \right) \cdot \sum_{j=i}^{j=n} \left(\frac{N_i^0 \cdot e^{-\lambda_j \cdot t}}{\prod_{\substack{p=i \\ p\neq j}}^{p=n} (\lambda_p - \lambda_j)} + \frac{P_i \cdot (1 - e^{-\lambda_j \cdot t})}{\lambda_j \cdot \prod_{\substack{p=i \\ p\neq j}}^{p=n} (\lambda_p - \lambda_j)} \right) \right]$$

Skrable K. et al. *A general equation for the kinetics of Linear first order phenomena and suggested applications* (1974)

Validation with DARWIN®

1. **Nuclear Data:** Fission Yields and Radioactive Decay Data from **JEFF-3.1**
2. **Fissioning System:** **1 g** (2.563E+21 at) of **^{235}U**
3. **Thermal Flux:** Constant **thermal** (E_n<0.1 eV) flux of **1 n·cm^{-2}·s^{-1}**
4. **Irradiation Durations:** 0.001 s, 10 s, 600 s
5. **Decay Duration:** 600 s
6. **Comparison:** 22 points of the decay-curve
   (0, 0.001, 0.01, 0.1, 0.5, 1, 2, 3, 5, 8, 10, 20, 30, 50, 70, 100, 150, 200, 300, 400, 500, 600 seconds after the end of the irradiation)

Thanks to Jean-François Lebrat for the DARWIN simulations

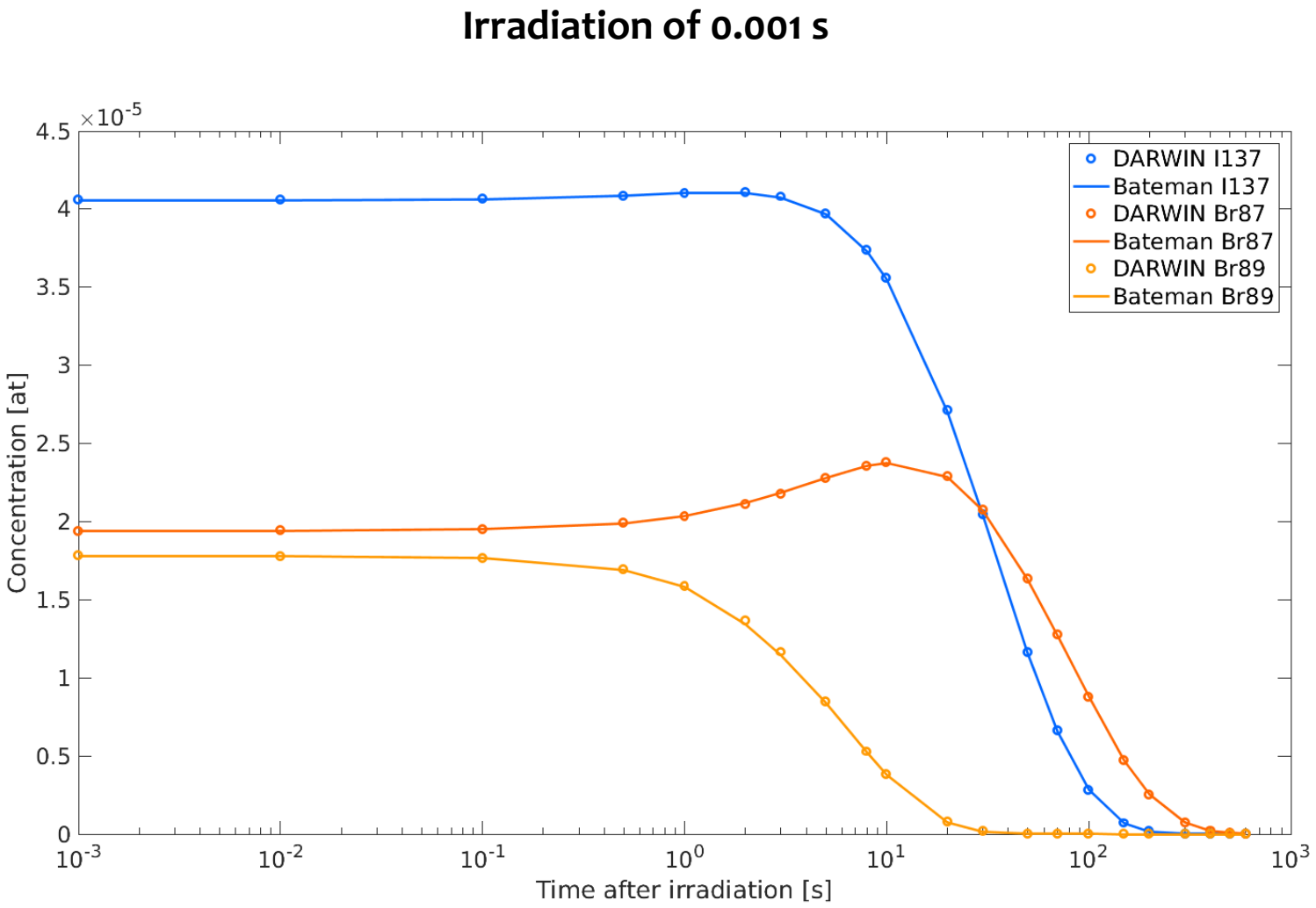
San-Felice L. et al. *Experimental validation of the DARWIN2.3 Package for fuel cycle applications* (2013)

