Neutron spectroscopy with MONSTER: β-decay and reactions

Alberto Pérez de Rada Fiol

T. Martínez, D. Cano-Ott, J. Llanes Gamonoso, V. Alcayne, D. Bachiller-Perea, E. Mendoza, J. Plaza, A. Sanchez-Caballero, D. Villamarín

MONSTER Collaboration

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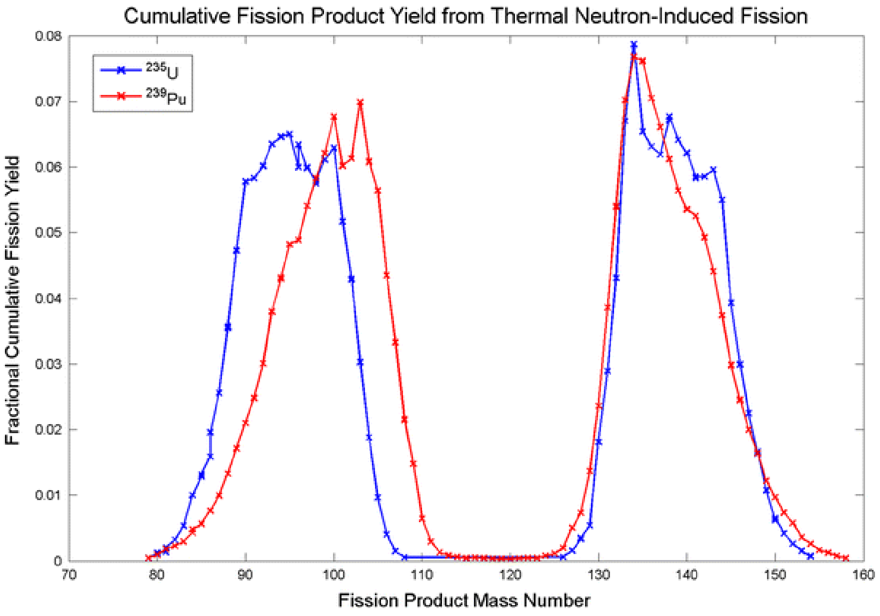
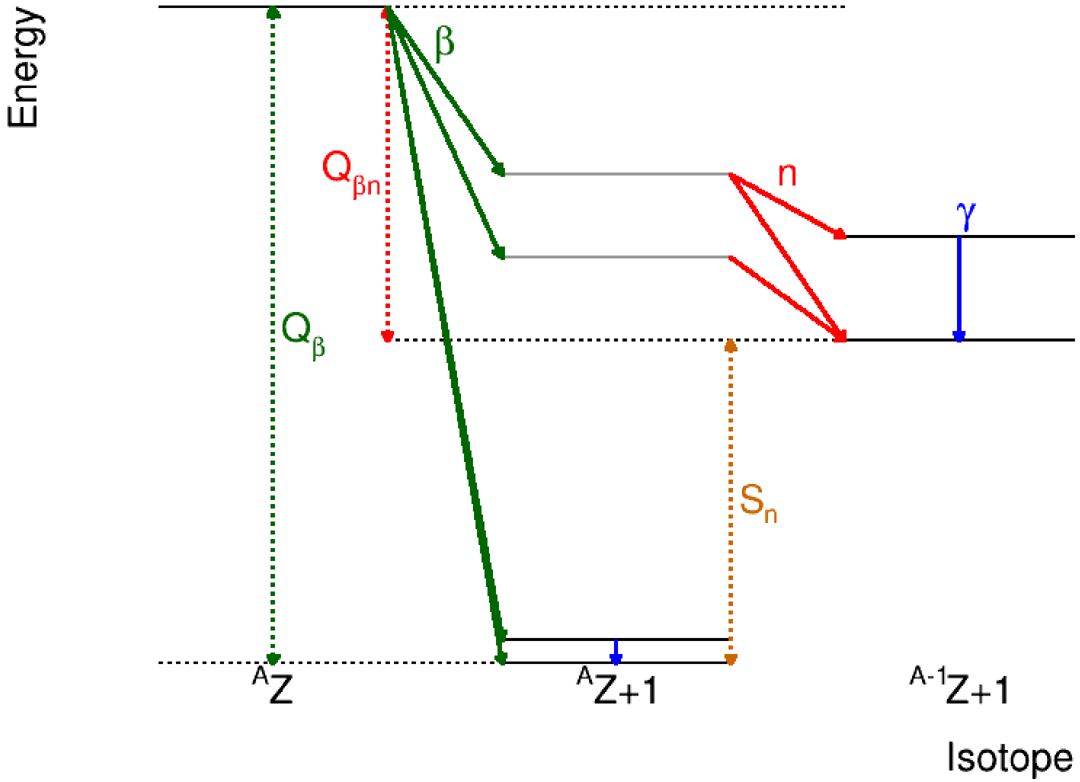
β-delayed neutron emission

β-delayed neutron emission occurs in the neutron-rich side of the chart of nuclides

β-delayed neutrons are interesting for:
- Nuclear structure
- Nuclear astrophysics
- Fission reactor kinetics and control



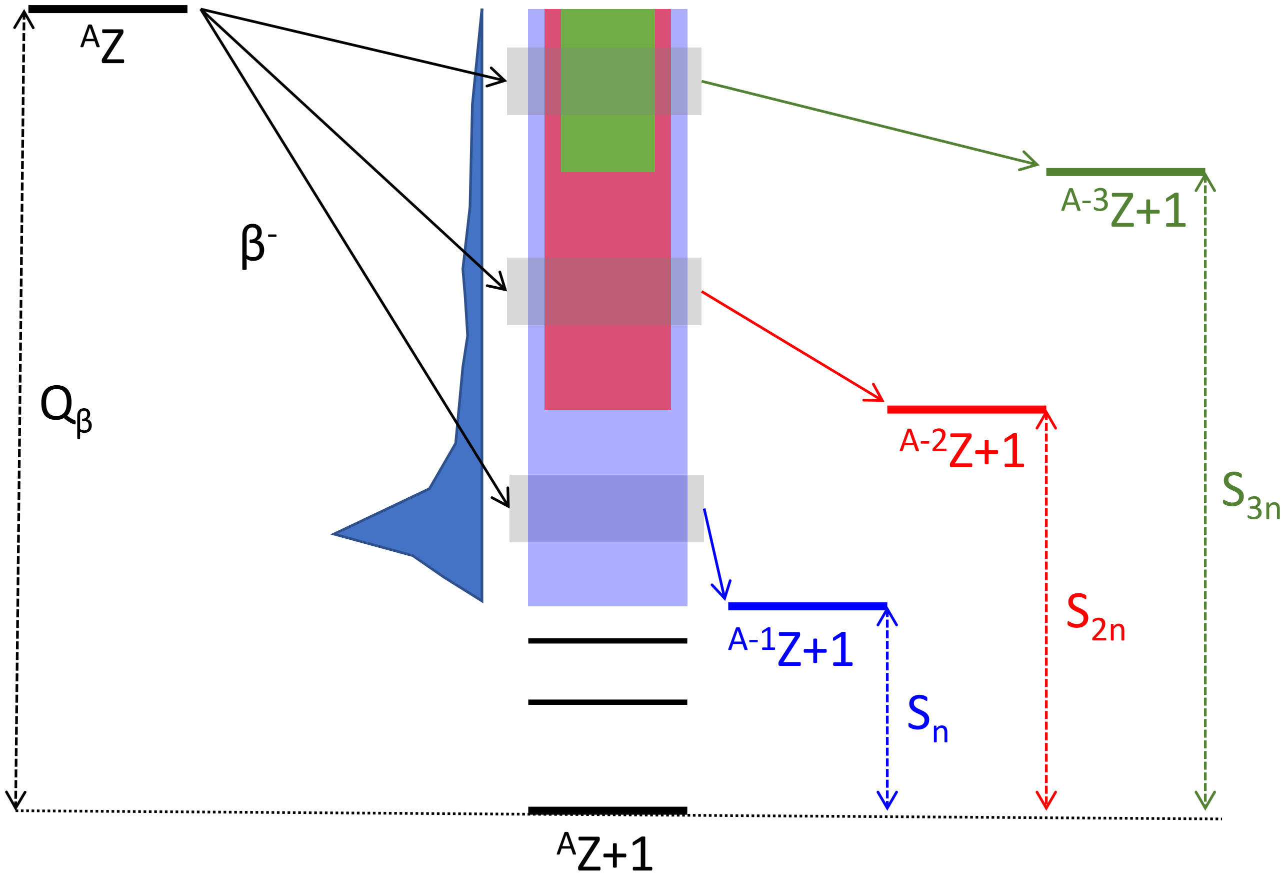


Priority list for reactor studies:

^{86}Ge, ^{85,86}As, ^{91}Br, ^{93}Rb, ^{98m,98}Y, ^{135}Sb, ^{139}I, ^{88}As, ^{96}Rb, ^{105,106}Nb, ^{137}Sb, ^{136}Te, ^{140}I, ^{143,144}Cs

I. Dillmann *et al.*, INDC(NDS)-0643, (2014)

Nuclear structure



For $S_n < E < Q_\beta$ typically $\Gamma_n(E) >> \Gamma_\gamma(E)$

β-strength function:

$$S_\beta(E) = \frac{1}{D}\sum_{J^\pi}\left|M_{fi}\right|^2 \rho(E,J^\pi)$$

$$S_\beta(E) = \frac{I_\beta(E)}{f(Z+1, Q_\beta - E)T_{1/2}}$$

β-decay properties:

$$P_n = \frac{\int_{S_n}^{Q_\beta} S_\beta(E) f(Z+1, Q_\beta - E)\left\langle\frac{\Gamma_n(E)}{\Gamma_{tot}(E)}\right\rangle dE}{\int_0^{Q_\beta} S_\beta(E) f(Z+1, Q_\beta - E) dE}$$

$$S(E_n) = \int_{S_n}^{Q_\beta}\left\langle\frac{\Gamma_n(E,E_n)}{\Gamma_n(E)}\right\rangle I_{\beta n}(E) dE$$

