Cross section measurements in the resolved resonance range

26/02/2025

E. Mendoza, CIEMAT

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Introduction

The topic of this talk is *cross section measurements in the RRR*.

My expertise is quite focused in neutron capture (n_TOF):

- E. Mendoza et al., *Measurement and analysis of the* **^{243}Am** *neutron capture cross section at the n_TOF facility at CERN*, Phys. Rev. C 90, 034608 (2014).
- E. Mendoza et al., *Measurement and analysis of the* **^{241}Am** *neutron capture cross section at the n_TOF facility at CERN*, Phys. Rev. C 97, 054616 (2018).
- J. Balibrea, E. Mendoza et al., *Measurement of the alpha ratio and (n,γ) cross section of* **^{235}U** *from 0.2 to 200 eV at n_TOF*, Phys. Rev. C 102, 044615 (2020).
- V. Alcayne, E. Mendoza et al., *Measurement of the* **^{244}Cm** *capture cross sections at both CERN n_TOF experimental areas*, EPJ Web of Conf. 239, 01034 (2020).
- V. Alcayne, A. Kimura, E. Mendoza et al., *Measurement and analysis of the* **^{246}Cm** *and* **^{248}Cm** *neutron capture cross-sections at the EAR2 of the n_TOF facility at CERN*, Eur. Phys. Jour. 60, 246 (2024).
- A. Sánchez-Caballero, …, E. Mendoza 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).

In this talk I will try to make an overview of the experimental procedures performed in a TOF experiment, focusing in neutron capture measurements (at n_TOF). I will also try to present possible biases in the analysis procedure.

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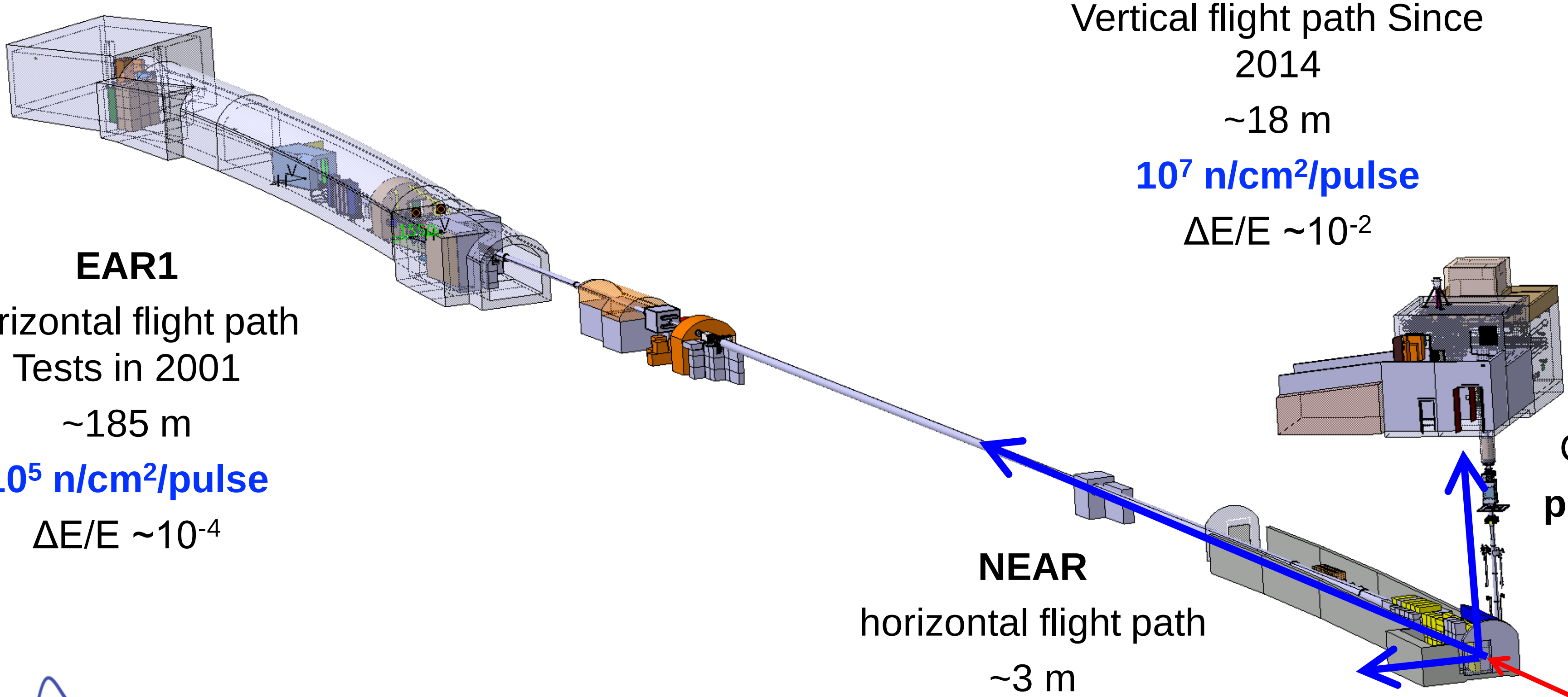
The n_TOF facility at CERN

EAR1
horizontal flight path
Tests in 2001
~185 m
10^5 n/cm^2/pulse
ΔE/E ~10^{-4}



EAR2
Vertical flight path Since 2014
~18 m
10^7 n/cm^2/pulse
ΔE/E ~10^{-2}

Spallation source
CERN PS @ 0.8 Hz
p 20 GeV/c, 7ns RMS
$7 \cdot 10^{12}$ p/pulse
$2 \cdot 10^{15}$ n/pulse

NEAR
horizontal flight path
~3 m
10^8 n/cm^2/pulse

*N. Patronis et al. EPJ Techniques and Instrumentation **10**, 13 (2023)*

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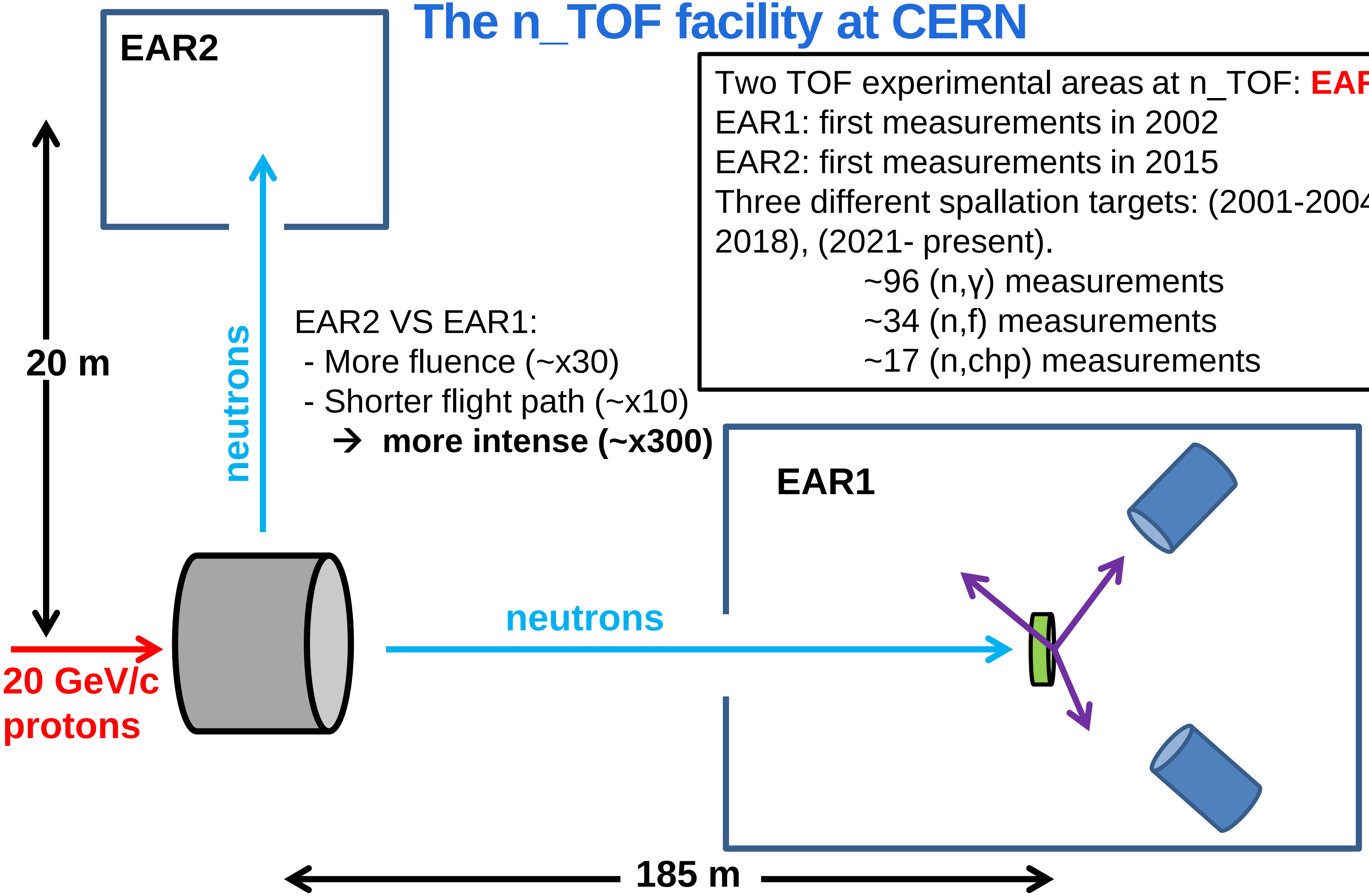
The n_TOF facility at CERN

Two TOF experimental areas at n_TOF: **EAR1** and **EAR2**
EAR1: first measurements in 2002
EAR2: first measurements in 2015
Three different spallation targets: (2001-2004), (2009-2018), (2021- present).

~96 (n,γ) measurements
~34 (n,f) measurements
~17 (n,chp) measurements



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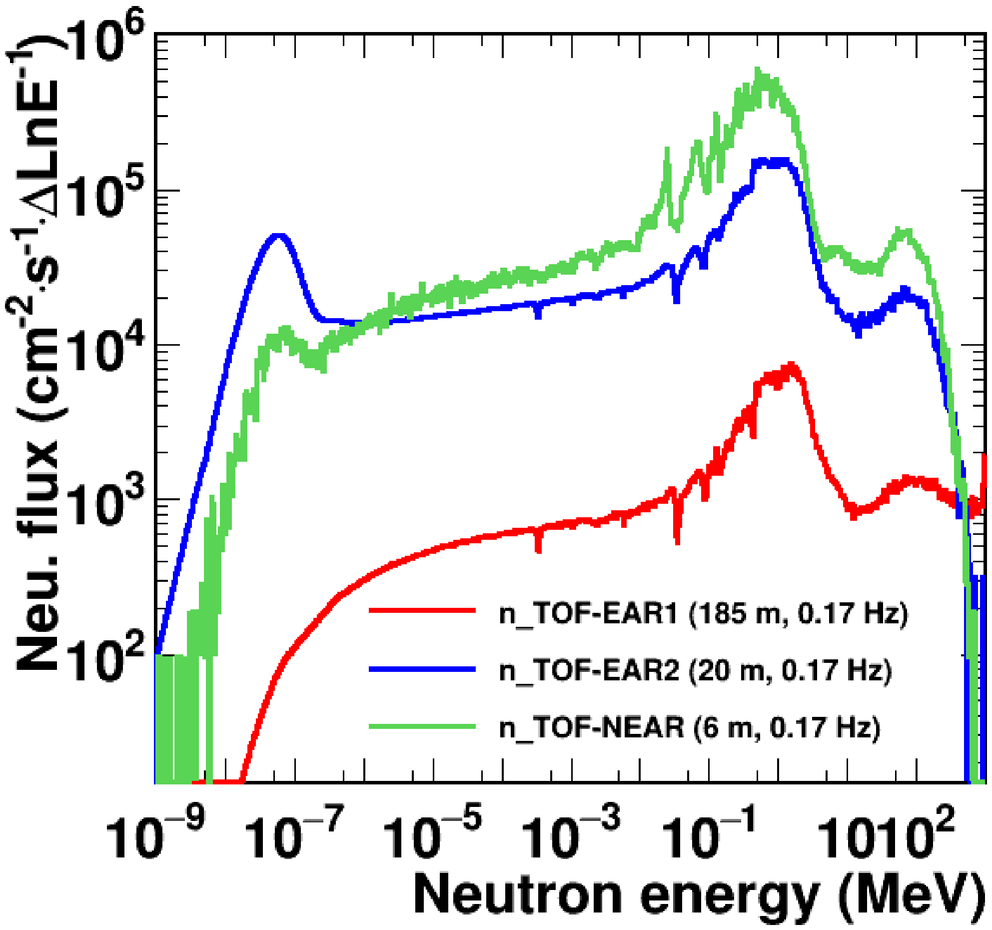
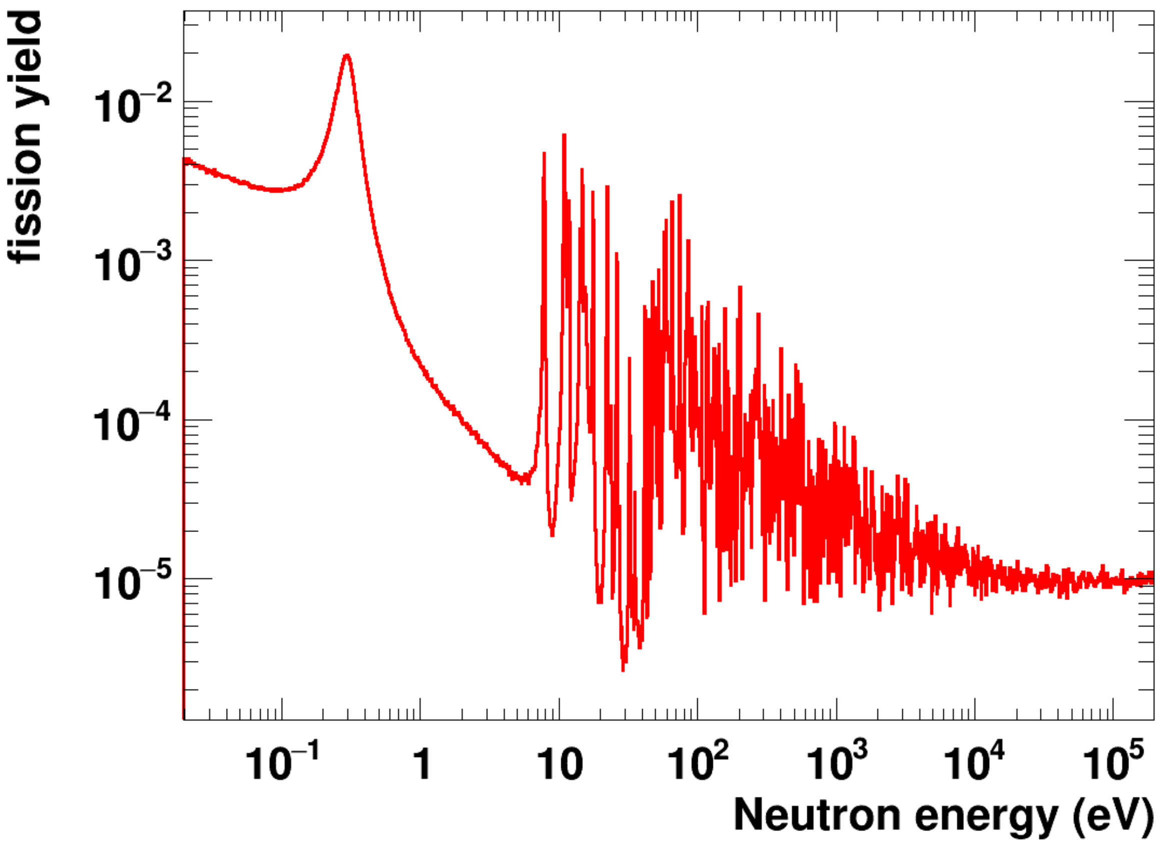
The n_TOF facility at CERN



^{239}Pu(n,f) measurement @ n_TOF-EAR1 (2022)



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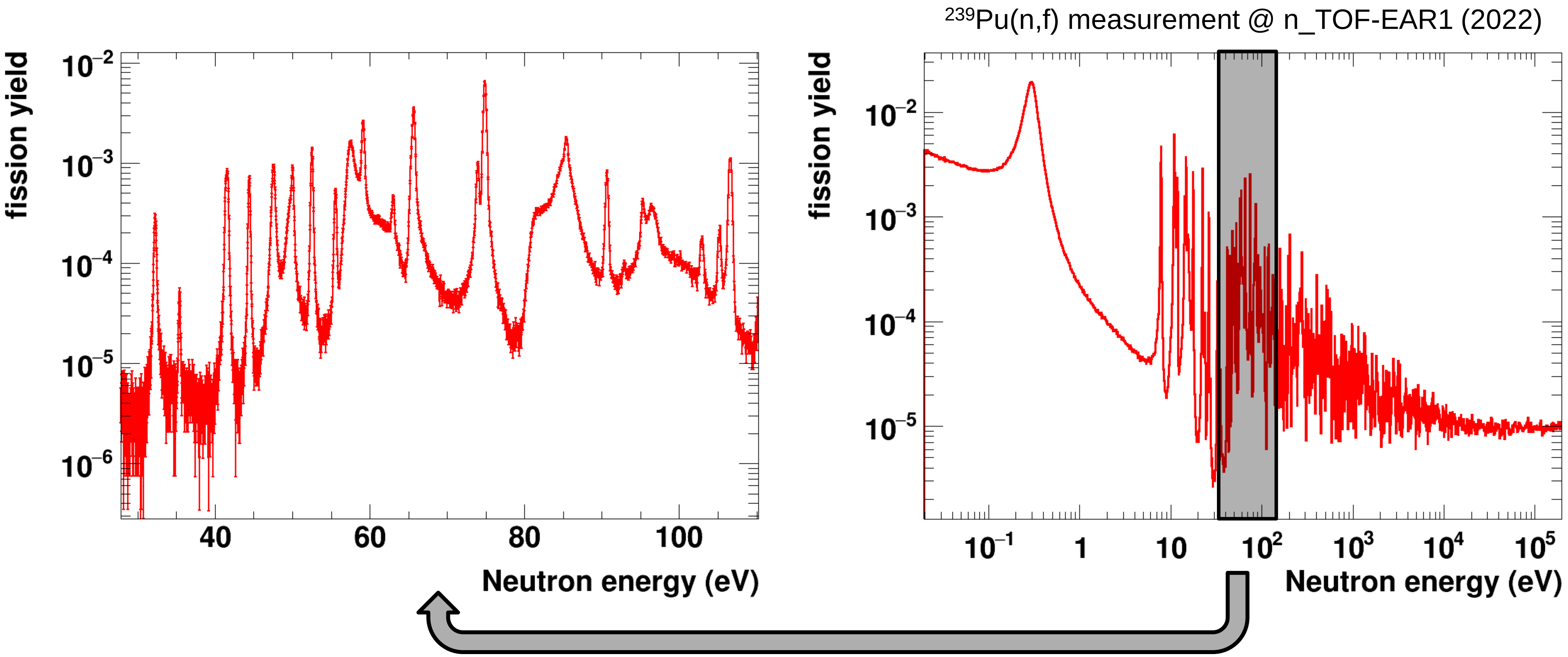
The n_TOF facility at CERN



