Innovative analysis technique of neutron time-of-flight spectra, validation, and first results in (α,n) reaction studies

Alberto Pérez de Rada Fiol

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

MONSTER Collaboration

MANY Collaboration

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- ^{85,86}As β-decays @ IGISOL

- Introduction
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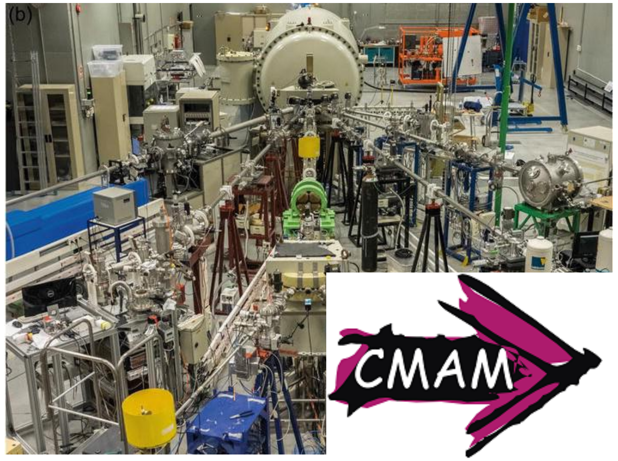
The MANY Collaboration

Two Spanish facilities

Infraestructuras Científicas y Técnicas Singulares



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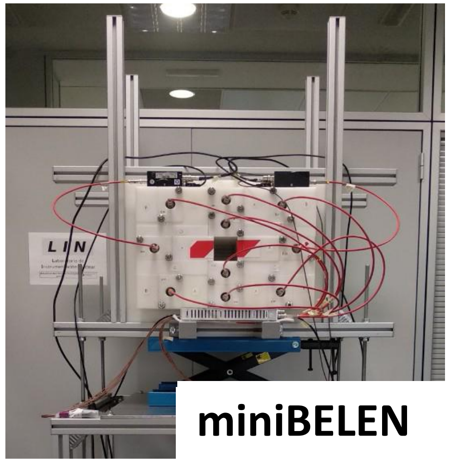
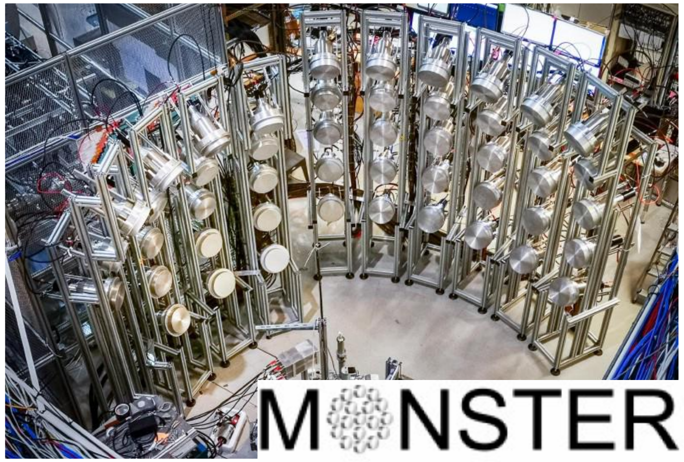
Universidad Complutense Madrid

IEM
Instituto de Estructura de la Materia

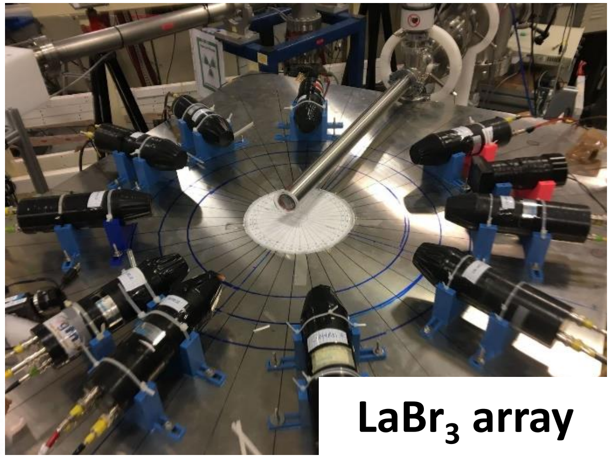
Three Spanish detectors



miniBELEN



MONSTER



$LaBr_3$ array

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Motivation

Knowledge on (α,Xn) reactions is required in several fields:

- **Nuclear structure.** Most of our actual experimental knowledge on (α,Xn) reactions comes from nuclear structure experiments between the 1950s and the 1970s
- Neutron background in underground experiments (nuclear astrophysics, **Dark Matter**) due to radiogenic α-decay chains
- **Nuclear astrophysics.** Neutron sources in collapsing stars linked to the r-process. E_α below ~1 MeV (around the Gamow peak)
- **Nuclear technologies, non-proliferation and homeland security.** α-emitters present in fresh/irradiated nuclear fuels can create a neutron source through (α,Xn) reactions with (light) surrounding nuclei: fluorine, oxide and carbide fuels, vitrified nuclear waste…
  - Determination of the ^{235}U enrichment
  - NDAnalysis of irradiated fuels / fuels enriched in MA / MOX fuels
  - Neutron source term in the deep geologic repository

SaG4n
E. Mendoza *et al.*, Nucl. Instrum. and Methods A, **960**, (2020) 163659
https://win.ciemat.es/SaG4n

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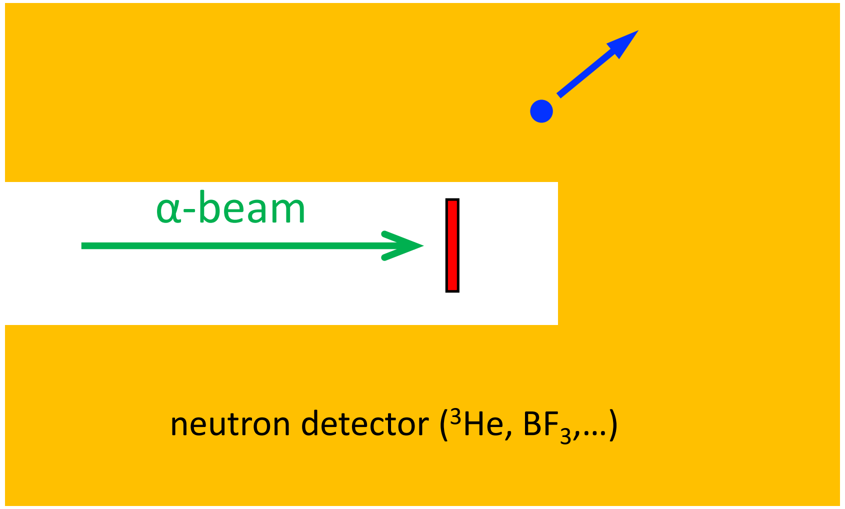
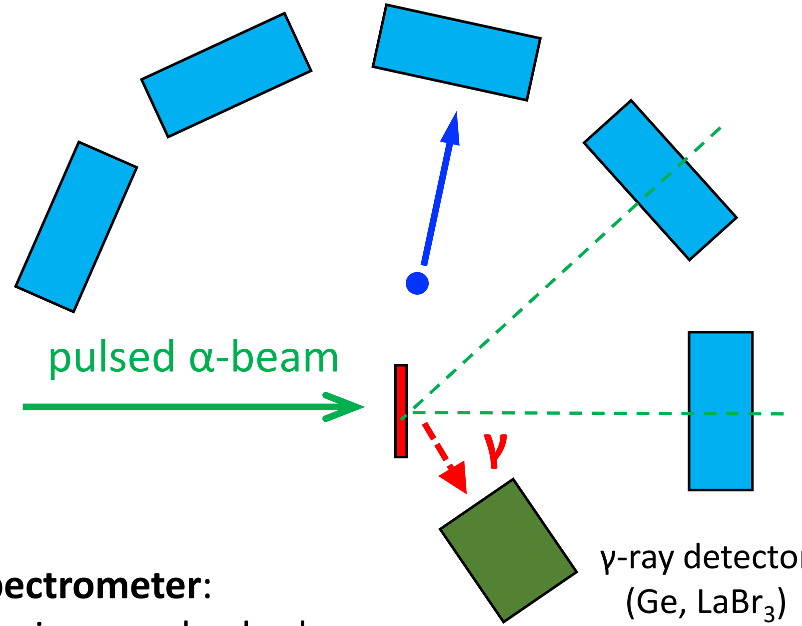
Measurement of (α,n) cross sections





4π neutron long counter:

- Continuous and pulsed α-beam
- Neutron detection efficiency $\varepsilon_n \neq \varepsilon_n(E_n)$
- Weak dependence on the angular distribution
- High efficiency (> 20%)
- Insensitive to γ-ray background

See talk by A. Tarifeño and N. Mont on the **miniBELEN** detector

TOF spectrometer:

- Requires a pulsed α-beam.
- Provides the cross section and E_n (via TOF)
- Possible correlation with γ-rays
- Information for the eff correction $\varepsilon_n(E_n)$
- Requires measurements at different angles
- Low efficiency (~ 1%)
- Possible neutron/gamma discrimination

This talk about the **MONSTER** detector

MONSTER

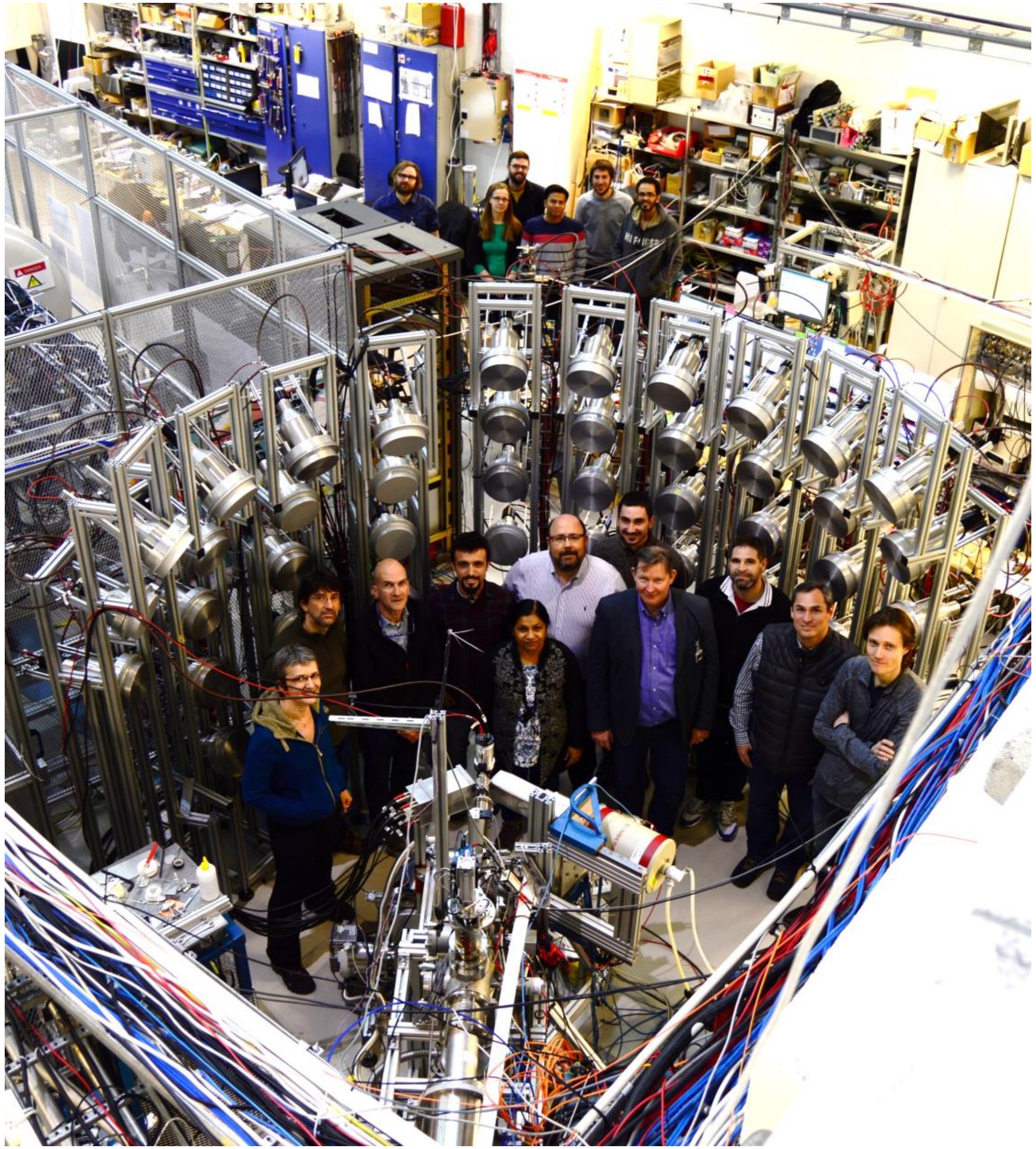
MOdular **N**eutron time-of-flight **S**pectrome**TER** is a detection system designed for DESPEC

