Evaluation issues in the Resolved Resonance Range of Pu

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APRENDE Experimentalists-Evaluators workshop (WP2-WP4), 6-7/06/2026, EPFL Lausanne

JEFF-4 evaluations with CEA/Cadarache participation

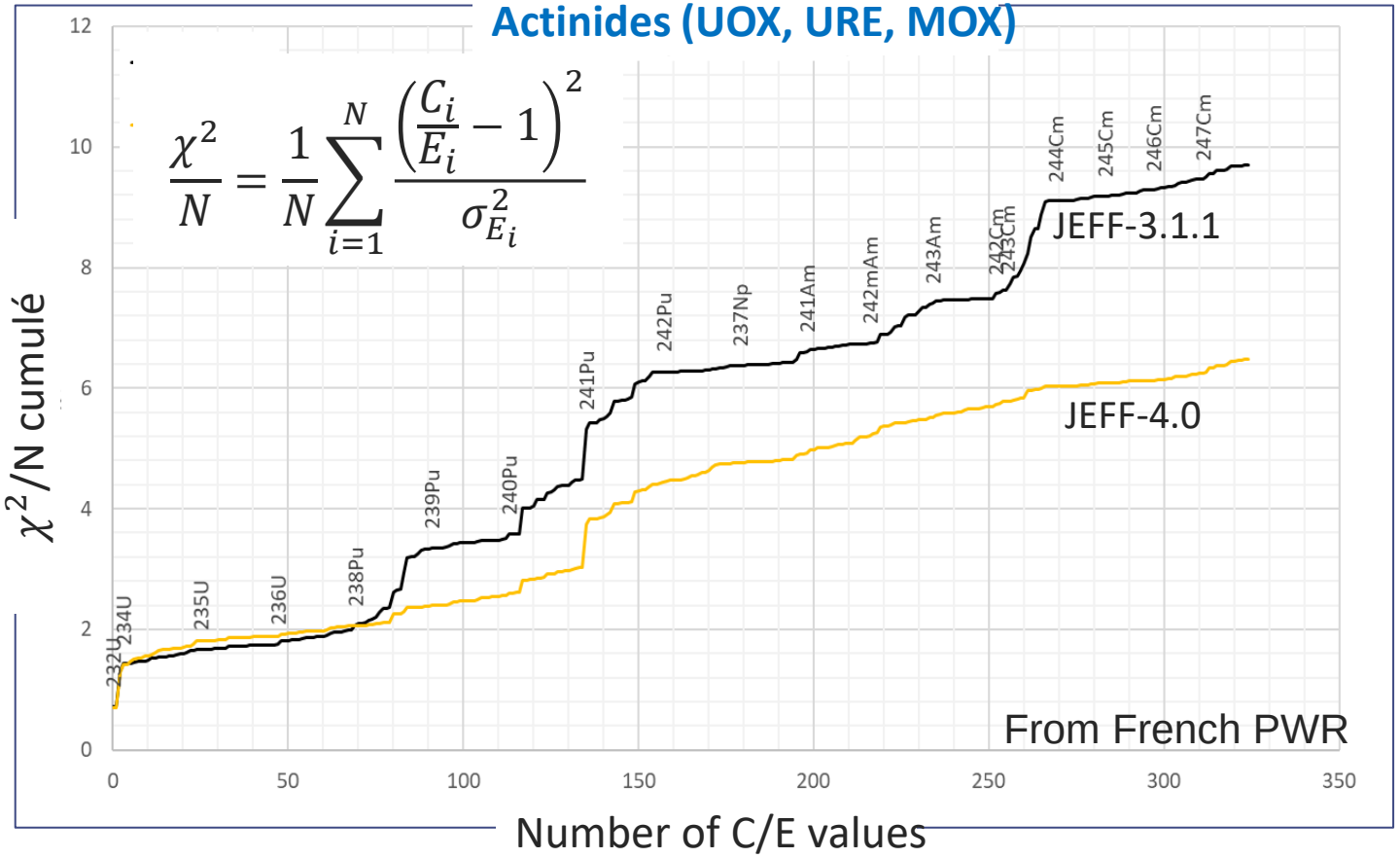
Test libraries	General purpose files		Fission Yields	Thermal Scattering Laws	Decay Data	Alpha reaction sublibrary
	Fission Products	Actinides				
Evaluations disponibles JEFF4T4	• Tc99 • Rh105 • Ag107, Ag109 • Pd108 • Te127m • Xe124, Xe126, Xe128, Xe-129, Xe130, Xe131, Xe132, Xe134, Xe135, Xe136 • Cs133, Cs134, Cs135 • Pm147, Pm148g, Pm148m, Pm149 • Gd153 • Eu151, Eu153, Eu154, Eu155 • Lu173, Lu175, Lu176 • La139 • Tm171 • Os186, Os188, Os187	• Np237 • U235,U236 • Am241, Am243 • Pu238, Pu239, Pu240, Pu241, Pu242	• Pu239 • U235	• UO2 • PuO2		
Nouvelles évaluations JEFF4T5	• Mo95, Mo97 • Nd143, Nd144, Nd145 • Pd105, Pd106 • Ru101 • Te128 • Sm147, Sm148, Sm149	• U234, U233, U235, U238 • Np239 • Th227, Th228, Th229, Th232, Th233 • Cm244, Cm246	• Pu241 • U233	• ThO2 • Zy4		
A finaliser JEFF4	• Sm150, Sm151				• Sb129m • Am242g	• $^{9}Be+\alpha$

Outline

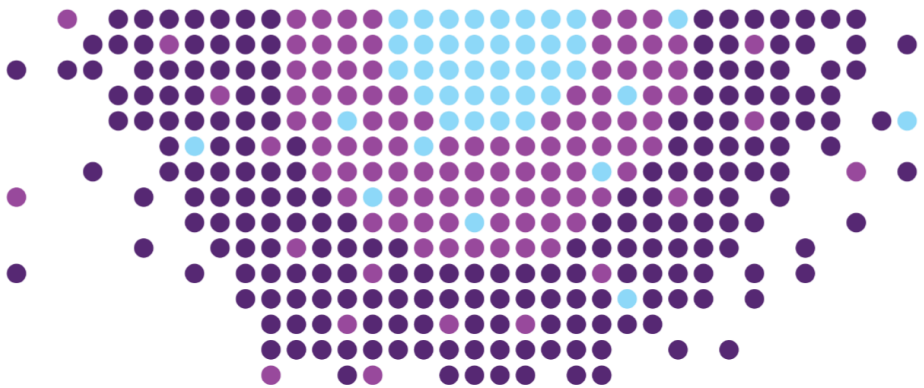
- Review PIE trends for UOX, URE and MOX fuels
- Work plan for Pu239
- Work plan for Pu238, Pu240, Pu242
- Focus on Pu239 fission observables with TALYS
- Conclusions

Review PIE trends for UOX, URE and MOX fuels

Jean Charles Jaboulay (CEA Cadarache)



Luca Fiorito (SCK)



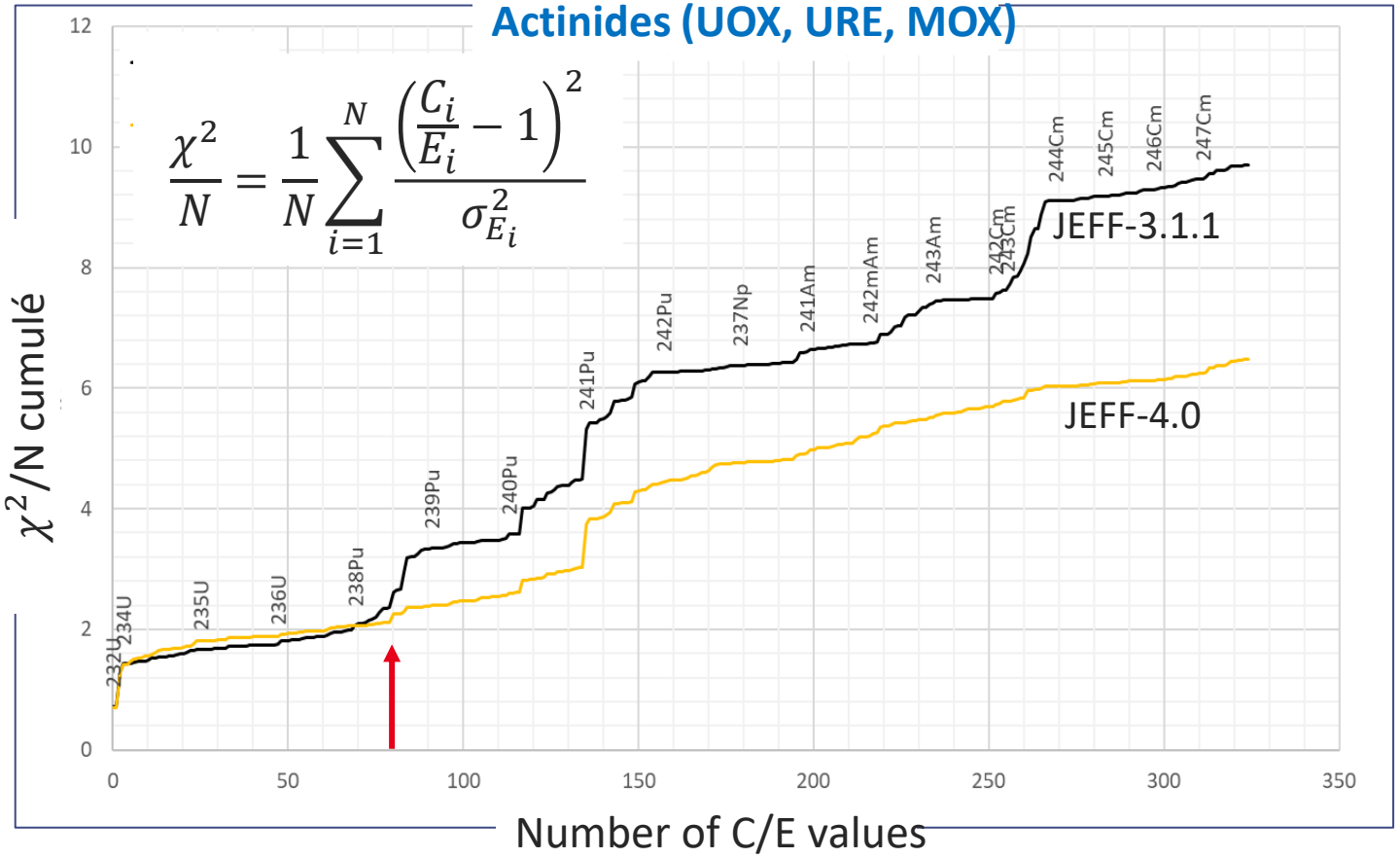
sck cen
Belgian Nuclear Research Centre

Luca Fiorito and Pablo Romojaro - 20/11/2025

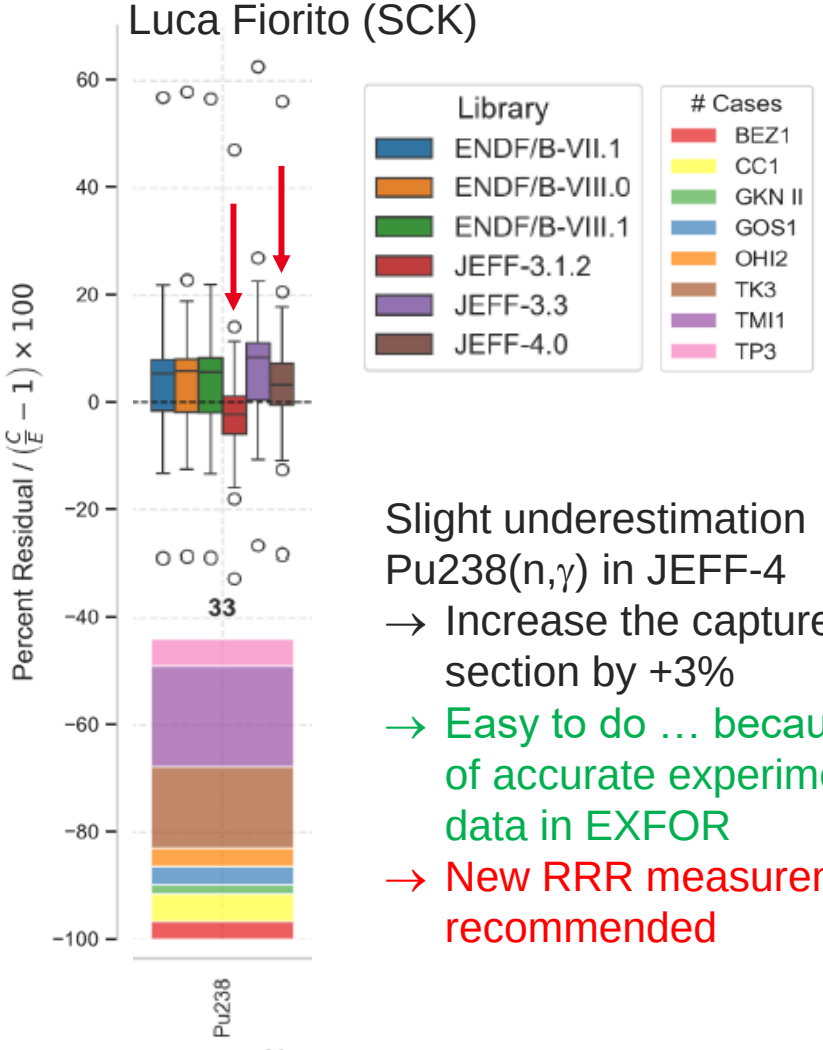
JEFF-4.0 feedback from SFCOMPO benchmark cases