New Bateman Solver
Comparison in the precursors' concentration

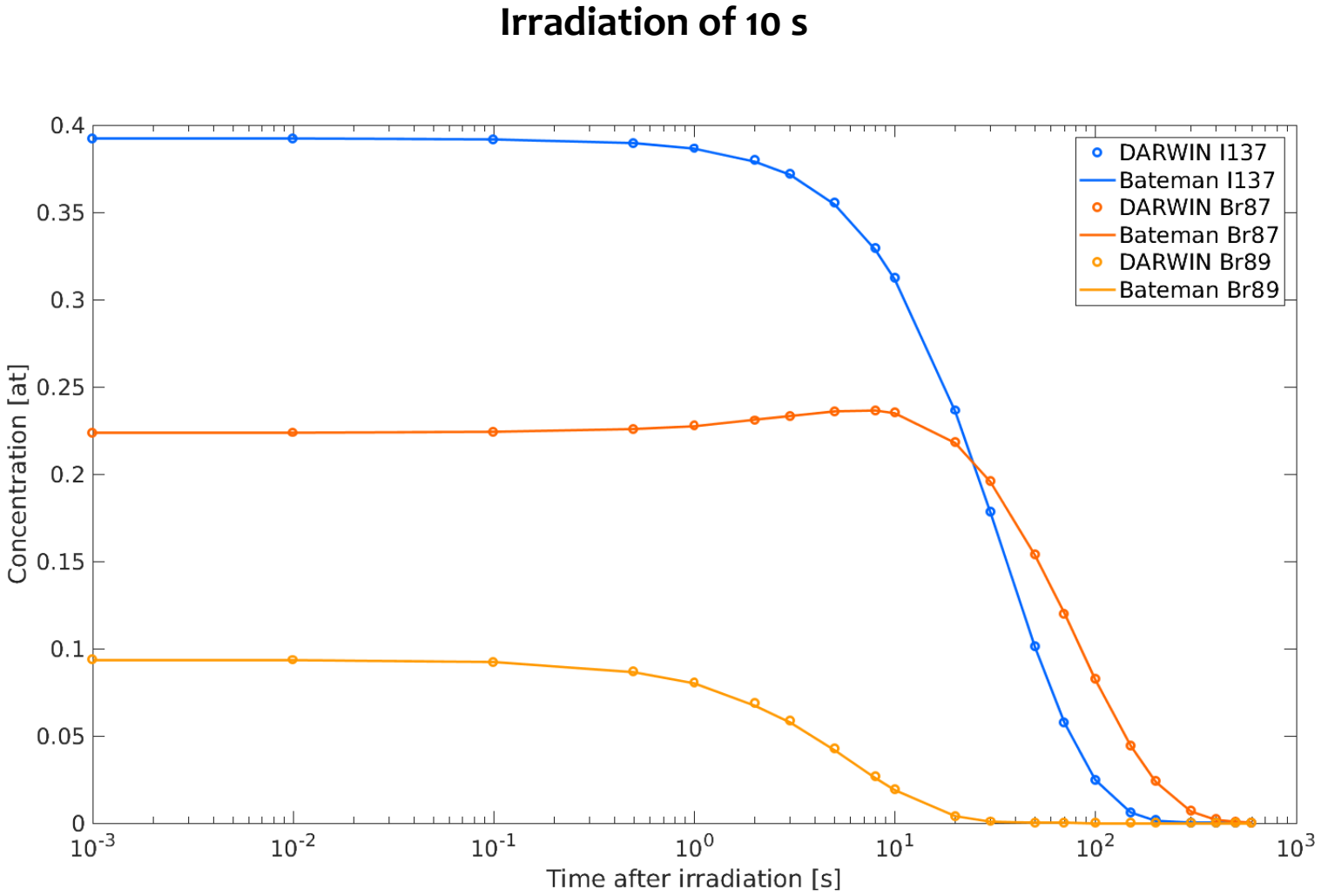
Table 1: Discrepancies in the concentration at the end of the irradiation. The results are given in percentage. [1], [2] and [3] refer to an irradiation length of 0.001 s, 10 s and 600 s, respectively. The precursors are shown in order of importance with respect to the delayed-neutron emission