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

DAISY

Digital data AcquIsition SYstem

Custom DAQ software developed at CIEMAT

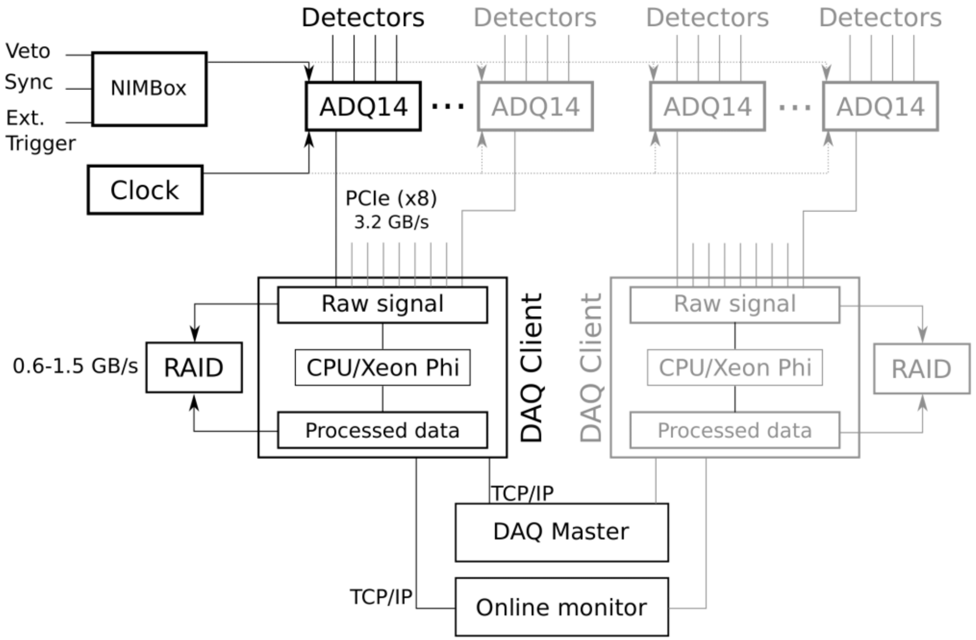
D. Villamarín *et al.*, Nucl. Instrum. and Methods A, **1055**, (2023) 168526

Hardware:

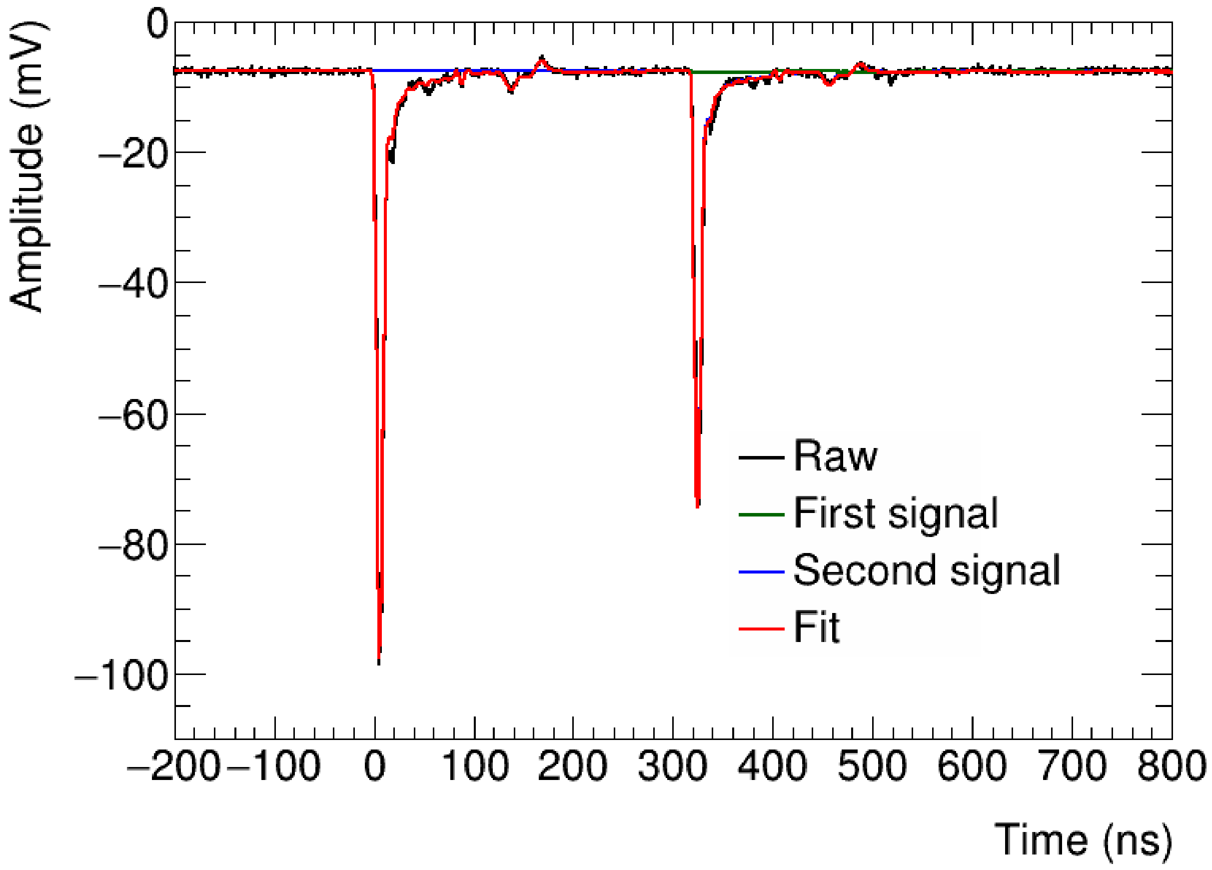
- 15 x ADQ14DC Teledyne SP Devices cards (14 bits, 1 GS/s, 4 ch)
- 2 x Counter/Timer PCIe6612 National Instruments
- NI Octoclock CDA-2990 (10 MHz, 8 ch)
- Wiener NIM/TTL Programmable modules
- 2 x PCs + 2 x PCIe crates
- 3 x 96 TB RAID 6

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

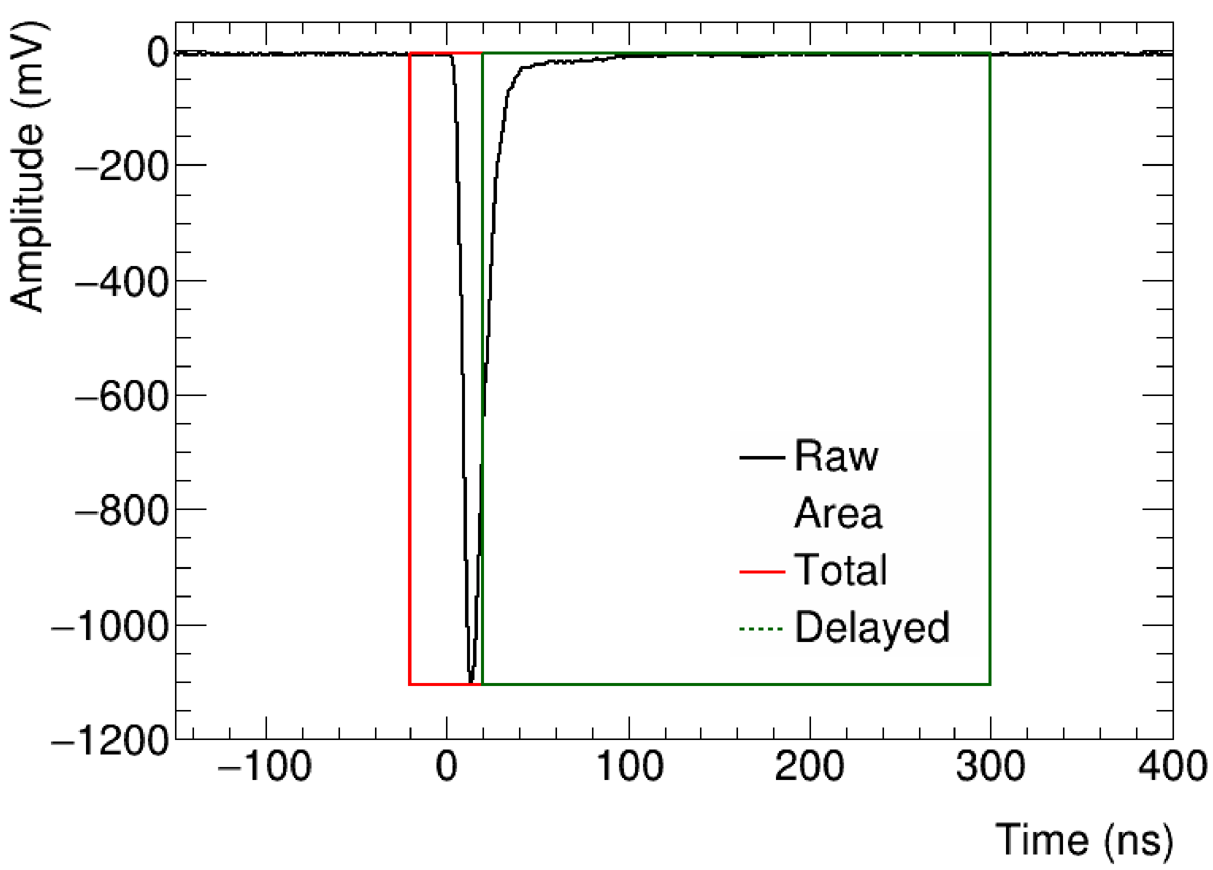
- Resolving pileups
- Without adding dead time



Pulse shape analysis



Frame with two signals fitted to the average signal (β-detector)



MONSTER frame with the signal digitally integrated in regions:

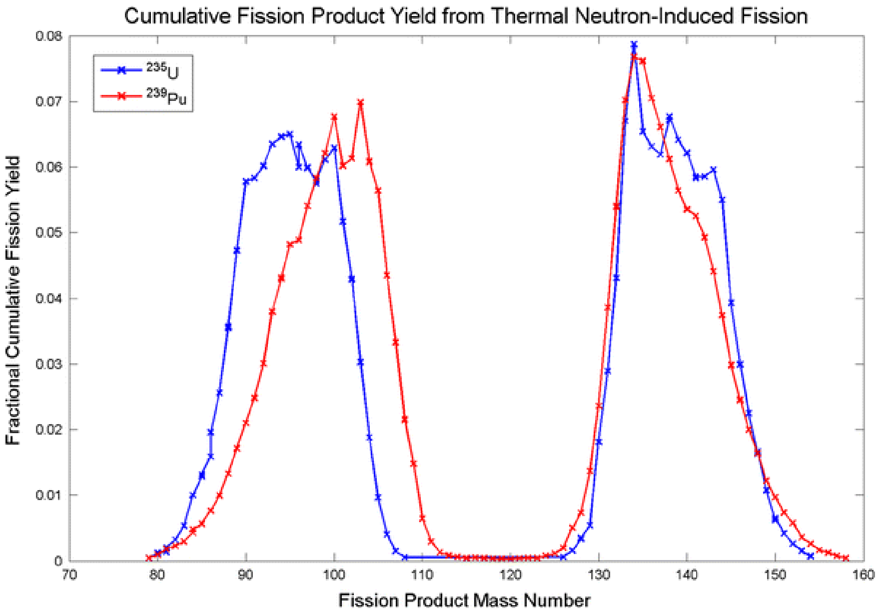
$$PSD = \frac{A_{delayed}}{A_{total}}$$

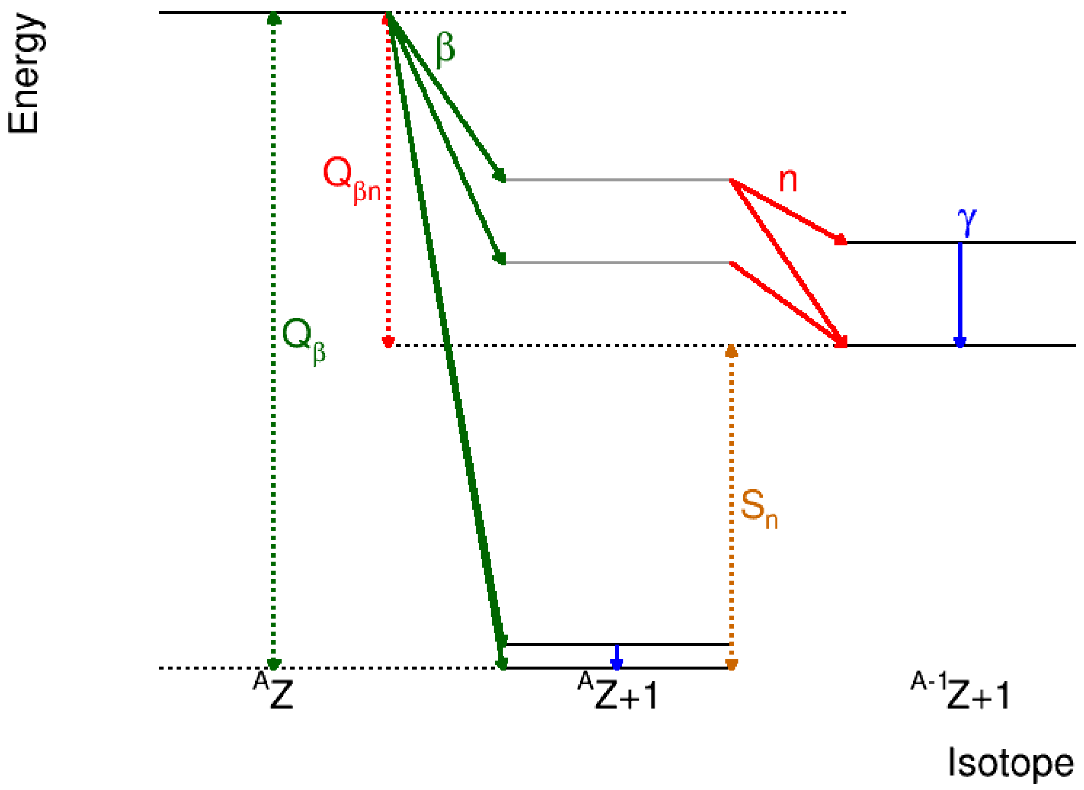
β-delayed neutron emission

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)