E. Valencia *et al.*, Phys. Rev. C, **95**, (2017) 024320

Far enough from stability $S_{xn} < Q_\beta$ leads to multiple neutron emission

The β-delayed neutron emission spectrum gives information about nuclear structure and complements reaction data

MONSTER

MONSTER

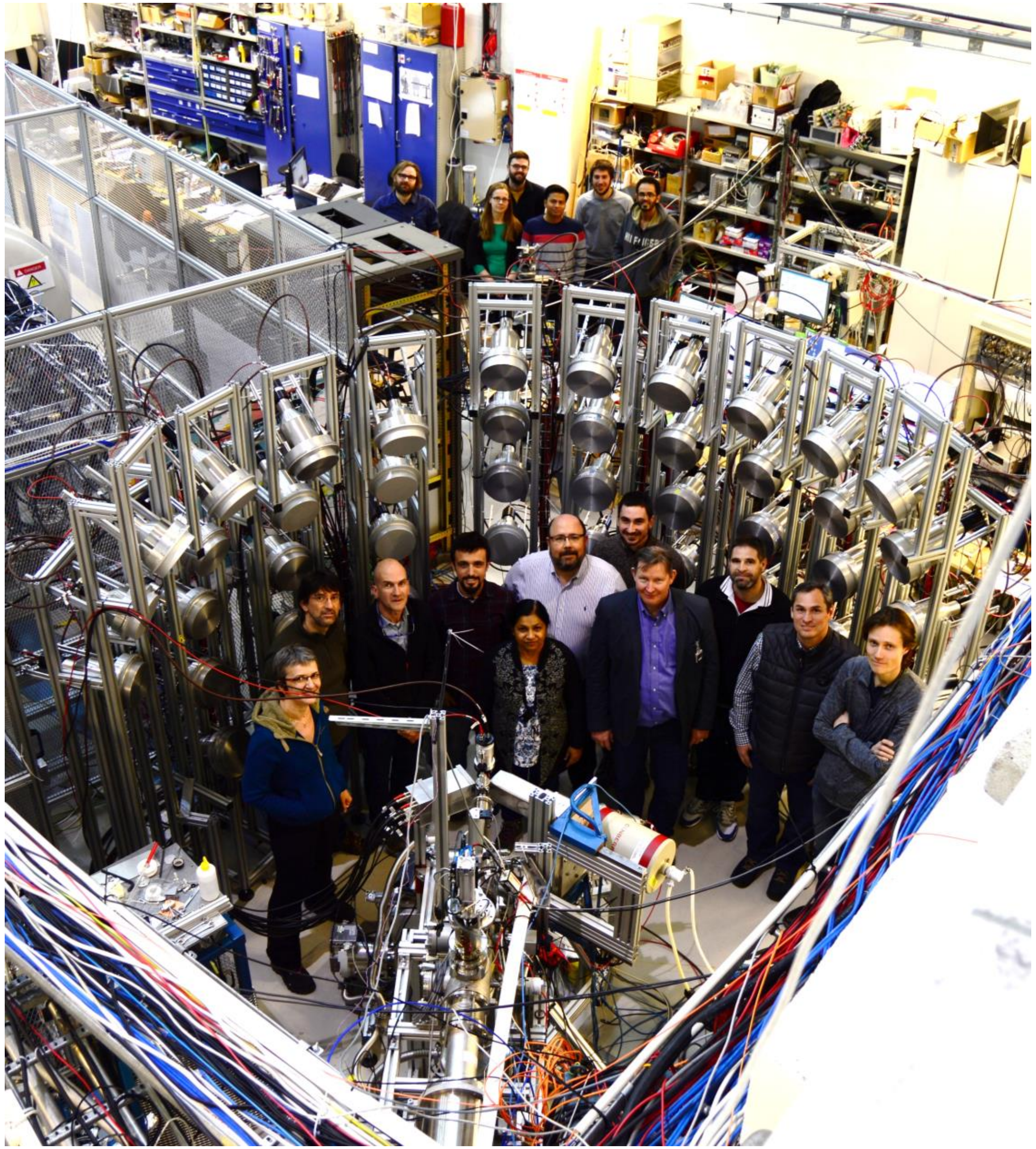
MOdular Neutron time-of-flight SpectromeTER is a detection system designed for DESPEC MONSTER TDR, (2013)

It’s the result of an international collaboration between CIEMAT, JYFL-ACCLAB, VECC, IFIC, and UPC

Main characteristics:

- Low neutron energy threshold
- High intrinsic neutron detection efficiency
- Discriminates between detected neutrons and γ-rays by their pulse shape
- Good time resolution
- The energy of the neutrons is determined with the TOF technique

A. R. Garcia *et al.*, JINST, **7**, (2012) C05012
T. Martinez *et al.*, Nuclear Data Sheets, **120**, (2014) 78



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DAISY

Digital data AcquIsition SYstem

Custom DAQ software developed at CIEMAT

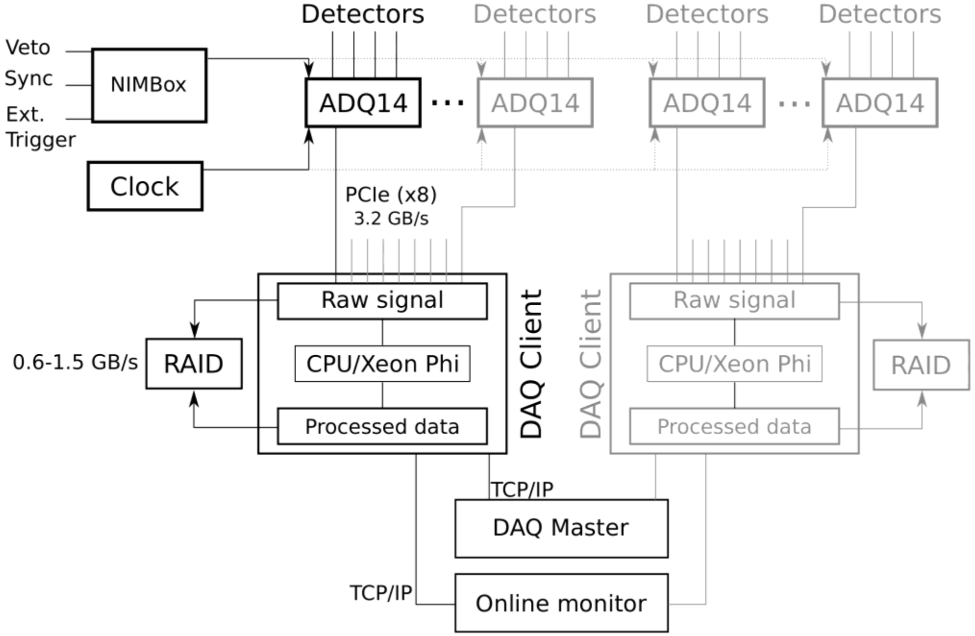
D. Vilamarín, Nucl. Instrum. and Methods A, **1055**, (2023) 168526

Hardware:

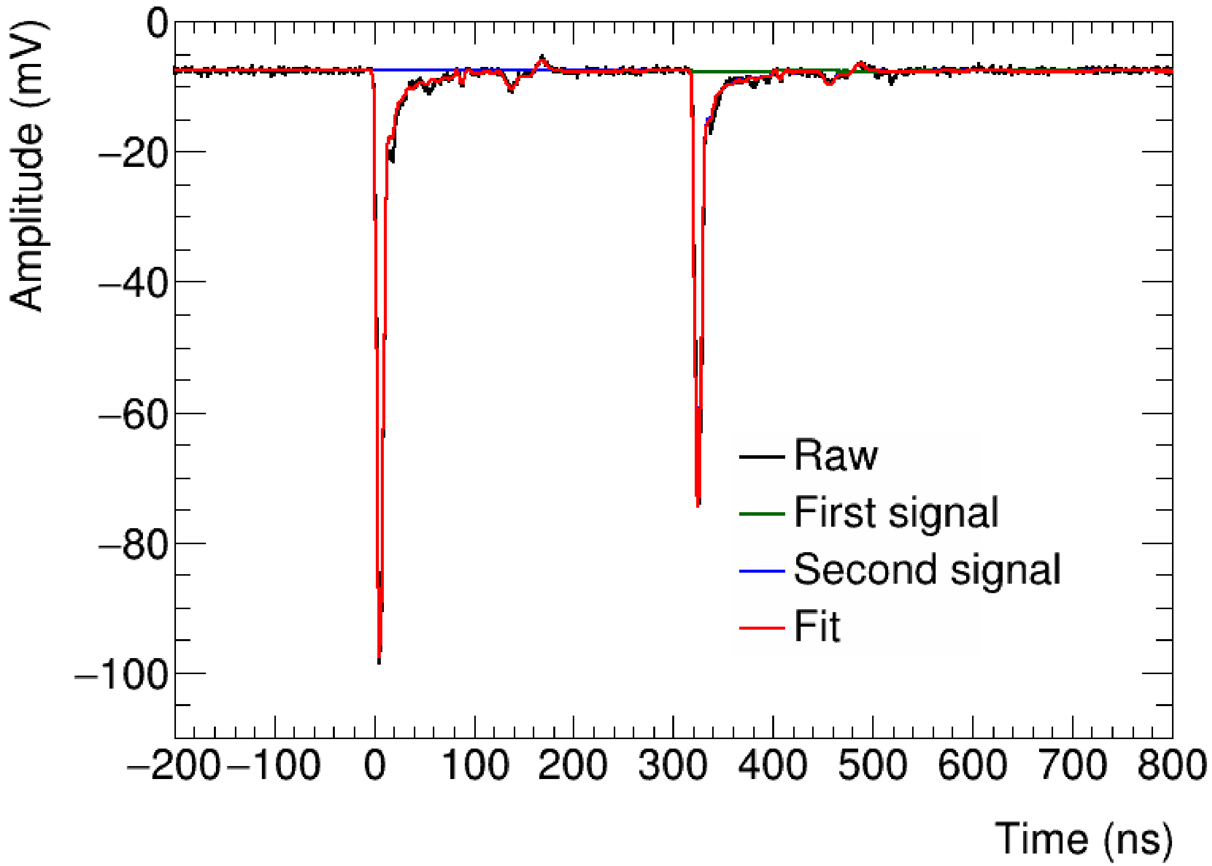
- 15 x ADQ14DC Teledyne SP Devices cards (14 bits, 1 GS/s, 4 ch)
- 2 x Counter/Timer PCIe6612 National Instruments
- NI Octoclock CDA-2990 (10 MHz, 8 ch)
- Wiener NIM/TTL Programmable modules
- 2 x PCs + 2 x PCIe crates
- 3 x 96 TB RAID 6

