Proposal: measurement of ^{239}Pu(n,γ) and α–ratio at EAR1 with TAC + fission detectors

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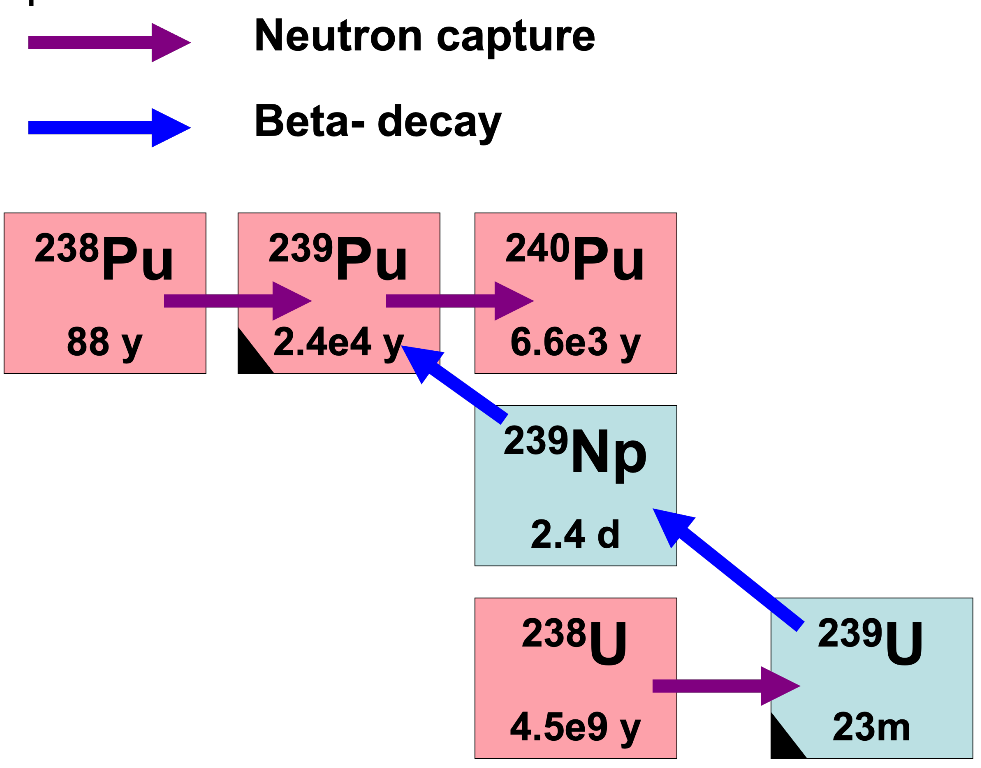
This activity is part of the scientific program approved by the European Commission *H2020* ***Supplying Accurate Nuclear Data for energy and non-energy Applications*** – **SANDA** project.

WP2. New nuclear data measurements for energy and non-energy applications.

Subtask 2.2.1. Capture measurements of fissile isotopes. Collaboration between CIEMAT, University of Lodz and JRC-Geel

^{239}Pu production in LWR

Standard fresh nuclear fuel for thermal reactors has a 5% ^{235}U and a 95% ^{238}U. ^{239}Pu is produced during the reactor operation mainly by neutron captures in ^{238}U + decays of ^{239}U and ^{239}Np. The ^{239}Pu is fissile and thus its neutron induced fission contributes to the power.



Motivation

^{239}**Pu** is a very important isotope in actual Light Water Reactors (LWR), contributing up to **30% of the energy produced**.

After ^{238}U and ^{235}U, ^{239}**Pu is the most abundant actinide in the spent nuclear fuel** (SNF).T The SNF contains ~1% mass contribution of ^{239}Pu (60 GWd/tU). On average, ~700 kg are produced every 4.5 years of LWR operation. The uncertainty in this mass is dominated by nuclear data (*A. Villacorta, PhD thesis*).

^{239}Pu is considered as a **major component of the nuclear waste** and also as a valuable resource. Pu-loaded fuel burning:

- MOX fuel is used in LWRs (France, …)
- Use of MOX and highly enriched fuels in ^{239}Pu is planned for Fast Reactors (Na-cooled, Pb-cooled, Gas-cooled) and some Small Modular Reactor designs.

^{239}Pu cross section data **are necessary** for improving the simulation capabilities for actual reactors (higher burnups, life extension, burnup credit). For these reasons, more accurate ^{239}Pu capture and fission cross section data are needed and those measurements have been listed in the NEA/OCDE **High Priority Request List**.

Status of the ^{239}Pu(n,γ) cross section

Until recently, the only *high resolution* capture measurement in the RRR (with enough data points to perform a reasonable resonance analysis) available in EXFOR is:

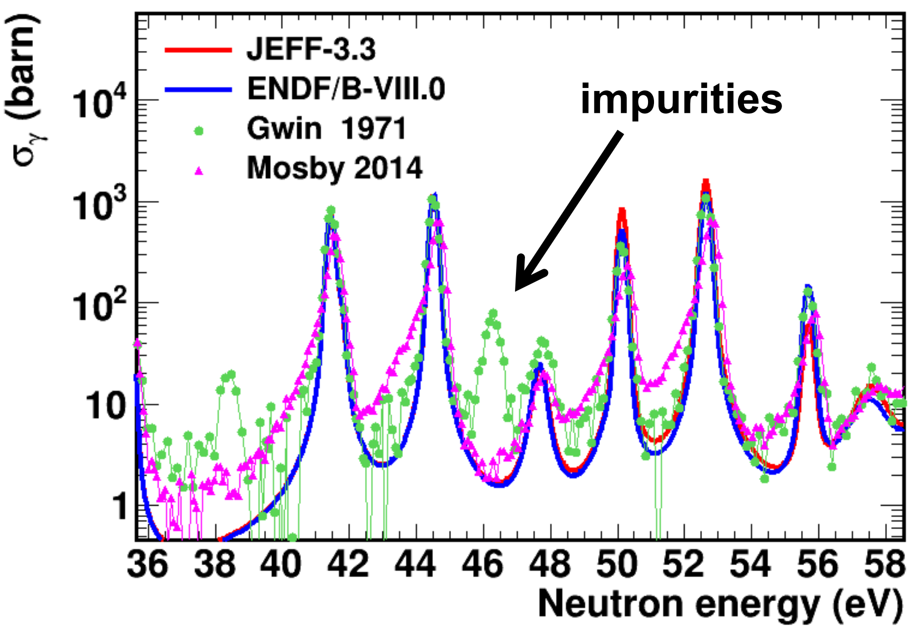
- Gwin et al., Nucl. Sci. Eng. **45**, 25 (1971) → (0.02 eV to 30 keV)

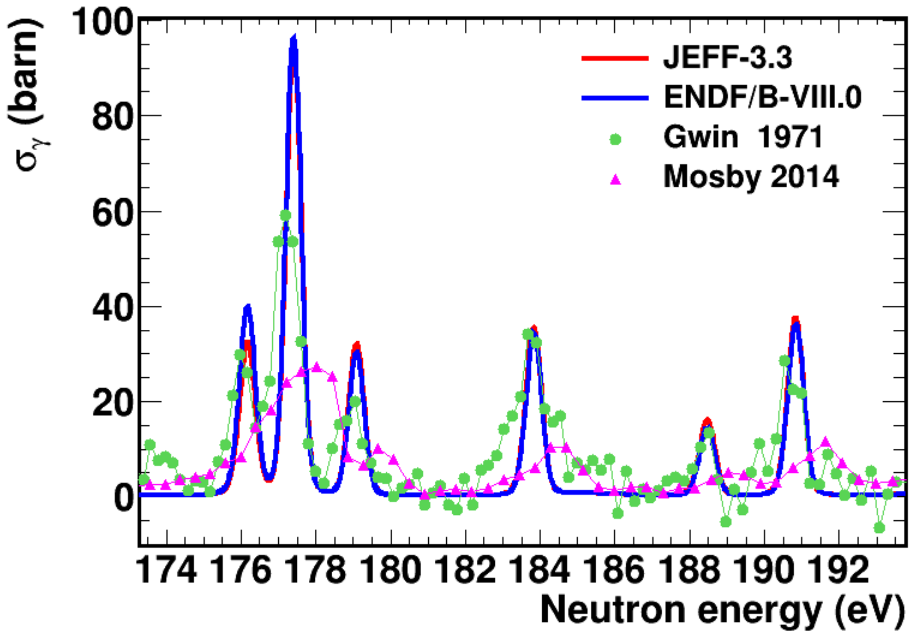
There is a new measurement performed at LANSCE, in the energy range between 10 eV and 1.3 MeV (Note: one measurement → three papers).

- S. Mosby et al., Phys. Rev. C 89, 034610 (2014)
- S. Mosby et al., Phys. Rev. C 97, 041601 (2018)
- S. Mosby et al., Nucl. Data Sheets 148, 312 (2018)

The data from Mosby et al. have been normalized to ENDF/B-VII.1 between 17 and 18 eV.

Status of the $^{239}Pu(n,\gamma)$ cross section data





Goals of the proposal

We propose to measure the **α–ratio, the fission and the capture cross sections** at the n_TOF EAR1, using the **Total Absorption Calorimeter and a (multi target) ionisation chamber** developed at the University of Lodz.

This is a very challenging measurement due to the competing (~5 times larger) **fission γ –ray background** and to the **high α–activity of ^{239}Pu (2 MBq/mg)**.

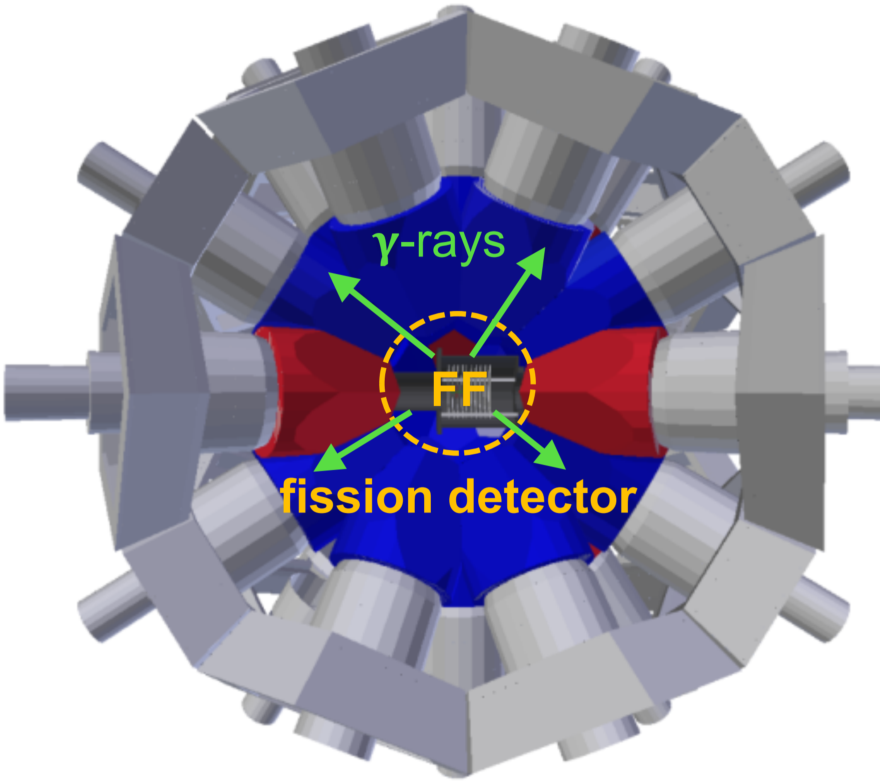
We will apply the expertise and methodologies developed for the ^{235}U(n,γ) measurement and analysis (*Balibrea et al.*, PRC 102, 2020) and perform a measurement with an **improved experimental setup**.

Experimental technique

Fission tagging: **γ**-rays in coincidence (fission background) and anticoincidence (capture signal) with the fission detector. (*J. Balibrea et al.*, PRC 102, 2020)

$$Y_\gamma = \frac{c_{aco,\gamma} - \frac{1-\epsilon_f^*(E_n)}{\epsilon_f^*(E_n)} c_{tag} - c_{oth,\gamma}}{\epsilon_\gamma \phi_N}$$

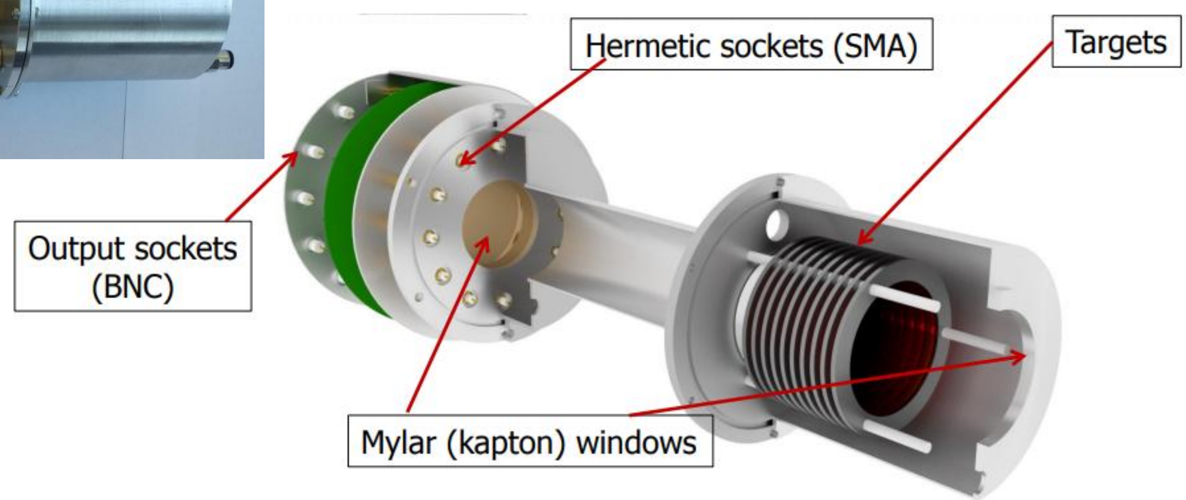
c_{tot} = counts in the TAC.
c_{tag} = counts in the TAC in coincidence.
with the ionisation chambers.
c_{oth}= background in the TAC.
ϵ_f^* = fission tagging efficiency.
ϵ_γ = capture detection efficiency.



