APRENDE/WP2/Pu239
Towards new measurements and evaluation of the ^{239}Pu resonance parameters

New n_TOF measurements of ^{239}Pu cross sections

06/07/2026

A. Sanchez-Caballero, CIEMAT

Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Introduction

The topic of this talk is *new measurements and evaluation of the ^{239}Pu resonance parameters*.

My (not too long) expertise is mainly focused in the measurement of fission and neutron capture cross sections of ^{239}Pu (n_TOF):

- A. Sánchez-Caballero et al., *Experimental setup of the ^{239}Pu neutron capture and fission cross-section measurements at n_TOF, CERN*, EPJ Web of Conf. 294, 01003 (2024).
- J. Perkowski, …, A. Sánchez-Caballero, et al., *Multi-section fission ionization chamber for measurement of ^{239}Pu(n,γ) reaction in fission tagging method*, Nucl. Instr. and Methods Phys. Res. A 1067, 169649 (2024).
- A. Sánchez-Caballero et al., *Low-uncertainty measurement of the ^{239}Pu(n,f) cross section at n_TOF in a very broad energy range from 0.02 eV up to 10 MeV*, Phys. Lett. B 872, 140070 (2026).
- PhD Thesis: *Measurement of the ^{239}Pu neutron capture and fission cross sections at the n_TOF facility at CERN*, Universidad Complutense de Madrid (2026). URL: https://doi.org/10.17181/179rm-jc146.

In this talk I will try to make an overview of the most critical points of the data analysis to extract the fission and capture (and α-ratio) of the ^{239}Pu TOF measurement at n_TOF. I will try to focus on the aspects of the analysis that may result most relevant for evaluators, for example, the estimation of the different uncertainty contributions, estimation of backgrounds, normalizations, etc.

Funded by
the European Union

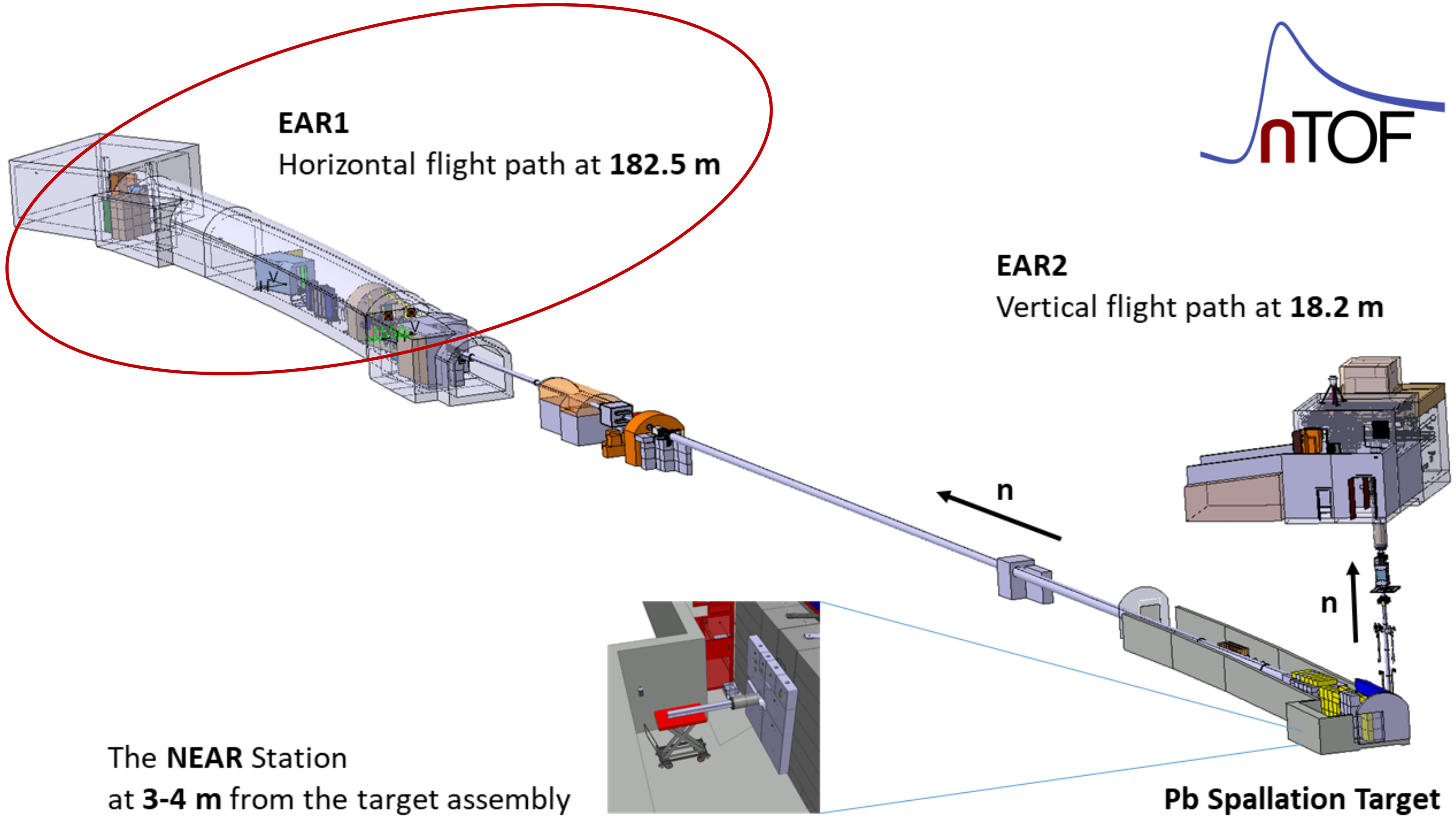
Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Context: experimental setup

- Experiment performed at n_TOF EAR1 (~185 m flight path) in Sep-Nov 2022.
- Around 8 times larger flight path than in previous ^{239}Pu measurements, which enables higher energy resolution.

n_TOF features

- 25 years operation, with relevant measurements for nuclear technology, nuclear astrophysics, medical science and basic research.
- Neutron beam by **spallation** of 20 GeV protons into a lead target.
- Pulses of about 1 Hz repetition rate → no overlapping pulses.
- $8 \cdot 10^{12}$ protons per pulse, 7 ns RMS, with option for lower intensities.
- **Three experimental areas** for different purposes (EAR1, EAR2 and NEAR).
- EAR1: moderated neutrons with a layer of borated water.



Funded by the European Union

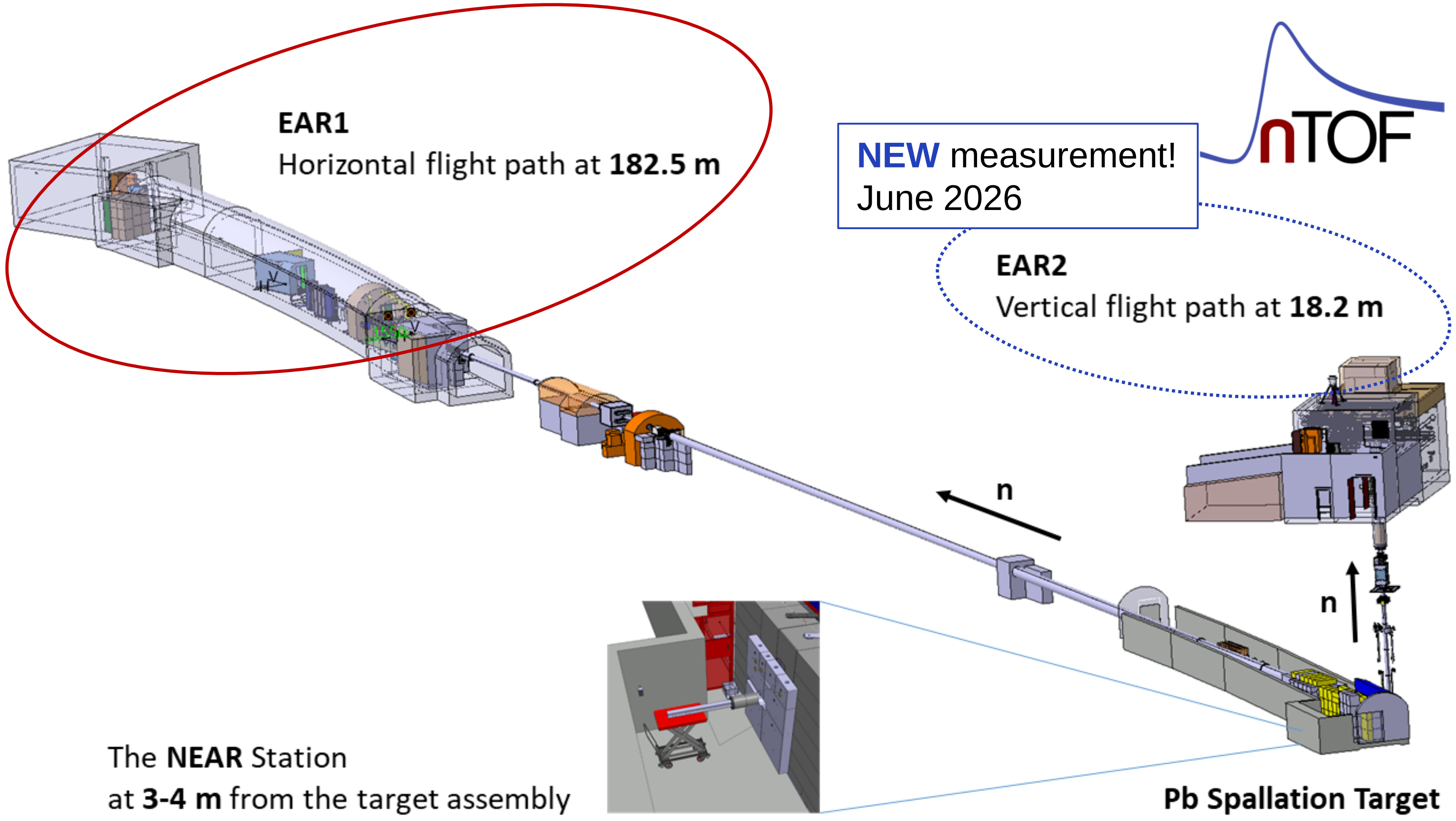
Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Context: experimental setup

- Experiment performed at n_TOF EAR1 (~185 m flight path) in Sep-Nov 2022.
- Around 8 times larger flight path than in previous ^{239}Pu measurements, which enables higher energy resolution.

n_TOF features

- 25 years operation, with relevant measurements for nuclear technology, nuclear astrophysics, medical science and basic research.
- Neutron beam by **spallation** of 20 GeV protons into a lead target.
- Pulses of about 1 Hz repetition rate → <u>no overlapping pulses</u>.
- $8{\cdot}10^{12}$ protons per pulse, 7 ns RMS, with option for lower intensities.
- **Three experimental areas** for different purposes (EAR1, EAR2 and NEAR).
- EAR1: moderated neutrons with a layer of borated water.



Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

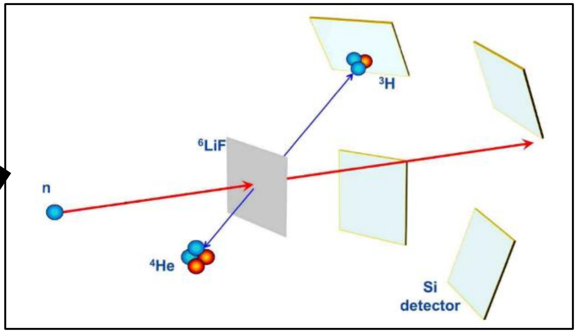
Context: experimental setup

Proton Beam Monitors

- Wall Current Monitor (WCM).
- Beam Current Transformer (BCT).

Neutron Beam Monitor (SiMon)

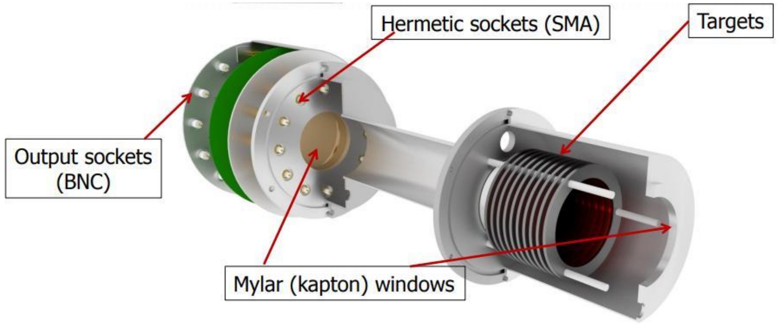
- Four silicon detectors to monitor neutron beam intensity using $^{6}Li(n,\alpha)^{3}H$ standard reaction.



^{239}Pu-specific detectors at EAR1

FFD[1]

Fission Fragment Detector

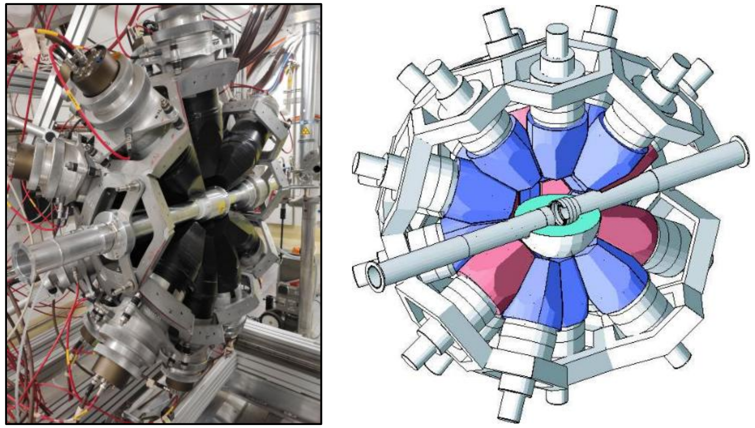


[1] Perkowski et al., Nucl. Instrum. Methods Phys. Res. A 1067, 169649 (2024)

- Detection of charged particles.
- Fast pre-amplifiers.
- Filled with Ar + (10%)CF_4 gas.

TAC[2]

Total Absorption Calorimeter



[2] Guerrero et al., Nucl. Instrum. Methods Phys. Res. A 608(3), 424 (2009)

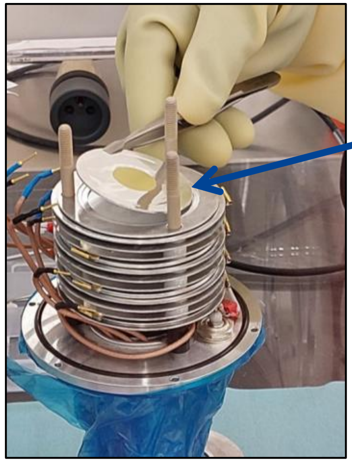
- To detect capture and fission γ-rays.
- Composed of 40 BaF_2 crystals operated in coincidence.
- Events characterized by E_{sum} (total deposited energy from contributing crystals) and m_{cr} (crystal multiplicity).

Funded by
the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Context: experimental setup

- Experimental campaign **divided into two different configurations**:

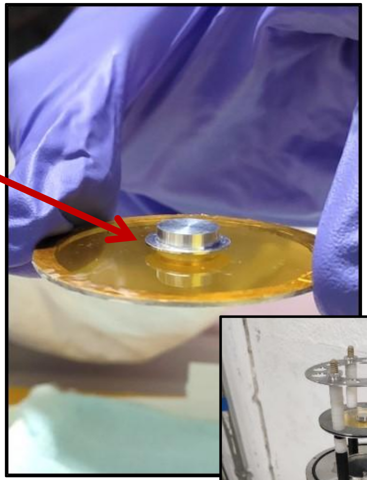


1. FC config.

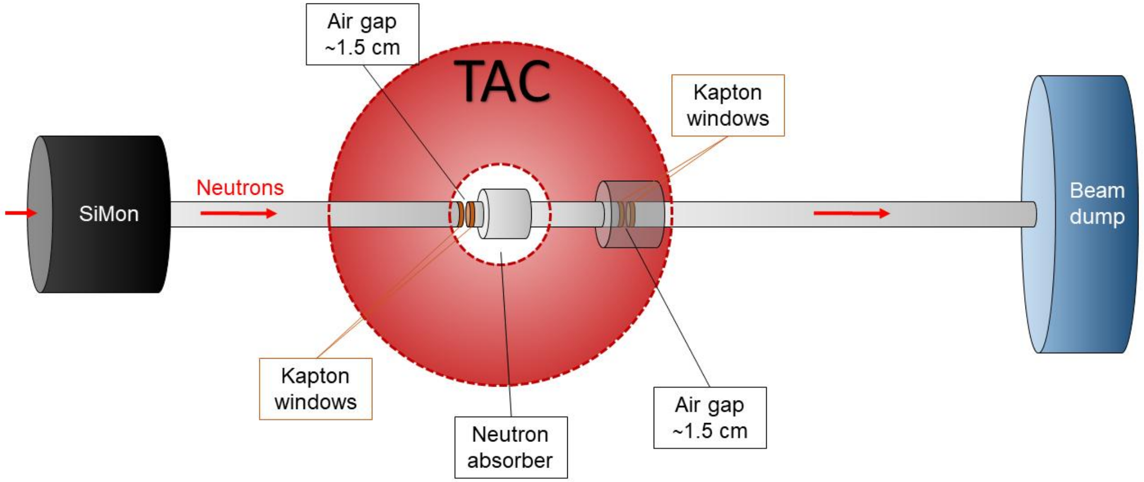
- **10 thin Pu samples** (<10 mg total mass) within fission chamber.
- Use FFD + TAC simultaneously.
- Measure fission and capture (up to ~1 keV), and the α-ratio.