Pu238(n,γ)

Jean Charles Jaboulay (CEA Cadarache)



Luca Fiorito (SCK)



Slight underestimation Pu238(n,γ) in JEFF-4

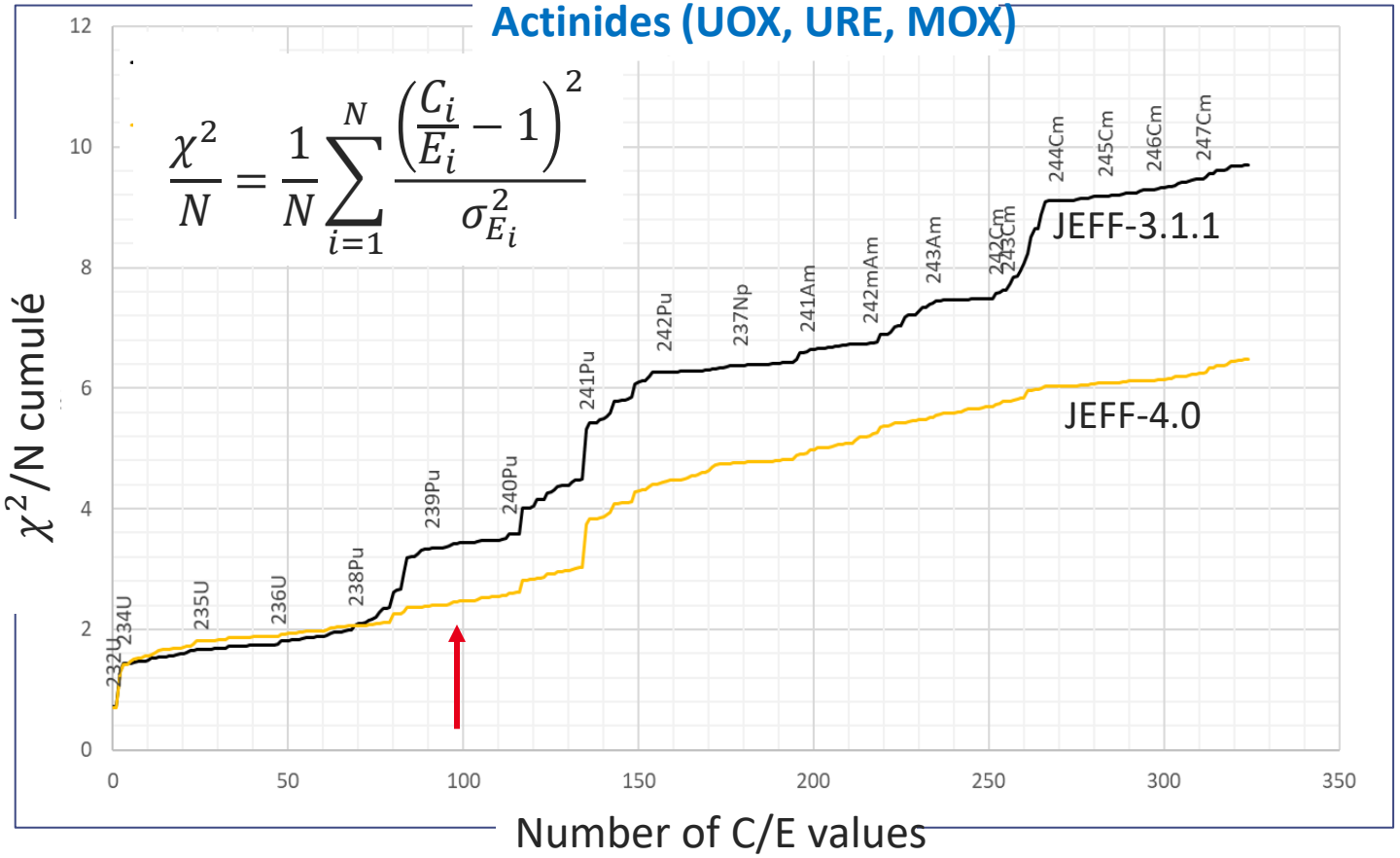
→ Increase the capture cross section by +3%

→ Easy to do … because lack of accurate experimental data in EXFOR

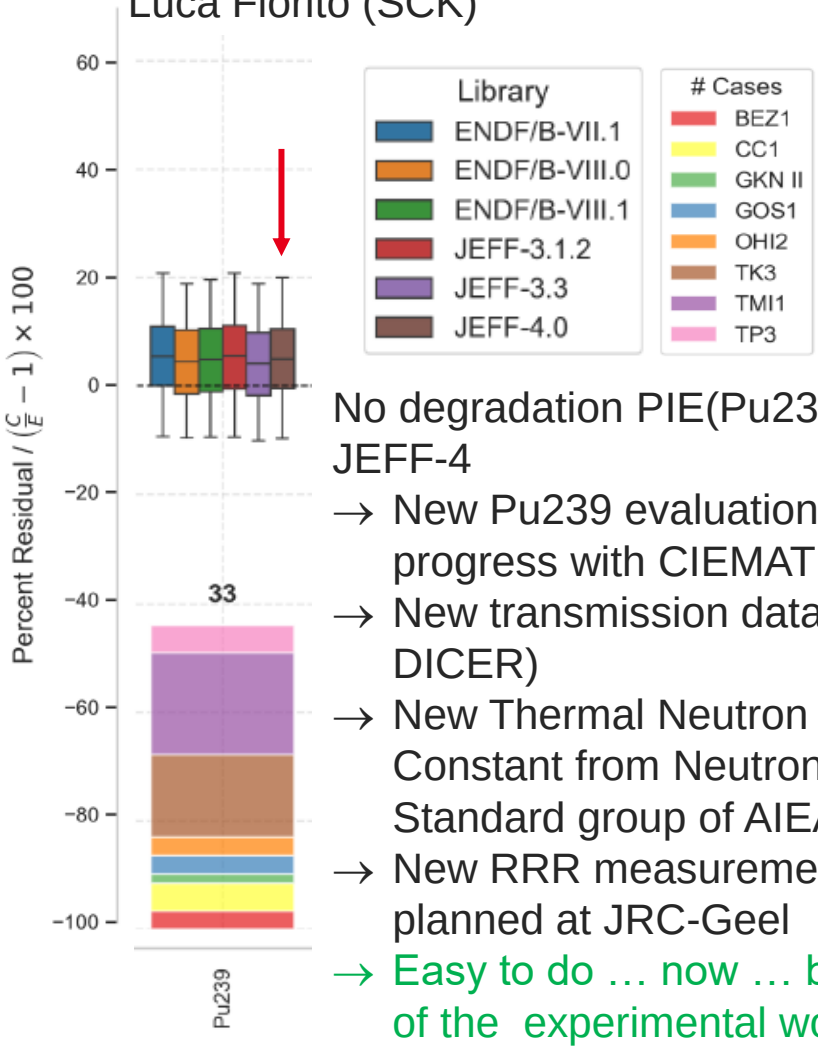
→ New RRR measurements is recommended

Pu239(n,γ)

Jean Charles Jaboulay (CEA Cadarache)



Luca Fiorito (SCK)



No degradation PIE(Pu239) with JEFF-4

→ New Pu239 evaluation in progress with CIEMAT data

→ New transmission data (LANL, DICER)

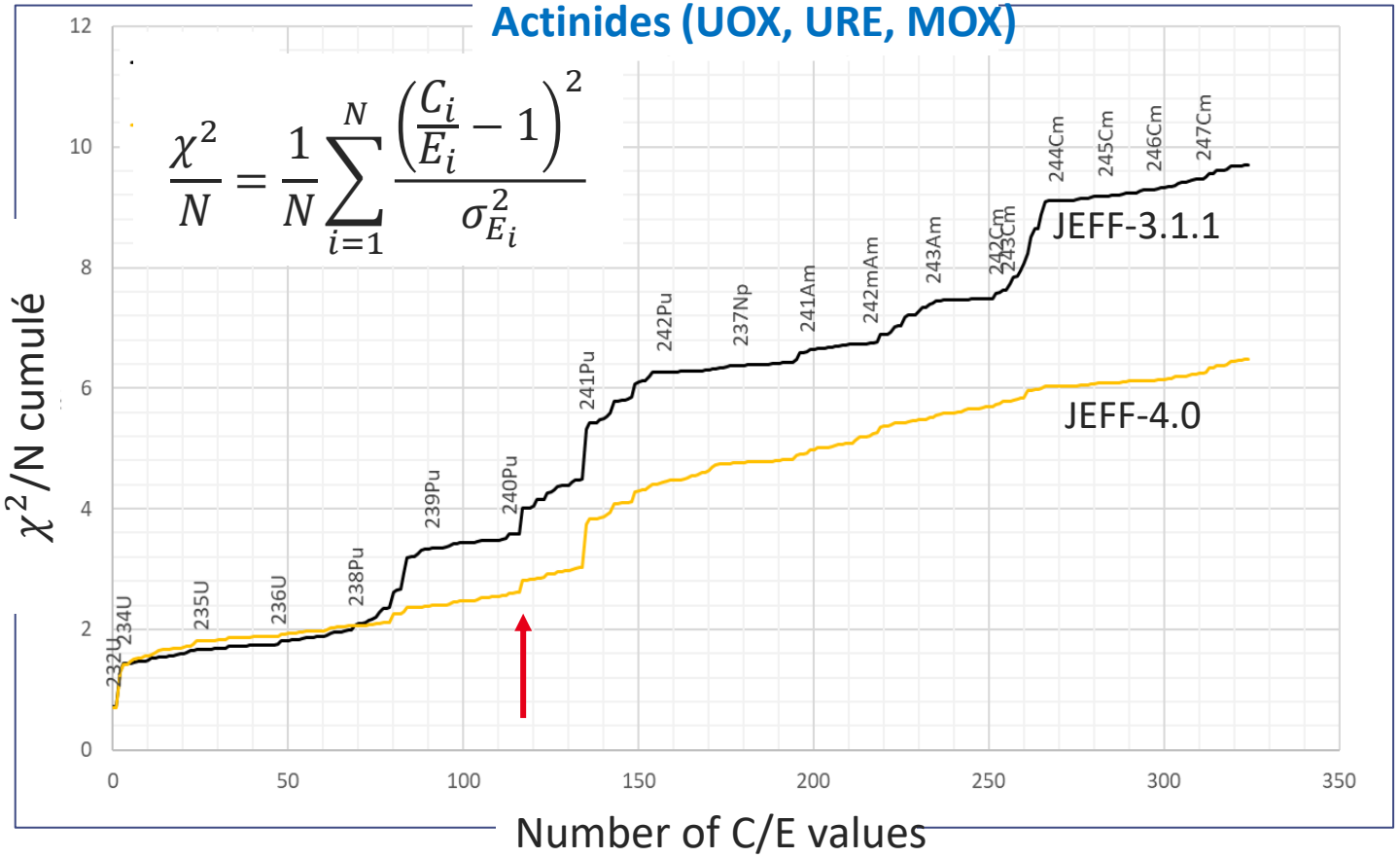
→ New Thermal Neutron Constant from Neutron Data Standard group of AIEA