The fission chamber

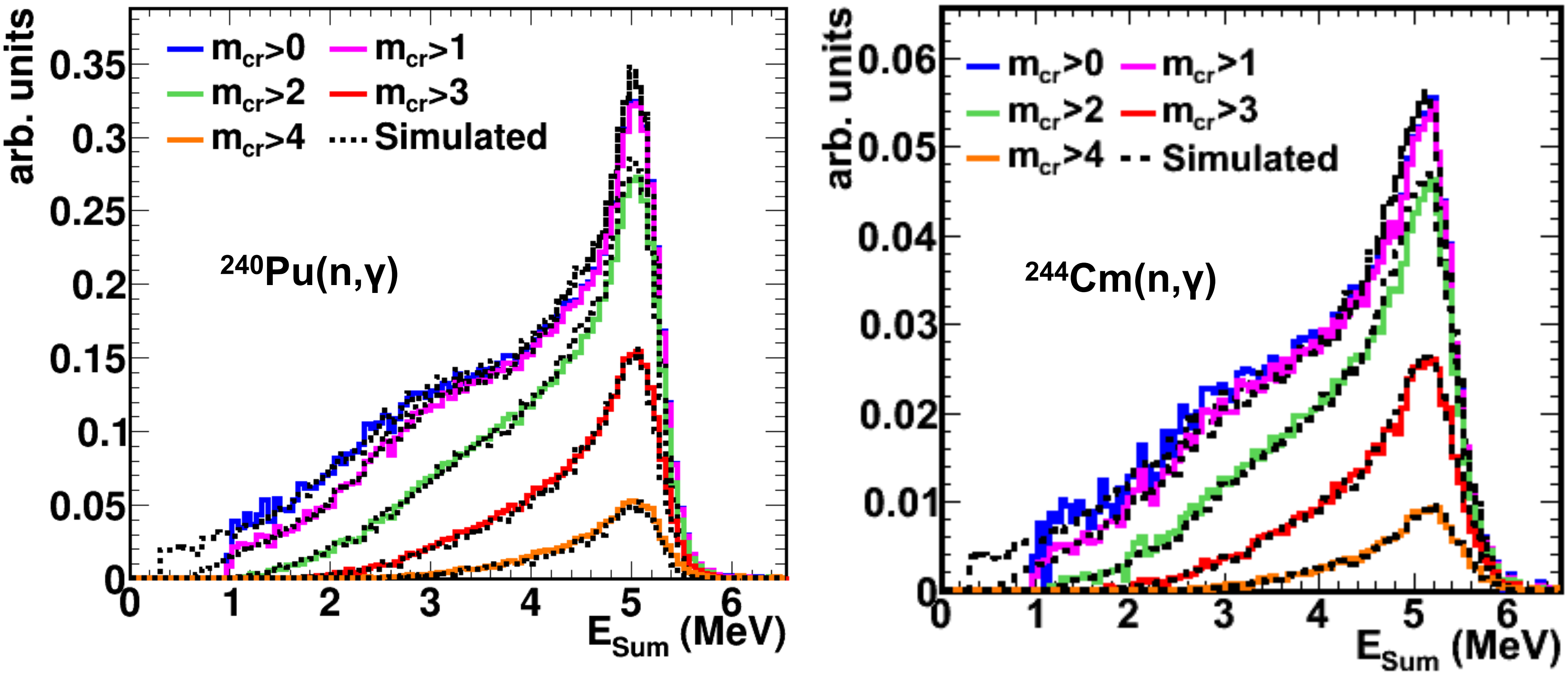
The multi target fission chamber has been designed taking into account the following important characteristics:

1. **Low mass** intercepting the neutron beam, to minimize the background in the TAC due to captures and elastically scattered neutrons.
2. Good **discrimination** between **alphas (2 MBq/mg)** and **fission fragments**.
3. Small **pile-up** effects.



The capture efficiency

The simulation of realistic capture cascades using **NuDEX** (*E. Mendoza et al., ND2019 EPJ Conf. Proceedings*) allows to determine the capture efficiency with a high accuracy (~1%).



Comparison between experimental and simulated deposited energy spectra in the TAC due to $^{240}Pu(n,\gamma)$ and $^{244}Cm(n,\gamma)$ cascades, measured in 2017.

The samples

I. Ten thin ^{239}Pu **samples will be manufactured at JRC-Geel** with a total mass of ~**10 mg (1 mg/sample)**.

The samples will be placed inside the fission detector, in the center of the TAC. The limitations come from the signal-to-background ratio.

Overall uncertainties: ~3% below 100 eV and 4-6% between 100 eV and 1keV.

II. A thick sample, in order to extend the measurement to higher neutron energies.

This sample will be measured **without fission detector**. With **~80 mg** we could extend the measurement **up to 10 keV**.

Overall uncertainties: 3-4% between 100 eV and 10 keV.

The n_TOF measurement will improve significantly the previously existing data by:

- providing a **capture yield** with an overall uncertainty **~3%** (0.025 eV – 10 keV). Normalisation to the better-known ^{239}Pu(n,f) cross section measured simultaneously.

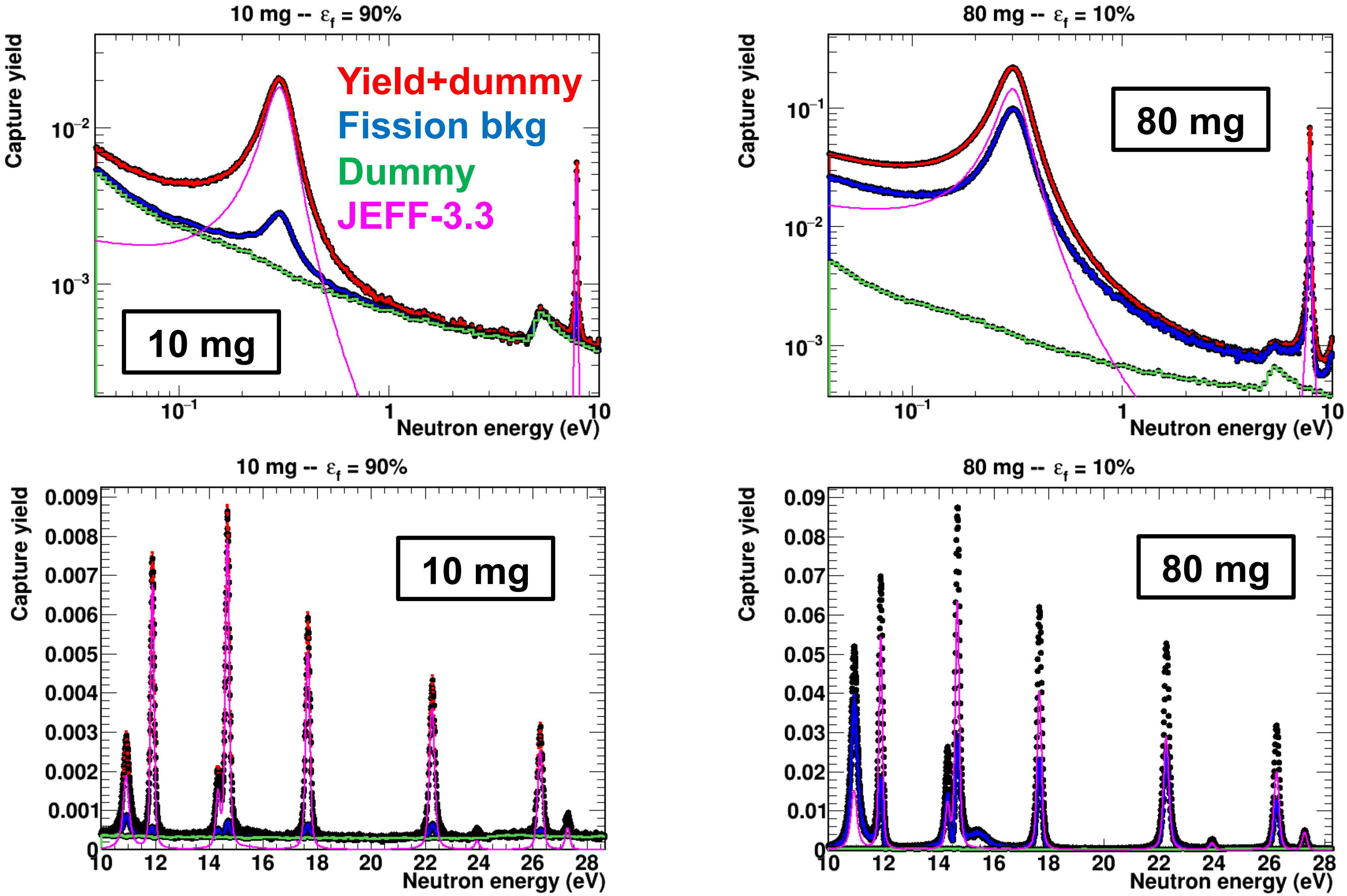
- Providing an absolute **α–ratio**, thanks to the accurate determination of the fission and capture detection efficiencies. (*J. Balibrea et al.*, PRC 102, 2020)

- Providing data with significantly **better energy resolution**, measured with a flight path 10 times longer than in *Mosby et al.* and *Gwin et al.*, which will improve significantly the resonance analysis.

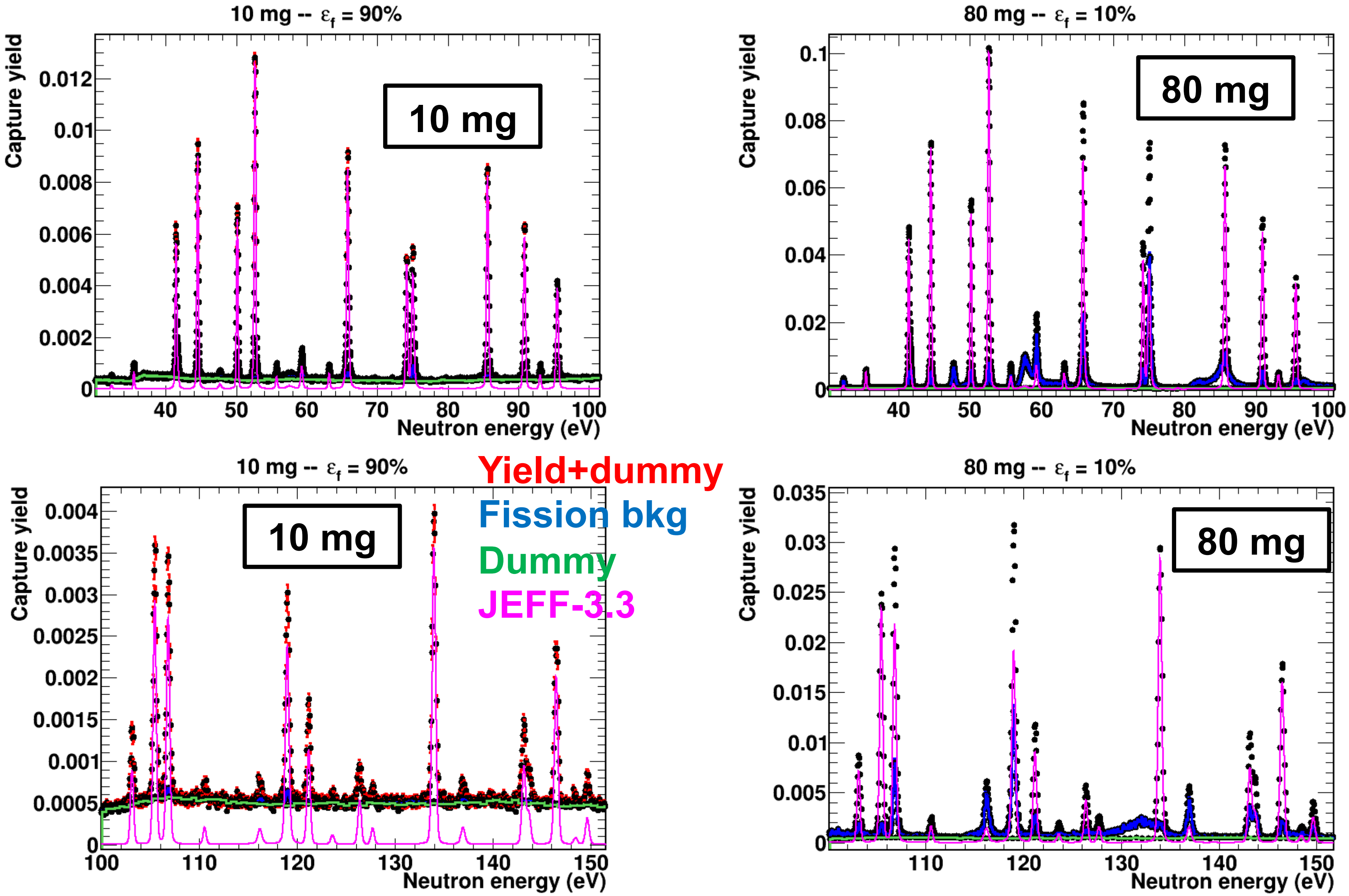
- **Solving the existing discrepancies** between the recent JEFF-3.3 and ENDF/B-VIII.0 evaluations.

- Providing very valuable information on the **distribution of the γ-rays** cascades emitted in **^{239}Pu(n,γ) and ^{239}Pu(n,f)** reactions, as has been the case in previous experiments performed with the TAC (**information on photon strength functions**).