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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
- 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

Bayes theorem

The ingredients of the Bayes theorem:

- C_i: independent causes -> neutron energy distribution
- E_j: effects -> TOF spectrum
- $P(E_j|C_i)$: response matrix

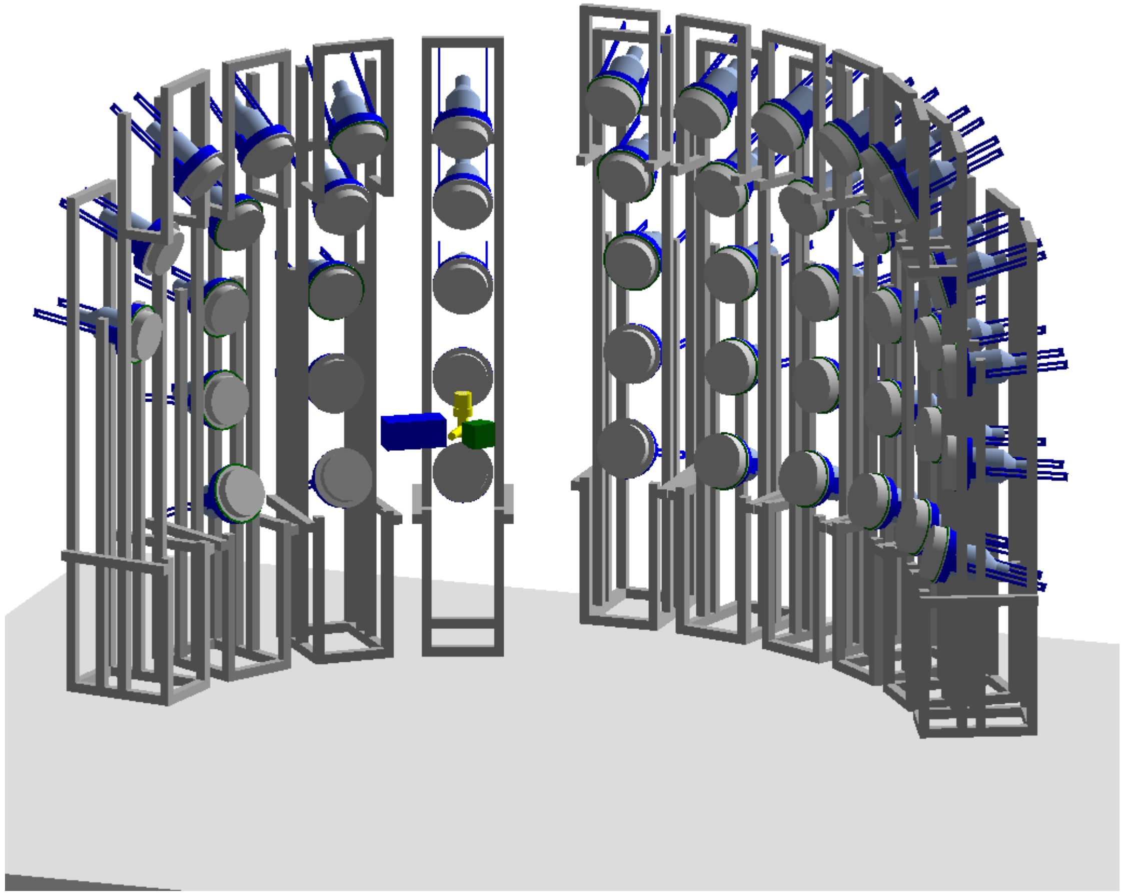
$$P(C_i|E_j) = \frac{P(E_j|C_i)P_0(C_i)}{\sum_{l=1}^{n_C} P(E_j|C_l)P_0(C_l)}$$

The unfolding is done applying an iterative Bayesian method to obtain the neutron energy spectrum:

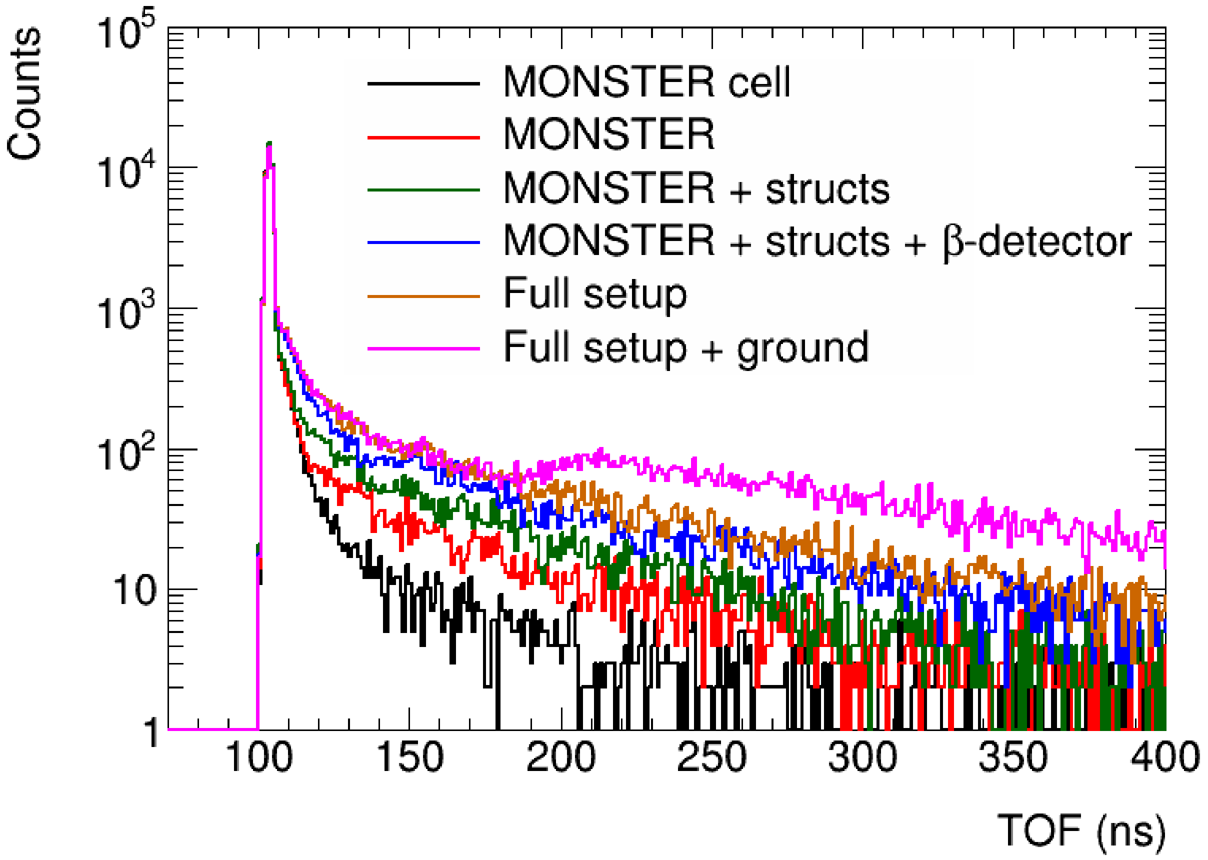
G. D'Agostini., Nucl. Instrum. and Methods A, **362**, (1995) 487

- Start from a uniform distribution: $P_0(C_i) = 1/n_C$
- Obtain the new $\widehat{\boldsymbol{P}}(C)$ distribution
- Replace $\widehat{\boldsymbol{P}_0}(C)$ by $\widehat{\boldsymbol{P}}(C)$ and repeat until a stable solution is reached

Monte Carlo simulation of the TOF response function



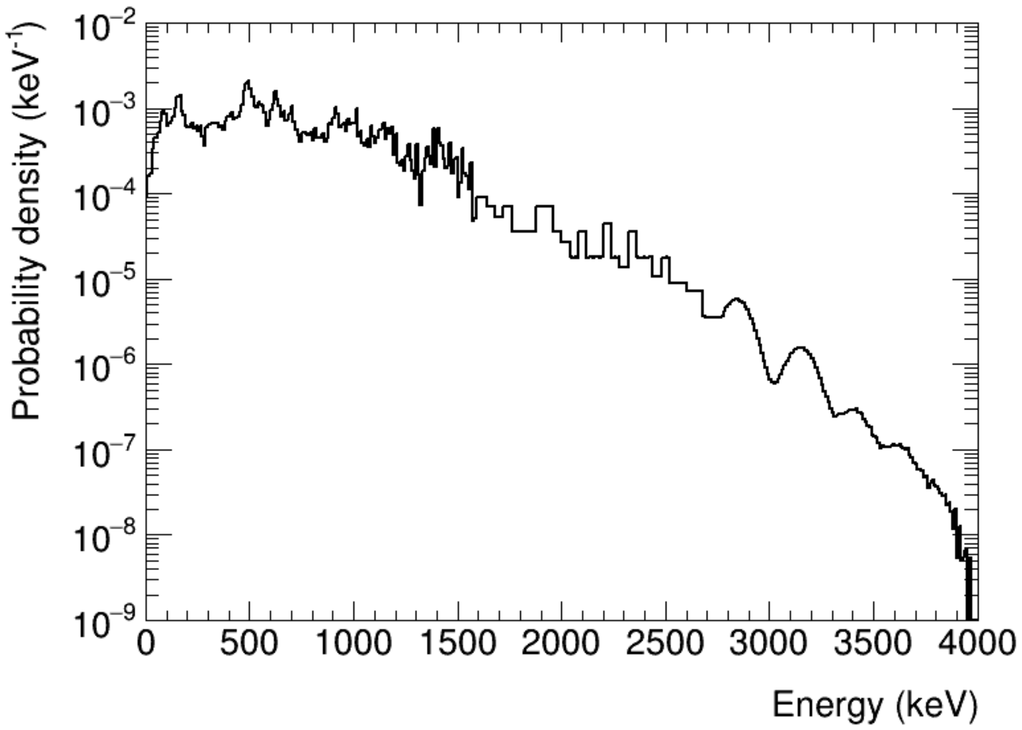
Very detailed simulated setup, including all relevant geometries and light yield curves



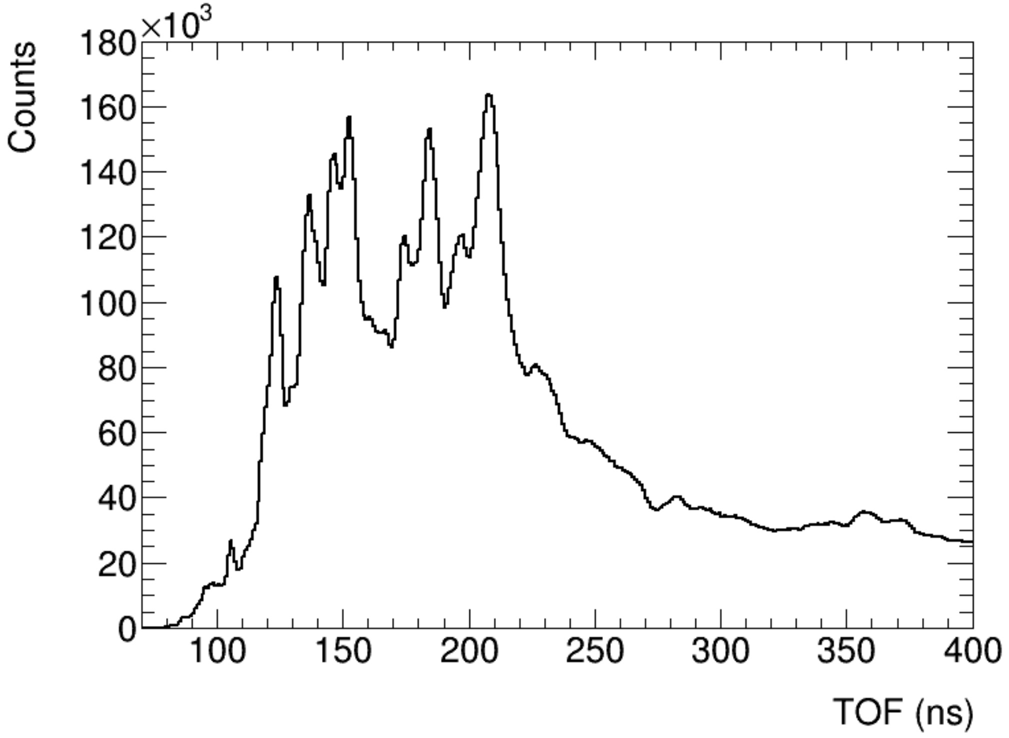
TOF response to 2 MeV neutrons for different setups, including effects due to time and spatial resolutions