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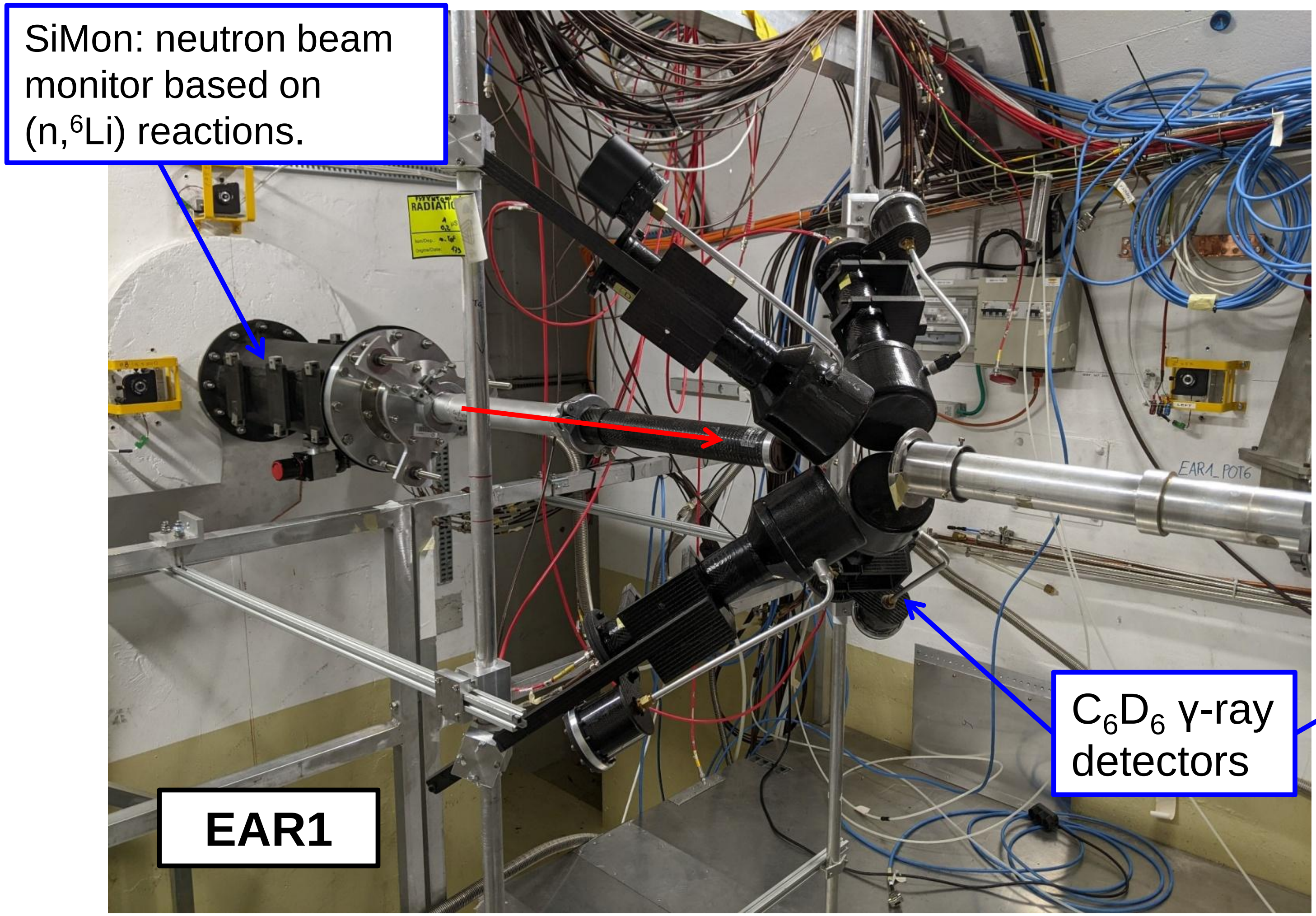
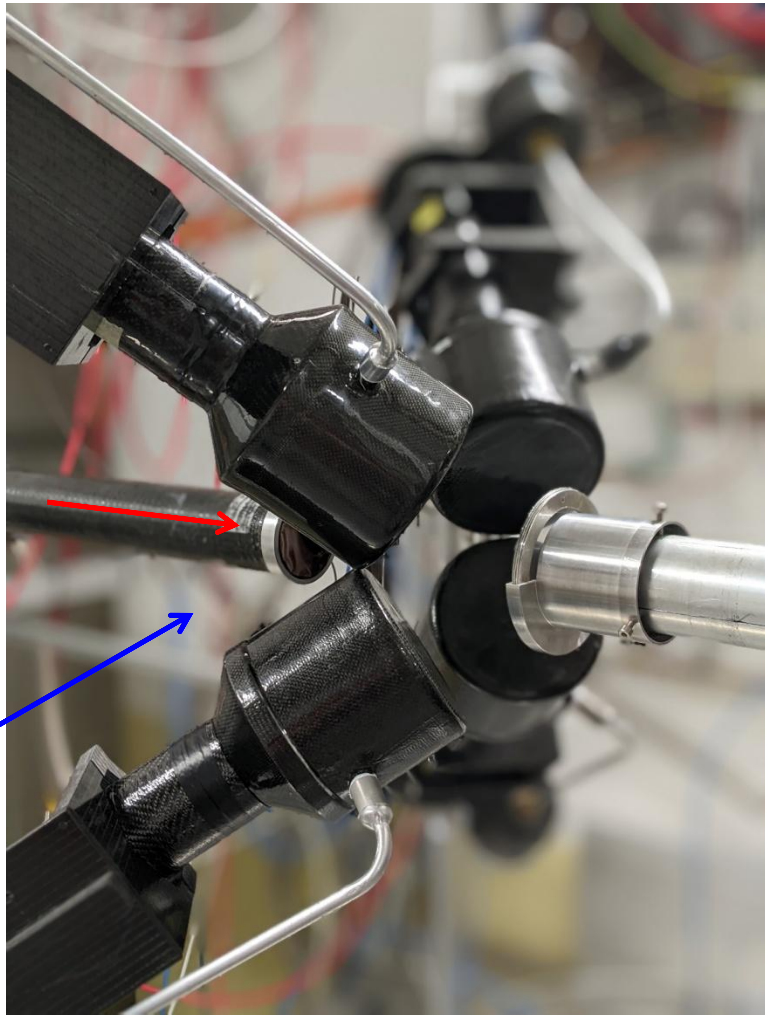
Detection systems





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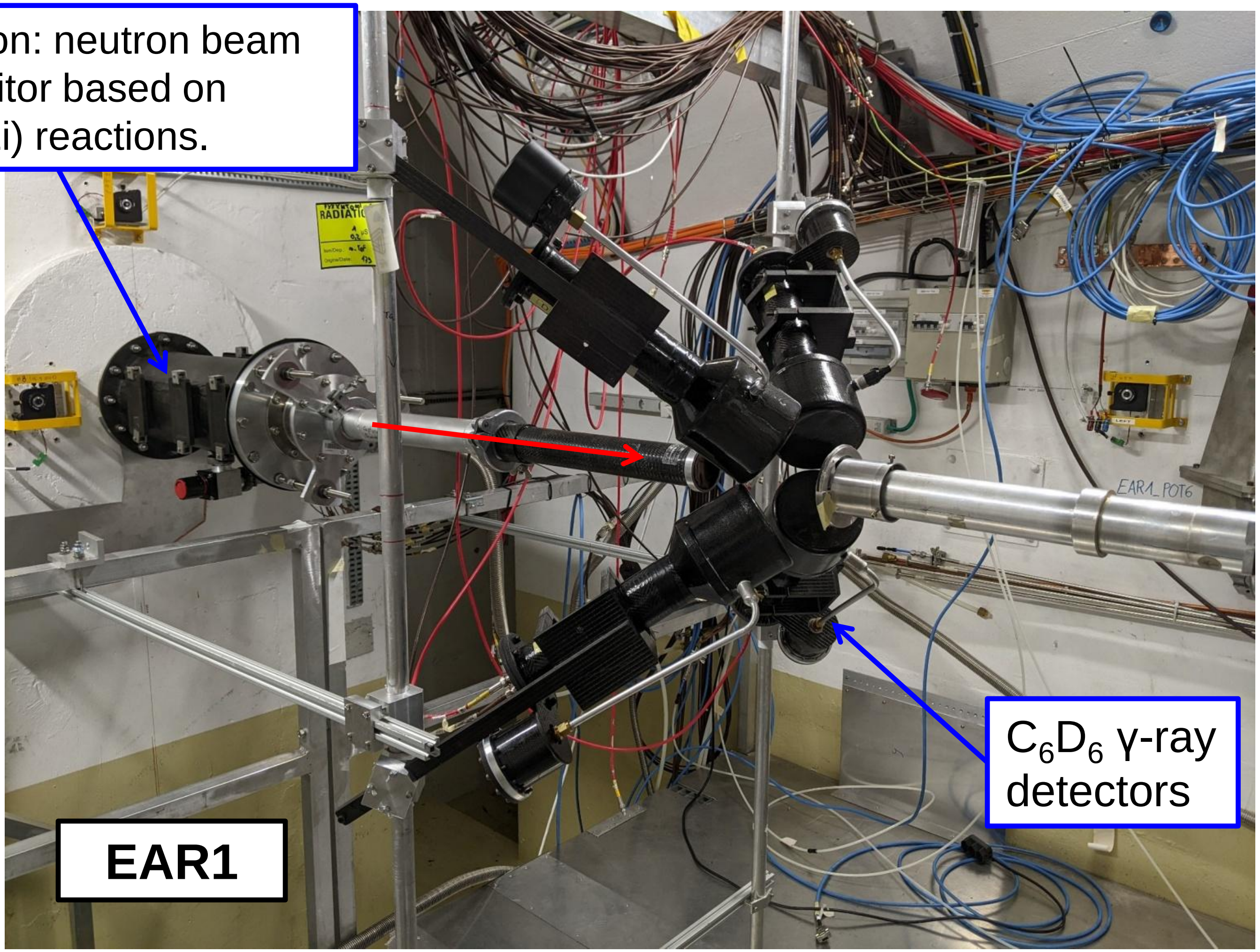
Detection systems

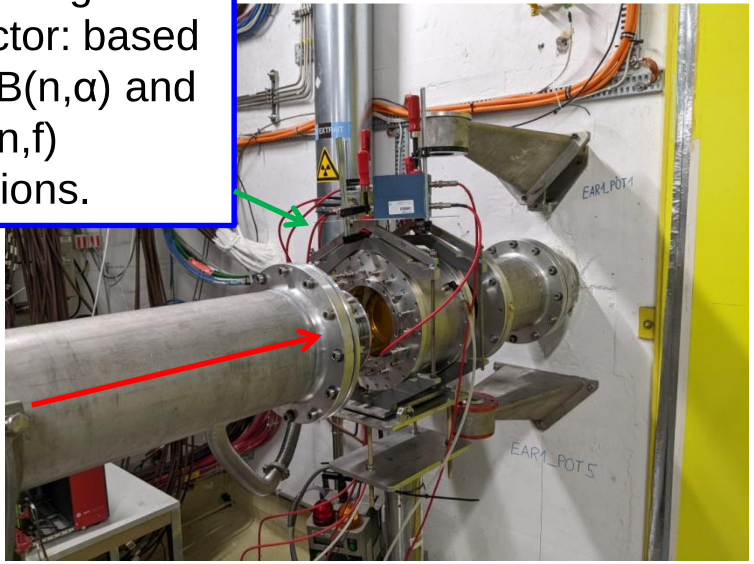
SiMon: neutron beam monitor based on (n,^{6}Li) reactions.

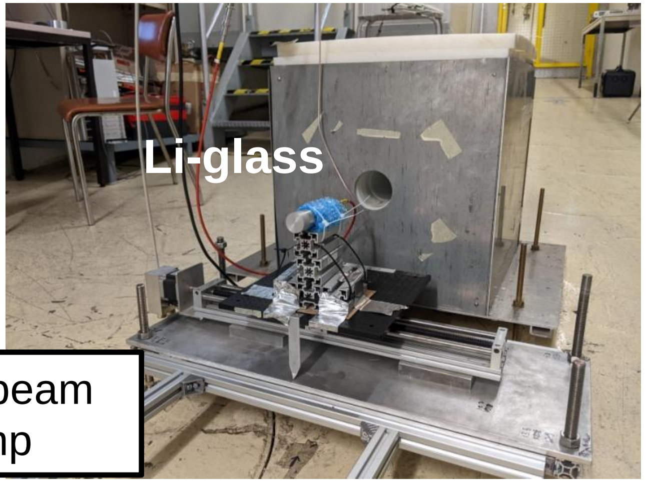


C_6D_6 γ-ray detectors

EAR1

Micromegas detector: based on ^{10}B(n,α) and ^{235}U(n,f) reactions.





EAR1 beam dump

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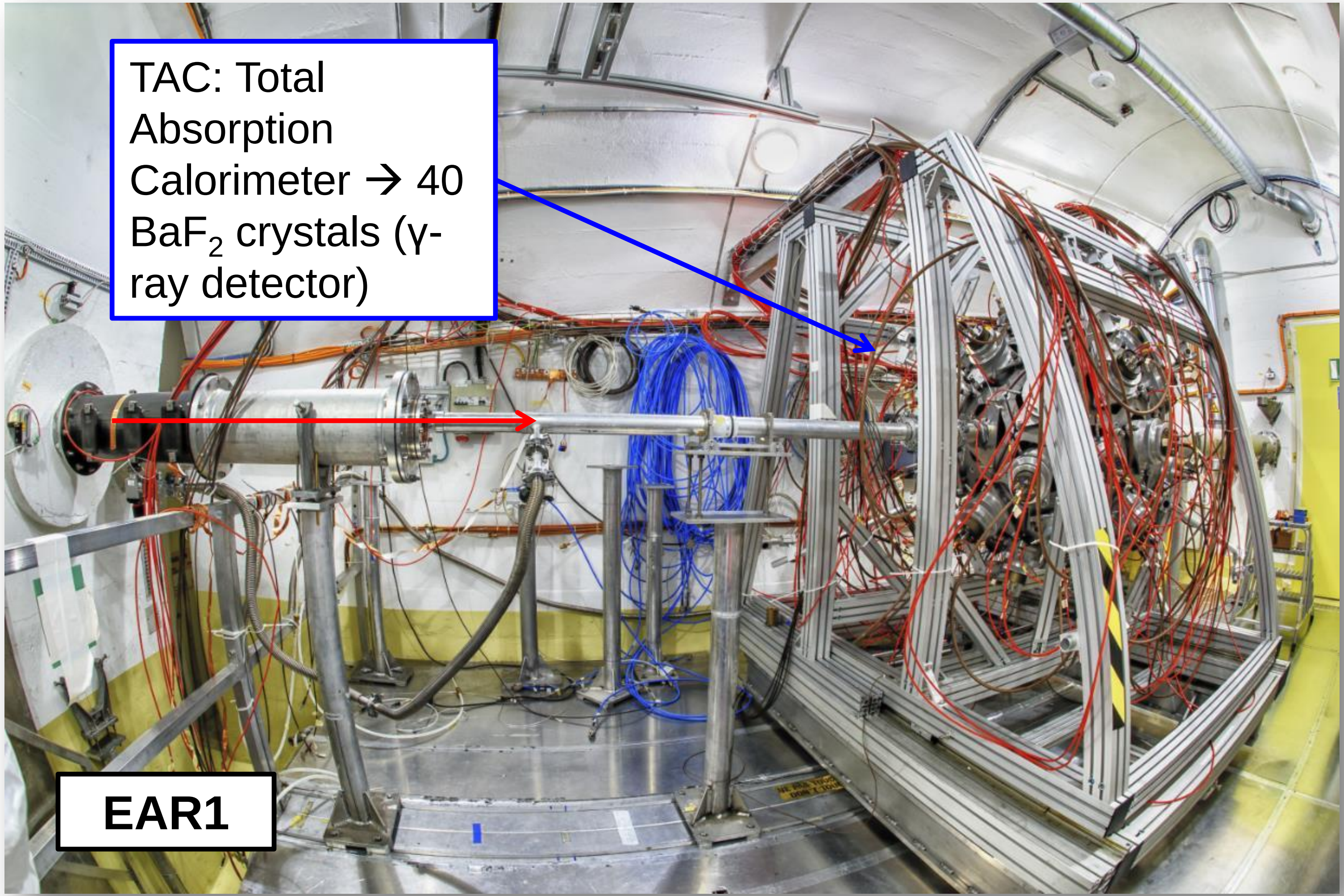
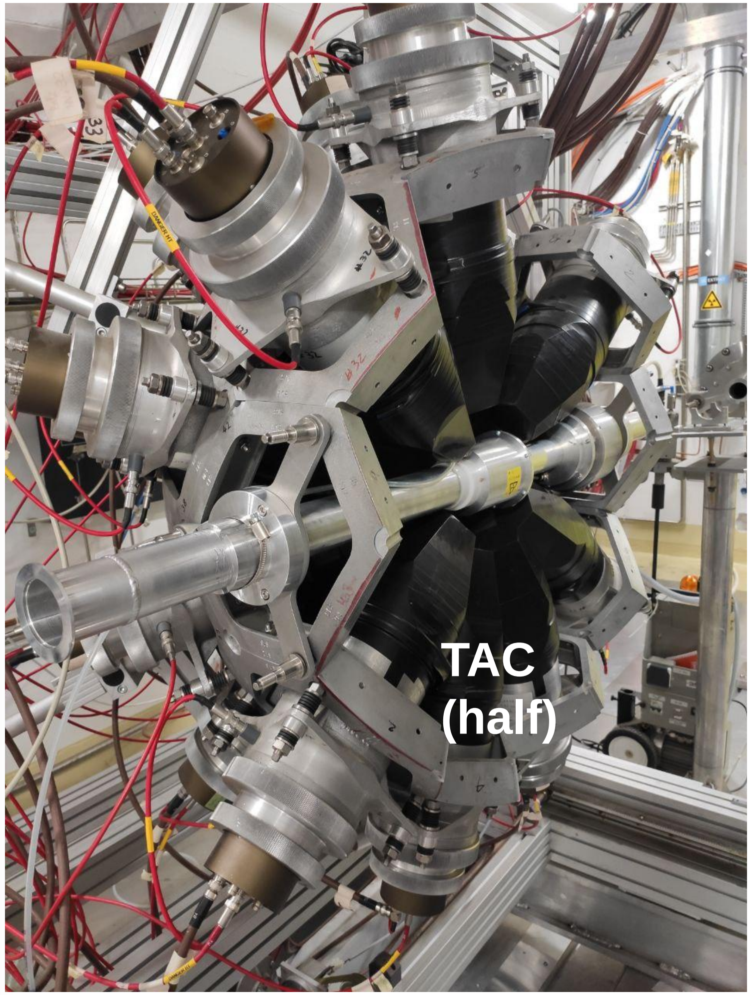
Detection systems





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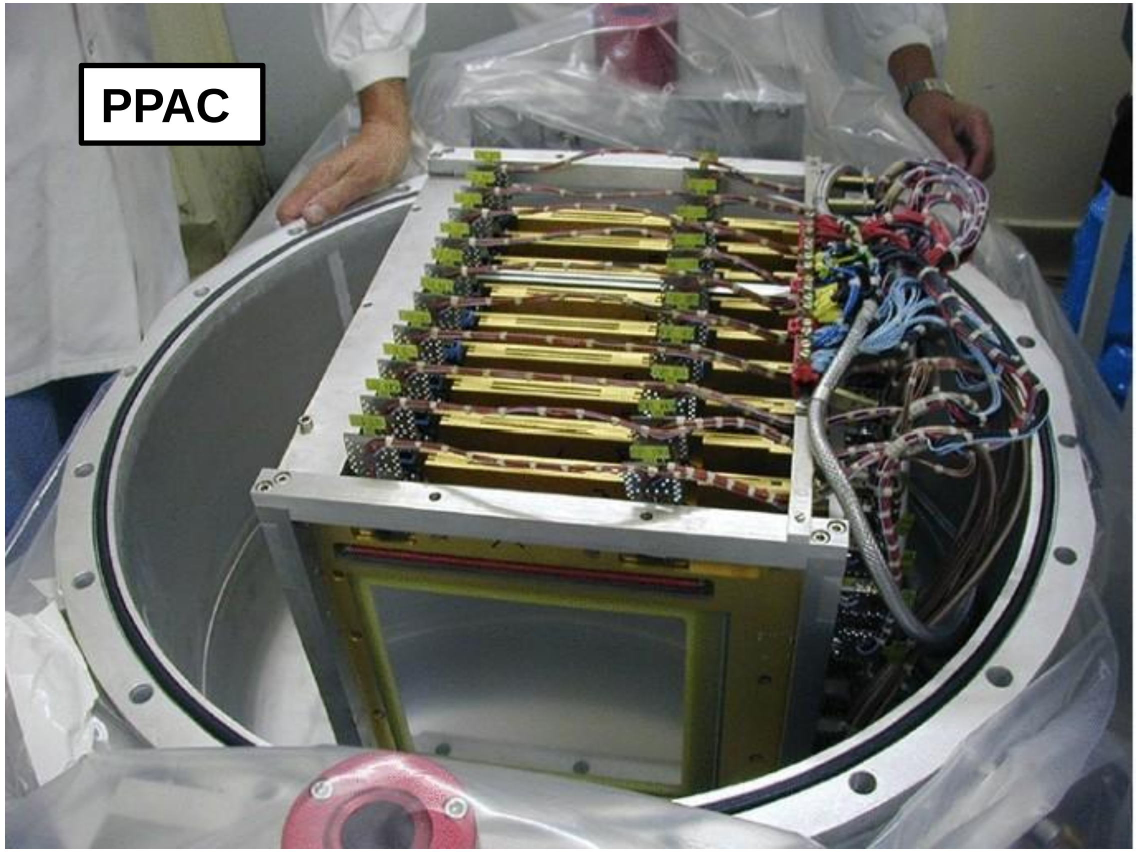

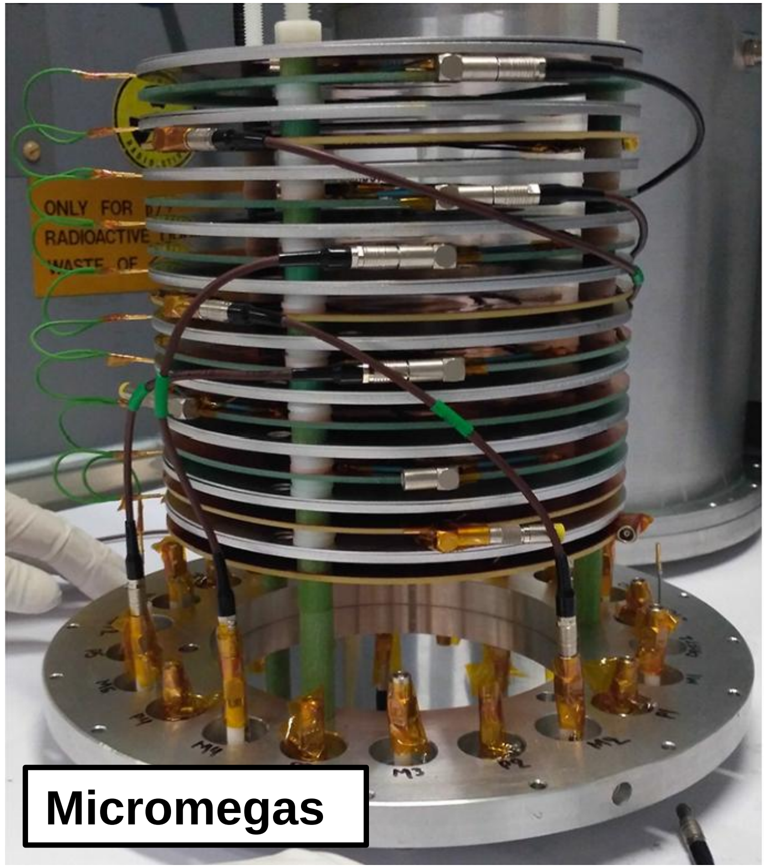

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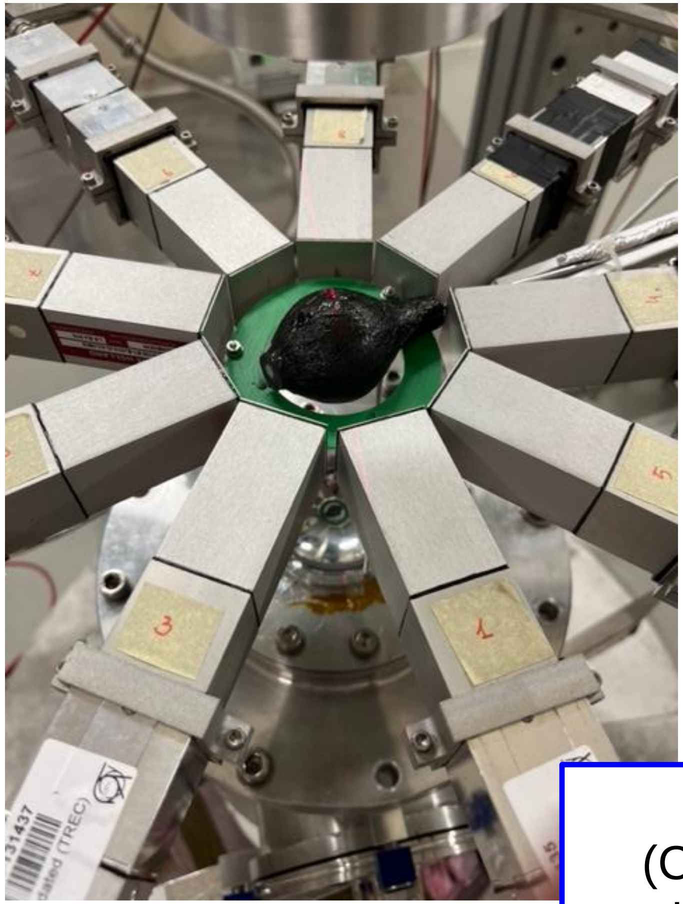
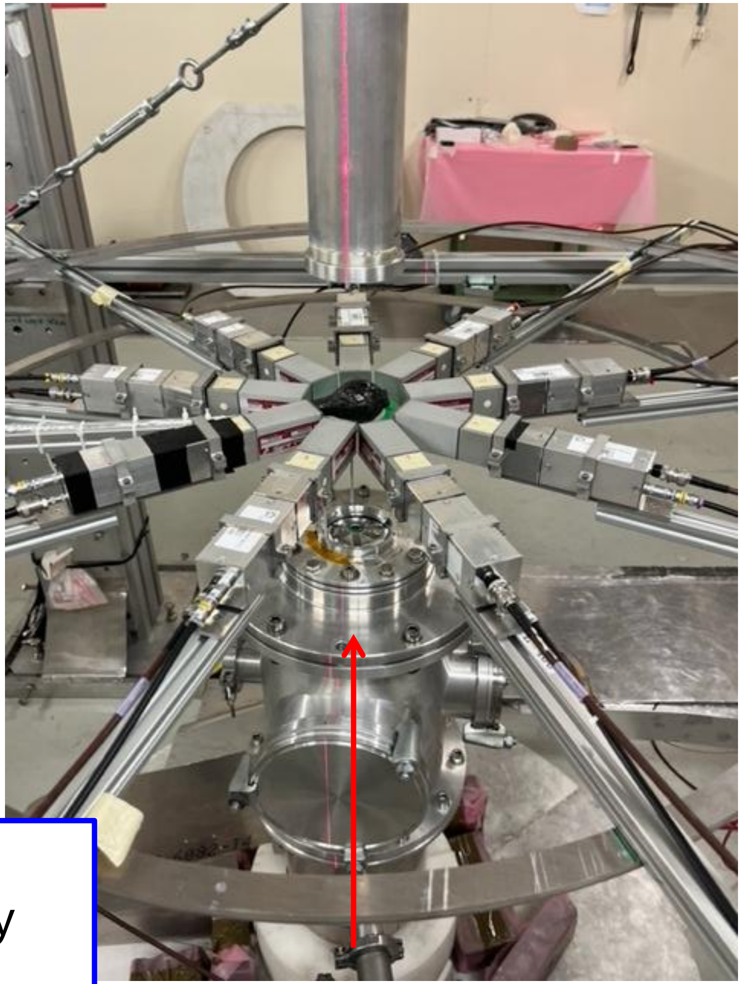
Detection systems



