Measurement of the of $^{235}U(n,\gamma)$ cross-section with fission tagging

PhD Thesis of J. Balibrea, D. Cano-Ott, E. Mendoza
and the **n_TOF collaboration**

CIEMAT - Spain

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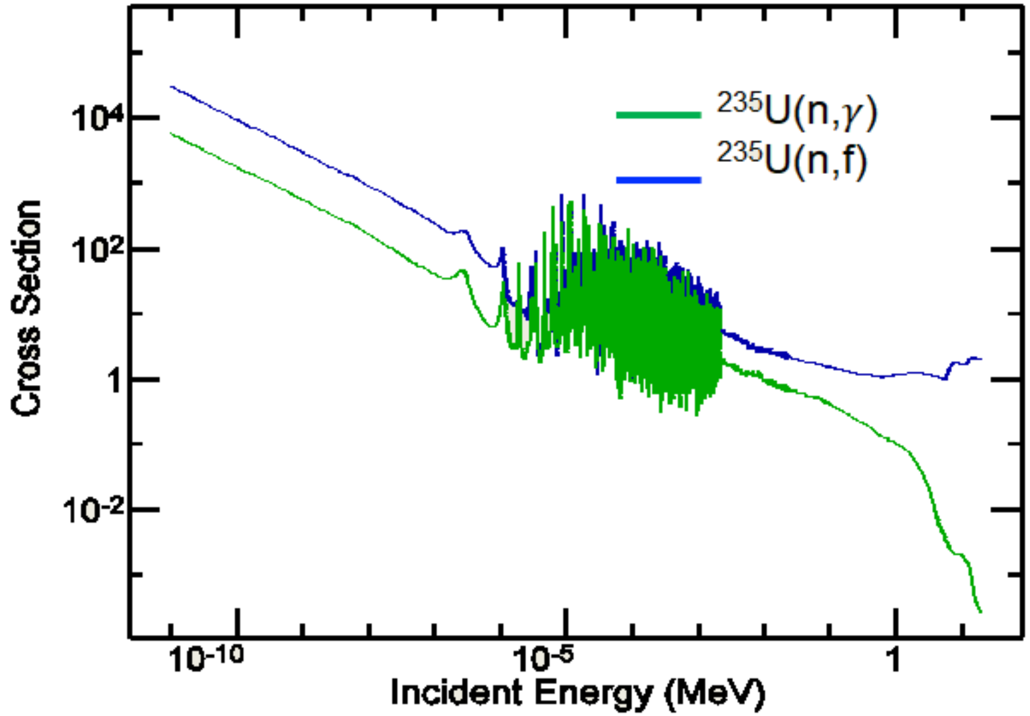
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

IAEA meeting “On the resonance parameters of actinides”

nTOF

Measurement of (n,γ) cross-sections of fissile isotopes

Difficult: the (n,γ) cascades compete with the large (n,f) γ-ray background

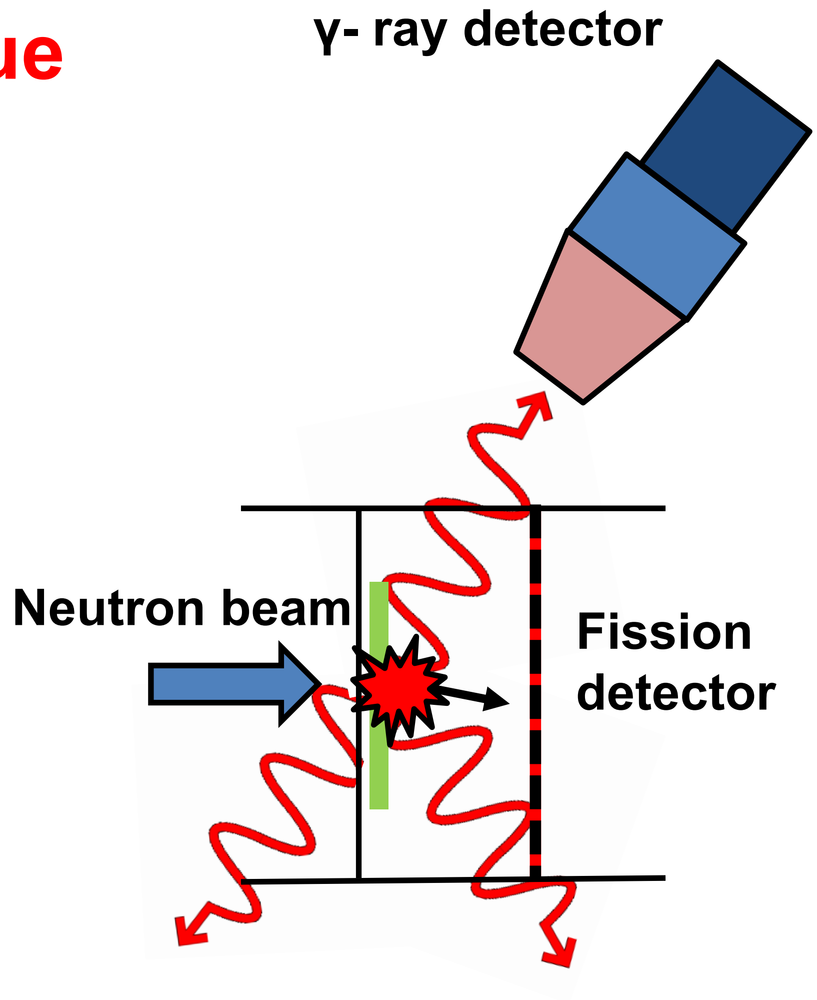


- Capture signals: **low γ-ray multiplicity cascades**, **m_γ~4-5**, with **γ-energy** close to **$S_n(^{236}U)+E_n$**.

- γ-ray background due to fission**:** the **(n,f)** channel has a larger cross-section and produces **higher γ-ray multiplicity & energy cascades** (**m_γ~8-9)** with **γ-energy** up to **20 MeV** (+ **prompt fission neutrons, $\bar{\nu}$~2.43** and **$\overline{E_n}$~1.1 MeV).**

- **Same neutron energy dependence.**

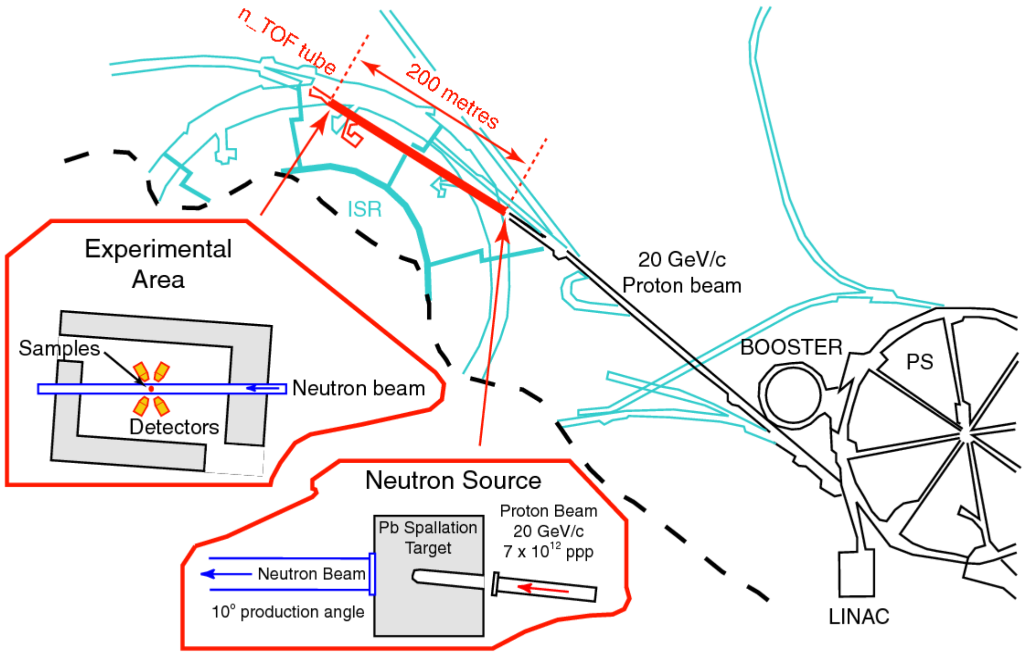
The fission tagging technique

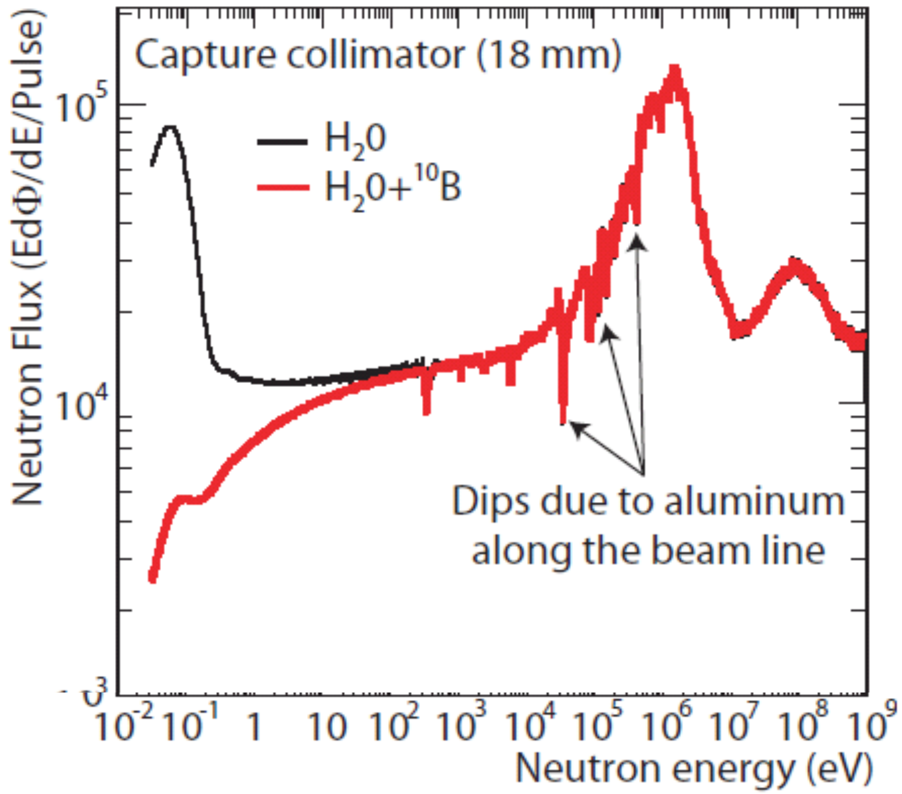


- **Developed** in the early **1960s** at Los Alamos.
- **Measure simultaneously fission and capture** by means of fission and electromagnetic detectors, respectively.
- The **fission γ-ray cascades are tagged** from the **time coincidences** between both detection systems.
- **C. Guerrero** *et al.* (2010). n_TOF facility (Pilot experiment)
- **M. Jandel** *et al.* (2012). DANCE @ LANL } Normalised to $\sigma_\gamma(E_i)$
- **This work** (2012). n_TOF facility } absolute $\alpha = \frac{\sigma_\gamma(E_n)}{\sigma_f(E_n)}$
- Y. Danon (2017). RPI } Normalised to $\sigma_\gamma(E_i), \sigma_f(E_i)$

