Mesures de décroissances beta avec la technique TAGS et impact sur les calculs de puissance résiduelle

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Plan

- Données de décroissance β pour la physique appliquée et fondamentale
- Effet Pandemonium et la solution de spectroscopie par absorption totale (Total Absorption Gamma-ray Spectroscopy - TAGS)
- Nouvelles des expériences TAGS (Action 3.1.2)
- Le projet $(NA)^2$STARS (Action 3.4.2)
- Calcules de puissance résiduelle (Action 3.3)
- Conclusion et prospectives

Rappelle des actions

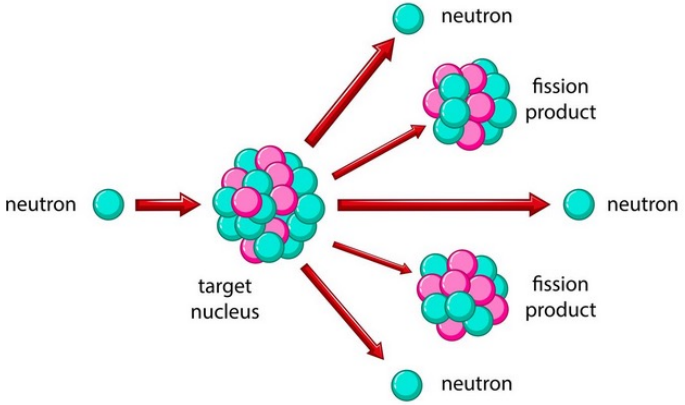
Action 3.1.2 : Mesures sans effet Pandemonium (TAGS)

Action 3.3 :

- 3.3.1 Comparaison des outils de simulation de la puissance résiduelle pour le cycle du combustible U/Pu
- 3.3.2 Comparaison des bases de données évaluées relatives aux données de décroissance ET aux rendements de fission
- 3.3.3 Propagation des incertitudes expérimentales sur les observables d'intérêt

Action 3.4.2 : Développement pour l'upgrade des spectromètres TAS Rocinante et DTAS => (NA)2STARS

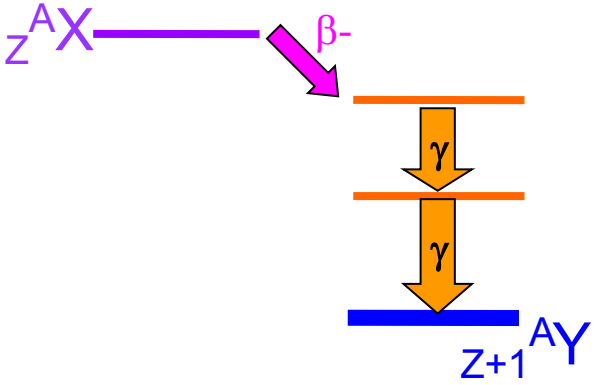
Beta decay of neutron rich nuclei



In nuclear reactors, fission process gives thermal energy:
n + ^{235}U -> ^{236}U* -> PF_1 + PF_2 + neutrons (200 MeV)

Fission Products (FP) are neutron-rich nuclei, undergoing β or β-n decay

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu}_e $$



- The released γ and β contribute to the *"decay heat"*
- *The antineutrinos* escape and can be detected
- β-n emitters: *delayed neutron fractions*

Decay heat

- Residual power (~8% of nominal power)
- Safety and economical interests

Estimate through the « summation method »: summation of all the fission product contributions

$$ \mathbf{f}(t) = \sum_i (\bar{E}_{\beta,i} + \bar{E}_{\gamma,i}) \lambda_i \mathbf{N}_i(t) $$

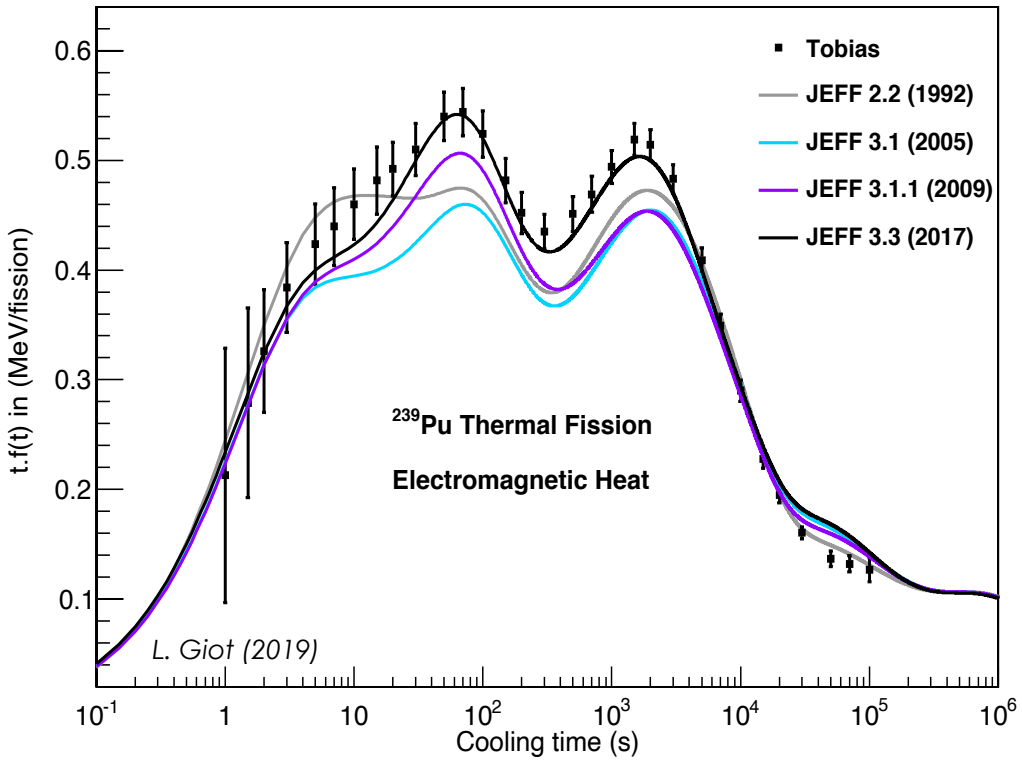
⇒ The only predictive method for future reactors

⇒ Usually cross-checked through comparison with integral experiments

Decay Heat and Pandemonium effect

- 1990s : 50 TAGS measuremets by Greenwood et al @ IDAHO National Laboratory
  Inclusion of 29 noyaux dans JEFF-3.1.1, M. Kellett & O. Bersillon, EPJ Web Conf 146 0209 (2017)

- **2007, 2009, 2014, 2022 : TAGS experiments @Jyväskylä, Collab. (IFIC, Surrey, Subatech)**
  9 nucleus included in JEFF-3.3 : ^{87,86}Br, ^{92,94}Rb, ^{105}Mo, $^{104\text{-}107}$Tc



→ **We need to improve our knowledge about beta decay properties of FP**

→ **One reason of the discrepancies: the Pandemonium Effect**

Reactor Antineutrinos

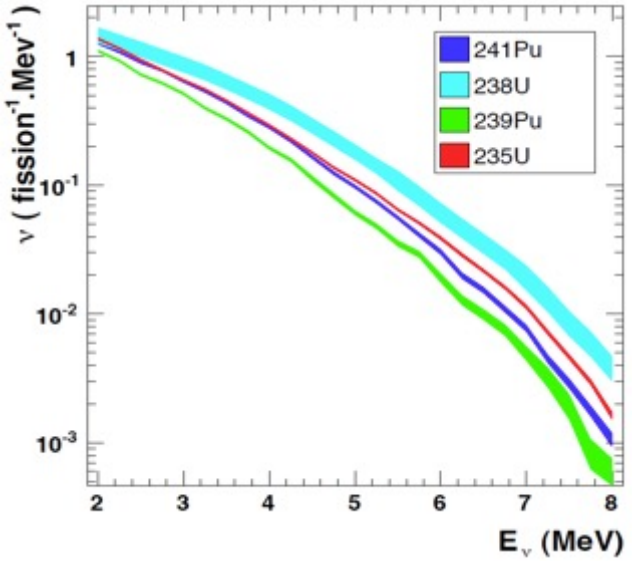
⇒ reactor applied physics

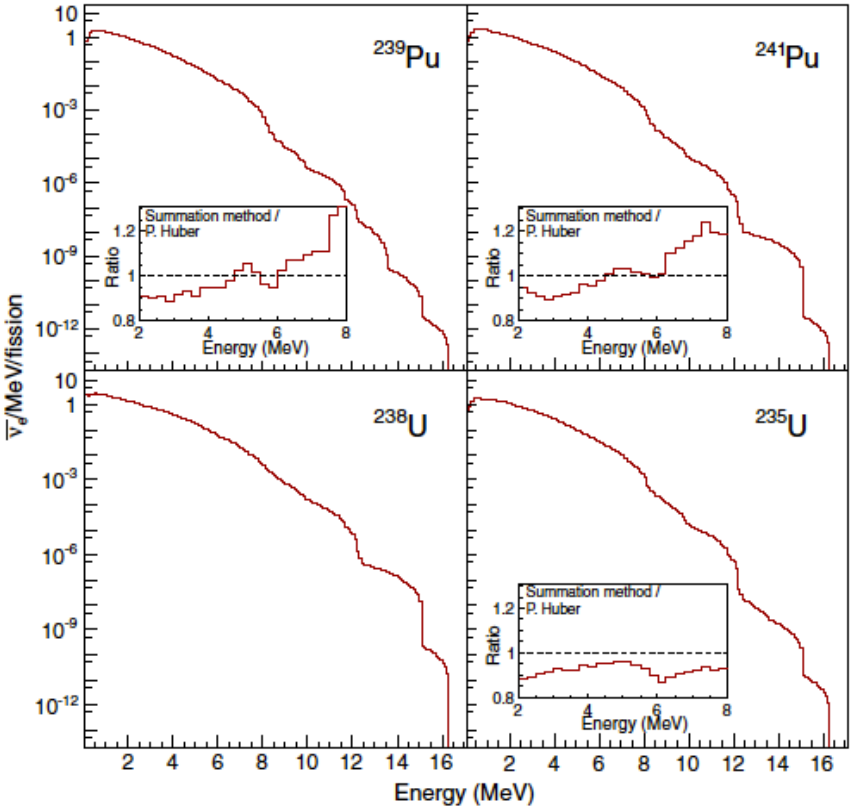
✧ Fuel composition and reactor monitoring