Integrates custom pulse shape analysis software developed at CIEMAT to analyze signals online:

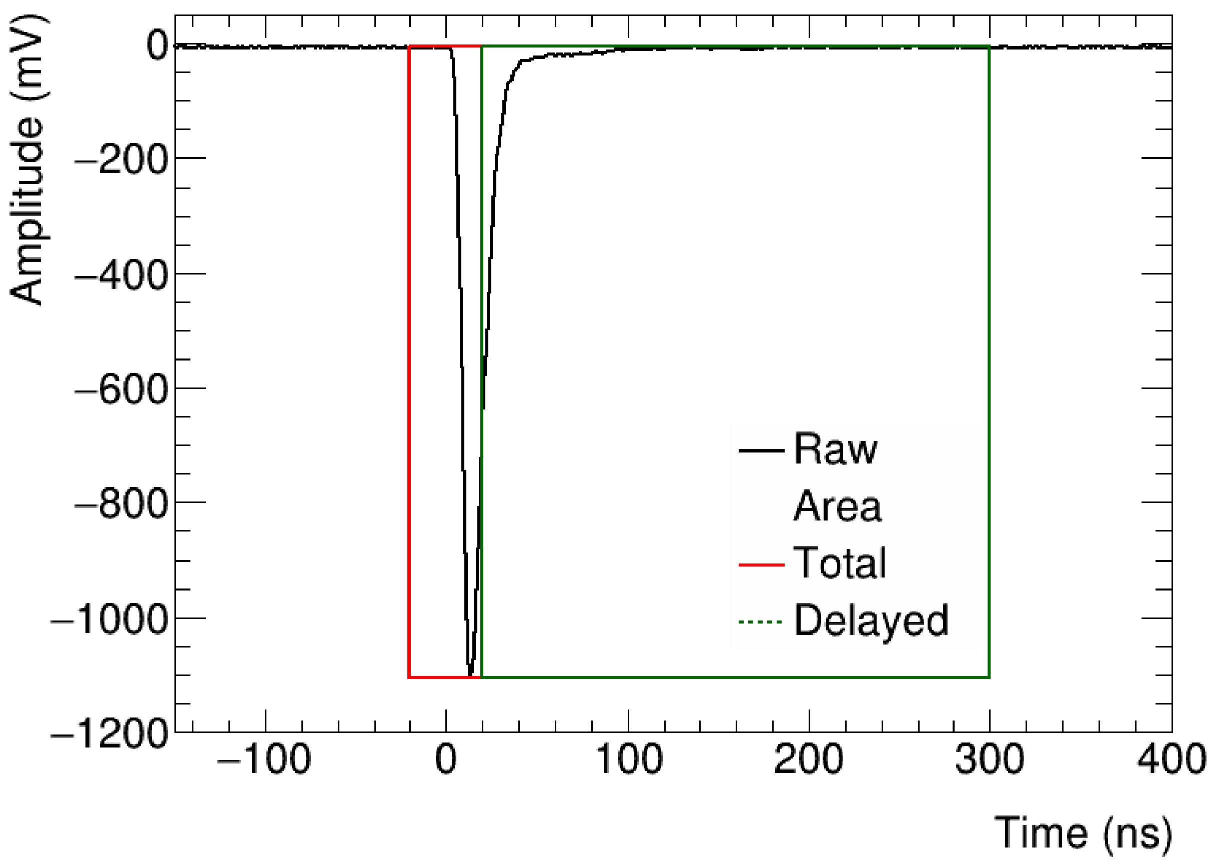
- Resolving pileups
- Without adding dead time



Pulse shape analysis



β-detector frame with the signals fitted to the average signal



MONSTER frame with the signal digitally integrated in regions:

$$PSD = \frac{A_{delayed}}{A_{total}}$$

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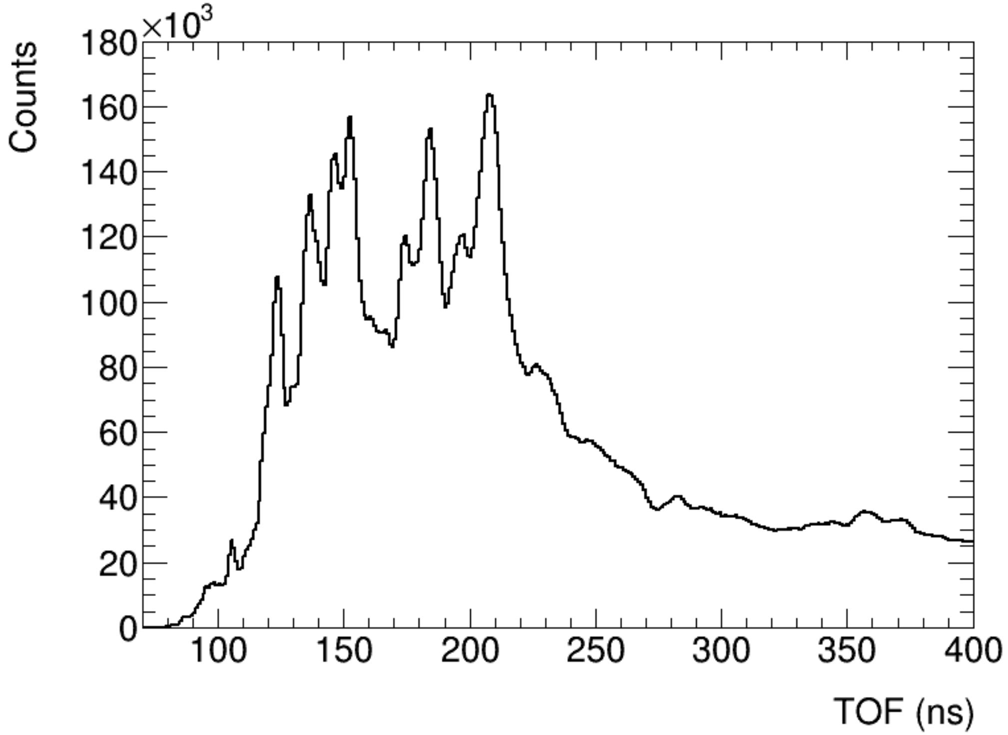
Inverse problem

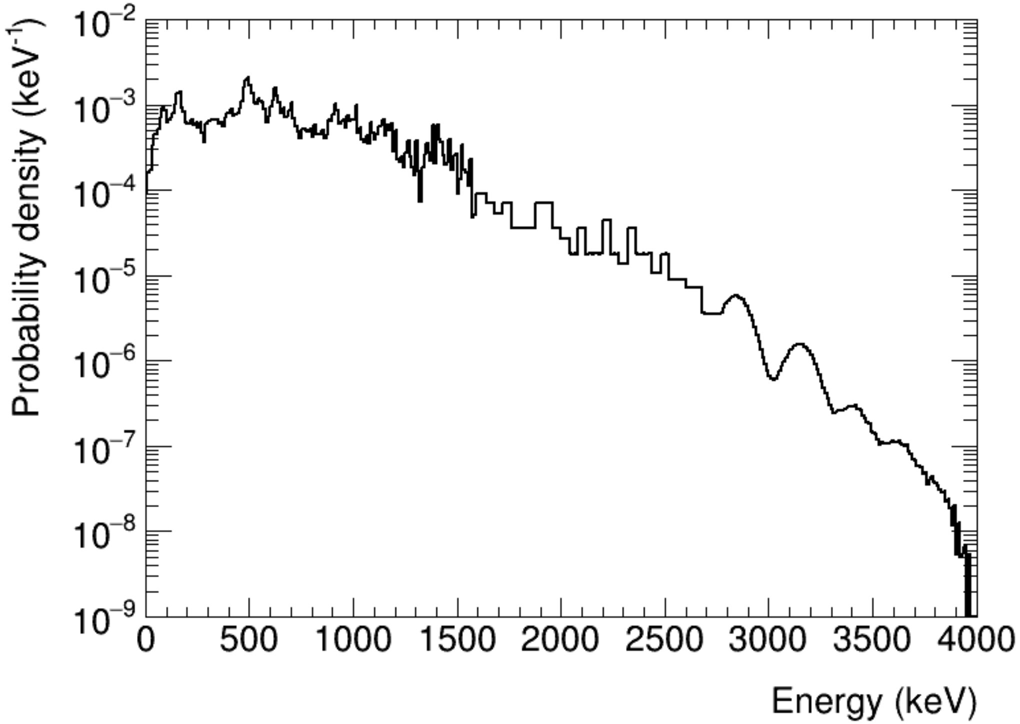
$$TOF = R \cdot E_n$$

TOF spectrum

Response matrix

Neutron energy distribution





Inverse problem

$$TOF = R \cdot E_n$$

TOF spectrum

Response matrix

Neutron energy distribution

The response matrix transforms the original neutron energy distribution into the measured TOF spectrum

What is needed:

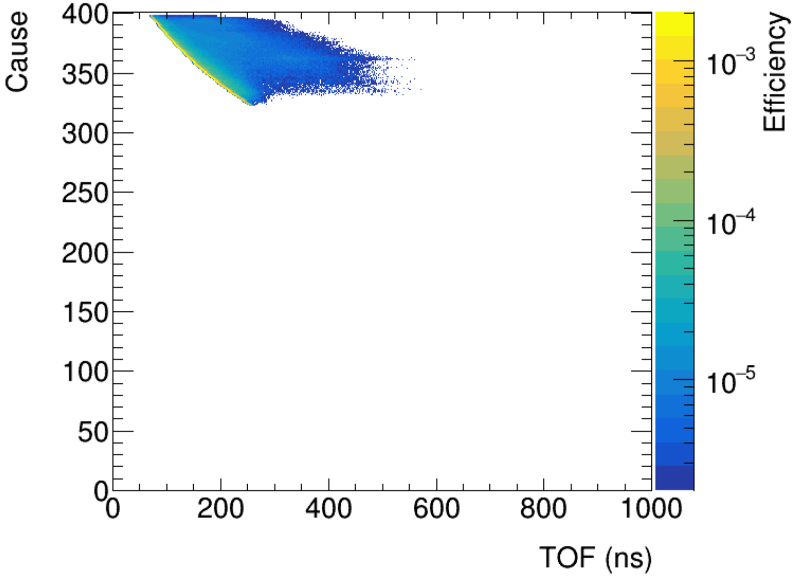
- Method for solving the inverse problem -> Iterative Bayesian method G. D'Agostini, Nucl. Instrum. and Methods A, **362**, (1995) 487
- Construction of the response matrix R covering the whole neutron energy range and providing the TOF response for each considered neutron energy -> Accurate Monte Carlo simulations with Geant4

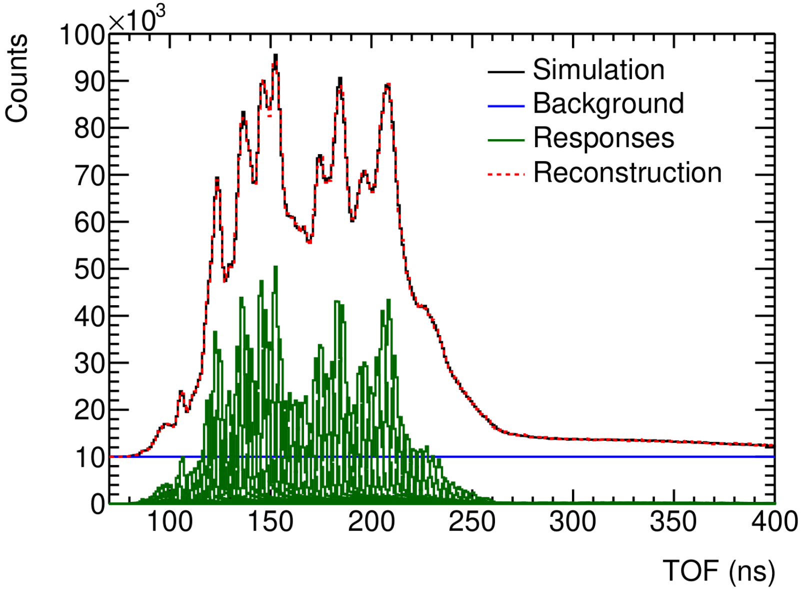
Validation with the analysis of a virtual experiment's TOF data with a known solution (neutron energy distribution):

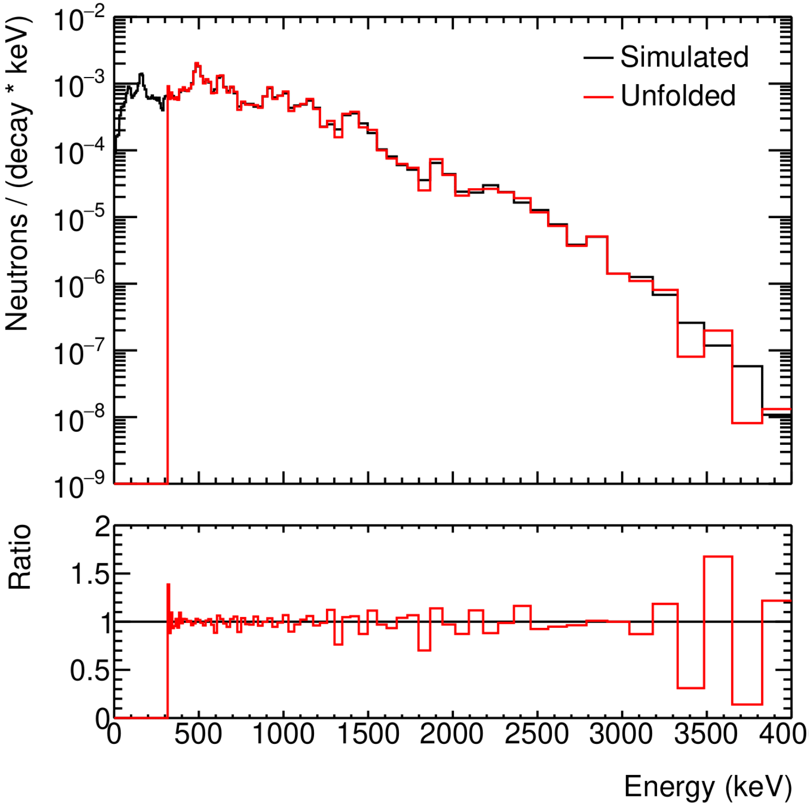
- R is discretized in TOF and E_n. The best binning in TOF and E_n has to be determined
- Study of systematical effects on the obtained solution. Different Rs for different thresholds, background, and β-detection efficiency

Analysis of a realistic β-decay experiment

The realistic experiment combines several experimental effects, such as the flight path and TOF resolutions, the neutron detection threshold, and includes the effect of the β-detector threshold







A very accurate reproduction of the neutron energy distribution is achieved over a large energy range

A. Pérez de Rada Fiol *et al.*, Rad. Phys. Chem., **226**, (2025) 112243

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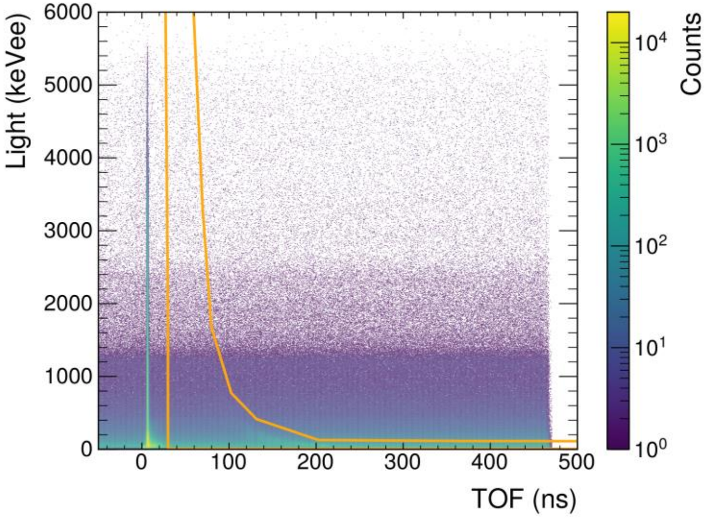
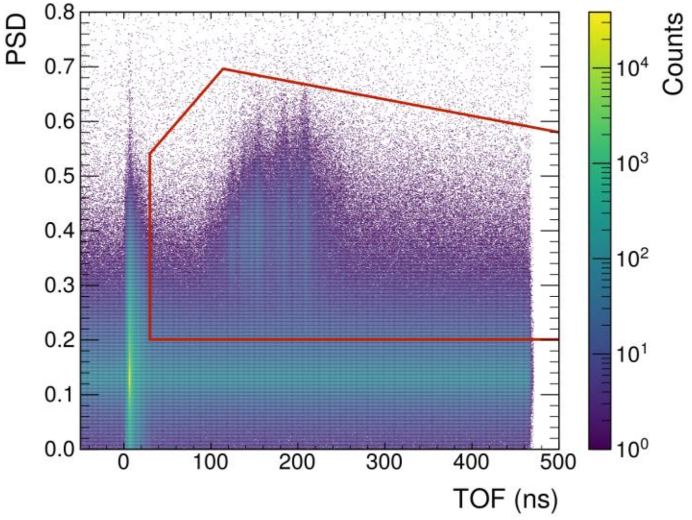
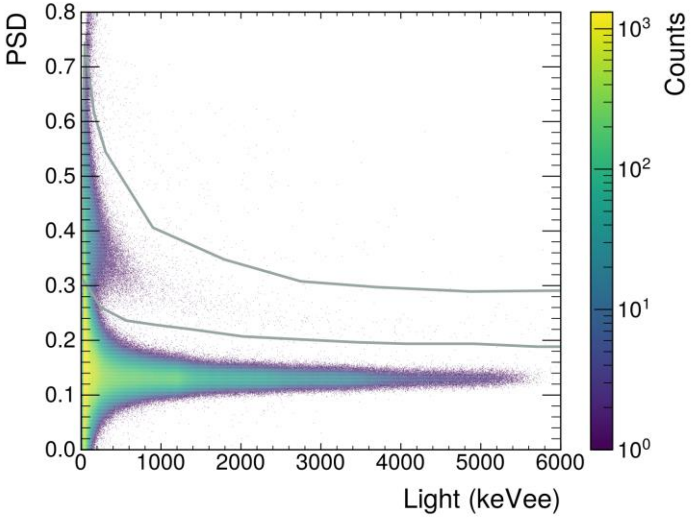
Analysis of the TOF data