EAR2



sTED
(C_6D_6 γ-ray
detectors)

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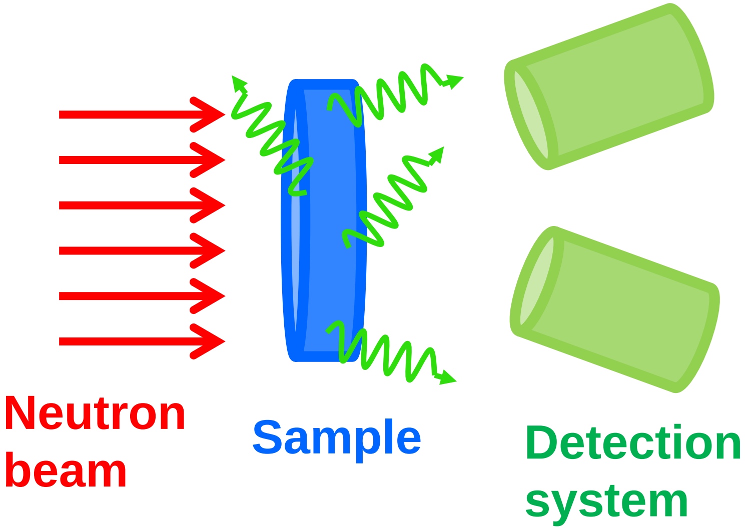
Neutron capture measurements

The experimental capture yield is usually calculated from a expression similar to this:

$$\boldsymbol{Y_{(n,\gamma)}(E_n) = \frac{C(E_n) - B(E_n)}{\varepsilon(E_n) \cdot \phi(E_n)}}$$



where:

- $Y_{(n,\gamma)}$ is the capture yield.
- E_n is the neutron energy.
- $C(E_n)$ are the number of counts in the detector [per unit something].
- $B(E_n)$ is the background.
- $\varepsilon(E_n)$ is the detection efficiency.
- $\phi(E_n)$ are the number of neutrons impinging in the sample [per unit something].

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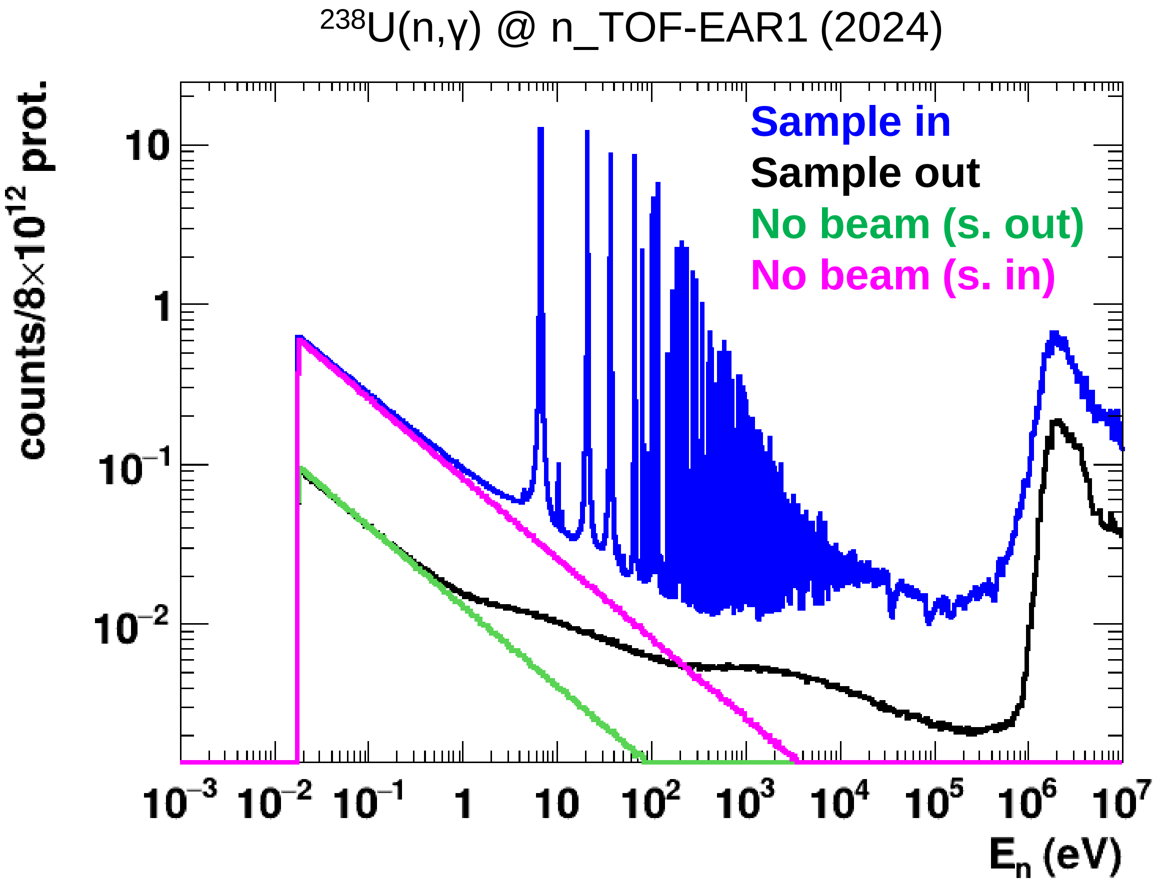

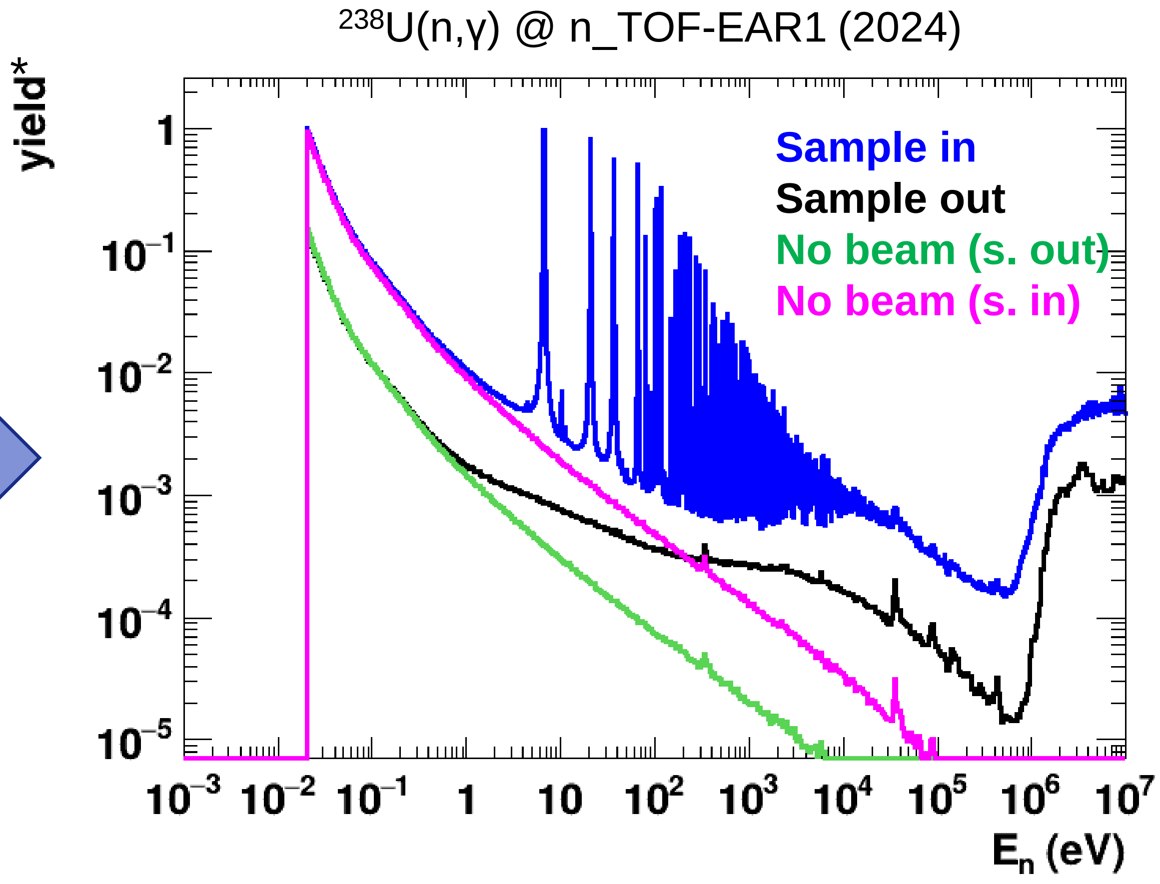

$$Y_{(n,\gamma)}(E_n) = \frac{C(E_n) - B(E_n)}{\varepsilon(E_n) \cdot \phi(E_n)}$$

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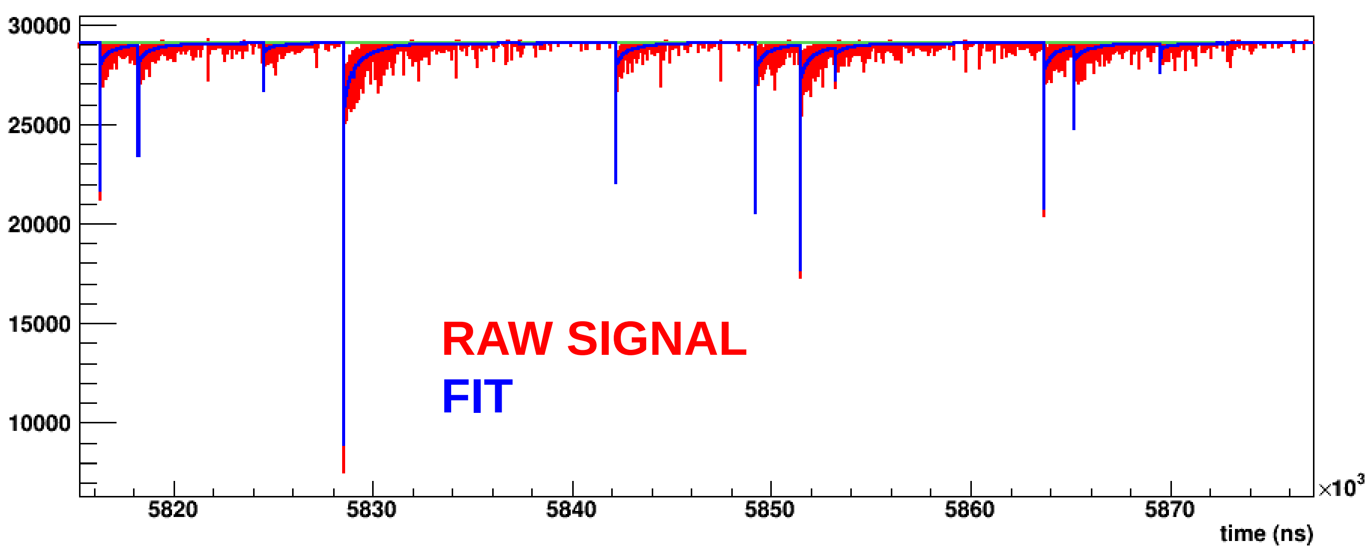
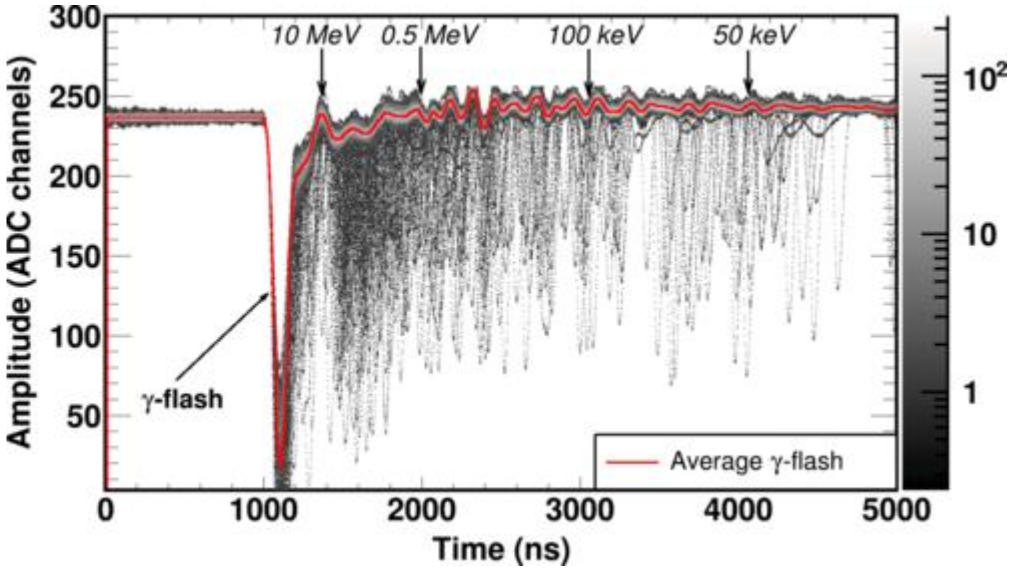
Signal processing

Signals from all detectors are digitized and stored for later analysis by dedicated pulse analysis routines.
In most cases there is not much of a problem with this, but there are some exceptions:

- Pulse pile-up
- Signals close to the *γ-flash*



Signals from the a BaF_2 module of the TAC



Signals close to the γ-flash in a $^{240}Pu(n,f)$ measurement. Figure from A. Stamatopoulos et al., PRC 102, 014616 (2020).

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Pulse pile-up

Pile-up effects appear when the counting rate is large enough so the probability that two signals overlap is not small.

Very often pile-up effects are small (or negligible) and can be corrected without any problem (C_6D_6).

Pile-up occurs when counting rates are high, i.e.:

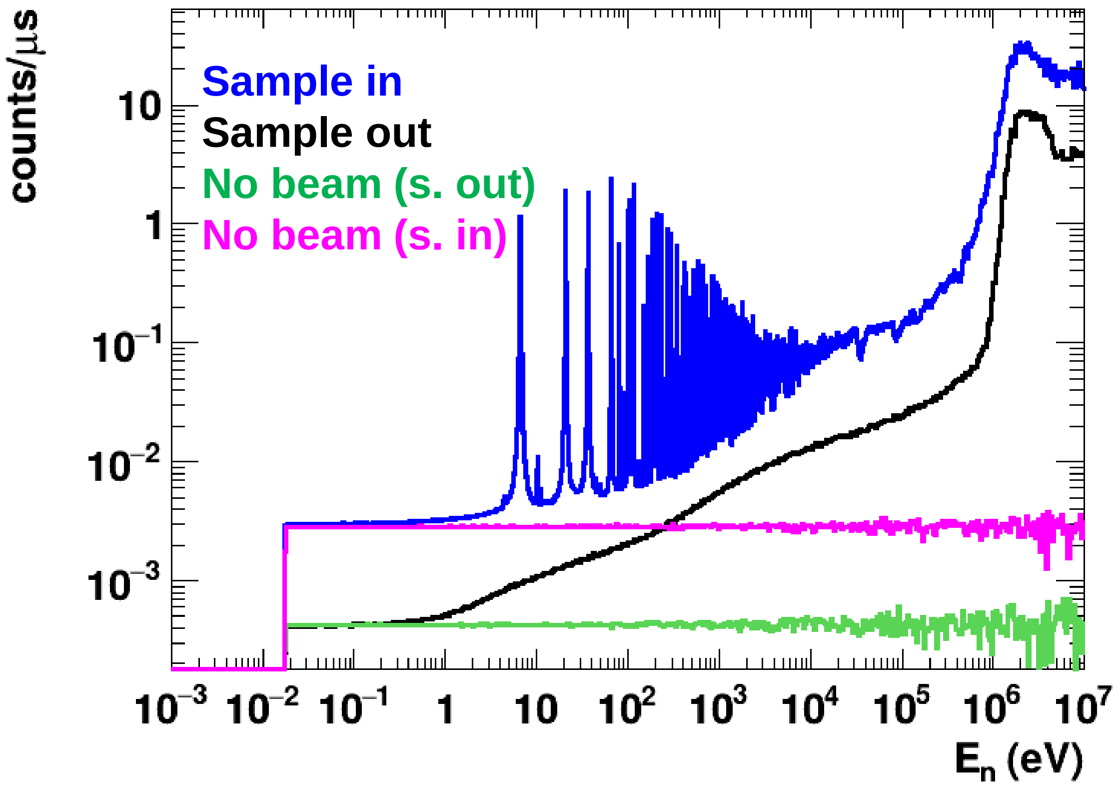
- Strongest resonances.
- At high neutron energies.
- At all neutron energies (high radioactive samples).

BaF_2 signals are much wider than C_6D_6 → sizeable pile-up.

Some works regarding pile-up corrections:

- *E. Mendoza et al., NIMA 768, 55 (2014).*
- *C. Guerrero et al., NIMA 777, 63 (2015).*

$^{238}U(n,\gamma)$ @ n_TOF-EAR1 (2024)



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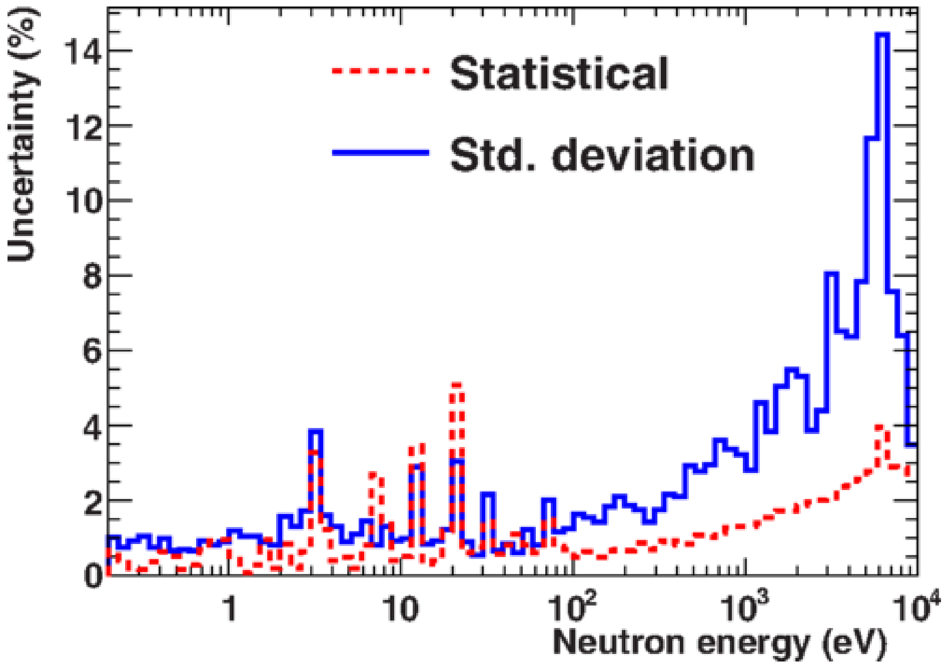

Uncertainties in a $^{241}Am(n,\gamma)$ measurement performed with the TAC. Figure from E. Mendoza et al., PRC 97, 054616 (2018).

Possible biases:
- In the strongest resonances.
- Increasing with the neutron energy.