⇒ neutrino fundamental physics

✧ Measurement of neutrino physics parameters

✧ Anomalies between measured and calculated fluxes and spectra





Summation Method for reactor antineutrinos

$$N(E_\nu) = \sum_n Y_n(Z,A,t) \cdot \sum_i b_{n,i}(E_0^i) P_\nu(E_\nu, E_0^i, Z)$$

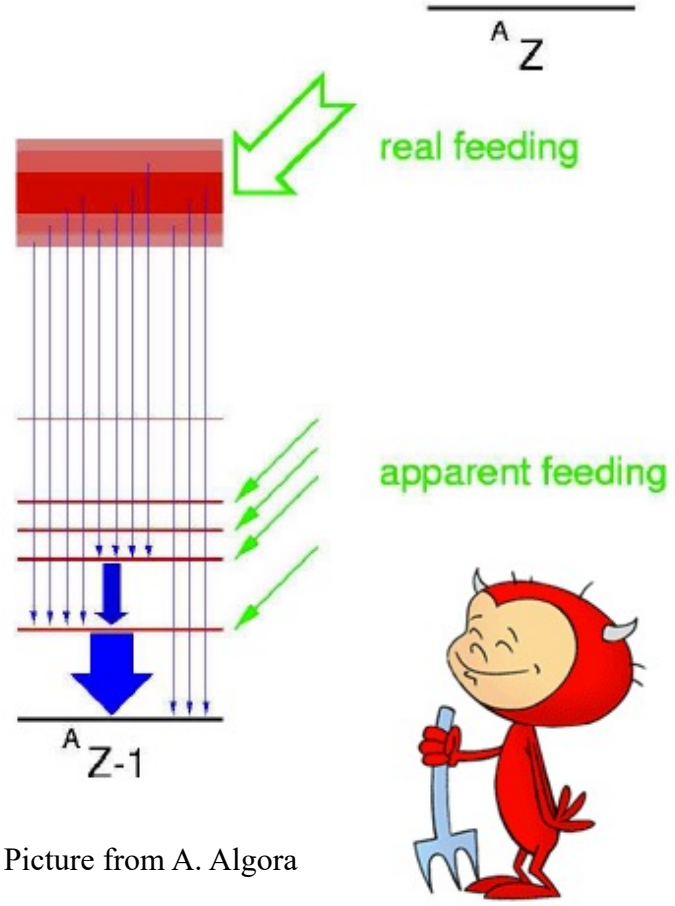
M. Estienne's talk

Ratio between spectra calculated with summation method and converted spectra from ILL measurements, this second is overestimated of about 5% respect to the summation one

→ **The reactor antineutrino estimate also suffer from beta decay data basis bias**

Pandemonium effect **

Due to the use of Germanium detectors to measure the decay schemes by single γ-ray spectroscopy: lower efficiency at higher energy



Picture from A. Algora

- At high energy: high level density and and many possible decay path

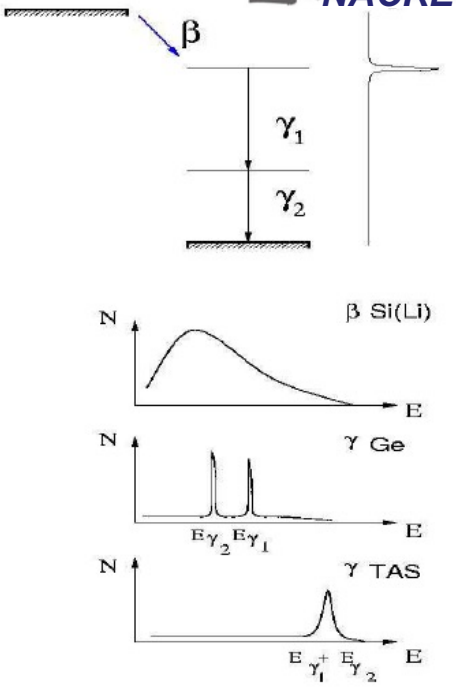
- High energy gammas difficult to be detected by Ge.

→ underestimate of β branches towards high energy excited states: overestimate of the high energy part of the FP β spectra

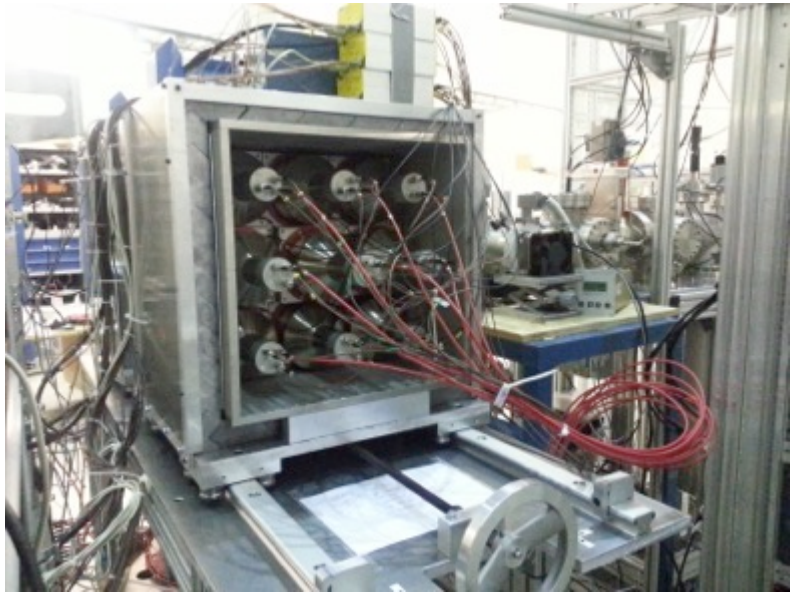
** J.C.Hardy et al., Phys. Lett. B, 71, 307 (1977)

TAGS solution

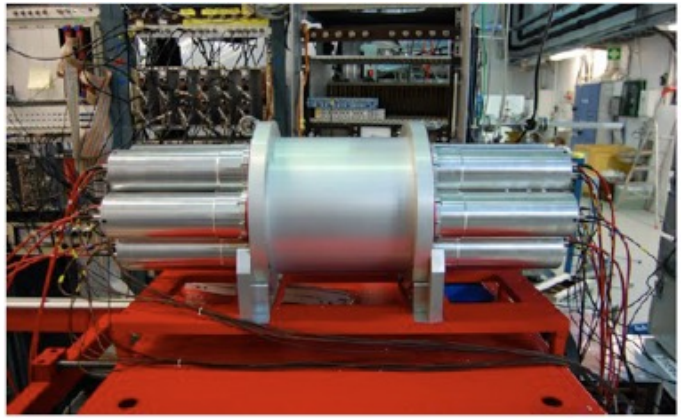
Solution: Total Absorption Gamma-ray Spectroscopy (TAGS)
Big cristal, 4π => A TAS is a calorimeter with efficiency as close a possible to 100%



- **DTAS: 17+1 NaI and plastic detector for β**



- **Rocinantes: 12 BaF_2 and a Si detector for β**



TAGS developed by the IFIC Valencia team (Spain, , A. Algora, J.L. Tain, B. Rubio, et al.) : Proceedings of the Int. Conf. For nuclear Data for Science and technology (ND2013), Nucl. Inst. and Meth. B **376** (2016) 334

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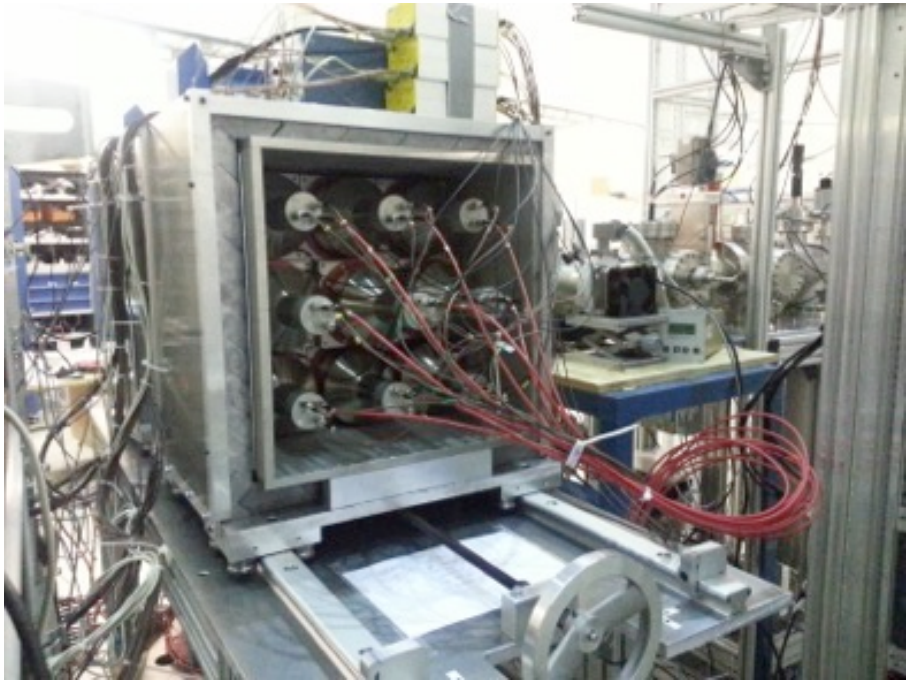
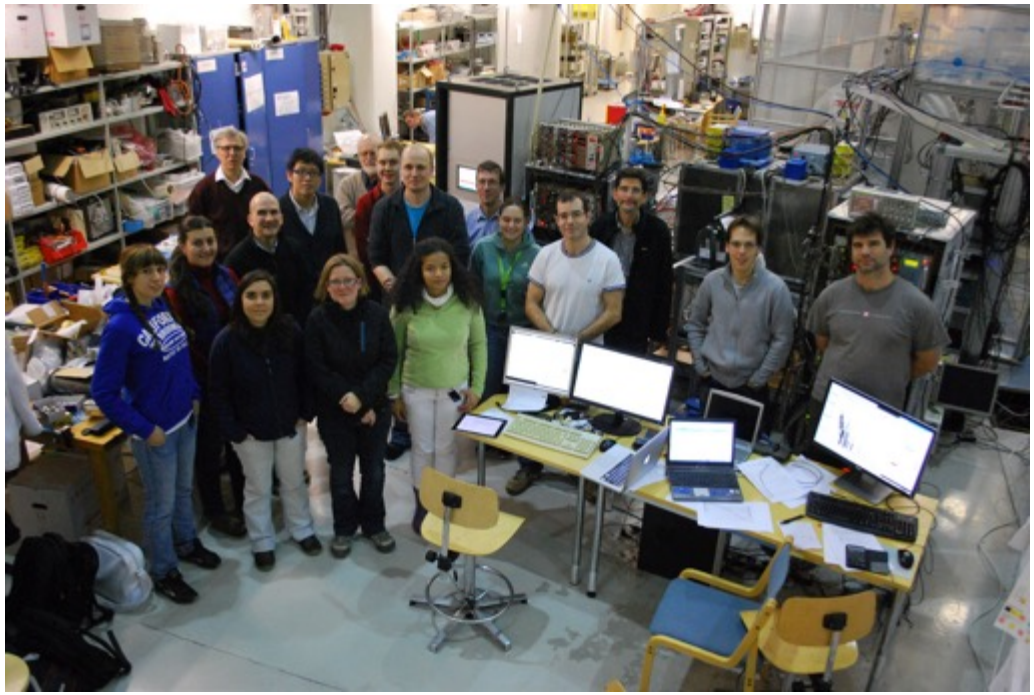
2014 experiment @ Jyvaskyla