2. TS config.

- 1 **thick sample** (~100 mg).
- Use only TAC.
- Measure capture above 1 keV.
- Sample inside dummy chamber to have similar bkgds.



Both setups share similar beam line configuration:



Plutonium base material

- Produced by JRC-Geel and SCK CEN.
- Plutonium dioxide PuO_2.
- 99.9% purity of ^{239}Pu.
- From the same base material, two different type of samples were prepared.

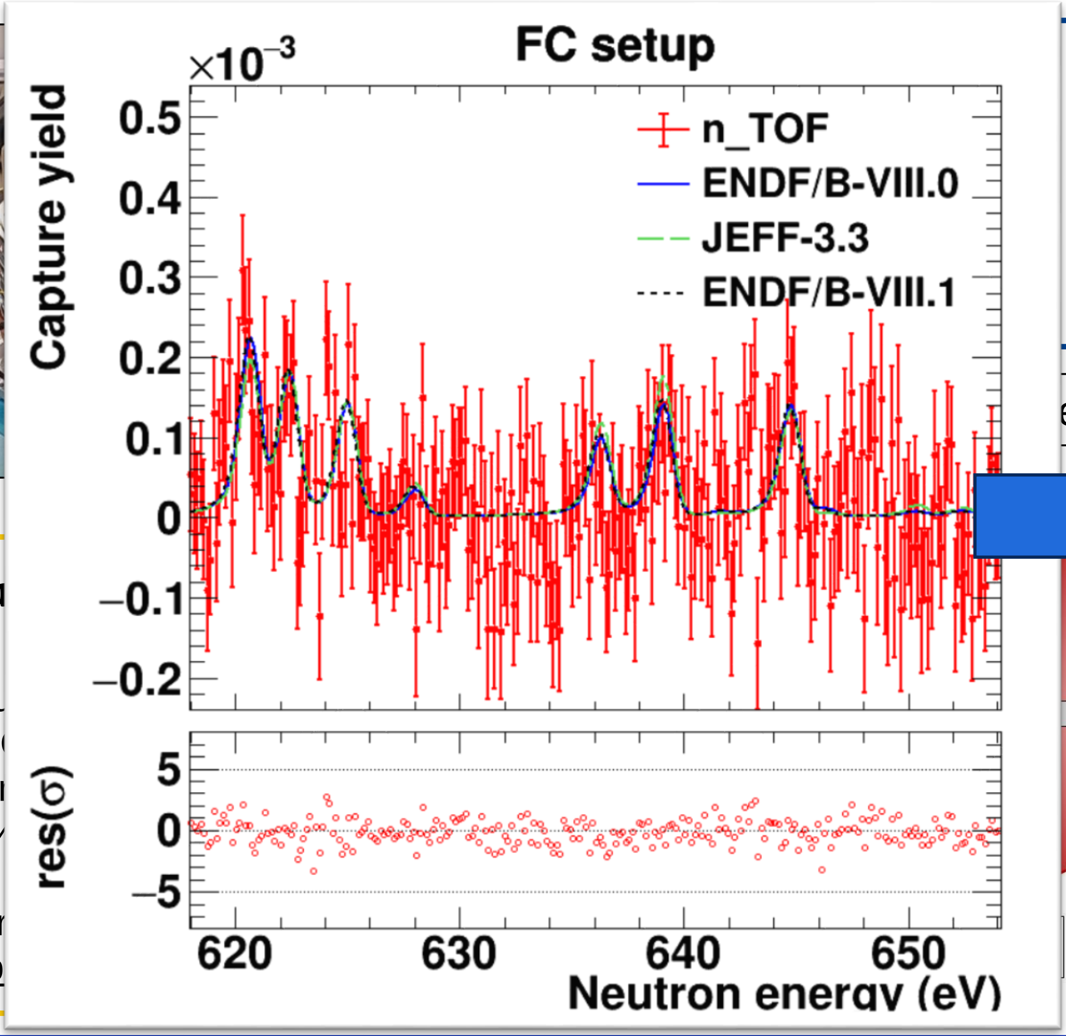
Isotopes	Abundance (%)
^{239}Pu	**99.90**
^{240}Pu	0.06
^{241}Pu	0.02
^{242}Pu	0.01

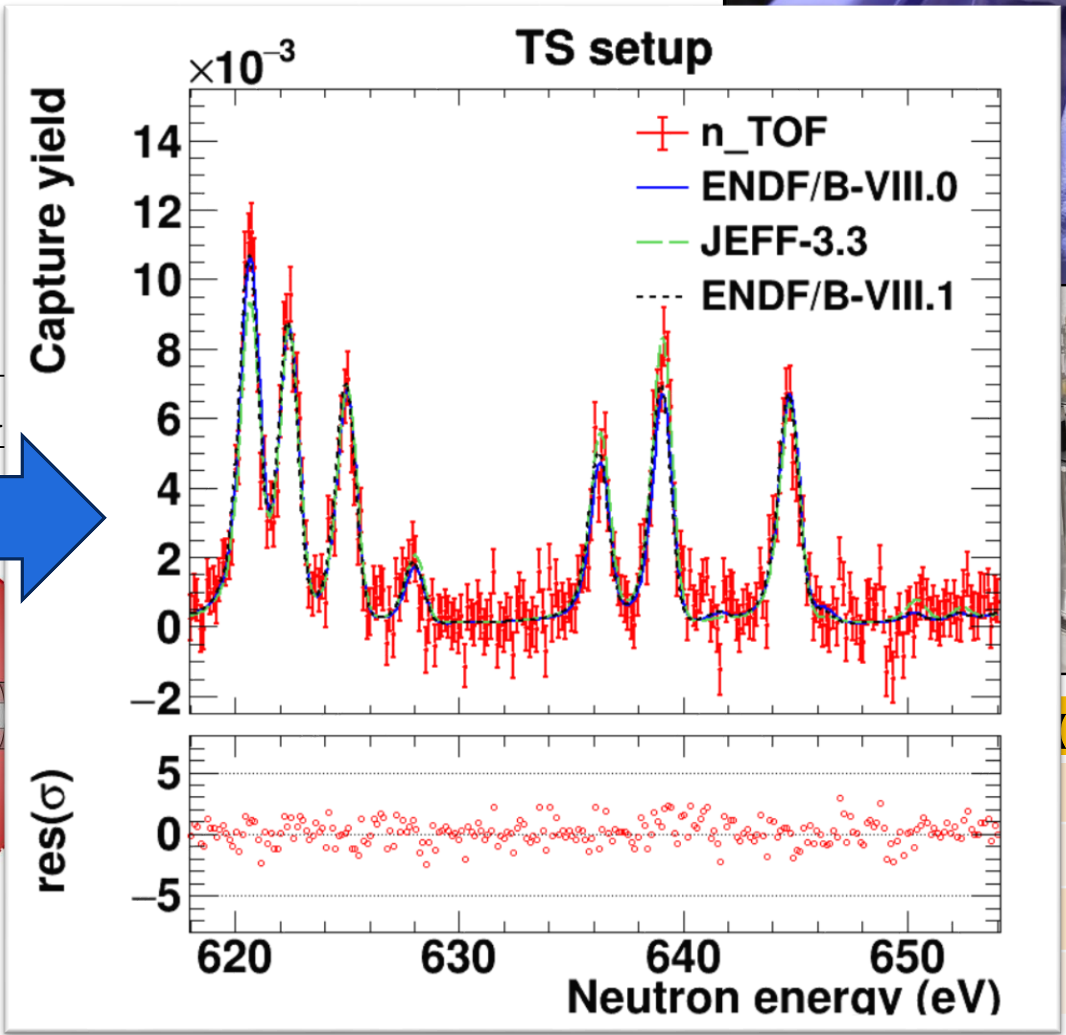
Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Context: experimental setup

- Experimental campaign **divided into two different configurations**:





ea

(%)

Plu

- Produ SCK
- Plutoı
- 99.9%
- From mater samp

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Analysis for the extraction of the fission yield

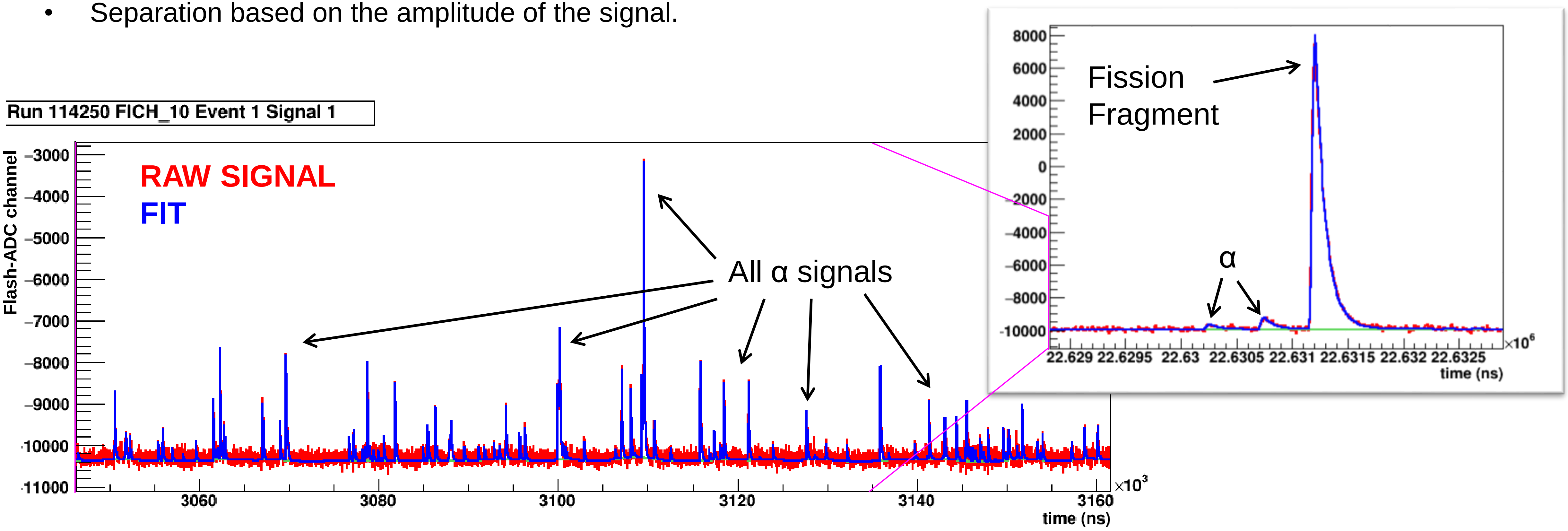
Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Funded by
the European Union

^{239}Pu(n,f) analysis: data reduction

Examples of fitted signals in the FFD with the Pulse Shape Analysis routine.

- Extremely high count rate from the a-decay of ^{239}Pu (~10^6 counts/s).
- An effective α-FF discrimination is fundamental for the analysis.
- Separation based on the amplitude of the signal.

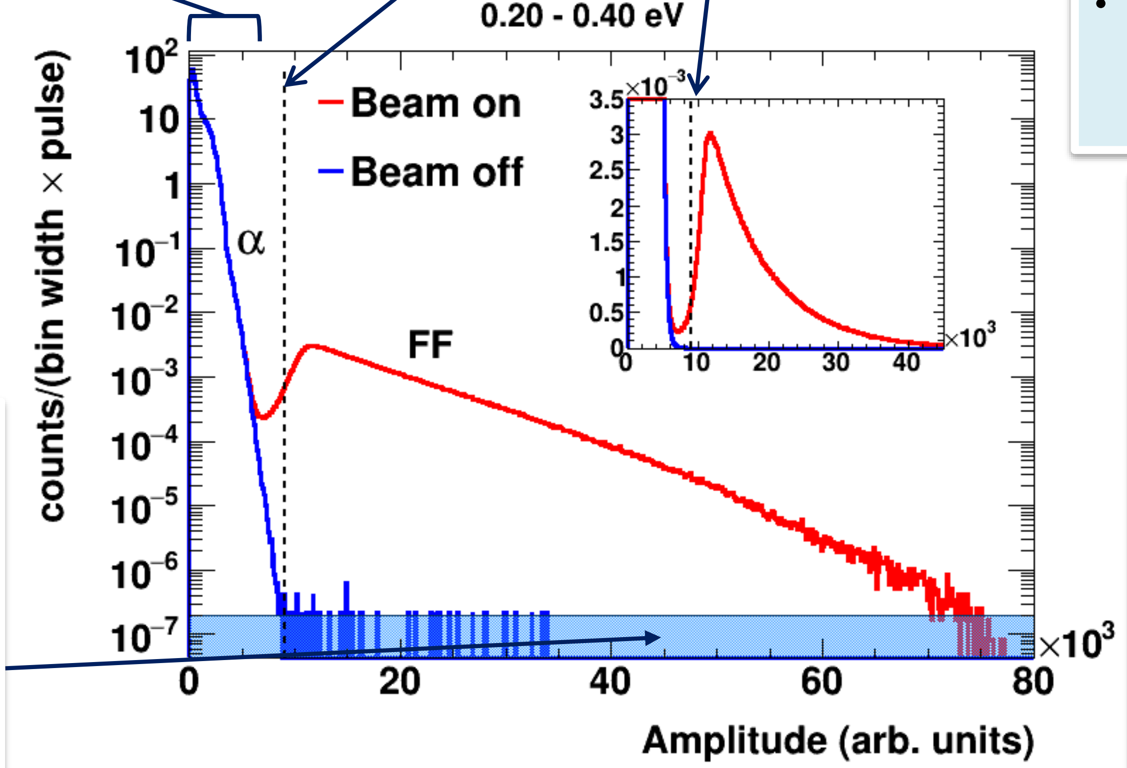


^{239}Pu(n,f) analysis: data reduction

Choice of the amplitude threshold to effectively separate signals between α-particles and fission fragments (FF).

Spectrum from the α-decay of ^{239}Pu radioactivity.

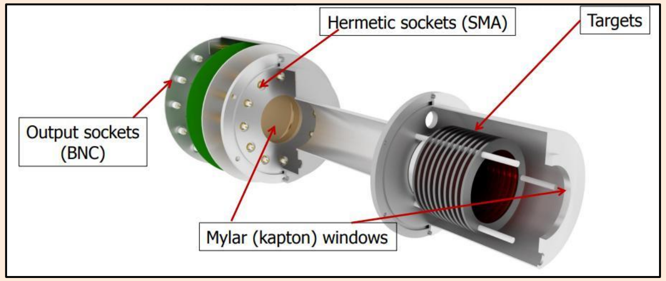
Applied threshold



Threshold

- At $9 \cdot 10^3$ amplitude units.
- Provides ~90% FF detection efficiency while effectively suppressing α-contribution.

Optimized design of FFD[1]



The ionization chambers and electronics were carefully designed by J. Perkowski and J. Andrzejewski (University of Lodz) to achieve this excellent α-FF separation.

Residual α-contribution

- Conservative approach: extrapolate as constant into the FF region.
- Result: estimated to be below 0.05% of the total FF events.
- Can be considered negligible.

[1] Perkowski et al., Nucl. Instrum. Methods Phys. Res. A 1067, 169649 (2024)

Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

^{239}Pu(n,f) analysis: yield extraction

Once the energy dependence of the neutron fluence for 2 cm diameter samples, $\varphi_{2\text{cm}}$, is known, and the detectors are characterized (thresholds, calibrations…) the extraction of the fission reaction yield Y_f(En) is straightforward.

Fission Fragment count rate

$$Y_f(E_n) = \frac{C_{\text{FF}}(E_n) - C_b(E_n)}{\varepsilon_{FF}(E_n)\,\phi(E_n)}$$

0

N_f

$\varphi_{2\text{cm}}(E_n)$ (next slide)

Normalization constant N_f

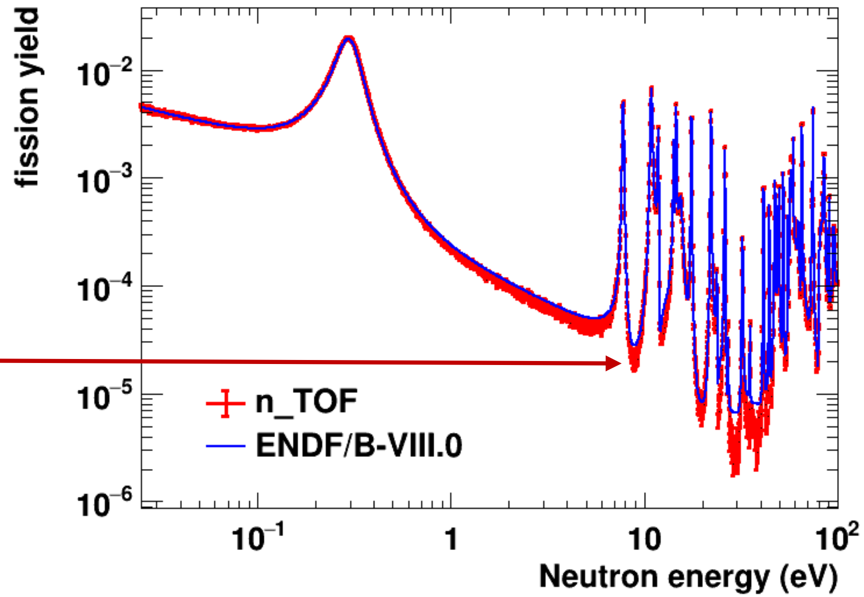
The fission yield was normalized to the recommended evaluated ^{239}Pu(n,f) cross section integral (9-20 eV) by I. Durán et al. (https://doi.org/10.1016/j.nds.2024.01.004).

- ε_{FF} replaced by normalization factor N_f.
- Absolute value of $\phi(E_n)$, sample mass, and efficiency not needed → significantly reduce uncertainties.
- No dependence on E_n.
- Automatically determines the normalization for the capture yield.