Expected capture yield



Expected capture yield



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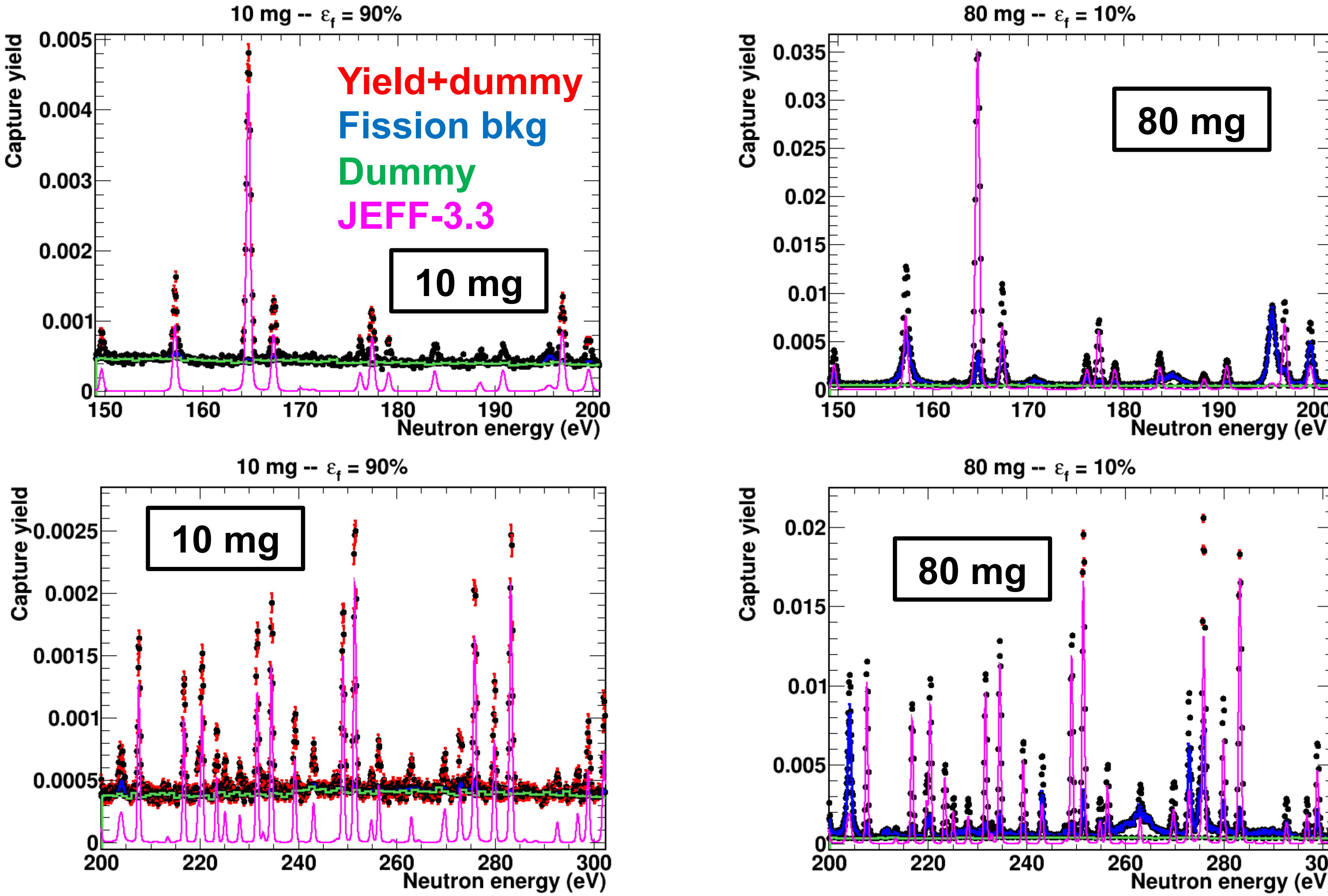

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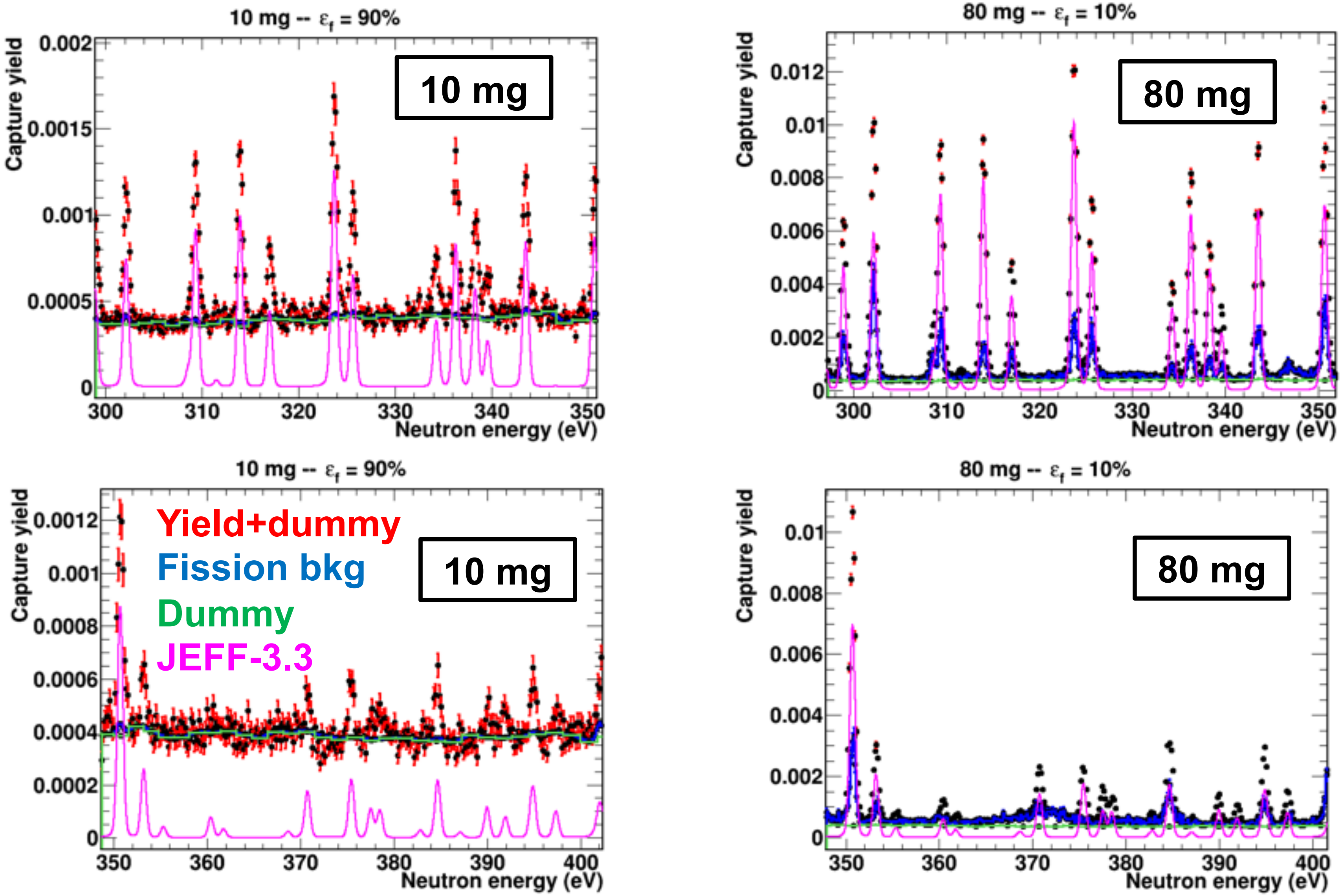

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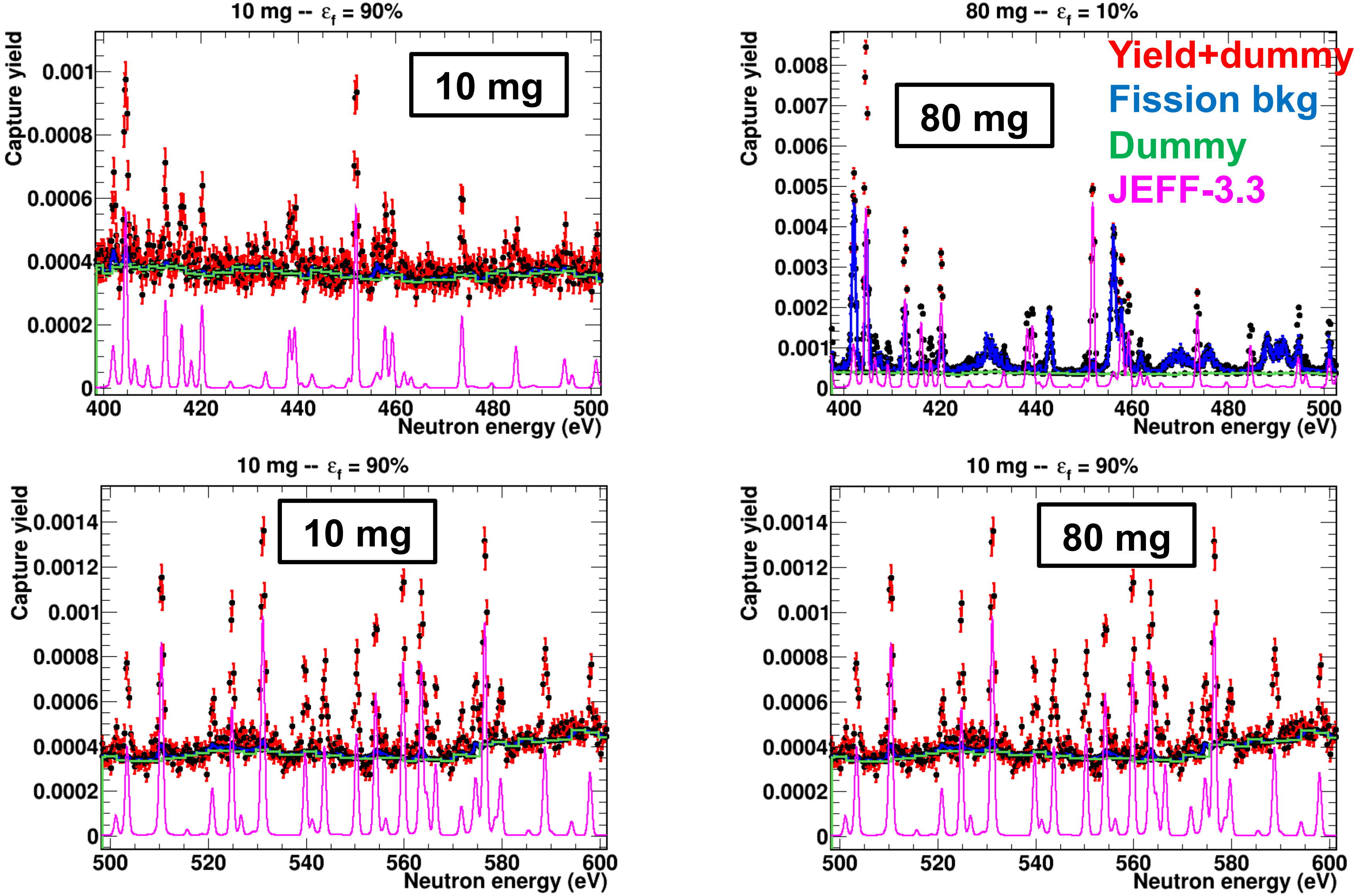