Action 3.1.2 : Mesures sans effet Pandemonium (TAGS)

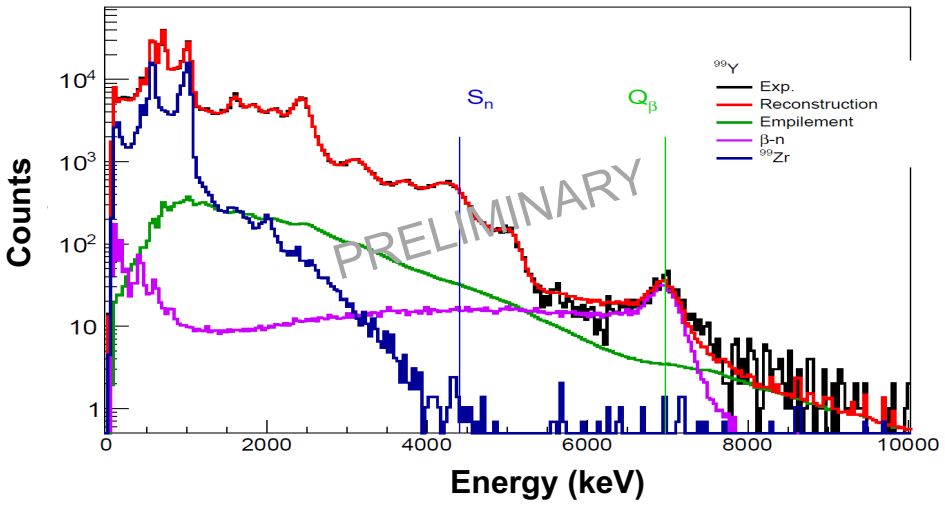




- 12 nuclei for antineutrino and 11 for decay heat were measured
- First use of new DTAS (17+1 NaI) developed by IFIC (Valencia)
- Successful use of the new IGISOL-4 facility
- First use of precision trap with IGISOL-4
- Experiment analyzed by Loic Le Meur (PhD @ Subatech) and Victor Guadilla (PhD IFIC and post-doc Subatech)

An Example: the Case of ^{99}Y

Action 3.1.2 : Mesures sans effet Pandemonium (TAGS)



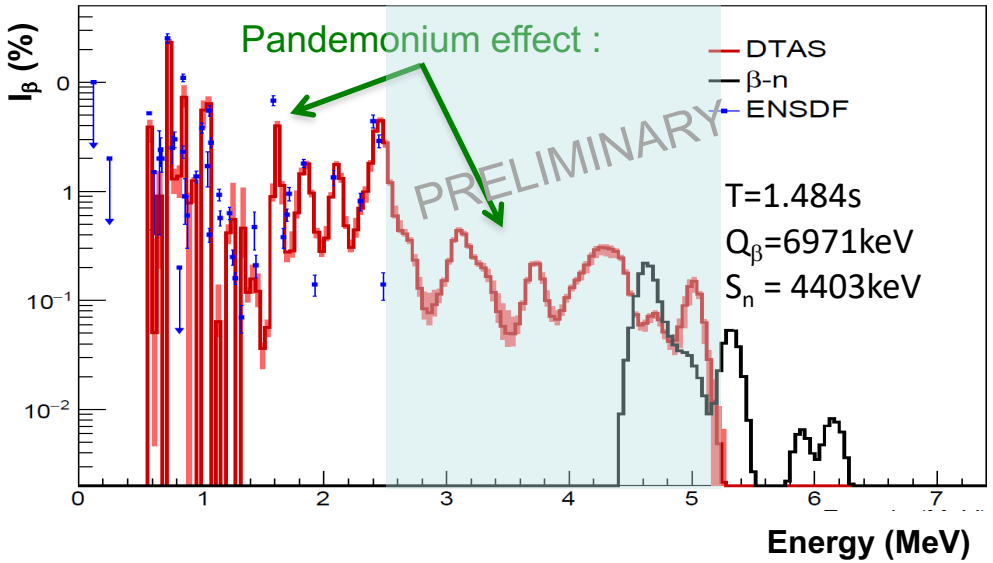
PhD Thesis work:
Loïc Le Meur (Subatech, Nantes)

$$d_i = \sum_j R_{ij} f_j \quad \Rightarrow \quad \mathbf{R_j} = \sum_{k=0}^{j-1} b_{jk} \mathbf{g_{jk}} \otimes \mathbf{R_k}$$

Deconvolution (Inverse problem) algorithms

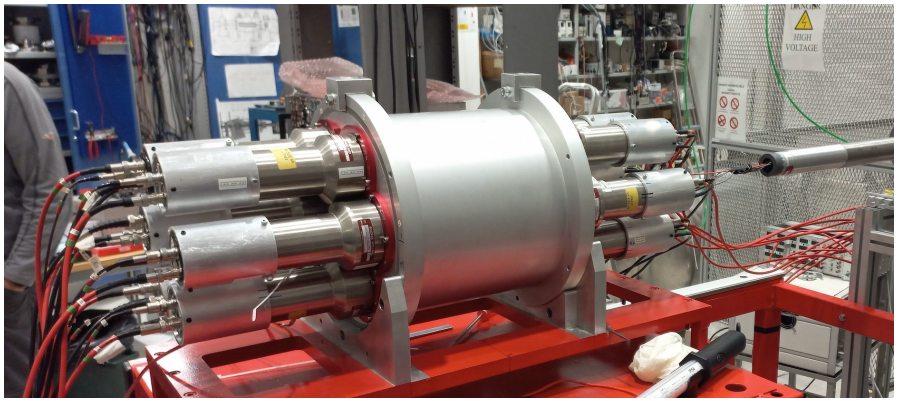
Monte Carlo simulations + Nuclear statistical model

- ^{99}Y → ^{99}Zr ($T_{1/2}$ = 1.484s)
- Experimental spectrum β tagged -> cleaned from background
- Daughter contaminant ^{99}Zr subtracted
- Comparison to ENSDF
  - ❑ Clear Pandemonium case



TAGS experiment at Jyväskylä in September 2022

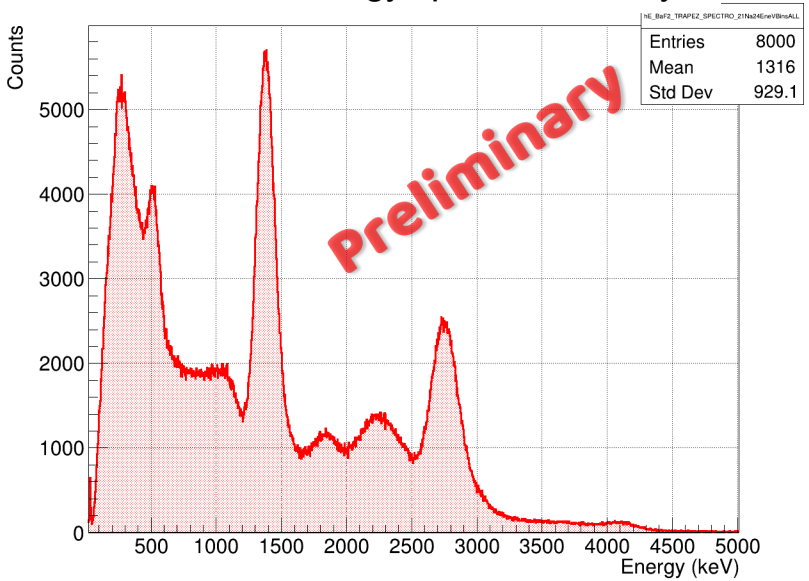
Action 3.1.2 : Mesures sans effet Pandemonium (TAGS)