→ New RRR measurements planned at JRC-Geel

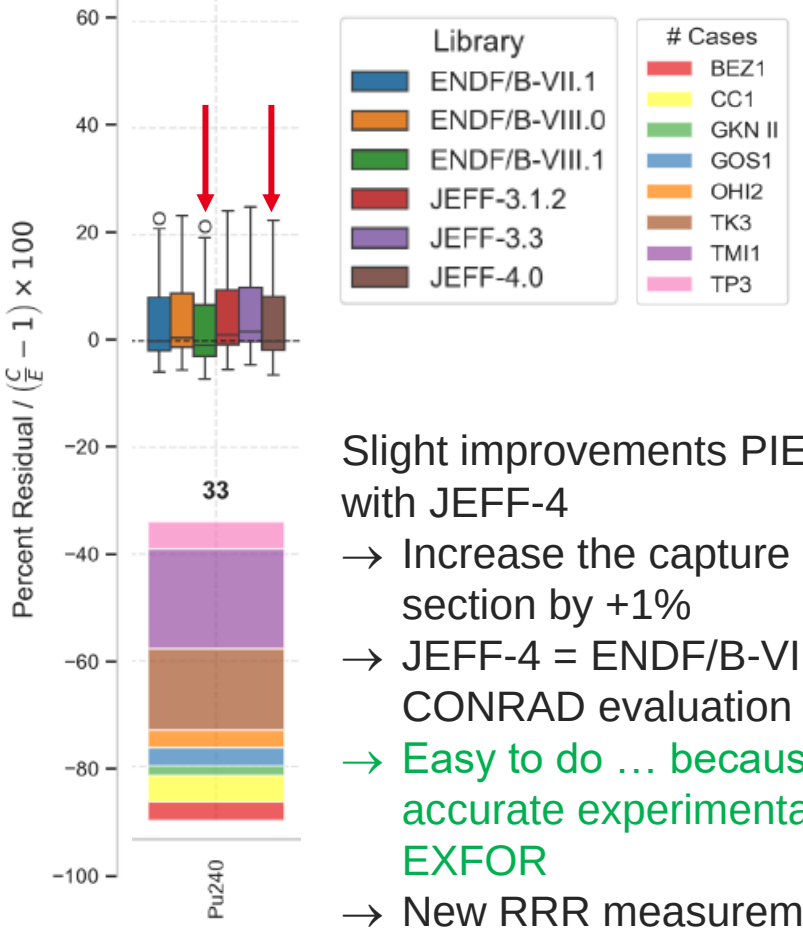
→ Easy to do … now … because of the experimental work performed by CIEMAT

Pu240(n,γ)

Jean Charles Jaboulay (CEA Cadarache)



Luca Fiorito (SCK)



Slight improvements PIE(Pu240) with JEFF-4

→ Increase the capture cross section by +1%

→ JEFF-4 = ENDF/B-VIII.1 = CONRAD evaluation

→ Easy to do … because lack of accurate experimental data in EXFOR

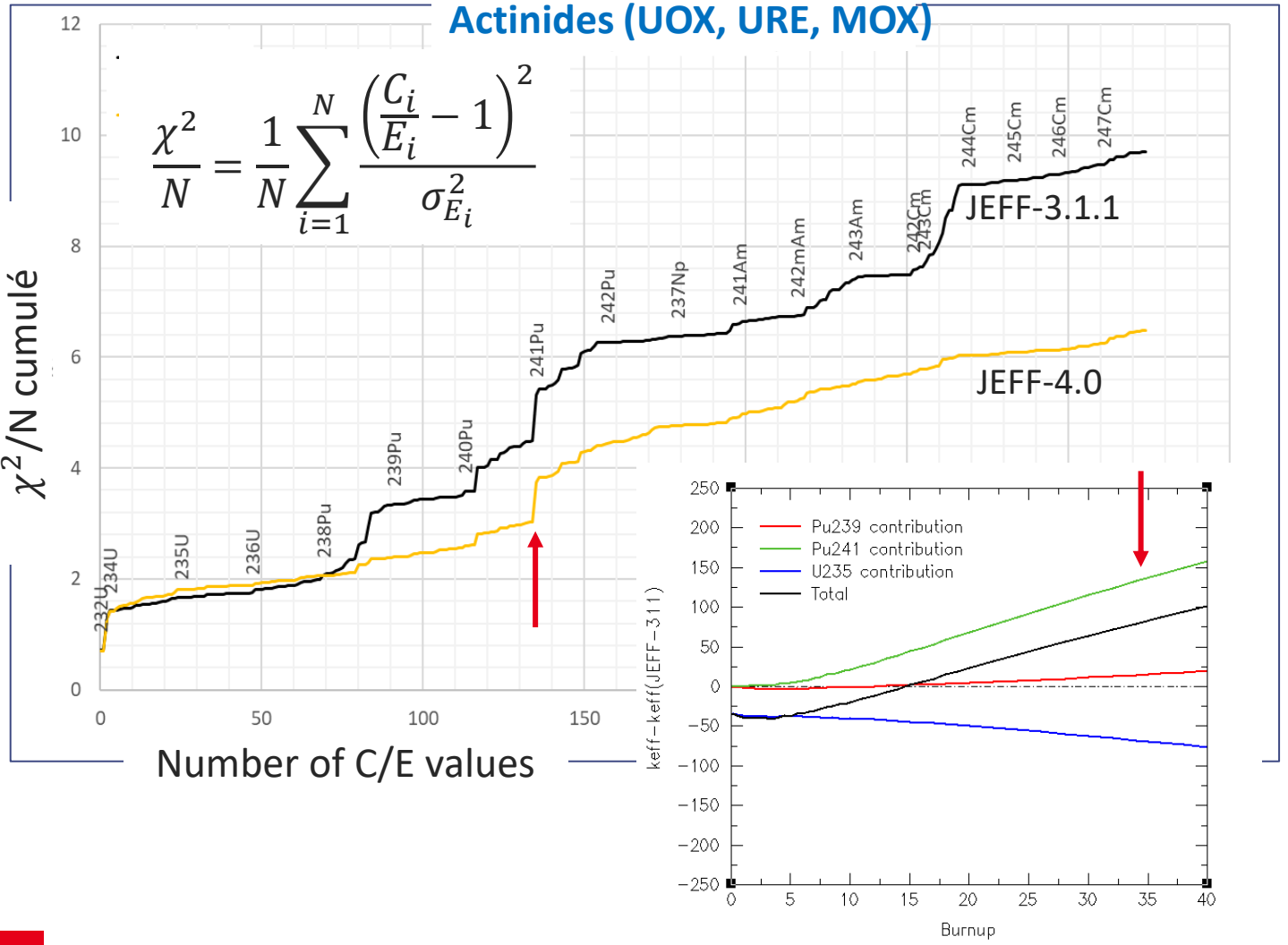
→ New RRR measurements planned at JRC-Geel

Pu241(n,γ)

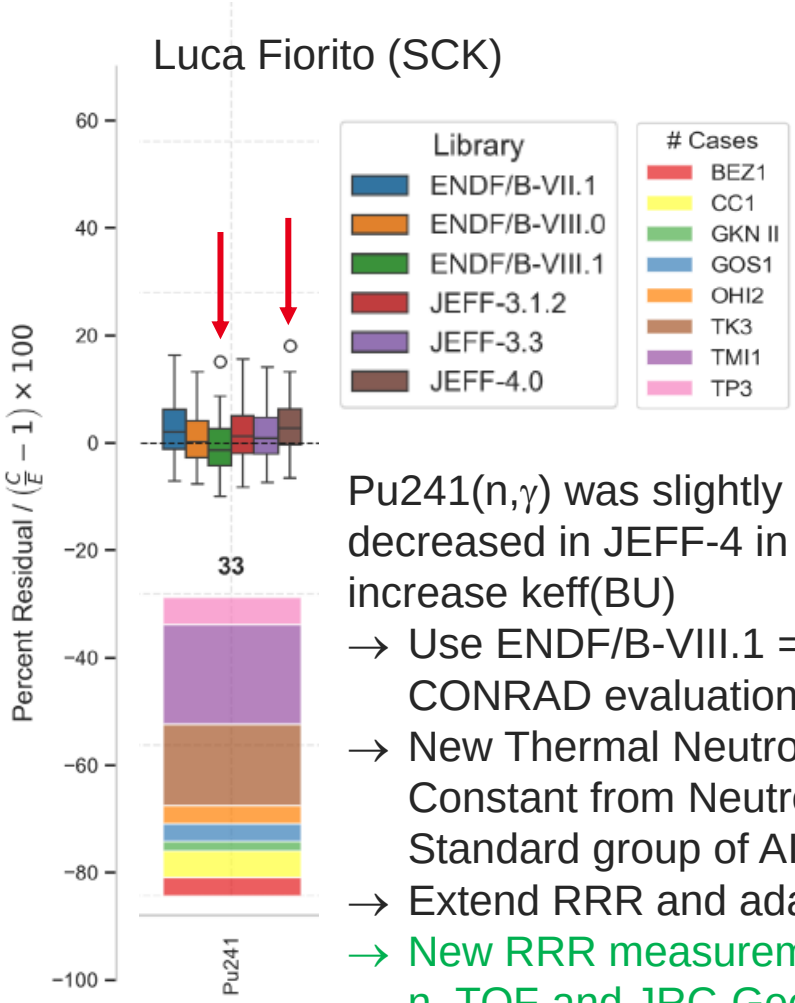
Jean Charles Jaboulay (CEA Cadarache)

Actinides (UOX, URE, MOX)

$$\frac{\chi^2}{N} = \frac{1}{N}\sum_{i=1}^{N}\frac{\left(\frac{C_i}{E_i}-1\right)^2}{\sigma_{E_i}^2}$$



Luca Fiorito (SCK)



Pu241(n,γ) was slightly decreased in JEFF-4 in order to increase keff(BU)

→ Use ENDF/B-VIII.1 = CONRAD evaluation

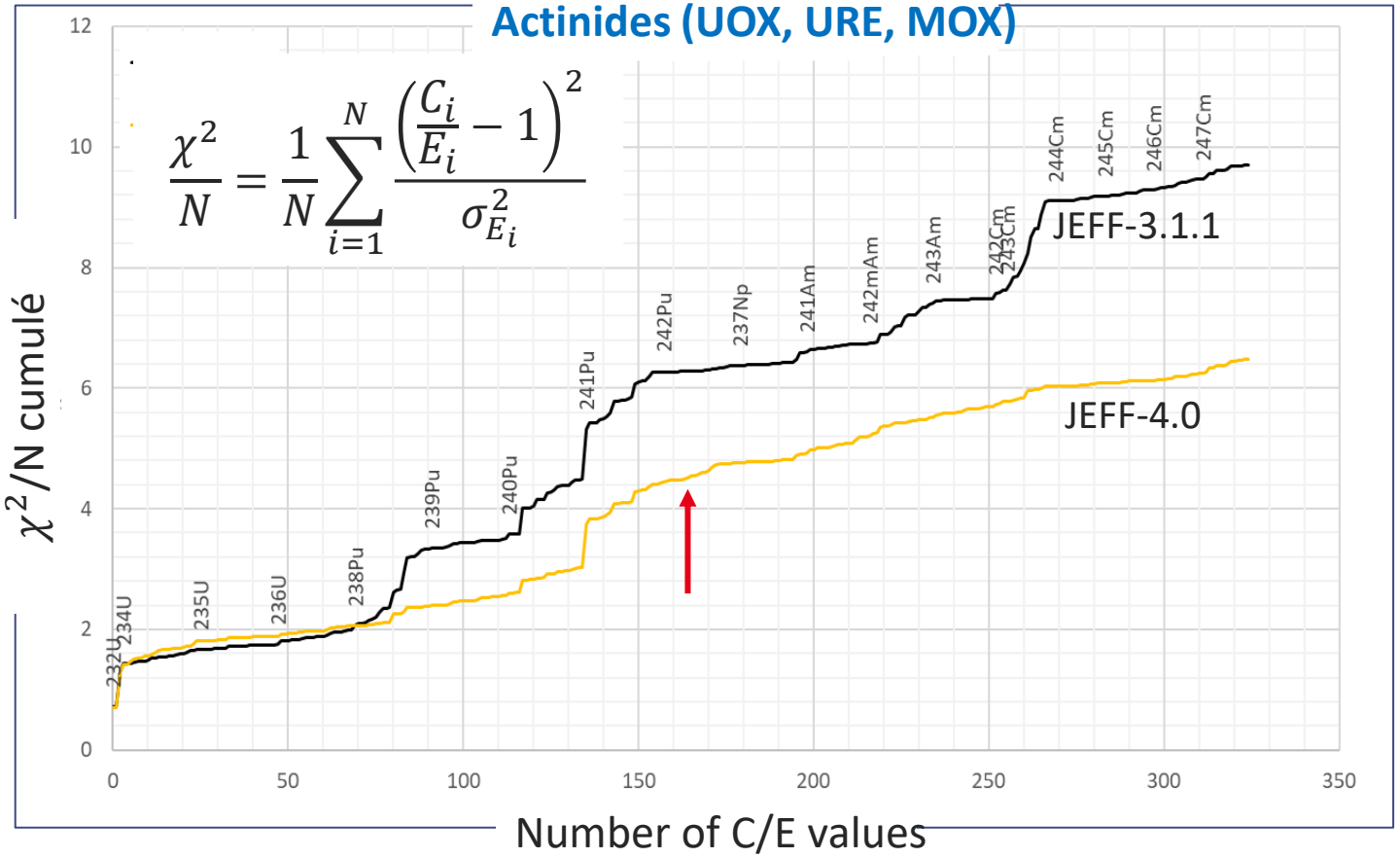
→ New Thermal Neutron Constant from Neutron Data Standard group of AIEA