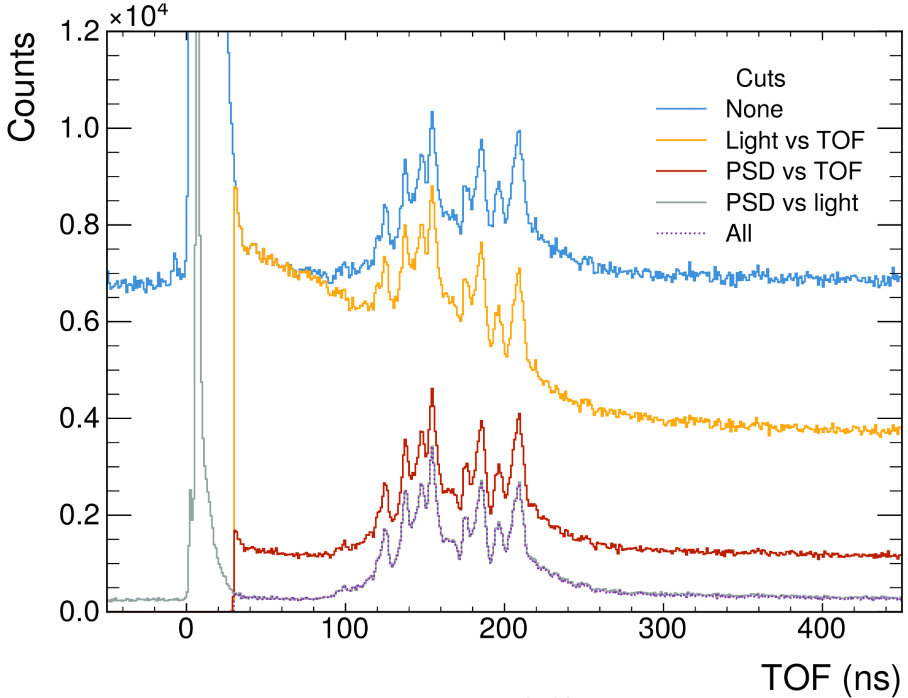






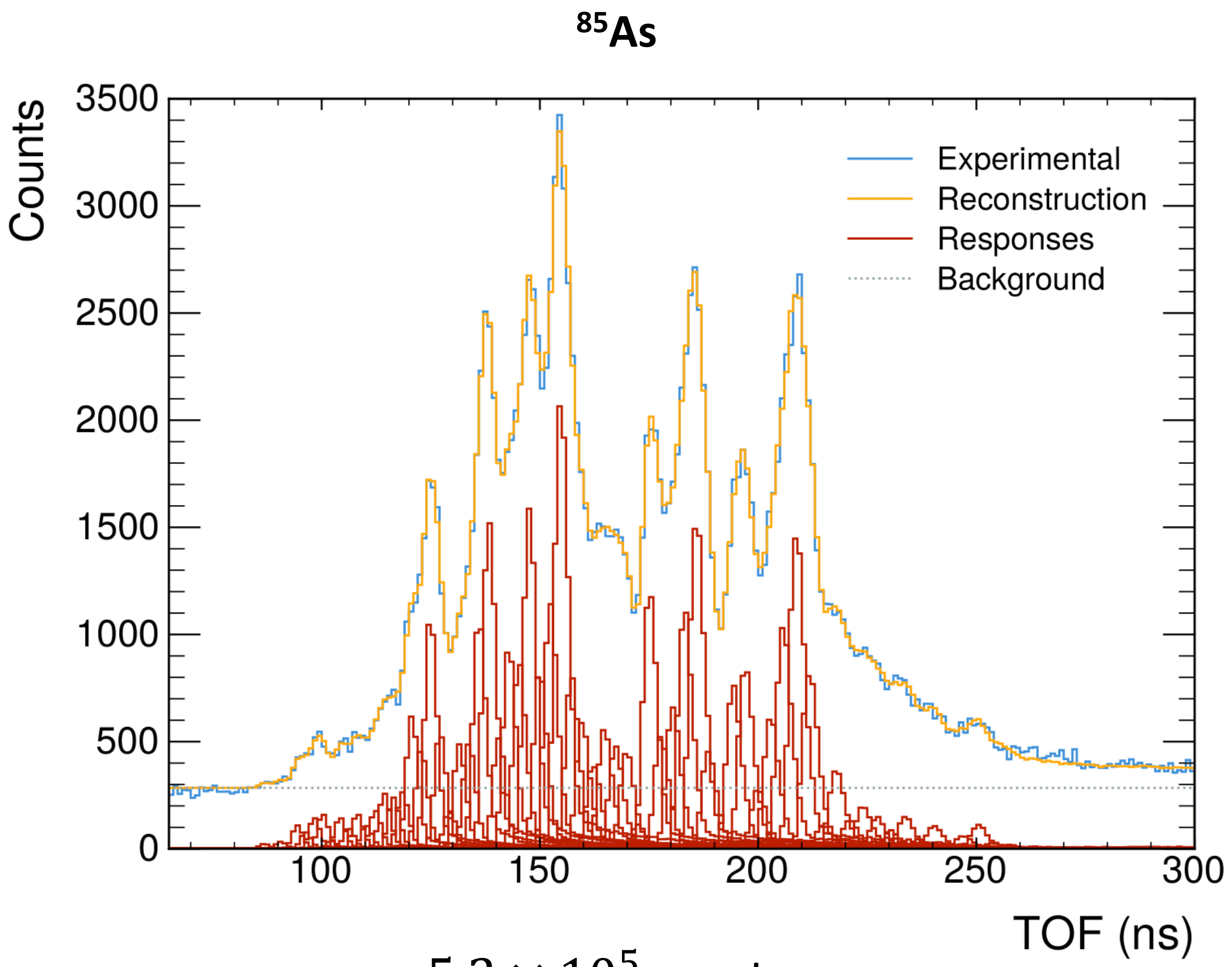
Neutron cut used in plastic scintillators

Different neutron cuts were studied to obtain a “clean” TOF spectrum

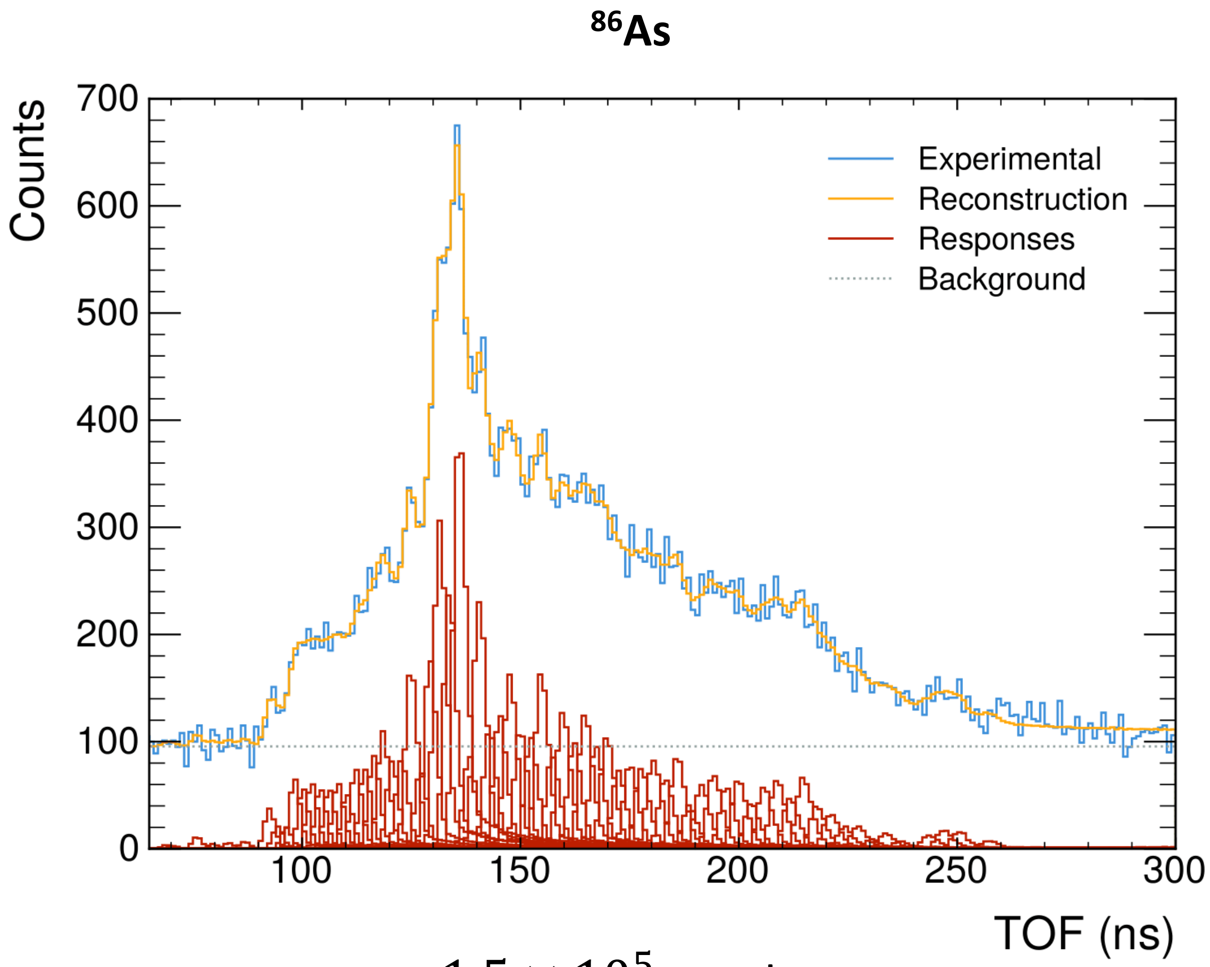


The importance of having PSD: the PSD vs light cut allows for more than one order of magnitude of uncorrelated γ-rays background suppression