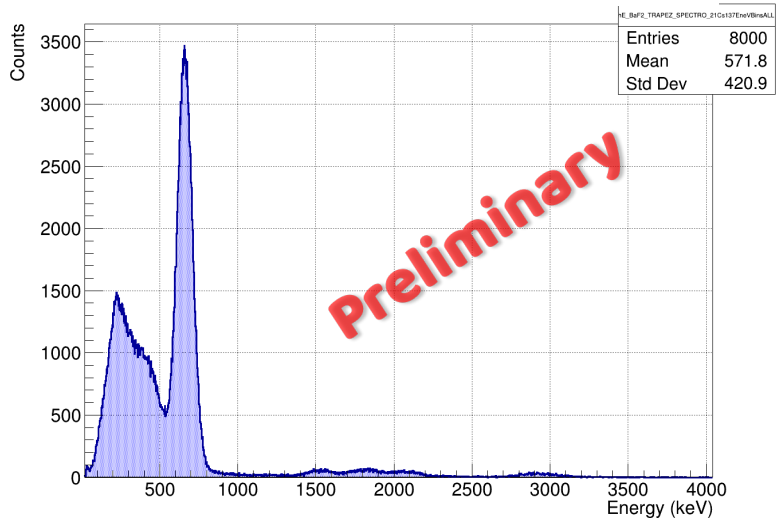
TAGS@IGISOL (Jyväskylä):

- Analysis performed by **Julien Pepin, PhD student co-tutored by Subatech Nantes et IFIC Valencia**
- New **post doc from nov. 23 : Soumen Nandi**
- New analyses code for raw data (alignment of 12 crystals and energy calibration) automatization of the procedure
- Calibration on going

^{24}Na source : energy spectrum of Crystal 1



^{127}CS source : energy spectrum of Crystal 1



Improvement of TAGS detectors: the (NA)²STARS project

- **Upgrade of the existent TAGS detector with 16 $LaBr_3$:Ce**
- **Large efficiency combined with very good energy resolution and timing of $LaBr_3$**
- **Large impact**: **GANIL, DESIR,** RIKEN, Jyväskylä, ISOLDE, FAIR, …
- **Broad Physics Case**: n-rich and n-deficient nuclei, further away from stability
- **Improved energy resolution of $LaBr_3$**
- **n/γ discrimination with TOF**
- **Higher segmentation: possible γ,γ correlation studies**
- Complement other setups

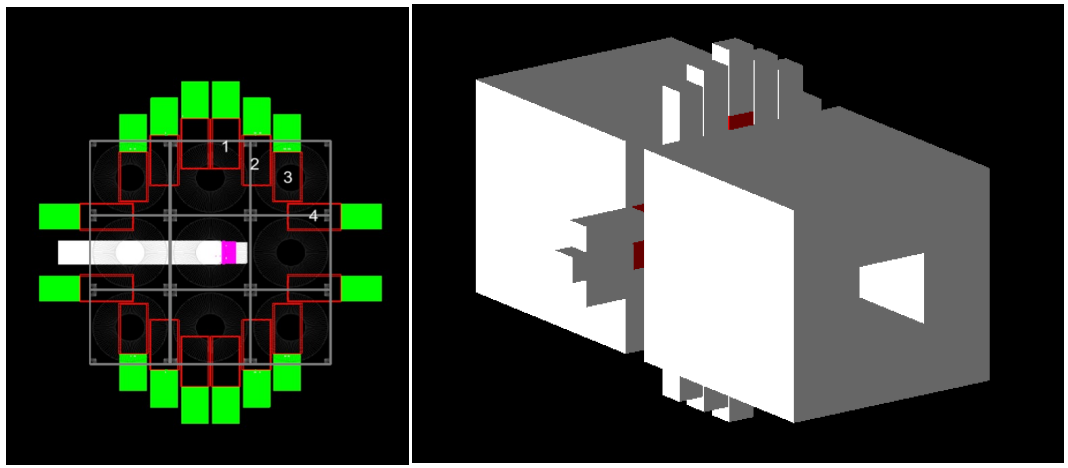


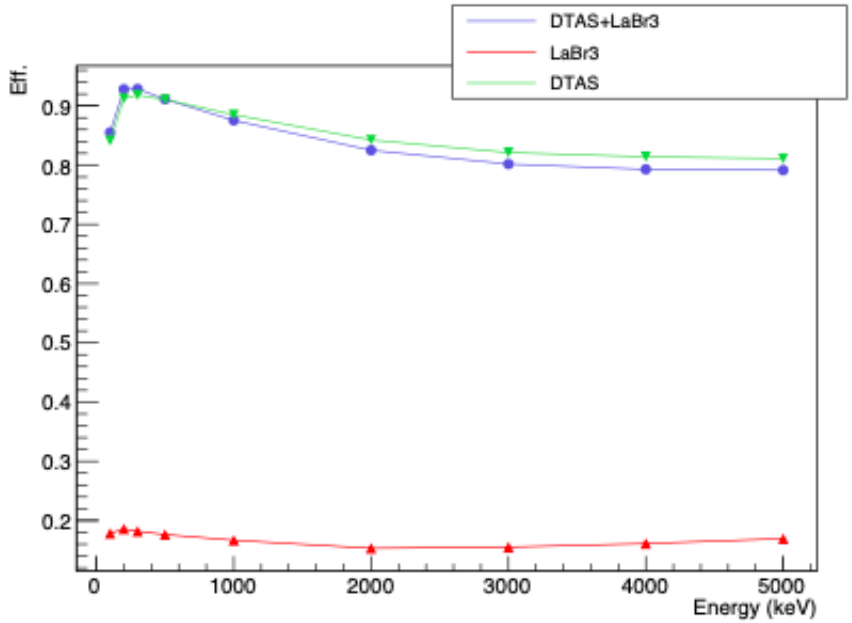
Fig. 4 : view of possible arrangement of the 16 LaBr3:Ce (red) in the middle of the NaI crystals (grey) (courtesy A. Beloeuvre).

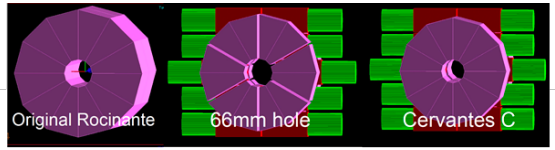
Courtesy A. Beloeuvre (PhD thesis Nantes October 2023)

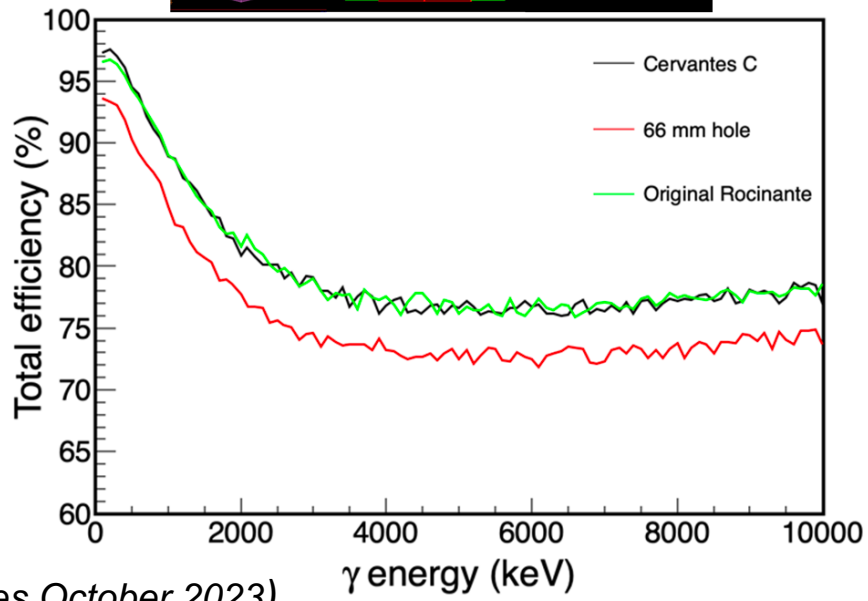
→New opportunities in beta decay measurements for Decay Heat and Reactor Neutrino applications, nuclear astrophysics and structure with a higher resolution, segmented TAGS detector

Status of the (NA)²STARS project

- **Simulation of different configurations performed**







Courtesy A. Beloeuvre (PhD thesis Nantes October 2023)

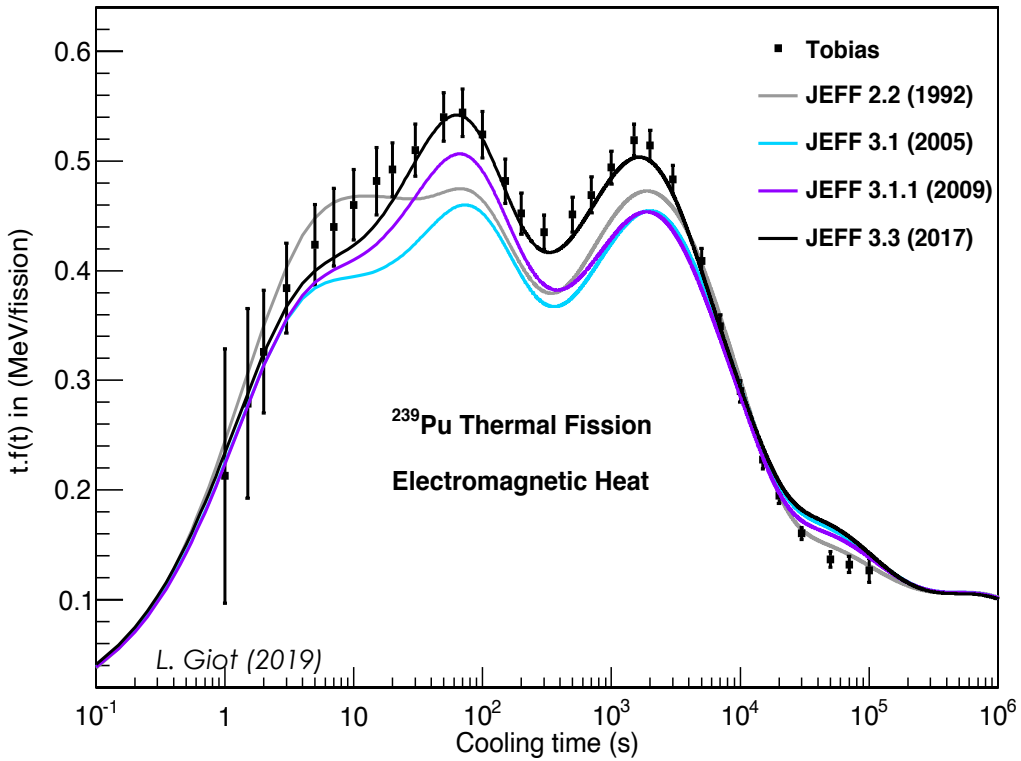
- **Already 8 crystals among partners, performances tests ongoing**
- **Use of $LaBr_3$ modules in complement of other project → participation to Falstaff experiment @ NFS in November 2022 (D. Dore's talk)**
- **Partnership with GANIL → project proposal submitted to GANIL council end 2022 and discussed beginning 2023, very good feedback**
- **Memorandum of Understanding presently under construction with the project partners (Subatech, IP2I Lyon, GANIL, IFIC Valencia, Nuclear Physics Institute of the Czech Academy of Sciences (NPI CAS), CIEMAT Madrid, Univ. of Surrey (UK), IEM CSIC Madrid)**