→ Extend RRR and adapt ν_p

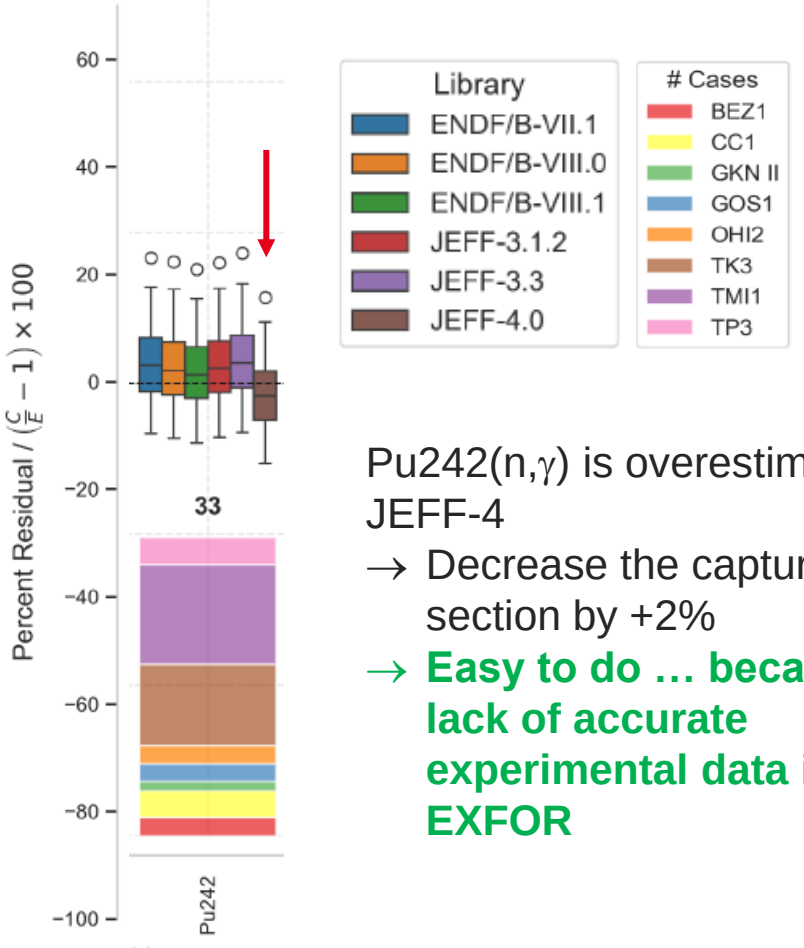
→ New RRR measurements at n_TOF and JRC-Geel

Pu242(n,γ)

Jean Charles Jaboulay (CEA Cadarache)



Luca Fiorito (SCK)



Pu242(n,γ) is overestimated in JEFF-4

→ Decrease the capture cross section by +2%

→ **Easy to do … because lack of accurate experimental data in EXFOR**

Outline

- Review PIE trends for UOX, URE and MOX fuels
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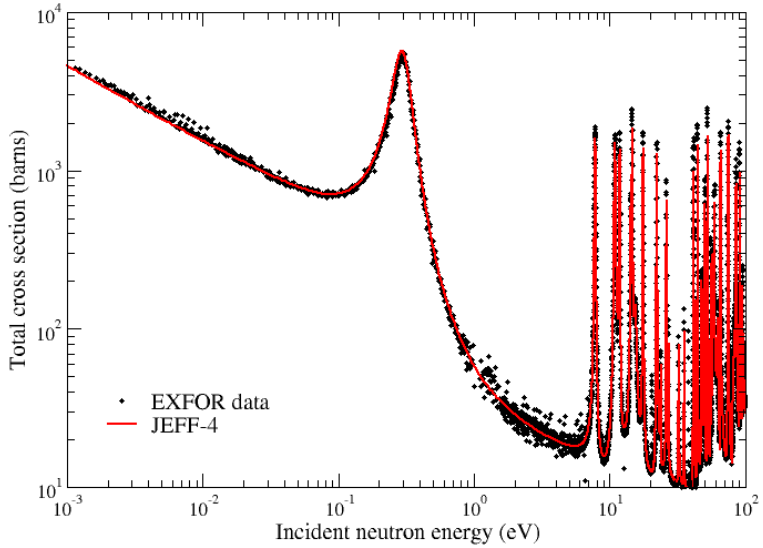
Pu239 work plan

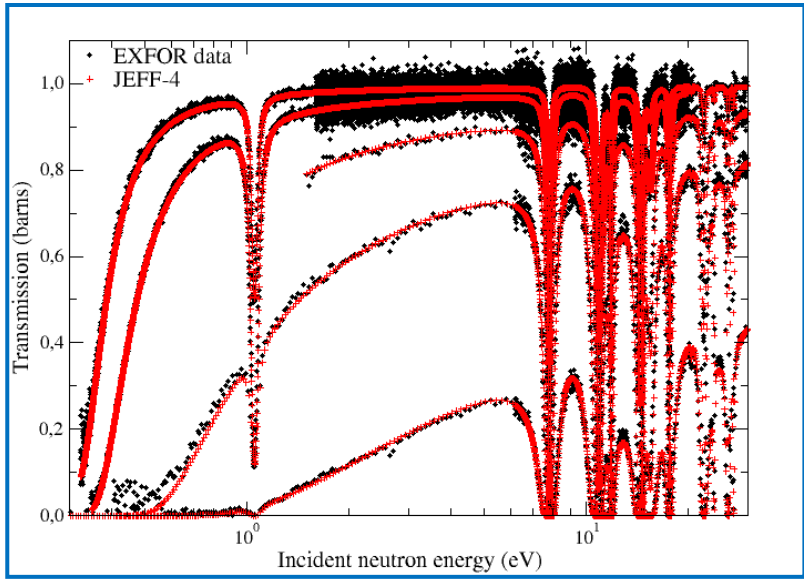
Many new Pu239 data expected in the coming years ….

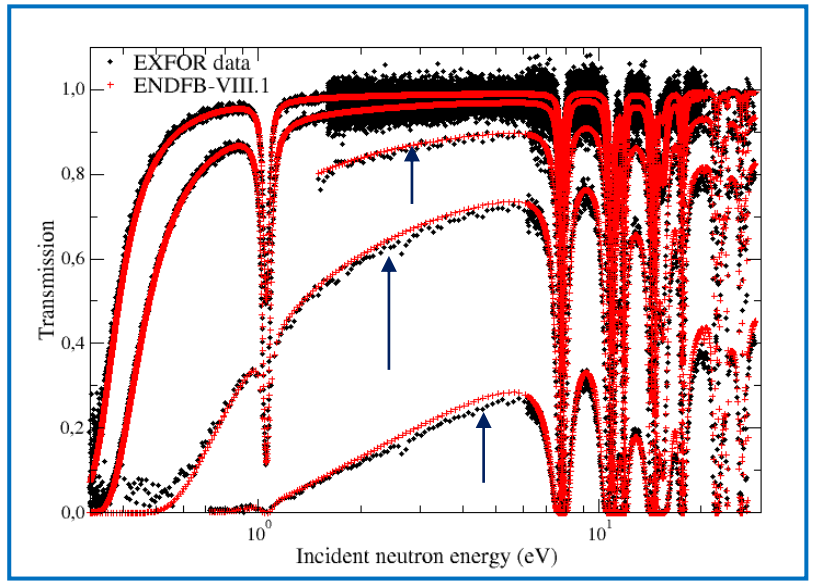
	Thermal and resonance ranges	Fast energy range
(n,tot)	• New Thermal Neutron Constants (2027) • New transmission at JRC-Geel (2026-2027)	
(n,γ)	• New Thermal Neutron Constants (2027) • New data from CIEMAT • Use Mosby data from LANL (2018) • Use PROFIL trends	• Use Mosby data (2018) • Use PROFIL trends
(n,f)	• New Thermal Neutron Constants (2027) • New data from CIEMAT	• New Standard Cross Sections (2027) • New measurements from CENBG
(n,n) (n,n') (n,xn)	• New Thermal Neutron Constants (2027)	• New measurements (n,xn), (n,n'γ) from IPHC • **Use integral data to disentangle (n,n) and (n,n') contributions (see work done for U238)**
ν_p	• New measurements at JRC-Geel (in progress)	• Use data from Paola Marini (2022, already included in JEFF-4)
ν_d	• Use ALDEN data measured at ILL • Use CRP recommendations (already included in JEFF-4)	• New ALDEN measurements planned at JRC-Geel
PFNS	• Use CRP recommendations (already included in JEFF-4) • New PFNS at thermal energy using VENDETA (ILL)	• Use Denise Neudecker evaluations • Use CEA/DAM evaluations (already included in JEFF-4)
FY	• New evaluation in progress (CEA Cadarache)	

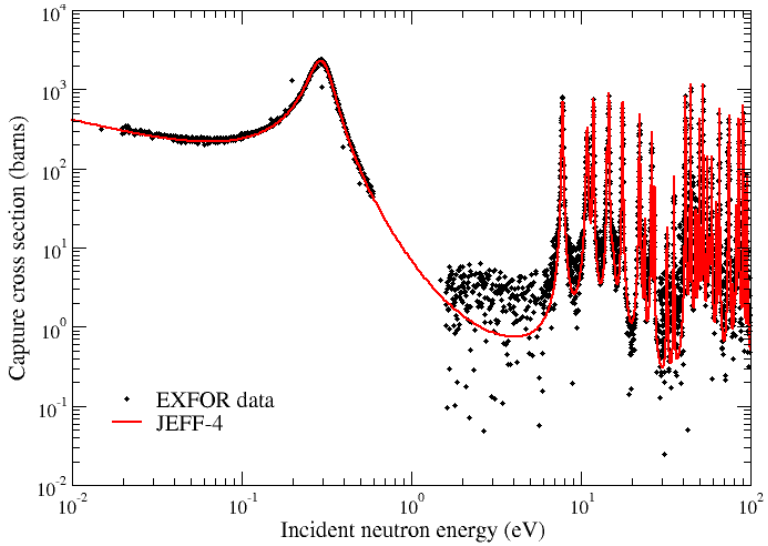
… Need to work on (n,n) and (n,n') as was done for U238 !