Zero background

No background in the fission yield was observed after the α-FF separation.

Obtained yield compared with evaluation (ENDF/B-VIII.0)



n_TOF data below evaluations in the valleys between resonances
↓
Indication of no residual background

Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Neutron fluence shape determination

The Neutron fluence (shape) for the **full beam is known** from the SiMon monitoring data and the n_TOF evaluated flux. However, **corrections** are required to take into account the **smaller sizes of the samples** (Beam Interception Factor, BIF).

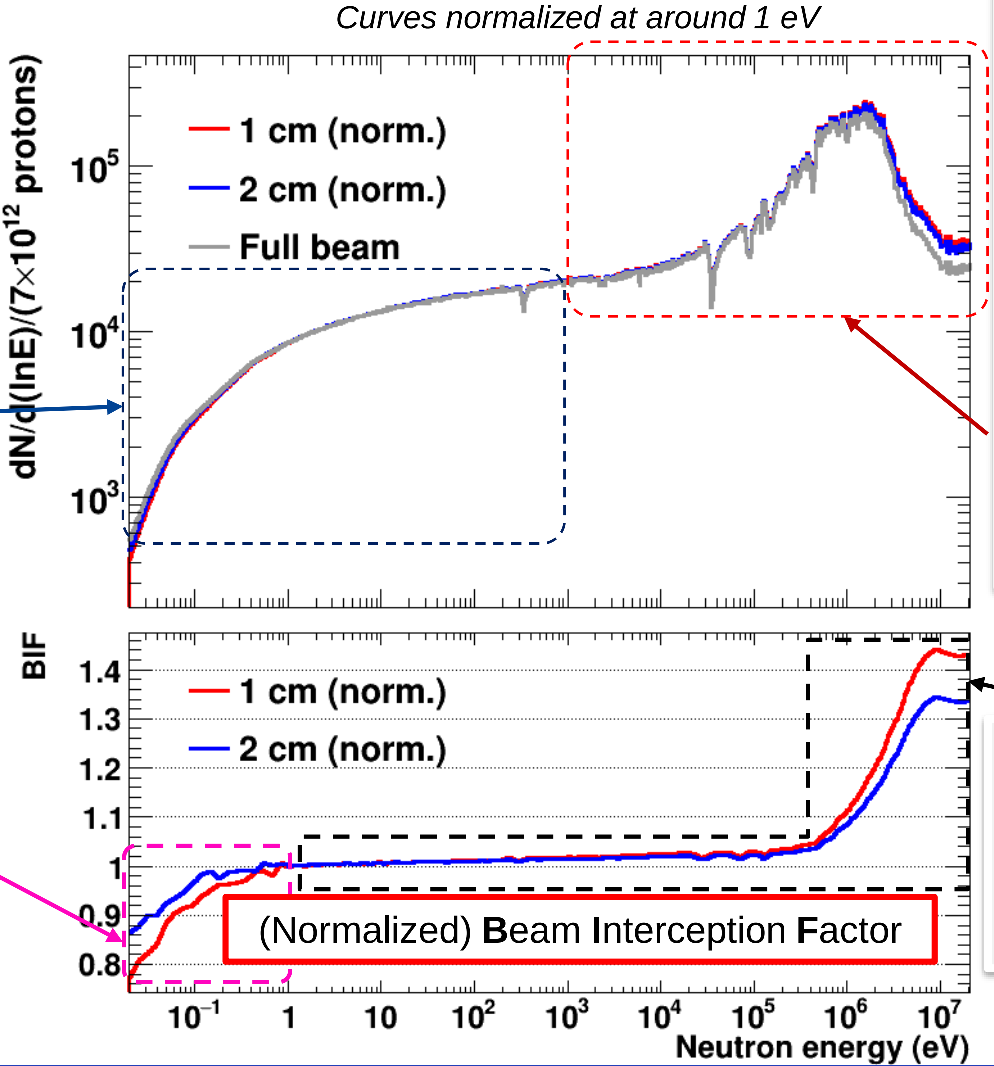
SiMon for 0.02 eV < E_n < 1 keV

The transmission through different dead-materials (aluminum, mylar) and the LiF foil of SiMon was taken into account (effect of about 1%), using FLUKA simulations.

BIF correction from ^{197}Au(n,γ)

The correction for the sample diameters **below 1 eV** was performed using ancillary measurements with gold samples of the same diameter.

^{197}Au(n,γ) cross section is smooth and well-known in this region.



EAR1 evaluated neutron fluence for E_n > 1 keV

Shape taken from the neutron beam commissioning at EAR1, using several detectors based on standard reactions:

- ^{6}Li(n,t)^{4}He
- ^{10}B(n,α)^{7}Li
- ^{235}U(n,f)

BIF from simulations

For **E_n>1 eV**, the BIF was determined from simulations with FLUKA.

Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

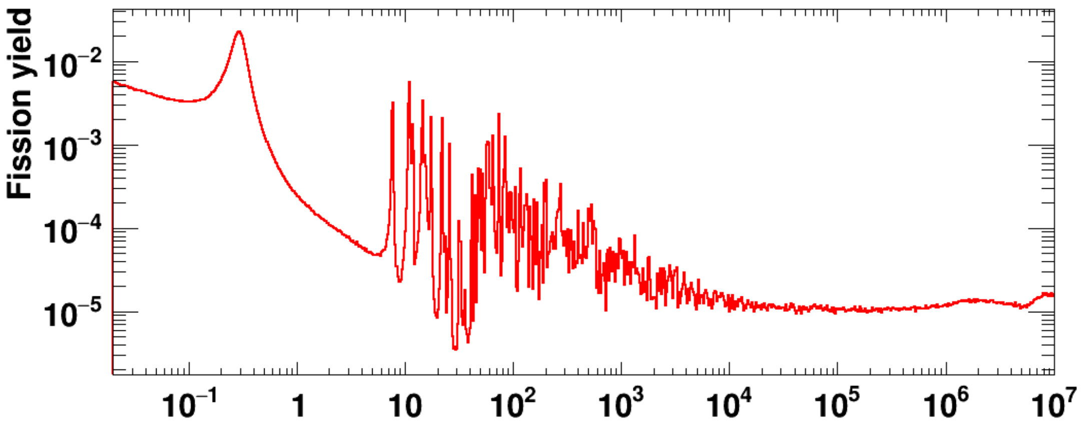
^{239}Pu(n,f) analysis: yield extraction

We have all required ingredients to extract the fission yield, and estimate uncertainties:

$$Y_f(E_n) = \frac{C_{\mathrm{FF}}(E_n) - C_b(E_n)}{\varepsilon_{FF}(E_n)\,\phi(E_n)}$$

$C_b(E_n) \rightarrow 0$

$\varepsilon_{FF}(E_n) \rightarrow N_f$



Funded by
the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

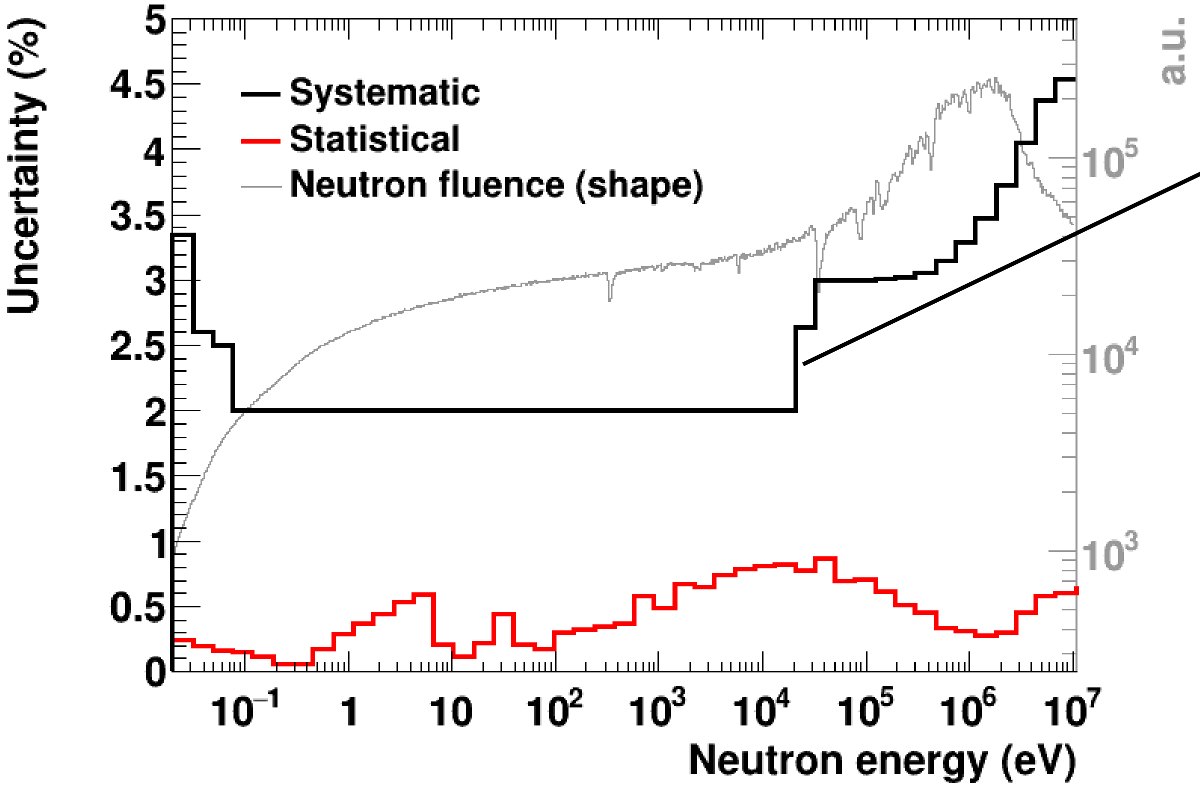
$^{239}Pu(n,f)$ analysis: uncertainty quantification

Since we are normalizing to an evaluation and we do not have any additional correction rather than the neutron fluence shape crossing our sample, the uncertainty due to systematic effects is reduced to this:

$$Y_f(E_n) = \frac{C_{\mathrm{FF}}(E_n) - C_b(E_n)}{\varepsilon_{FF}(E_n)\,\phi(E_n)}$$

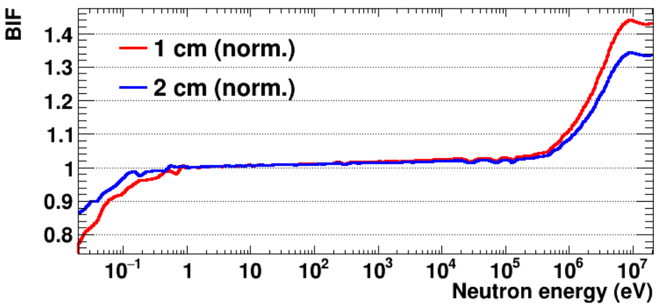
0

N_f



$\phi(E_n)$ (shape) uncertainty

The base uncertainty (2%) is taken from the n_TOF evaluated flux for EAR1, and increased in the regions where the BIF corrections where considerable



Normalization uncertainty

Not included as systematic effect, but should be taken as the used I_3 uncertainty (~0.6%):

I_3 = 1059 ± 6 eV·b

From I. Durán et al. (https://doi.org/10.1016/j.nds.2024.01.004)

Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Analysis for the extraction of the capture yield

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

^{239}Pu(n,γ) analysis: yield formula

Clearly, the extraction of the capture yield is not as straightforward as in the fission yield case:

$$Y_f(E_n) = \frac{C_{\mathrm{FF}}(E_n) - C_b(E_n)}{\varepsilon_{FF}(E_n)\,\phi(E_n)}$$

0

N_f

$$Y_{\gamma,\mathrm{FC}}(E_n) = \frac{1}{N_{2\mathrm{cm}}}\,\frac{C_{\mathrm{aco}}(E_n) - \frac{1-\varepsilon_{ft}}{\varepsilon_{ft}} C_{\mathrm{rf}}(E_n) - C_b^*(E_n)}{\varepsilon_{\gamma,FC}(E_n)\,\varphi_{2\mathrm{cm}}(E_n)}$$

Fission term

For the particular case of the FC setup, it requires:

- Determination of fission-tagging efficiency ε_{ft} (FFD) and capture ε_{γ} (TAC) efficiencies (standard procedure through experimental data or simulations).
- An accurate estimation of all background components (environmental, time-dependent, neutron scattering, **fission background**, etc.)

Funded by
the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

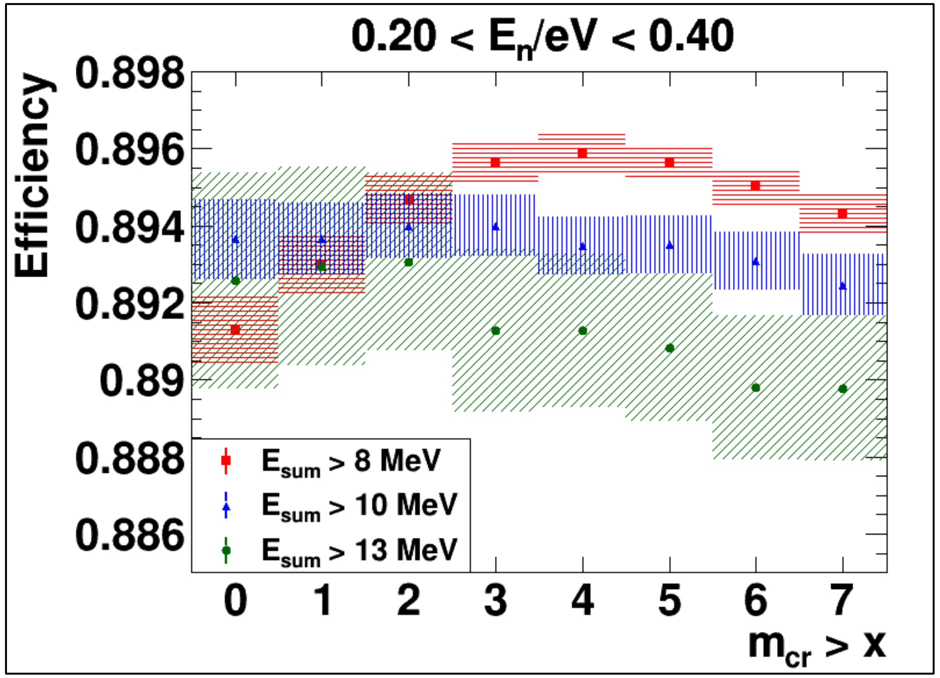
^{239}Pu(n,γ) analysis: how do we determine ε_{ft}?

Determined experimentally using the coincidences between FFD and TAC as in previous fission-tagging measurements[1-3], using TAC threshold favoring fission events.

$$\varepsilon_{ft} = \frac{C_{tag}}{C_F}$$

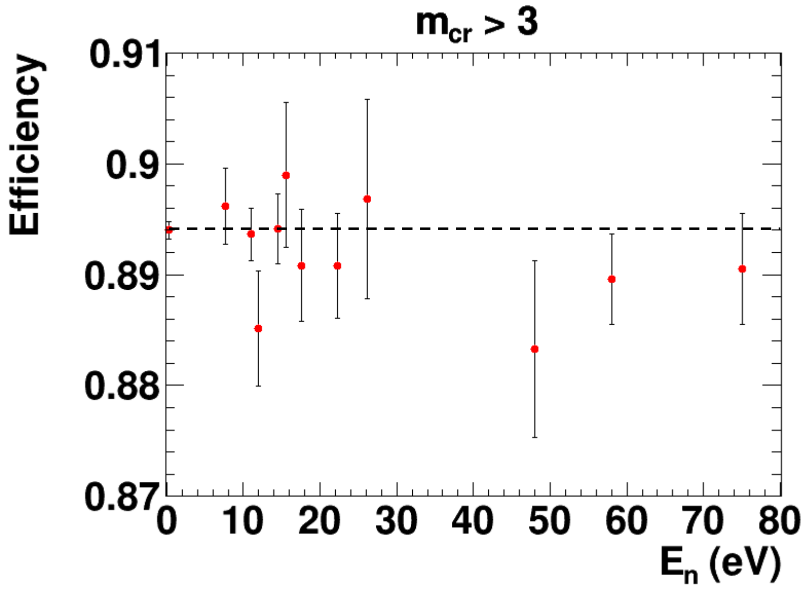
Tagged counts (C_{tag})

Total fission counts in the TAC (C_F)



$$\varepsilon_{ft} = 89.4(5)\%$$

Value independent (within unc.) of E_{sum} and m_{cr} cuts and E_n.



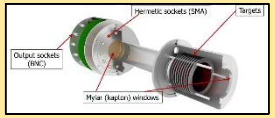
[1] C. Guerrero et al., Eur. Phys. J. A 48, 29 (2012).
[2] J. Balibrea-Correa et al., Phys. Rev. C 102, 044615 (2020).
[3] M. Bacak et al., EPJ Web of Conferences 211, 03007 (2019).