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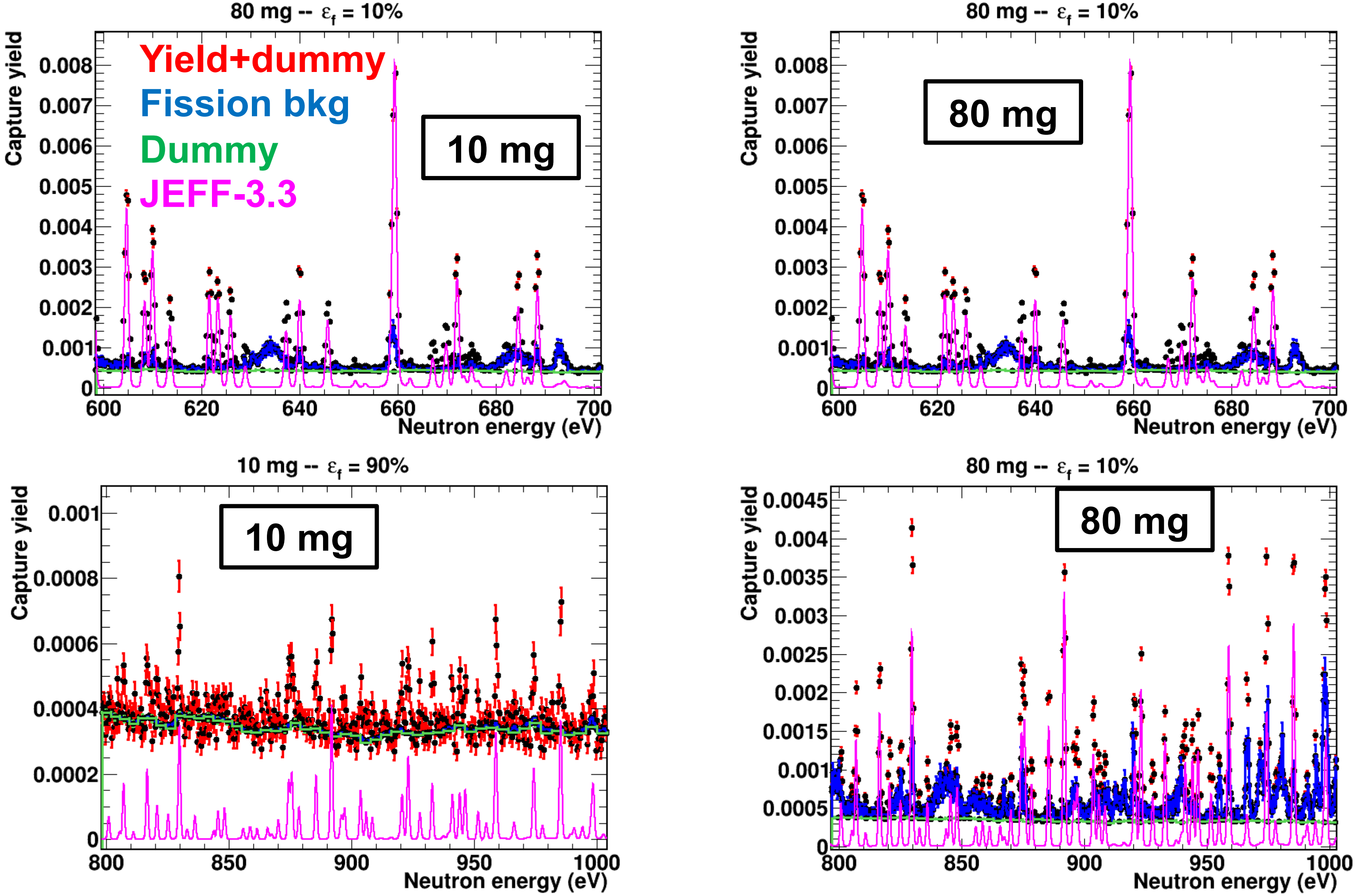
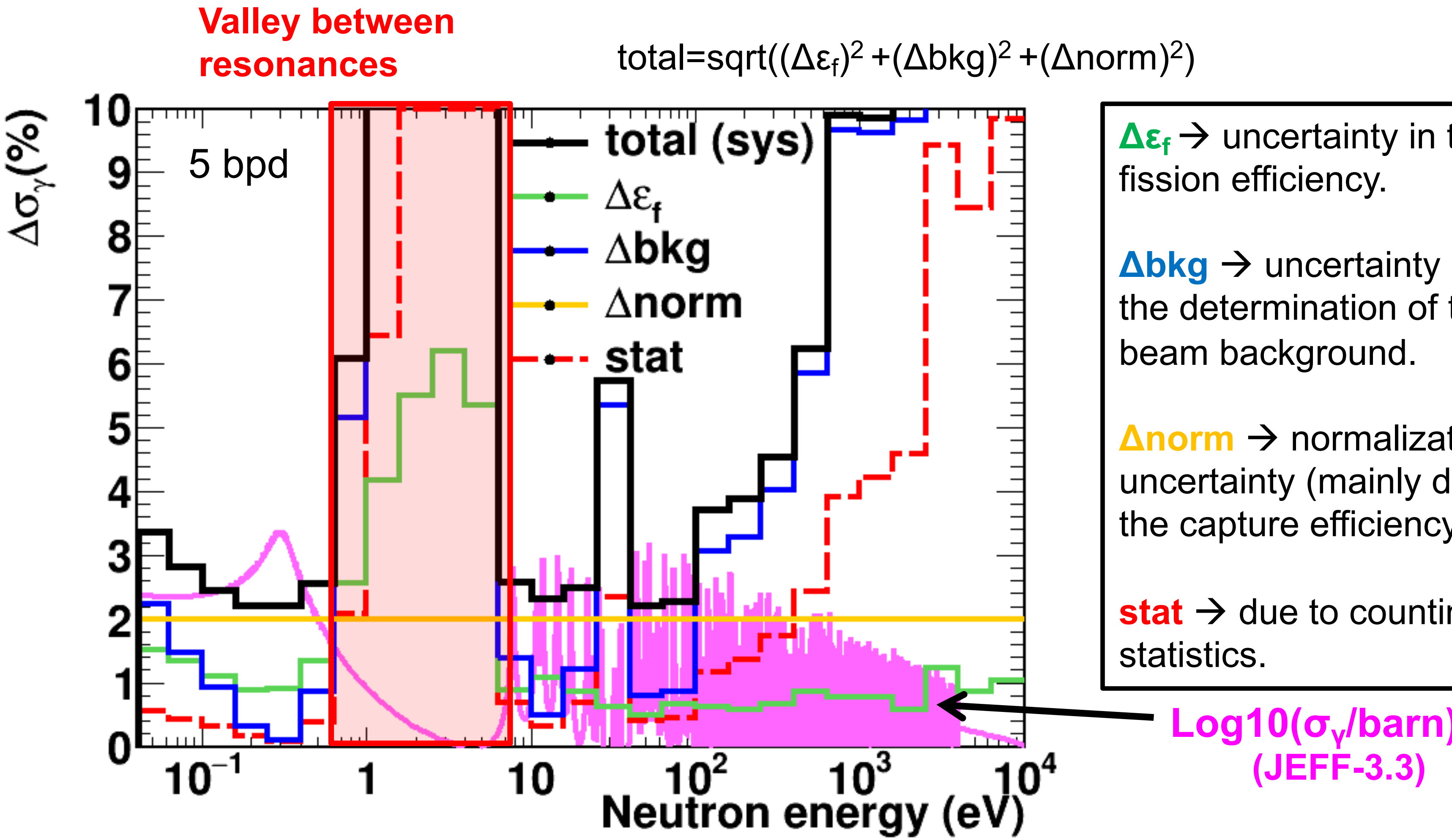


Estimation of uncertainties



$\Delta\varepsilon_f$ → uncertainty in the fission efficiency.

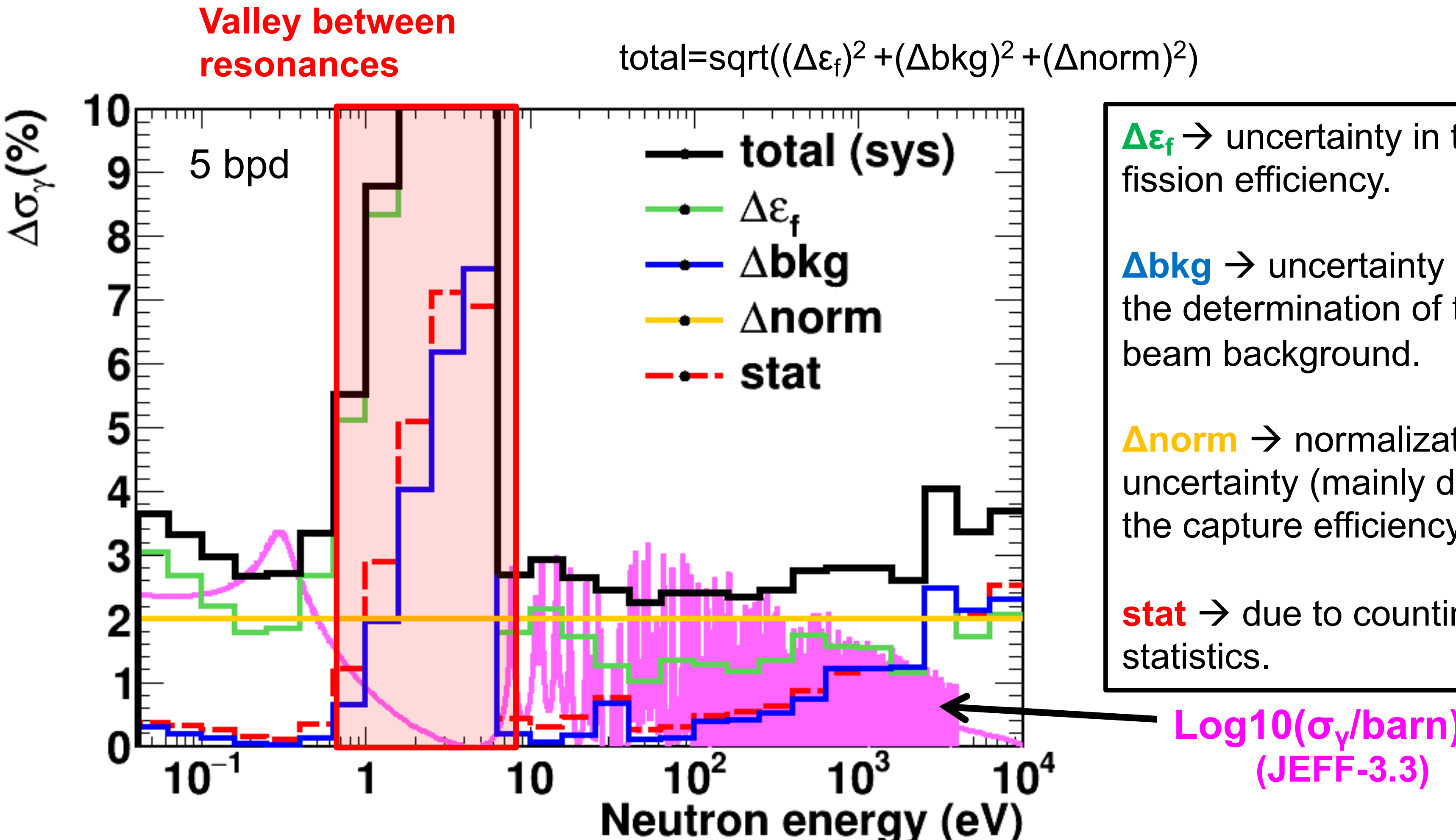
Δbkg → uncertainty in the determination of the beam background.

Δnorm → normalization uncertainty (mainly due to the capture efficiency).

stat → due to counting statistics.

Estimated uncertainties in the measured ^{239}Pu capture cross section, using a **10 mg** ^{239}Pu sample.

Estimation of uncertainties



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Estimated uncertainties in the measured ^{239}Pu capture cross section, using a **80 mg** ^{239}Pu sample.

Beam time request

Measurement	Purpose	Protons
^{239}Pu samples (10x1 mg)	(n,γ) cross section measurement (up to 0.5 keV)	$1.2 \cdot 10^{18}$
Dummy chamber (10x1 mg)	Canning related background	$0.8 \cdot 10^{18}$
^{239}Pu sample (50 – 100 mg)	(n,γ) cross section measurement (0.01–10 keV)	$0.8 \cdot 10^{18}$
Dummy (50 – 100 mg)	Canning related background	$0.5 \cdot 10^{18}$
Sample out	Beam related background	$0.5 \cdot 10^{18}$
^{197}Au	Validation of the measurement	$0.5 \cdot 10^{18}$
Graphite	Background due to elastic scattering	$0.3 \cdot 10^{18}$
^{239}Pu without neutron absorber	Determination of the $^{239}Pu(n,\gamma)$ cascades	$0.4 \cdot 10^{18}$
^{239}Pu (no beam)	Background without beam	0
Total		**$5 \cdot 10^{18}$**

Conclusions

- More accurate ^{239}Pu capture and fission cross section data are needed, as they have been listed in the NEA/OCDE High Priority Request List (HPRL).

- We propose to measure the α–ratio, (the fission) and the capture cross sections at the EAR1, using the **TAC and ionization chambers** developed at the University of Lodz. One CIEMAT PhD student (Adrián Sánchez) has started to work in this topic.

- The ^{239}Pu **samples will be manufactured at JRC-Geel**. These samples will be placed inside the fission detector, in the center of the TAC.

- We request **$5.0 \cdot 10^{18}$ protons on target** to perform this measurement.
  - **10 thin samples** (**1 mg each**). We expect to determine the capture cross section and the α-ratio of ^{239}Pu with an accuracy of **~3% below 100 eV and 4-6% between 100 eV and 1 keV**.
  - **One sample of 50-100 mg**. With this sample the measurement could be extended up to ~10 keV, with an accuracy in the capture cross section of **3-4%**. If we succeed, then we request an additional **$1.0 \cdot 10^{18}$ protons**, i.e. a total of **$5.0 \cdot 10^{18}$ protons on target**.

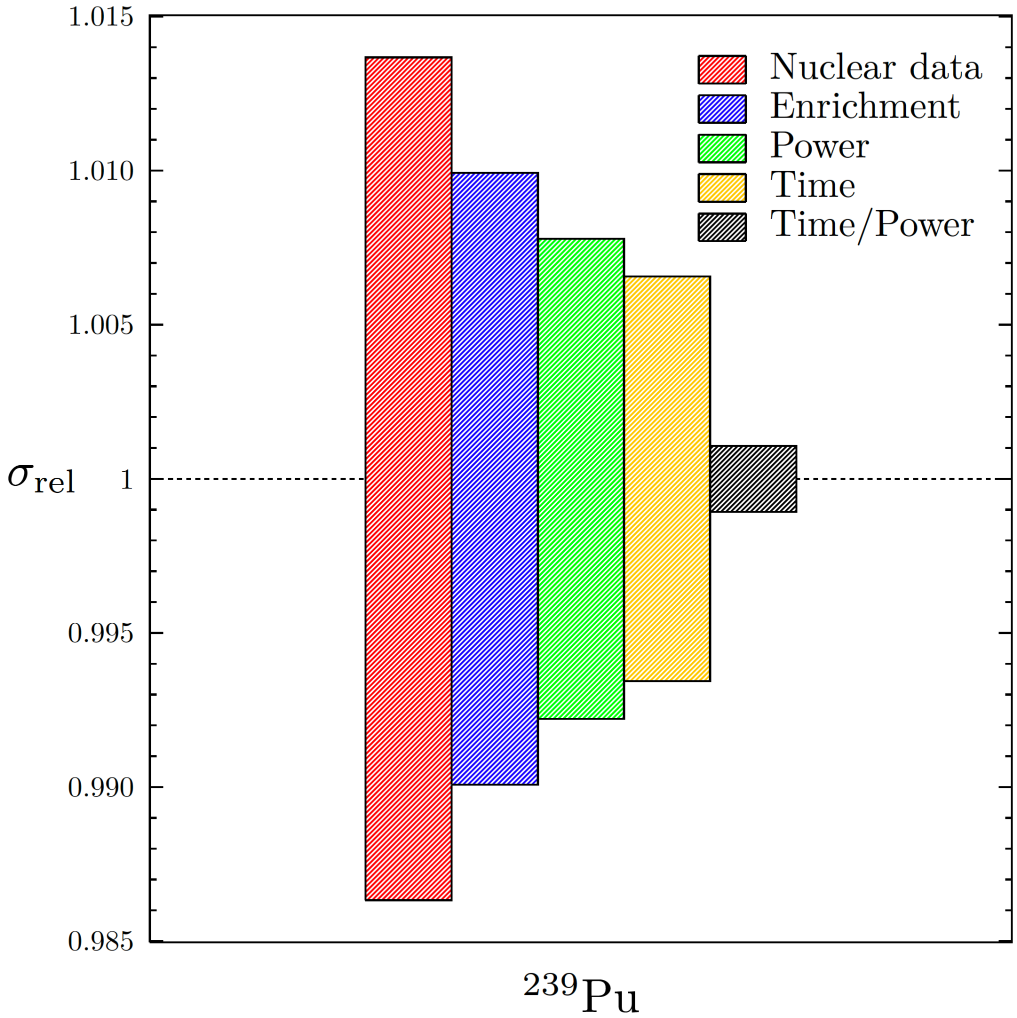
Acknowledgments

- This work is partially supporte by the EC **H2020 SANDA** project (subtask 2.2.1) to perform this measurement and the Spanish Ministry of Science grant PGC2018-096717-B-C21.