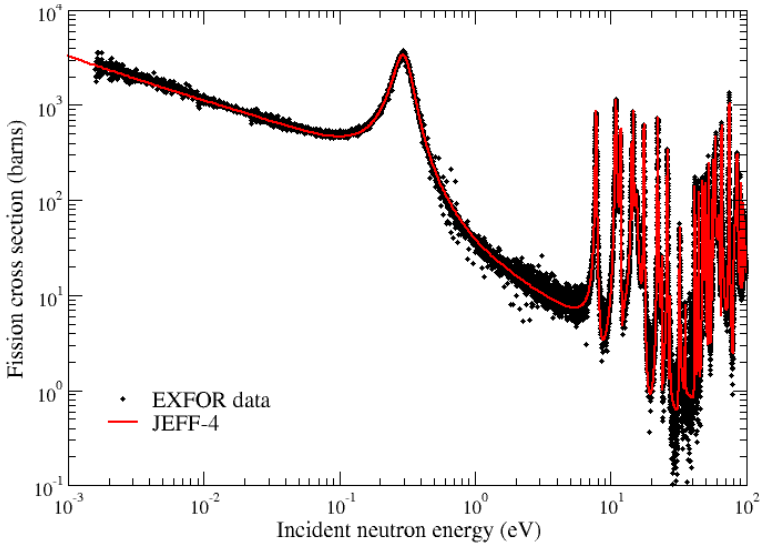
Pu239 work plan (RRR)











Issues total cross section at low energy …

→ JEFF-4: “improved“ description of the potential scattering contribution to follow thick transmission data measured at ORELA

→ ENDF\B-VIII.1: thick transmission data measured at ORELA not used

→ DICER transmission data not yet available

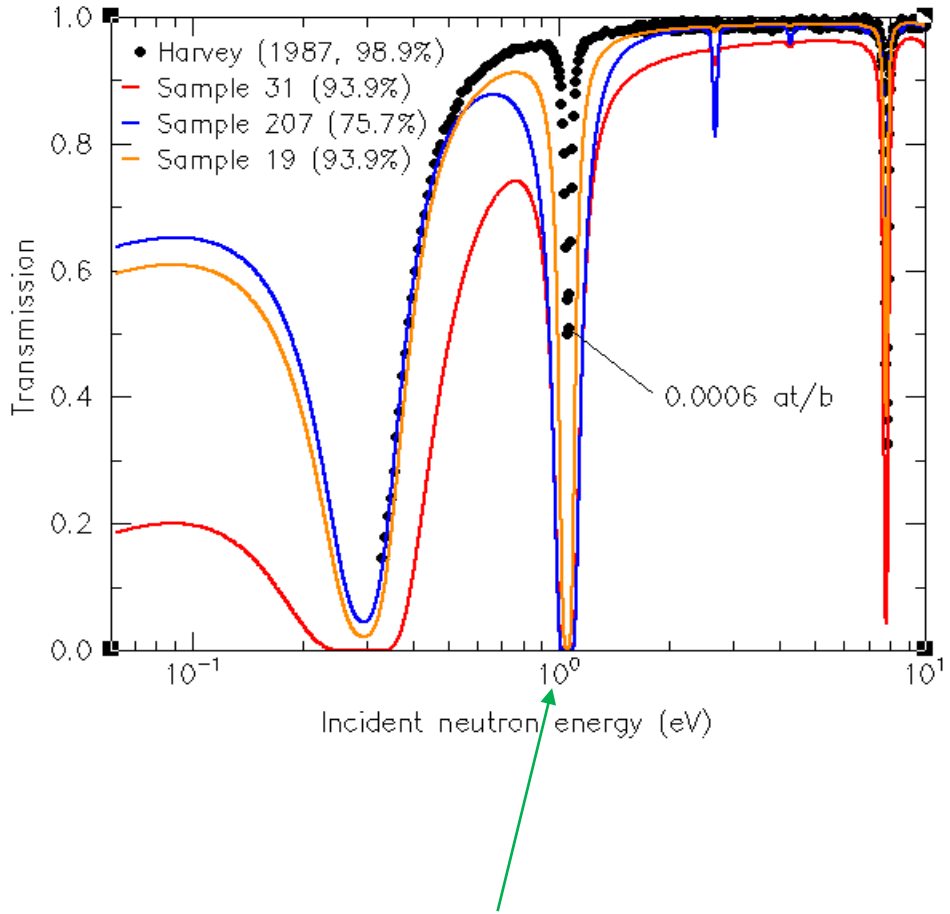
→ New transmission data planned in 2026-2027 at JRC-Geel

Pu239 work plan (RRR)

The transmission program consists in measuring four PuGa samples at L=10 m.

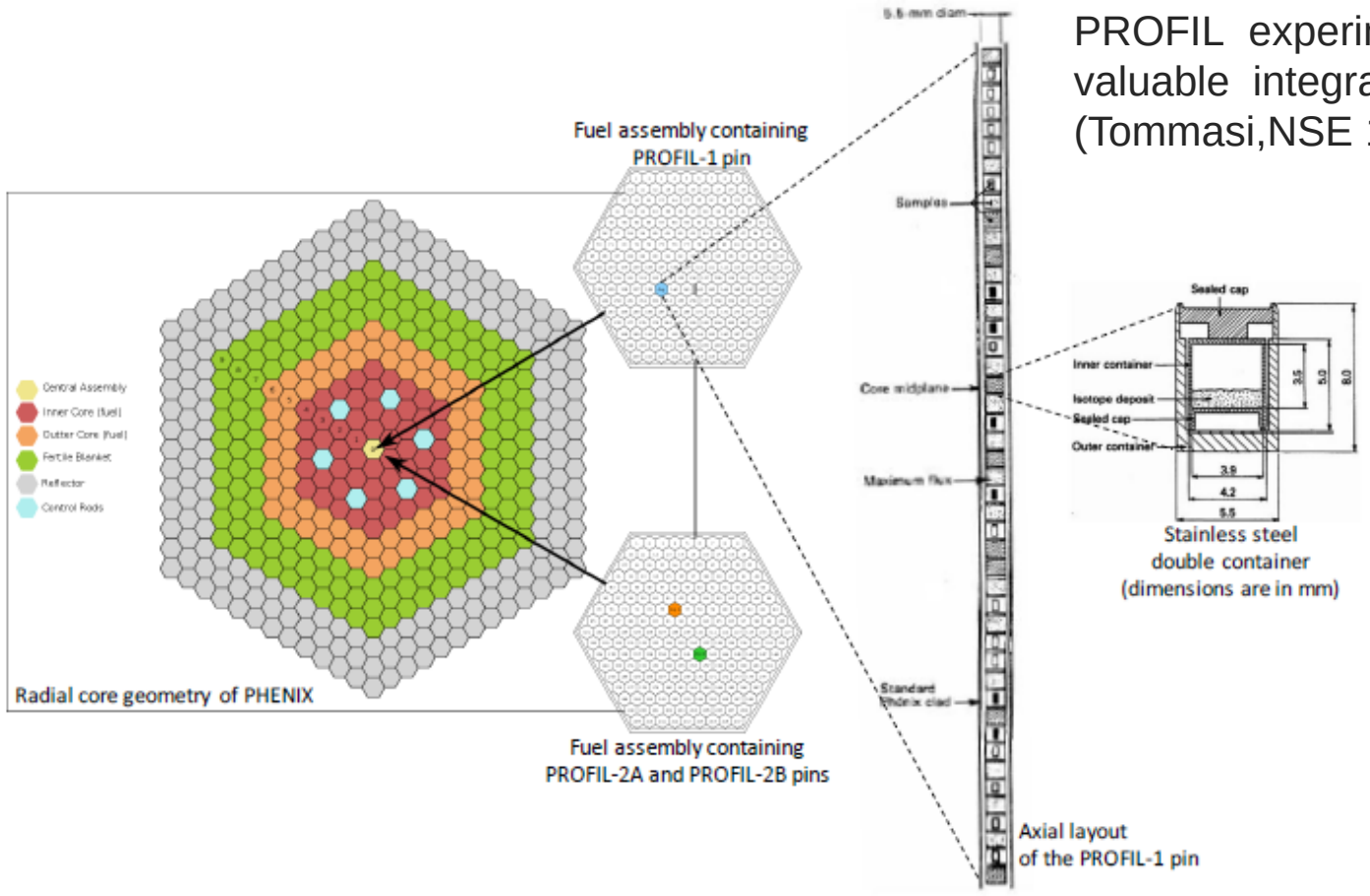
- "Thin" and "thick" samples with different ^{239}Pu and ^{240}Pu content were selected
- The simultaneous analysis of thin and thick samples will allow to determine the ^{239}Pu resonance parameters up to 100 eV and the first ^{240}Pu resonance at 1 eV.
- The flight length L=10 m will ensure an overlap with the ORELA data (measured by Harvey) with a good energy resolution.

	Thin sample	Thick sample	Thin sample	Thick sample
	Sample 19	**Sample 31**	**Sample 207**	**Sample 210**
Mass PuGa	0.92057(19) g	5.02867(20) g	0.92754(6) g	4.97190(5) g
Mass Pu	0.90156(70) g	4.92482(336) g	0.89428(21) g	4.79336(84) g
Pu content	97.9348 %	97.9348 %	96.4090 %	96.4090 %
Ga content	2.0652 %	2.0652 %	3.5910 %	3.5910 %
Diameter	20.0 mm	26.0 mm	20.0 mm	26.0 mm
thickness	0.2 mm	0.6 mm	0.2 mm	0.6 mm



By product → 1st resonance of Pu240

Pu239 work plan (RRR)



PROFIL experiments performed in the fast reactor PHENIX provide valuable integral trends on neutron cross sections and fission yields (Tommasi,NSE 160,232, 2008)

Normalization Mosby data with PROFIL

↓

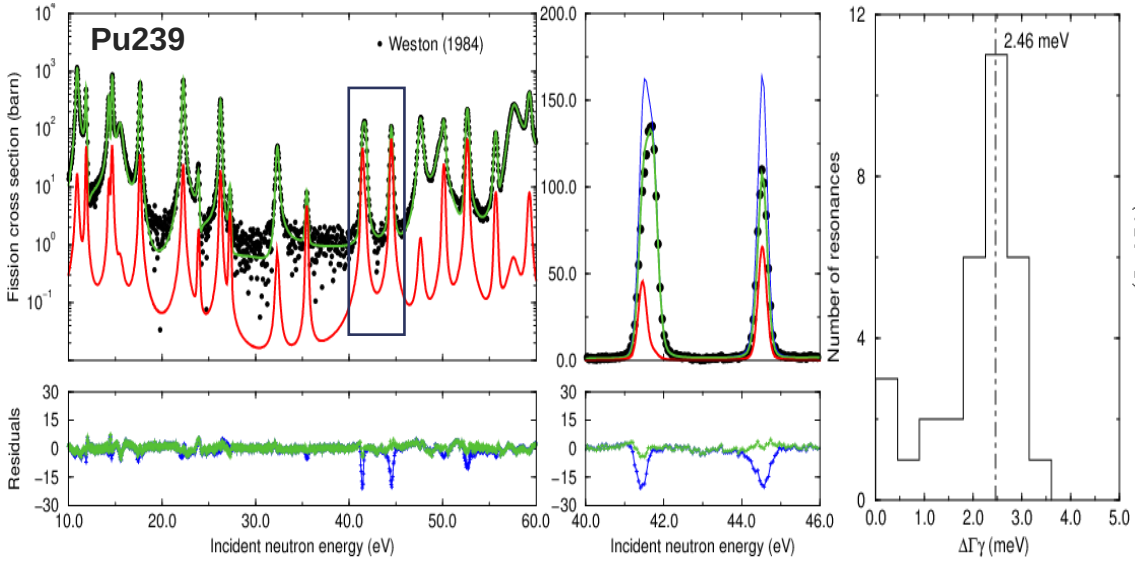
$\langle \sigma_\gamma \rangle$ [37-100 eV] = 39(1) barns