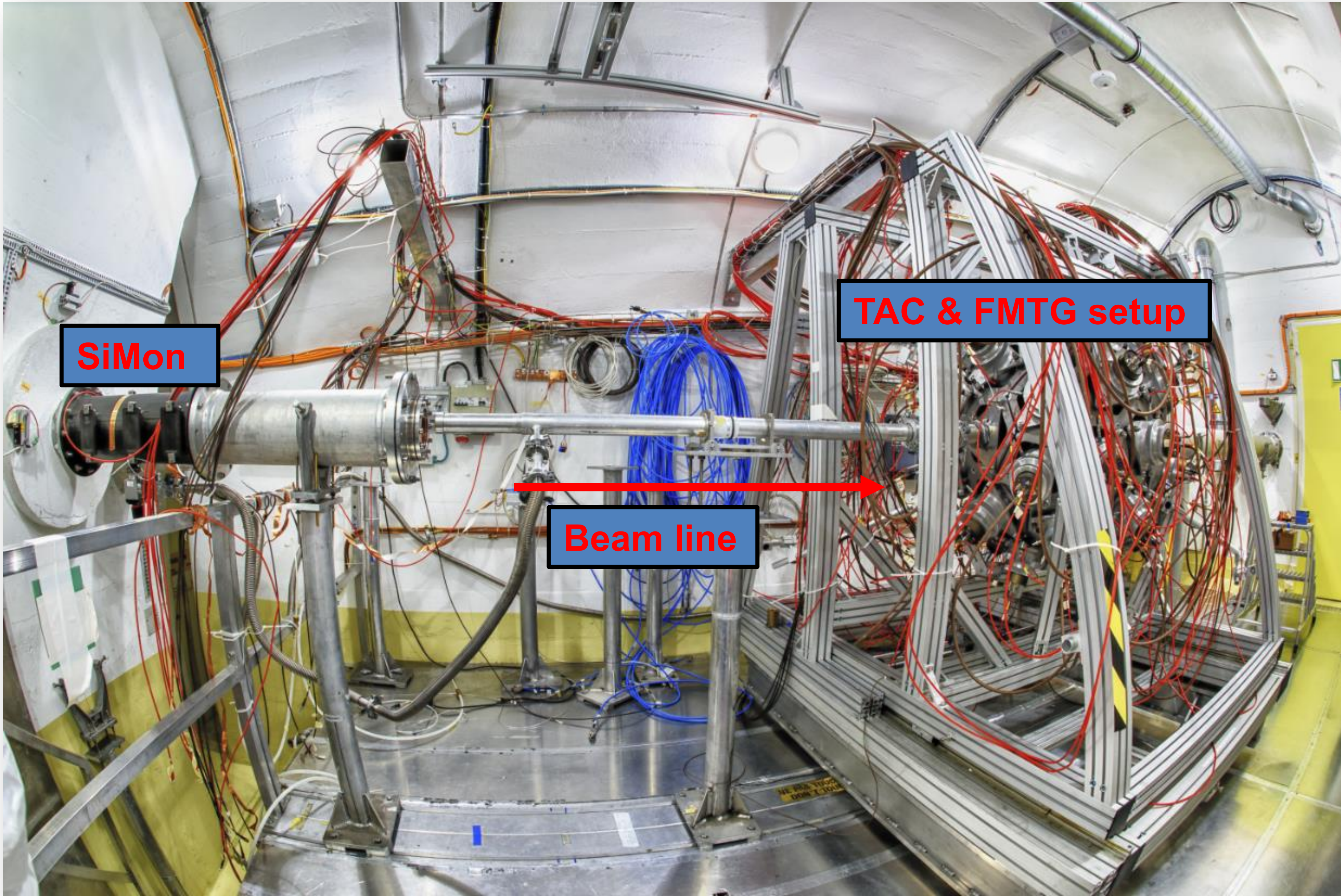
The CERN n_TOF facility

The n_TOF facility is a high instantaneous intensity spallation neutron source driven by the CERN PS synchrotron (20 GeV/c with up to $8x10^{17}$ ppp)