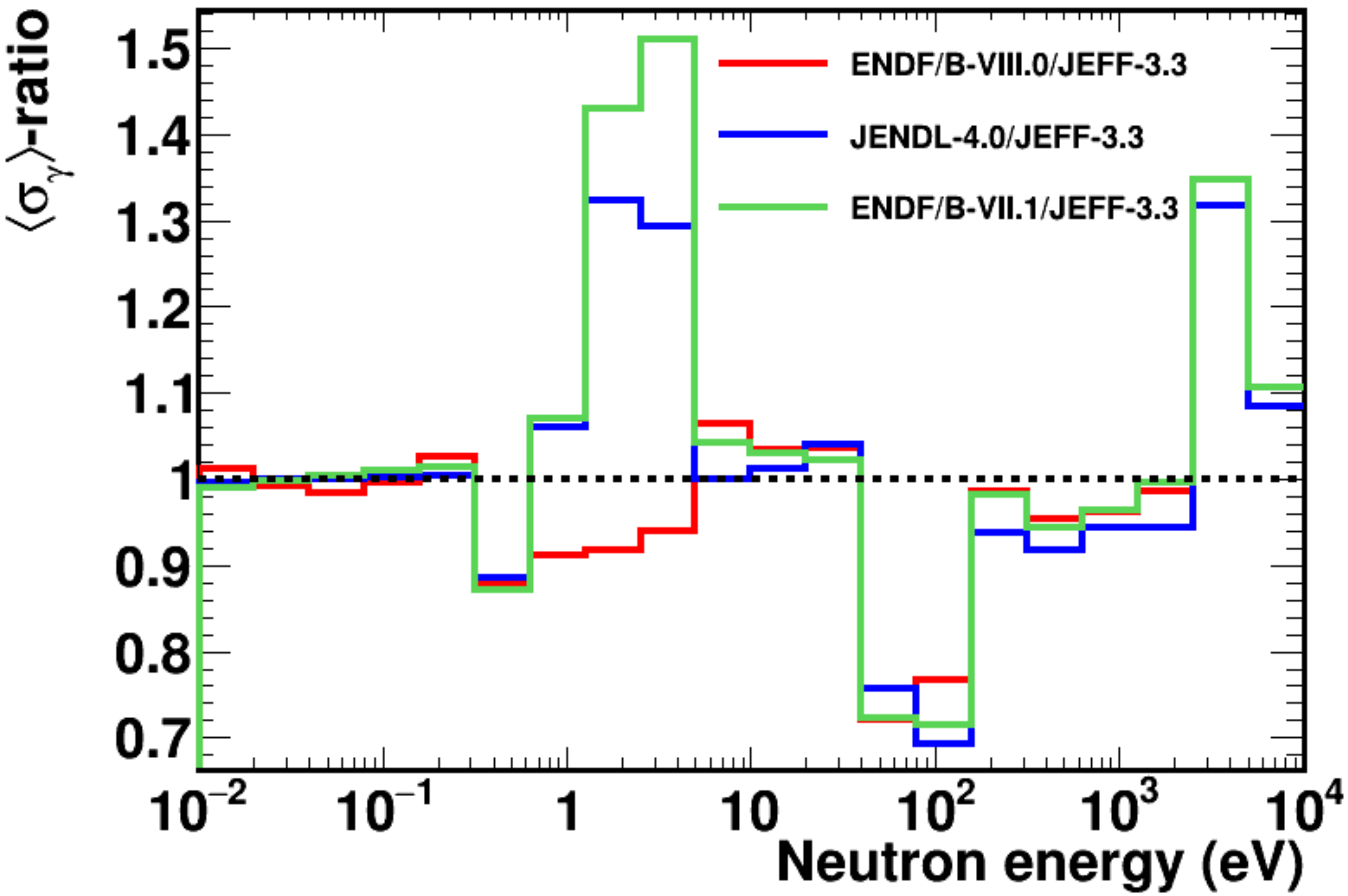
- Additional funds have been provided for a **four years contract for a student which will perform his PhD in this measurement**.

Spare slides

Uncertainty in the ^{239}Pu mass in SNF after discharge

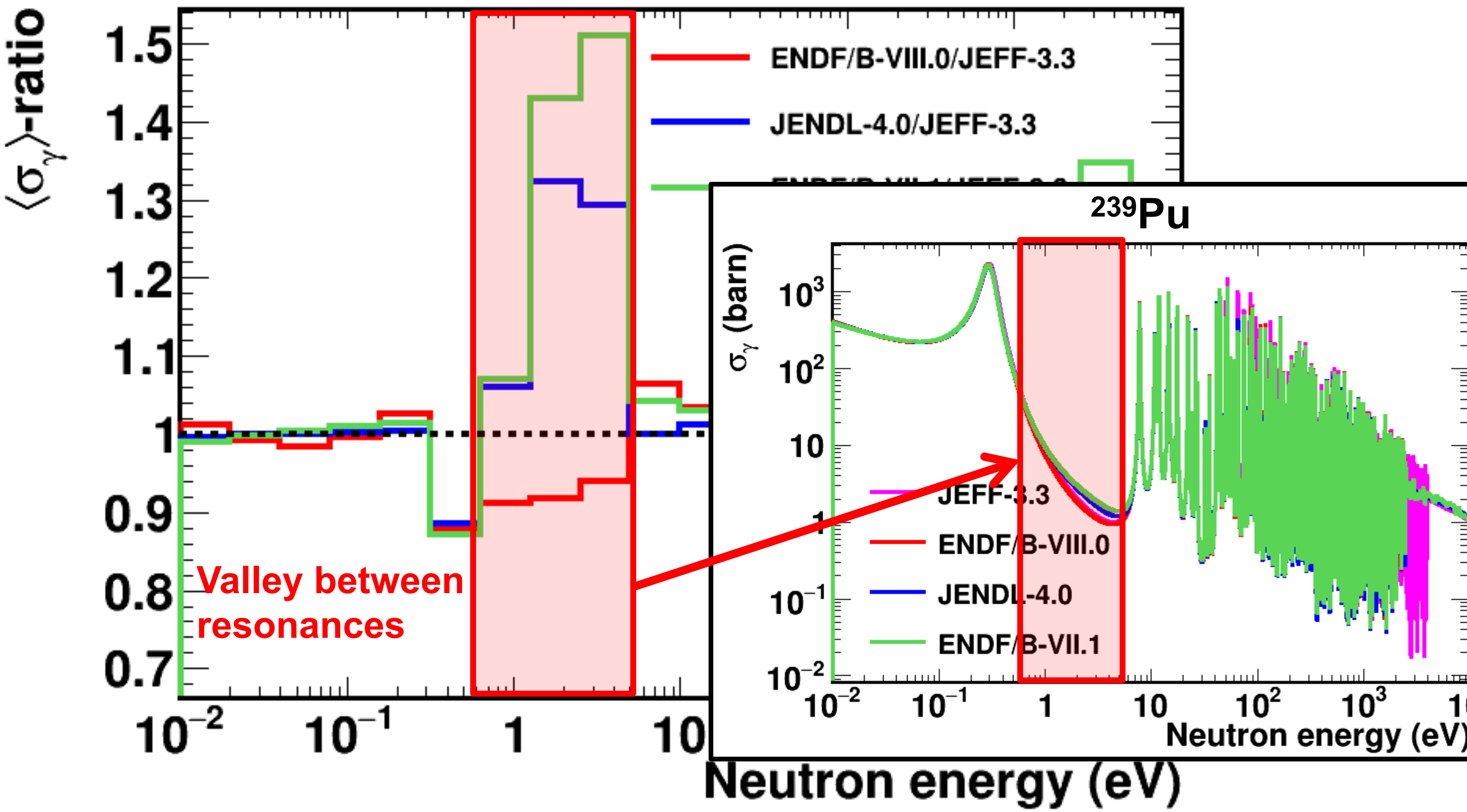


Status of the $^{239}Pu(n,\gamma)$ cross section



Ratio between the $^{239}Pu(n,\gamma)$ cross sections of ENDF/B-VIII.0, JENDL-4.0 and ENDF/B-VII.1 and JEFF-3.3.

Status of the ^{239}Pu(n,γ) cross section



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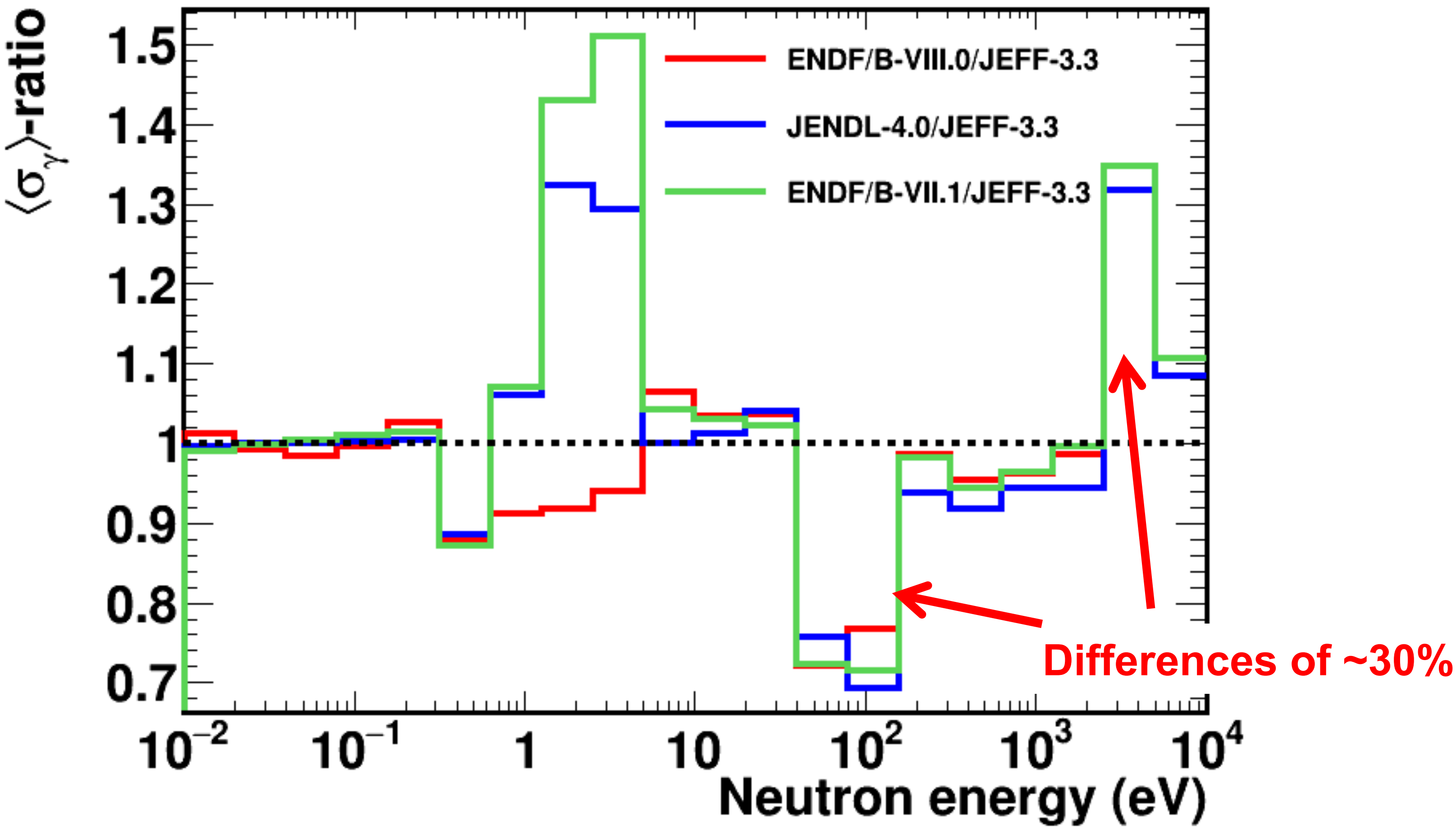