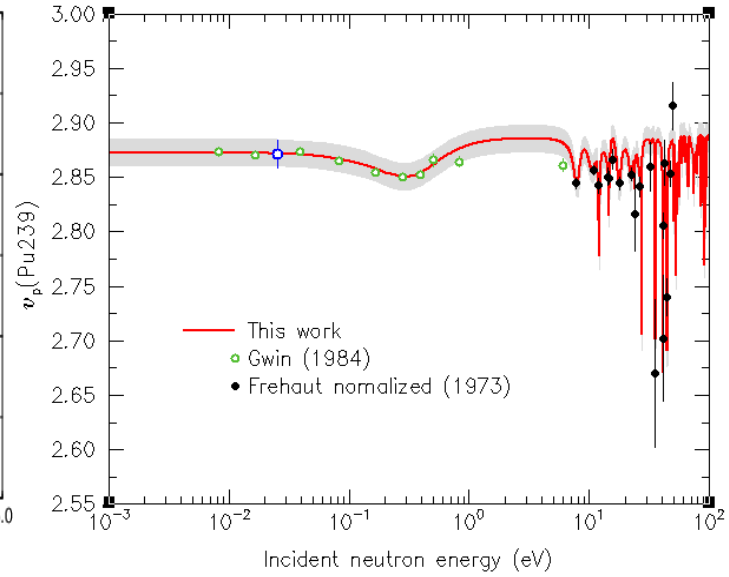
↓

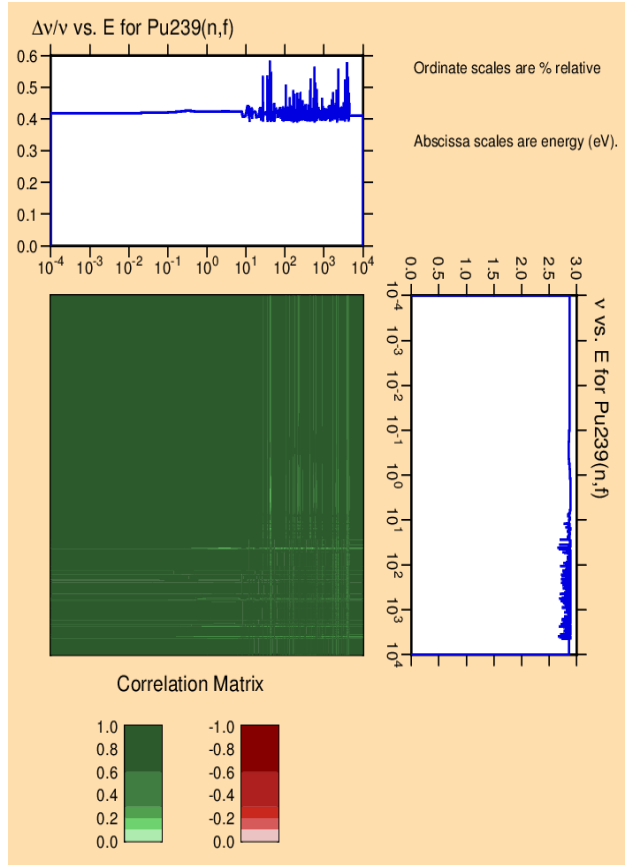
Confirmed by CIEMAT data !

Pu239 work plan (RRR)

⇒ **Prompt neutron multiplicity :** Two-step (n,γf) reaction included in the fitting procedure





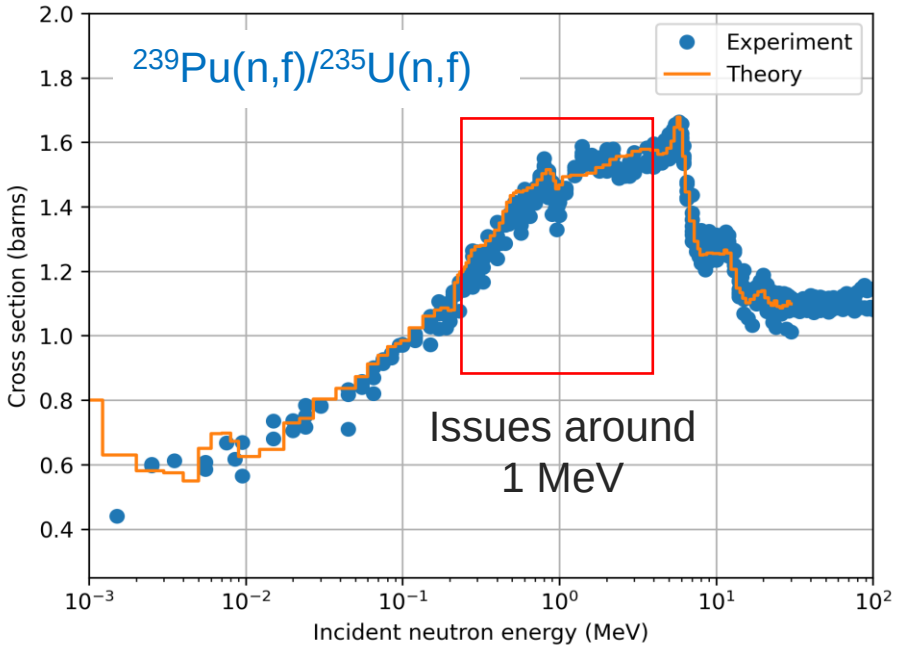


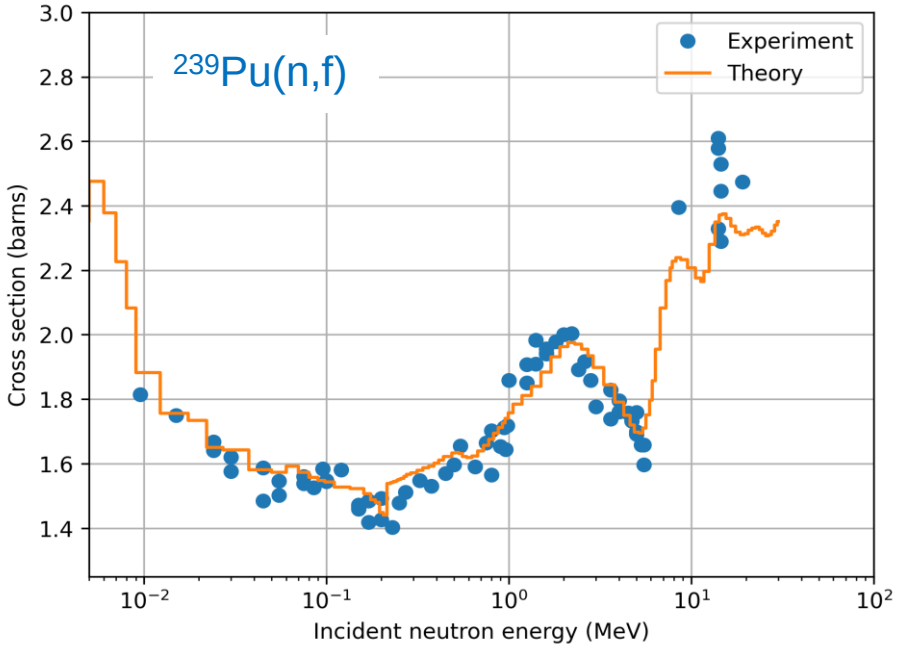
⇒ The (n,γf) reaction lead to an increases of 2.5 meV of the average radiation width, consistent with the 2 partial widths $\Gamma^0_{\gamma f} = 1.8\,meV$ and $\Gamma^1_{\gamma f} = 2.3\,meV$ introduced in the fitting procedure

⇒ New measuerements at JRC-Geel …

Pu239 work plan (Continuum)

⇒ **Comparison JEFF-4 (=Theory) vs. Neutron Data Standard data base (=Experiment)**





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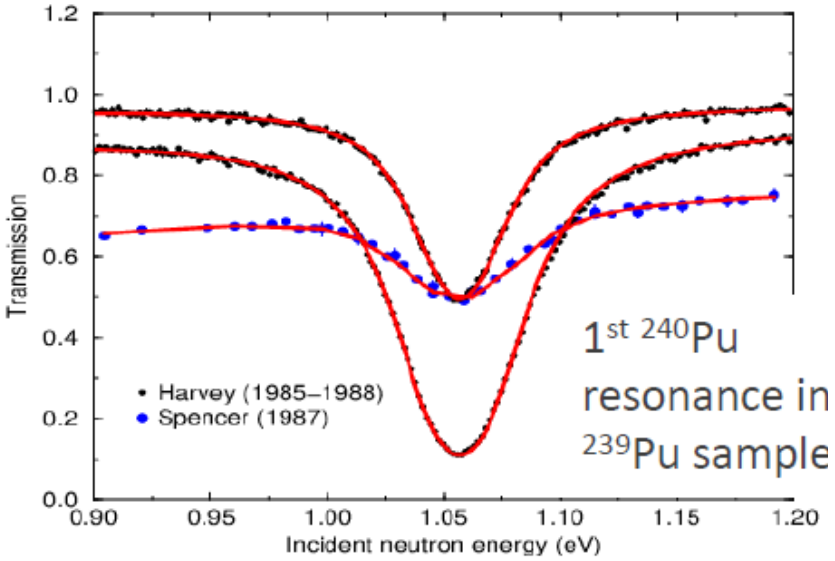
Pu240 and Pu242 work plan (RRR)

Pu240 impurities in Pu239 sample

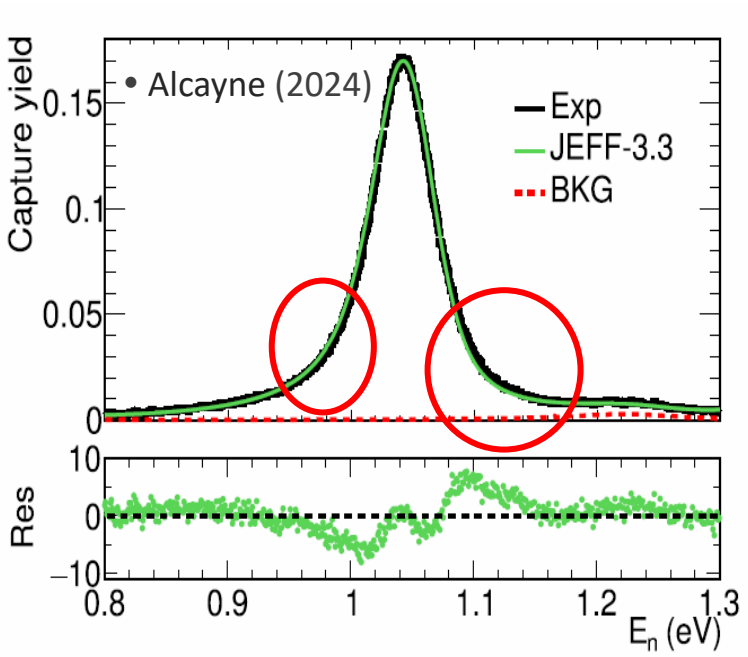
→ non-negligible uncertainties on the reported at/barns

→ new measurements at JRC-Geel



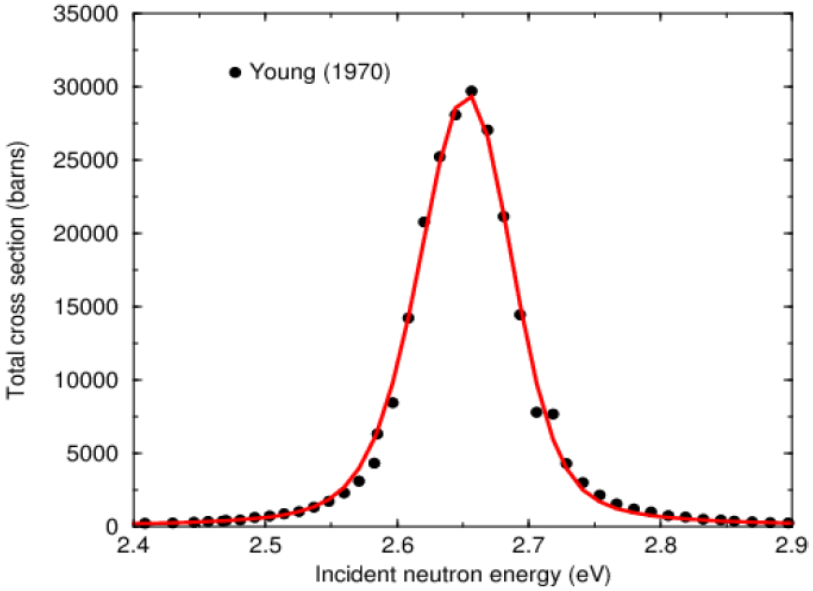
Pu240 in Cm(n,γ) measurements performed at n_TOF

→ $S_{CLM}(\alpha,\beta)$ contributions ?