Funded by the European Union

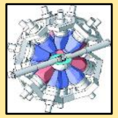
Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

^{239}Pu(n,γ) analysis: background overview

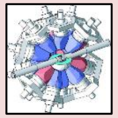
FC setup (FFD + TAC)



+

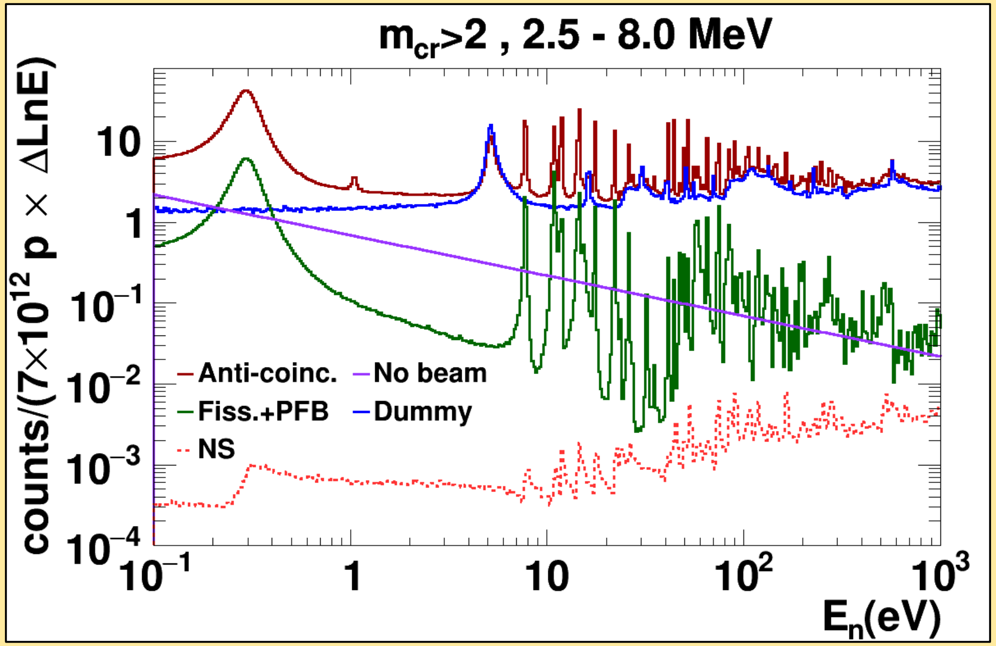


TS setup (TAC)

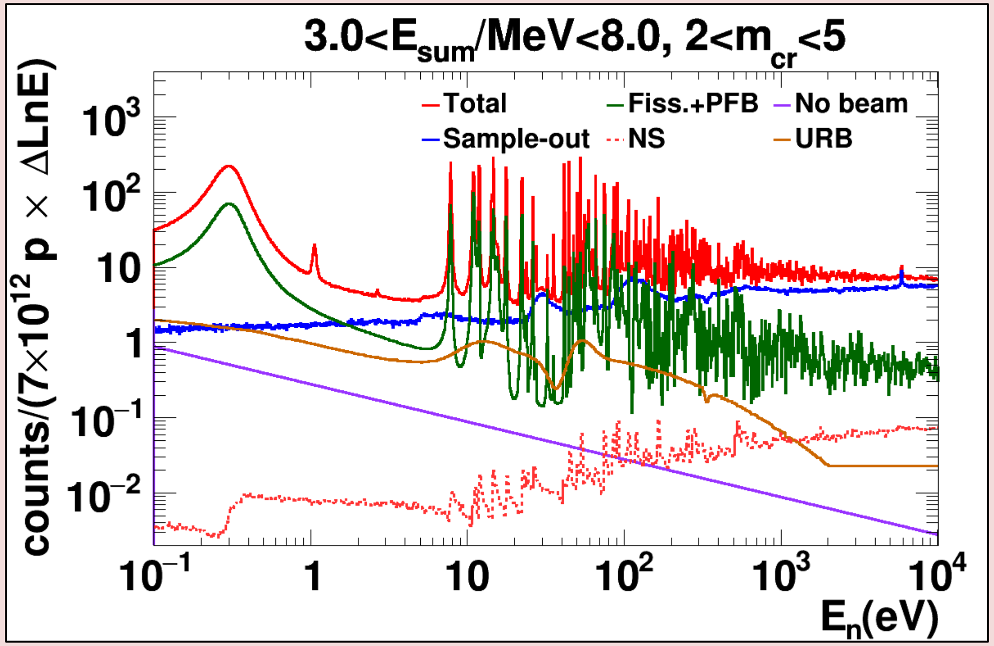


Background contributions in both setups: some components share similar approaches but others (fission) require completely different procedures.

TAC count rates as a function of neutron energy



TAC count rates as a function of neutron energy

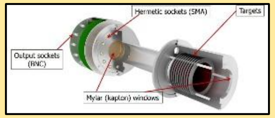


Funded by the European Union

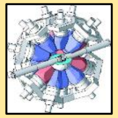
Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

^{239}Pu(n,γ) analysis: background overview

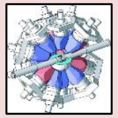
FC setup (FFD + TAC)



+



TS setup (TAC)

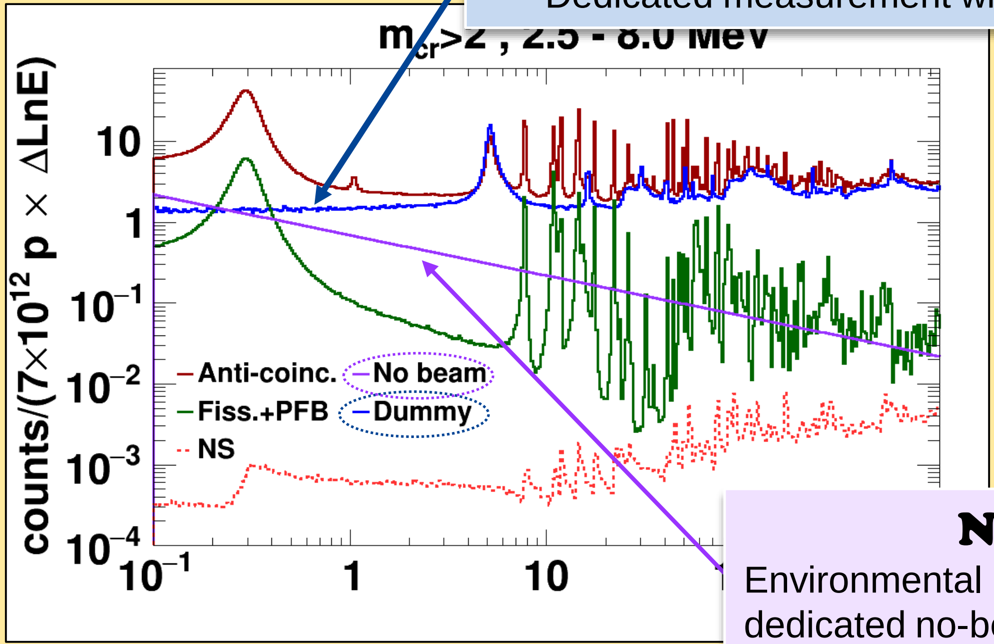


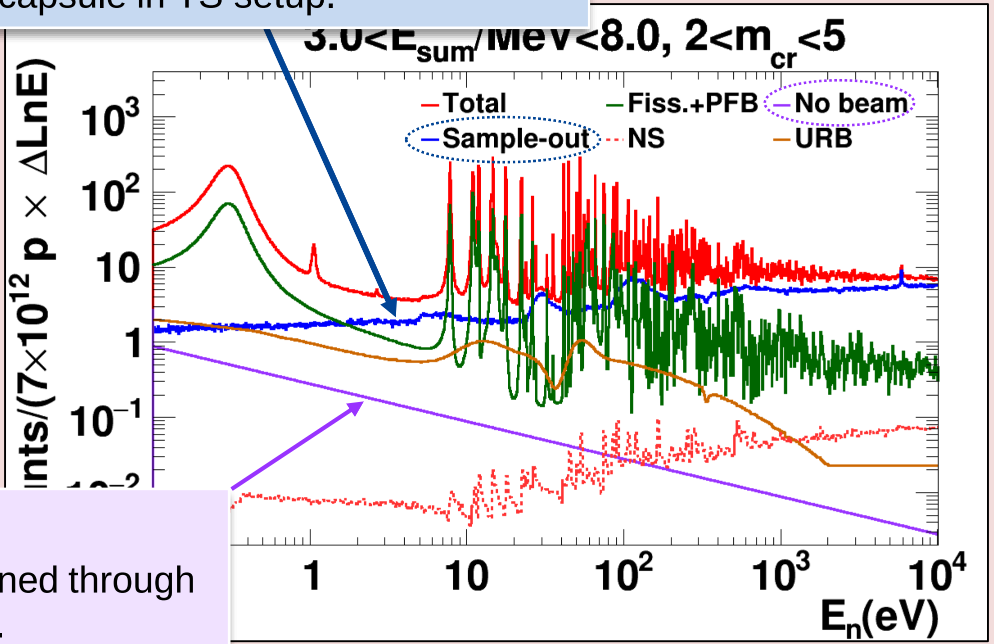
Dummy background

Neutron beam-induced background not related with the ^{239}Pu samples.

- Dedicated measurement with a dummy chamber without plutonium in FC setup.
- Dedicated measurement with a dummy, empty capsule in TS setup.

TAC count rates as a … *of neutron energy*





No-beam bkgd.

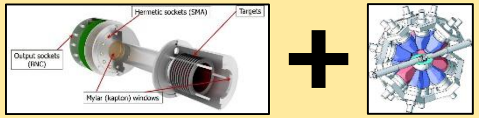
Environmental background determined through dedicated no-beam measurements.

Funded by the European Union

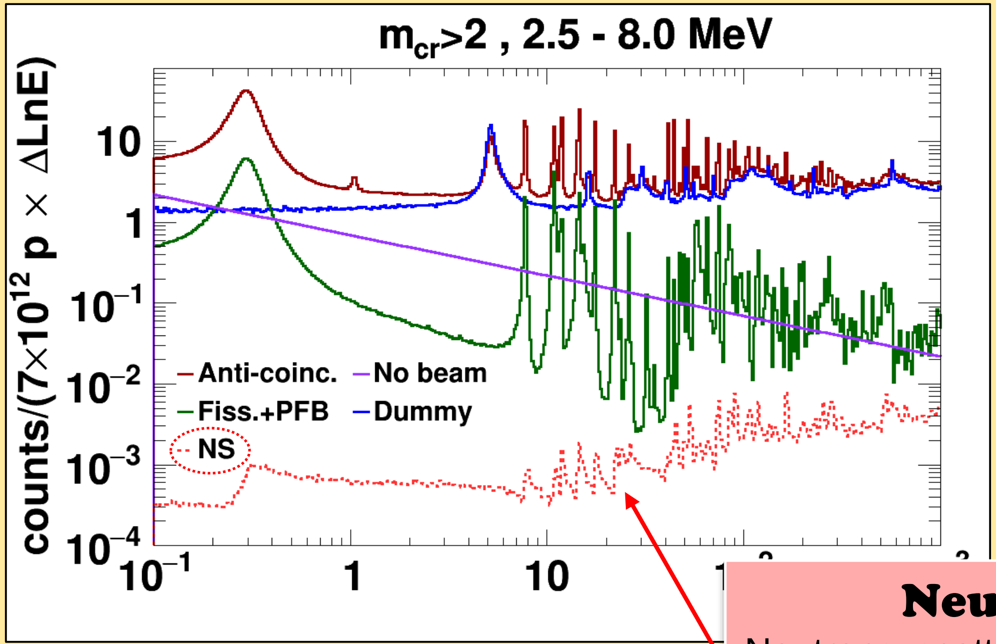
Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

$^{239}Pu(n,\gamma)$ analysis: background overview

FC setup (FFD + TAC)



TAC count rates as a function of neutron energy

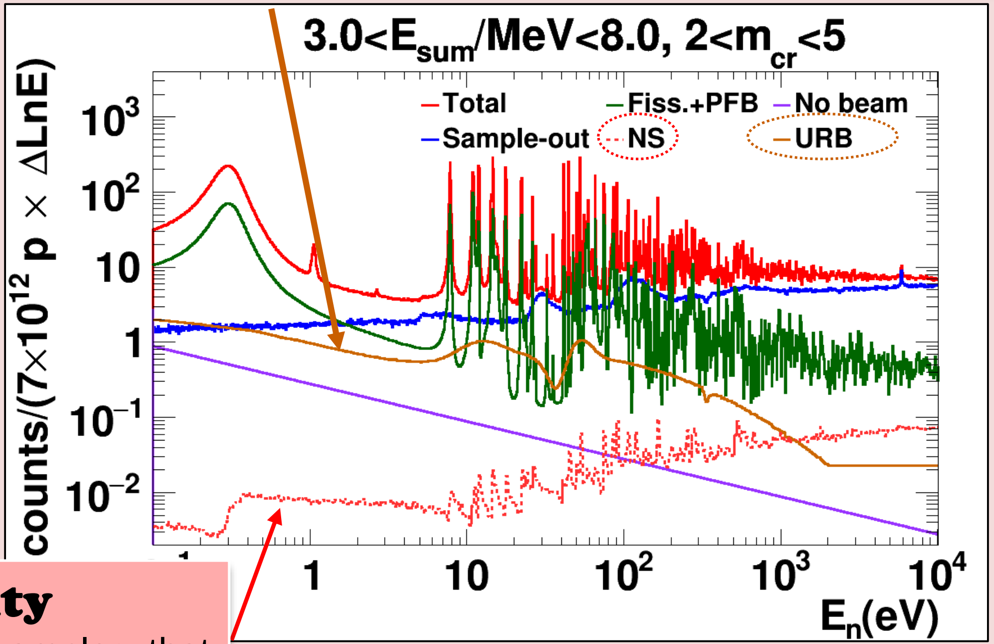


TS setup (TAC)

Unidentified Residual Background (URB) in TS setup

Residual background with unknown origin.

- Subtracted using the valleys between resonances.
- Common in capture measurements.



Neutron sensitivity

Neutrons scattered in the ^{239}Pu samples that reach the BaF_2 crystals.

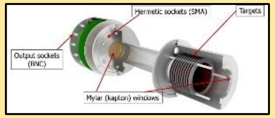
- Determined by Monte Carlo simulations.

Funded by the European Union

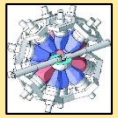
Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

^{239}Pu(n,γ) analysis: background overview

FC setup (FFD + TAC)

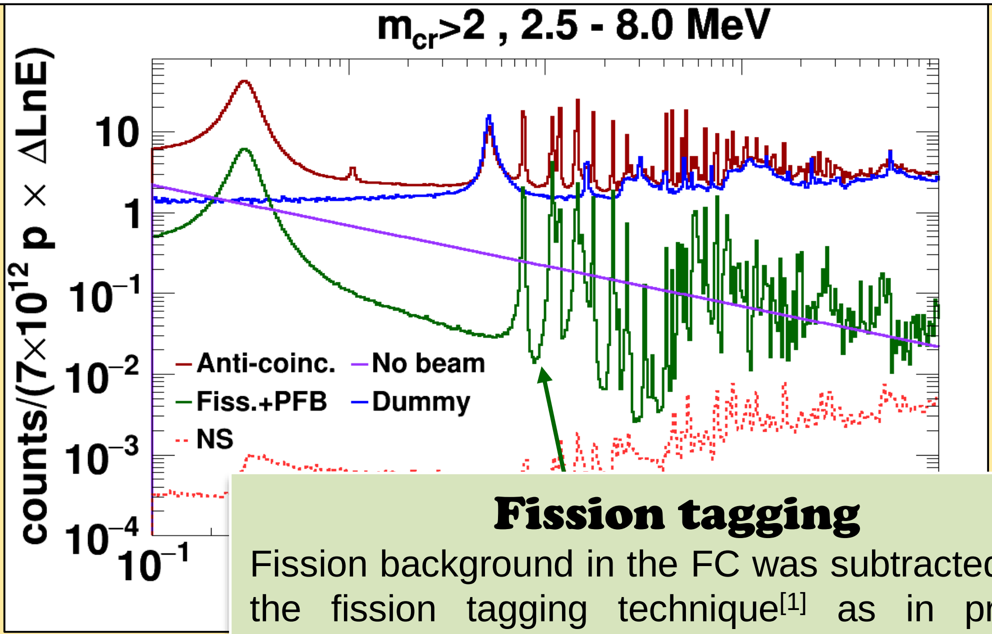


+



Fission term

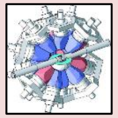
$$Y_{\gamma,\mathrm{FC}}(E_n) = \frac{1}{N_{2\mathrm{cm}}} \frac{C_{\mathrm{aco}}(E_n) - \frac{1-\varepsilon_{ft}}{\varepsilon_{ft}} C_{\mathrm{rf}}(E_n) - C_b^*(E_n)}{\varepsilon_{\gamma,FC}(E_n)\,\varphi_{2\mathrm{cm}}(E_n)}$$



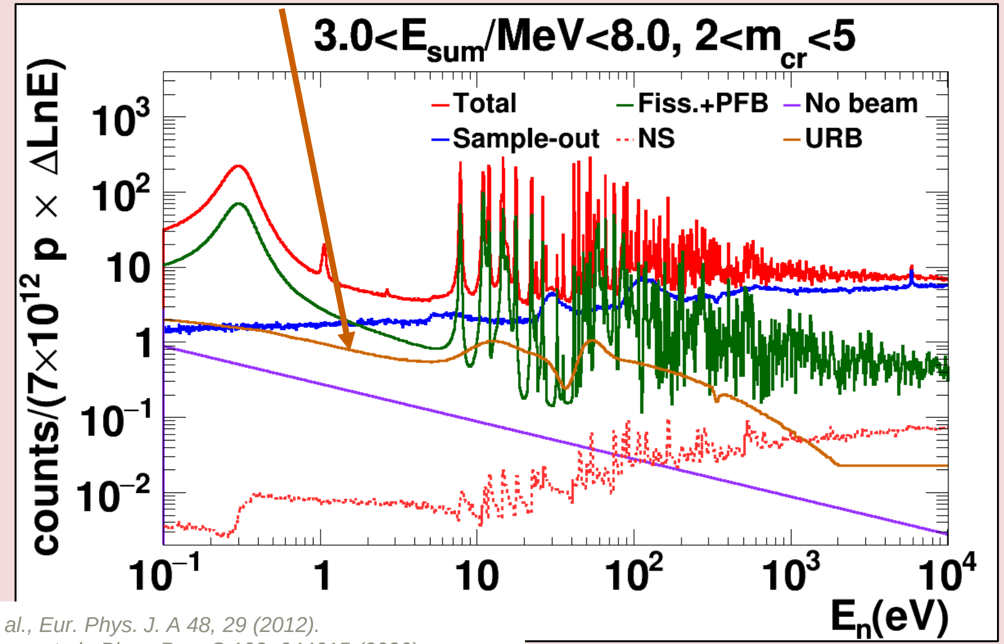
Fission tagging

Fission background in the FC was subtracted using the fission tagging technique[1] as in previous n_TOF measurements of fissile isotopes[2,3].