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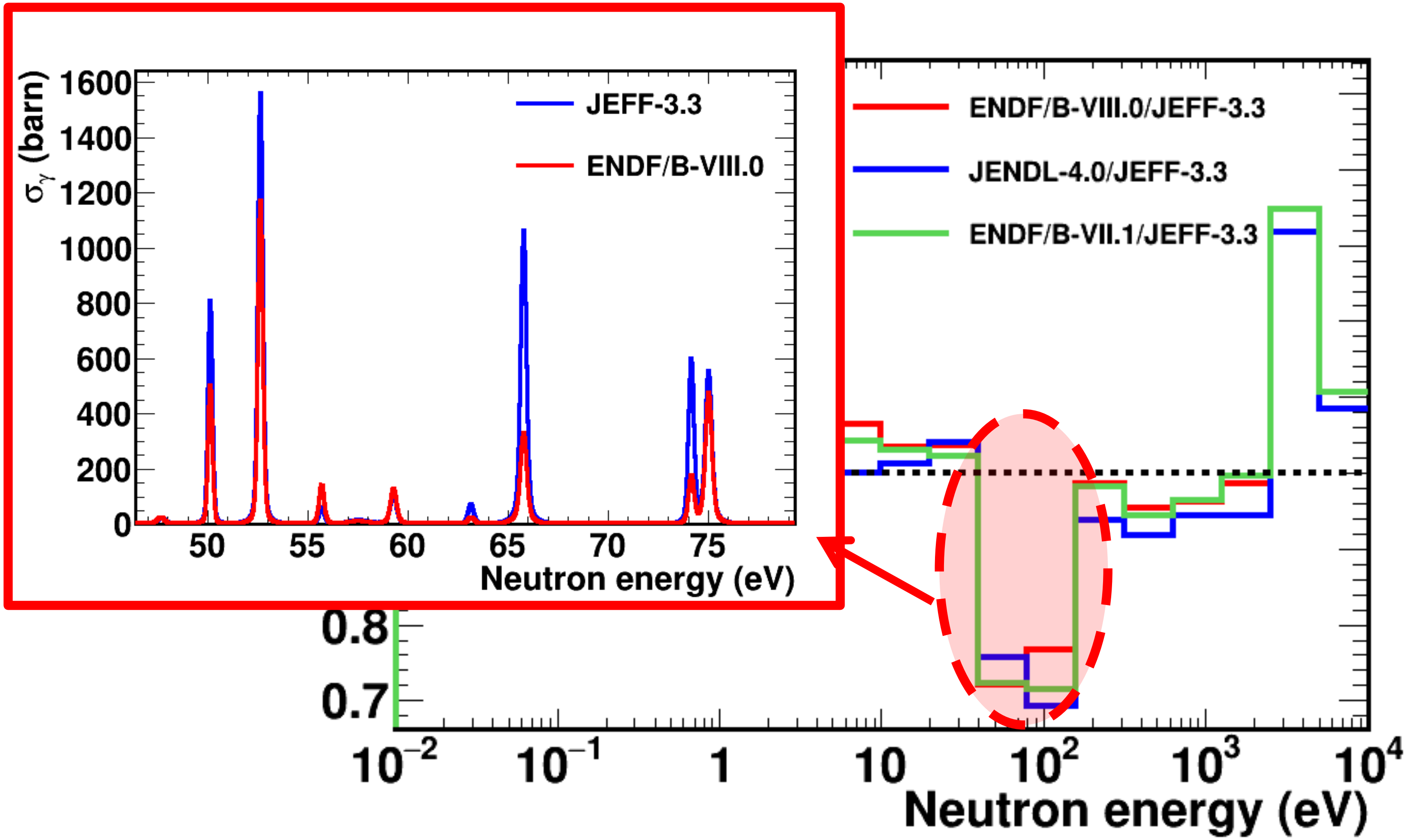

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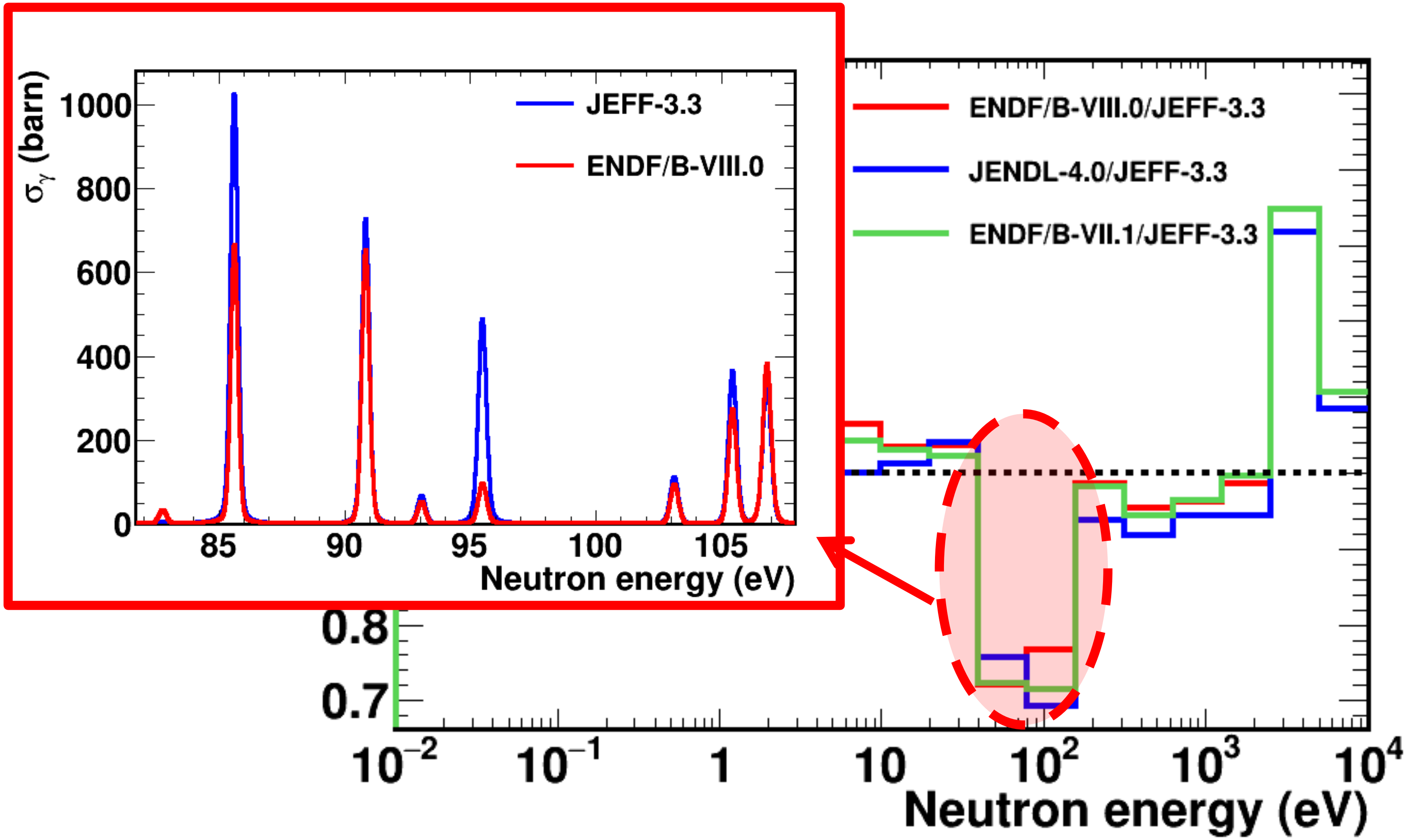

Ratio between the $^{239}Pu(n,\gamma)$ cross sections of ENDF/B-VIII.0, JENDL-4.0 and ENDF/B-VII.1 and JEFF-3.3.

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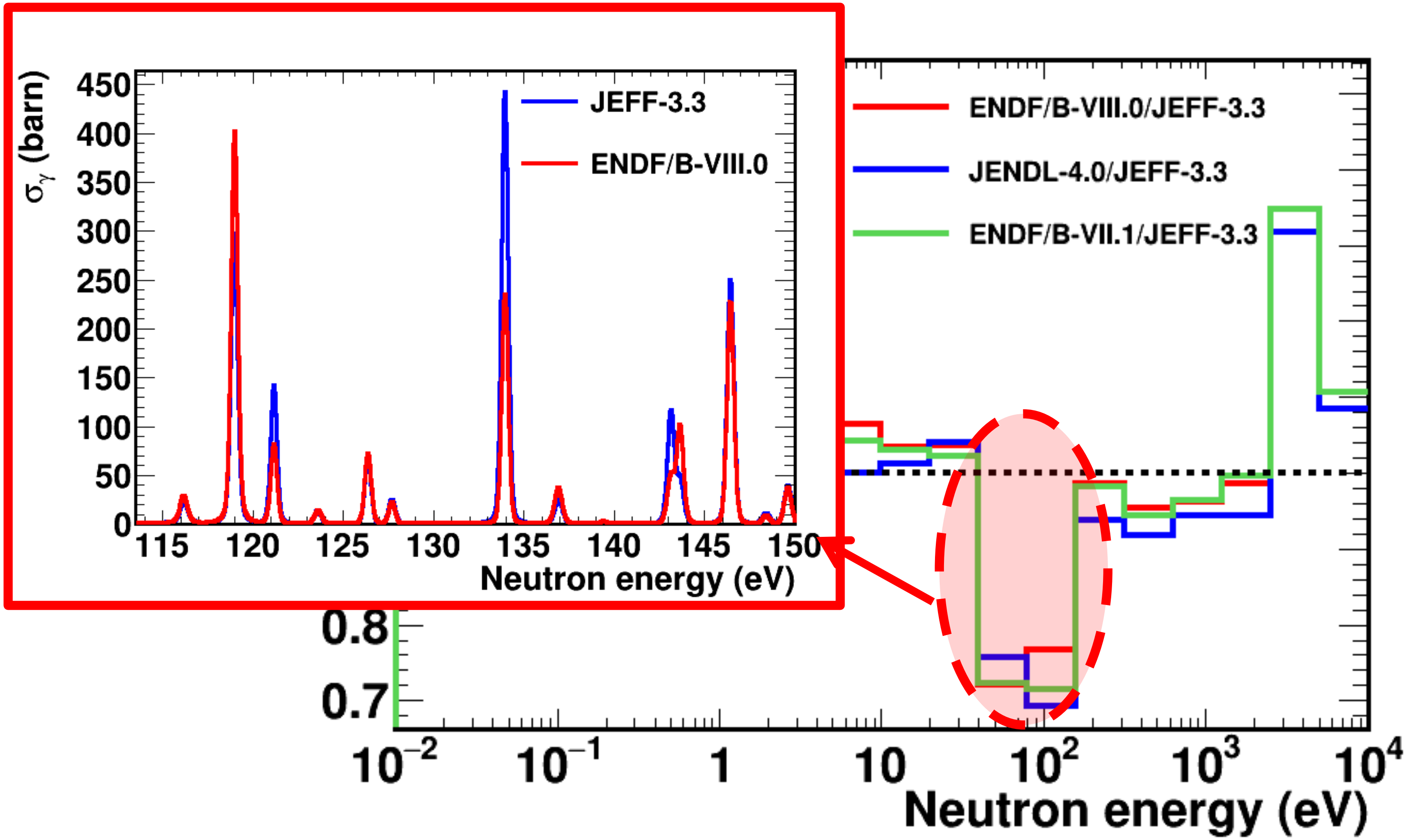


Ratio between the $^{239}Pu(n,\gamma)$ cross sections of ENDF/B-VIII.0, JENDL-4.0 and ENDF/B-VII.1 and JEFF-3.3.

The measurement technique

We will use the **fission tagging technique**, already developed for the ^{235}U(n,γ) measurement (see the *Balibrea et al*. draft submitted recently to PRC for more details).

We have performed a very detailed analysis to estimate the uncertainties we will have in the α–ratio and in the capture cross section after performing the measurement. The estimations have been validated with the results of the ^{235}U(n,γ) measurement.

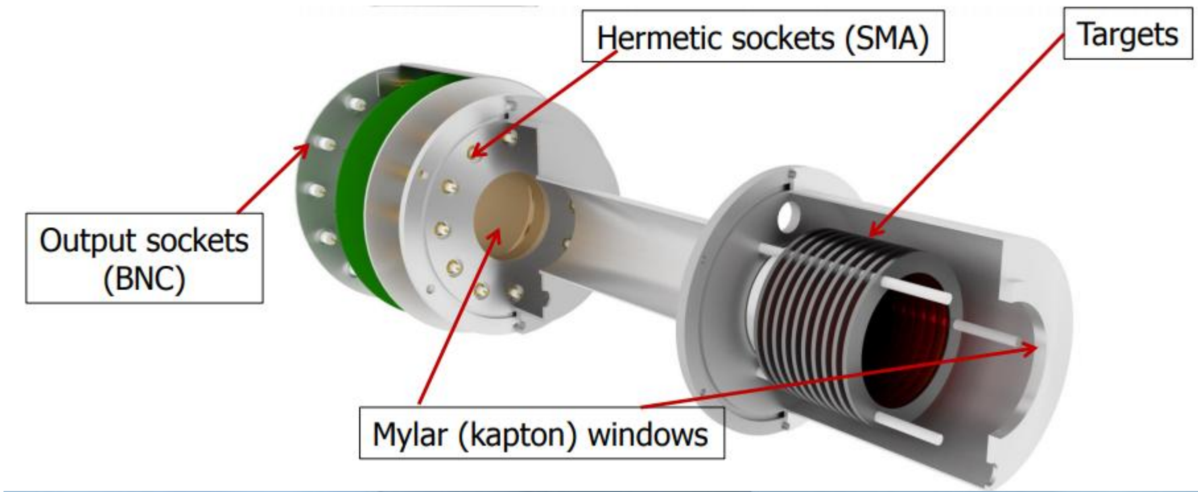
According to these estimations:

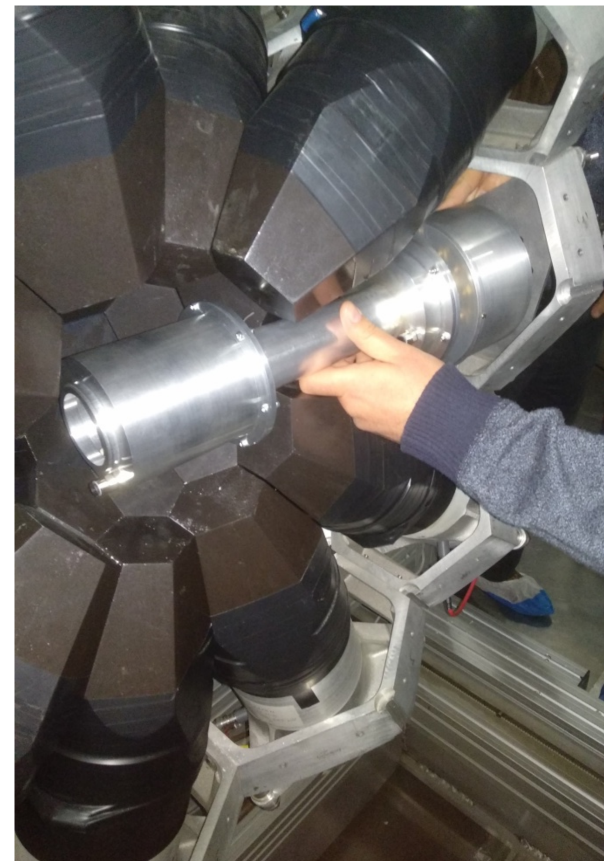
- With a **10 mg** sample: σ_γ and α-ratio can be determined with **~3% below 100 eV and 4-6% between 100 eV and 1keV**.
- With an **80 mg** sample : σ_γ and α-ratio can be determined with a bit less accuracy below 100 eV, but **3-4% between 100 eV and 10 keV**.