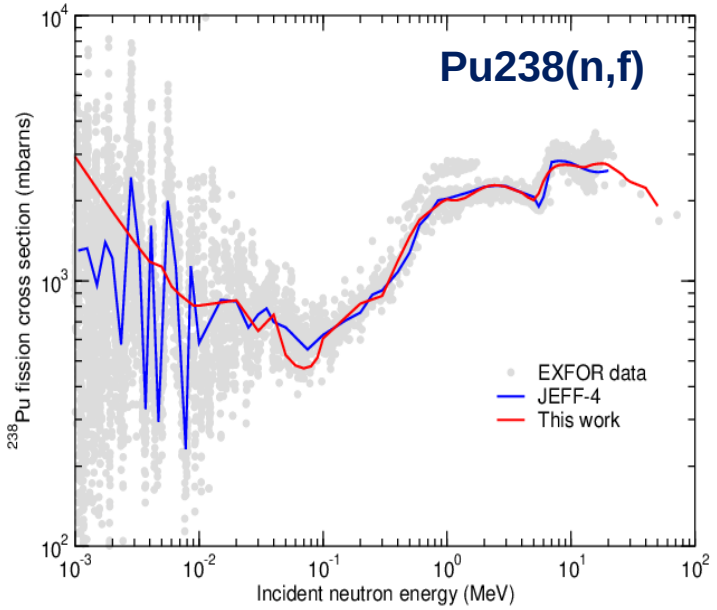
Pu242

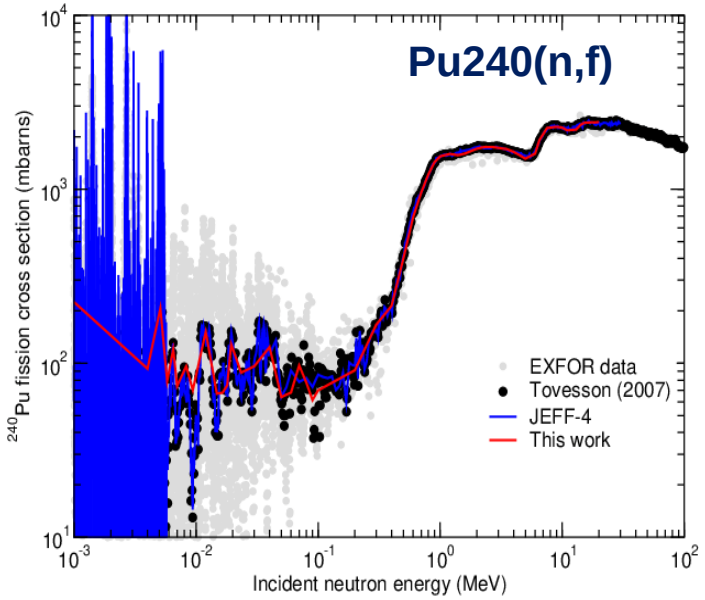
→ decrease the normalization of Young by -2% will solve the issue

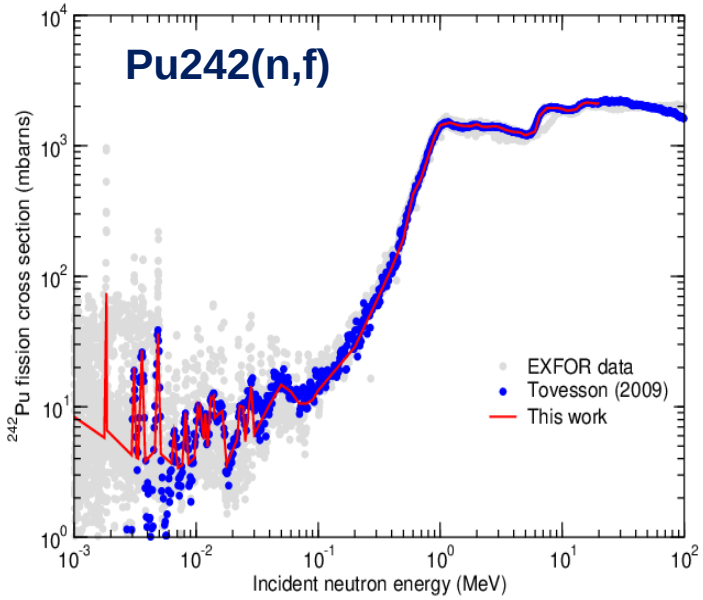


Pu238, Pu240, Pu242 work plan (Continuum)

⇒ Comparison JEFF-4 vs. EXFOR data







⇒ Average ⟨C/E⟩(JEFF-4) values obtained from various integral trends

	Pu238	Pu240	Pu242
(n,f)	0.95(4)	1.03(5)	1.00(4)
(n,γ)	0.99(3)	1.00(1)	1.05(3)

This work = TALYS calculations, CEA Cadarache

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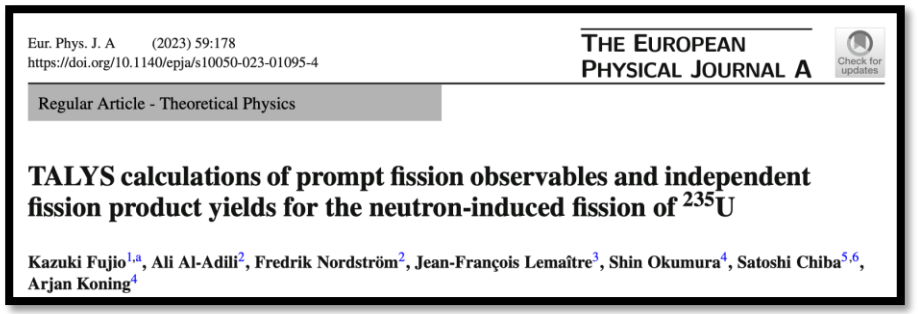
The TALYS fission method

Fission fragment generators (GEF, FREYA, HF3D)

FF yields Excitation energies TKE


Eur. Phys. J. A (2023) 59:178
https://doi.org/10.1140/epja/s10050-023-01095-4

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Theoretical Physics

TALYS calculations of prompt fission observables and independent fission product yields for the neutron-induced fission of ^{235}U

Kazuki Fujio[1,a], Ali Al-Adili[2], Fredrik Nordström[2], Jean-François Lemaître[3], Shin Okumura[4], Satoshi Chiba[5,6], Arjan Koning[4]

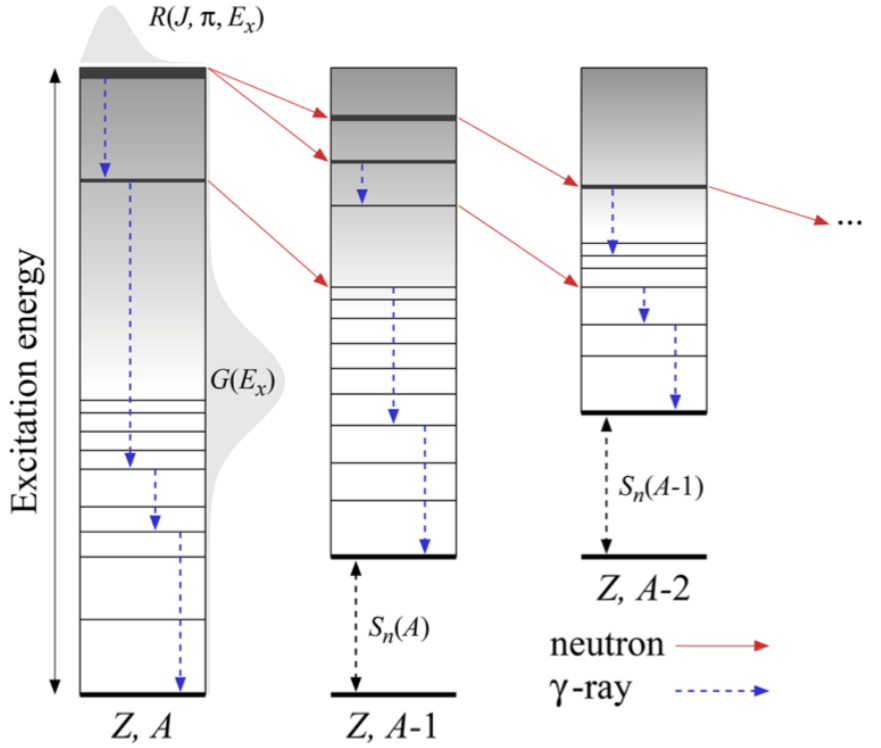
```
# Ntotal = 211 Z = 89 A = 214 E = 1.00e-03 MeV
#  Zl  Al Zh  Ah Yield      TKE[MeV]   TXE[MeV]   El[MeV]    Wl[MeV]    Eh[MeV]    Wh[MeV]
#  28  64 61 151 2.0000e-06 1.3766e+02 1.7345e+01 4.3850e+00 2.4961e+00 1.2960e+01 2.7294e+00
#  27  65 62 150 3.0000e-06 1.2572e+02 2.5033e+01 5.9633e+00 1.3826e+00 1.9070e+01 2.4351e+00
#  28  65 61 150 5.0000e-06 1.3886e+02 1.4374e+01 5.1500e+00 4.0314e+00 9.2240e+00 1.7201e+00
```

Energy reconstruction

$$G(E_x) = \frac{1}{\sqrt{2\pi}\sigma_{E_x}} \exp\left(-\frac{(E_x - \bar{E}_x)^2}{2\sigma_{E_x}^2}\right)$$

Angular momentum

$$R(J,\pi,E_x) = \frac{1}{2}\frac{J+0.5}{f^2\sigma^2\,(E_x)} \exp\left(-\frac{(J+0.5)^2}{2f^2\sigma^2\,(E_x)}\right)$$



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Fragment databases in TALYS

ffmodel

Model for the distribution of fission fragments.

Examples

ffmodel 0: tables by user in subdirectory user/
ffmodel 1: GEF model , fission fragments generated by Ali Al-Adili and Fredrik Nordstroem.
ffmodel 2: Okumura model [156]
ffmodel 3: SPY model [157]
ffmodel 4: Langevin-4D model

Range

0 ≤ ffmodel ≤ 4

Default

ffmodel 1

GEF

For GEF: 737 fissioning systems, at 0-20 MeV excitation energiers!

HF3D (Kawano)

New: FREYA

Optimal parameters from FREYA

Table 1. FREYA input parameters for ^{239}Pu(n_{th},f).

Parameter	Default	Optimized
e_0 (1/MeV)	10.370	10.287
x	1.150	1.058
c	1.200	1.153
c_S	0.870	0.810
dTKE (MeV)	1.100	−0.858