Only the array at 2 m is considered in this analysis

Simulated β-decay of an ^{85}As-like nucleus

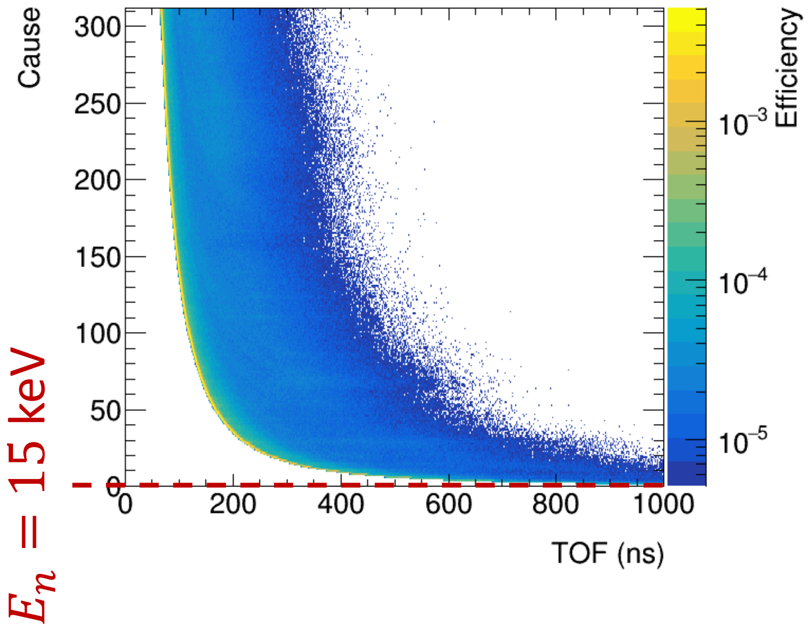


^{85}As β-delayed neutron energy spectrum extracted from ENDF/B-VIII.0

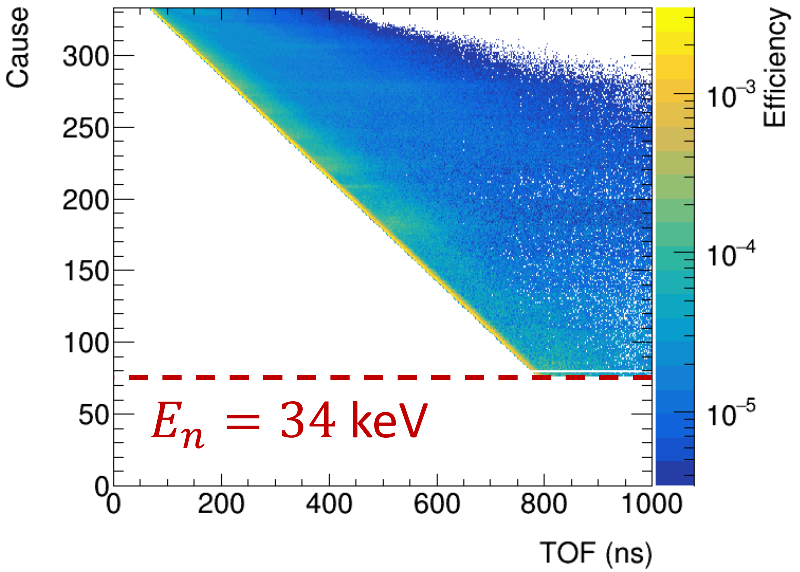


Simulated TOF response considering only the neutron-emission part of the β-decay

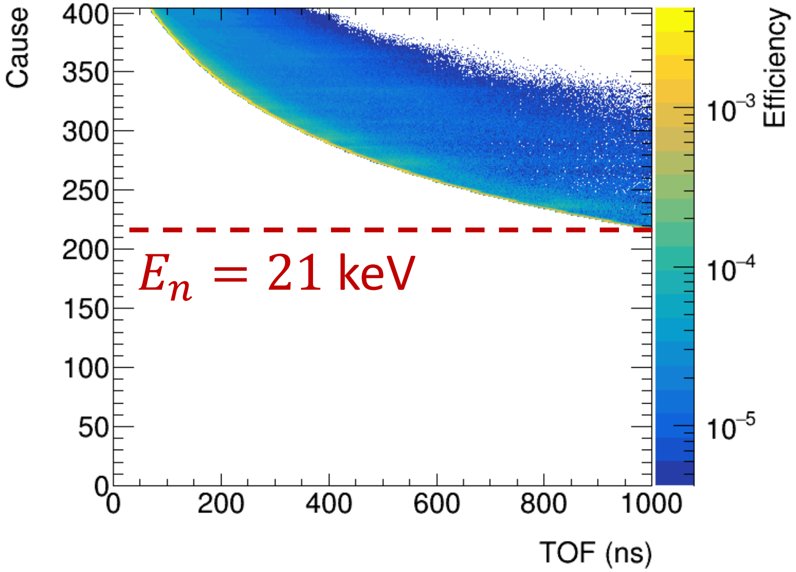
Binning of the response matrix



Cause bins of constant width in energy of 15 keV

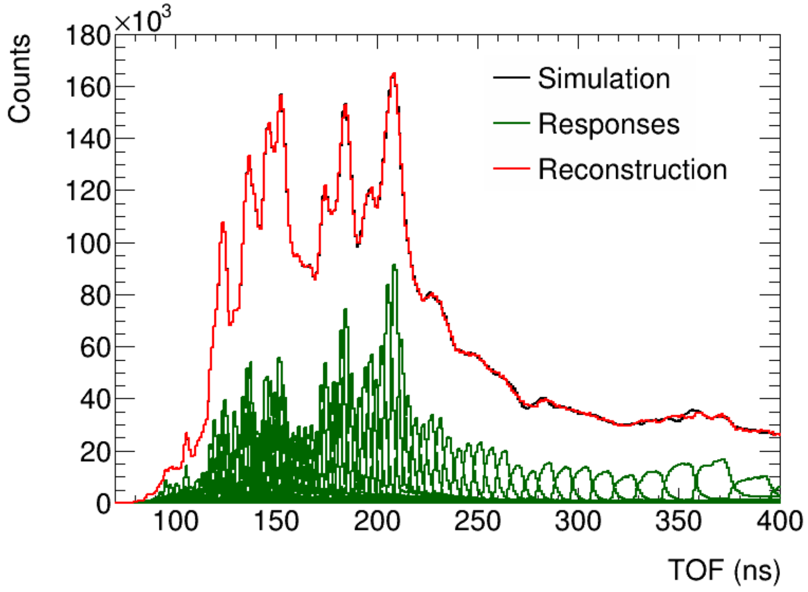


Cause bins of variable width in energy corresponding to a constant width in time of 2.8 ns

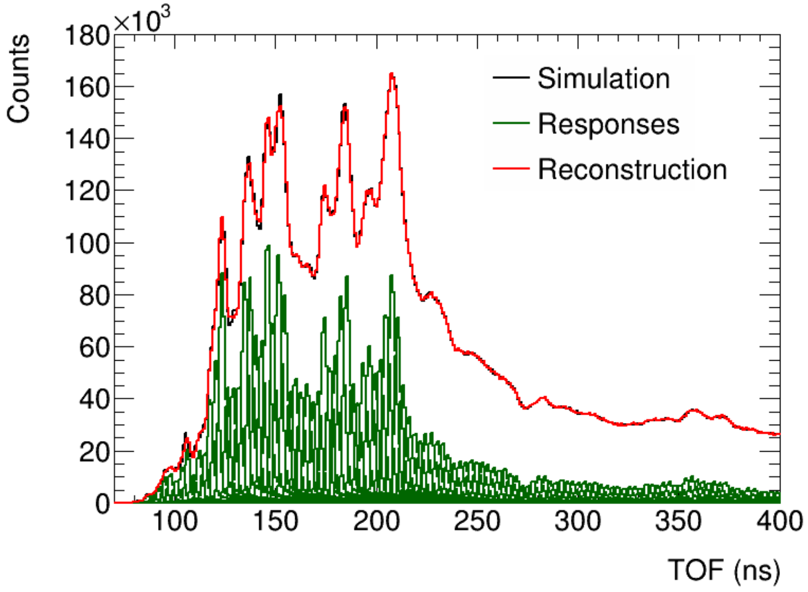


Cause bins of variable width in energy according to the system's energy resolution

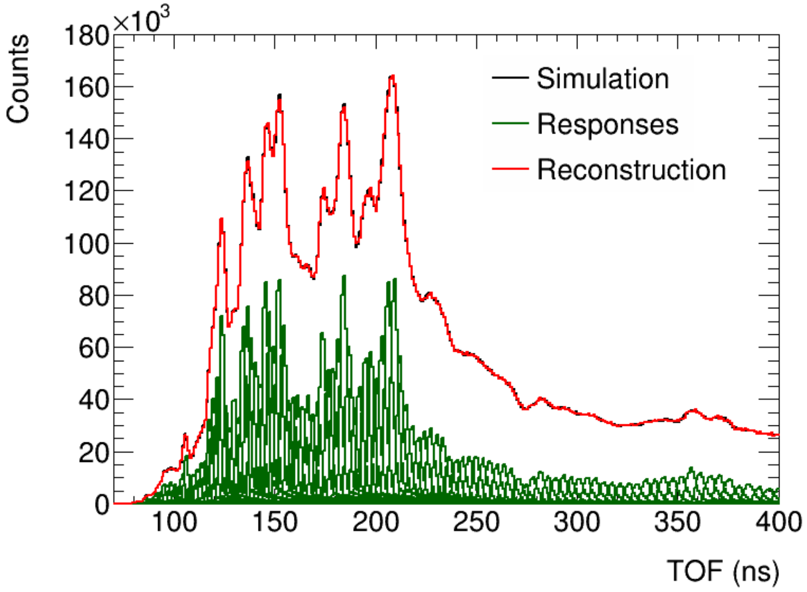
Binning of the response matrix (cont.)