The fission chamber

The fission chamber has been already designed and built at the University of Lodz. It has been already presented at:

- n_TOF Detectors Meeting, CERN, Feb 2020 → link
- n_TOF Collaboration Meeting, Prague, October 2019 → link





The fission chamber

The fission chamber has been designed taking into account the following important characteristics:

1. **Low mass** intercepting the neutron beam, to minimize the background in the TAC due to capture and elastic scattered neutrons.
2. Good **discrimination** between **alphas** and **fission fragments**.
3. Small **pile-up** effects.

Before the measurement at n_TOF, **the fission chamber will be tested** in a ^{239}Pu(n,f) measurement at **JRC-Geel**.

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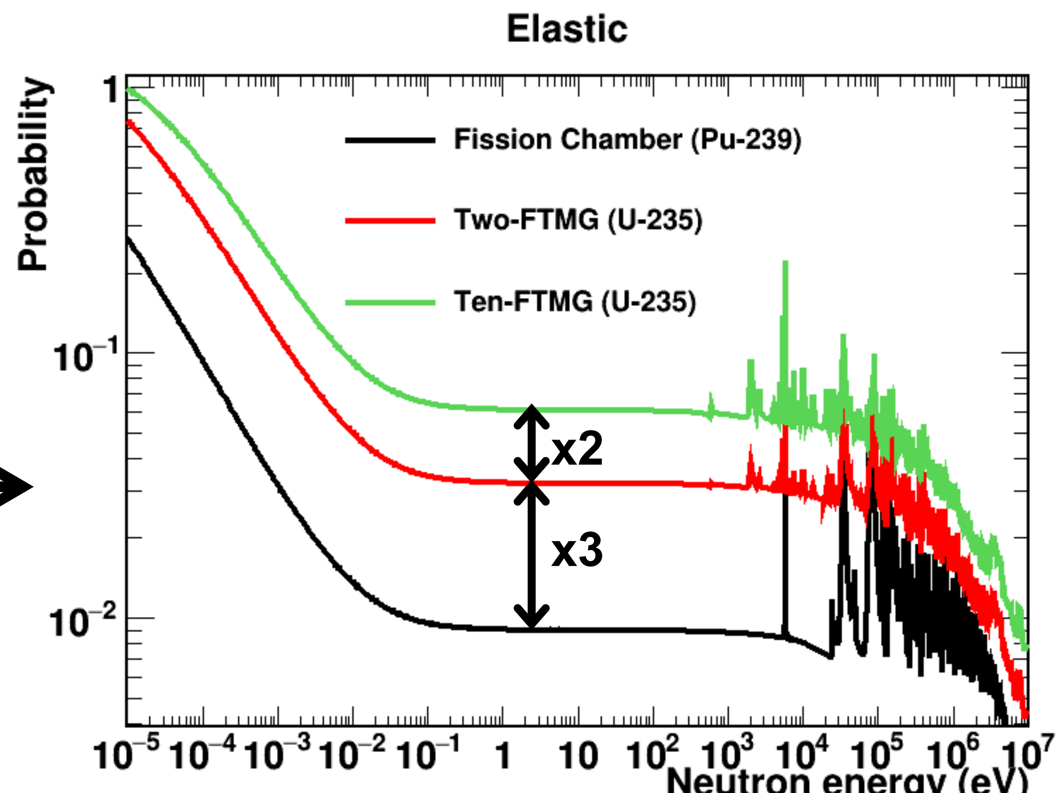

Probability of elastic scattering as a function of the neutron energy, in the new fission chamber (black) and in the fission detectors used in the ^{235}U measurement (red and green).

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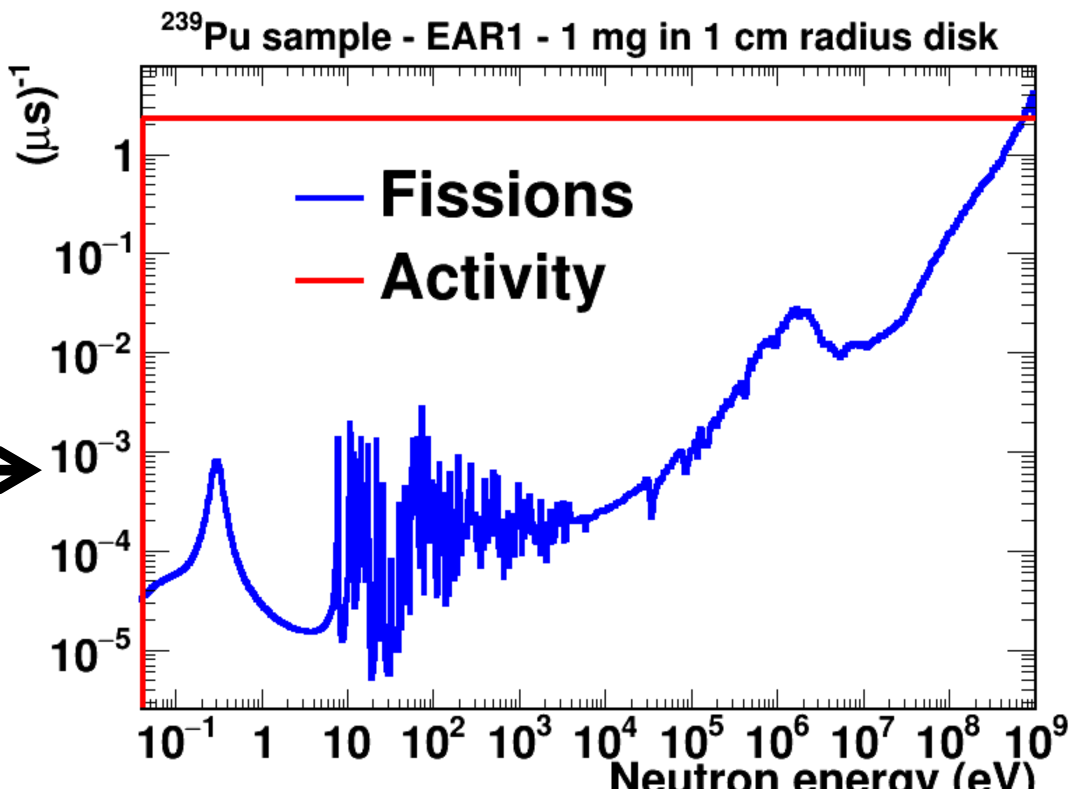

Expected α–activity in one sample (1 mg) together with the expected fission rates, as a function of the neutron energy.

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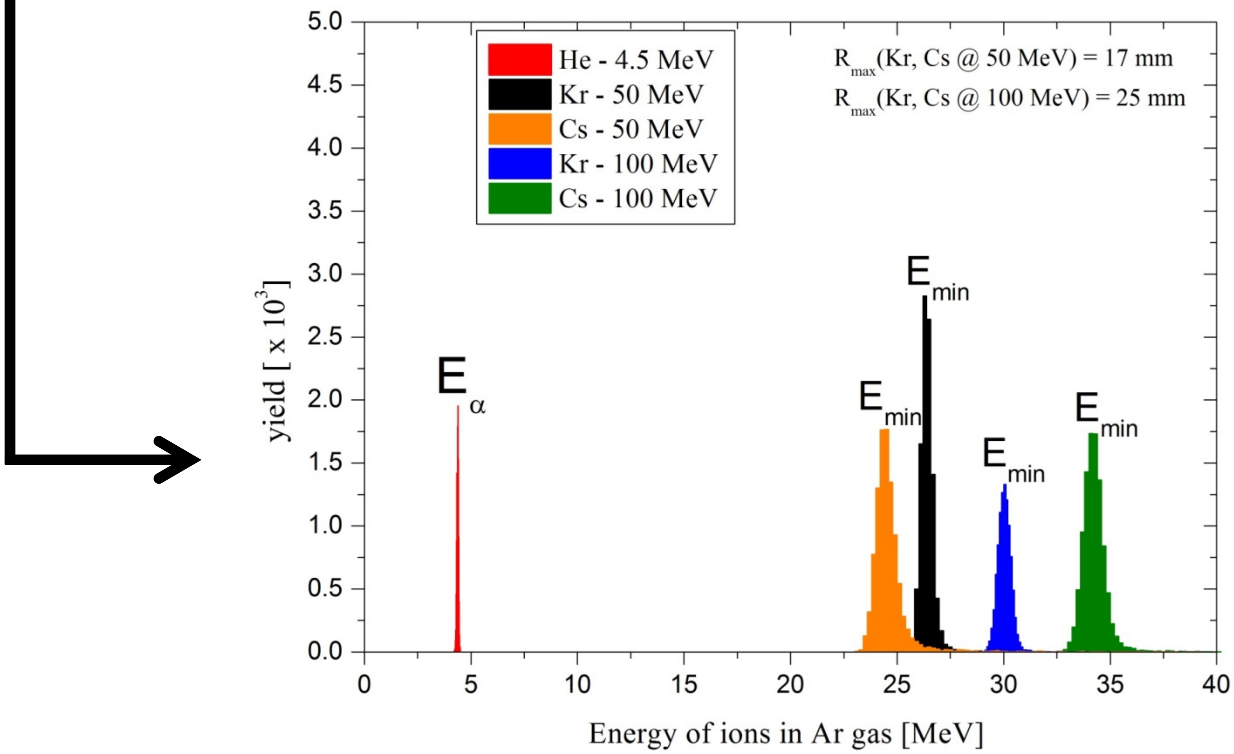

The simulations of energy distributions in 5 mm of gas of α particles and the chosen fission fragments (Kr, Cs) prepared with using the SRIM code.

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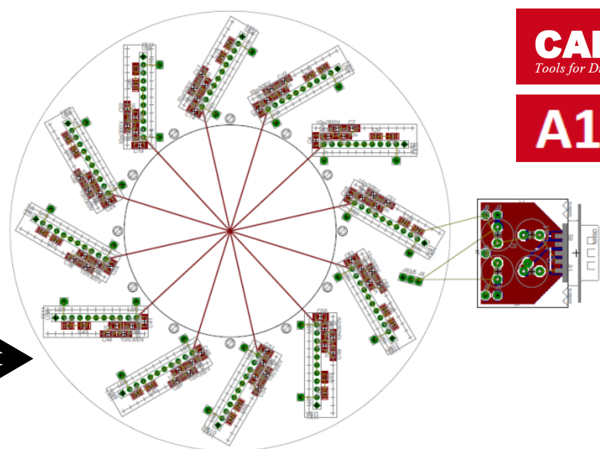

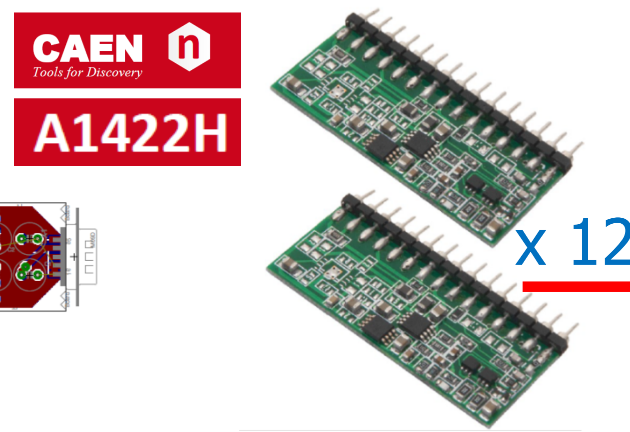

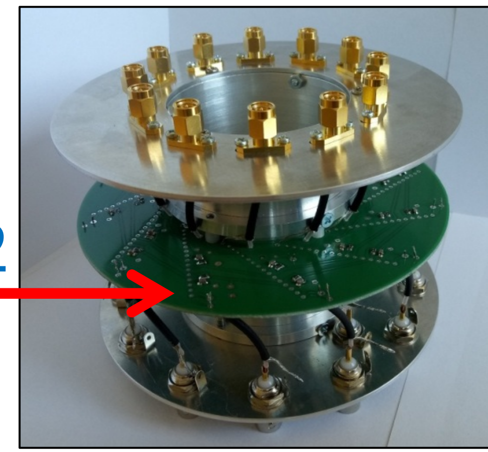

We should receive fast ~ 40 ns rising time of pulses thanks to proposed gas mixture (90% Ar + 10% CF_4) and electronics