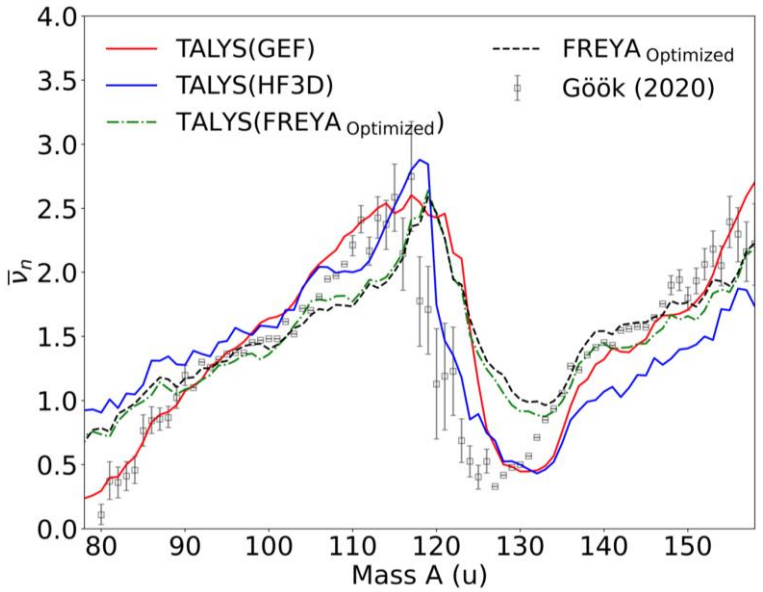
Funded by the European Union

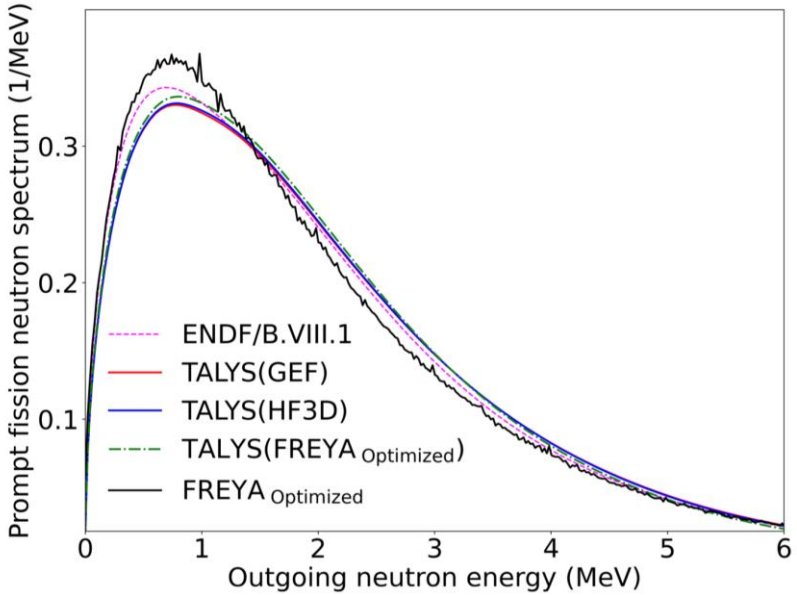
The TALYS fission method

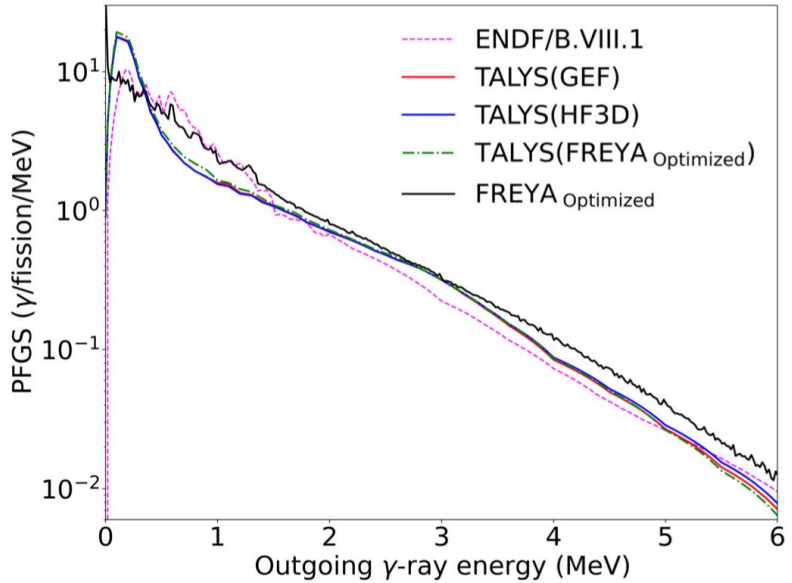
De-excitation of fission fragments in ^{239}Pu(n_{th}, f): A FREYA-TALYS study

Peter Karlsson[1,*], *Ali* Al-Adili[1,2,3,**], *Ramona* Vogt[4,5], *Jørgen* Randrup[6], *Alexander* Tuckey[7], *Henrik* Haug[2,3], *Andreas* Solders[1], *Stephan* Pomp[1], *Henrik* Sjöstrand[1], and *Arjan* Koning[8]

	$\bar{\nu}_n$ (n/f)	$\bar{\epsilon}_n$ (MeV/n)	$\bar{\nu}_\gamma$ (γ/f)	$\bar{\epsilon}_\gamma$ (MeV/γ)
FREYA Default	2.65	2.05	8.76	0.79
FREYA Optimized	2.91	2.07	8.67	0.80
TALYS(GEF)	2.83	2.14	8.06	0.70
TALYS(HF3D)	2.65	2.12	7.99	0.70
TALYS(FREYA Default)	2.55	2.06	8.29	0.69
TALYS(FREYA Optimized)	2.79	2.06	8.57	0.68
ENDF/B.VIII.1	2.86	2.13	7.56	0.84







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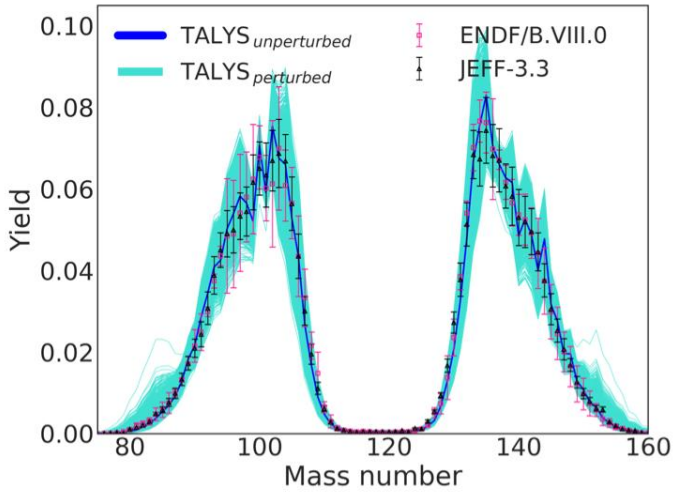
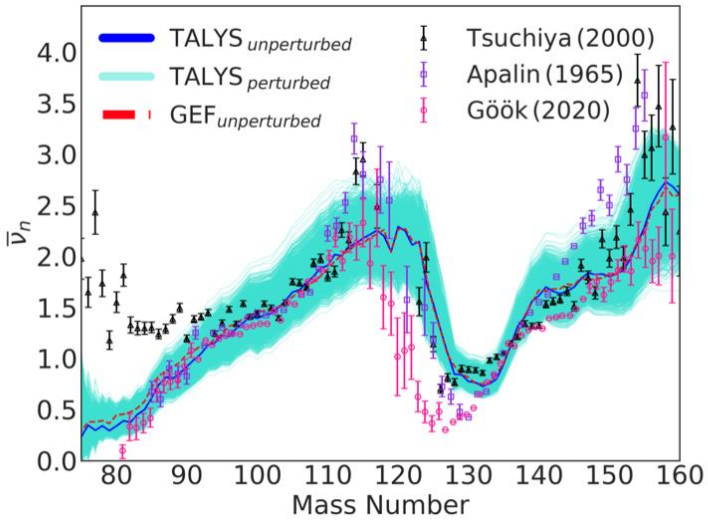
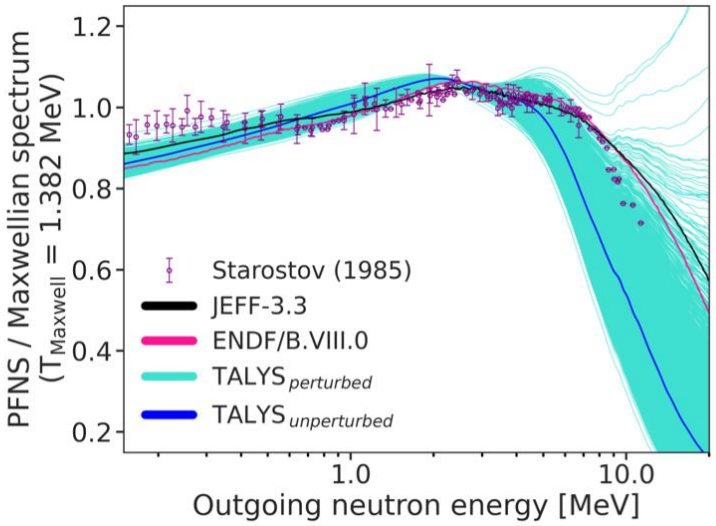
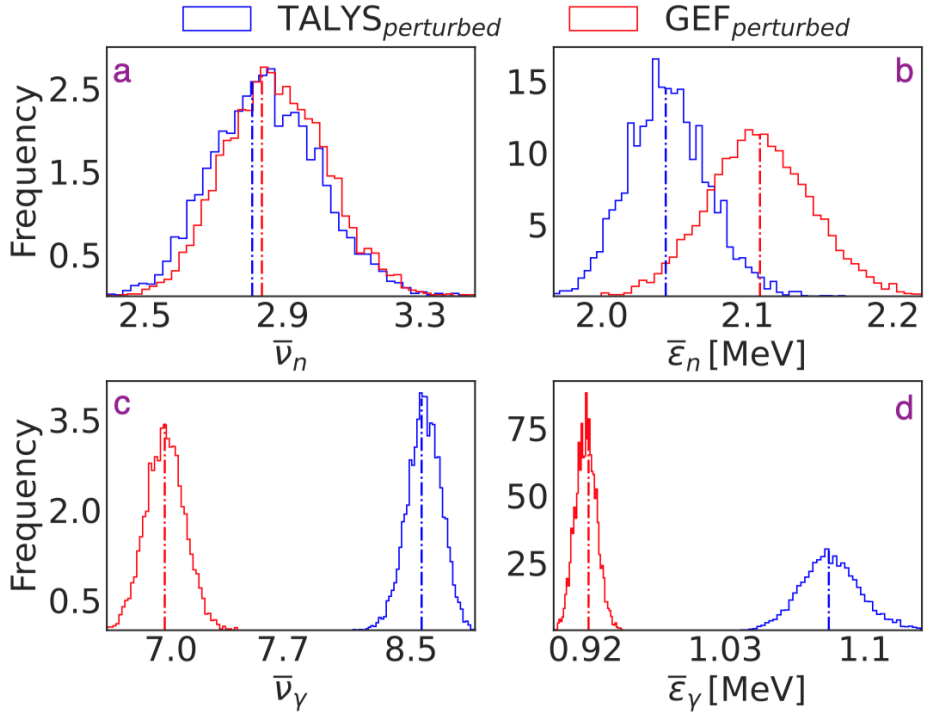
Outlook

- Total Monte Carlo method
- Improved
Angular momentum population
- Improved
Gamma ray characteristics









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Outline

- Review PIE trends for UOX, URE and MOX fuels
- Work plan for Pu239
- Work plan for Pu238, Pu240, Pu242
- Focus on Pu239 fission observables with TALYS
- Conclusions

Conclusions

Pu239

- New RRR analysis using DICER (total xs), n_TOF data (capture and fission xs) and PROFIL trend
- Transmission experiments planned at GELINA in 2026-2027 using PuGa and MINERVE-OSMOSE samples
- Integral Data Analysis in the framework of PhD thesis of Pierre-Louis Sazerat (CEA Cadarache)
- Collaboration with Mathieu Hursin (EPFL)
- **New Pu239 evaluation available for test …**

⇒ **For fission observables see also Kessedjian's talk "Pu fission yields evaluation : needs"**

Pu240

- New RRR analysis using transmission planned at GELINA
- **Use RRR of ENDF\B-VIII.1 = CONRAD evaluation**

Pu241

- New RRR analysis using n_TOF data (capture and fission xs) from Emmeric Dupont et al.
- Increase prompt neutron multiplicity by 0.1-0.2 % ?
- **Use RRR of ENDF\B-VIII.1 = CONRAD evaluation**

Pu242

- New RRR analysis ⇒ decrease normalization of Young data by -2%
- **New Pu242 evaluation available for test …**

Get in touch for more information:

https://aprende-project.eu/

contact@aprende-project.eu

Thank you!

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Back up slides

Integral trends from oscillation measurements and PIE

About 300 C/E collected on specific isotopes and reactions :

- TRIGA reactor at JSI (Vladimir Radulović, Gašper Žerovnik)
- PROTEUS reactor at PSI (Gregory Perret)
- CROCUS reactor at EPFL (Thomas Ligonnet, Vincent Lamirand, Axel Laureau)
- AMS results (Toni Wallner)
- FCA assembly of JAEA (Virginie Huy)
- VENUS reactor at SCK-CEN (Frederico Grimaldi)
- DIMPLE reactor at AEE Winfrith (Christopher Dean)
- MINERVE reactor at CEA Cadarache (Frederico Di Corce, Pierre Leconte, David Bernard, Tangi Nicol)
- PHENIX reactor at CEA Marcoule (Jean Tommasi, Edwin Privas)
- MASURCA reactor at CEA Cadarache (Jean Francois Lebrat)
- EOLE reactor at CEA Cadarache (Jean Francois Vidal)
- MELUSINE reactor at CEA Grenoble (David Bernard)
- PIE from power reactor (Mathieu Hursin, Vanessa Vallet, David Bernard, Axel Rizzo, Jean-Charles Jaboulay)