TS setup (TAC)



$$Y_{\gamma,\mathrm{TS}}(E_n) = \frac{1}{N_{1\mathrm{cm}}} \frac{C_{\mathrm{tot}}(E_n) - C_f(E_n) - C_b^*(E_n)}{\varepsilon_{\gamma,TS}(E_n)\,\varphi_{1\mathrm{cm}}(E_n)}$$

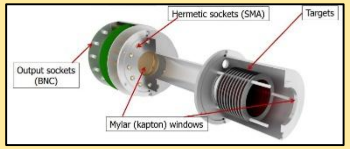


[1] C. Guerrero et al., Eur. Phys. J. A 48, 29 (2012).
[2] J. Balibrea-Correa et al., Phys. Rev. C 102, 044615 (2020).
[3] M. Bacak et al., EPJ Web of Conferences 211, 03007 (2019).

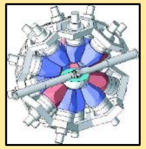
Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

^{239}Pu(n,γ) analysis: fission background (FC setup)



+



Fission subtraction in the FC setup

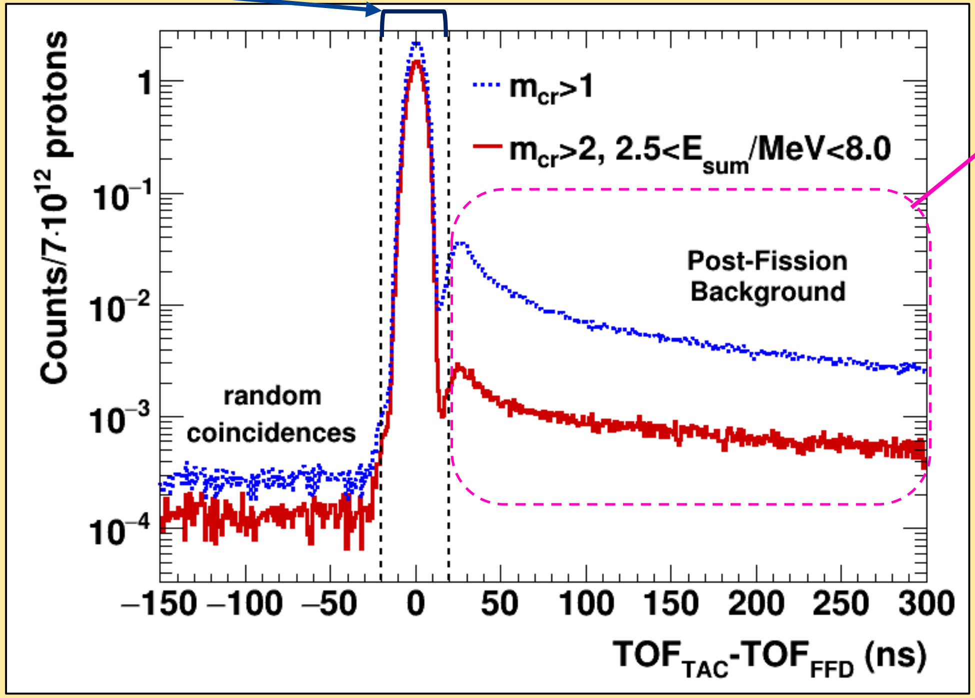
Fission tagging

Coincidences between FFD and TAC

Prompt Fission Coincidence window:

±20 ns

It covers practically the full prompt-fission peak while minimizing the probability of tagging non-fission events (<<1%). Consistent with previous fission tagging measurements.

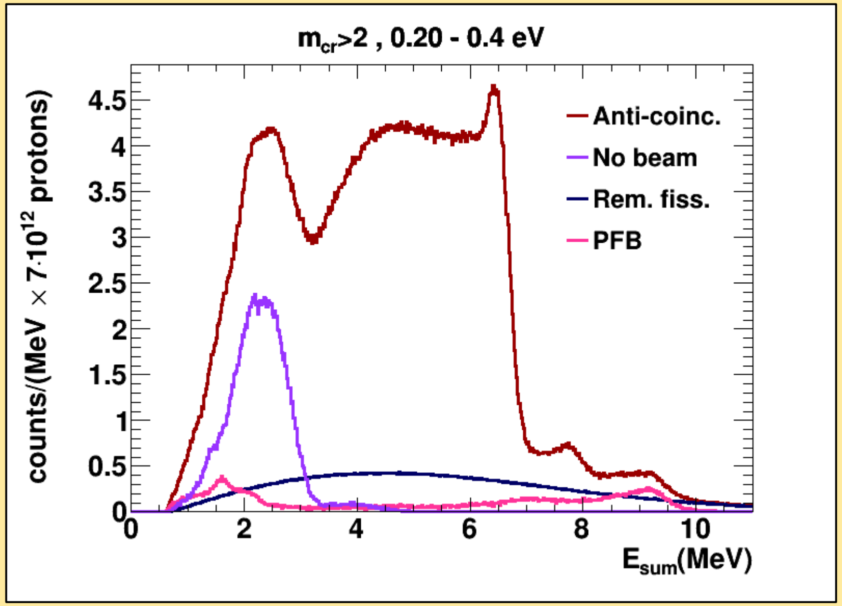


PFB

Post-**F**ission **B**ackground

Fission-related counts with ΔT>20 ns up to 3 us.

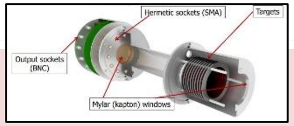
Attributed primarily to fission neutrons.



Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

^{239}Pu(n,γ) analysis: fission background (TS setup)



Fission subtraction in the TS setup

General idea: to use the results of fission and capture that were accurately measured in the FC setup below 200 eV.

Followed approach:

1. Subtract all known non-fission backgrounds (excluding also PFB) and divide by the neutron fluence to obtain a *quasi-yield Y**.
2. This quasi-yield can be reasonably interpreted by a linear combination of the capture and fission yields:

We know ✓ — Measured in the TS setup: $Y^*(E_n)$

We want to know: $Y_{\gamma,TS}(E_n)$

$$Y^*(E_n) = \hat{\lambda}_{\gamma,TS} Y_{\gamma,TS}(E_n) + \hat{\lambda}_{F,TS} Y_{F,TS}(E_n)$$

$\hat{\lambda}_{\gamma,TS}$, $\hat{\lambda}_{F,TS}$: Coefficients related with capture and fission detection efficiencies

Extrapolate to the rest of neutron energies using the found $\hat{\lambda}_{\gamma,TS}$ and $\hat{\lambda}_{F,TS}$ (constant) values.

$Y_{F,TS}(E_n)$ is taken from the FC setup:

- Derived from the RPs for the resonance region.
- Directly from the measured yield with the FFD above 2.5 keV.

Restricted below 200 eV at selected resonances

$$Y^*(E_n) ✓ = \hat{\lambda}_{\gamma,TS} Y_{\gamma,TS}(E_n) ✓ + \hat{\lambda}_{F,TS} Y_{F,TS}(E_n) ✓$$

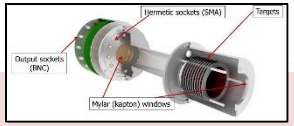
$\hat{\lambda}_{\gamma,TS}$ and $\hat{\lambda}_{F,TS}$ can be determined by matching the experimental and expected capture yields in these resonances.

$Y_{\gamma,TS}(E_n)$, $Y_{F,TS}(E_n)$: Yields derived with SAMMY using RPs from the FC setup

Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

$^{239}Pu(n,\gamma)$ analysis: fission background (TS setup)



Fission subtraction in the TS setup

Results for the optimal coefficients

$$\lambda_{\gamma}^{min} = 1.038(31)$$

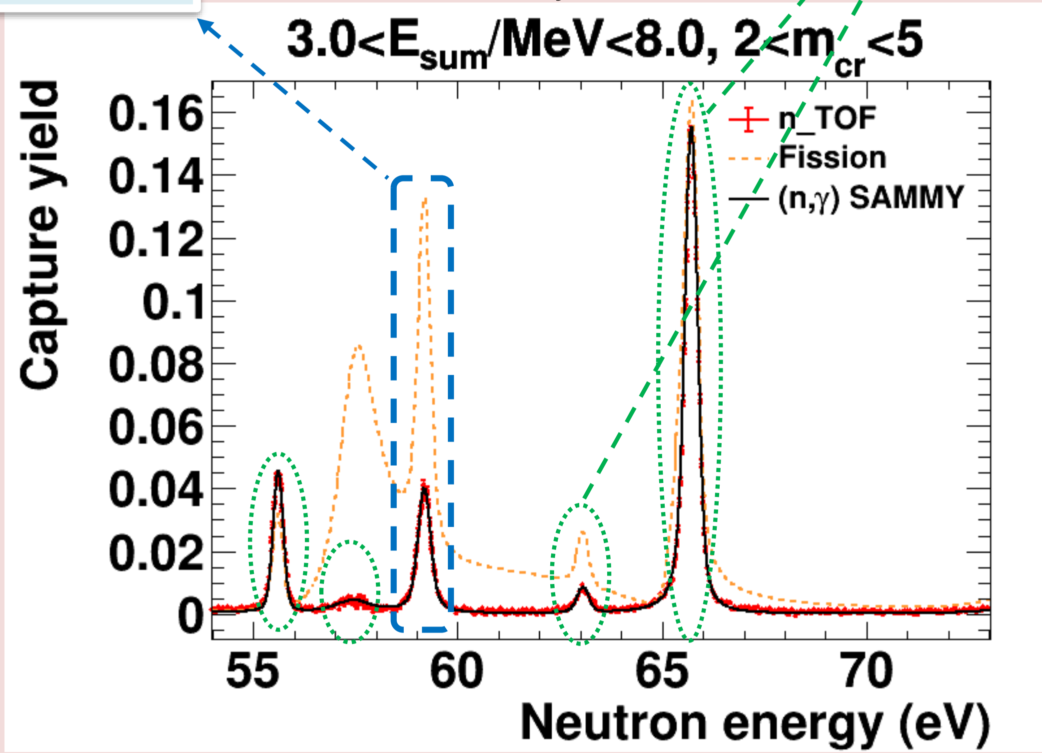
$$\lambda_{F}^{min} = 1.038(31)$$

Resonances included in the fit

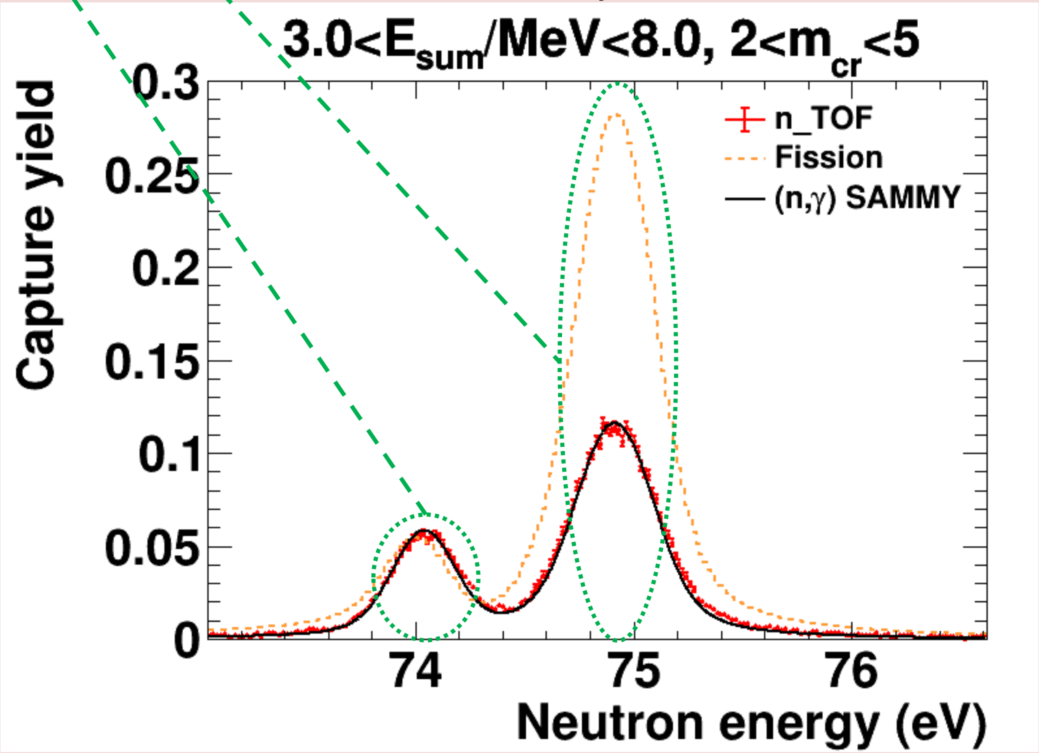
Resonances **NOT included** in the fit

Excellent compatibility between TS and FC capture yield even in resonances not used for the optimization problem with large fission → obtained fission bkgd. for higher energies.

Result on the fitted yield resonances



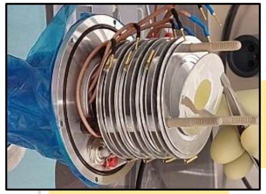
Result on the fitted yield resonances



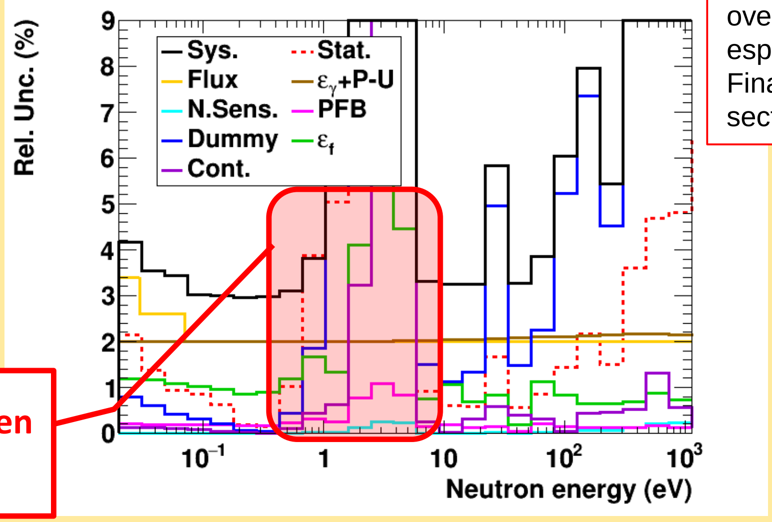
Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

^{239}Pu(n,γ) analysis: uncertainty quantification



FC setup

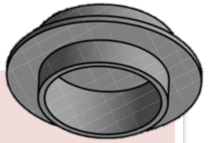


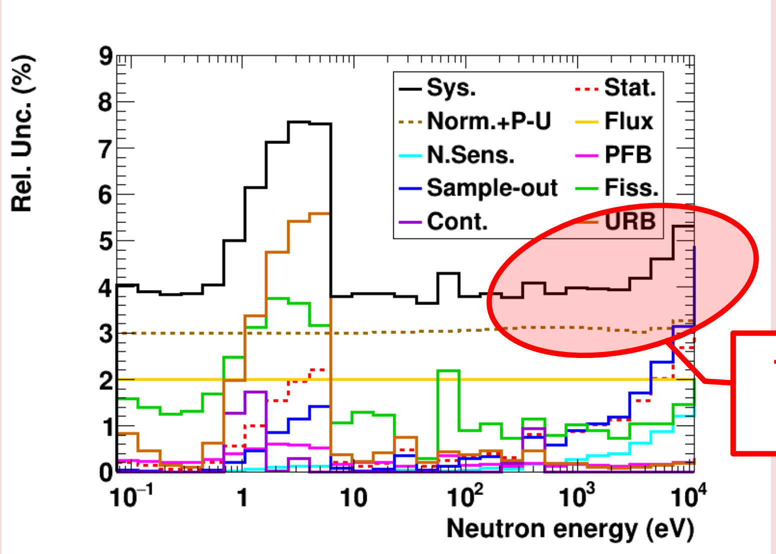
Important:
Dummy uncertainties are overestimated in this plot, especially above 100 eV. Final values in the cross-section will be lower.

Valley between resonances

- Neutron sensitivity (N. Sens.): estimated to 15%.
- Dummy: 0.5-1.5% uncertainties due to correction.
- Capture eff. and pile-up (ε_γ+P-U): 2% plus pile-up corrections (negligible in FC setup).
- Fission (ε_f): 0.6% uncertainty from fission tagging.
- Post-Fission Background (PFB): estimated to 5%.
- Correction of contaminants: estimated to 5% for silver and copper resonances.