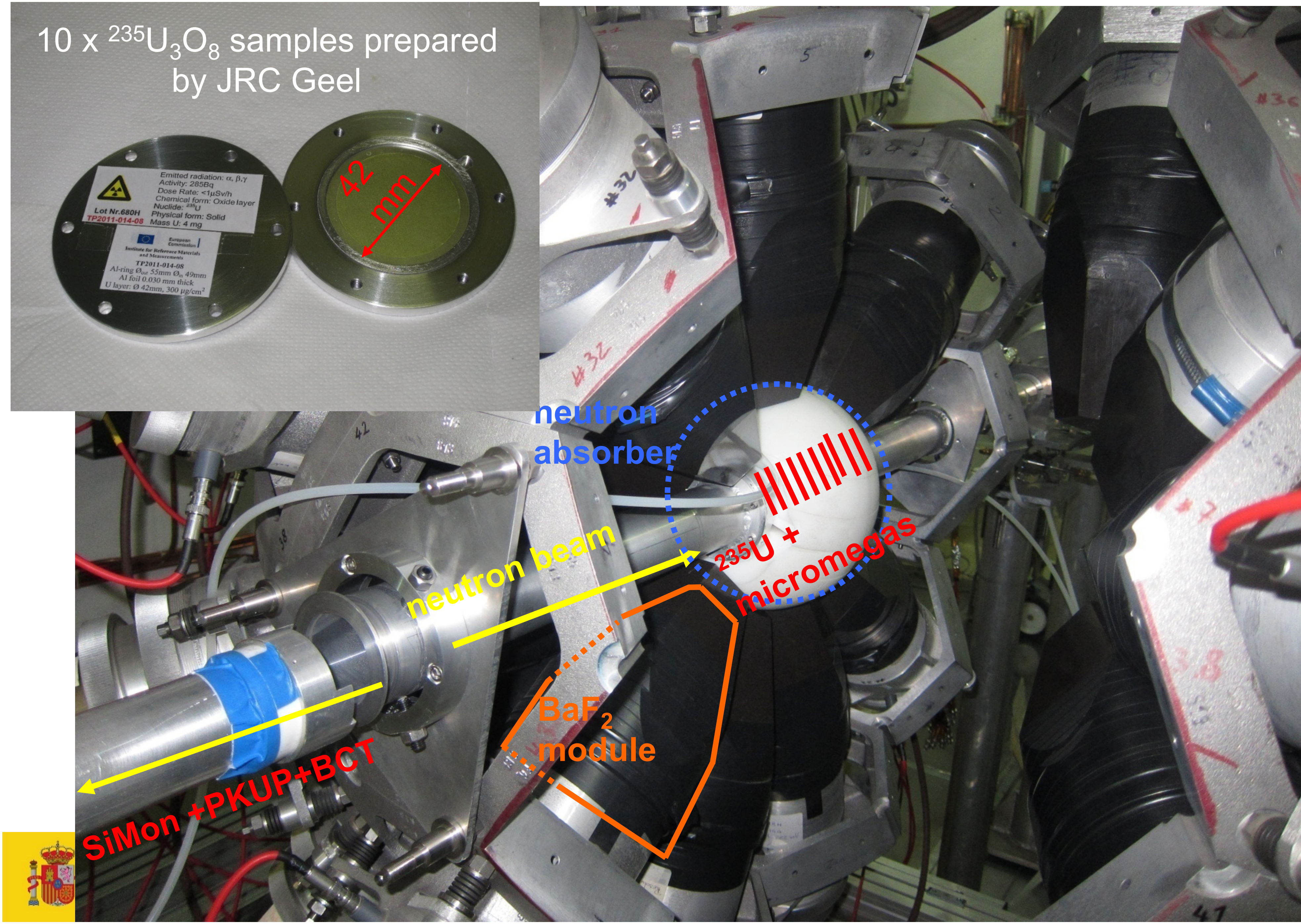




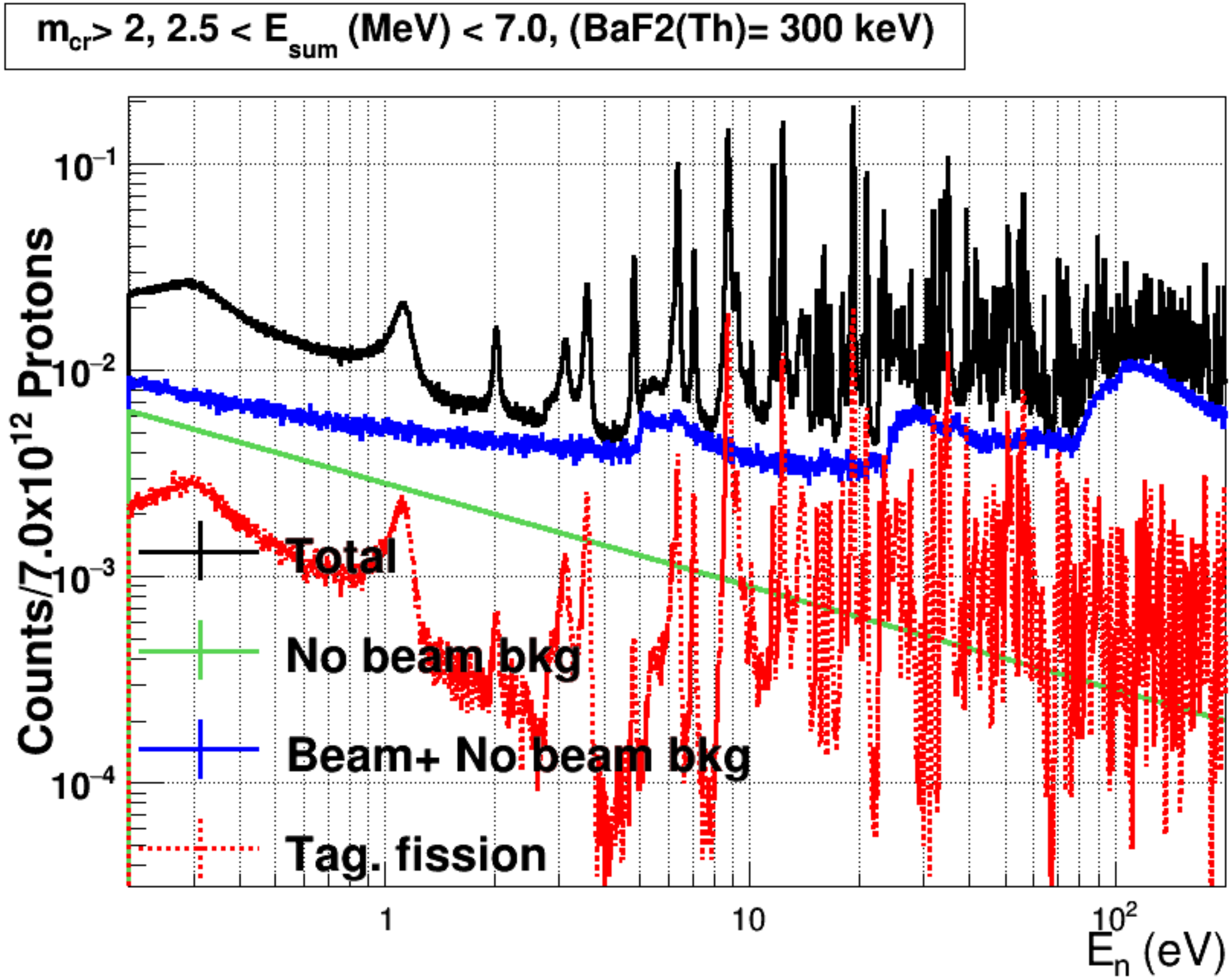
n_TOF-EAR1



TAC & FTMG experimental setup



Time of Flight spectra registered by the TAC

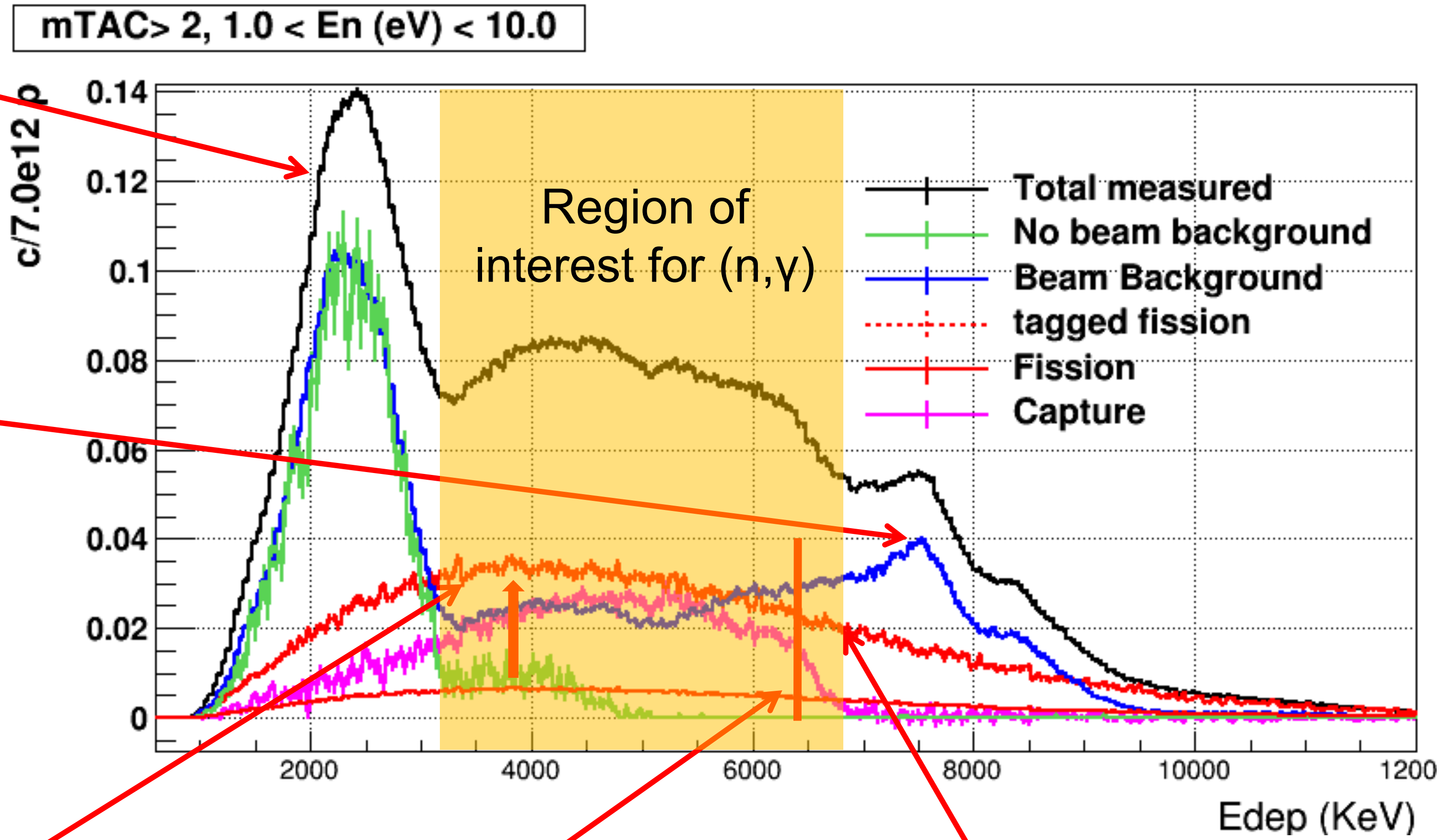


Deposited energy registered by the TAC

Total energy deposited in TAC

Background measured with a dummy sample. Components: $^{nat}Cu(n,\gamma)$, $^{27}Al(n,\gamma)$ and elastic scattering from the gas

TAC response to capture reactions (after the background subtraction)



Neutron separation energy of ^{236}U

The fission background has to be corrected by the tagging efficiency

Normalization of the measurement

We have measured the ratio of the capture and the fission cross section:

Experimental

$$\boxed{\frac{\int \sigma_\gamma(E_n)dE_n}{\int \sigma_f(E_n)dE_n}} = \boxed{\frac{\varepsilon_f}{\varepsilon_\gamma}\frac{\int \frac{C_T(E_n)-C_B(E_n)}{\phi(E_n)}dE_n}{\int \frac{C_f(E_n)}{\phi(E_n)}dE_n}}$$

C_T Total counts (TAC)
C_B Background counts (TAC)
C_f Fission counts (FTMG)
ε_γ TAC detection efficiency
ε_f FTMG dection efficiency
Φ Neutron fluence.

The neutron-induced **fission cross section** has been normalized to the **integral value** from **7.8 to 11.0 eV** which is accurately well known (**< 0.5%**):

$$\int_{7.8eV}^{11eV} \sigma_f(E_n)dE_n = (246 \pm 1)\, barns \cdot eV$$

The **results does neither depend** on **the mass samples** nor on **the integral neutron fluence**. **The ratio doesn't depend** on the **neutron fluence energy dependence**.

Sensitivity of α and the (n,γ) cross-section to ε_f

The neutron capture cross-section and α are very sensitve to the fission tagging detection efficiency.

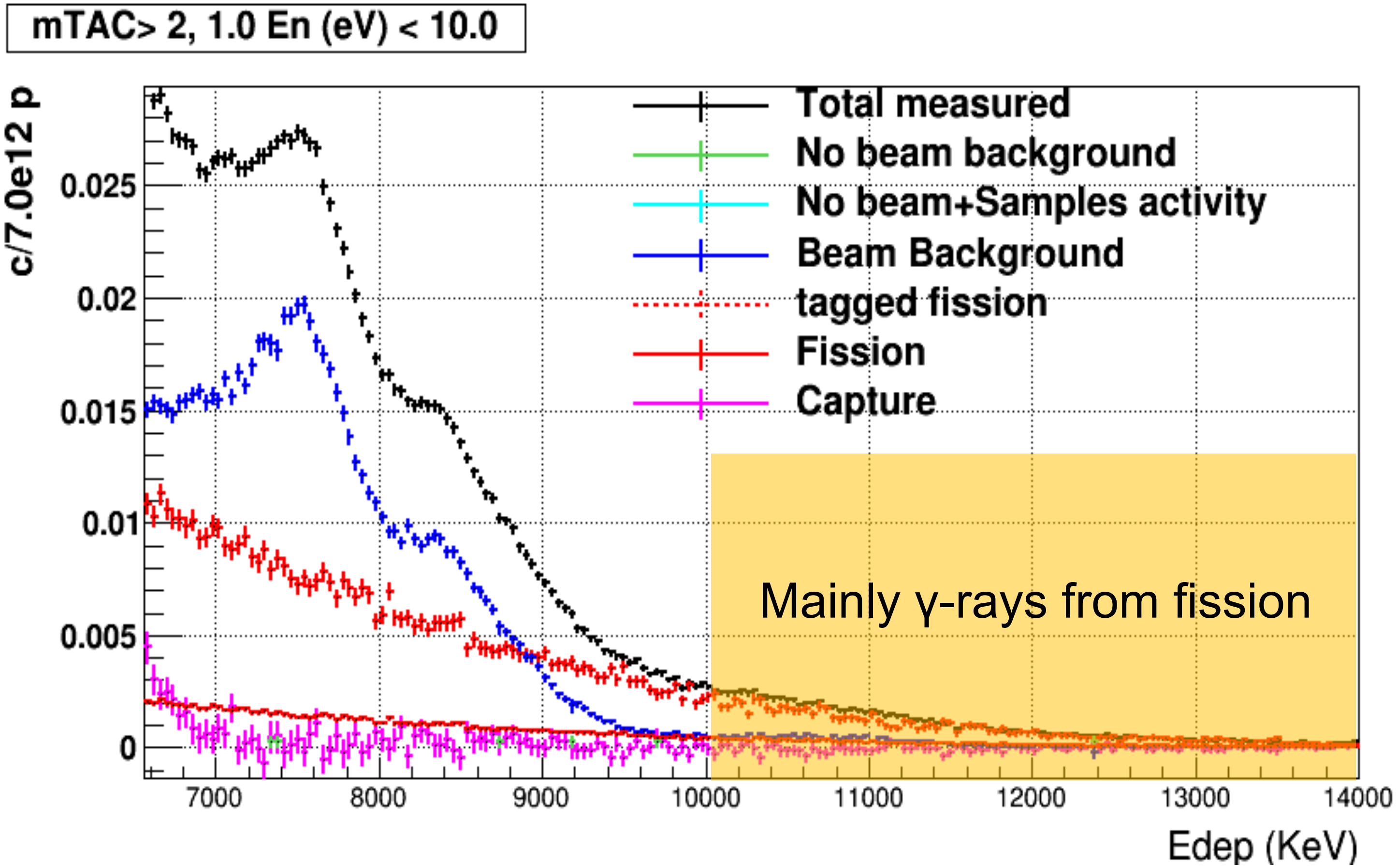
$$\left(\frac{\Delta\alpha(E_n)}{\alpha(E_n)}\right)_{\varepsilon_f} \approx \left(1 + \frac{\sigma_f(E_n)}{\sigma_\gamma(E_n)}\right)\frac{\Delta\varepsilon_f}{\varepsilon_f}$$

ε_f **is critical for** the accurate determination of **the neutron capture cross-section**.