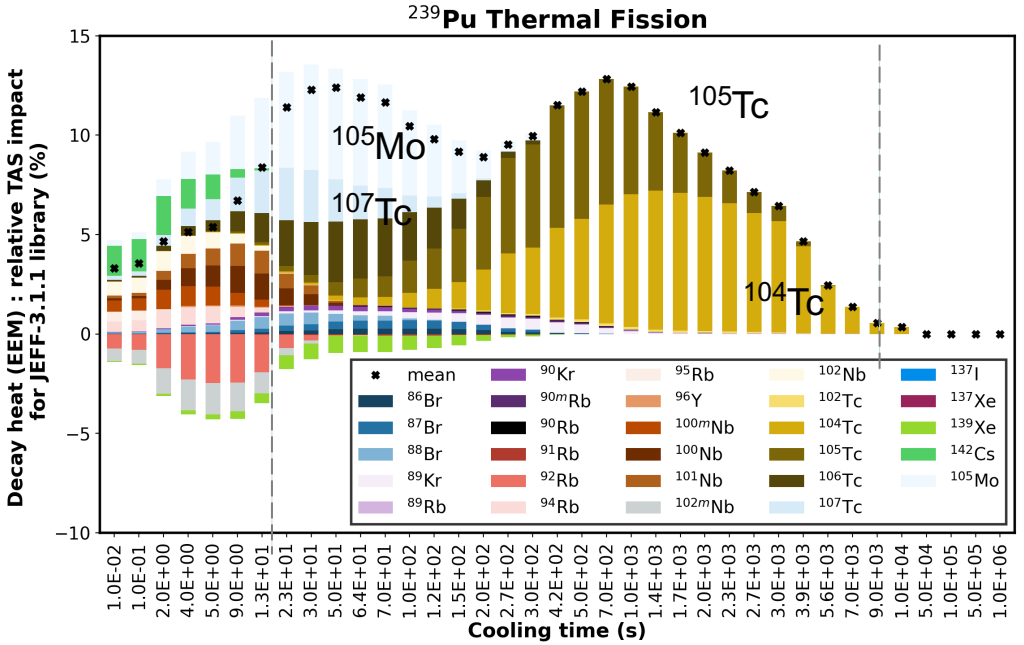
Action 3.4.2 : Développement pour l'upgrade des spectromètres TAS Rocinante et DTAS

Energie moyenne de décroissance et Effet Pandémonium

- **1990s : 50 mesures TAGS par Greenwood et al @ IDAHO National Laboratory**
  Inclusion of 29 noyaux dans JEFF-3.1.1, M. Kellett & O. Bersillon, EPJ Web Conf 146 0209 (2017)

- **9 noyaux inclus dans JEFF-3.3 : ^{87,86}Br, ^{92,94}Rb, ^{105}Mo, $^{104\text{-}107}$Tc**





Action 3.3.1 : Comparaison des outils pour le calcul de la puissance résiduelle

Groupe travail coordonné par la section données nucléaires de l'AIEA

- Serpent2 @Subatech for DH calculations with JEFF libraries w/o TAGS data
- Serpent2 @Subatech also used for comparison :

wrt FISPACT-II + ENDF w/o TAGS data (P. Dimitriou, AIEA)

wrt OYAK98 + JENDL w/o TAGS data (T. Yoshida, Tokyo Inst. Tech. & F. Minato, JAEA)

Action 3.3.2 : Impact TAGS data US et Europe sur le calcul puissance résiduelle

Article de revue publié en 2023, coordonné par l'AIEA

Eur. Phys. J. A (2023) 59:78
https://doi.org/10.1140/epja/s10050-023-00969-x

THE EUROPEAN PHYSICAL JOURNAL A

Review

Improving fission-product decay data for reactor applications: part I—decay heat

A. L. Nichols[1,2], P. Dimitriou[3,a], A. Algora[4,5], M. Fallot[6], L. Giot[6], F. G. Kondev[7], T. Yoshida[8], M. Karny[9], G. Mukherjee[10], B. C. Rasco[11], K. P. Rykaczewski[11], A. A. Sonzogni[12], J. L. Tain[4]

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Action 3.3.2 : Impact TAGS data US et Europe sur le calcul puissance résiduelle

Article de revue publié en 2023, coordonné par l'AIEA

- Impact of the 28 published TAGS nuclei on Decay Heat calculations for 15 systems were studied

Table 1 Irradiated fuel inventories and decay-heat calculations [38,39,40].

thermal neutron pulse (0.0253 eV)	^{235}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{242m}Am, ^{243}Am, ^{243}Cm, ^{245}Cm
fast neutron pulse (400 keV or 500 keV)	^{232}Th, ^{233}U, ^{238}U, ^{237}Np

Fission pulse DH measurements available

- Systems chosen to compare with FISPACT-II DH calc. and classical libraries (ENDF/B-VII.1, JEFF3.1.1, JENDL4-0)

M. Fleming, J. C. Sublet, 2015, CCFE-R15-28

A. Nichols et al., EPJ A 59:78, 2023

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Action 3.3.2 : Impact TAGS data US et Europe sur le calcul puissance résiduelle

TAS Collaboration : IFIC Valencia, Univ. of Surrey, Subatech

3 experimental campaigns (2007, 2009, 2014) + Experiment 09/2022 @Jyvaskyla

MTAS Collaboration : Univ. of Warsaw, ORNL, Univ of Tennessee

Experiments @ Argonne National Laboratory's CARIBU facility

Isotope	Rel.	Isotope	Rel.	Isotope	Rel.
35-Br-86†*	1	41-Nb-99†	1	52-Te-135†	2
35-Br-87†*	1	41-Nb-100†*	1	53-I-136†	1
35-Br-88†*	1	41-Nb-101†*	1	53-I-136m†	1
36-Kr-89†	1	41-Nb-102†*	2	53-I-137†*	1
36-Kr-90†	1	42-Mo-103†*	1	54-Xe-137†	1
37-Rb-90m	2	42-Mo-105*	1	54-Xe-139†	1
37-Rb-92†*	2	43-Tc-102†*	1	54-Xe-140†	1
38-Sr-89	2	43-Tc-103†*	1	55-Cs-142*	3
38-Sr-97	2	43-Tc-104†*	1	56-Ba-145	2
39-Y-96†	2	43-Tc-105*	1	57-La-143	2
40-Zr-99†	3	43-Tc-106*	1	57-La-145	2
40-Zr-100†	2	43-Tc-107*	2		
41-Nb-98†*	1	51-Sb-132†	1		

Parent nuclides identified per WPEC-25 for TAGS meas. for $^{235}U/^{239}Pu$ reactors, (NEA, T. Yoshida/ A. Nichols, 2007)

+ $^{91,94,95}Rb$, ^{96m}Y

+ $^{89,90}Rb$

In total, 29 published nuclei (^{96m}Y published after IAEA report)

A. Algora et al., EPJ A 57, 2021

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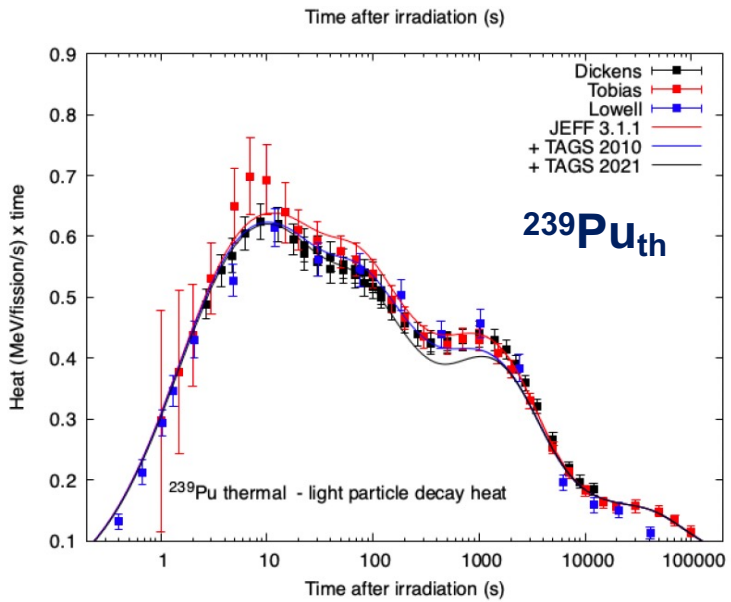
Action 3.3.2 : Impact TAGS data US et Europe sur le calcul puissance résiduelle