TS setup*





Target region of the TS setup

- Sample-out: 0.5% uncertainty (no correction needed).
- Fission (Fiss.): set at 3% for the subtraction method.
- Normalization and pile-up (Norm.+P-U): a 3% plus smaller uncertainties due to the pile-up corrections.
- Correction of contaminants: estimated to 5% for ^{240}Pu and ^{242}Pu first resonances.
- Unidentified Residual Background (URB): estimated to 8%.

Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Extraction of ^{239}Pu resonance parameters with SAMMY

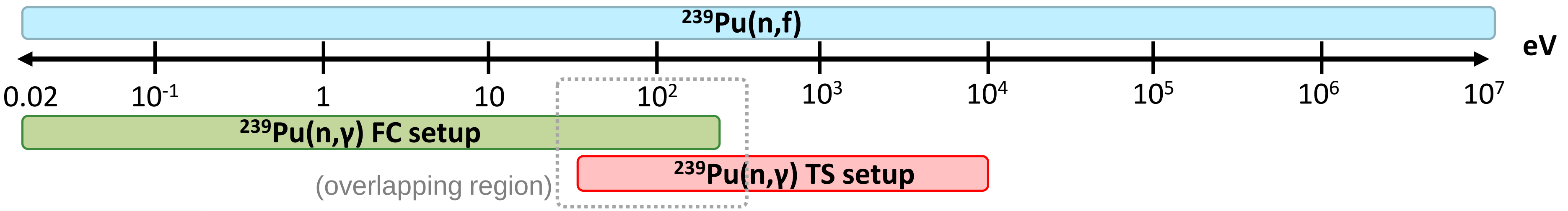
Funded by
the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

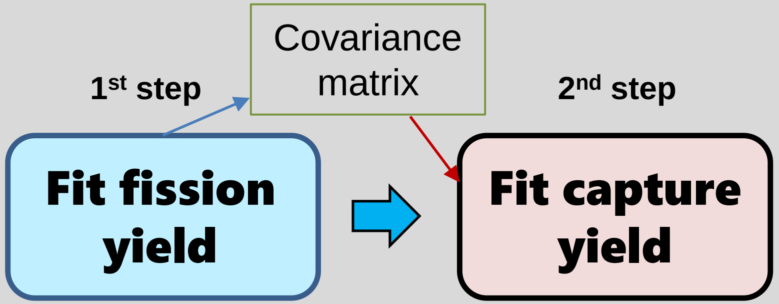
^{239}Pu resonance parameters: SAMMY fit

To obtain a final set of resonance parameters (RPs) combining the three measured datasets:

- **Fission yield (FC setup).**
- **Capture yield (FC setup).**
- **Capture yield (TS setup).**



It was followed a sequential fit, as recommended in SAMMY User's Guide:



(Only one iteration)

Two set of RPs: FC and TS capture data

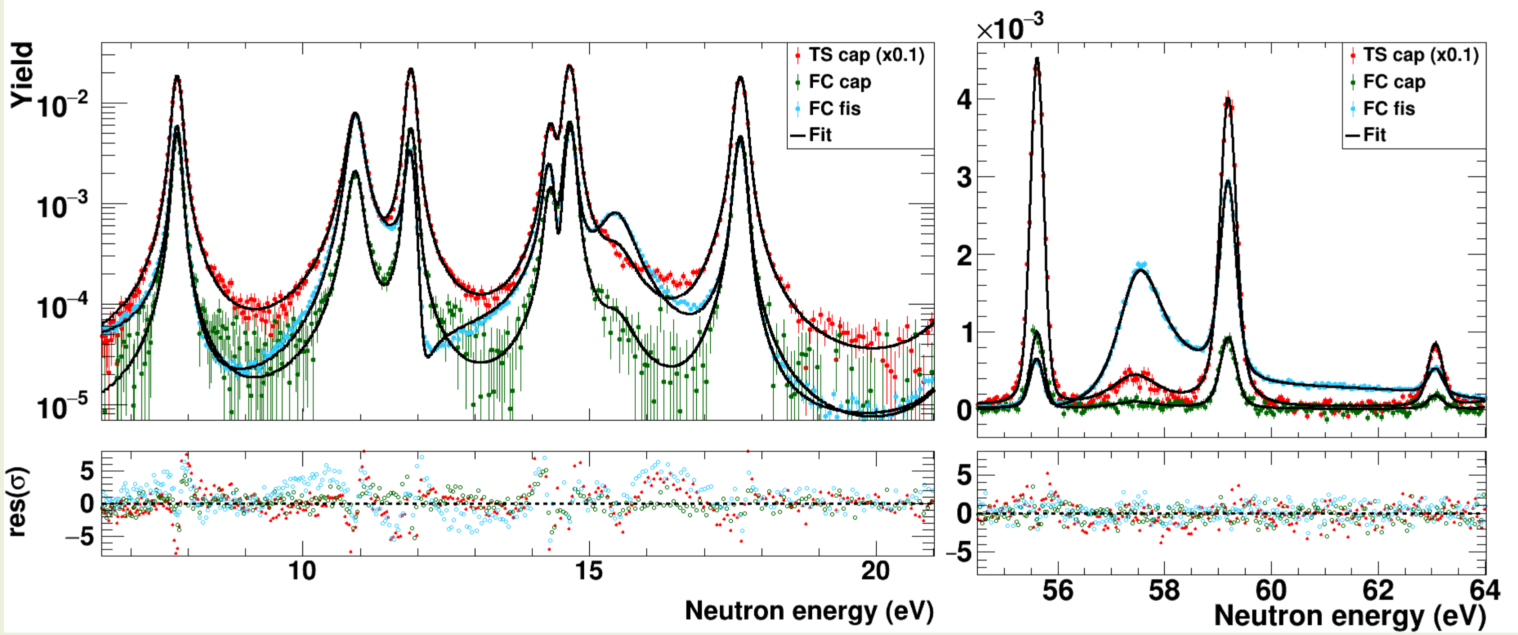
↓

Combine both using:

- FC data below 200 eV.
- TS data above 200 eV.
- TS data below 200 eV in <u>specific resonances</u>. (low statistics in FC)

The resonance analysis obtained the resonance parameters for 1000 resonances up to 2.5 keV:

- Neutron energy E_n, neutron width Γ_n, capture width Γ_g, and fission width Γ_f.



Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Conclusions

I have presented a summary of the particular data analysis to extract the ^{239}Pu capture and fission cross sections from the measurement performed at n_TOF in 2022.

This data analysis, especially in the challenging case of capture, required of some significant corrections, which were associated with their corresponding estimated uncertainties. It is important to fully understand all steps of the analysis to identify the strengths and limitations of the provided data.

We will put our efforts to communicate as clear as possible all these effects and corrections when the data is published, but all feedback and recommendations are welcome.

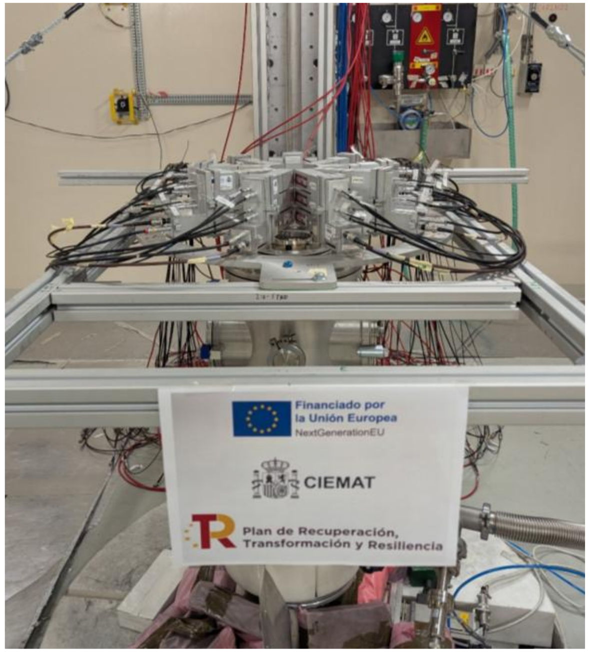
Funded by the European Union

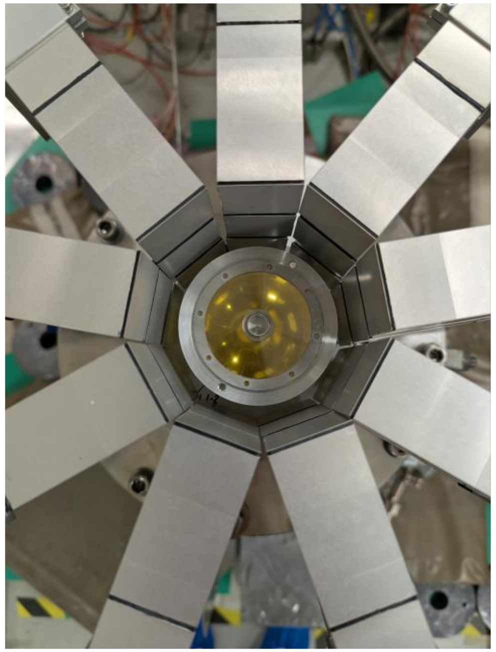
Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

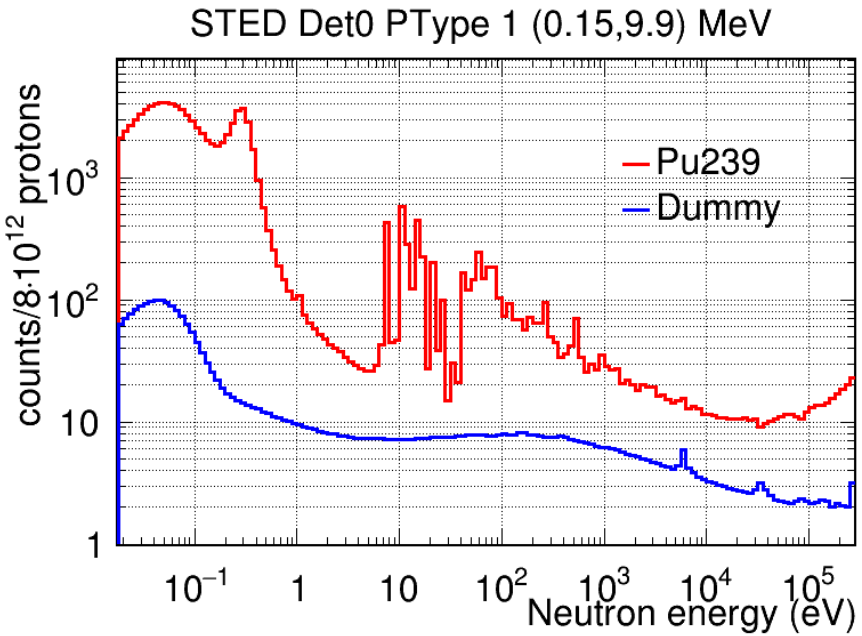
Bonus: new ^{239}Pu measurement at n_TOF (EAR2)

On June this year, a new measurement with the same ^{239}Pu thick, encapsulated sample was performed at n_TOF, but this time in the 20 m flight path of EAR2.

It was conducted with an optimized floor shielding to reduce the beam-related background (dummy), using the 27 sliced-TEDs (sTEDs) detectors.







The idea is to subtract the fission as was done in the TS setup in EAR1 and measure the capture cross-section until 100-200 keV.

Funded by
the European Union
Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

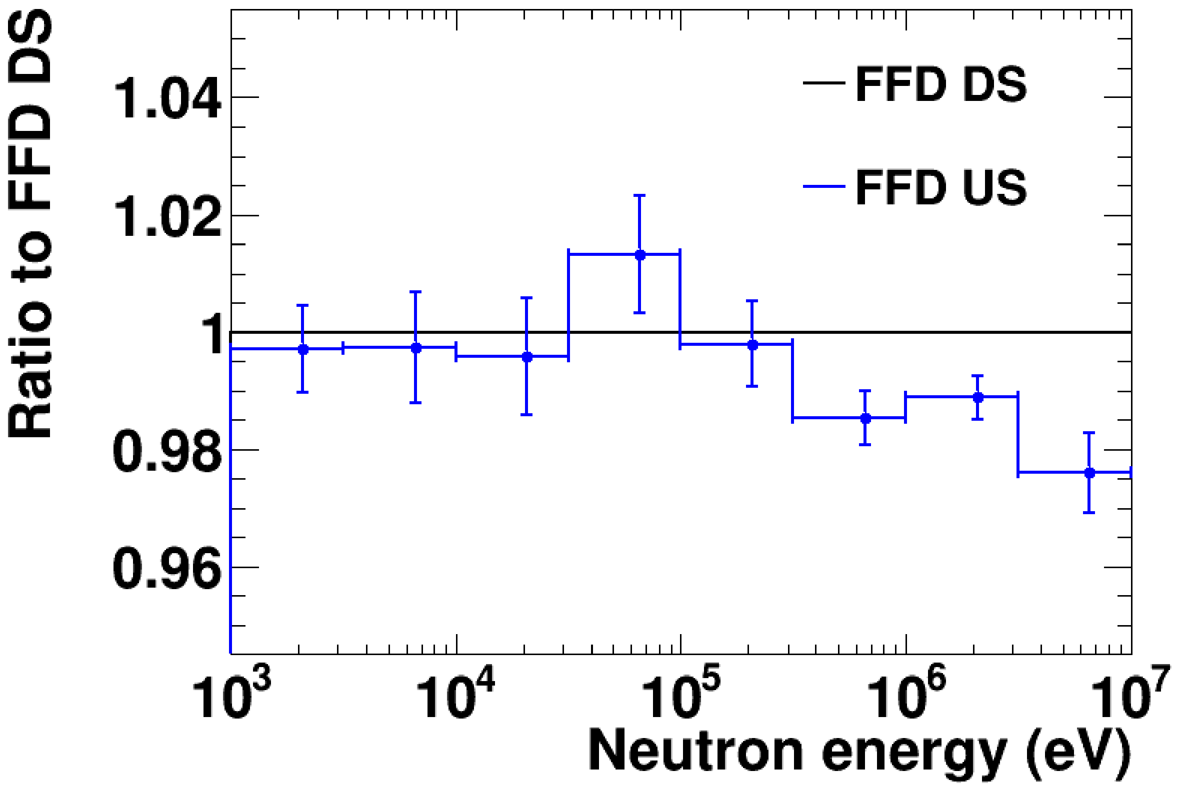
Backup slides

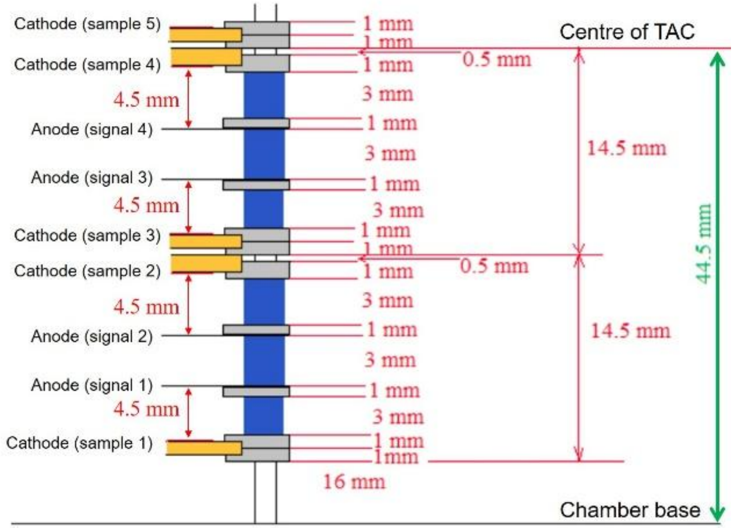
Funded by
the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

^{239}Pu(n,f) analysis: sample-related effects

DS = sum of DownStream samples
US = sum of UpStream samples





Other effects

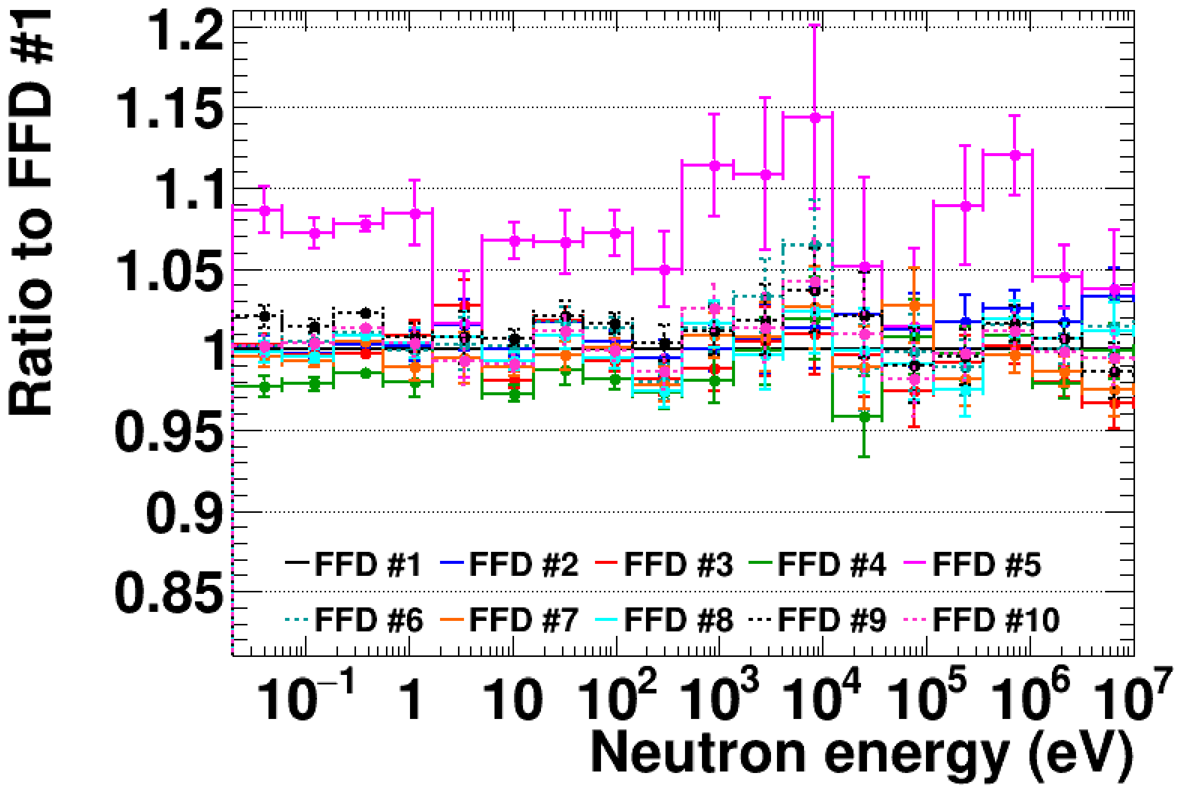
- No gain shifts of the spectra observed throughout the campaign.
- No pile-up effects, comparing high vs. low intensity pulses.
- Sample-related effects: such as angular anisotropy of FFs or sample inhomogeneities. Effects below 1% at high neutron energies (>100 keV), small compared with uncertainties due to other external corrections (neutron fluence).