Energy width



Time width



Energy resolution width

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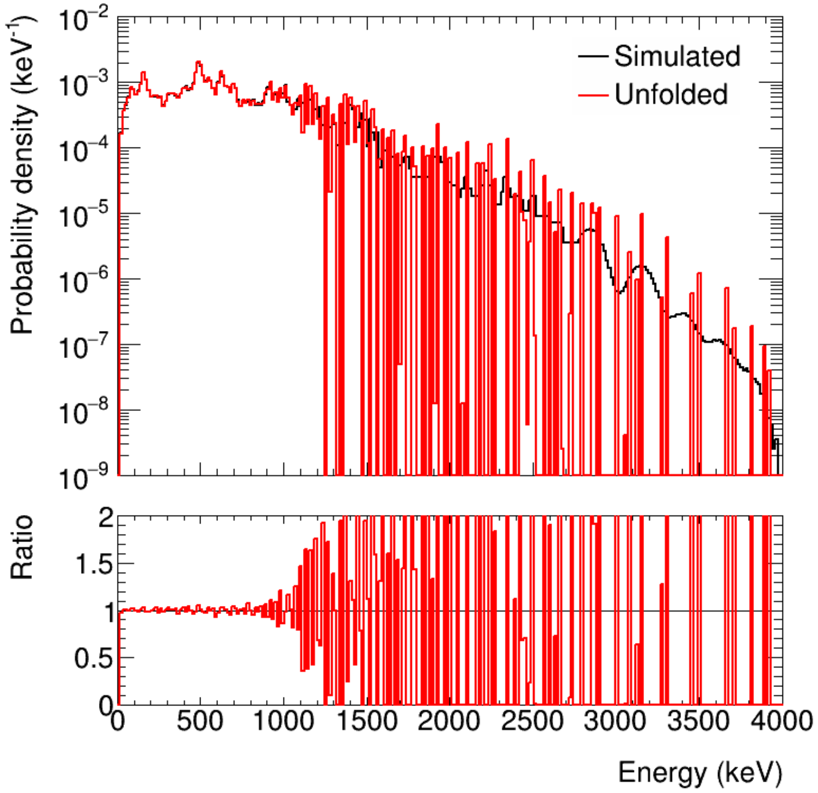
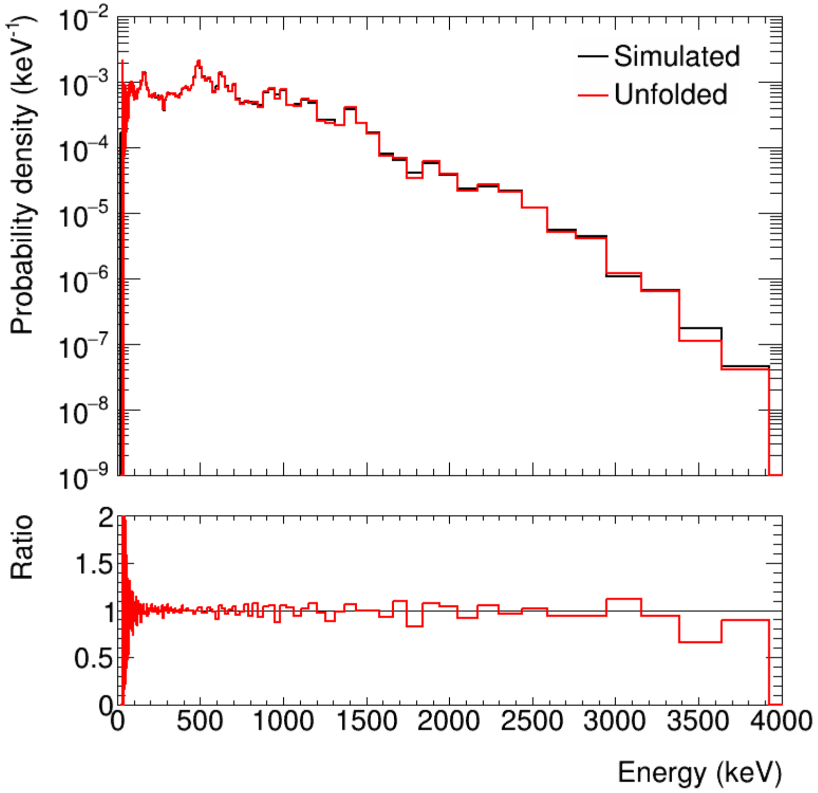
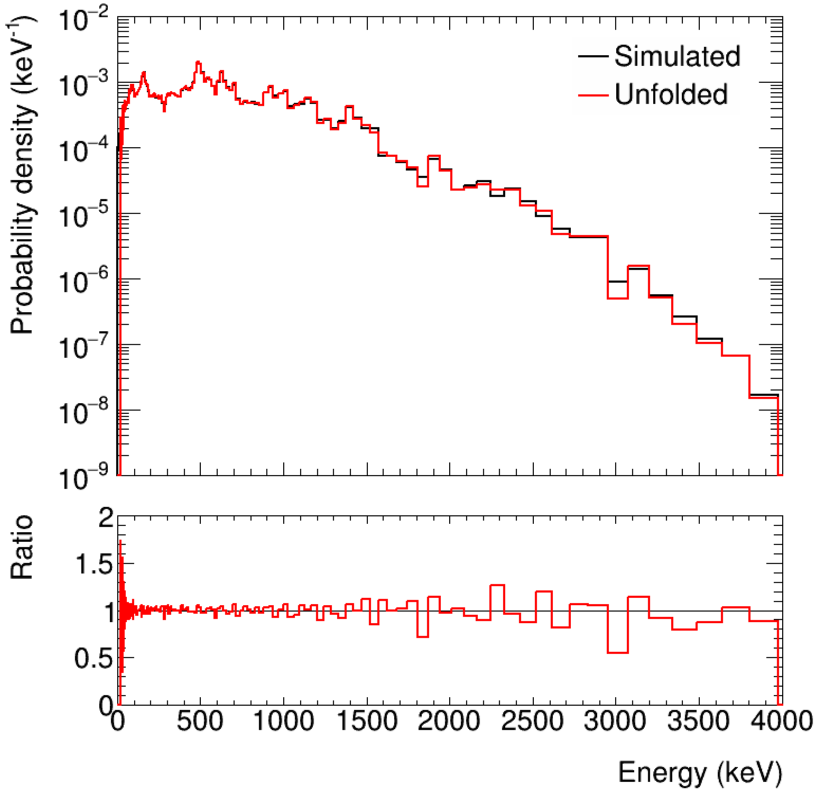
Binning of the response matrix (cont.)



Energy width



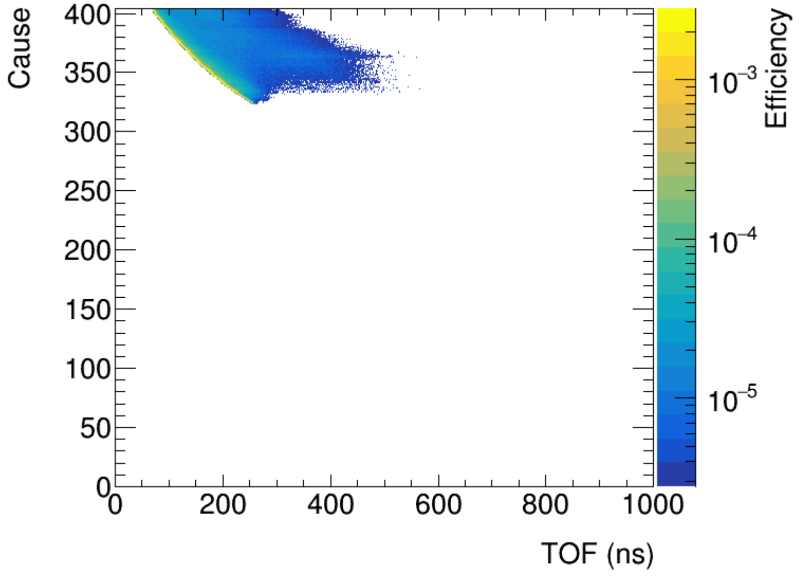
Time width

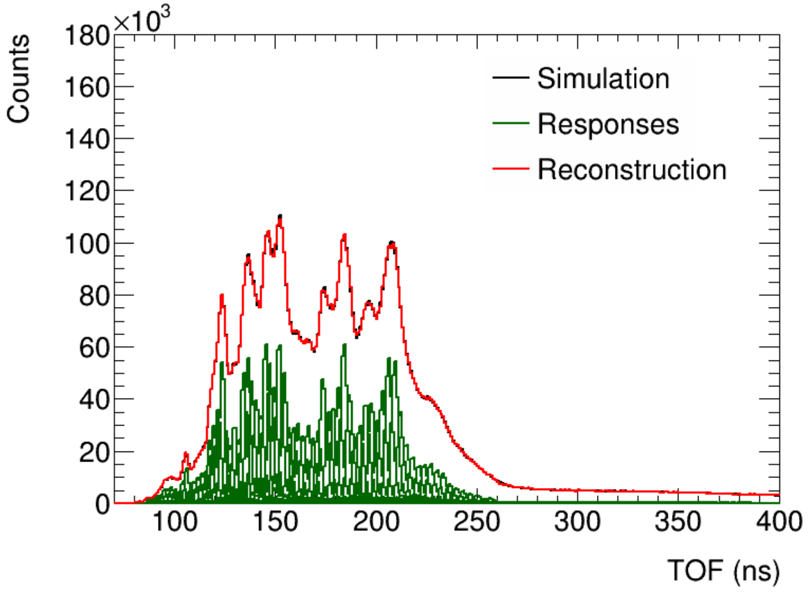


Energy resolution width

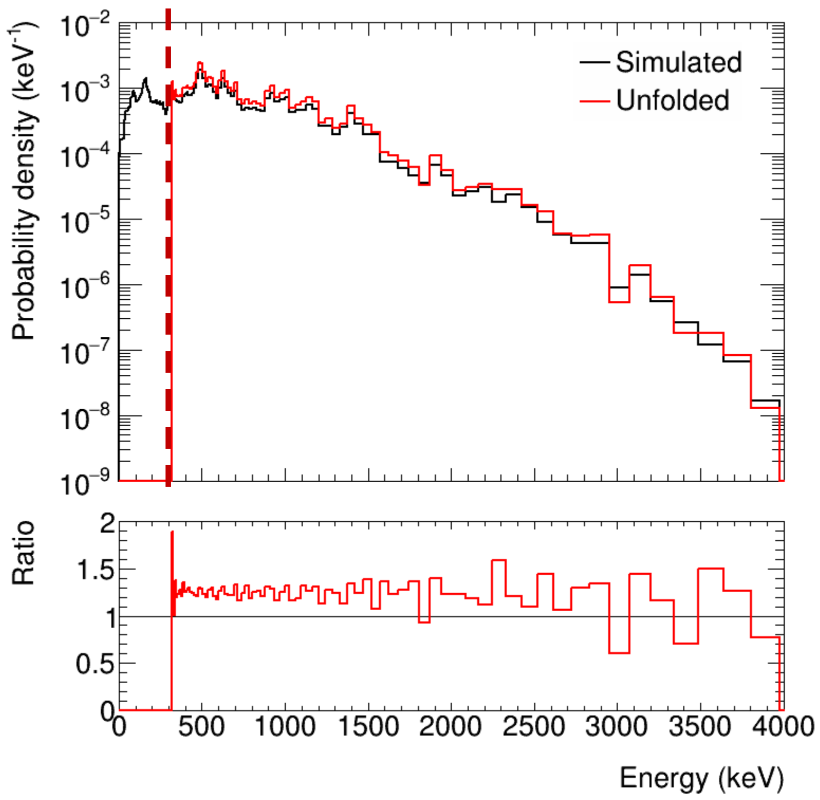
The binning according to the system's energy resolution offers better overall reproduction of the original neutron energy distribution over the whole energy range

Effect of the threshold



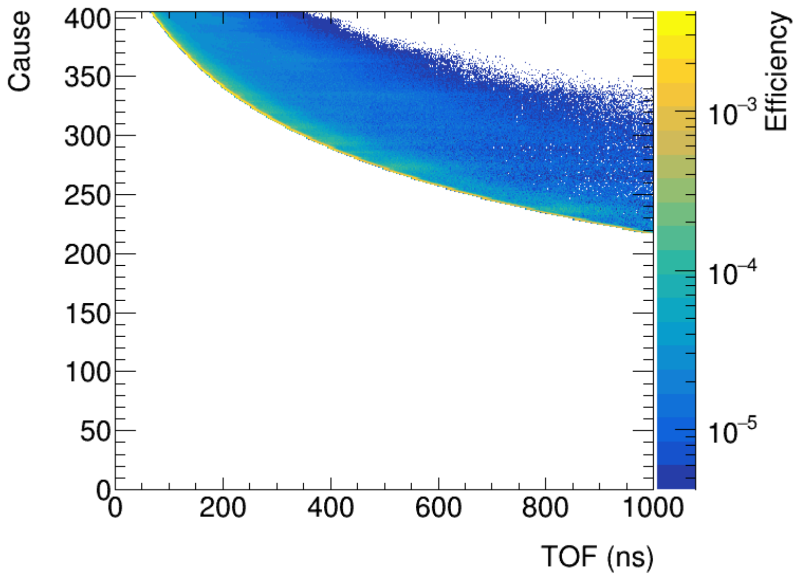


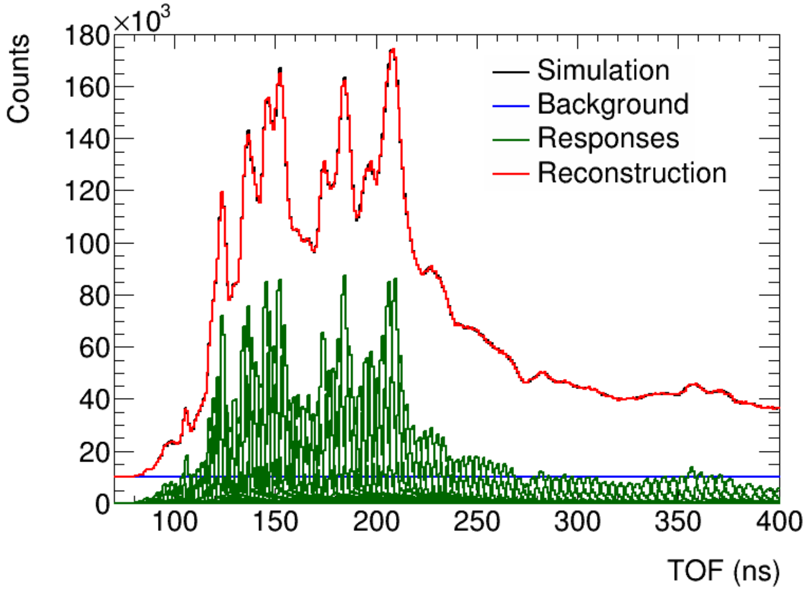
$E_n > 300$ keV

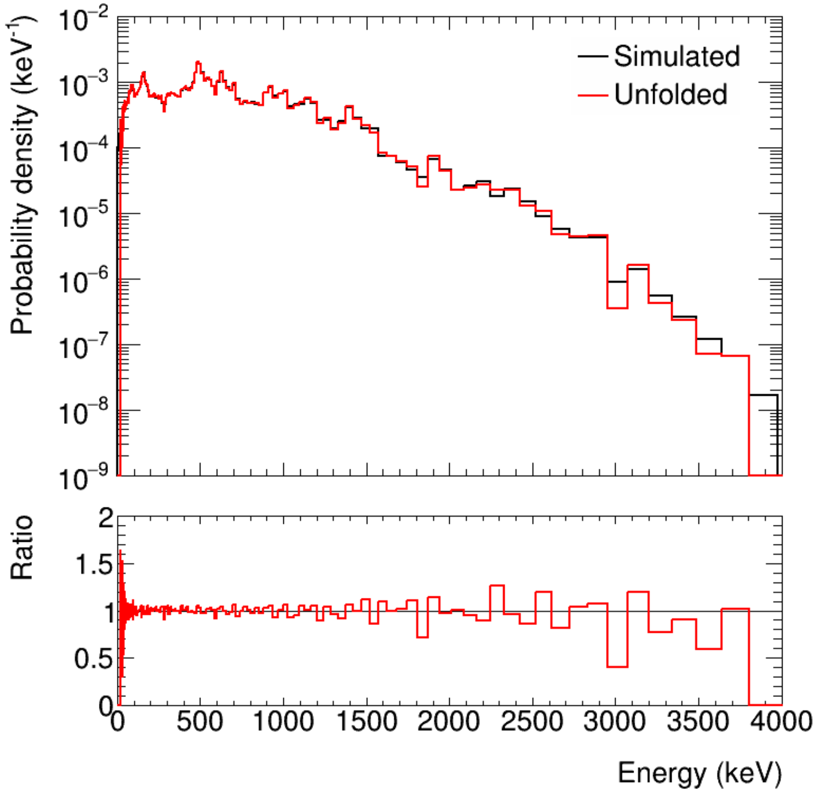


Applying a neutron detection threshold limits the lower neutron energy that can be detected and introduces a bias on the obtained energy distribution due to the normalization to the unity