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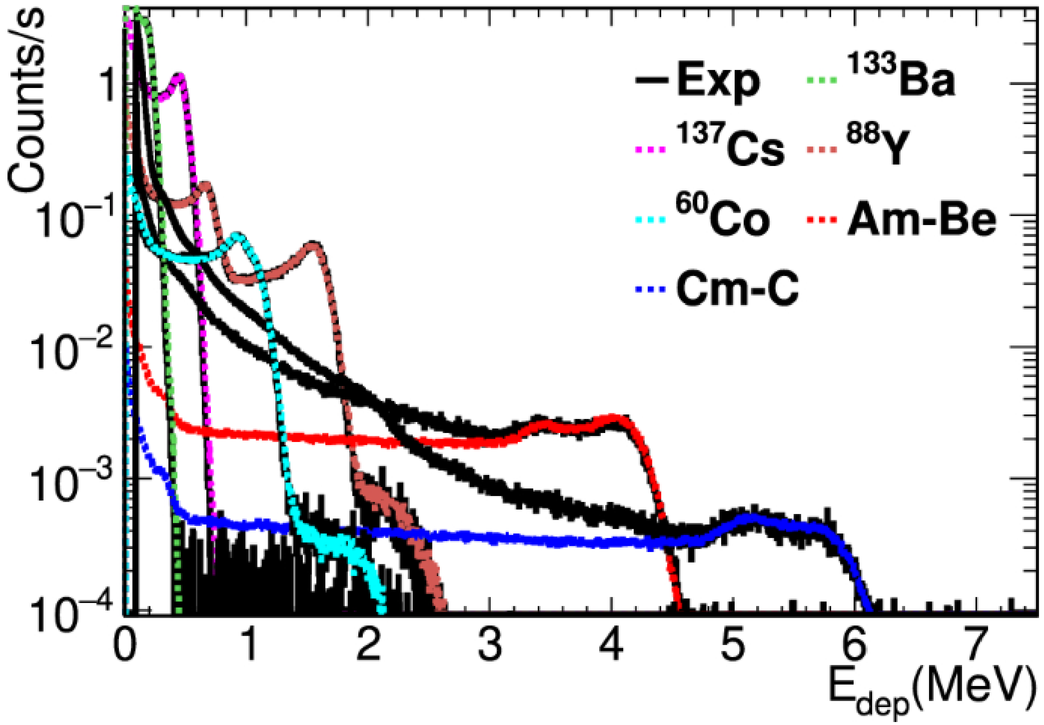
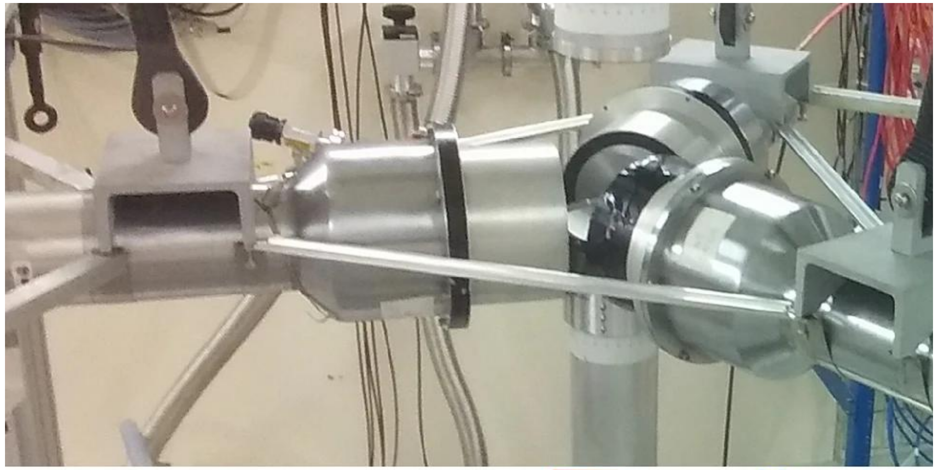
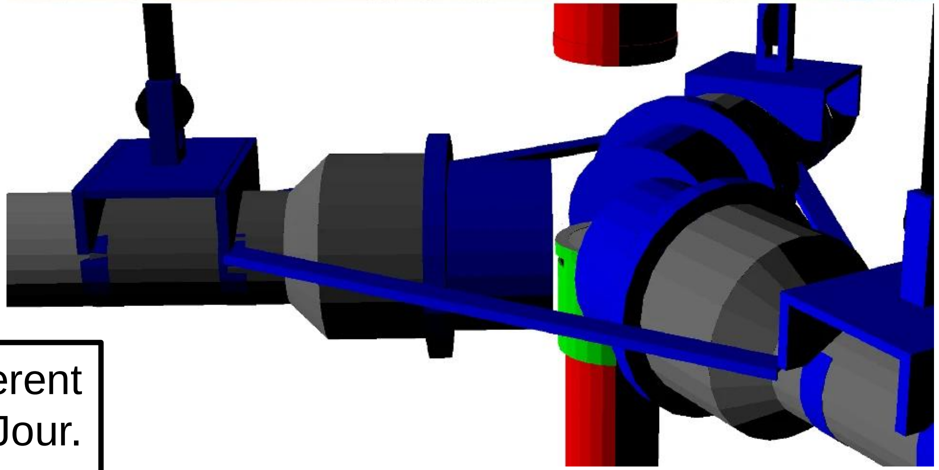
Calibrations

Energy calibrations are performed with calibration sources.

The gain of the detectors may vary along time → gain monitoring.







Experimental setup (right) and amplitude spectra when measuring with different calibration γ-ray sources (left). Figures from V. Alcayne et al., Eur. Phys. Jour. 60, 246 (2024) → 246,248Cm(n,γ) measurement at n_TOF-EAR2.

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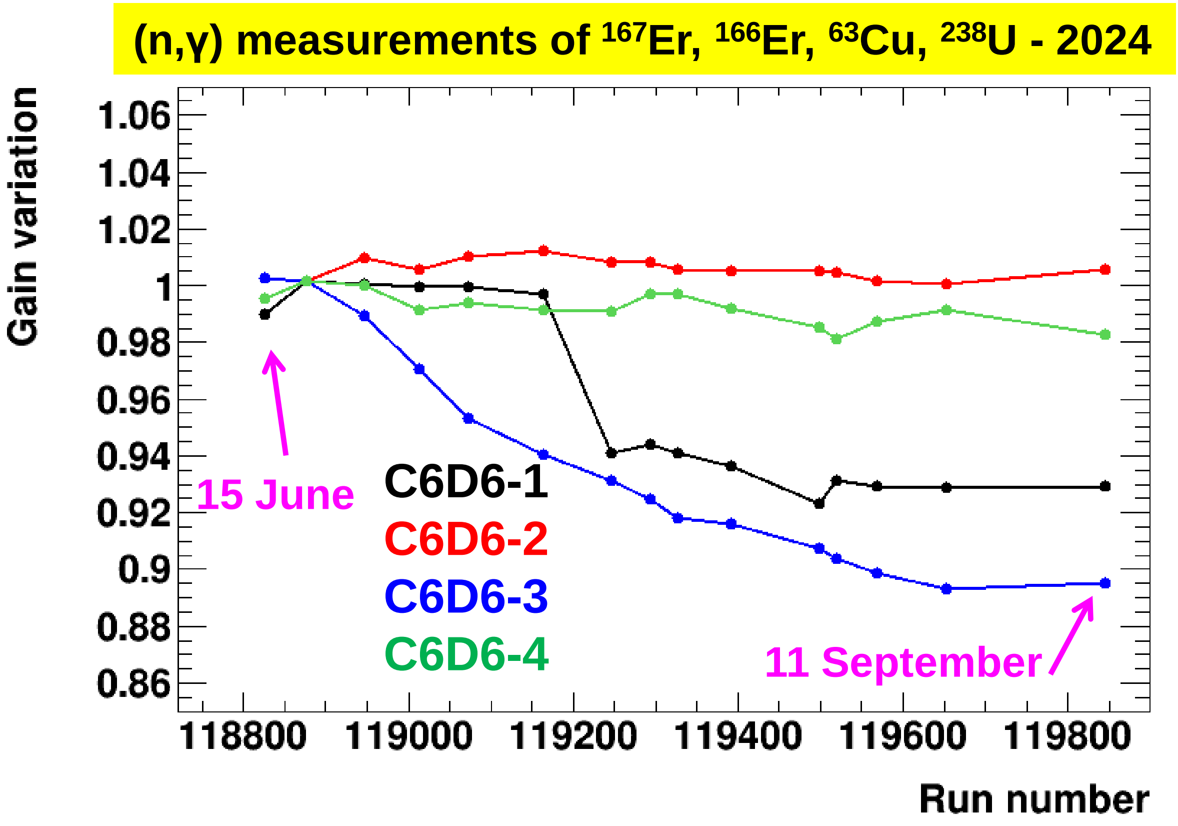

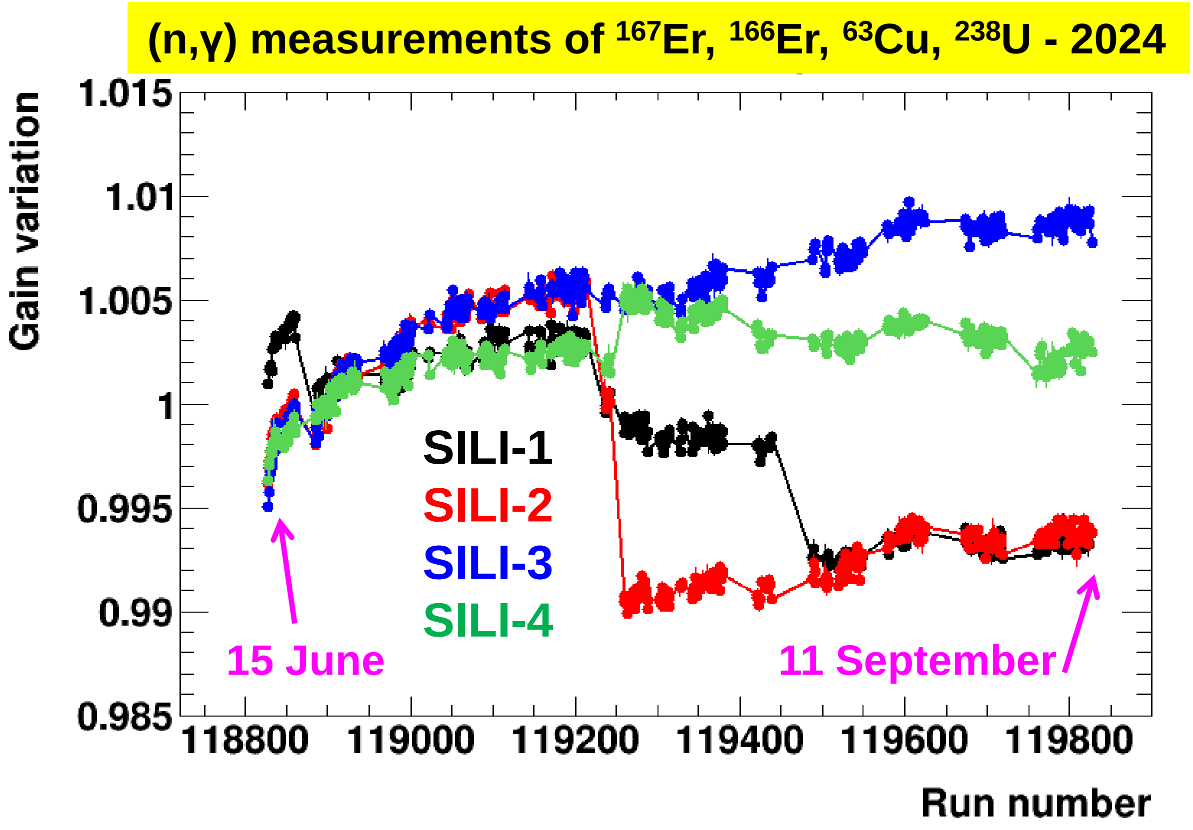

Variations in the gain of four C_6D_6 detectors (left) and four SiMon detectors (right) during 3 months of experimental campaign in 2024.

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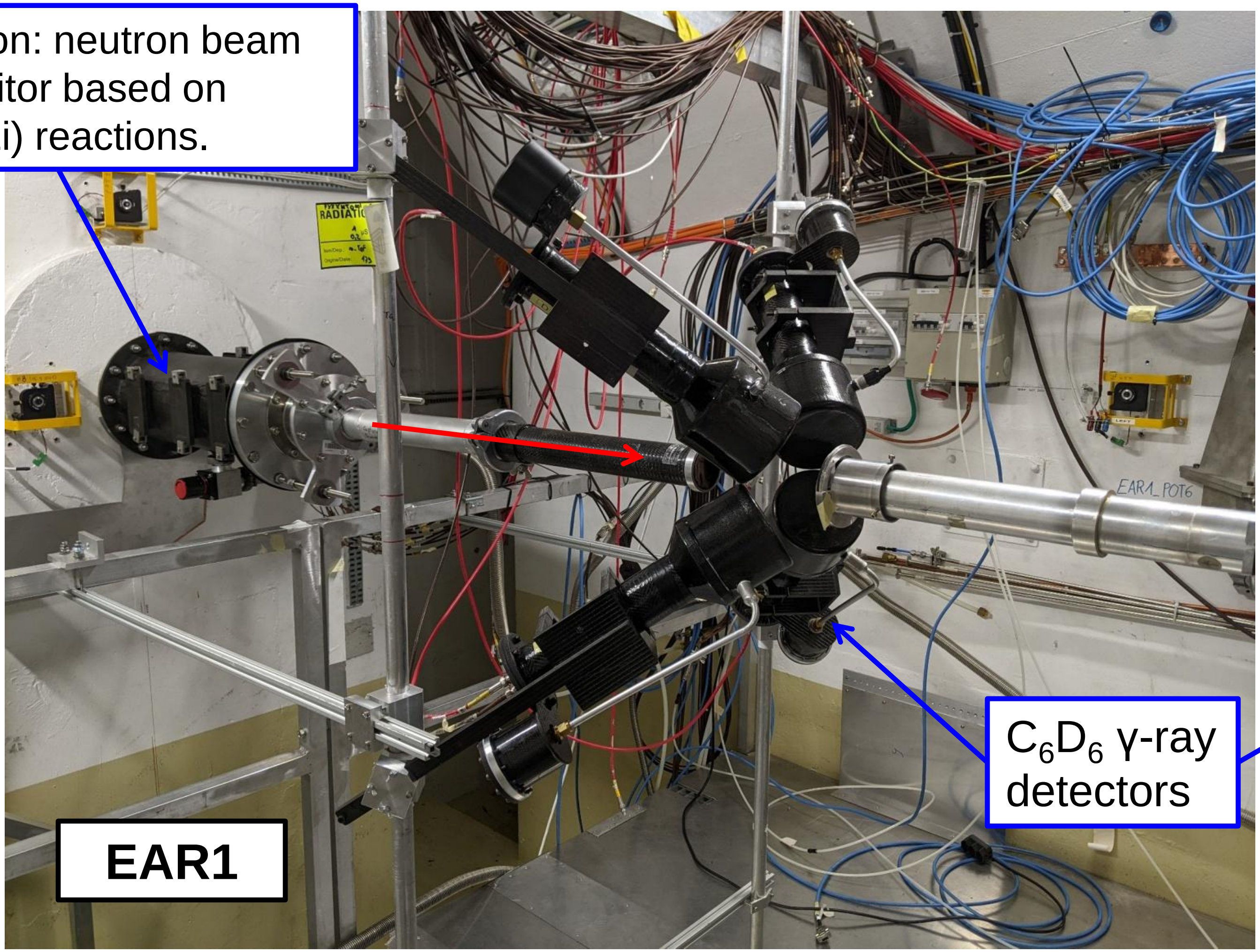
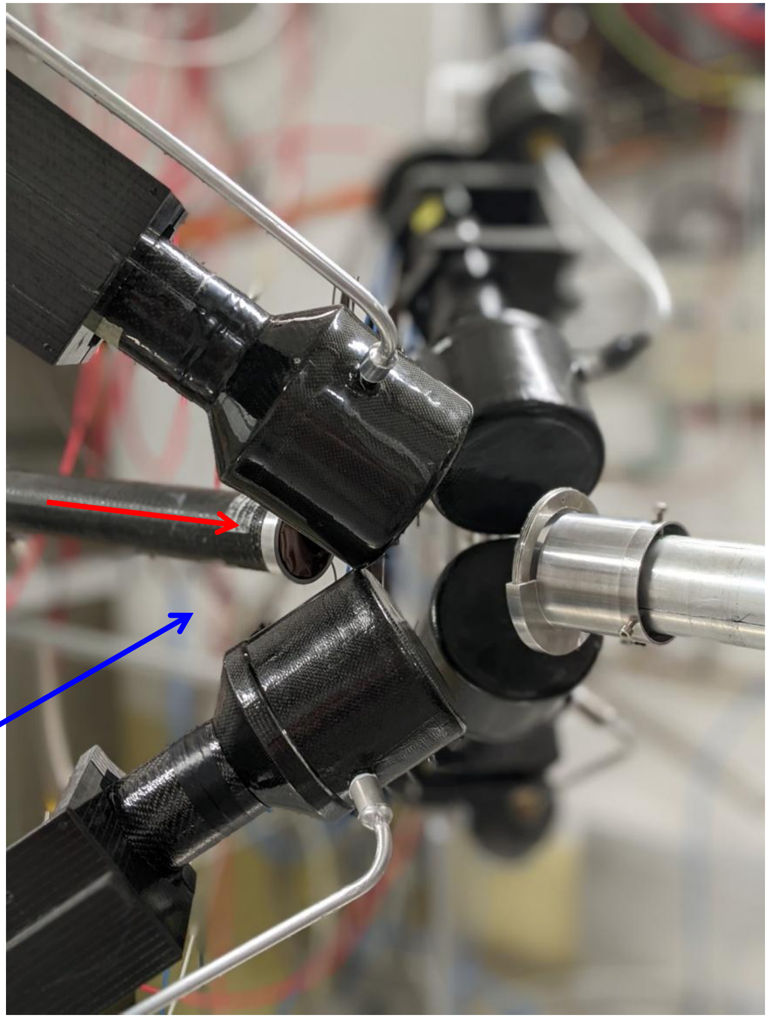
Detection systems





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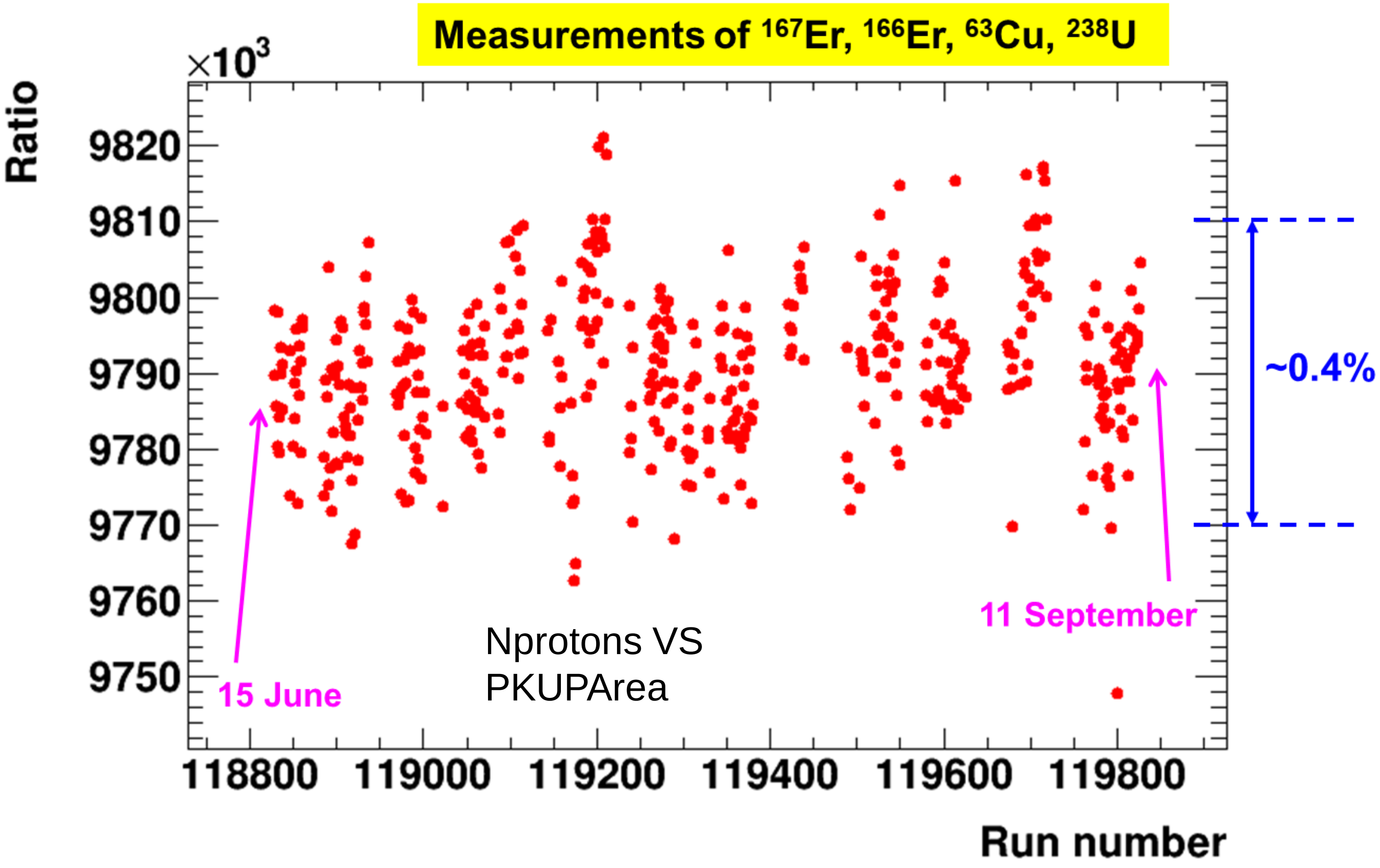
Consistency checks

After performing calibrations, several consistency checks are performed.
Example: ratios between beam monitors should be constant along time.

$$Y_{(n,\gamma)}(E_n) = \frac{C(E_n) - B(E_n)}{\varepsilon(E_n) \cdot \phi(E_n)}$$



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Background

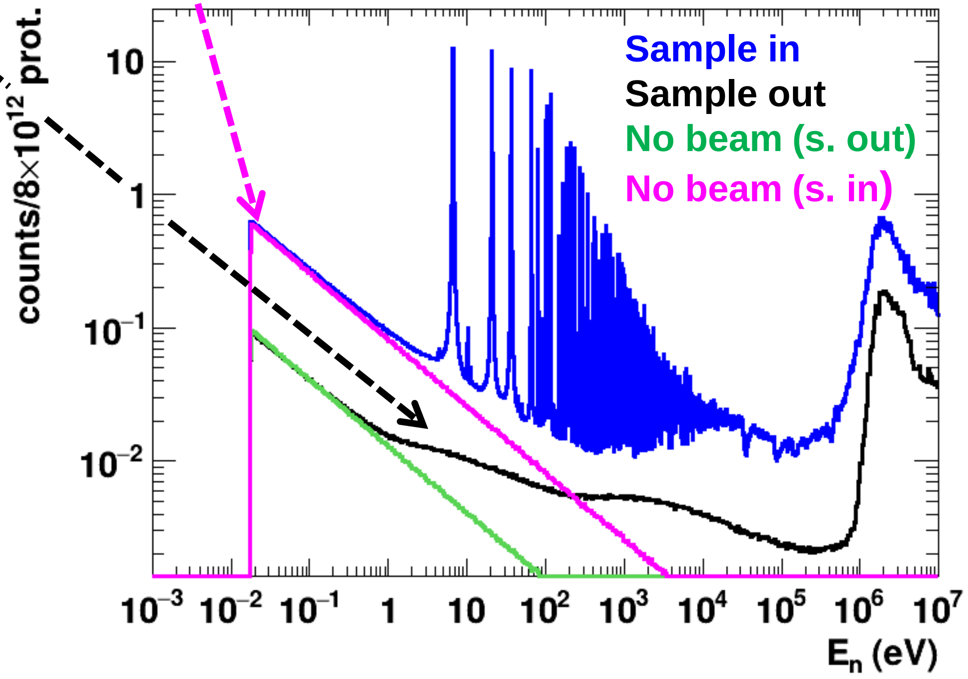
The calculation of the background is one of the most difficult tasks in neutron capture measurements.

$$Y_{(n,\gamma)}(E_n) = \frac{C(E_n) - B(E_n)}{\varepsilon(E_n) \cdot \phi(E_n)}$$

We can classify the background in different components:

1. Background not related with the neutron beam (ambient background + sample activity).
2. Background related with the neutron beam, excluding the interaction of the neutron beam with the sample.
3. Background related with the interaction of the neutron beam with the sample.