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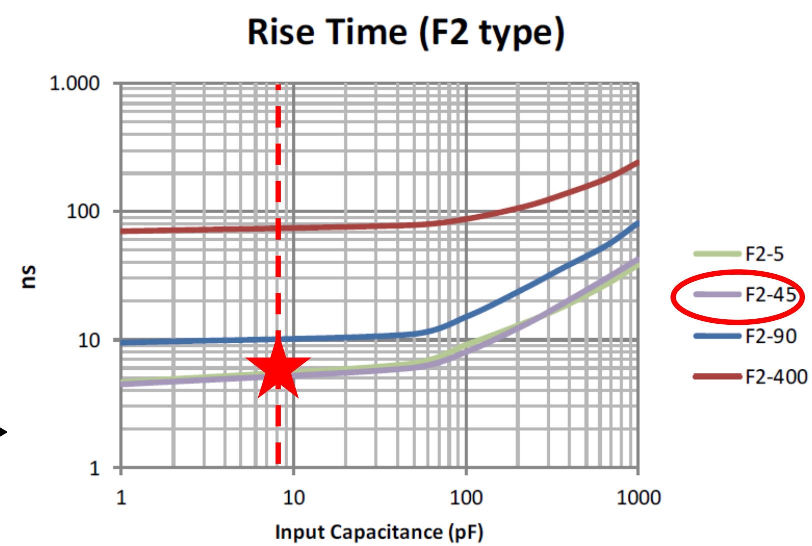

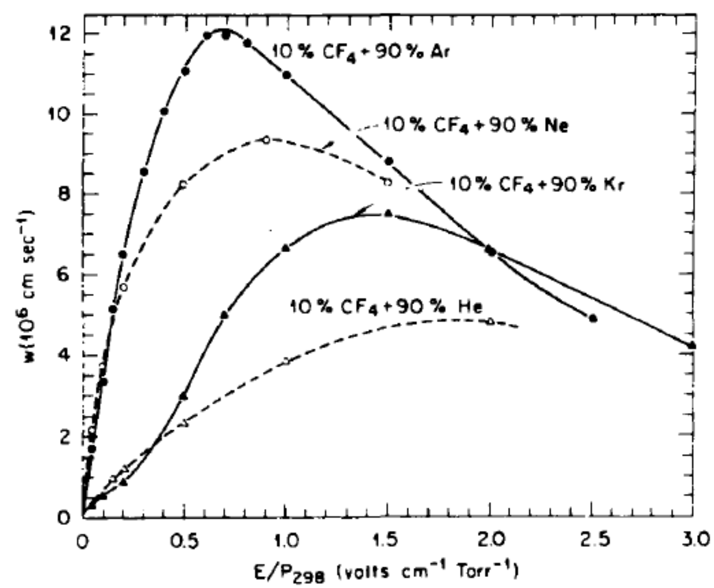

L.G.Christophorou, et. al., Nuclear Instruments and Methods, 163 (1979) 141

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$$Y_\gamma = \frac{c_{tot,\gamma}(E_n) - \frac{c_{tag}(E_n)}{\epsilon_f^*(E_n)} - c_{oth,\gamma}(E_n)}{\epsilon_f(E_n)\phi_N(E_n)}$$

$$c_{tot,\gamma}(E_n) = c_{aco,\gamma}(E_n) + c_{tag}(E_n)$$

c_{tot} = counts in the TAC.
c_{tag} = counts in the TAC in coincidence. with the fission chamber.
c_{aco} = counts in the TAC in anti-coincidence. with the fission chamber.
ϵ_f^* = fission tagging efficiency.
ϵ_γ = capture detection efficiency.
ϵ_f = fission detection efficiency.

$$Y_\gamma = \frac{c_{aco,\gamma}(E_n) - \frac{1-\epsilon_f^*(E_n)}{\epsilon_f^*(E_n)} c_{tag}(E_n) - c_{oth,\gamma}(E_n)}{\epsilon_\gamma(E_n)\phi_N(E_n)}$$

and

$$\alpha = \frac{\epsilon_f}{\epsilon_\gamma} \frac{c_{aco,\gamma}(E_n) - \frac{1-\epsilon_f^*(E_n)}{\epsilon_f^*(E_n)} c_{tag}(E_n) - c_{oth,\gamma}(E_n)}{c_{aco,f}(E_n) + c_{tag}(E_n) - c_{bkg\ f}(E_n)}$$

$\sigma(n,\gamma)$ data on actinides measured after 2000 (EXFOR)

Isotope	Facility	Detector	E_{low} (eV)	E_{high} (eV)	EXFOR	Publication
U-233	n_TOF-1	TAC	0,7	1000	Yes	E. Berthoumieux et al., Conf. on Nuclear Data for Science and Technology, Nice 2007, p.571 (2007)
U-233	n_TOF-1	TAC	?	?	No	M. Bacak et al., ND2016, EPJ Conf. 146, 03027 (2017)
U-235	LANSCE	TAC + PPAC	4	1,00E+06	Yes	M. Jandel et al., Phys. Rev. Lett. 109, 202506 (2012)
U-235	n_TOF-1	TAC + MGAS	1	22	Yes	C. Guerrero et al., Eur. Phys. Jour. A 48, 29 (2012)
U-235	n_TOF-1	TAC + MGAS	0,2	200	No	J. Balibrea et al., Nucl. Data Sheets 119, 10 (2014)
U-235	RPI	NaI - TAC	0,02	3000	No	Y. Danon, et al., Nucl. Sci. and Eng. 187, 191 (2017)
U-238	LANSCE	TAC	1	6,30E+05	Yes	J.L. Ullmann et al., Phys. Rev. C 89, 034603 (2014)
U-238	GELINA	C_6D_6 TED	3,5	1200	Yes	H.I. Kim et al., Eur. Phys. Jour. A 52, 170 (2016)
U-238	n_TOF-1	C_6D_6 TED	1	700	Yes	F. Mingrone et al., Phys. Rev. C 95, 034604 (2017)
U-238	n_TOF-1	TAC	1	8,00E+04	Yes	T. Wright et al., Phys. Rev. C 96, 064601 (2017)
Np-237	KURRI	C_6D_6 - TED	0.005	1,00E+04	Yes	K. Kobayashi et al., Jour. Nucl. Sci. Tech. 39, 111 (2002)
Np-237	KURRI	BGO - TED	0,02	100	Yes	O. Shcherbakov et al., Jour. Nucl. Sci. Tech. 42, 135 (2005)
Np-237	KURRI	Ge	0,02	14	Yes	M. Mizumoto et al., Conf. on Nuclear Data for Science and Technology, Nice 2007
Np-237	LANSCE	TAC	0,02	5,00E+05	Yes	E.I. Esch et al., Phys. Rev. C 77, 034309 (2008)
Np-237	n_TOF-1	TAC	0,7	2000	Yes	C. Guerrero et al., Phys. Rev. C 85, 044616 (2012)
Np-237	J-PARC	NaI - TED	0,01	1000	Yes	K.Hirose et al., Jour. Nucl. Sci. Tech. 50, 188 (2013)
Pu-238	LANSCE	TAC	0,025	3,00E+04	Yes	A. Chyzh et al., Phys. Rev. C 88, 044607 (2013)
Pu-239	LANSCE	TAC	10	1000	Yes	S. Mosby et al., Phys. Rev. C 89, 034610 (2014)
Pu-240	n_TOF-1	TAC	0,7	2000	No	C. Guerrero et al., Conf. on Nuclear Data for Science and Technology, Nice 2007
Pu-242	LANSCE	TAC + PPAC	0,027	3,60E+04	Yes	M.Q. Buckner et al., Phys. Rev. C 93, 044613 (2016)
Pu-242	n_TOF-1	C_6D_6 - TED	2	4000	Yes	J. Lerendegui-Marco et al., Phys. Rev.C 97, 024605 (2018)
Am-241	LANSCE	TAC	0,02	3,20E+05	Yes	M. Jandel et al., Phys. Rev.C 78, 034609 (2008)
Am-241	GELINA	C_6D_6 - TED	0,025	110	No	C. Lampoudis et al., Eur. Phys. J. Plus 128, 86 (2013)
Am-241	J-PARC	Ge	0,01	10	Yes	H. Harada et al., Nucl. Data Sheets 119, 61 (2014)
Am-241	n_TOF-1	C_6D_6 TED	0,026	1,50E+05	Yes	K. Fraval et al., Phys. Rev.C 89, 044609 (2014)
Am-241	J-PARC	C_6D_6 TED	0,1	2,00E+04	Yes	K. Hirose et al., Nucl. Instr. Meth. A 856, 133 (2017)
Am-241	n_TOF-1	TAC	0,2	1,00E+04	Yes	E. Mendoza et al., Phys. Rev.C 97, 054616 (2018)
Am-241	J-PARC	C_6D_6 TED	0,025	100	No	K. Terada et al., Jour. Nucl. Sci. Tech. 55, 1198 (2018)
Am-242m	LANSCE	TAC + PPAC	0,1	8000	Yes	M.Q.Buckner et al., Phys. Rev. C 95, 061602 (2017)
Am-243	n_TOF-1	TAC	0,7	2500	Yes	E. Mendoza et al., Phys. Rev. C 90, 034608 (2014)
Cm-244	J-PARC	Ge	2	300	Yes	A. Kimura et al., Jour. Nucl. Sci. Tech. 49, 708 (2012)
Cm-244	n_TOF-2	C_6D_6 TED	1	300	No	V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018
Cm-244	n_TOF-1	TAC	1	50	No	V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018
Cm-246	J-PARC	Ge	2	300	Yes	A. Kimura et al., Jour. Nucl. Sci. Tech. 49, 708 (2012)
Cm-246	n_TOF-2	C_6D_6 TED	1	300	No	V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018

Data sets from n_TOF

Isotope	Facility	Detector	E_{low} (eV)	E_{high} (eV)	EXFOR	Publication
U-233	n_TOF-1	TAC	0,7	1000	Yes	E. Berthoumieux et al., Conf. on Nuclear Data for Science and Technology, Nice 2007, p.571 (2007)
U-233	n_TOF-1	TAC	?	?	No	M. Bacak et al., ND2016, EPJ Conf. 146, 03027 (2017)
U-235	LANSCE	TAC + PPAC	4	1,00E+06	Yes	M. Jandel et al., Phys. Rev. Lett. 109, 202506 (2012)
U-235	n_TOF-1	TAC + MGAS	1	22	Yes	C. Guerrero et al., Eur. Phys. Jour. A 48, 29 (2012)
U-235	n_TOF-1	TAC + MGAS	0,2	200	No	J. Balibrea et al., Nucl. Data Sheets 119, 10 (2014)
U-235	RPI	NaI - TAC	0,02	3000	No	Y. Danon, et al., Nucl. Sci. and Eng. 187, 191 (2017)
U-238	LANSCE	TAC	1	6,30E+05	Yes	J.L. Ullmann et al., Phys. Rev. C 89, 034603 (2014)
U-238	GELINA	C_6D_6 TED	3,5	1200	Yes	H.I. Kim et al., Eur. Phys. Jour. A 52, 170 (2016)
U-238	n_TOF-1	C_6D_6 - TED	1	700	Yes	F. Mingrone et al., Phys. Rev. C 95, 034604 (2017)
U-238	n_TOF-1	TAC	1	8,00E+04	Yes	T. Wright et al., Phys. Rev. C 96, 064601 (2017)
Np-237	KURRI	C_6D_6 - TED	0.005	1,00E+04	Yes	K. Kobayashi et al., Jour. Nucl. Sci. Tech. 39, 111 (2002)
Np-237	KURRI	BGO - TED	0,02	100	Yes	O. Shcherbakov et al., Jour. Nucl. Sci. Tech. 42, 135 (2005)
Np-237	KURRI	Ge	0,02	14	Yes	M. Mizumoto et al., Conf. on Nuclear Data for Science and Technology, Nice 2007
Np-237	LANSCE	TAC	0,02	5,00E+05	Yes	E.I. Esch et al., Phys. Rev. C 77, 034309 (2008)
Np-237	n_TOF-1	TAC	0,7	2000	Yes	C. Guerrero et al., Phys. Rev. C 85, 044616 (2012)
Np-237	J-PARC	NaI - TED	0,01	1000	Yes	K.Hirose et al., Jour. Nucl. Sci. Tech. 50, 188 (2013)
Pu-238	LANSCE	TAC	0,025	3,00E+04	Yes	A. Chyzh et al., Phys. Rev. C 88, 044607 (2013)
Pu-239	LANSCE	TAC	10	1000	Yes	S. Mosby et al., Phys. Rev. C 89, 034610 (2014)
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Pu-242	n_TOF-1	C_6D_6 - TED	2	4000	Yes	J. Lerendegui-Marco et al., Phys. Rev.C 97, 024605 (2018)
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Cm-244	n_TOF-2	C_6D_6 TED	1	300	No	V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018
Cm-244	n_TOF-1	TAC	1	50	No	V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018
Cm-246	J-PARC	Ge	2	300	Yes	A. Kimura et al., Jour. Nucl. Sci. Tech. 49, 708 (2012)
Cm-246	n_TOF-2	C_6D_6 TED	1	300	No	V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018

CIEMAT's contribution (11 of 35)

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Am-241	J-PARC	C_6D_6 TED	0,1	2,00E+04	Yes	K. Hirose et al., Nucl. Instr. Meth. A 856, 133 (2017)
Am-241	n_TOF-1	TAC	0,2	1,00E+04	Yes	E. Mendoza et al., Phys. Rev.C 97, 054616 (2018)
Am-241	J-PARC	C_6D_6 TED	0,025	100	No	K. Terada et al., Jour. Nucl. Sci. Tech. 55, 1198 (2018)
Am-242m	LANSCE	TAC + PPAC	0,1	8000	Yes	M.Q.Buckner et al., Phys. Rev. C 95, 061602 (2017)
Am-243	n_TOF-1	TAC	0,7	2500	Yes	E. Mendoza et al., Phys. Rev. C 90, 034608 (2014)
Cm-244	J-PARC	Ge	2	300	Yes	A. Kimura et al., Jour. Nucl. Sci. Tech. 49, 708 (2012)
Cm-244	n_TOF-2	C_6D_6 TED	1	300	No	V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018
Cm-244	n_TOF-1	TAC	1	50	No	V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018
Cm-246	J-PARC	Ge	2	300	Yes	A. Kimura et al., Jour. Nucl. Sci. Tech. 49, 708 (2012)
Cm-246	n_TOF-2	C_6D_6 TED	1	300	No	V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018