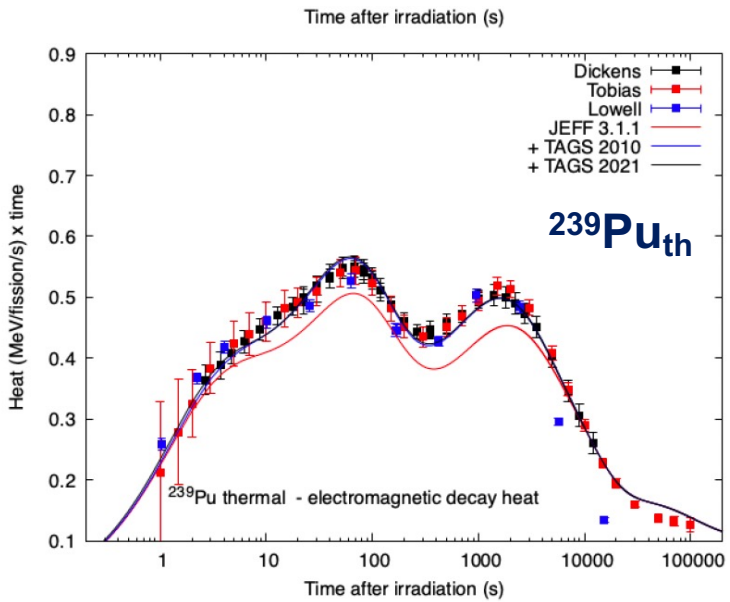
- For each fissioning system:

  3 sets of DH calculations combining the same FY library each time with :

  - Decay Data without the Algora 2010 TAGS data: reference library or baseline
  - Decay Data with the Algora 2010 TAGS data : ^{101}Nb, ^{105}Mo, $^{102, 104-107}$Tc (+TAGS 2010)
  - Decay Data with the 2021 TAGS published data : (+ TAGS 2021)

+ TAGS 2010 : improved agreement for $^{239}Pu_{th}$, $^{241}Pu_{th}$





Same conclusions with ENDF library

A. Nichols et al., EPJ A 59:78, 2023

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Action 3.3.2 : Impact TAGS data US et Europe sur le calcul puissance résiduelle

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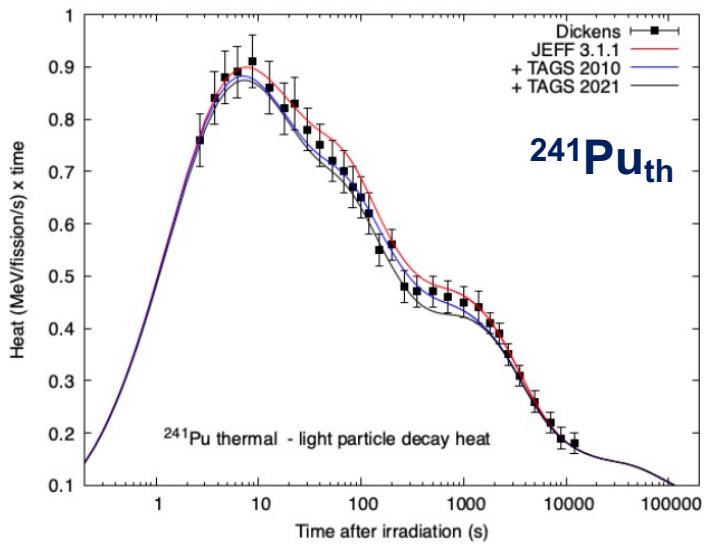
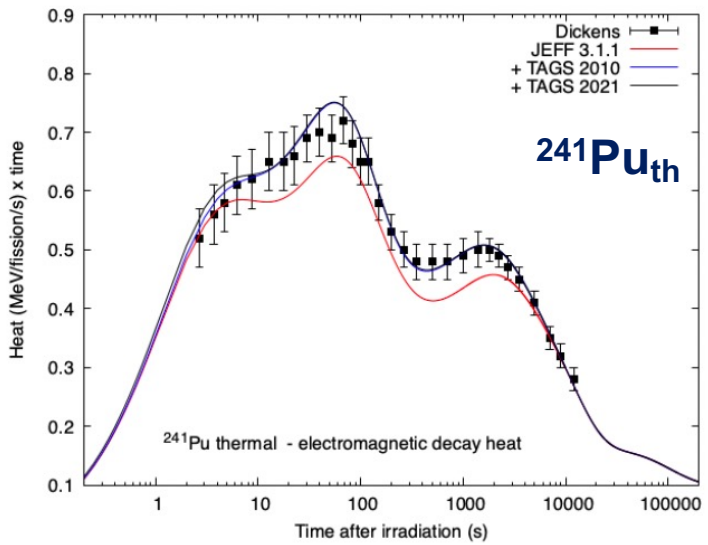
  - Decay Data with the 2021 TAGS published data : + TAGS 2021

+ TAGS 2010 : improved agreement for $^{239}Pu_{th}$, $^{241}Pu_{th}$





Same conclusions with ENDF library

A. Nichols et al., EPJ A 59:78, 2023

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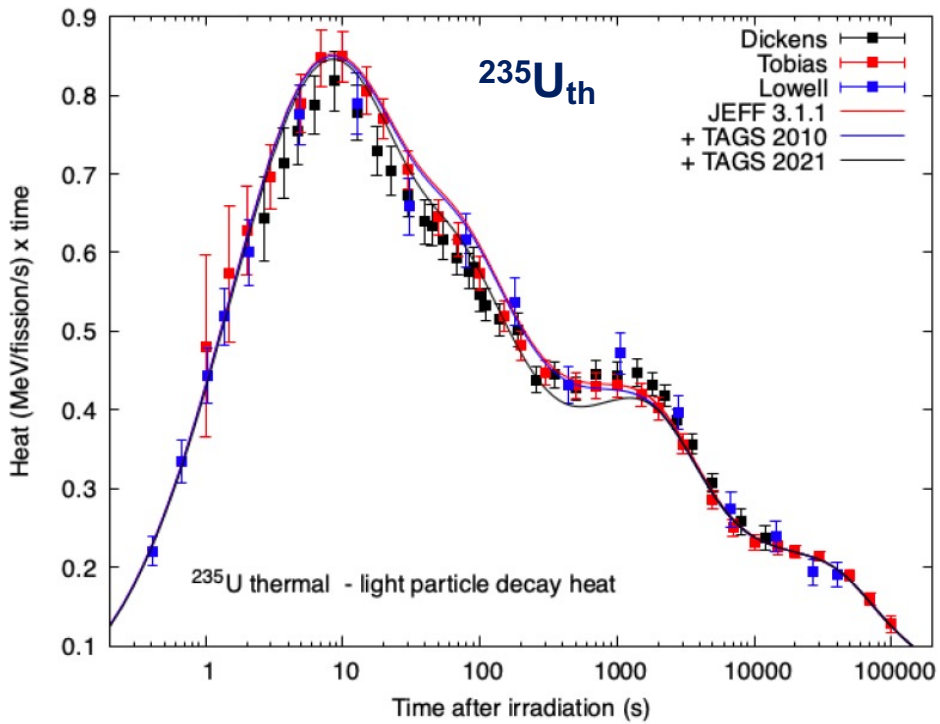
Action 3.3.2 : Impact TAGS data US et Europe sur le calcul puissance résiduelle

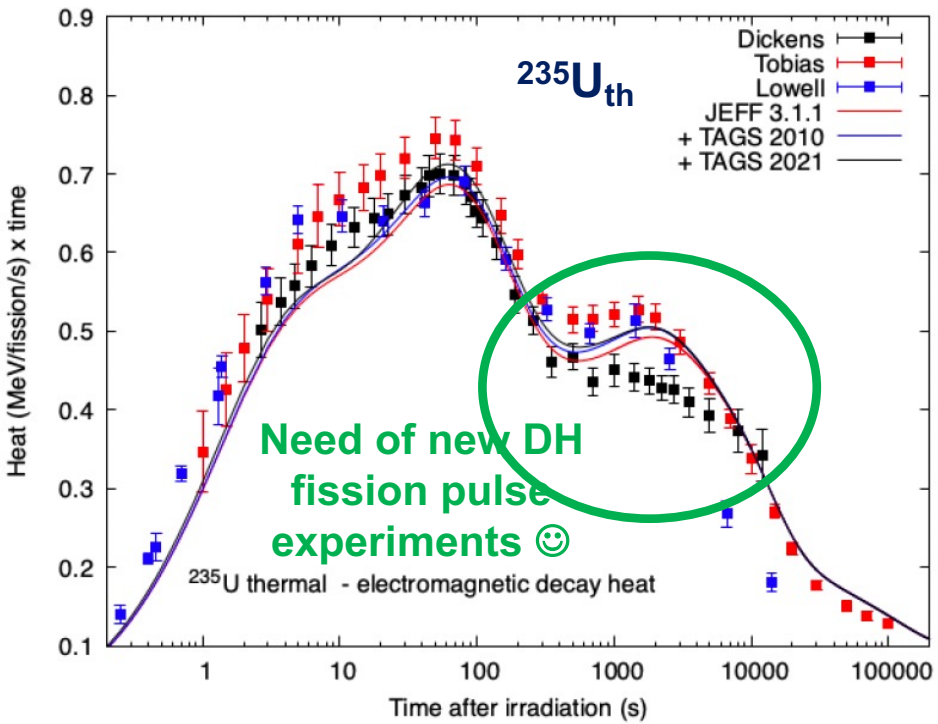
$^{235}U_{th}$

+ TAGS 2010 : no impact on ELP component

+ TAGS 2021 : ELP slightly improved in 10-400s but underestimation in 400-1000s

Hard to say on EEM wrt differences between the 3 experimental sets !