$^{238}U(n,\gamma)$ @ n_TOF-EAR1 (2024)



Backgrounds (1) and (2) are obtained from dedicated measurements.

Background (3) is more difficult to obtain.

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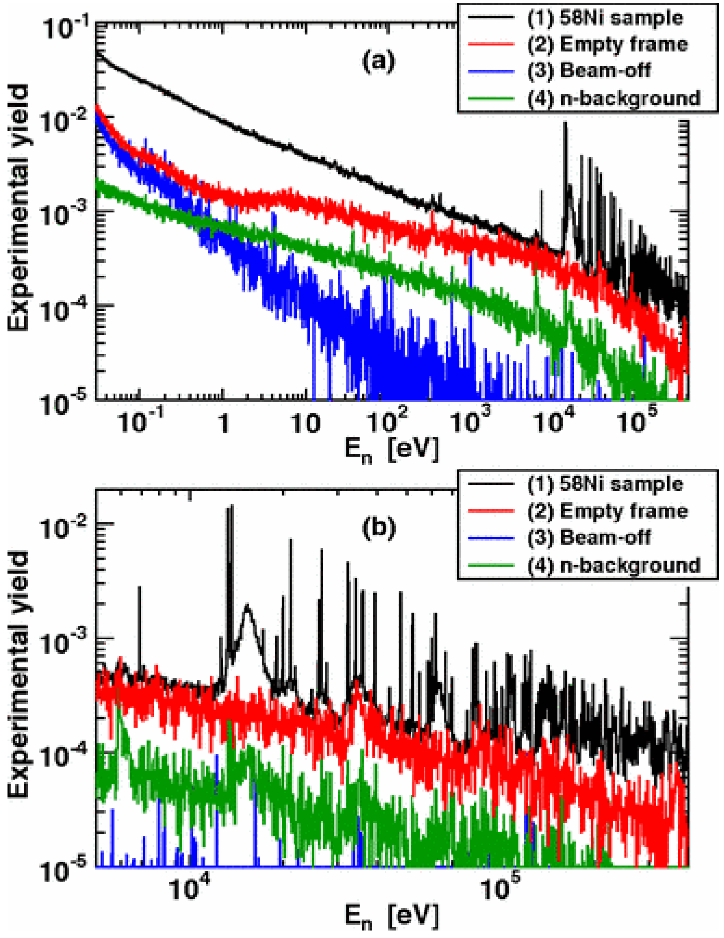
2. Background related with the neutron beam, excluding the interaction of the neutron beam with the sample.
3. Background related with the interaction of the neutron beam with the sample.

Backgrounds (1) and (2) are obtained from dedicated measurements.

Background (3) example: in the analysis of $^{58}Ni(n,\gamma)$ shown on the right this component has been obtained from MC calculations.

Sometimes background (3) is not taken much into account in the analysis …



$^{58}Ni(n,\gamma)$: P. Žugec et al. Phys. Rev. C 89, 014605 (2014).

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Background (3)

The relevance of background (3) is very case-dependent, and its origin may come from:

- In-beam γ-rays: relevant for heavy nuclei.
- Elastic scattered neutrons in the sample: more relevant for nuclei with large elastic to capture cross section ratios.
- Fission
- Inelastic channels (→ increasing threshold)
- Activation (→ MC calculations)
- Impurities (→ SAMMY analysis)

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Background (3) – In beam γ-rays and (n,n)

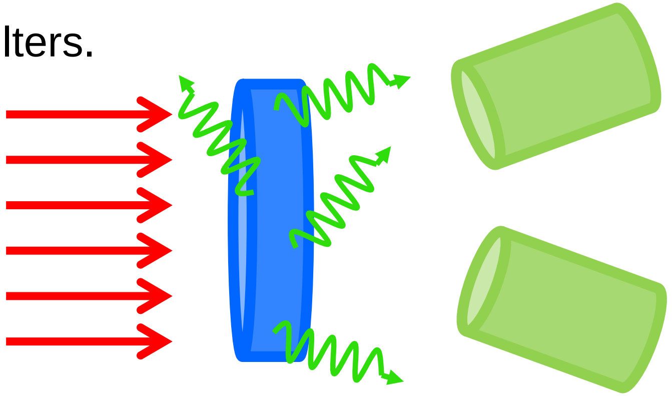
There are γ-rays coming along the beam together with the neutrons from the spallation target and surroundings that may be scattered in the sample → in beam γ-ray background.

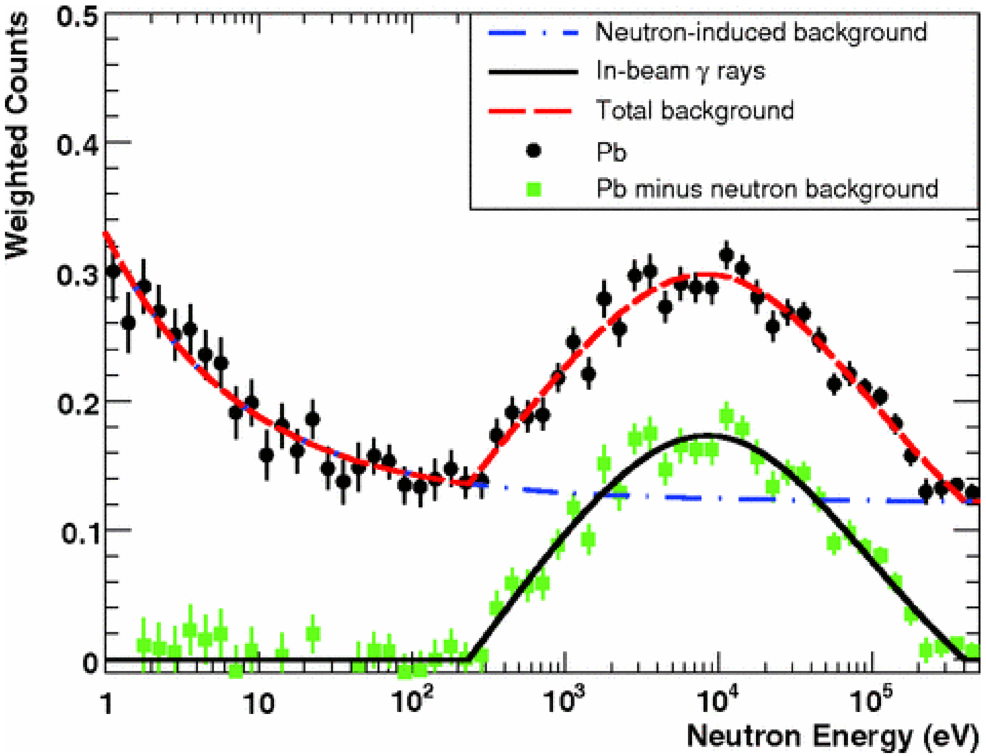
Elastic scattered neutrons: there is a *prompt* and a *delayed* contribution.

- Prompt: resonant structure.
- Delayed: energy-TOF relation is lost.

To determine these components:

- Measurements with a graphite and a Pb samples.
- Monte Carlo calculations.
- Measurements with filters.





$^{197}Au(n,\gamma)$ with C_6D_6: C. Lederer et al. Phys. Rev. C 83, 034608 (2011).

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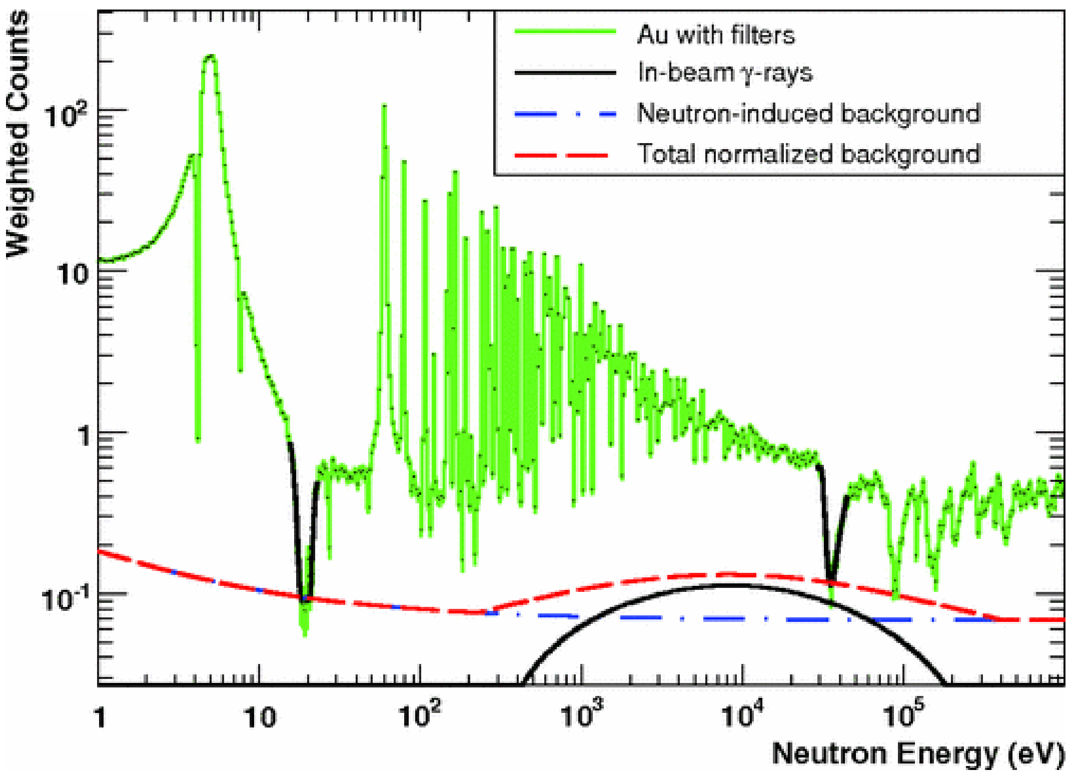

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Background (3) – In beam γ-rays and (n,n)

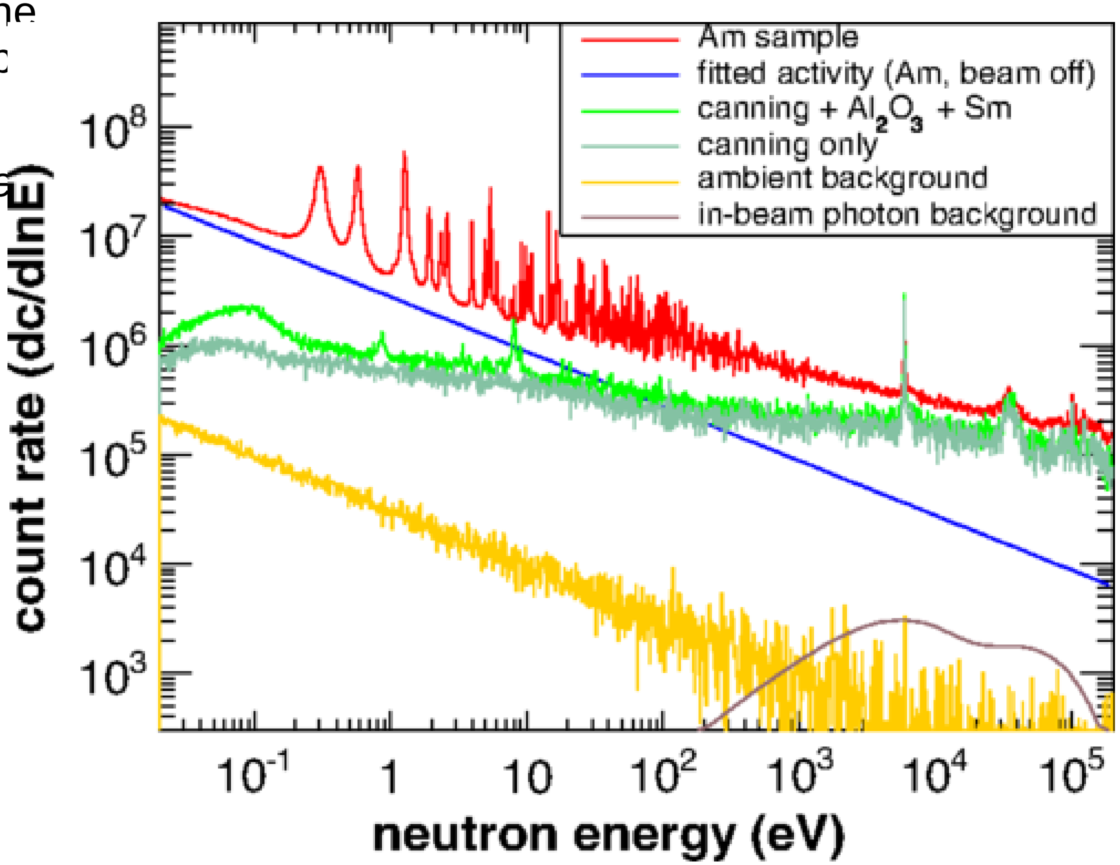
There are γ-rays coming along the beam together with the neutrons from the spallation target and surroundings that may b scattered in the sample → in beam γ-ray background.

Elastic scattered neutrons: there is a *prompt* and a *delaye* contribution.

- Prompt: resonant structure.
- Delayed: energy-TOF relation is lost.

To determine these components:

- Measurements with a graphite and a Pb samples.
- Monte Carlo calculations.
- Measurements with filters.



$^{241}Am(n,\gamma)$ with C_6D_6: K. Fraval et al. Phys. Rev. C 89, 044609 (2014).

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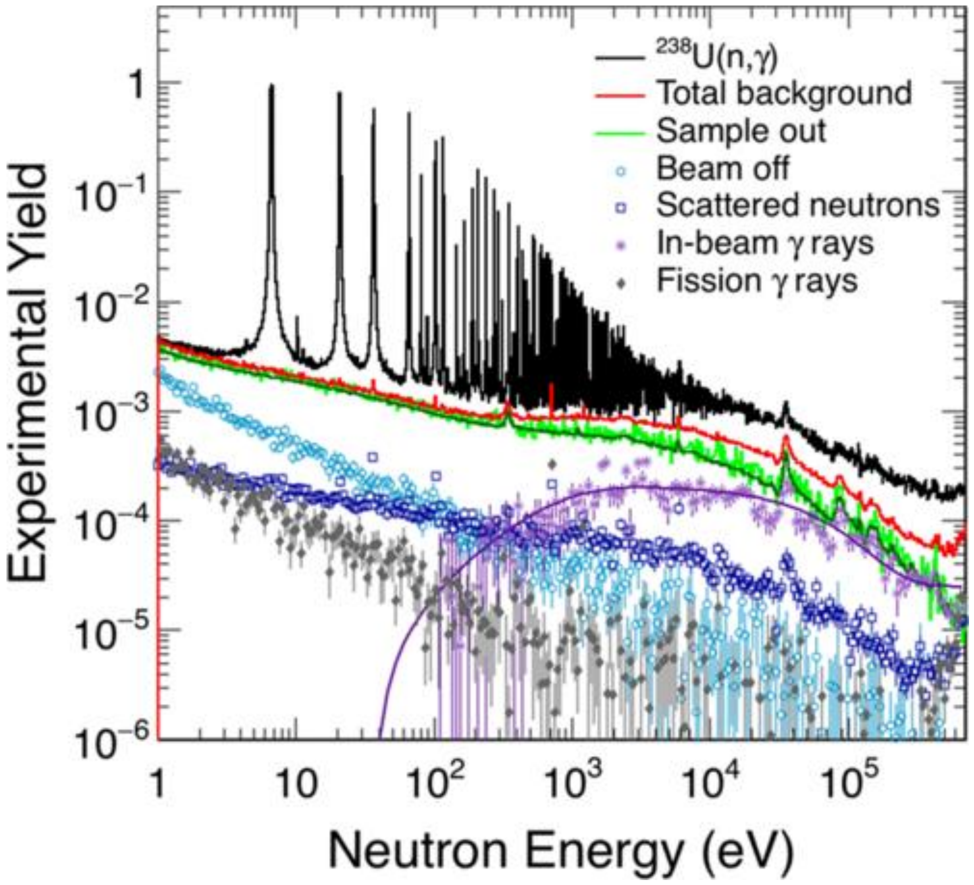

^{238}U(n,γ) with C_6D_6: F. Mingrone et al. Phys. Rev. C 95, 034604 (2017).

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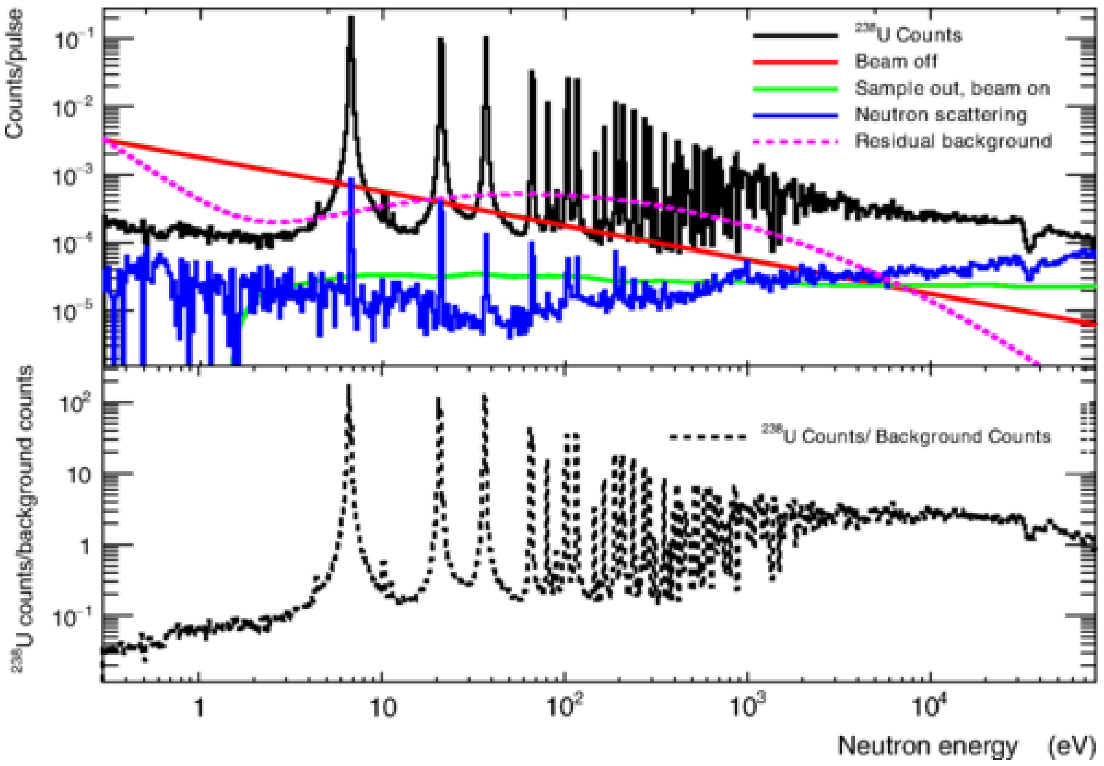

^{238}U(n,γ) with the TAC: T. Wright et al. Phys. Rev. C 96, 064601(2017).