Z	A	I	Symbol	$(C - C_{ref})/C_{ref}$ [1]	$(C - C_{ref})/C_{ref}$ [2]	$(C - C_{ref})/C_{ref}$ [3]
53	137	0	I	0.002 %	0.008 %	-0.004 %
35	89	0	Br	-0.005 %	-0.009 %	-0.015 %
37	94	0	Rb	-0.003 %	-0.021 %	-0.023 %
35	88	0	Br	0.007 %	0.007 %	-0.003 %
35	90	0	Br	-0.031 %	-0.032 %	-0.036 %
53	138	0	I	-0.009 %	-0.005 %	-0.012 %
39	98	1	Y	-0.033 %	-0.032 %	-0.033 %
53	139	0	I	-0.028 %	-0.025 %	-0.029 %
37	95	0	Rb	-0.172 %	-0.178 %	-0.178 %
35	87	0	Br	0.007 %	0.013 %	-0.001 %
37	93	0	Rb	-0.001 %	-0.004 %	-0.009 %
39	99	0	Y	-0.031 %	-0.043 %	-0.043 %
33	85	0	As	-0.032 %	-0.031 %	-0.033 %
35	91	0	Br	-0.128 %	-0.125 %	-0.124 %
51	135	0	Sb	-0.040 %	-0.038 %	-0.039 %
55	143	0	CS	-0.029 %	-0.035 %	-0.036 %
33	86	0	AS	-0.071 %	-0.071 %	-0.072 %
37	96	0	RB	-0.169 %	-0.230 %	-0.230 %
55	145	0	CS	-0.118 %	-0.115 %	-0.114 %
53	140	0	I	-0.076 %	-0.077 %	-0.080 %
55	144	0	CS	-0.028 %	-0.044 %	-0.044 %