Neutron TOF data unfolding



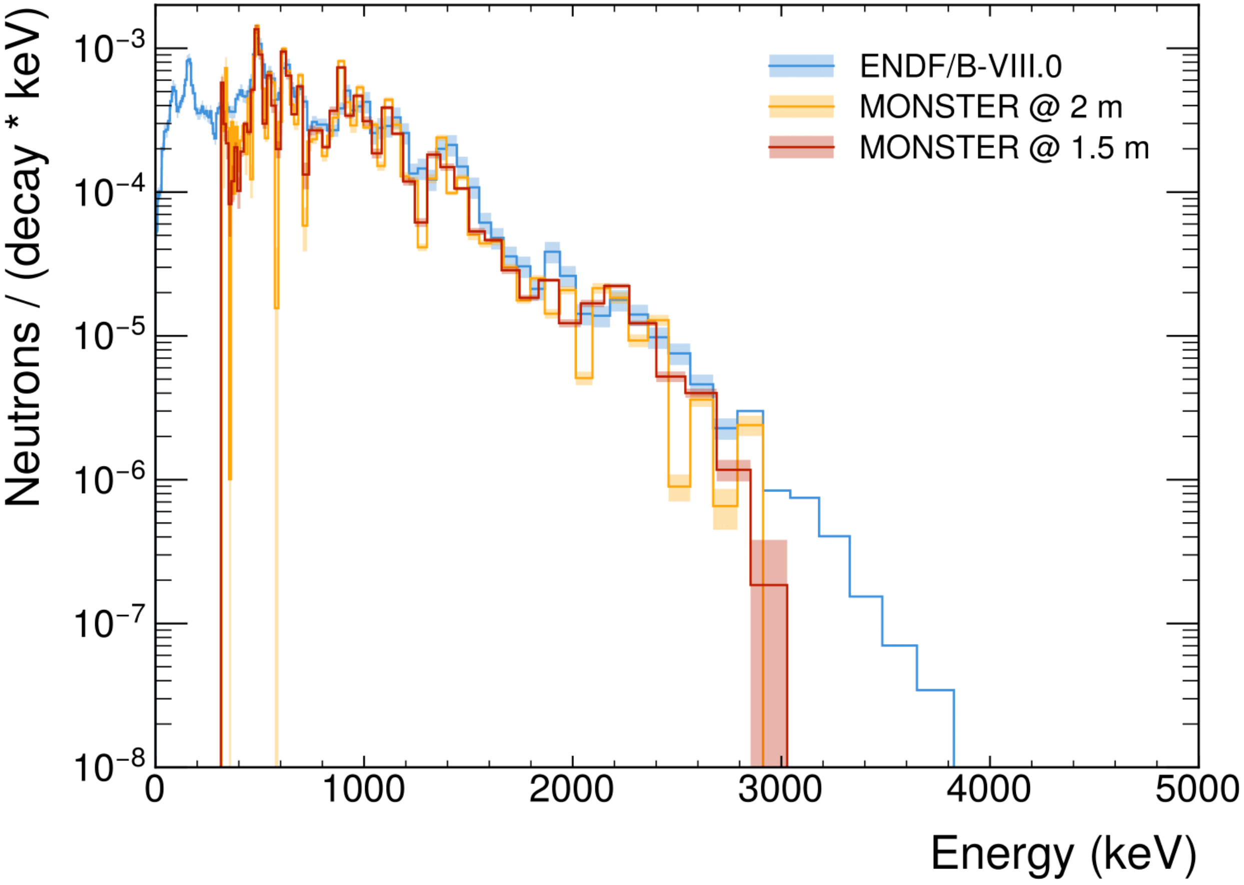
5.2×10^5counts



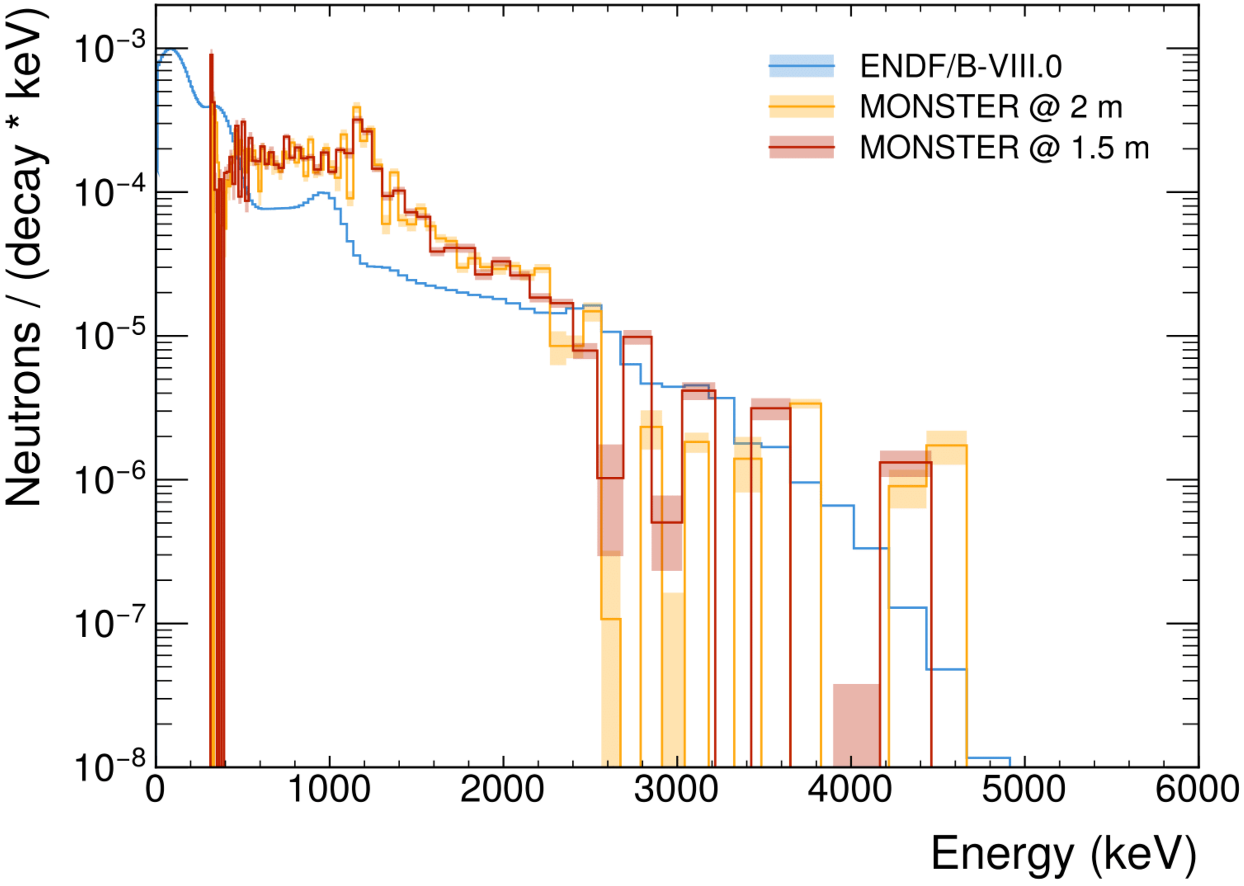
1.5×10^5counts

^{85,86}As β-decays @ IGISOL

^{85}As



^{86}As



Excellent agreement with previous data and evaluations

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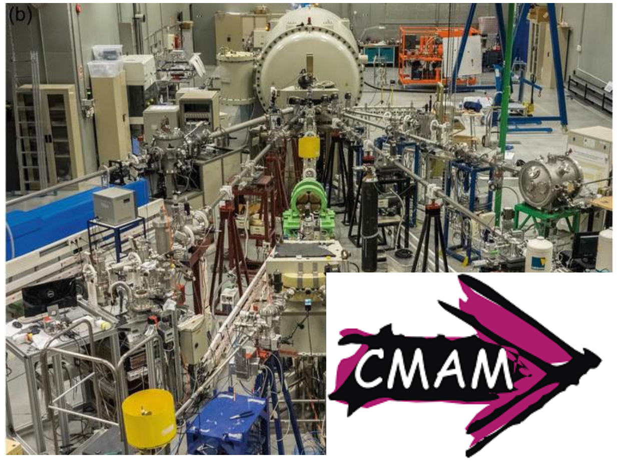
The MANY Collaboration