Effect of the background



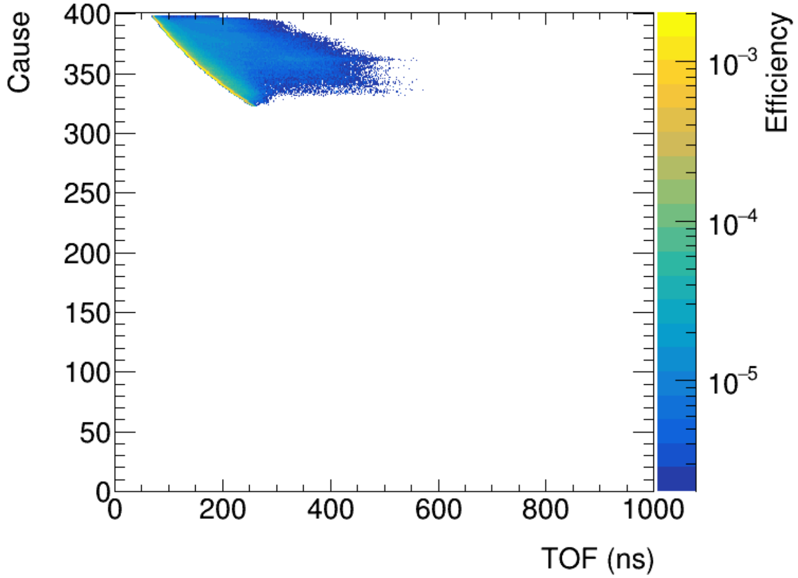


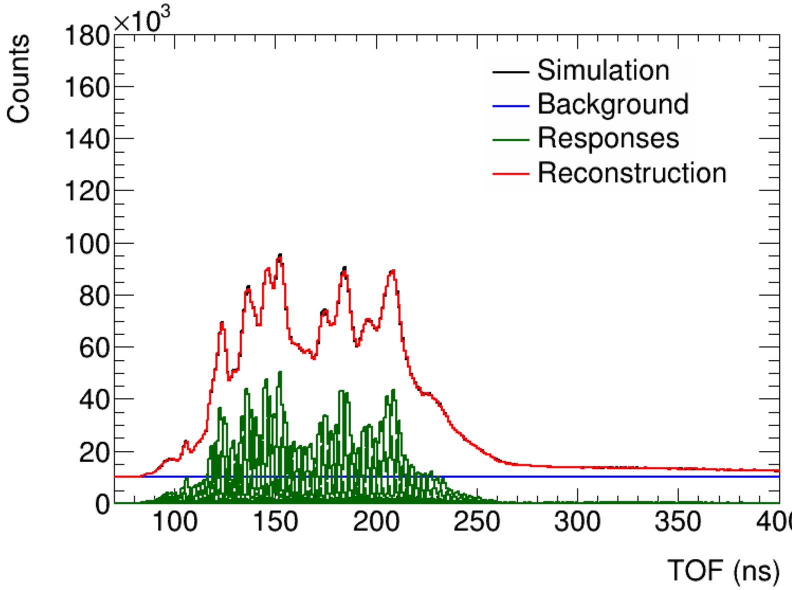


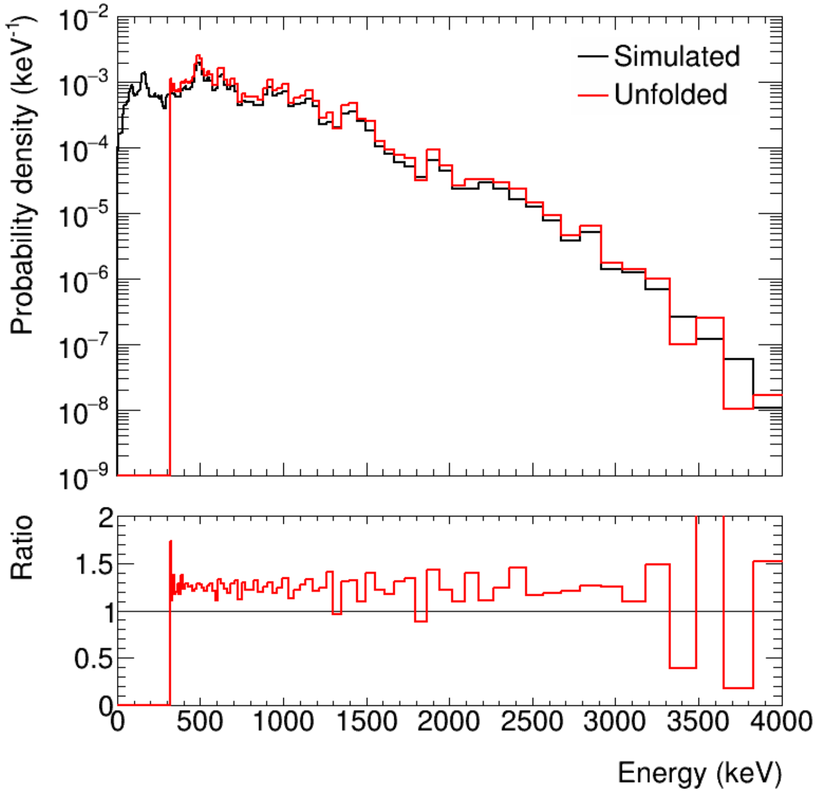
The background can be taken into account in a simple way barely affecting the result, although it can limit the detection of high-energy neutrons emitted with low intensity

Analysis of a realistic β-decay experiment

The realistic experiment combines all previously studied effects 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

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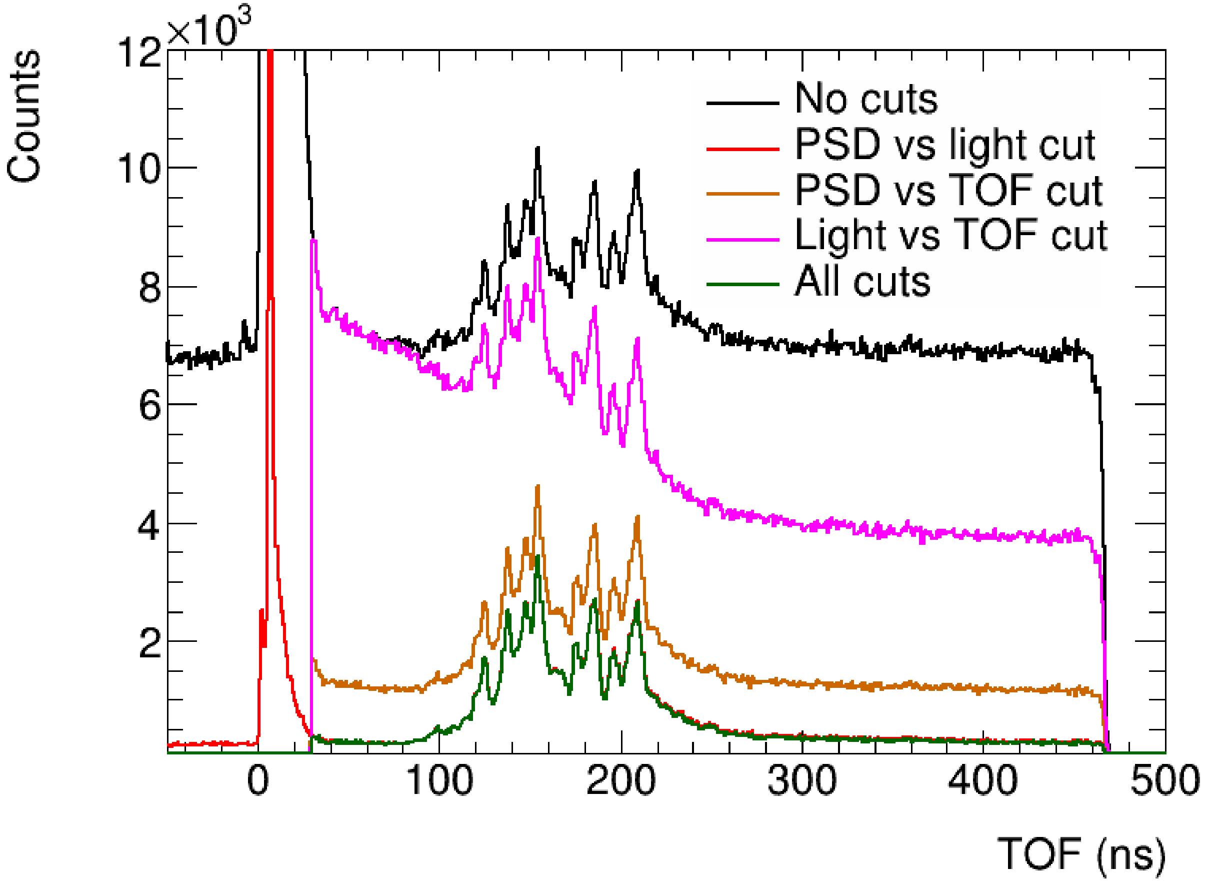
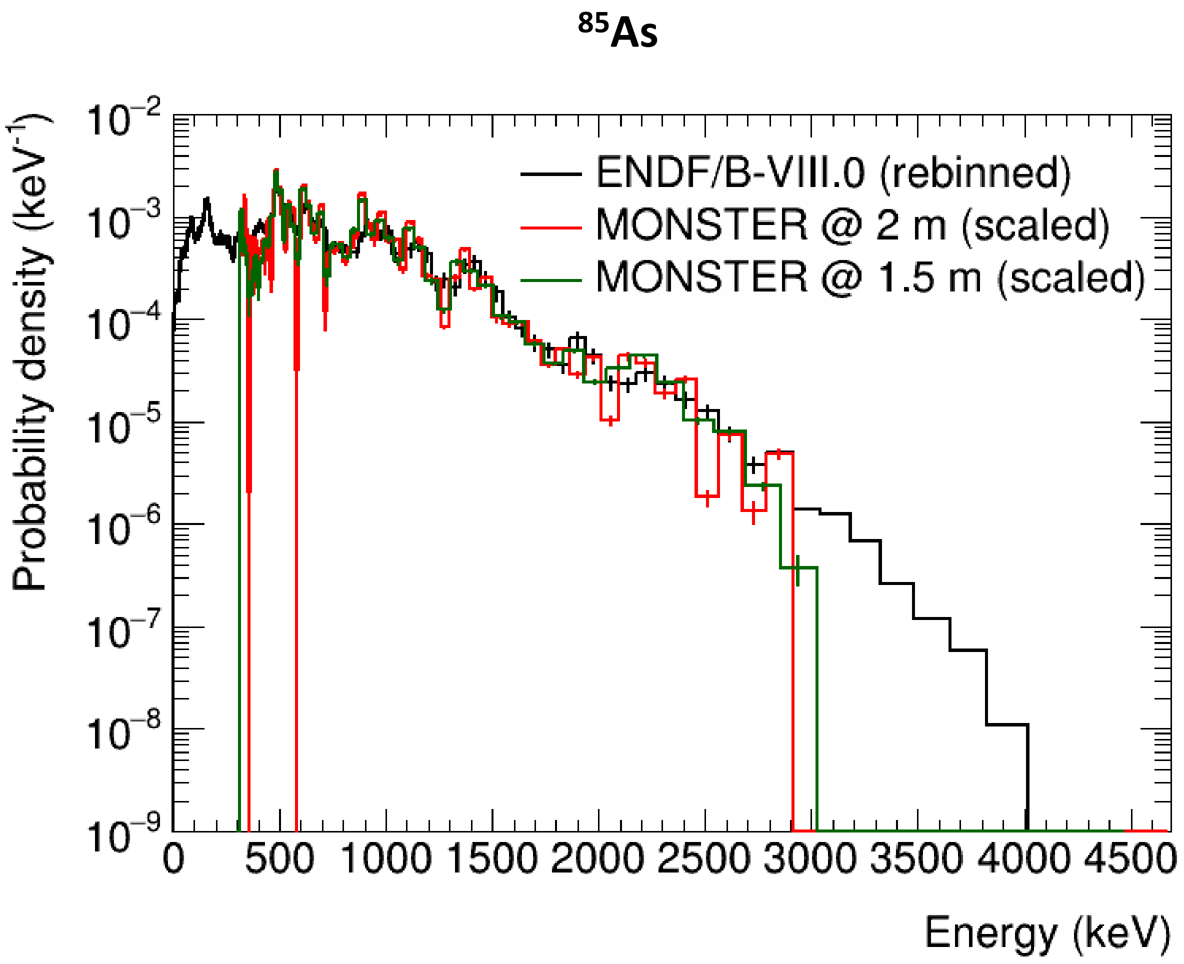
Cleaning neutron TOF spectra