The subtraction of the $^{235}U(n,f)$ γ-ray cascades

Calculation of the fission detection efficiency

$$\varepsilon_f = \frac{c_{tagged}}{c_T - c_B}$$



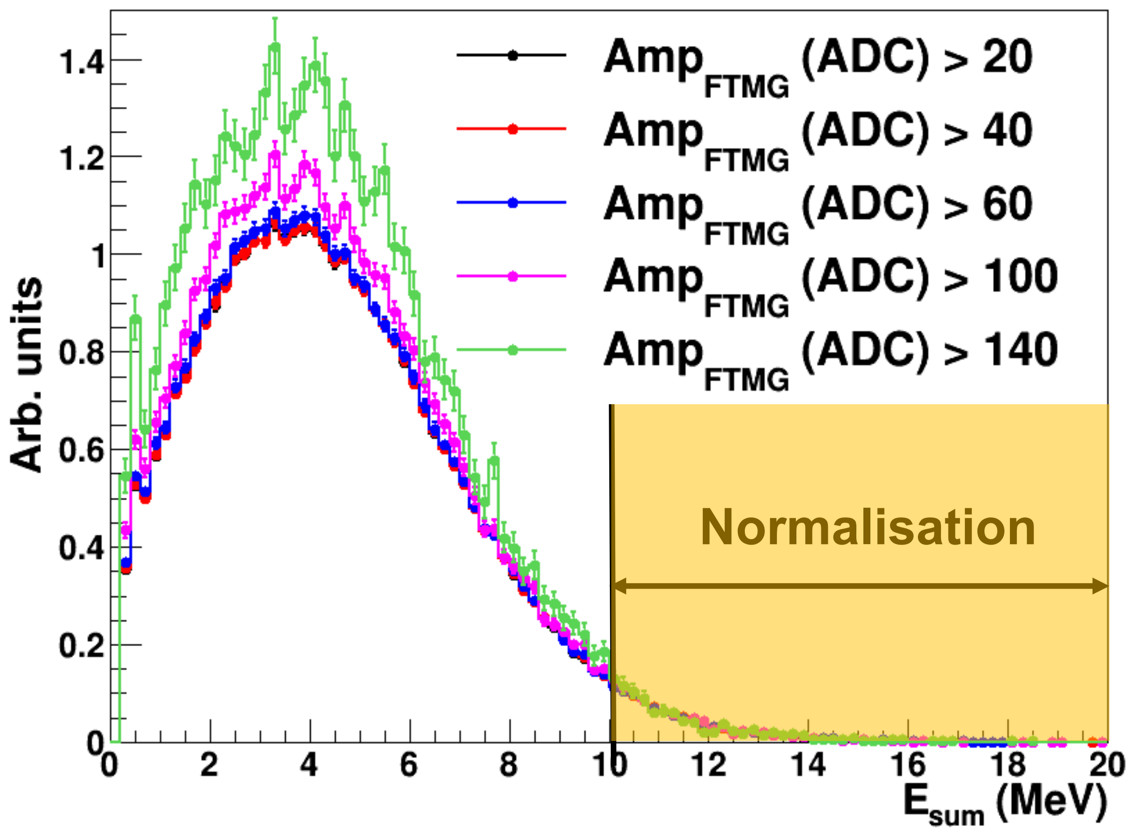
The fission detection efficiency ε_f is calculated using cuts in the E_{sum} in the TAC above the neutron separation energy, where no counts due to the (n,γ) electromagnetic cascades are detected (except for pileup or summing).

Prompt fission γ-ray cascades

Observed **slightly different prompt fission γ-rays** as a function of **Amp$_{\mathbf{FTMG}}$**

Not reported in previous experiments.

Possible explanation: γ-fission fragment **angular correlation** + FTMG **f. f. detection efficiency**

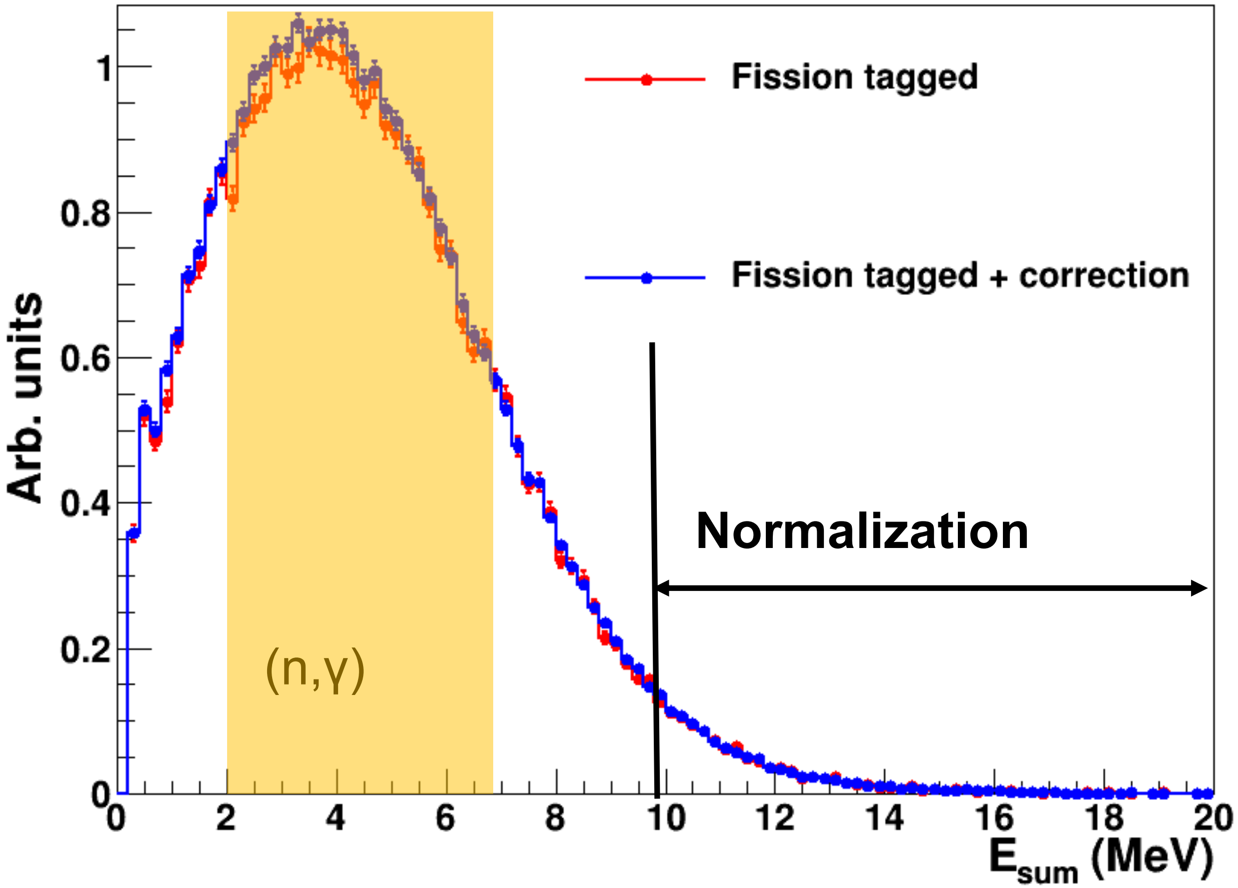


Fission tagging detection efficiency for (n,γ) conditions

The correction accounts for prompt fission events detected by the TAC but not by the FTMG (large emission angles and self-absorption in the ^{235}U targets):

- **FTMG detectors** have **individual efficiencies** close to **85%**.

- We have assumed that the shape of the **~15% of non-tagged fissions** have a similar prompt fission γ-shape to the low fission amplitude tagged fissions.



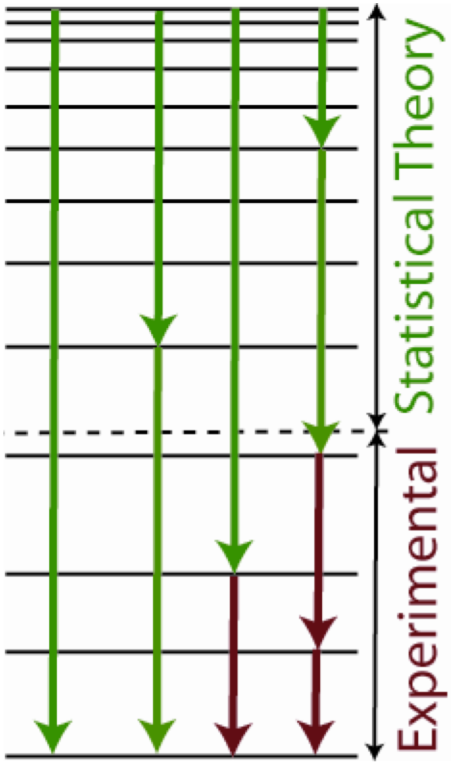
We need to subtract 2% more background counts in the (n, γ) from what is deduced from the tagged spectrum.

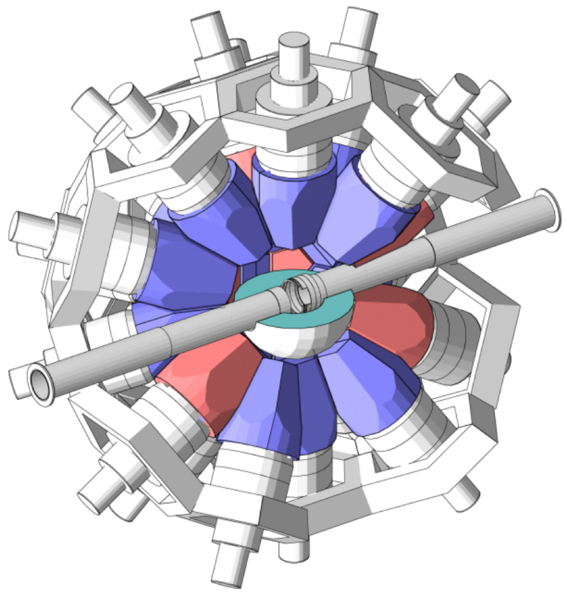
Uncertainty of
$\boldsymbol{\Delta\varepsilon_f = 2.2\%}$

resonance
inides”

TAC detection efficiency to $^{235}U(n,\gamma)$ events

Determination of the detection efficiency for the (n,γ) channel





Realistic cascade generator depends on:

- Known nuclear level scheme.
- Statistical model for the high excitation nuclear levels.
- Photon strength functions (PSF).
- Population and half-life of known long-lived isomers.