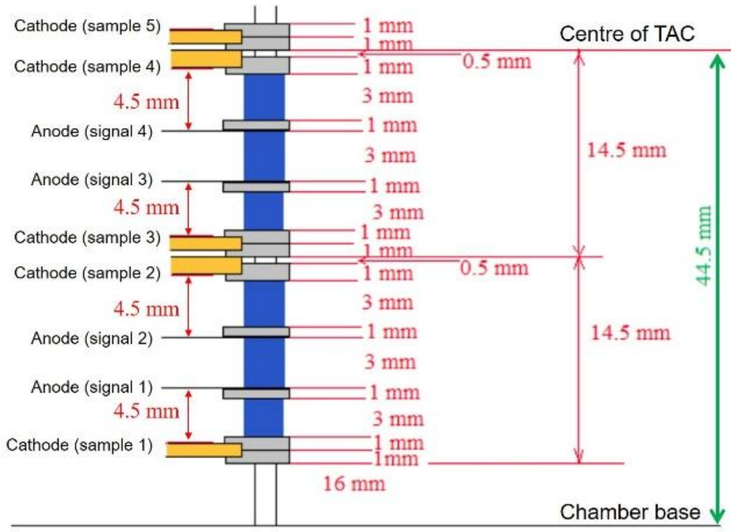
Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

^{239}Pu(n,f) analysis: sample-related effects

Ratio of count rates for single FFDs, relative to FFD#1.





Other effects

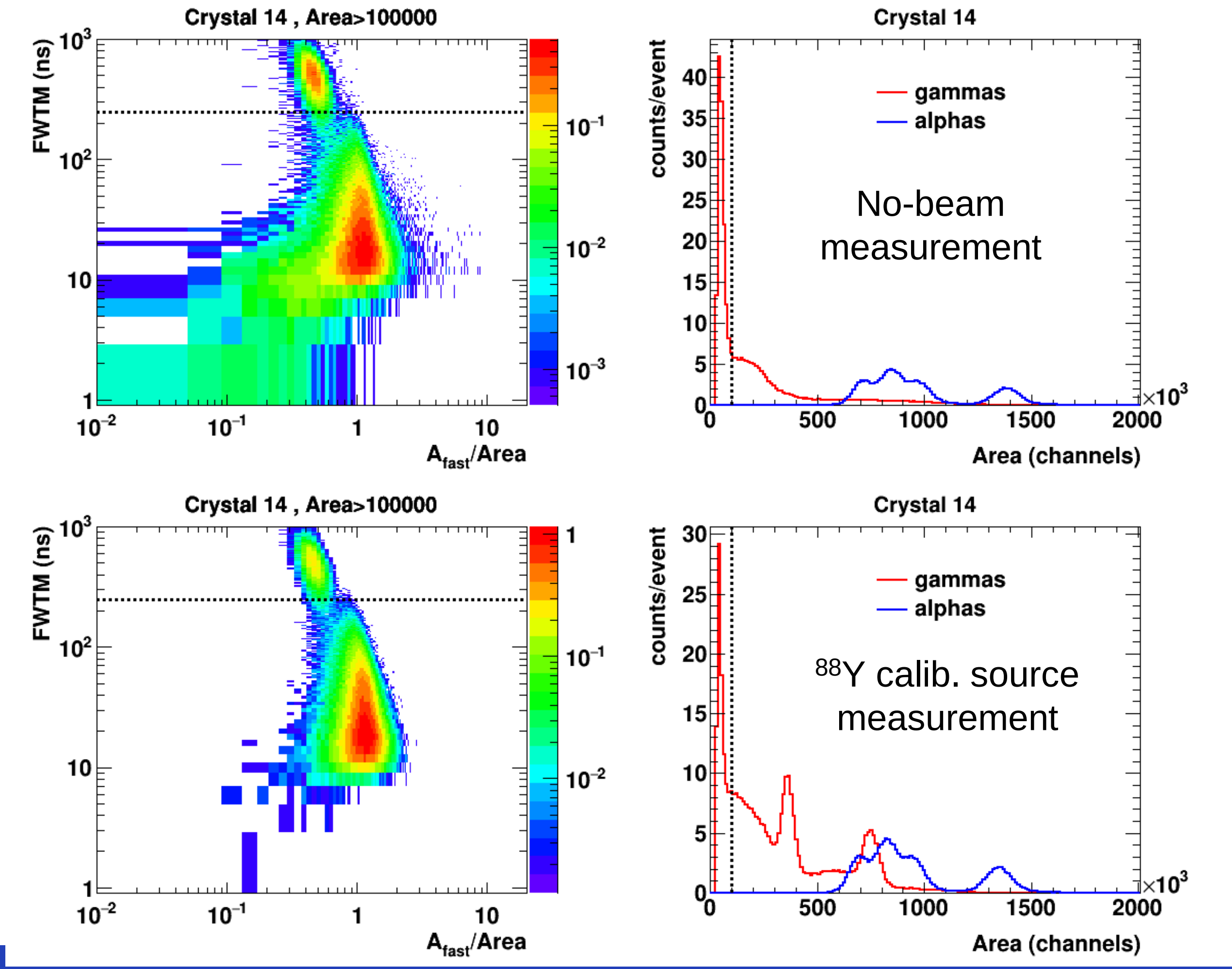
- No gain shifts of the spectra observed throughout the campaign.
- No pile-up effects, comparing high vs. low intensity pulses.
- Sample-related effects: such as angular anisotropy of FFs or sample inhomogeneities. Effects below 1% at high neutron energies (>100 keV), small compared with uncertainties due to other external corrections (neutron fluence).

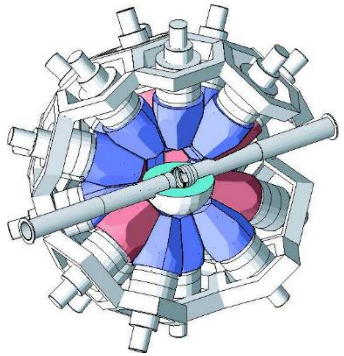
Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

3.2 TAC performance: α-γ discrimination

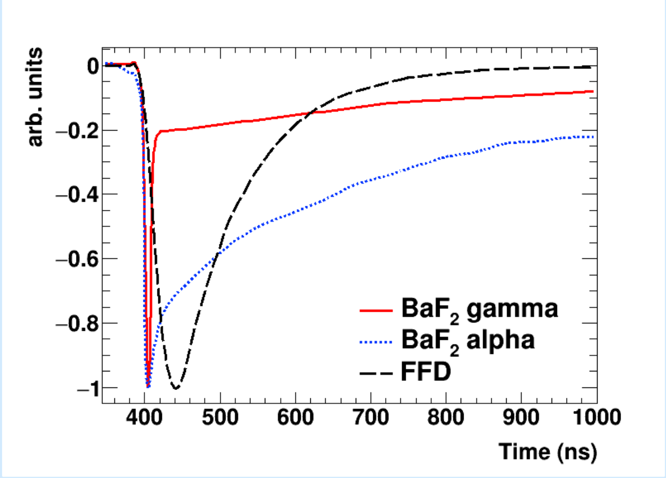
Both type of signals can be differentiated by applying a cut in the time width (FWTM) of the signals fitted by the PSA.





Total Absorption Calorimeter

Different signal shapes



FWTM cut selected one by one for each of the 40 BaF_2 crystals.

Additionally, a **threshold of 200 keV** on the deposited energy (E_{dep}) was applied to remove noise and very low-energy signals in the analysis.

Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

3.4 Determination of efficiencies

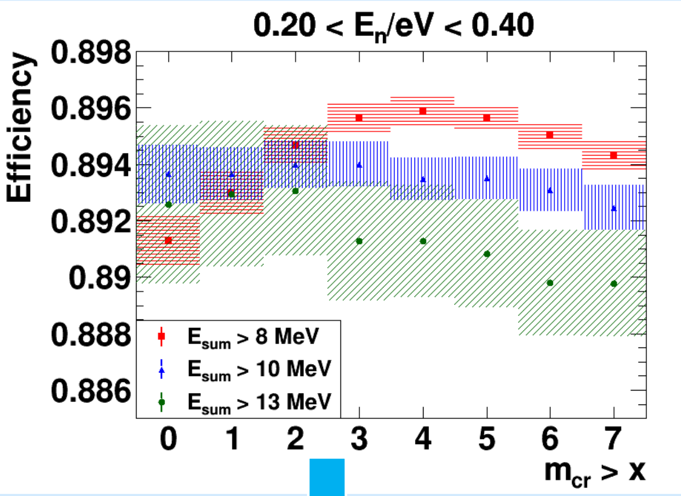
Fission-tagging efficiency

Determined experimentally using the coincidences between FFD and TAC as in previous fission-tagging measurements[1-3].

$$\varepsilon_{ft} = \frac{C_{tag}}{C_F}$$

Tagged counts (C_{tag})

Total fission counts in the TAC (C_F)



$$\varepsilon_{ft} = 89.4(5)\%$$

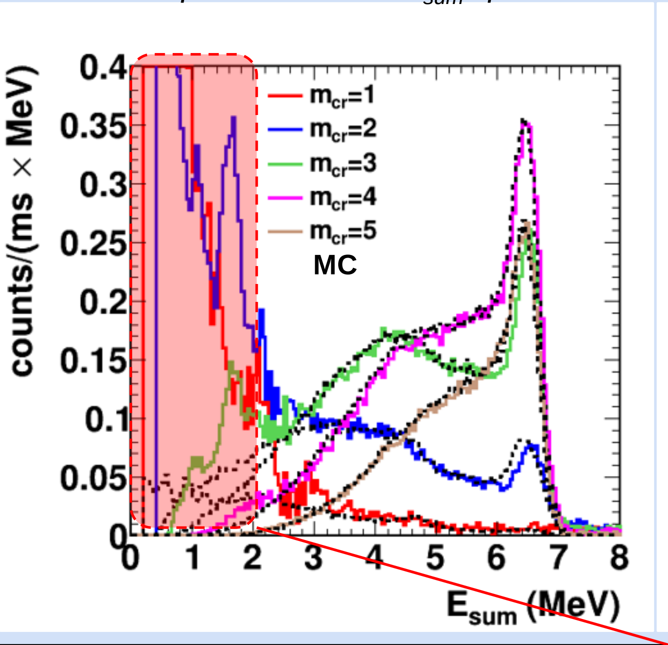
Value independent (within unc.) of E_{sum} and m_{cr} cuts and E_n.

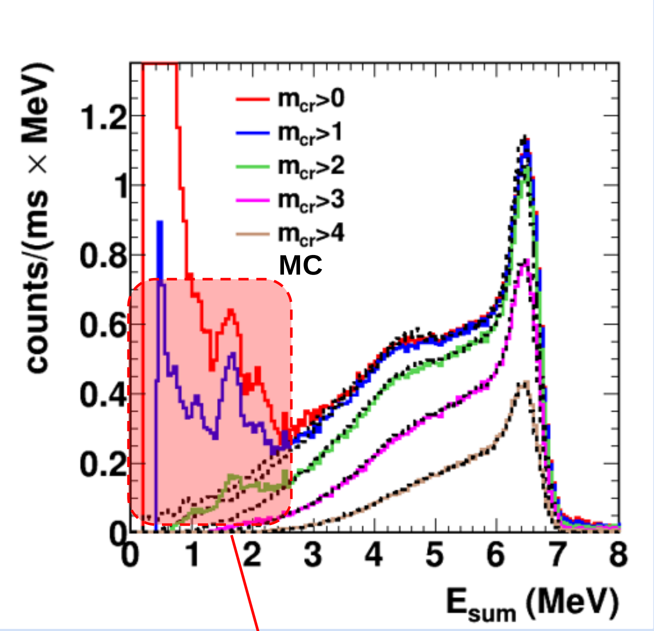
Capture detection efficiency in the TAC

Calculated with Monte Carlo simulations (Geant4) and NuDEX[4] to generate the ^{239}Pu(n,γ) γ-ray cascades.

Excellent agreement achieved between MC (dash line) and experimental data, with and without neutron absorber.

Comparison of TAC E_{sum} spectra between experimental and MC simulations.





Region strongly affected by background

[1] C. Guerrero et al., Eur. Phys. J. A 48, 29 (2012).
[2] J. Balibrea-Correa et al., Phys. Rev. C 102, 044615 (2020).
[3] M. Bacak et al., EPJ Web of Conferences 211, 03007 (2019).
[4] E. Mendoza et al., Nucl. Instr. Meth. A 1047, 167894 (2023).

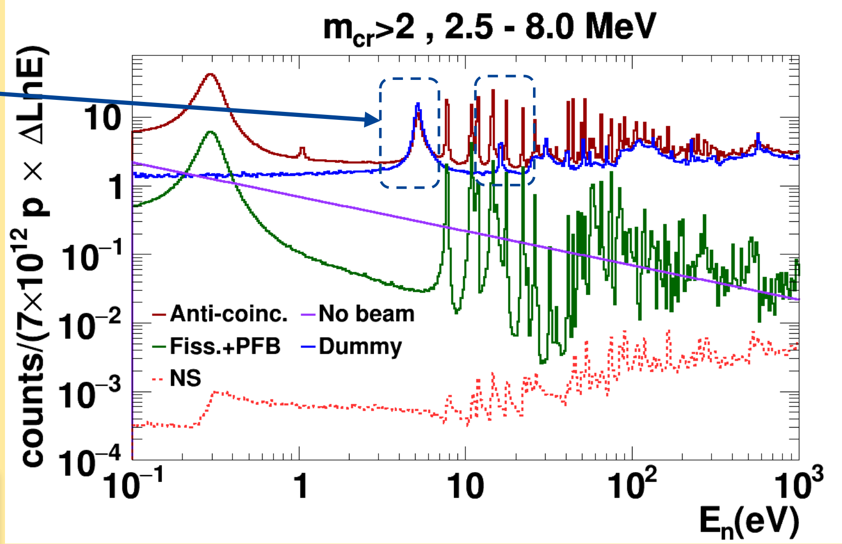
Funded by the European Union

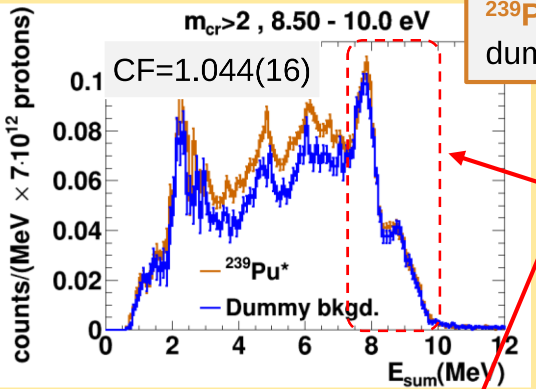
Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

4.3 TAC background subtraction: dedicated measurements

Dummy correction in the FC setup

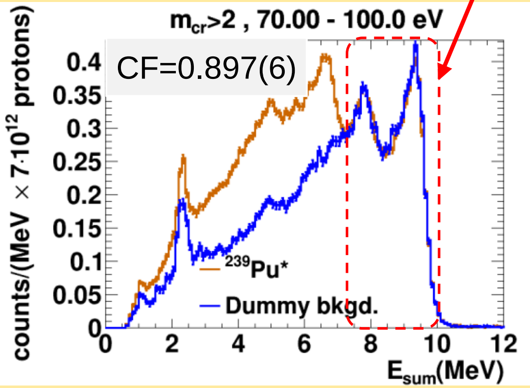
- Subtraction inconsistencies at some neutron energies due to different concentration of electronic materials (silver, copper) seen by the neutron beam between dummy and plutonium chamber.

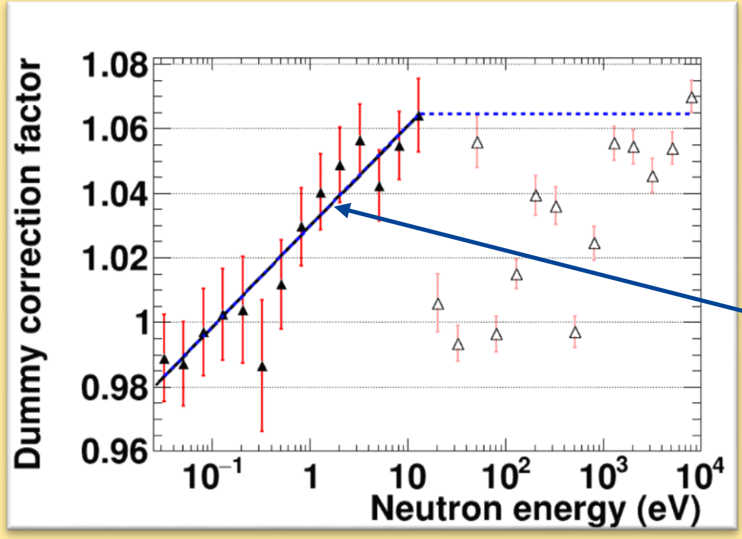




^{239}**Pu***: anti-coinc. data with all non-dummy bkgd. subtracted.