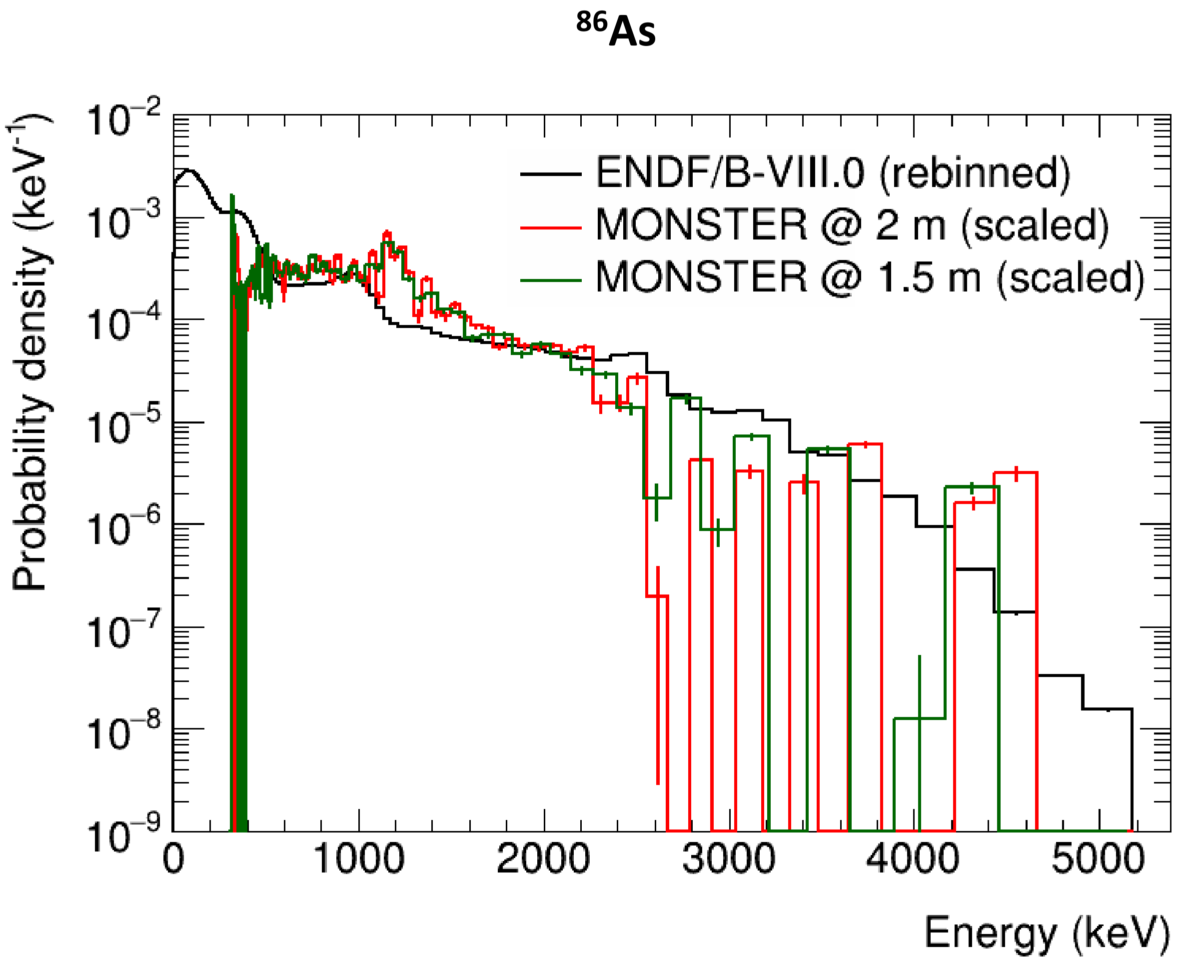
Different neutron cuts were studied to obtain a “clean” TOF spectrum



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

^{85,86}As β-delayed neutron energy distributions





Excellent agreement with previous data and evaluations

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Experimental setup

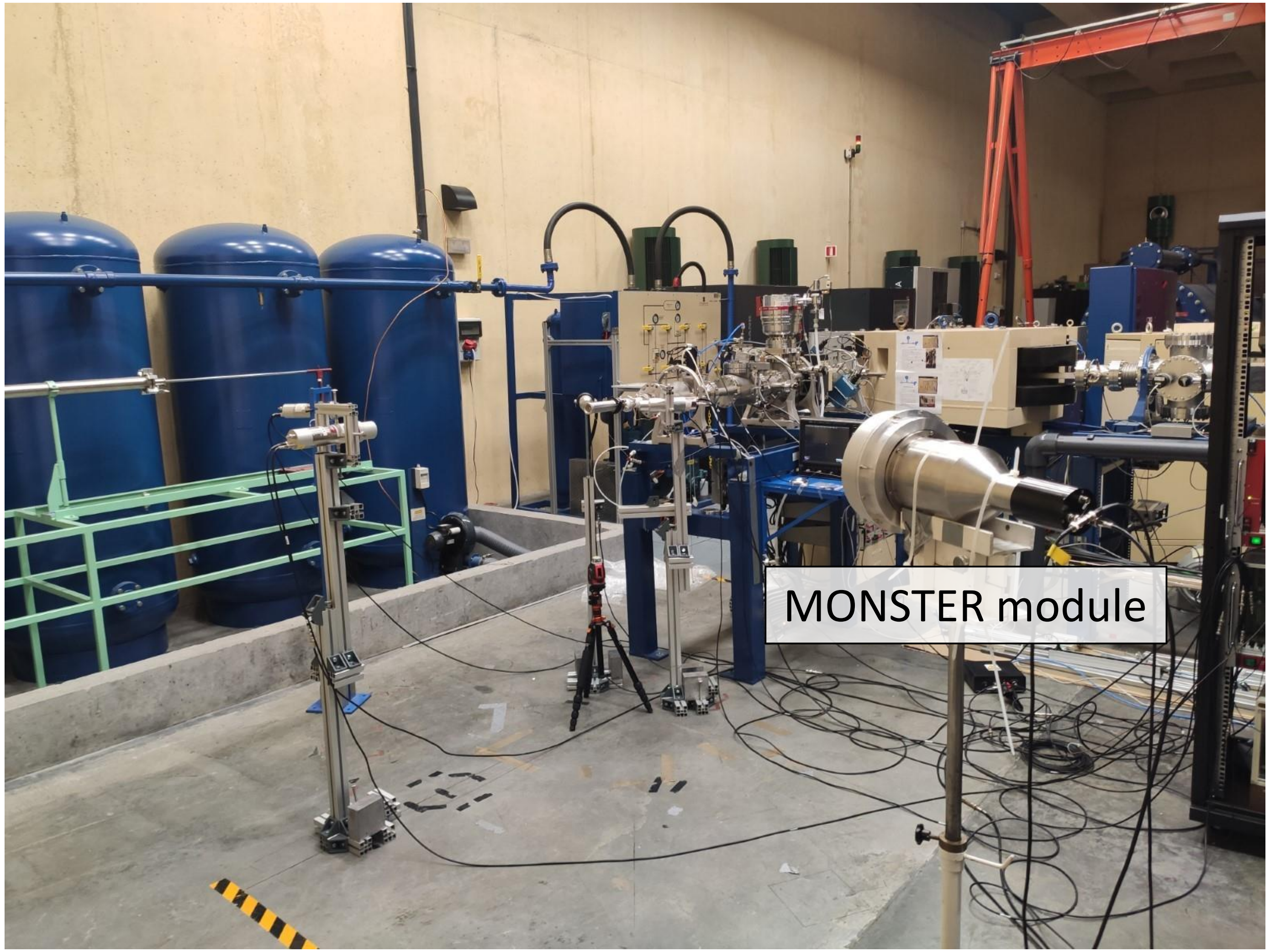
MONSTER module placed at 1 m and 2 m

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

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

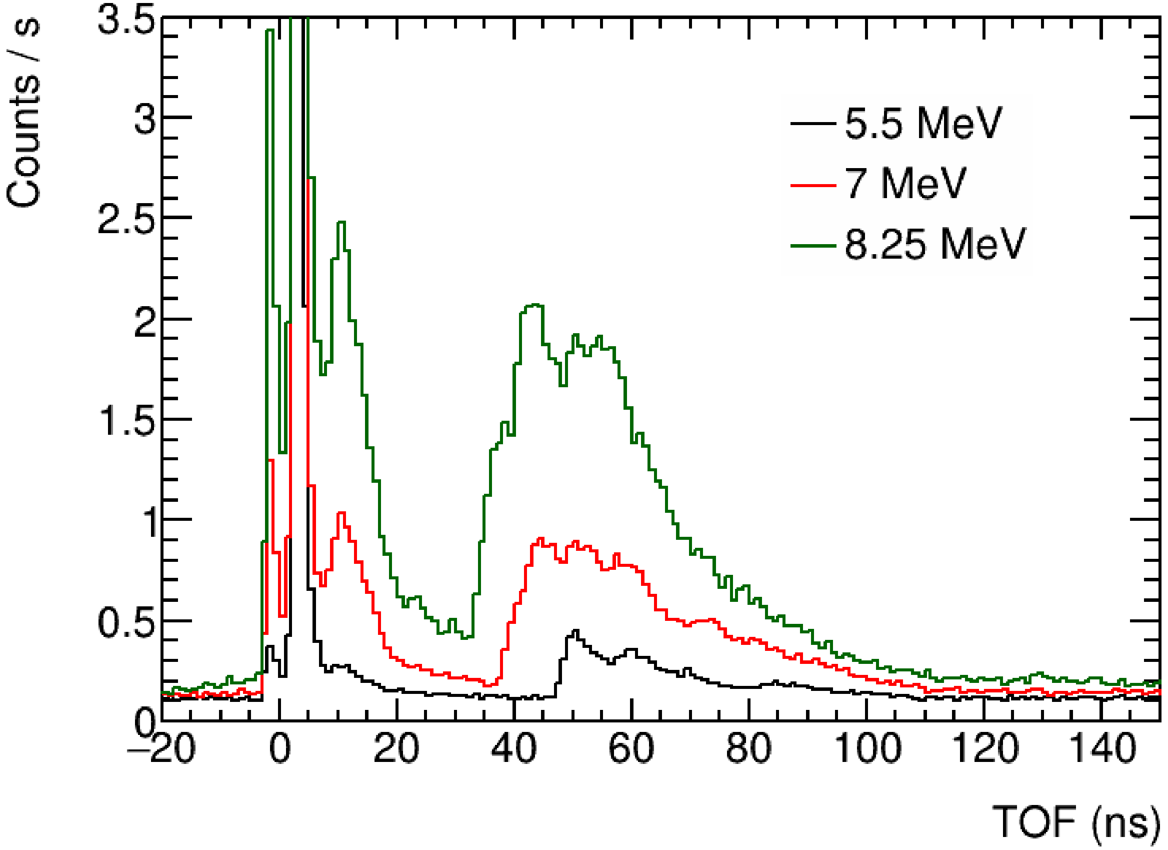
Data collected with DAISY:
- Channel 0: MONSTER
- Channel 1: empty
- Channel 2: accelerator RF
- Channel 3: current integrator