Detailed implementation of the TAC+FTMG geometry GEANT4, for the transport of the cascades

Monte Carlo simulations: TAC efficiency

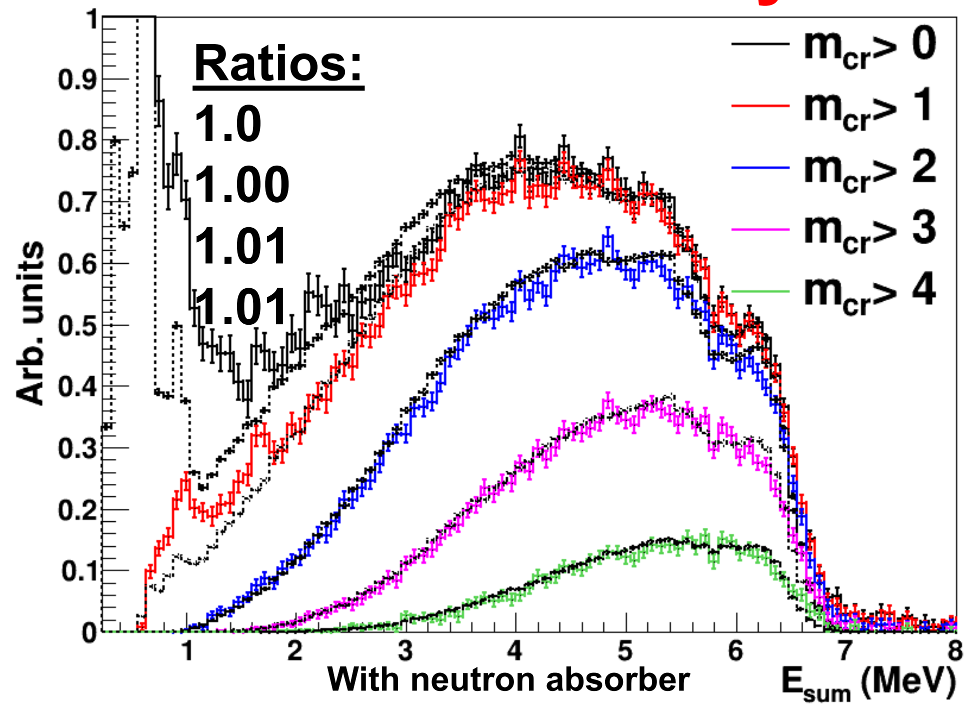
The capture γ-ray cascades have been provided by Milan Kritcka using **DICEBOX code** .

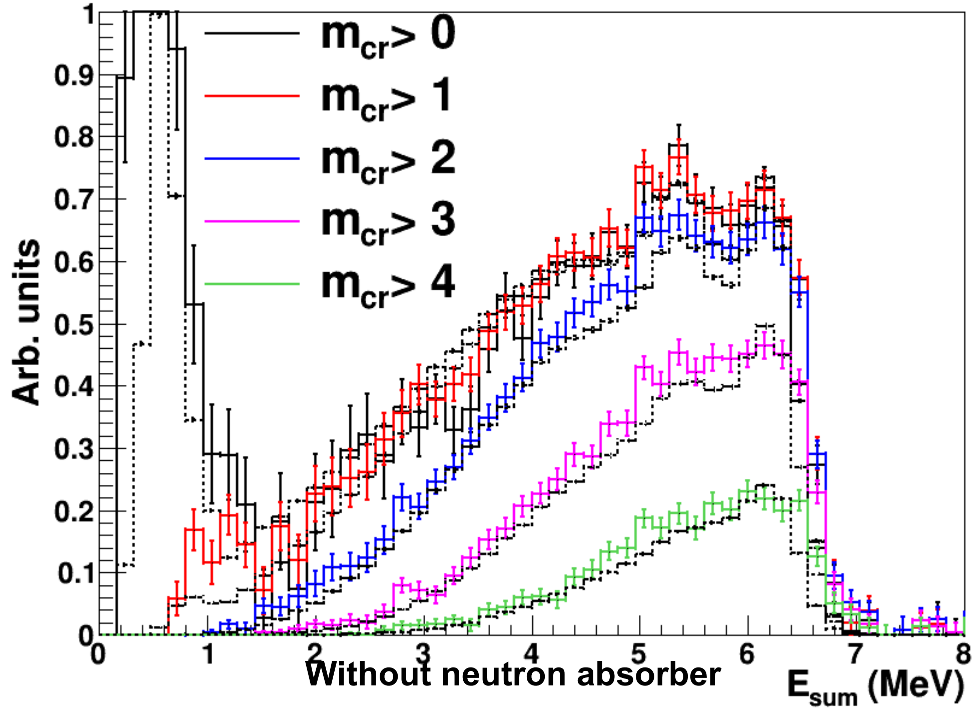
The parameters of the EM cascades **have been adjusted from DANCE** experimental data.

The cascades have been simulated in the detailed **TAC+FTMG geometry** already implemented in GEANT4 for **two different configurations**:

- 2FTMG with the neutron absorber.
- 2FTMG without the neutron absorber.

An **excellent agreement** is obtained **for all the multiplicities in the TAC** between the MC simulations and the experimental data. $\Delta\varepsilon_{\gamma} = 1.7\%$

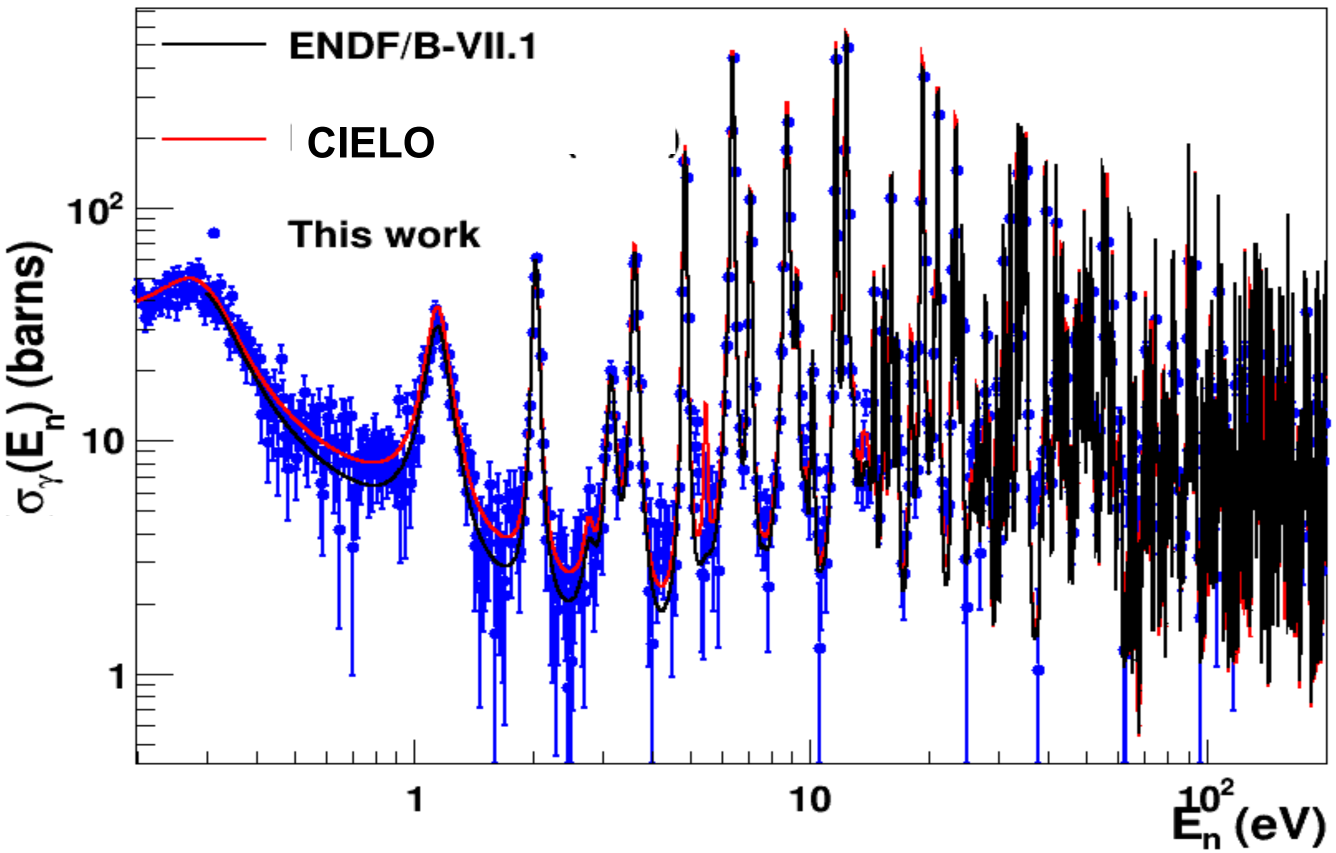




Results

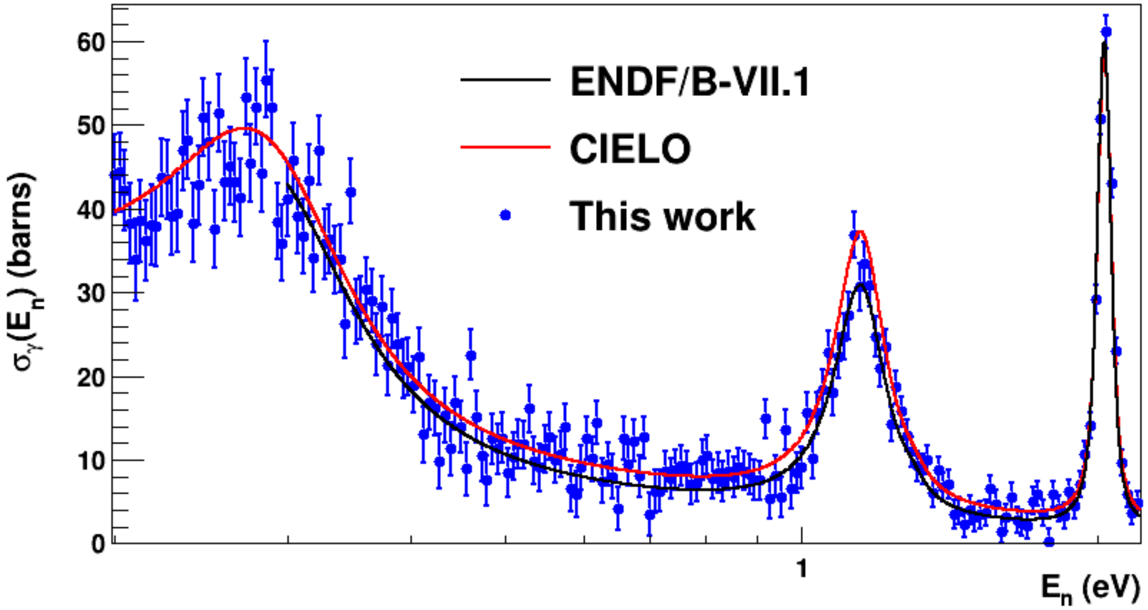
$^{235}U(n,\gamma)$ cross-section and CIELO

The **experimental $^{235}U(n,\gamma)$ cross-section data were made available to the CIELO project** for its evaluation together with all experimental data sets available.