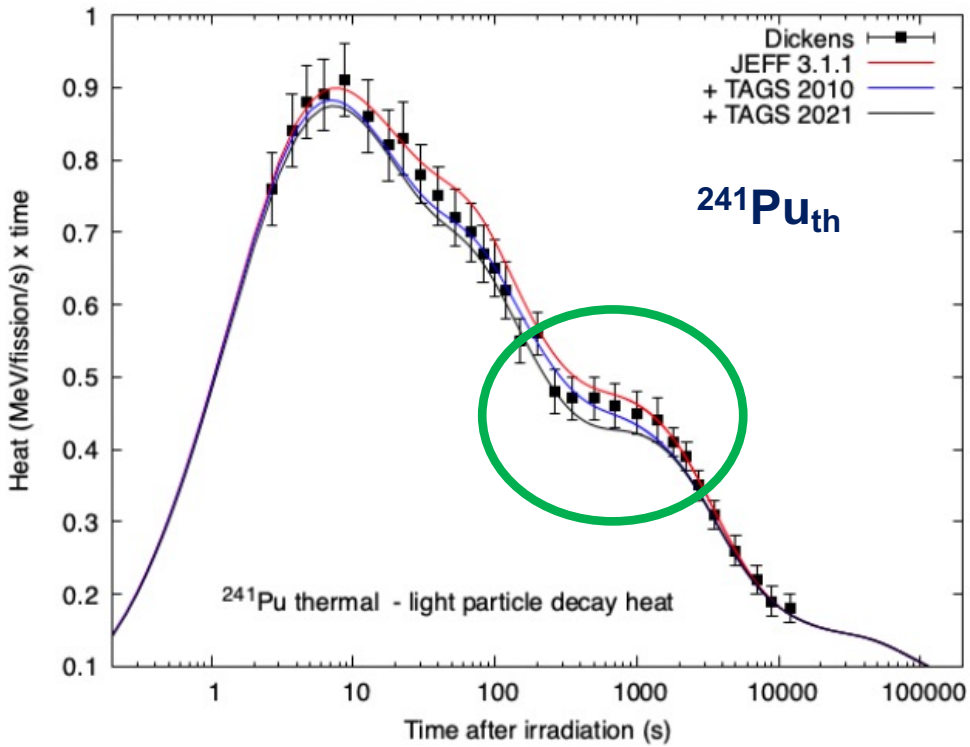


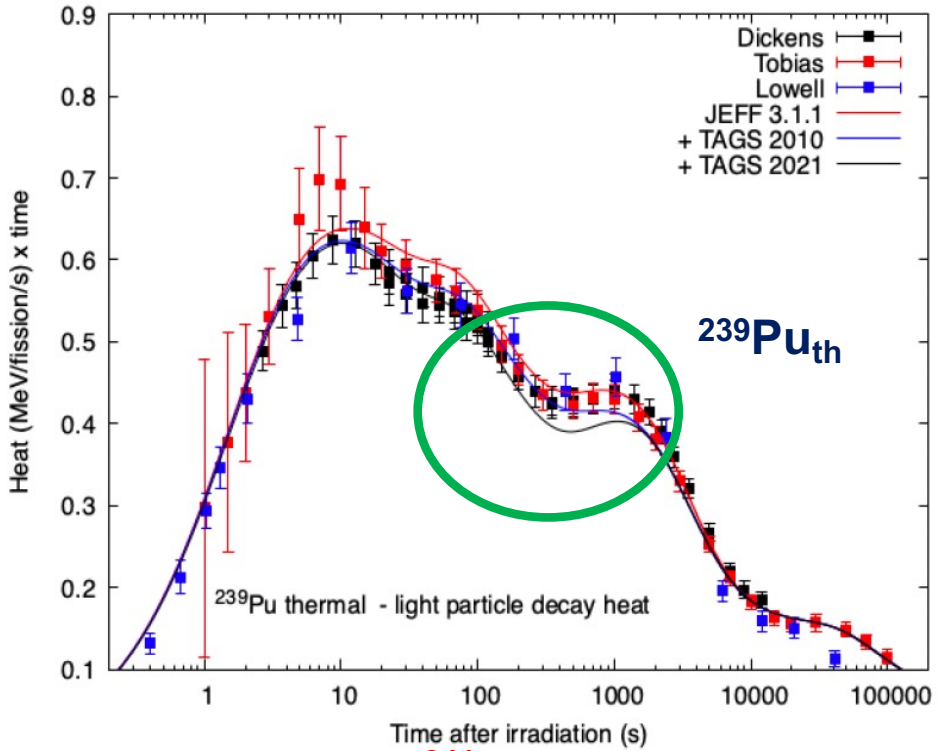


Same conclusions with ENDF library

Action 3.3.2 : Impact TAGS data US et Europe sur le calcul puissance résiduelle

+ TAGS 2021 : small under estimation of ELP component for $^{235}U_{th}$, $^{239}Pu_{th}$, $^{241}Pu_{th}$, at cooling times ranging from 30s to 1000s





=> Only one set of experimental data, till in the errors bars for $^{241}Pu_{th}$

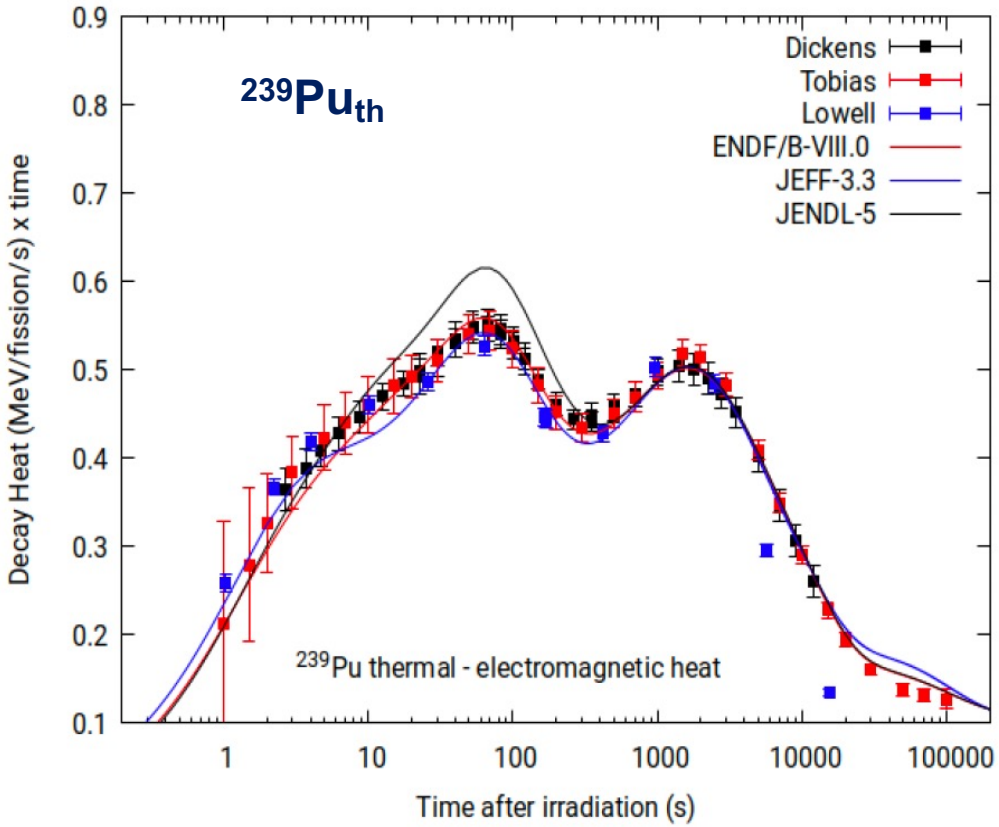
=> Needs for extra experimental data but also extra investigation on key FP suffering of Pandemonium effect

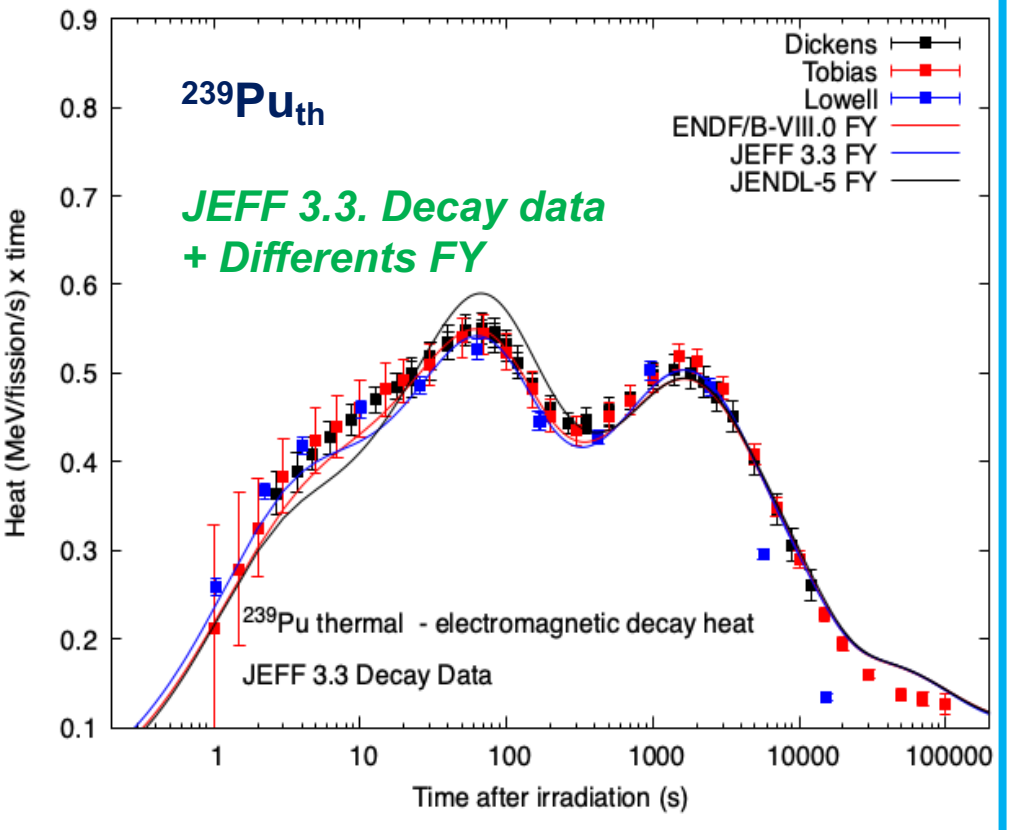
A. Nichols et al., EPJ A 59:78, 2023

Action 3.3.2 : Comparaison des bases de données évaluées relatives aux rendements de fission