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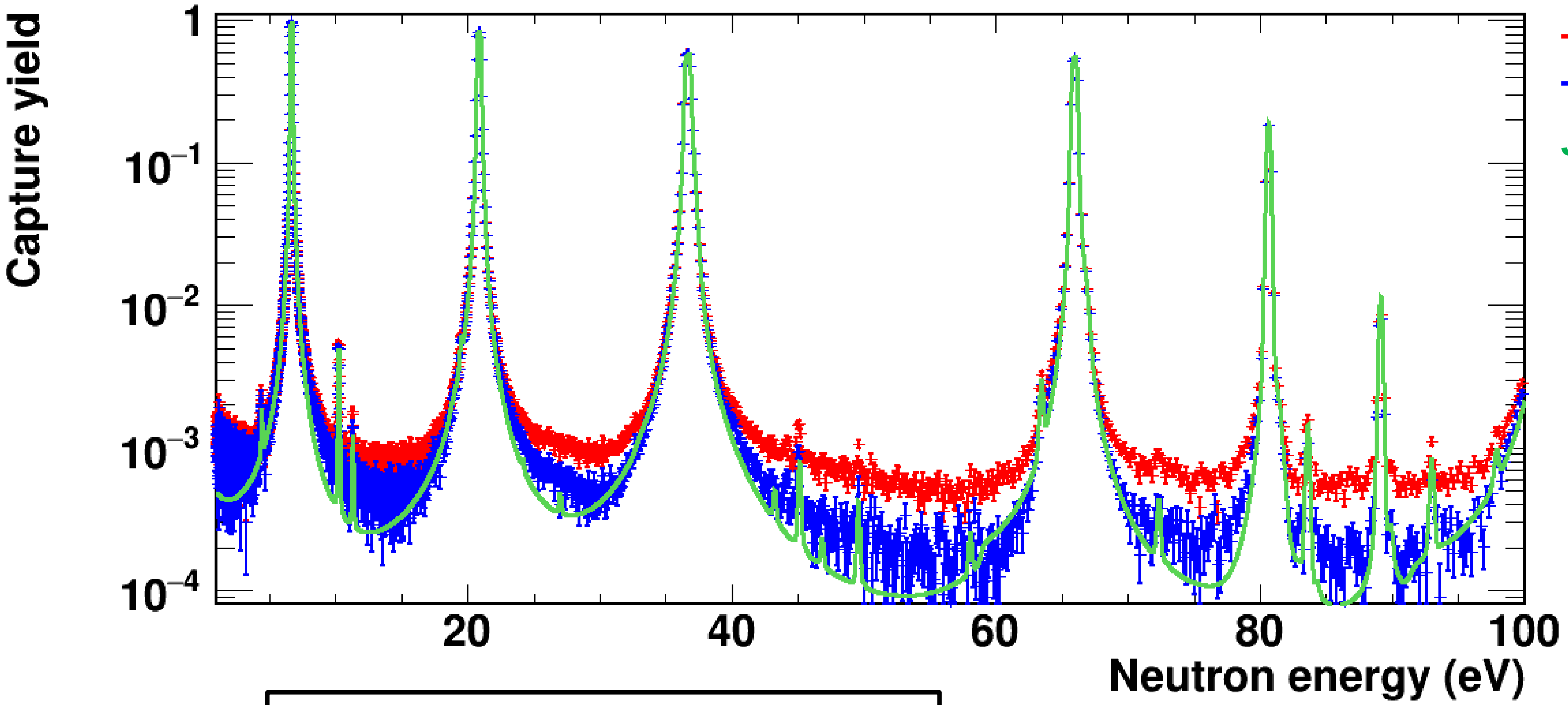

TAC – no *residual* bkg.
TAC – with *residual* bkg.
JEFF-3.3

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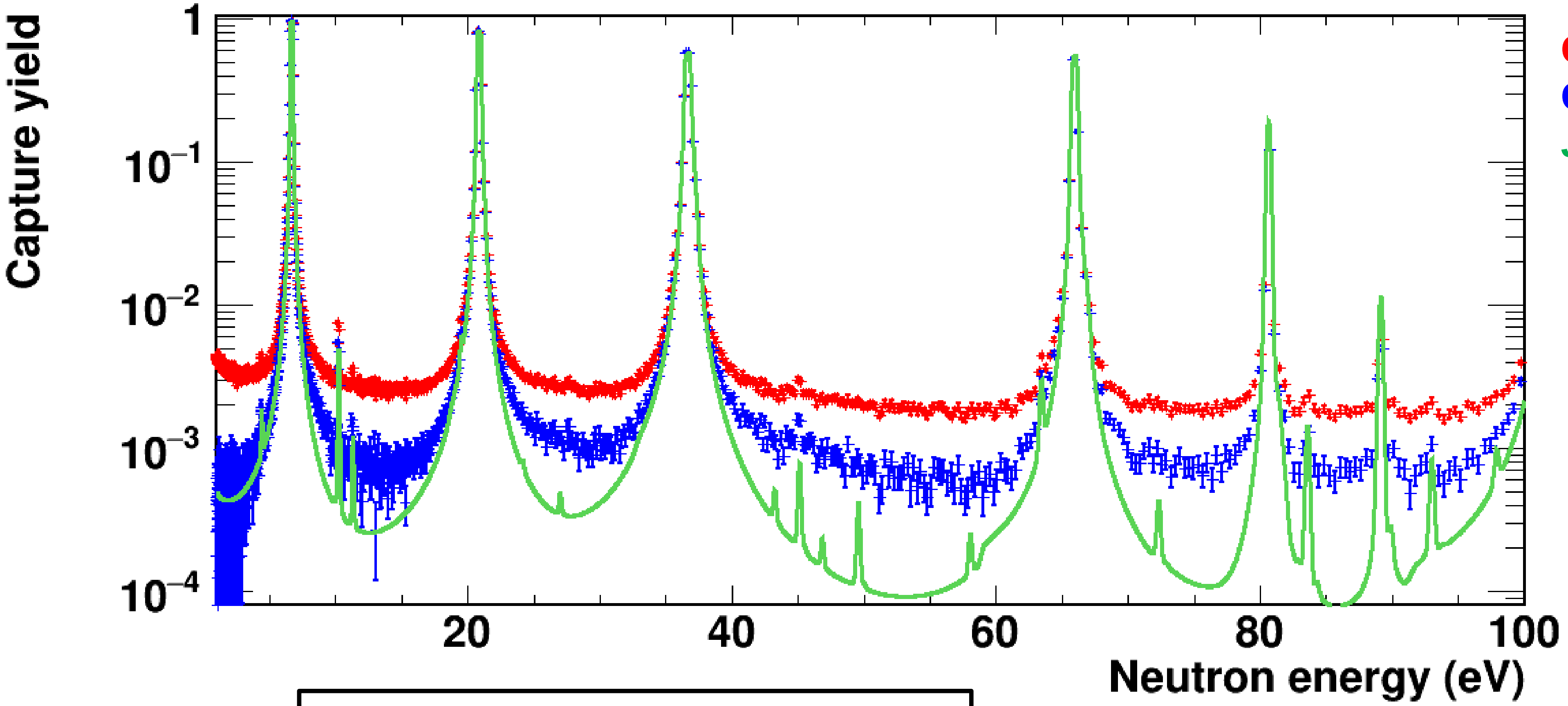

C_6D_6 – no *residual* bkg.
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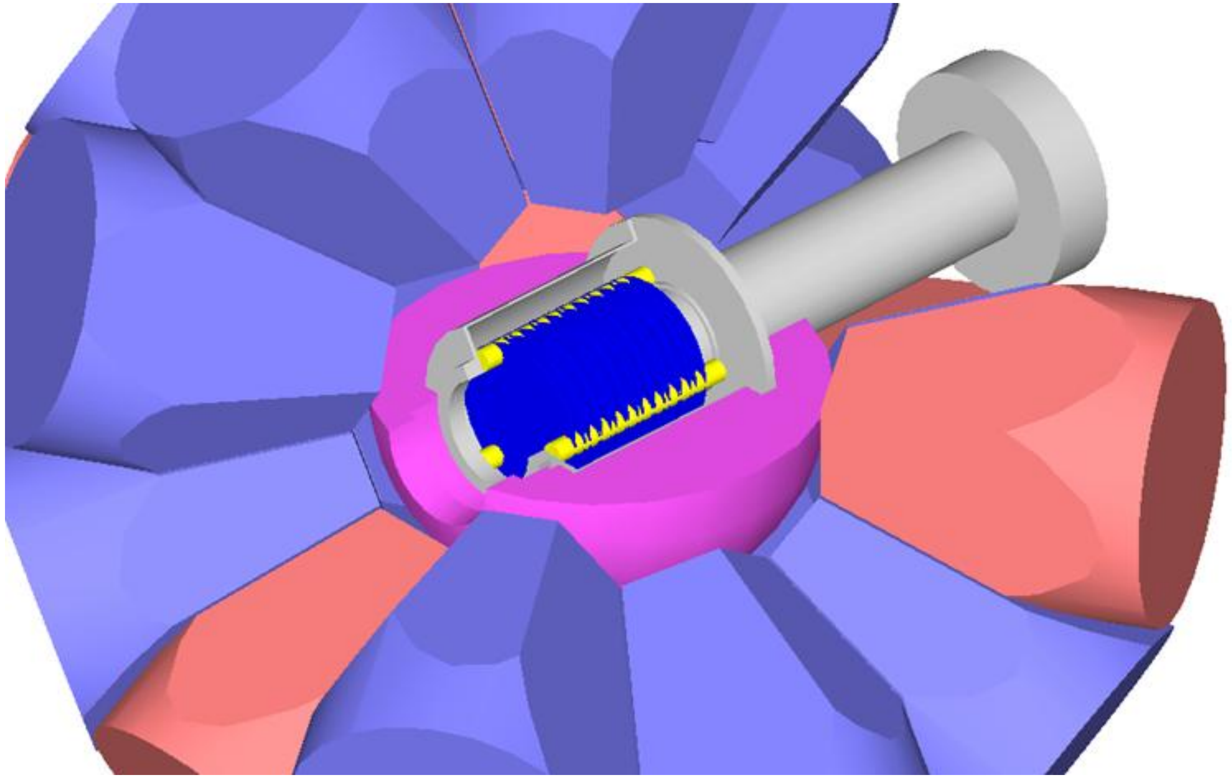

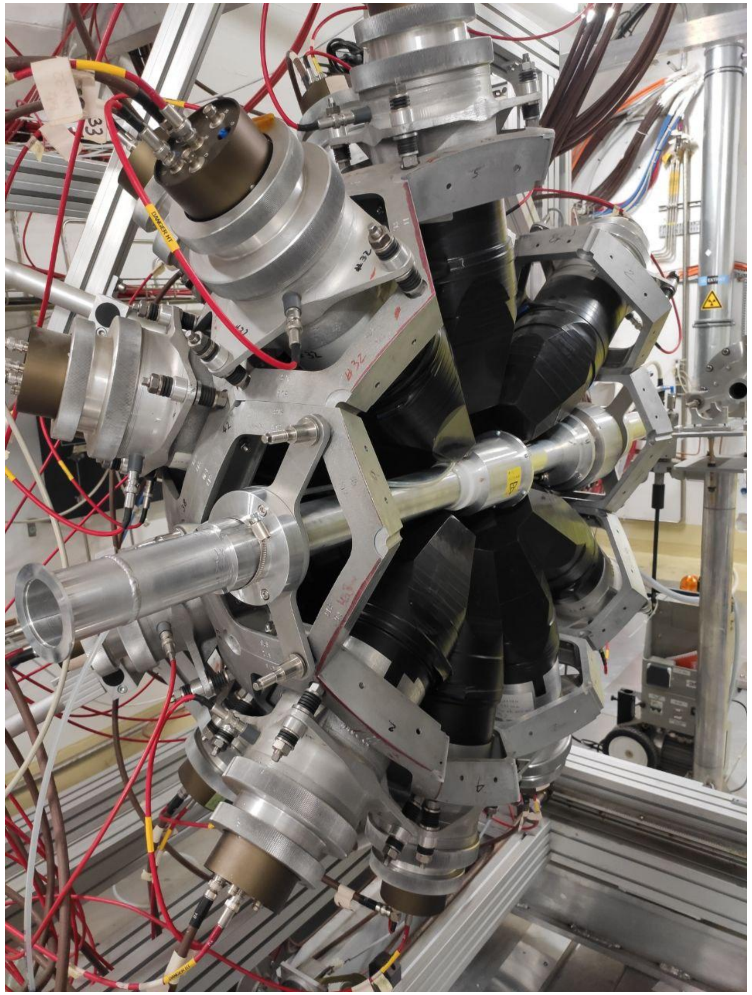

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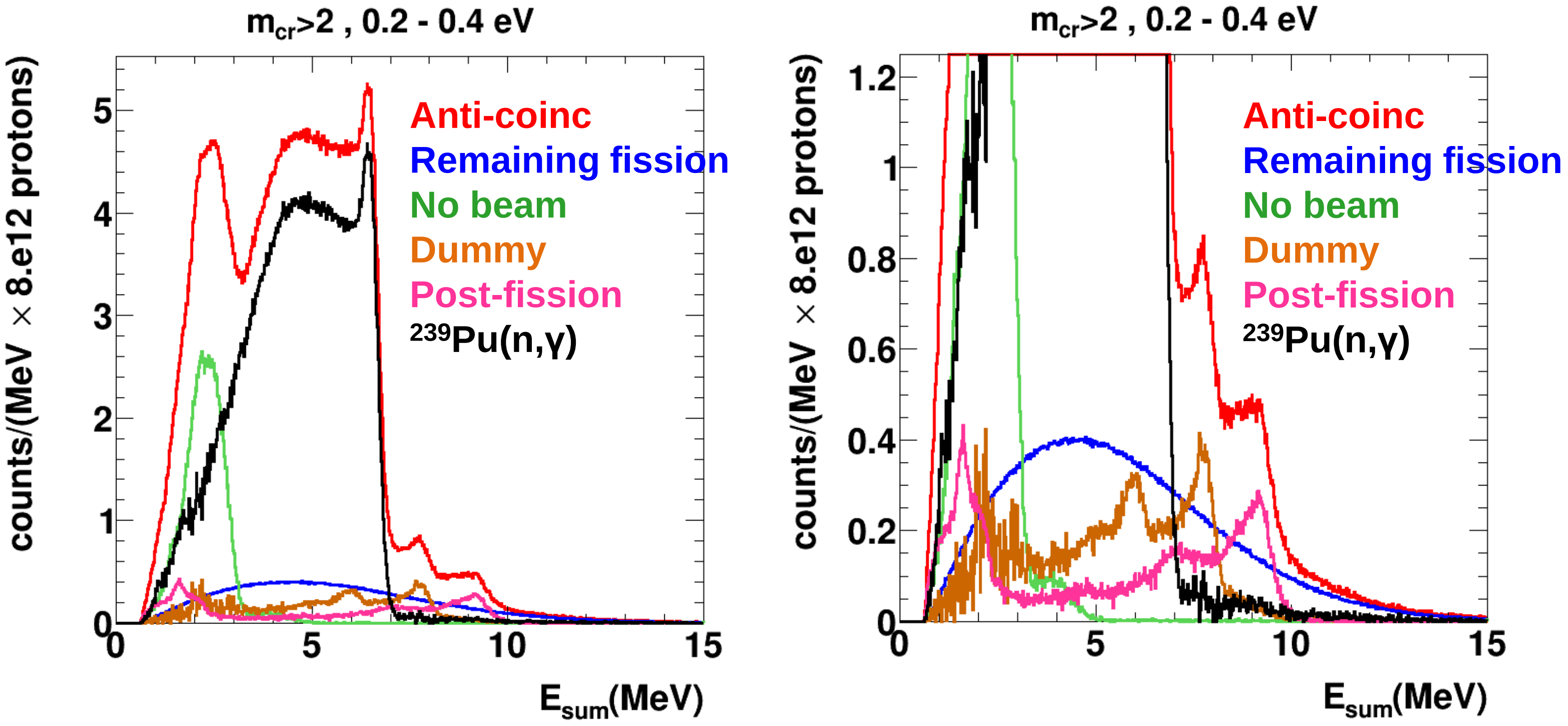
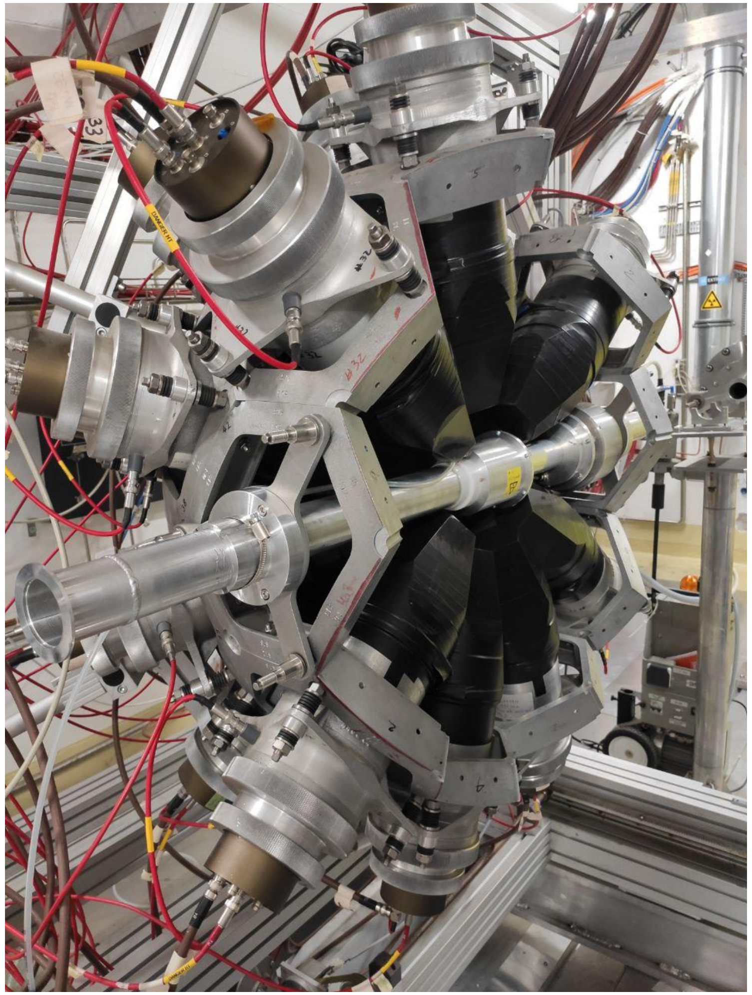
^{239}Pu(n,γ) measurement @ n_TOF-EAR1 (2022)





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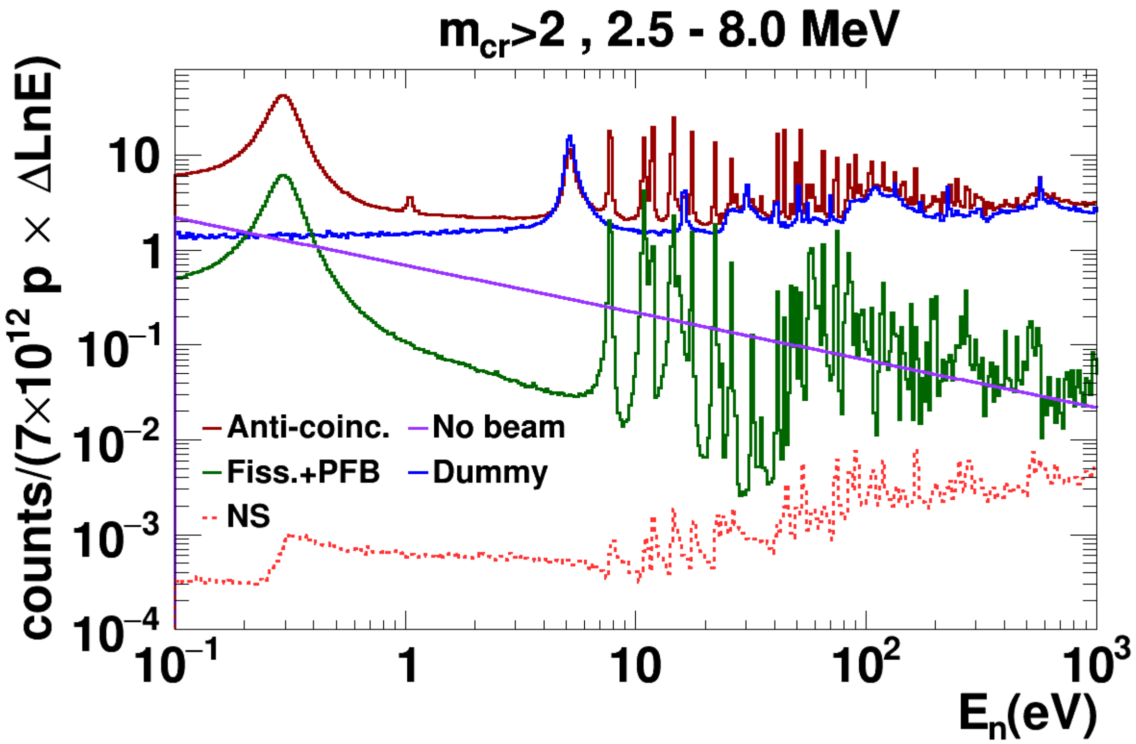
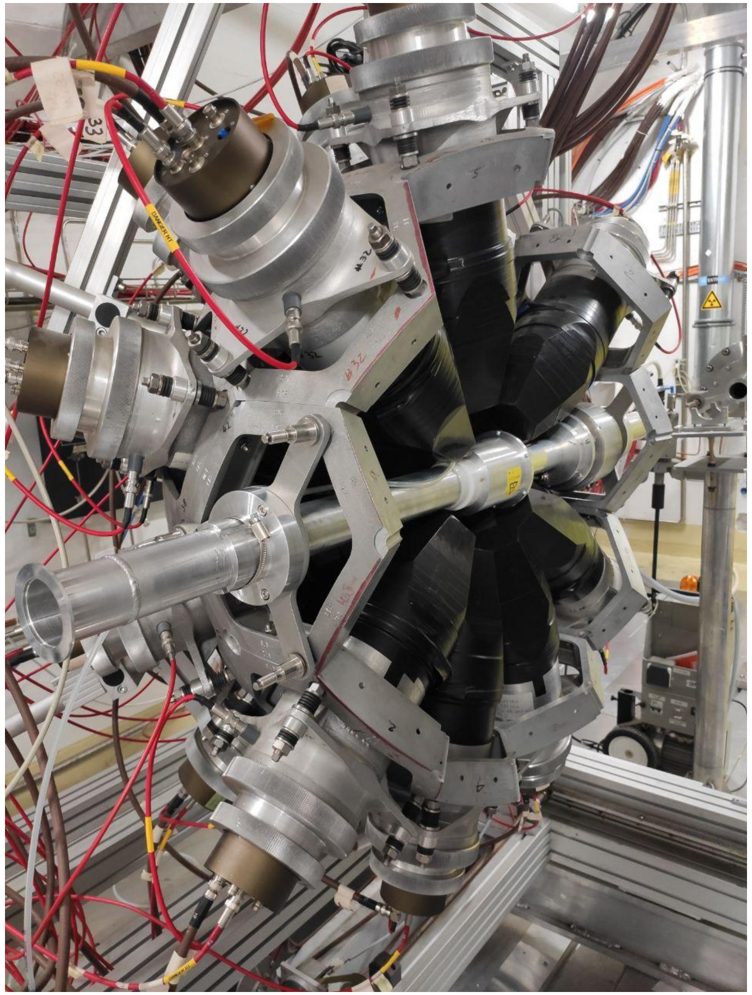
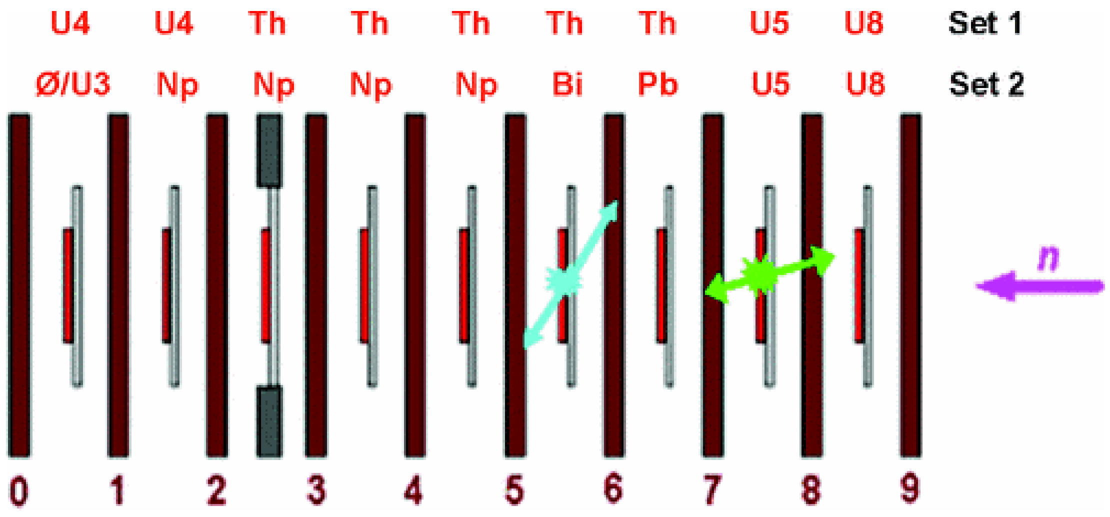