Region to calculate the Correction Factor (CF) through the ratio of integrals.





Resulting correction function vs En

In blue, the fitted function. Above 10 eV, the CFs are affected by the ^{239}Pu resonances, so the determination is not *clean* → extrapolated as a constant (compatible with >1 keV CFs).

Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

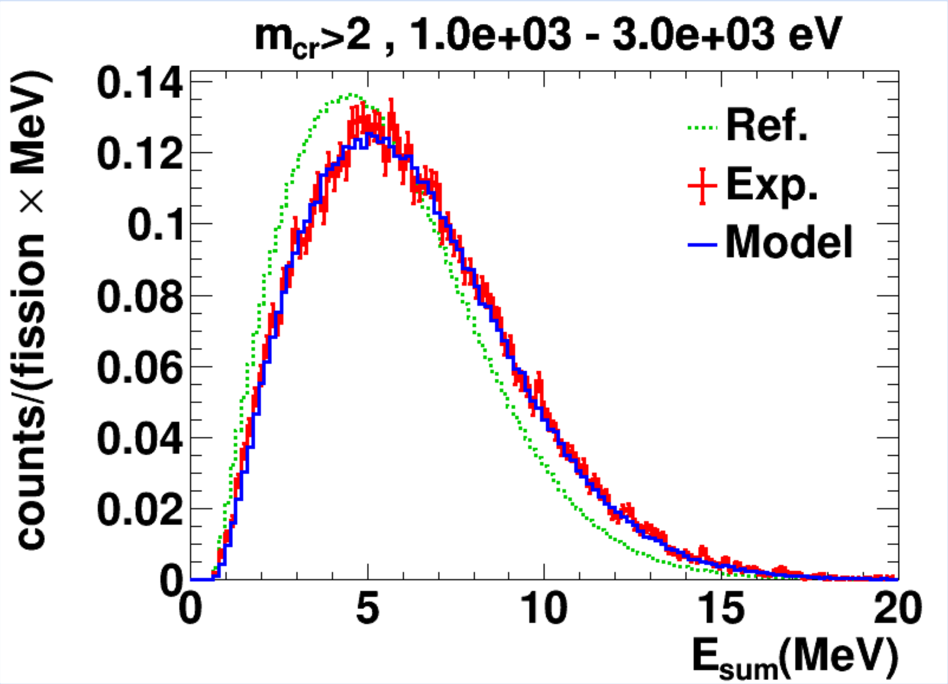
3.5 Pile-up correction

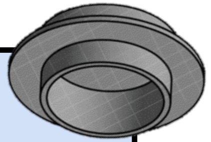
Observed pile-up effects that depend on the time-of-flight (neutron energy) within the same pulse, reproducible with artificial data buffers with sample signals. Same method as in previous measurements with the TAC[1].

Validation with experimental data

Able to reproduce gain shifts and data losses.

Comparison of E_{sum} prompt-fission spectra between experimental data and pile-up model at 1-3 keV.

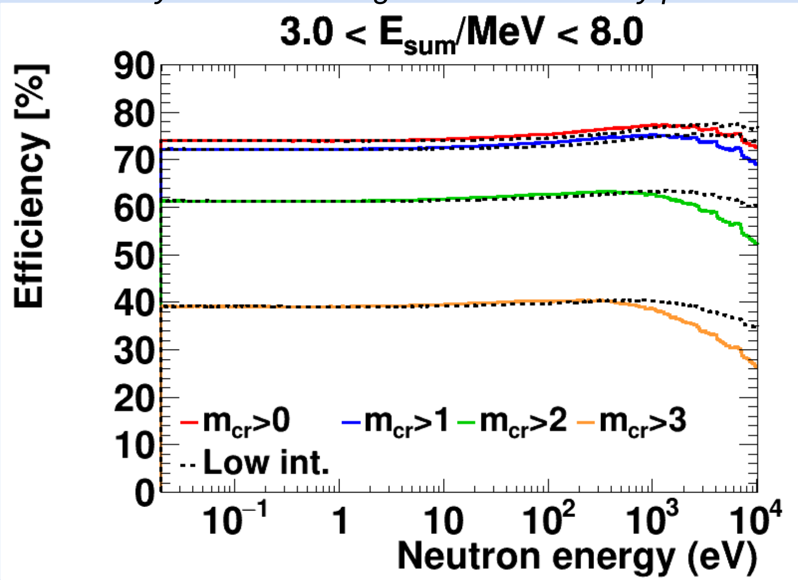




TS setup

- Significantly larger corrections than in the FC setup, especially for E_n>2 keV (up to 15%).
- Low intensity pulses: corrections below 2.5% up to 10 keV.

Efficiency curves with high and low intensity pulses.



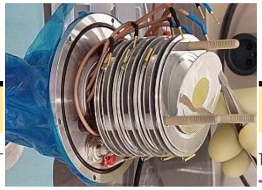
TS capture yield was measured using only low-intensity pulses to minimize pile-up corrections.

[1] E. Mendoza et al. Nucl. Instrum. Methods Phys. Res. A 768, 55 (2014).

Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

4.6 Analysis conditions and normalization: FC setup



Fission

The fission yield was normalized to the recommended evaluated $^{239}Pu(n,f)$ cross section integral in the 9-20 eV region by I. Duran et al. (https://doi.org/10.1016/j.nds.2024.01.004)

Capture

This directly determines the normalization in the capture yield, since both quantities were measured simultaneously with the same samples:

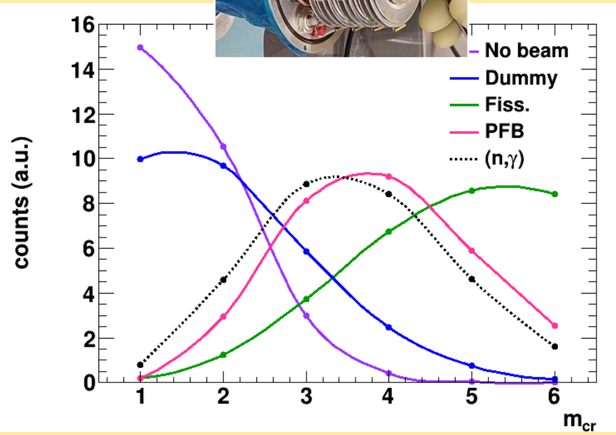
$$N_{2cm} = \frac{N_f}{\varepsilon_{FF}}$$

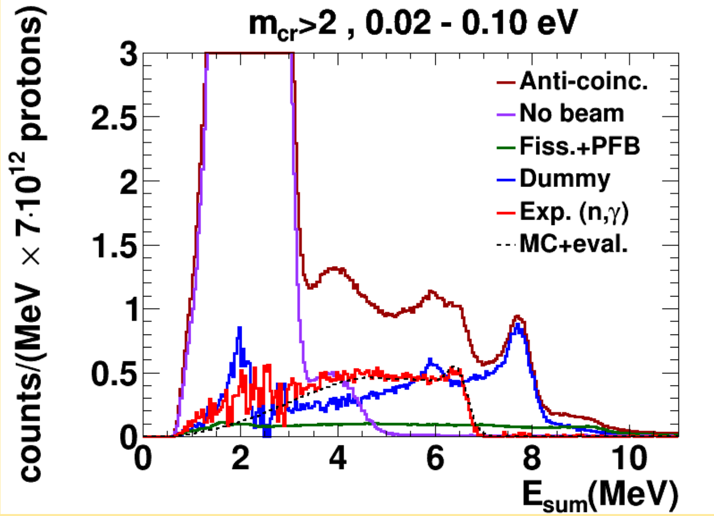
TAC analysis cond.

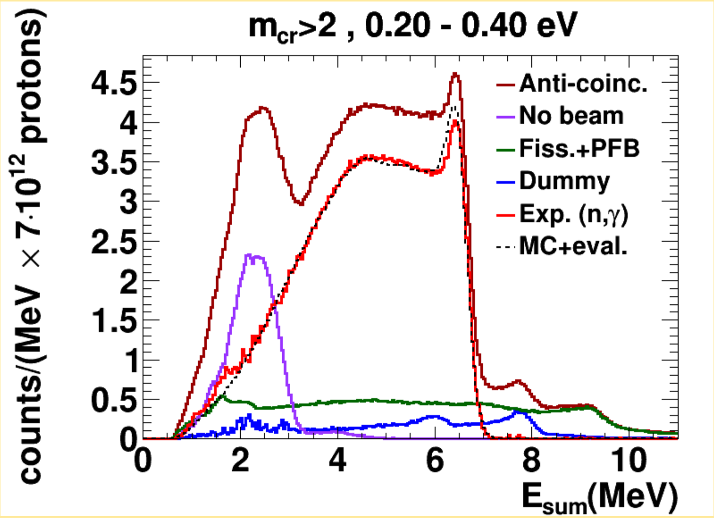
Chosen to improve signal-to-background ratios while keeping enough counting statistics:

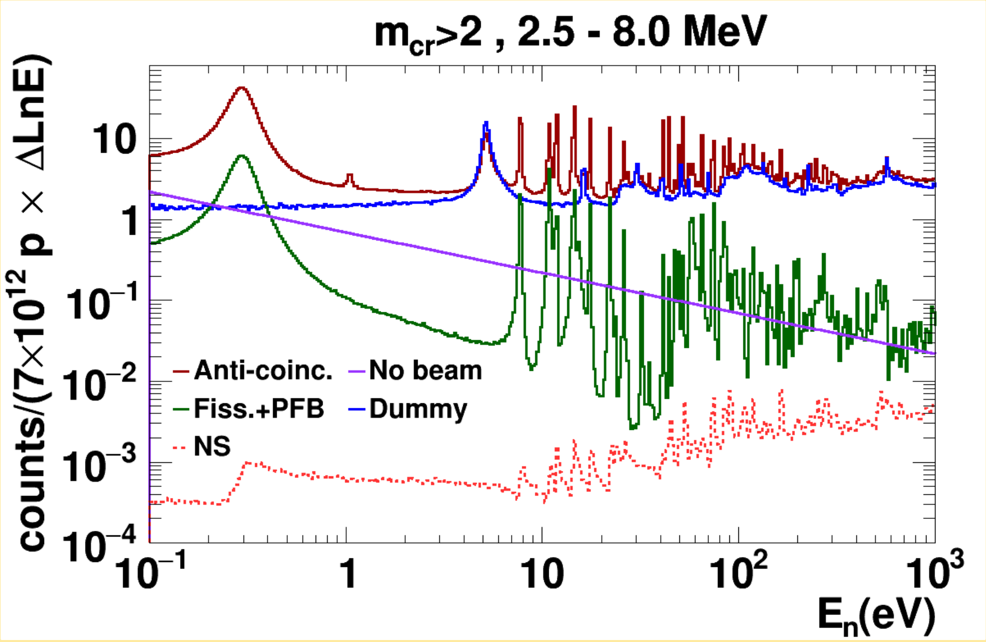
If $E_n < 0.1$ eV:
$m_{cr} > 2$; $4 < E_{sum}/\mathrm{MeV} < 7$

If $E_n > 0.1$ eV:
$m_{cr} > 2$; $2.5 < E_{sum}/\mathrm{MeV} < 8$









Funded by the European Union

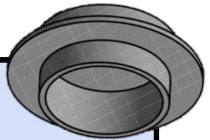
Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

4.6 Analysis conditions and normalization: TS setup

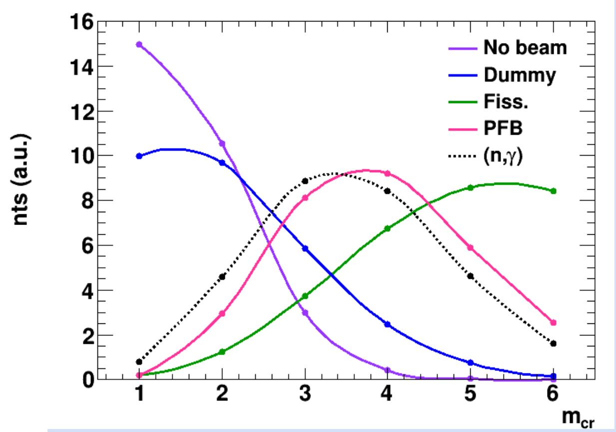
Normalization in TS setup

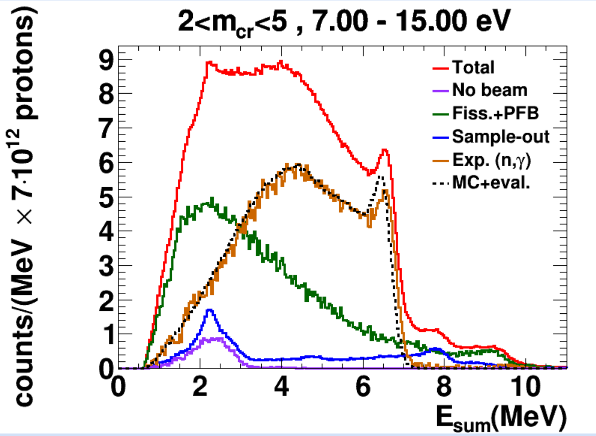
When the fission background was subtracted, a normalization was also determined to the data obtained from the FC setup.

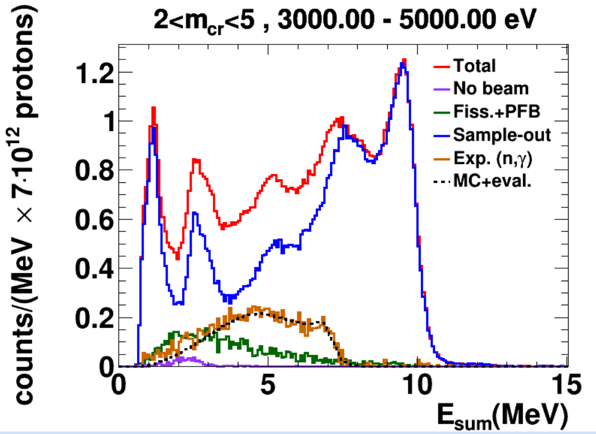
Analysis conditions in TS setup

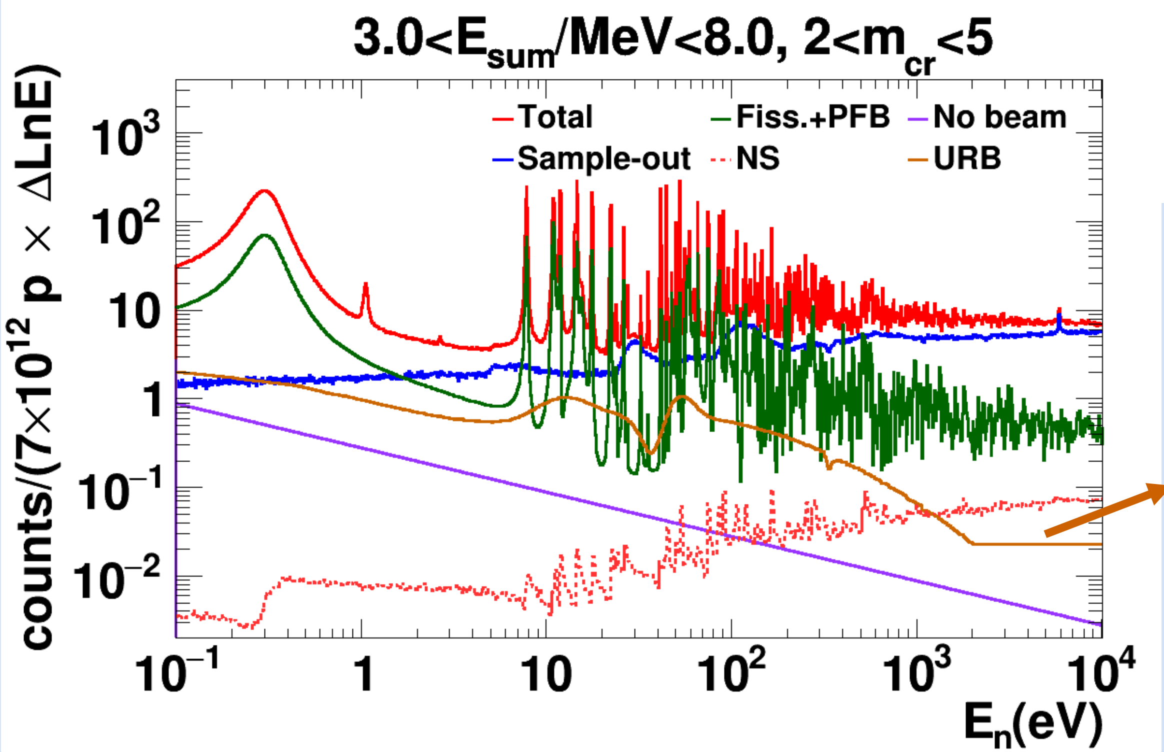


More restrictive TAC event selection criteria were applied to further suppress fission and unidentified backgrounds.









Unidentified Residual Bkgd. (URB)

Above 2 keV, extrapolated as constant background following a conservative approach, since there are no more available valleys to perform the fit.

Funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.