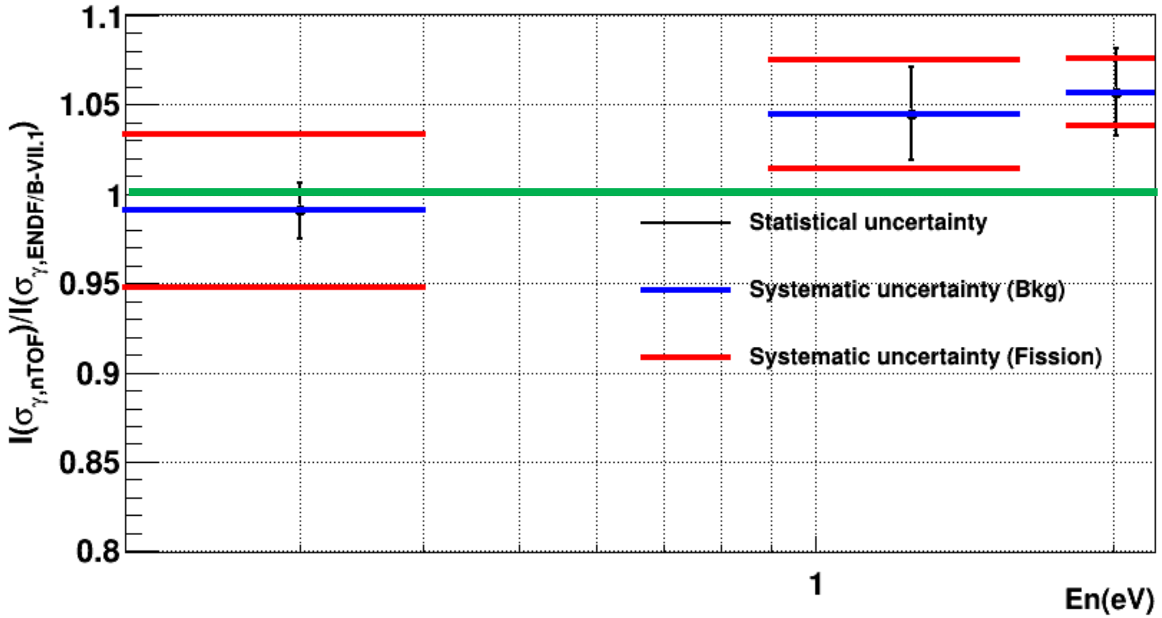


From this new evaluation, a **new neutron data** library for ^{235}U isotope is **under production** (ENDF/B-VIII.0).

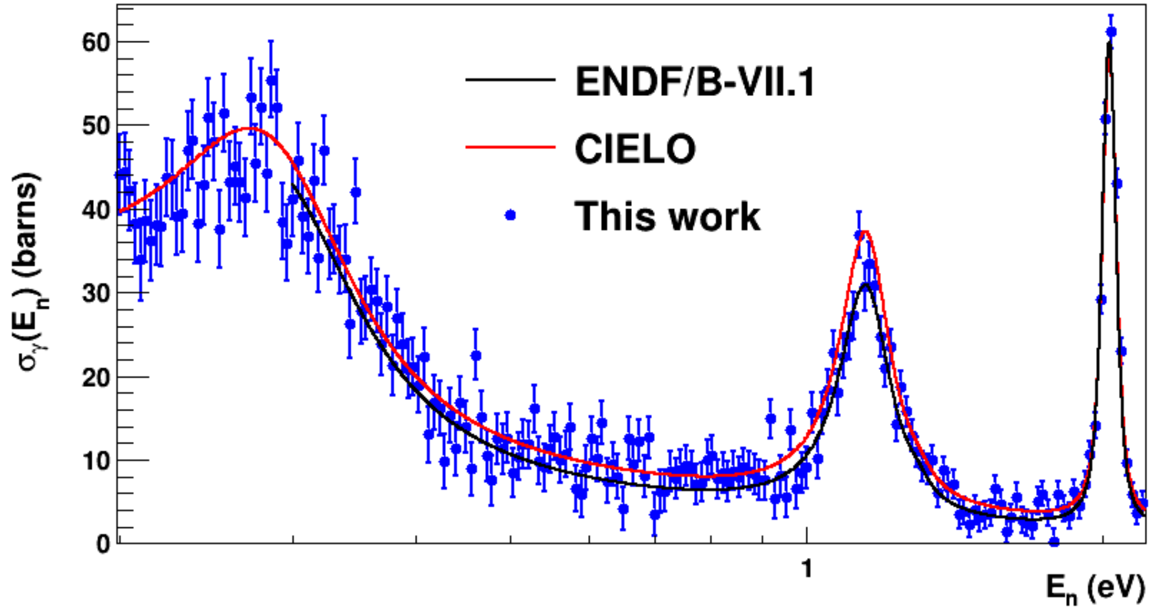
Neutron energy range: 0.2-2.2 eV



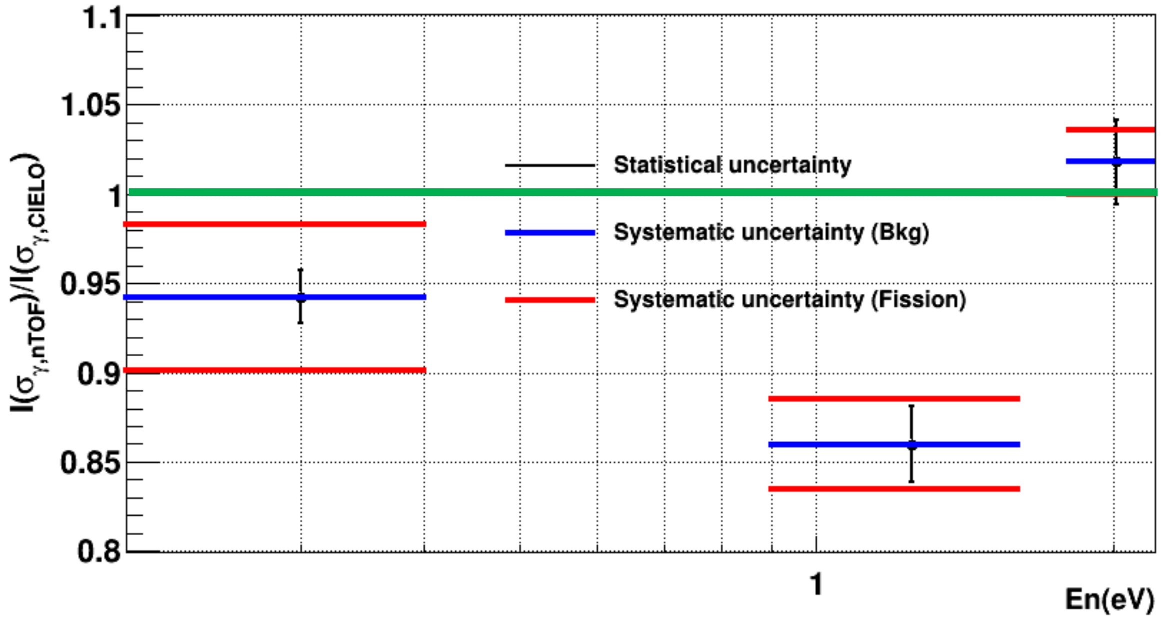
Neutron resonance integrals (ENDF/B-VII.1)



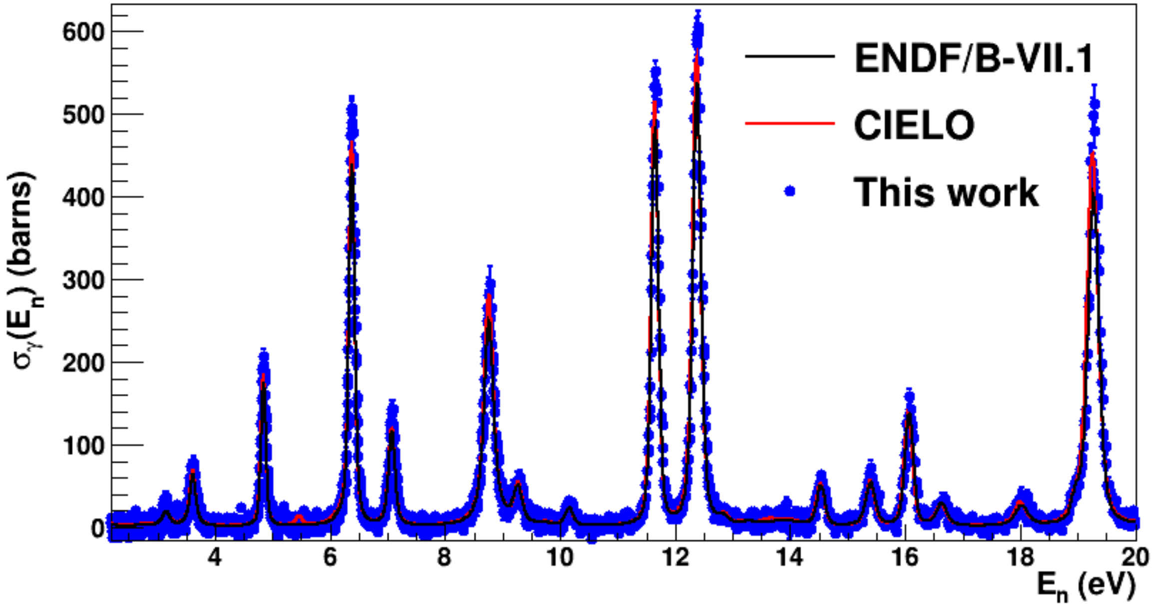
Neutron energy range: 0.2-2.2 eV



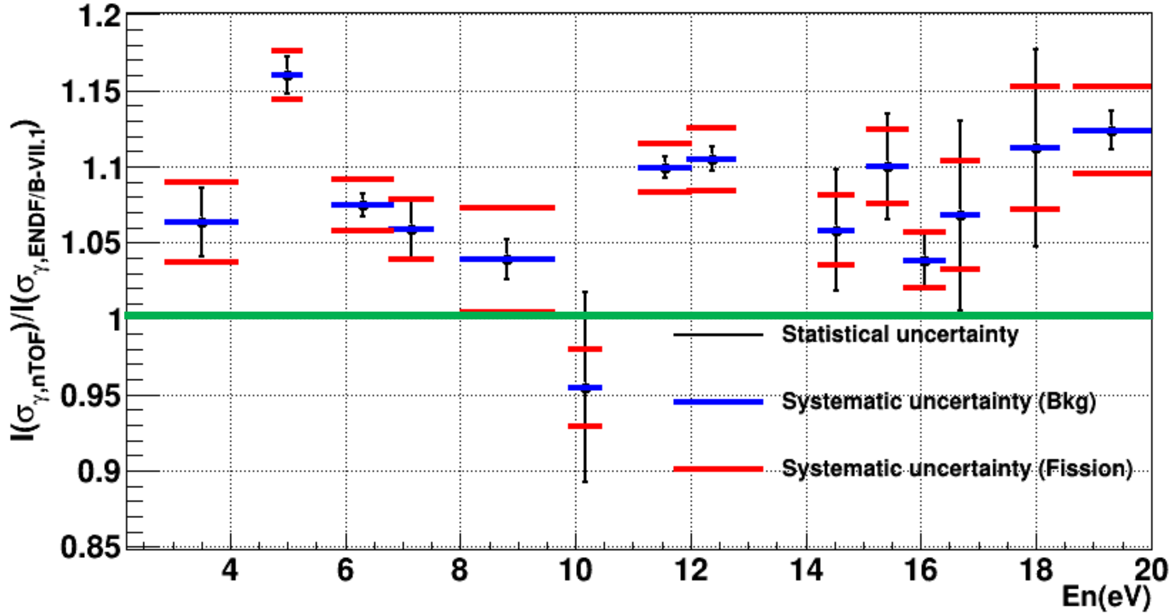
Neutron resonance integrals (ENDF/B-VIII.0)