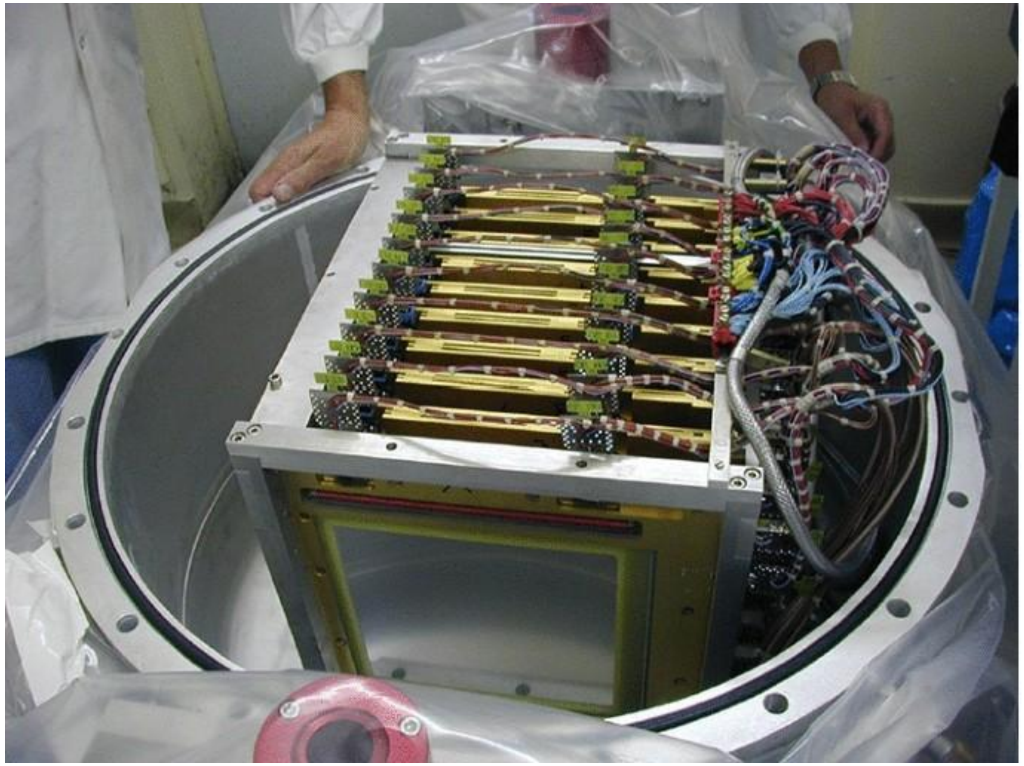
Incident neutrons

(n,f) measurements at n_TOF → cross section ratios.

$$Y_{(n,\gamma)}(E_n) = \frac{C(E_n) - B(E_n)}{\varepsilon(E_n) \cdot \phi(E_n)}$$



^{234}U(n,f) and ^{237}Np(n,f) with PPAC:
C. Paradela et al. Phys. Rev. C 82, 034601(2010).



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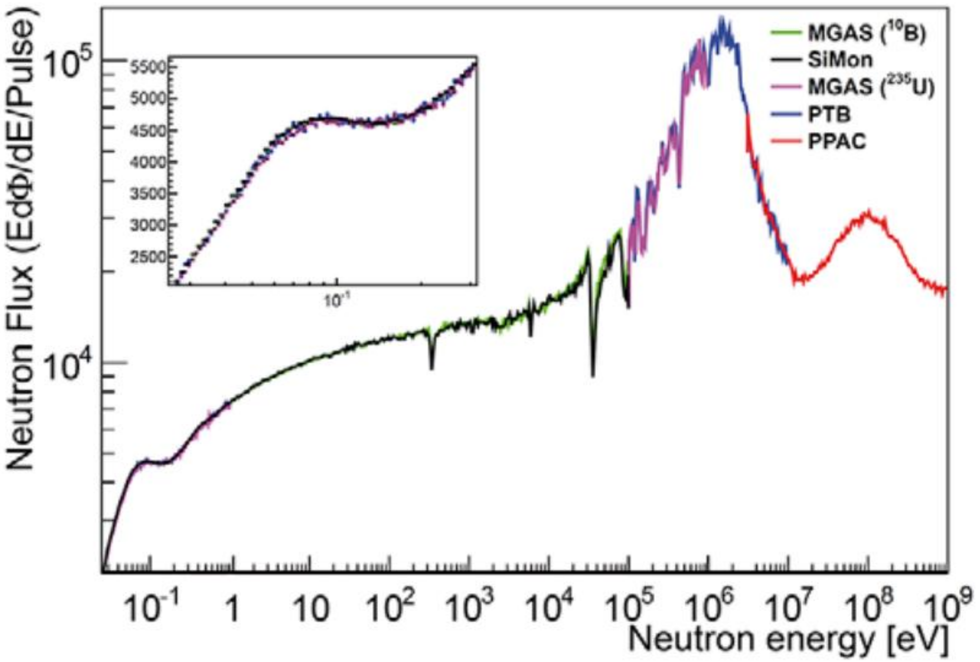
Incident neutrons

(n,γ) measurements at n_TOF → evaluated neutron fluence/flux.

Detectors based on ^{6}Li(n,t), ^{10}B(n,α) and ^{235}U(n,f) reactions.

$$Y_{(n,\gamma)}(E_n) = \frac{C(E_n) - B(E_n)}{\varepsilon(E_n) \cdot \phi(E_n)}$$



M. Barbagallo et al., Eur. Phys. Jour. A 49, 156 (2013).

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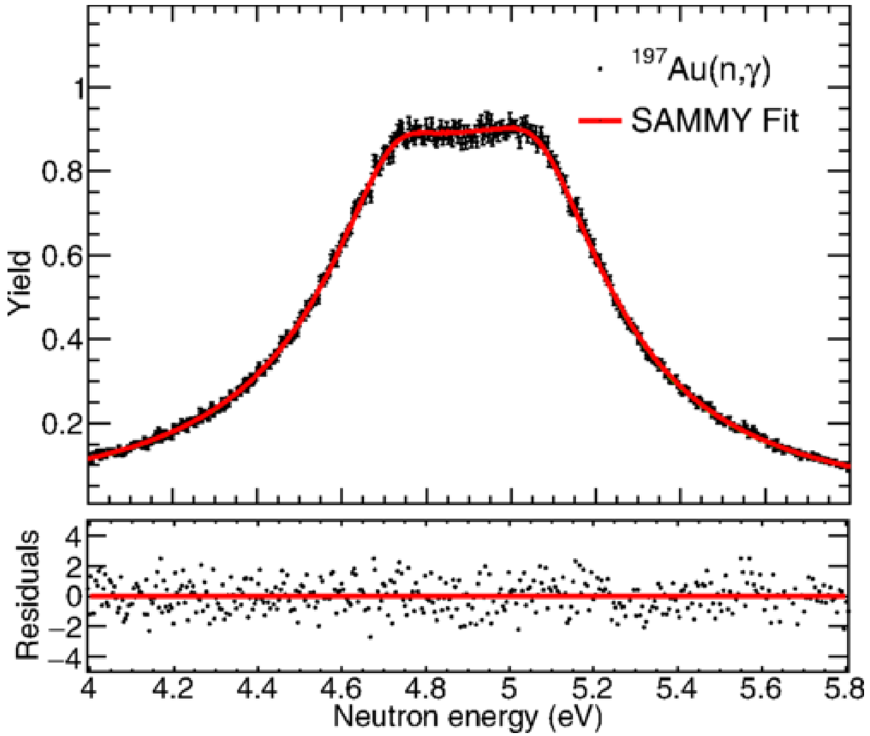

^{242}Pu(n,γ) with C_6D_6: J. Lerendegui et al. Phys. Rev. C 97, 024605 (2018).

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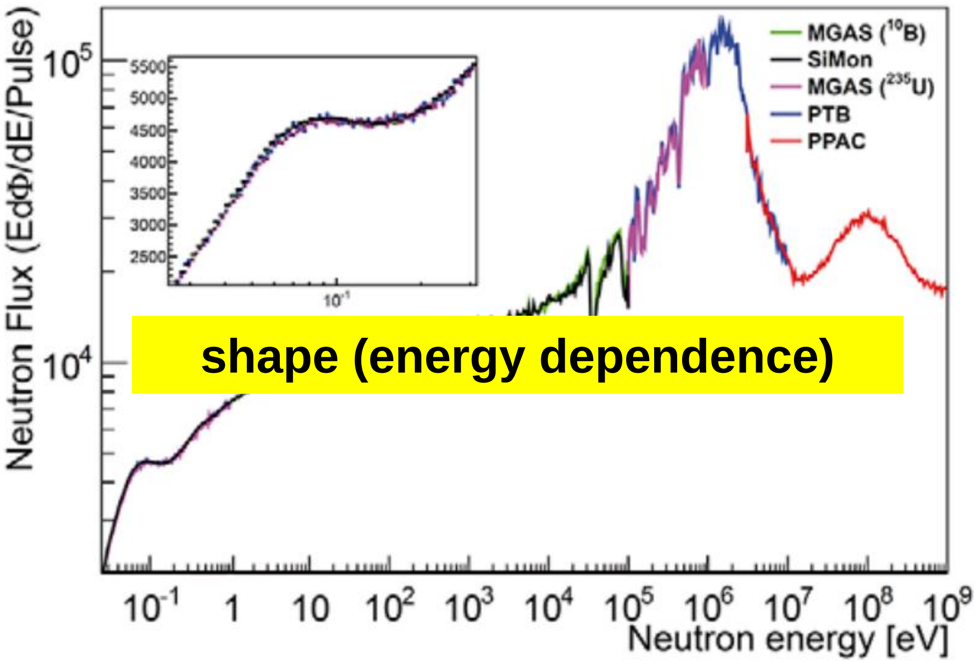

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M. Barbagallo et al., Eur. Phys. Jour. A 49, 156 (2013).

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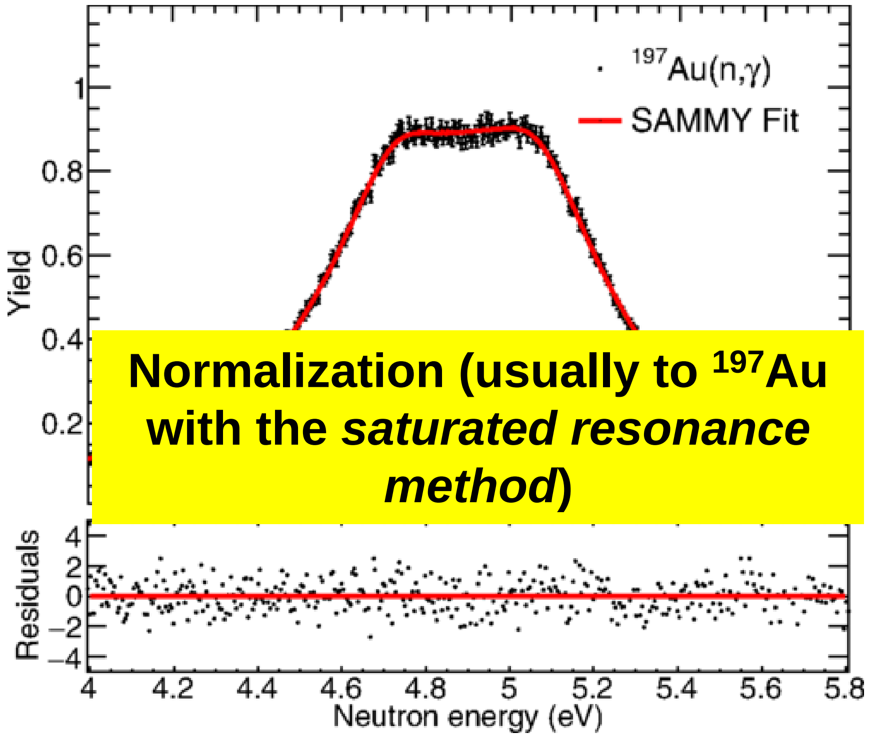

Normalization (usually to ^{197}Au with the *saturated resonance method*)

^{242}Pu(n,γ) with C_6D_6: J. Lerendegui et al. Phys. Rev. C 97, 024605 (2018).

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Detection efficiency

The (n,γ) detection efficiency may vary from one resonance to other.

To avoid this:

- **C_6D_6:** Total Energy Detection technique + Pulse Height Weighting Technique.
    - M. Moxon et al., Nucl. Instrum. Methods 24, 445 (1963).
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→ Idea: replace $\boldsymbol{\varepsilon(E_n)}$ by other variable (estimator) which does not depend (i.e. has a small dependency) on the (n,γ) cascade.

- **TAC**: measurements of heavy nuclei, with large level densities → (n,γ) cascades are not expected to vary much from one resonance to other.

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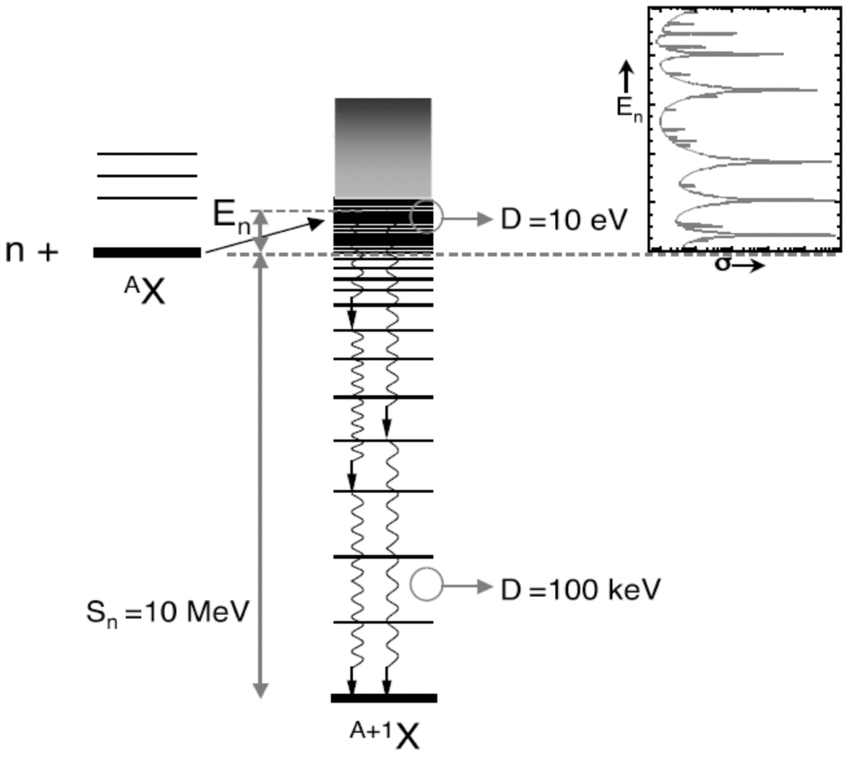

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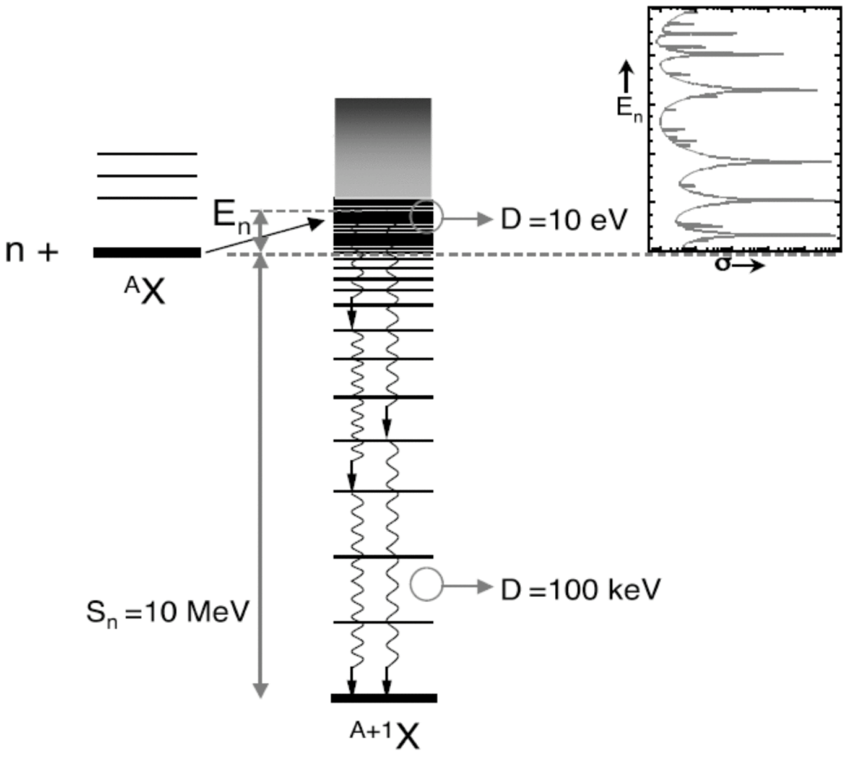

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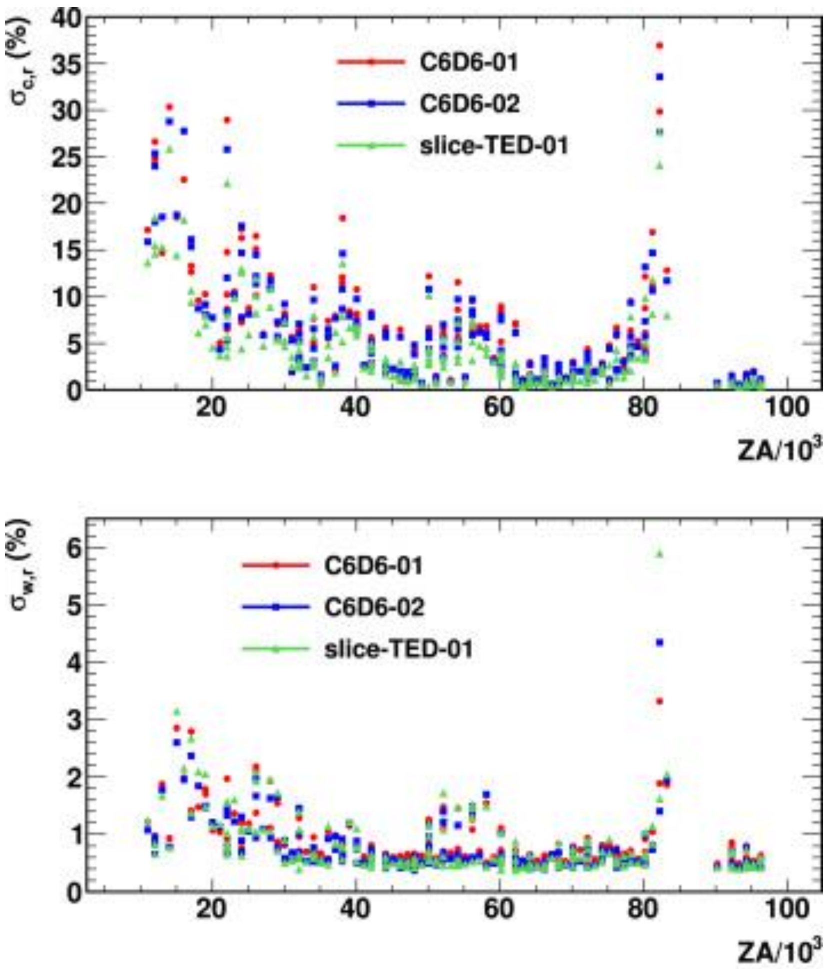

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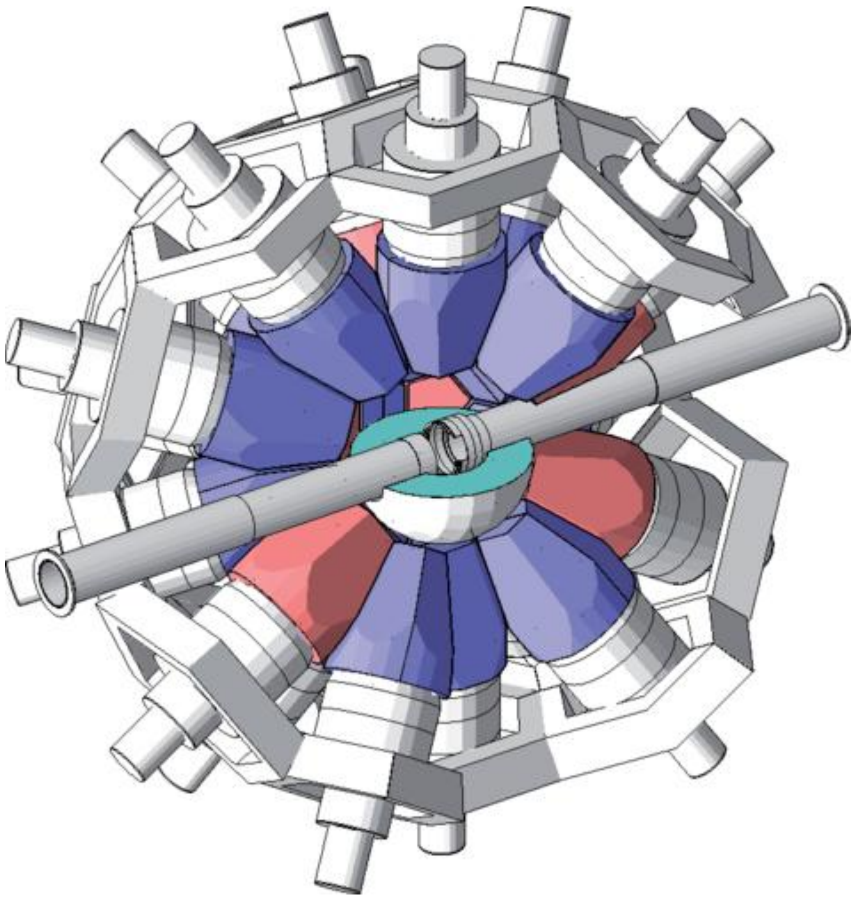