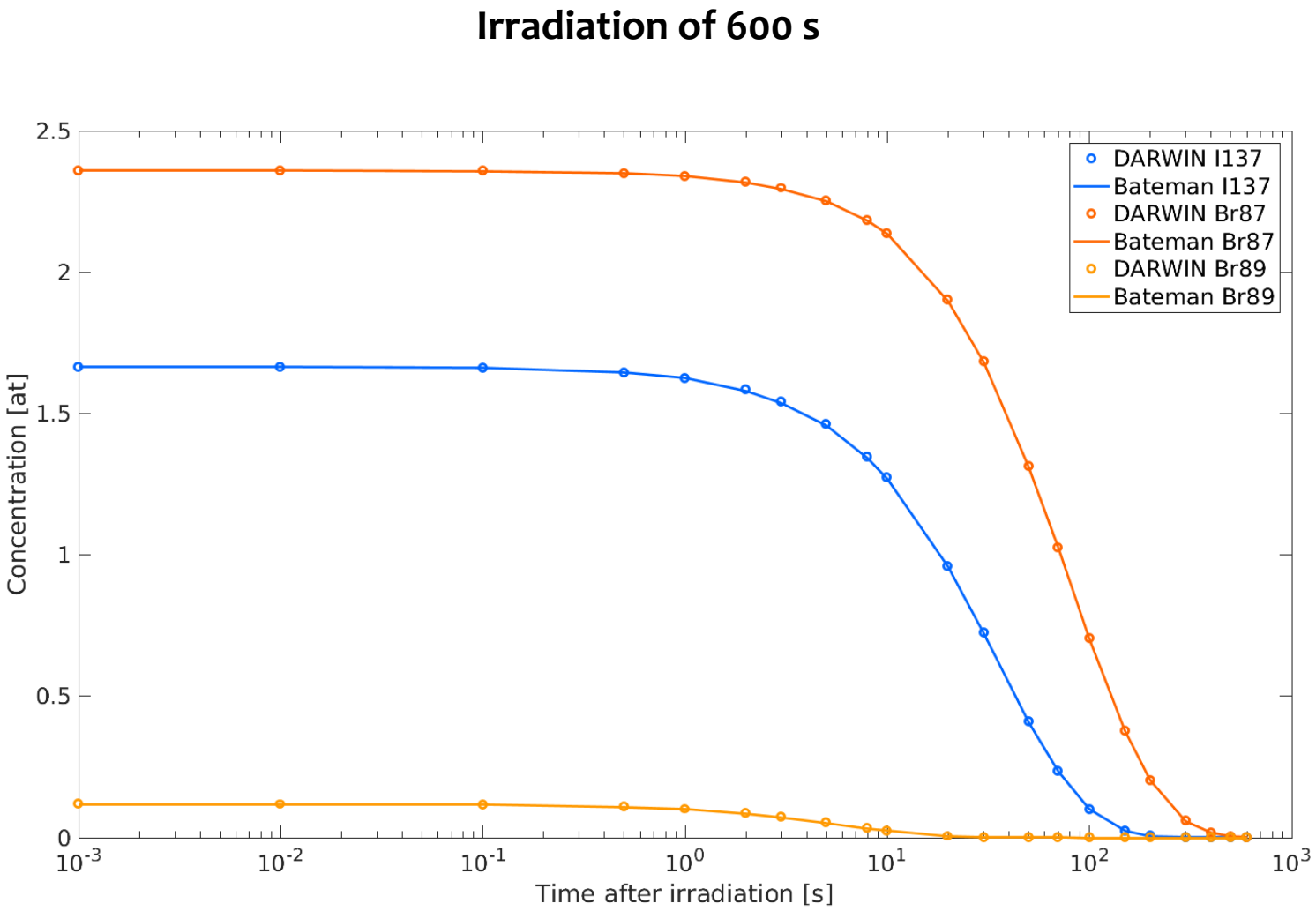
New Bateman Solver
Irradiation of 0.001 s



New Bateman Solver
Irradiation of 10 s



New Bateman Solver
Irradiation of 600 s



Conclusions:

1. The code has been written to study **the delayed-neutron-precursors' behavior**
2. Discrepancies larger than 1% are present for irrelevant precursors (first occurrence is the 79th precursors in the sorted-by-importance ranking)
3. Only $IT, \beta^-, \beta^-_n, \beta^-_{2n}, \beta^-_{3n}, \beta^-_{4n}$ are considered (no transmutation or absorption)

4. **The solver is validated for estimating delayed-neutron precursors' concentration**

Title
Subtitle