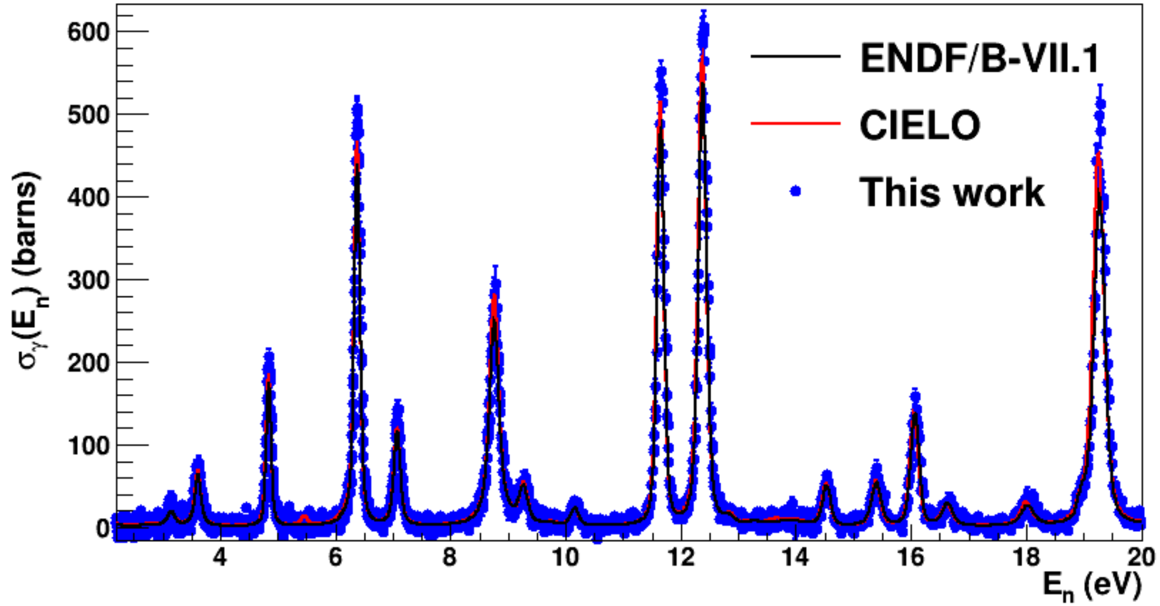
Neutron energy range: 2.2-20.0 eV



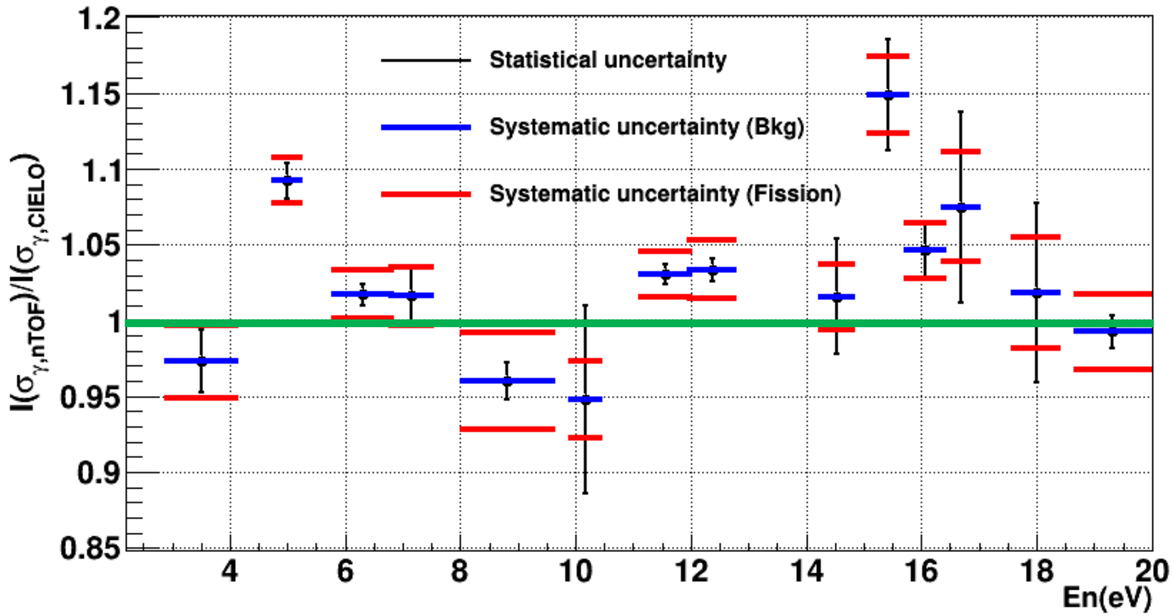
Neutron resonance integrals (ENDF/B-VII.1)



Neutron energy range: 2.2-20.0 eV



Neutron resonance integrals (ENDF/B-VIII.0)



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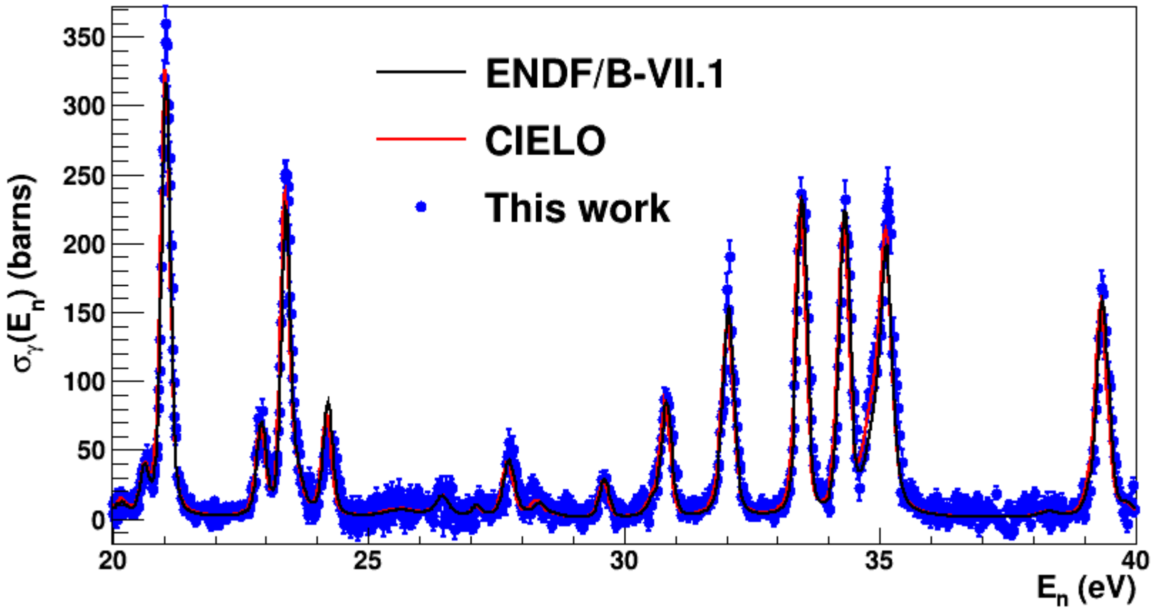
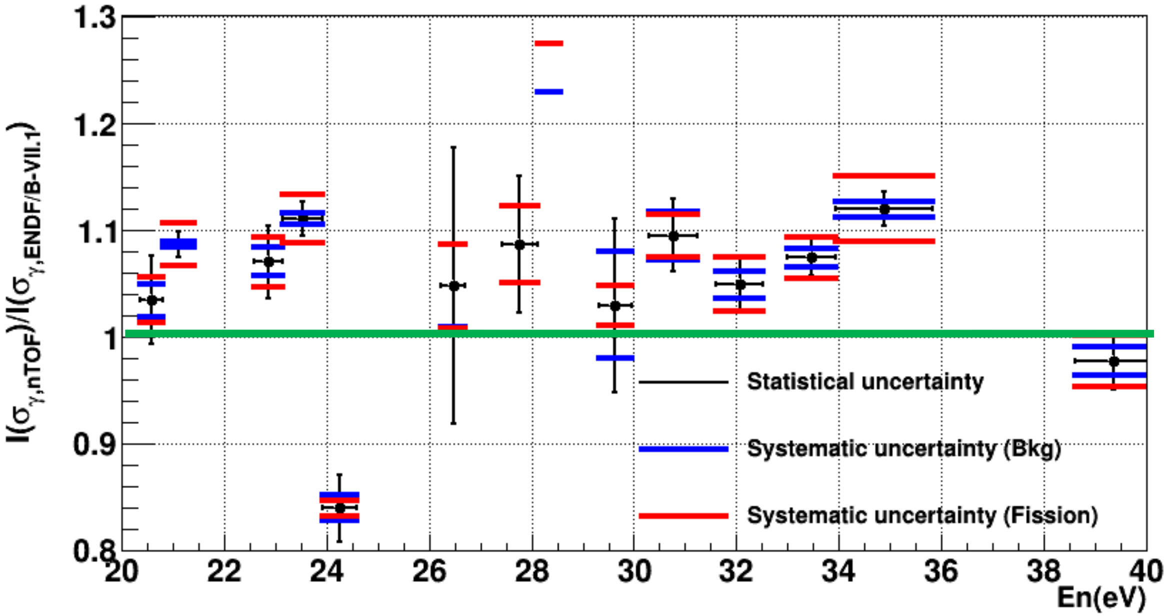
n_TOF