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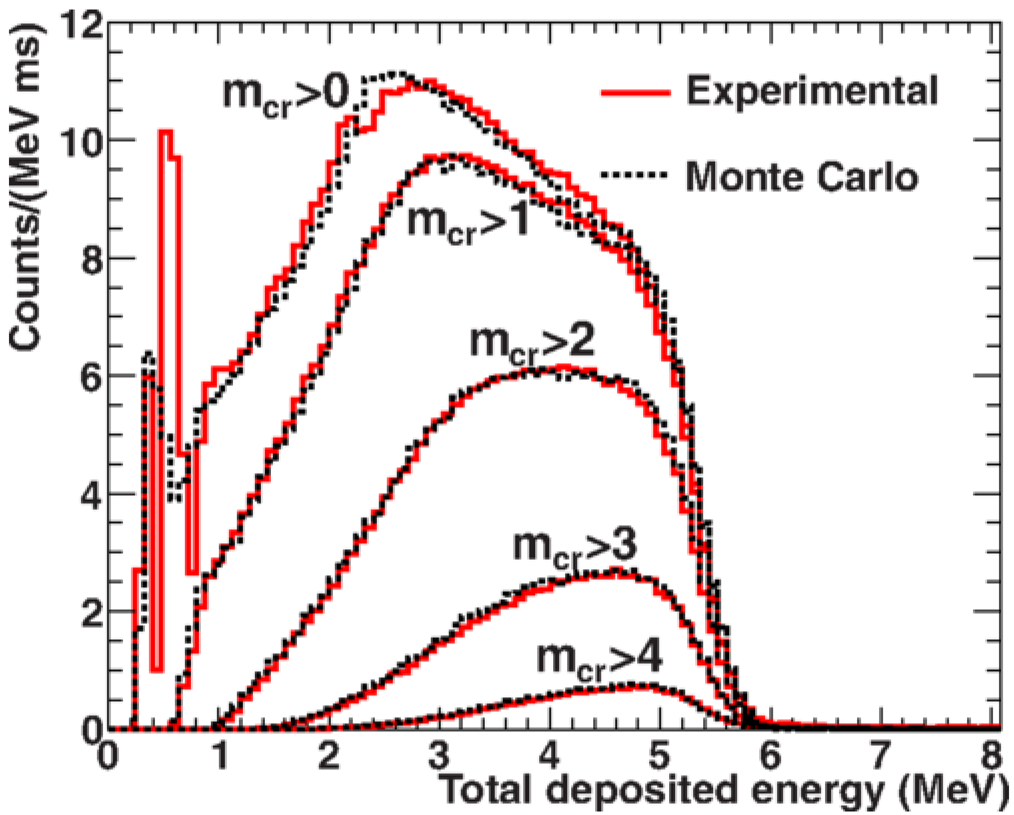

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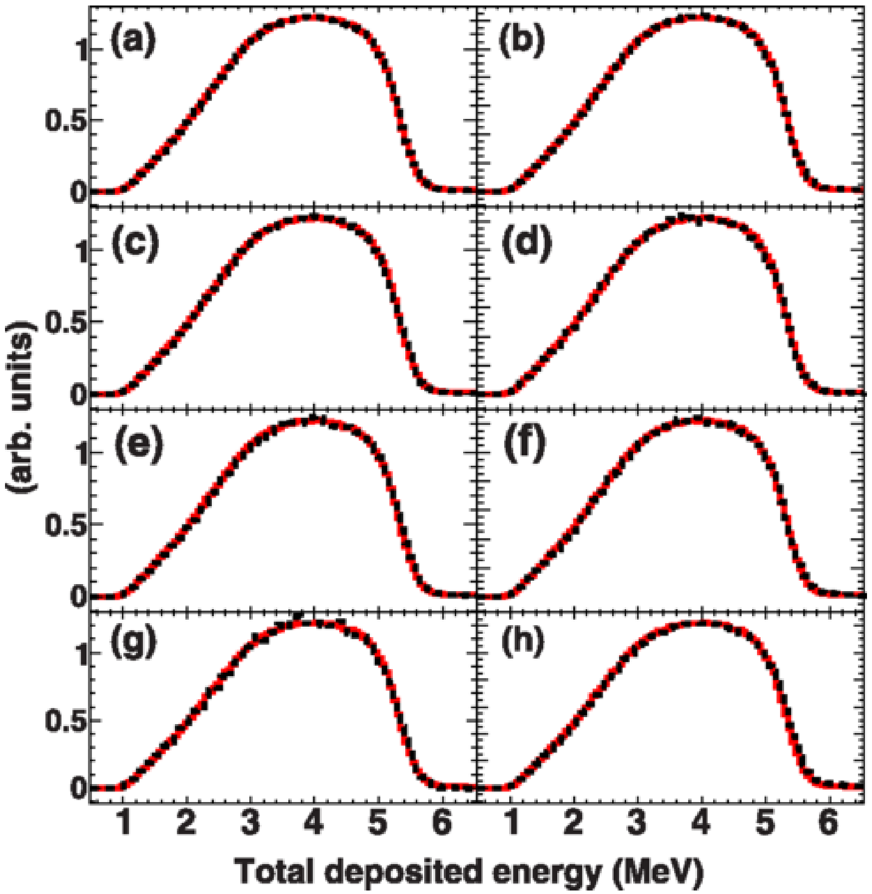

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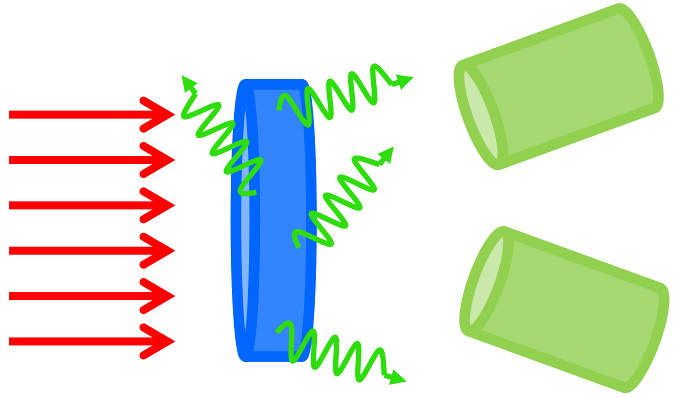
Neutron capture measurements

The experimental capture yield is usually calculated from a expression similar to this:

$$Y_{(n,\gamma)}(E_n) = \frac{C(E_n) - B(E_n)}{\varepsilon \cdot \phi(E_n)}$$



where:

- $Y_{(n,\gamma)}$ is the capture yield.
- E_n is the neutron energy.
- $C(E_n)$ are the number of counts in the detector [per unit something].
- $B(E_n)$ is the background.
- $\varepsilon(E_n)$ is the detection efficiency.
- $\phi(E_n)$ are the number of neutrons impinging in the sample [per unit something].

Finally, I will talk about two issues that do not appear explicitly in the previous equation:

- Resolution function
- Inhomogeneities

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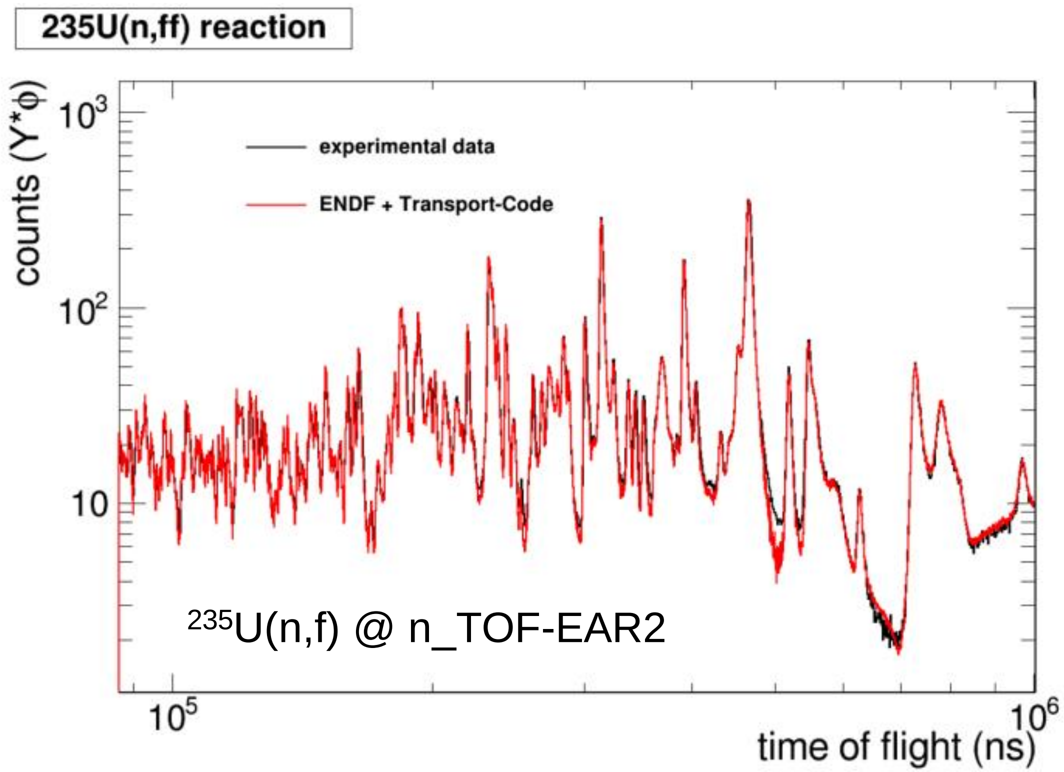
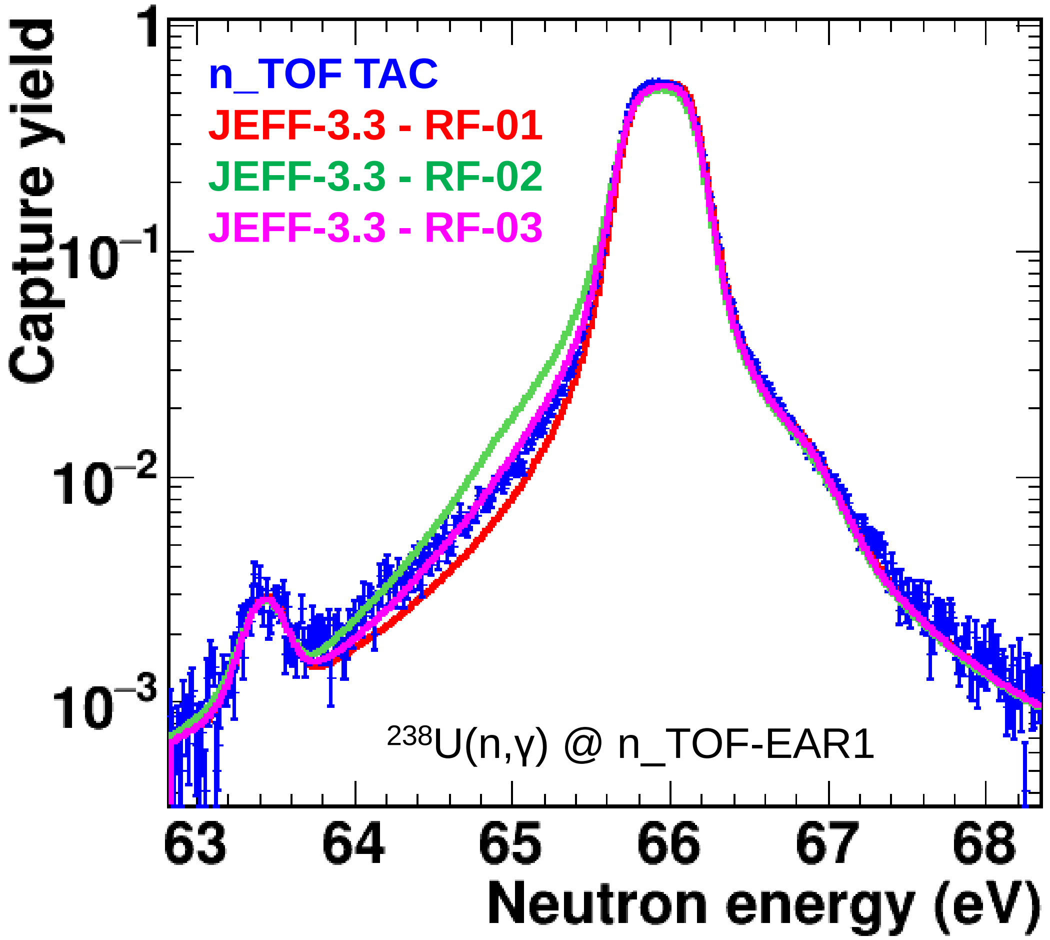
Resolution function

The n_TOF resolution function (RF) is obtained from MC calculations

The RF is validated with experimental data.

But there are some limitations …





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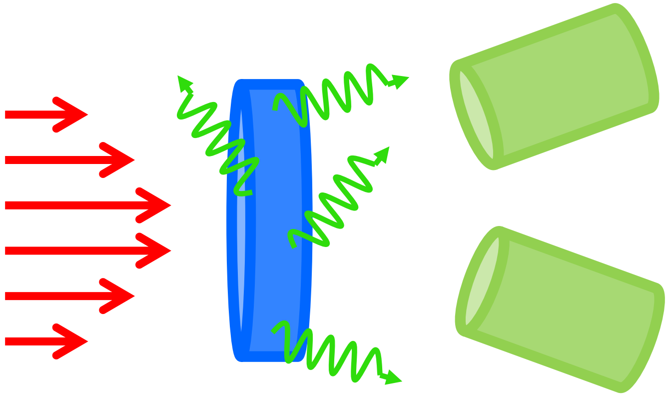
Inhomogeneities

Sample inhomogeneities may appear when measuring oxides.

Sample inhomogeneities may have a sizeable impact in the measured yield.

We may have two types of inhomogeneities:

- Local inhomogeneities: impact in the self shielding → affects the shape of the strongest resonances.
- Global inhomogeneities: affects the normalization.



Inhomogeneities do not affect the shape of the yield (or transmission) if the sample is thin (i.e. no self shielding).

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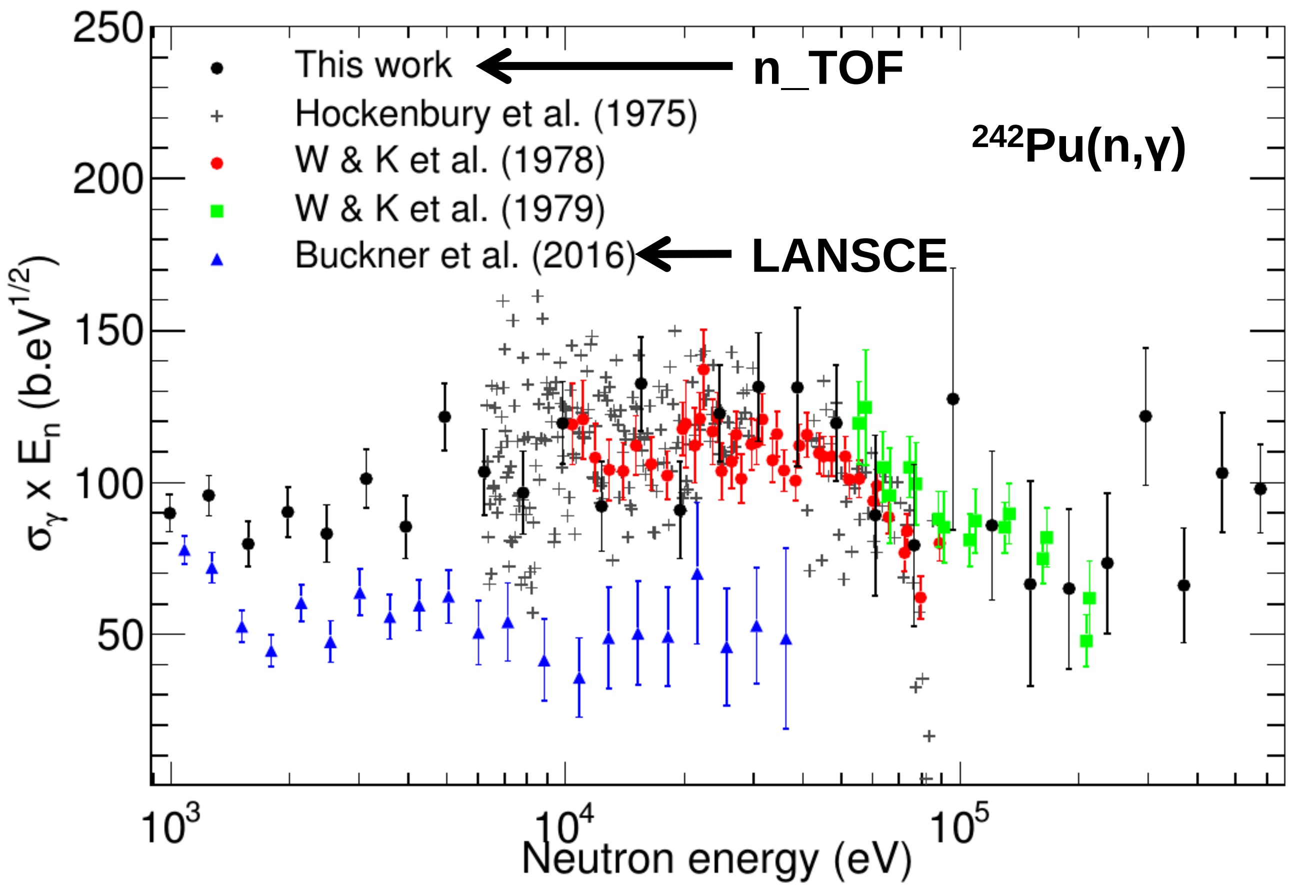
Discrepancies between measurements



J. Lerendegui-Marco, PhD Thesis
https://cds.cern.ch/record/2661485

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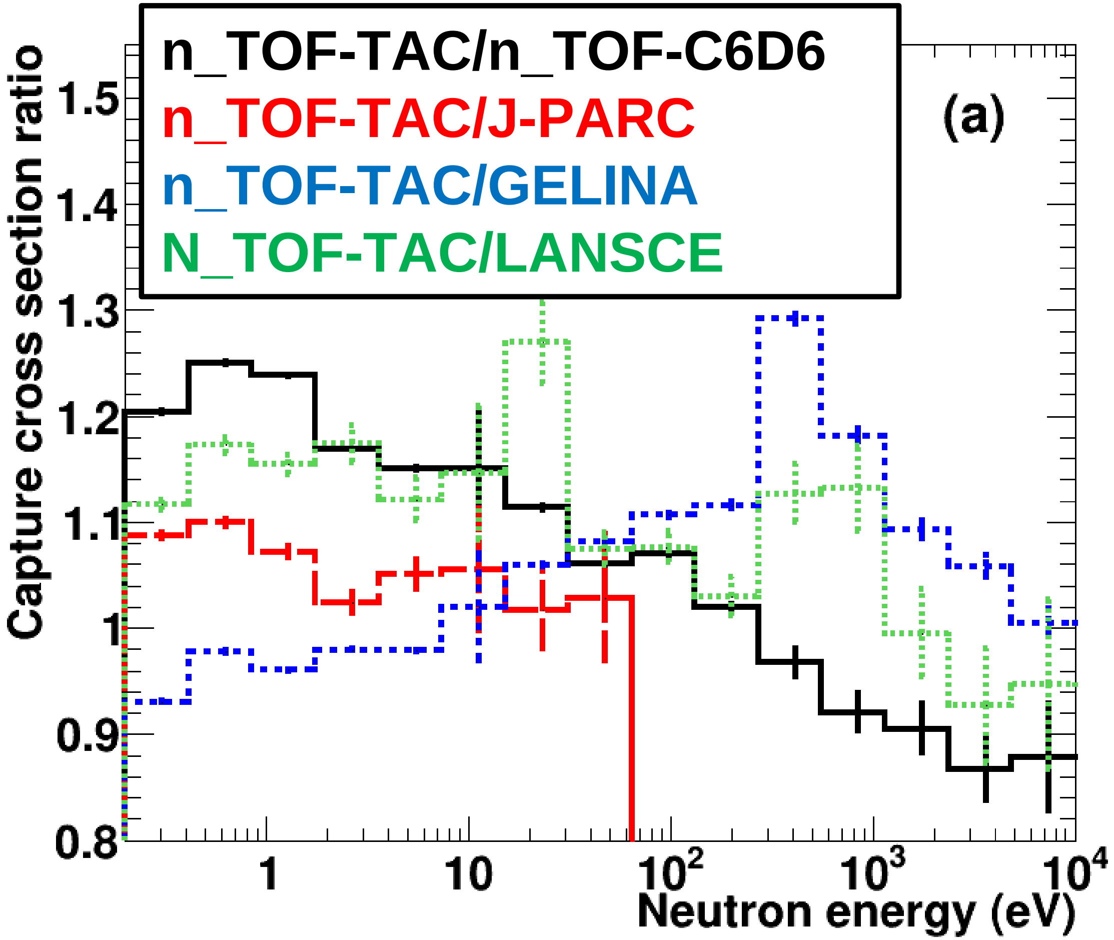

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Conclusions

I have presented an overview of an analysis of a (neutron capture) measurement in n_TOF.

Understanding the entire analysis process may help to understand different biases, what data may be more questionable, etc.

In case something is not clear in the EXFOR dataset (+ paper), or you think there is some problem with the data … please do not hesitate in contacting us for clarification. This will also help us to detect possible issues in our data.

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