Overestimation of EEM component for JENDL5 for $^{239}Pu_{th}$

Seems to be related mostly to Fission Yields …





A. Nichols et al., EPJ A 59:78, 2023

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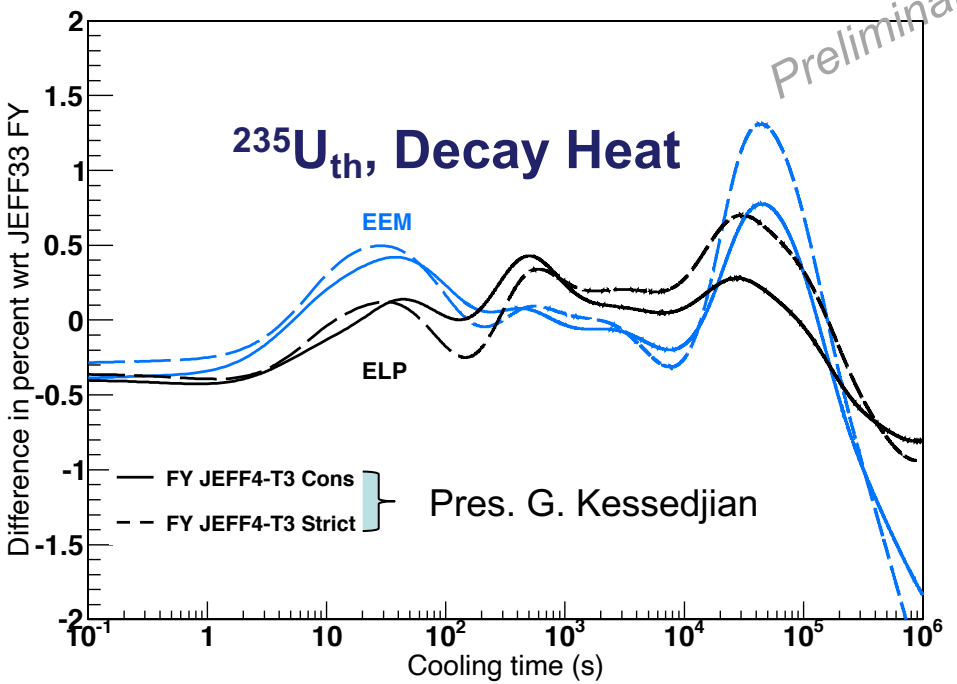
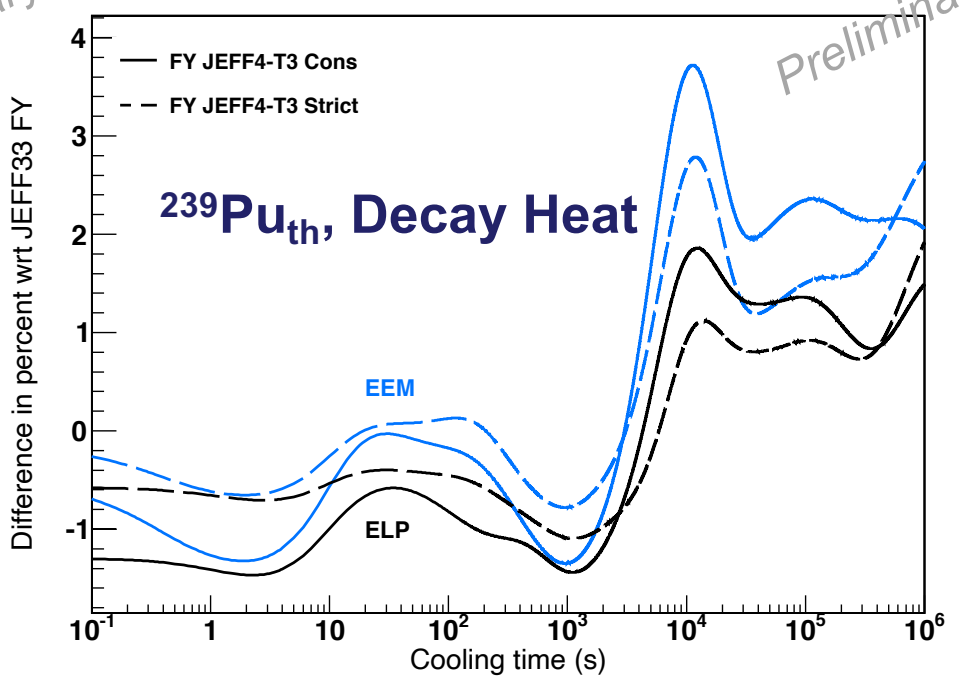
Action 3.3.2 : Comparaison des bases de données évaluées relatives aux rendements de fission

Premiers calculs de puissance résiduelle avec les rendements de fission JEFF4-T3 (NEA, 11/23), Analyse des effets en cours

Normalization issue in the FY release on the NEA website => will be replaced soon per a new version





En cours Action 3.3.3:

COCODRILO

Propagation incertitudes FY sur P_{Res} (matrices de cov. FY / JEFF4-T3), Thèse Y. Molla

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Conclusions and prospective

Action 3.1.2 : Mesures sans effet Pandemonium (TAGS) :

- Analyse de l'expérience 2014 terminée, la plupart des cas déjà publiées ou en cours de publication
- Expérience en septembre 2022 → analyse en cours

Action 3.4.2 : Développement pour l'upgrade des spectromètres TAS Rocinante et DTAS => (NA)2STARS :

- Financement en bonne voie, probable démarrage du projet cet année.

Action 3.3.1 Comparaison des outils de simulation de la puissance résiduelle:

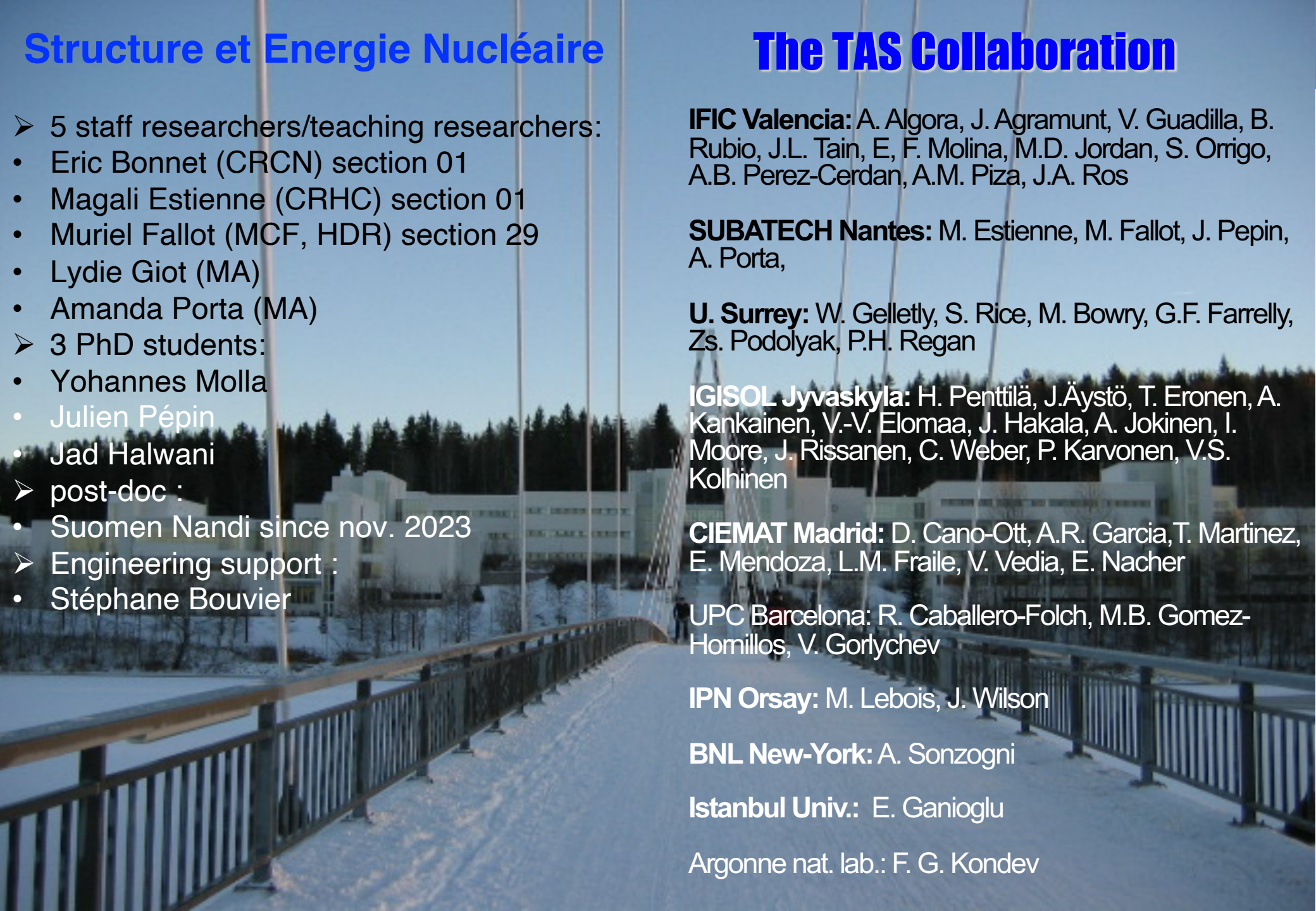
- Comparaison fait sur Serpent2, FISPAC-II and OYAK98

Action 3.3.2 Comparaison des bases de données évaluées relative aux données de décroissance ET aux rendements de fission :

- Analyse de l'impact des données TAGS sur le calcule de la puissance résiduelle
- Comparaison des bases de données évaluées relatives aux rendements de fission → en cours

Action 3.3.3 Propagation des incertitudes expérimentales sur les observables d'intérêt → en cours

MERCI de votre attention



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