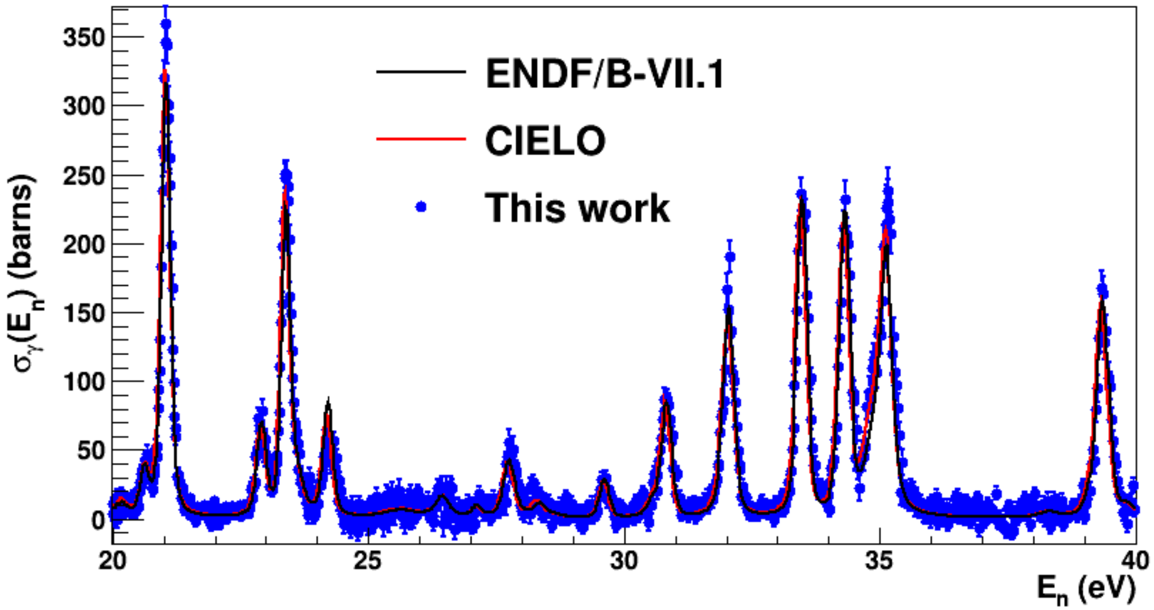
Neutron energy range: 20.0-40.0 eV



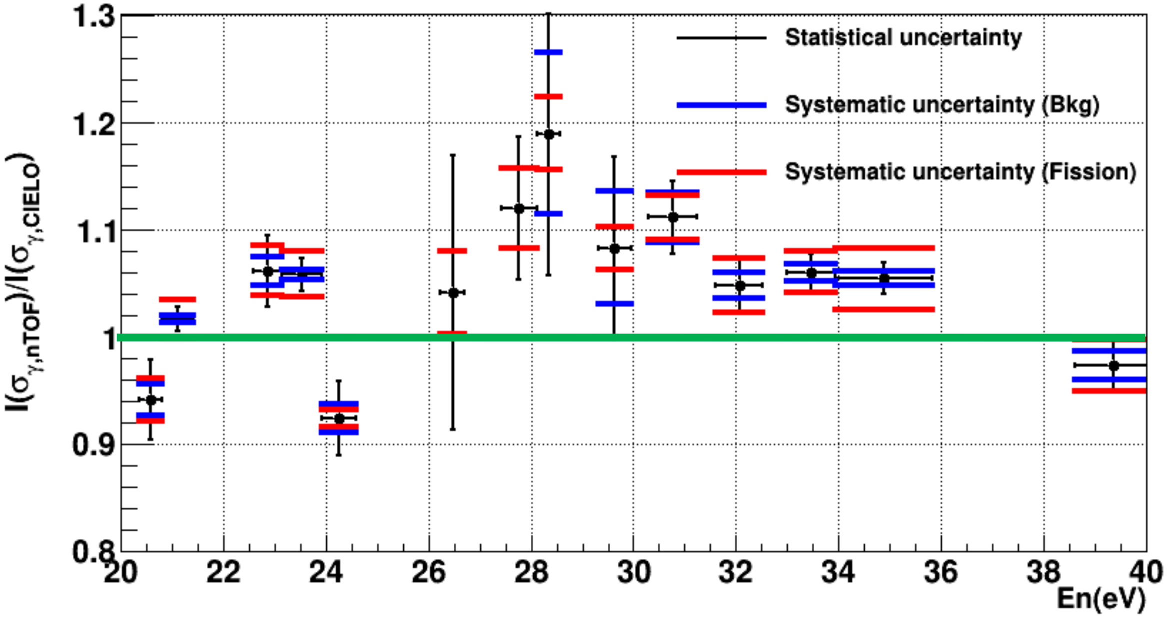
Neutron resonance integrals (ENDF/B-VII.1)



Neutron energy range: 20.0-40.0 eV

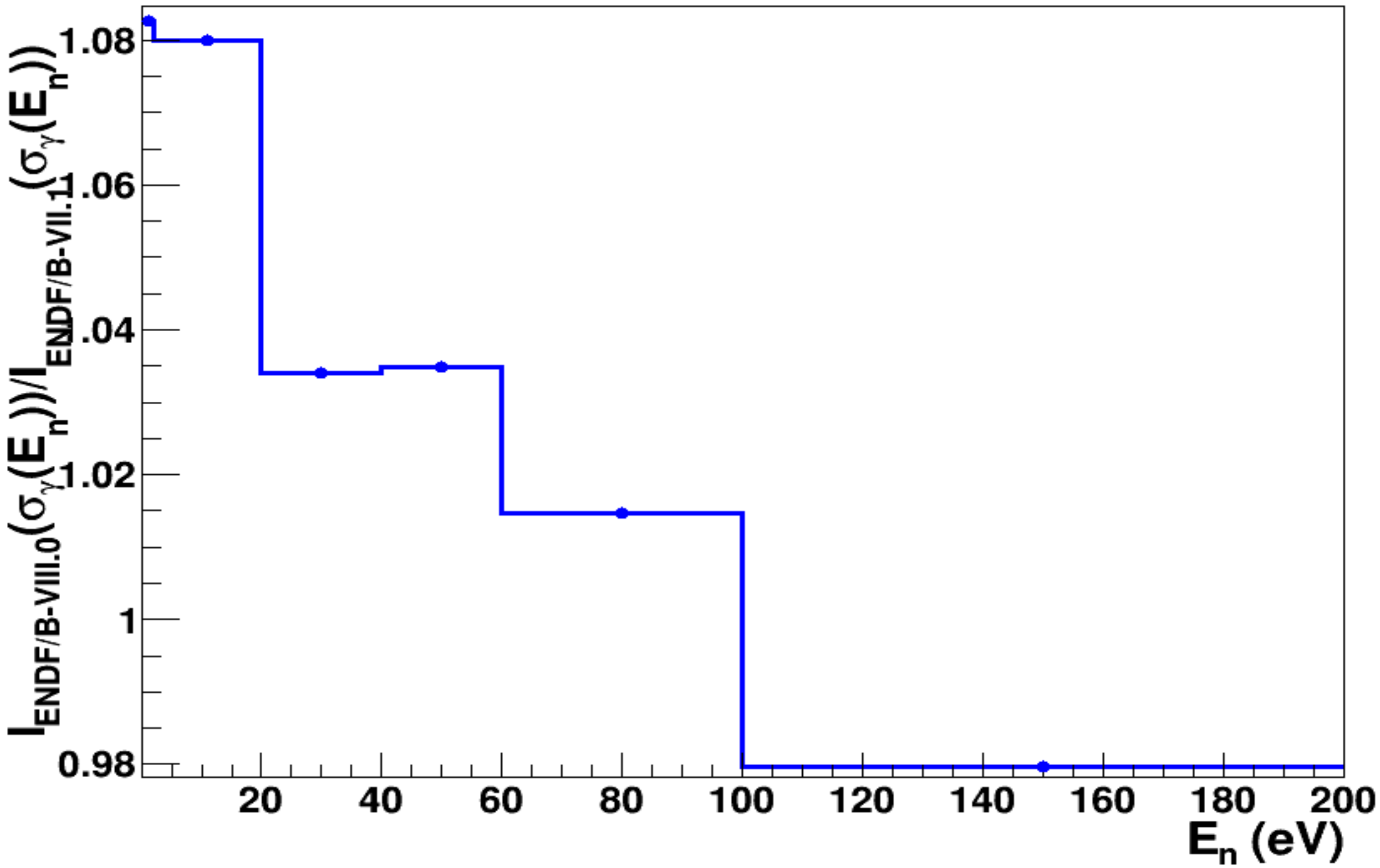


Neutron resonance integrals (ENDF/B-VIII.0)



Differences between evaluated libraries for capture

Our data have contributed to **the increase of the capture cross-section** (8%) in the **largest capture resonances in the range from 2.2 to 20 eV**.



Summary and conclusions

- The ^{235}**U(n,γ) cross-section** was **measured at the n_TOF** facility at CERN using the **fission tagging technique** in the neutron **energy range from 0.2 to 200 eV**.

- We have improved/developed a methodology for measuring the **absolute α-ratio:**

  - Accurate determination of the **ε_f and subtraction of the prompt fission γ-ray background $\Delta\varepsilon_f$=2.2%.**

    We have observed a **correlation observed detecting prompt fission γ-ray** events which **wasn't reported** in **previous experiments** with **similar experimental** setups.

  - Accurate determination of the (n,γ) **TAC detection efficiency. $\Delta\varepsilon_\gamma$=1.7%**.

- **Our data** has contributed mainly to the **ENDFB/VII.0 evaluated library (IAEA CIELO)** for the neutron **resonances between 2.2 and 20.0 eV**. The ^{235}U capture **cross-section** has been **increased by ~8%.**

- **Measuring the** (n,γ) cross section is a very difficult thing. EoI on the ^{239}**Pu(n,γ)** – CIEMAT, JRC-Geel & U. Lodz– for the new Nuclear Data project CHANDA-2.

Summary and conclusions

Acknowledgements

This work was supported partially by the Spanish national company for radioactive waste management ENRESA, through the CIEMAT-ENRESA agreements on 'Transmutación de residuos radiactivos de alta actividad' the Spanish Plan Nacional de I+D+i de Física de Partículas (project FPA2014-53290-C2-1) and the CHANDA project of the 7th Framework Programme.

Special thanks to the n_TOF Collaboration.

^{235}U(n,γ) cross-section and uncertainties

- **TAC conditions** with a satisfactory **compromise** between the TAC **detection efficiency** and the improvement of the **signal-to-background** ratio:

  $$\mathbf{2.5 < E_{sum} < 7.0 \quad and \quad 2 < m_{cr} < 6}$$

- The **experimental ^{235}U(n,γ) cross-section** obtained for both experimental configurations is **compatible within 2% in the largest first neutron resonances**.

- **Careful identification** of **uncertainty components** for analysis conditions.