Two Spanish facilities

Infraestructuras Científicas y Técnicas Singulares



CMAM

HiSPANoS
CNA
Centro Nacional de Aceleradores

UPC

UNIVERSIDAD DE SEVILLA

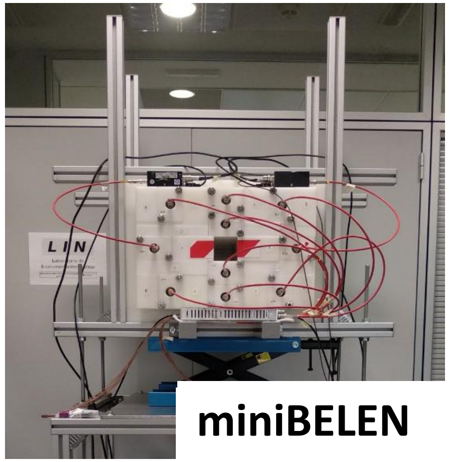
IFIC
INSTITUT DE FÍSICA CORPUSCULAR

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

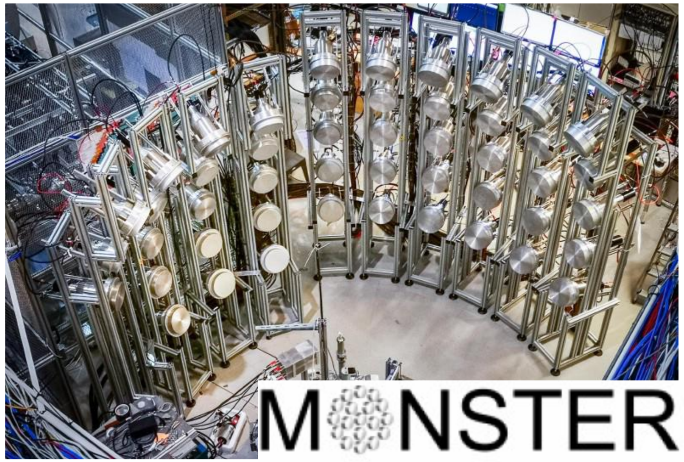
UNIVERSIDAD COMPLUTENSE
MADRID

IEM
Instituto de Estructura de la Materia

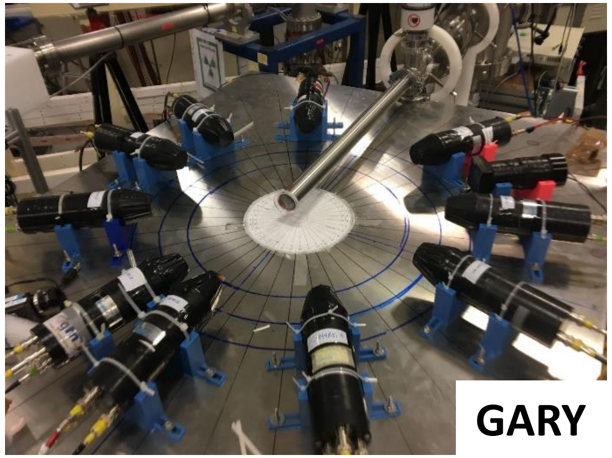
Three Spanish detectors



miniBELEN



MONSTER



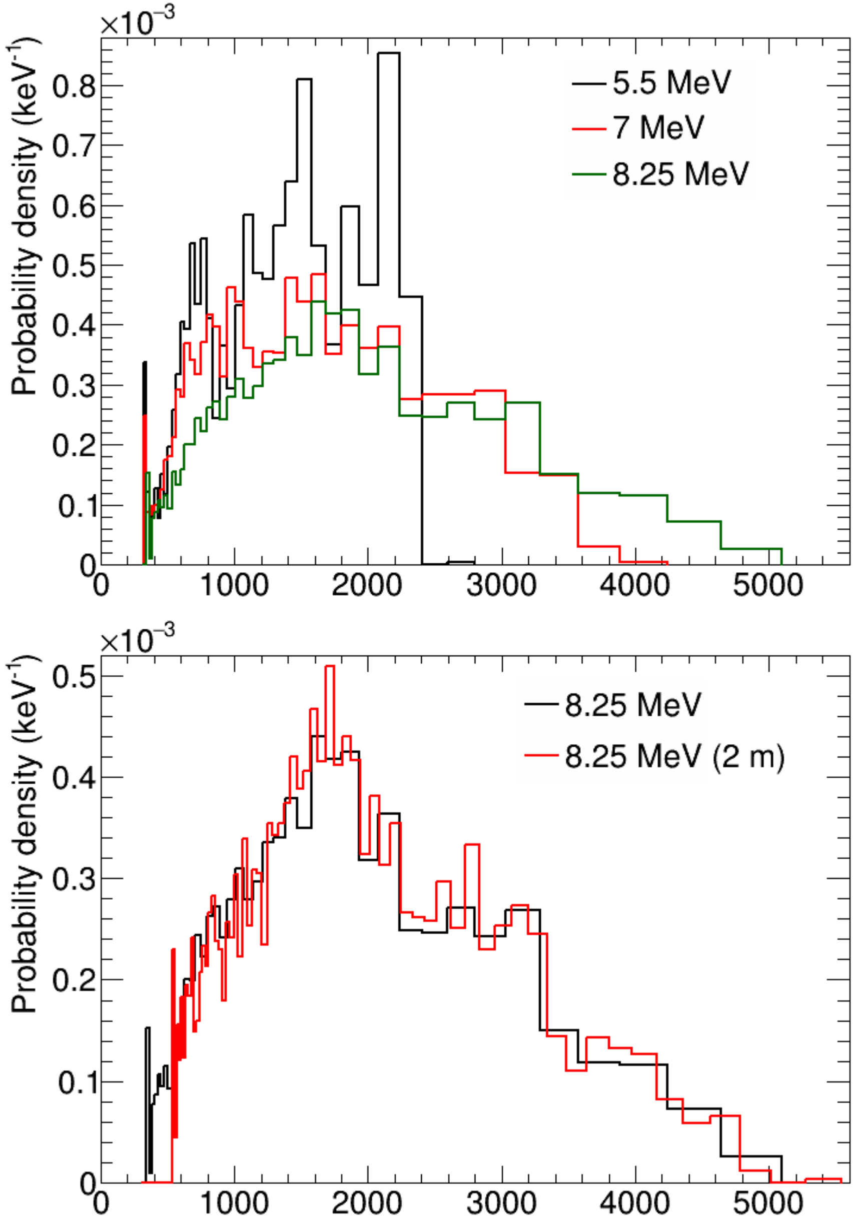
GARY

^{27}Al(α,n)^{30}P reaction @ HiSPANoS

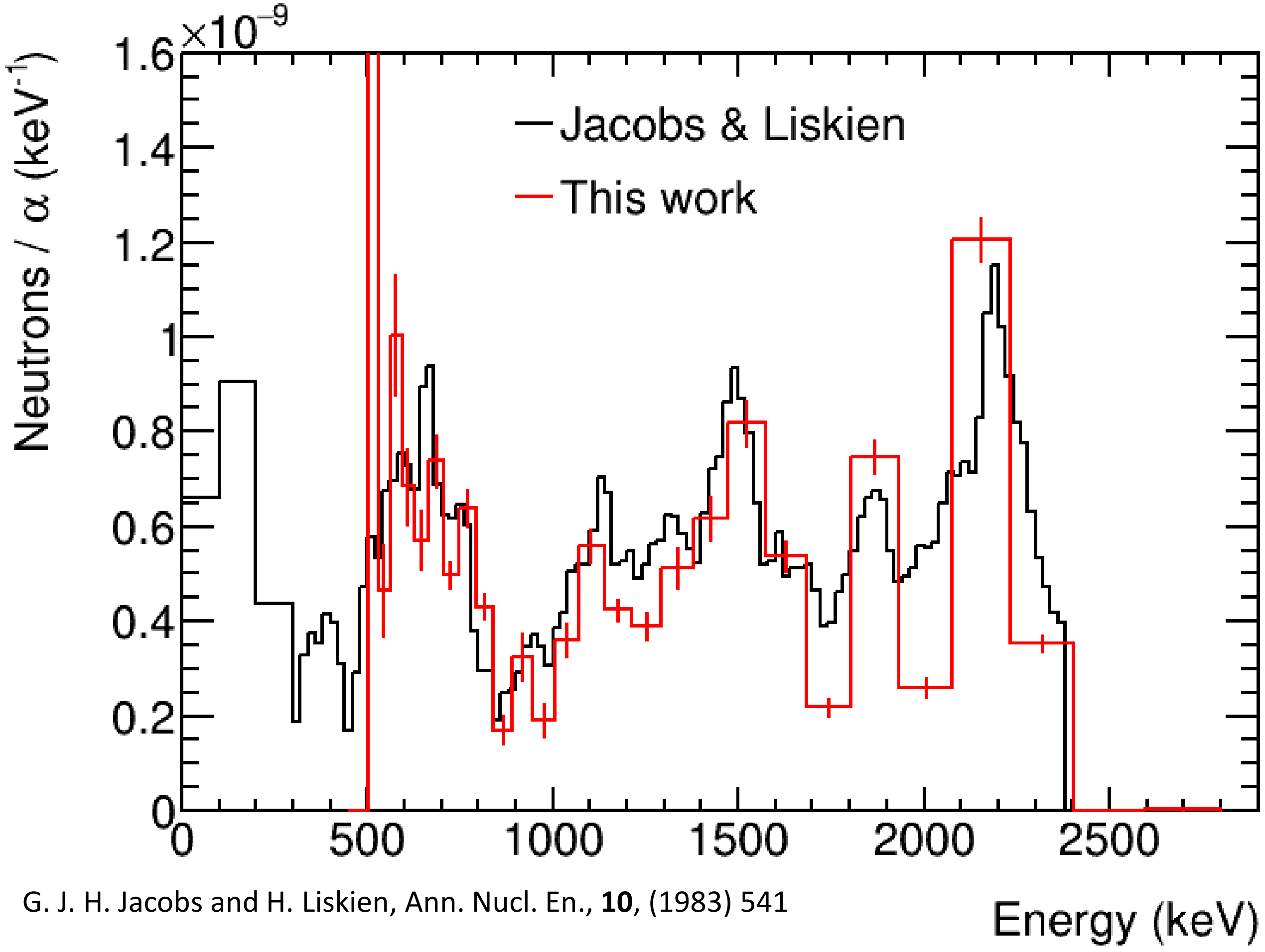
MONSTER module placed at 1 m and 2 m

Thick (300 µm) ^{27}Al (99 % purity) target

E_α = 5.5, 7, and 8.25 MeV
(Buncher not optimized for α-particles)



Comparison with existing data



G. J. H. Jacobs and H. Liskien, Ann. Nucl. En., **10**, (1983) 541

Uncertainties

Jacobs and Liskien:

- Target stability, charge measurement: 2.0 %
- Neutron detection efficiency: 3.2 - 5.2 %
- Integration procedure: 2.6 %
- Statistics: 2.0 %
- Neutron energy determination:
  - 0.5 % @ 200 keV
  - 1.7 % @ 7 MeV

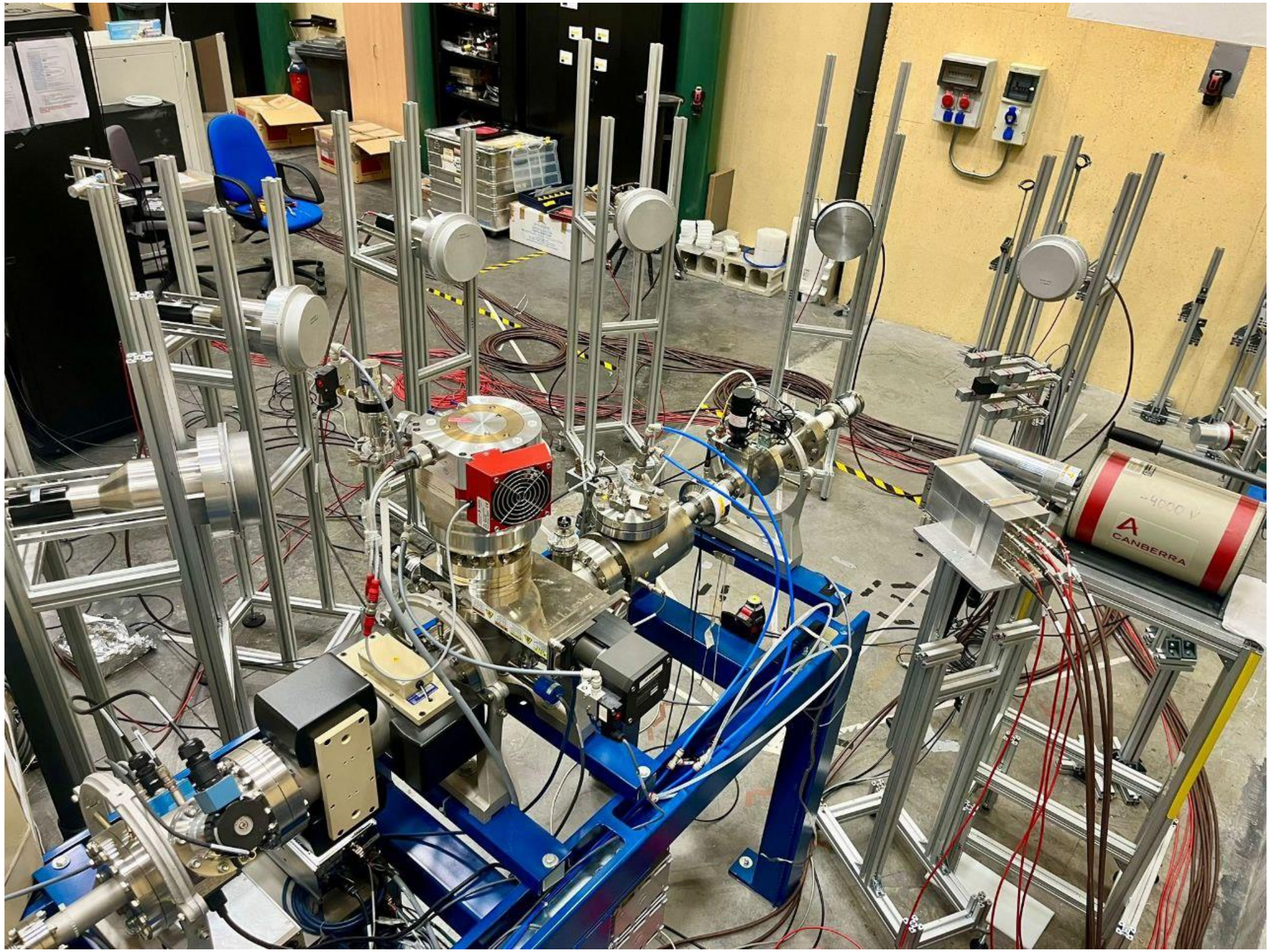
This work:

- Statistical
- Systematic (only):
  - Efficiency
  - Flight path
  - TOF resolution

Neutron yields

Threshold (keV)	Y_n^{JL}/Y_n
500	1.05
900	1.09
1750	1.01

November 2024 measurement



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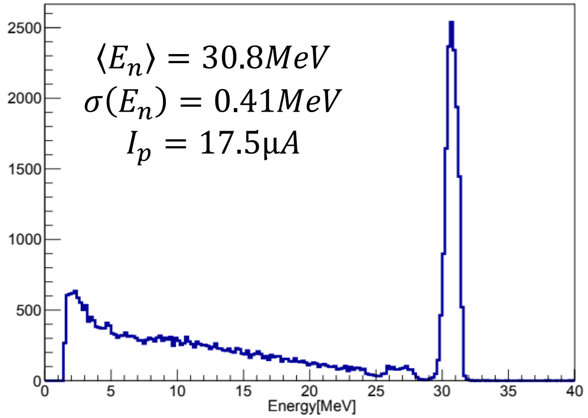
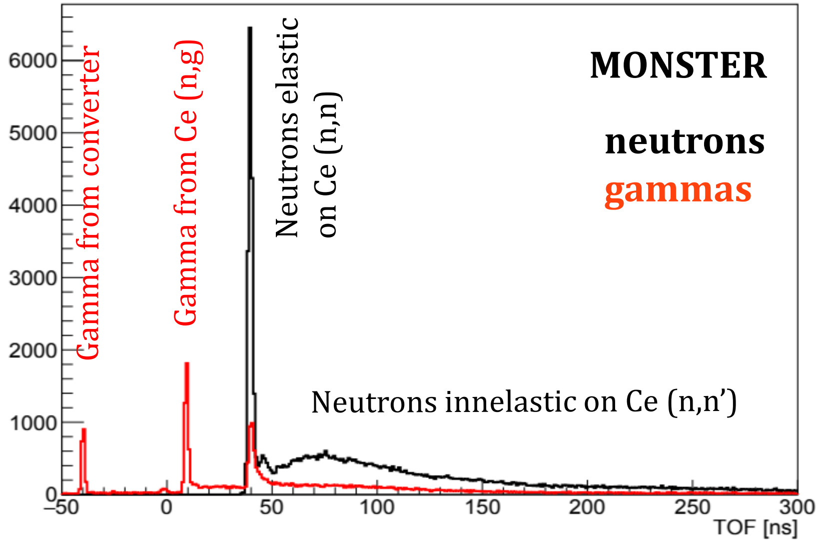
^{140}Ce(n,n’γ)^{140}Ce @ NFS - Setup

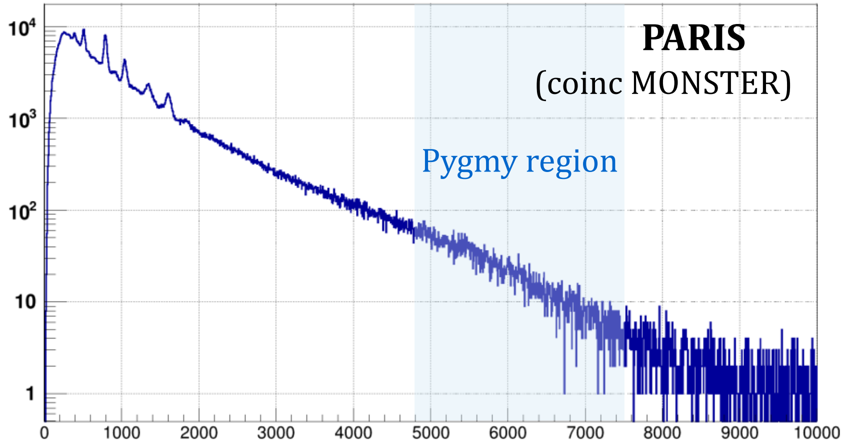
- Pygmy dipole resonance study with MONSTER and PARIS
- Colaboration between CEA-Irfu, IJCLab, CIEMAT, IFJ PAN, GANIL, LPC, IPN, …

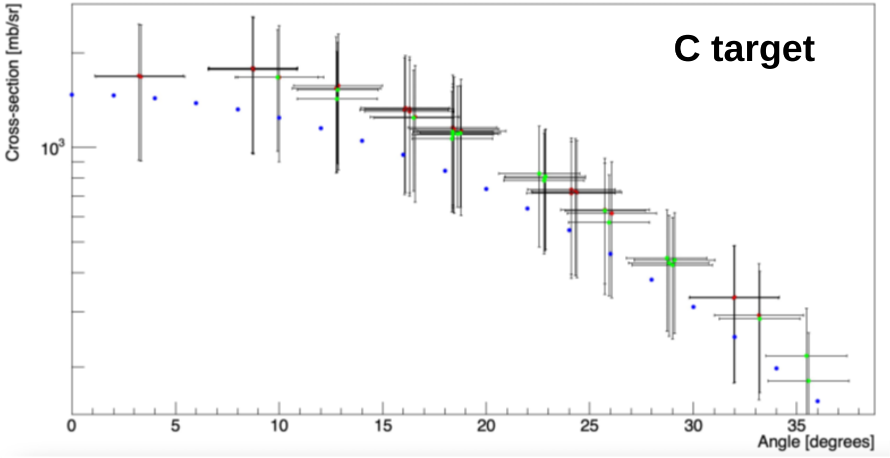
Neutron beam
(^{7}Li(p,n)^{7}Be reaction)

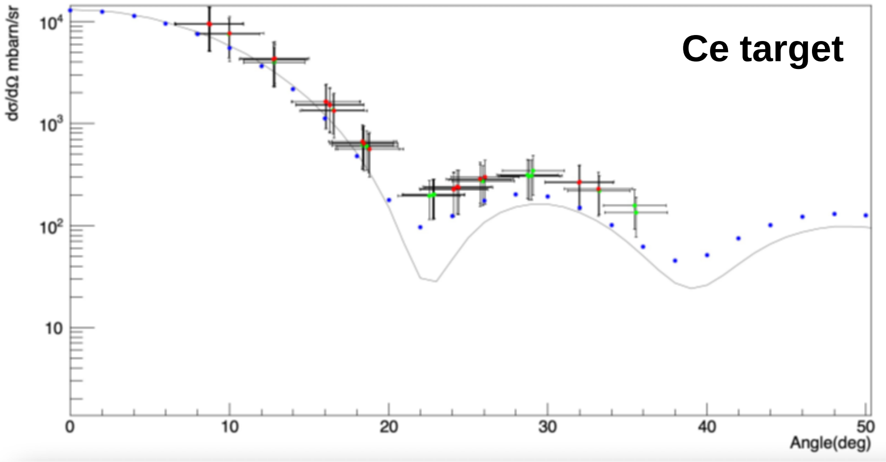


^{140}Ce(n,n'γ)^{140}Ce @ NFS – Preliminary results









Future measurements

(α,xn) reactions @ CNA and CMAM:

- ^{27}Al
- ^{9}Be

β-delayed neutron emission @ ALTO:

- ^{83,84}Ga
- ^{81}Zn

Neutron inelastic scattering @ NFS:

- Accessing the structure of the pygmy dipole resonance through neutron inelastic scattering at GANIL-SPIRAL2/NFS

And other proposals to come!

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Summary and conclusions

The main takeaways from this presentation are:

- Commissioning of MONSTER and its DAQ system DAISY:
  - Successful commissioning and ready to be used (for other kind of experiments too!)
  - Good neutron/γ-ray discrimination capabilities
  - Excellent energy resolution
- Validation of a new data analysis methodology for neutron TOF spectroscopy:
  - Unfolding of the TOF spectrum with a methodology based on the iterative Bayesian unfolding method and accurate Monte Carlo simulations
  - Validation of the unfolding methodology with a simulated experiment
- Results:
  - Procurement of the ^{85}As β-delayed neutron spectrum and the "first" ^{86}As β-delayed neutron spectrum
  - Demonstrated viability of (α,xn) and other reaction measurements with MONSTER
- Future measurements are being planned

The MONSTER Collaboration today

	CIEMAT	VECC	JYFL-ACCLAB	IFIC/UPC	Total
Detectors	45	15	8	6	**74**
Channels	56	8	8	0	**72**