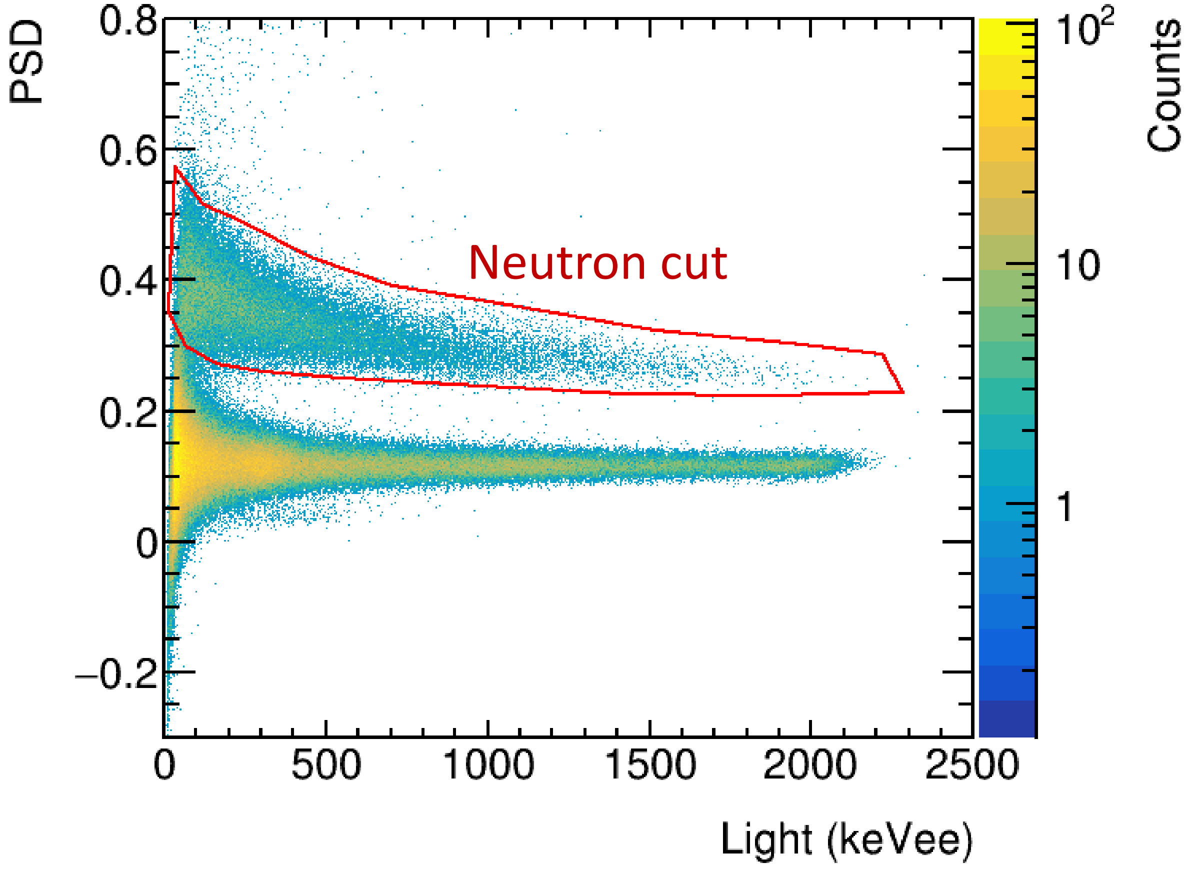
Custom pulse shape analysis software developed at CIEMAT to analyze signals online:
- Resolving pileups
- Without adding dead time



TOF spectra @ 1 m

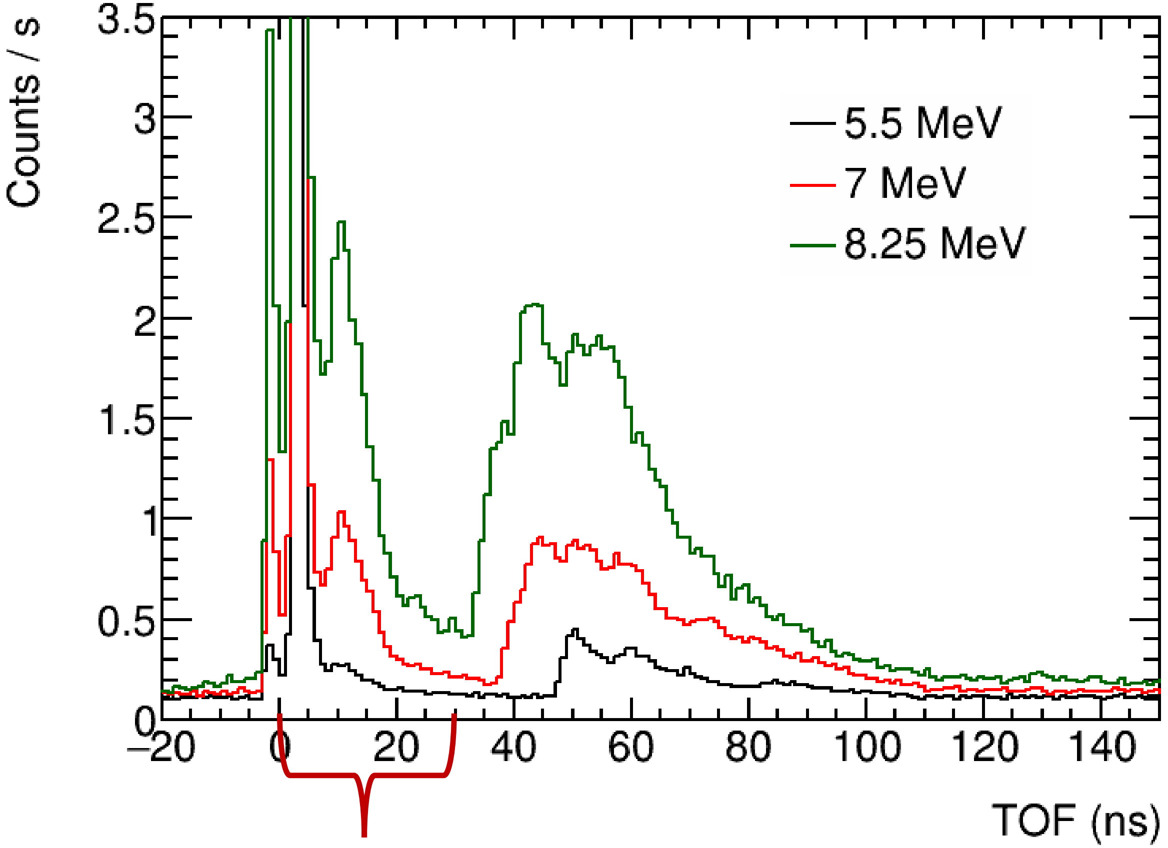
Raw TOF spectra





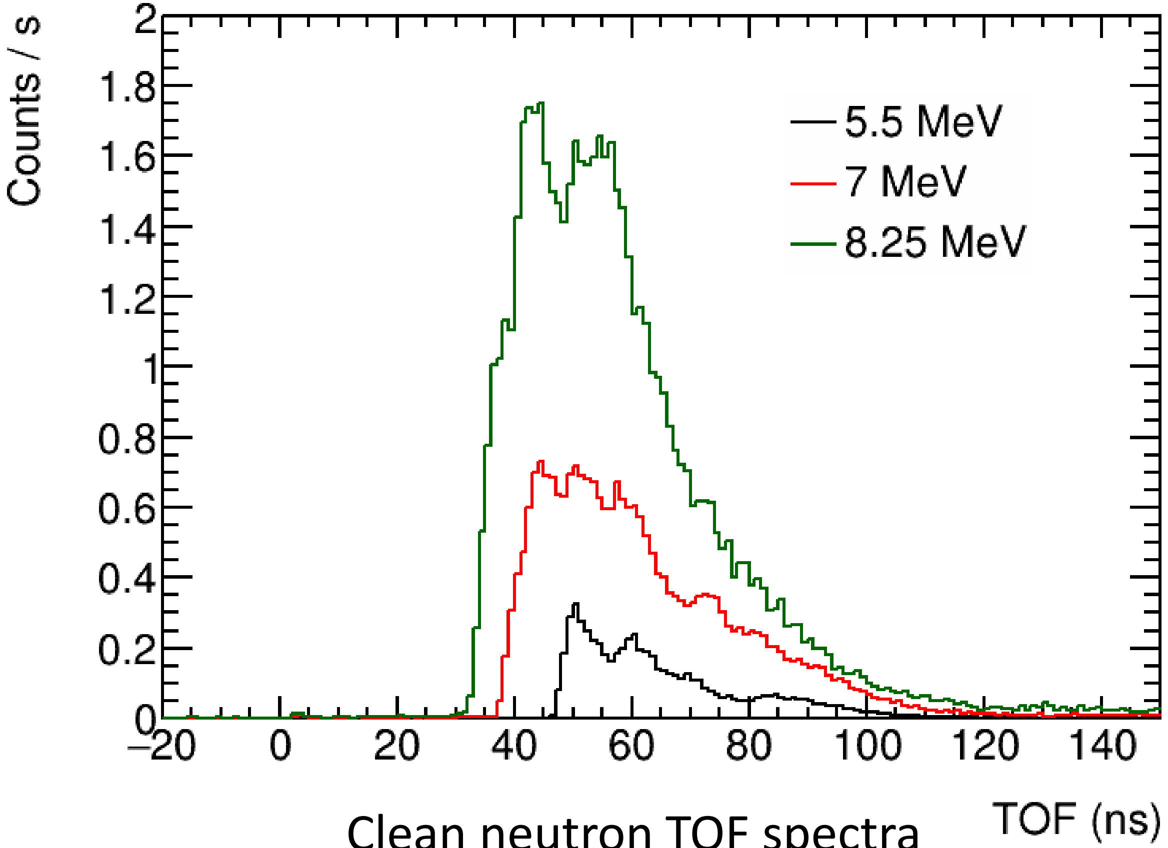
Neutron TOF spectra @ 1 m

Raw TOF spectra



Resolution functions -> Allow to correct for the double α bunch

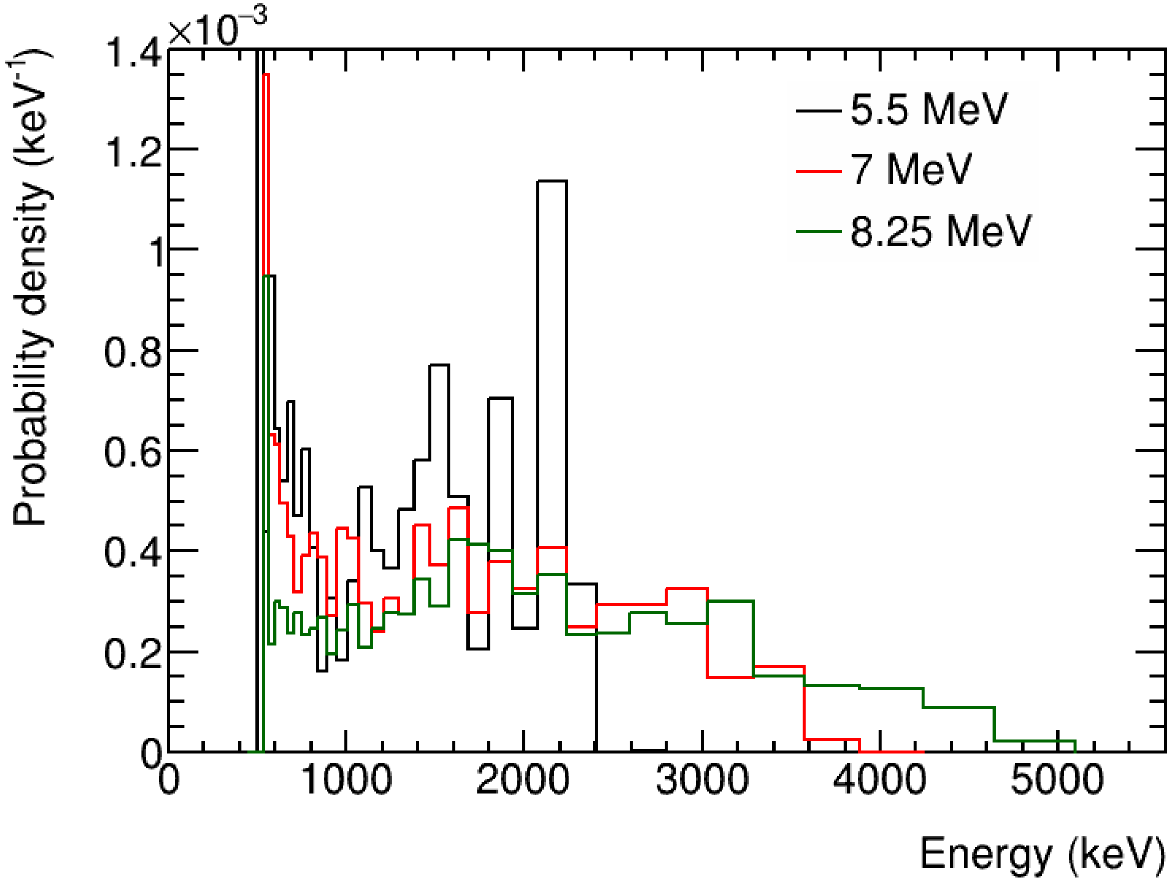
Neutron TOF spectra



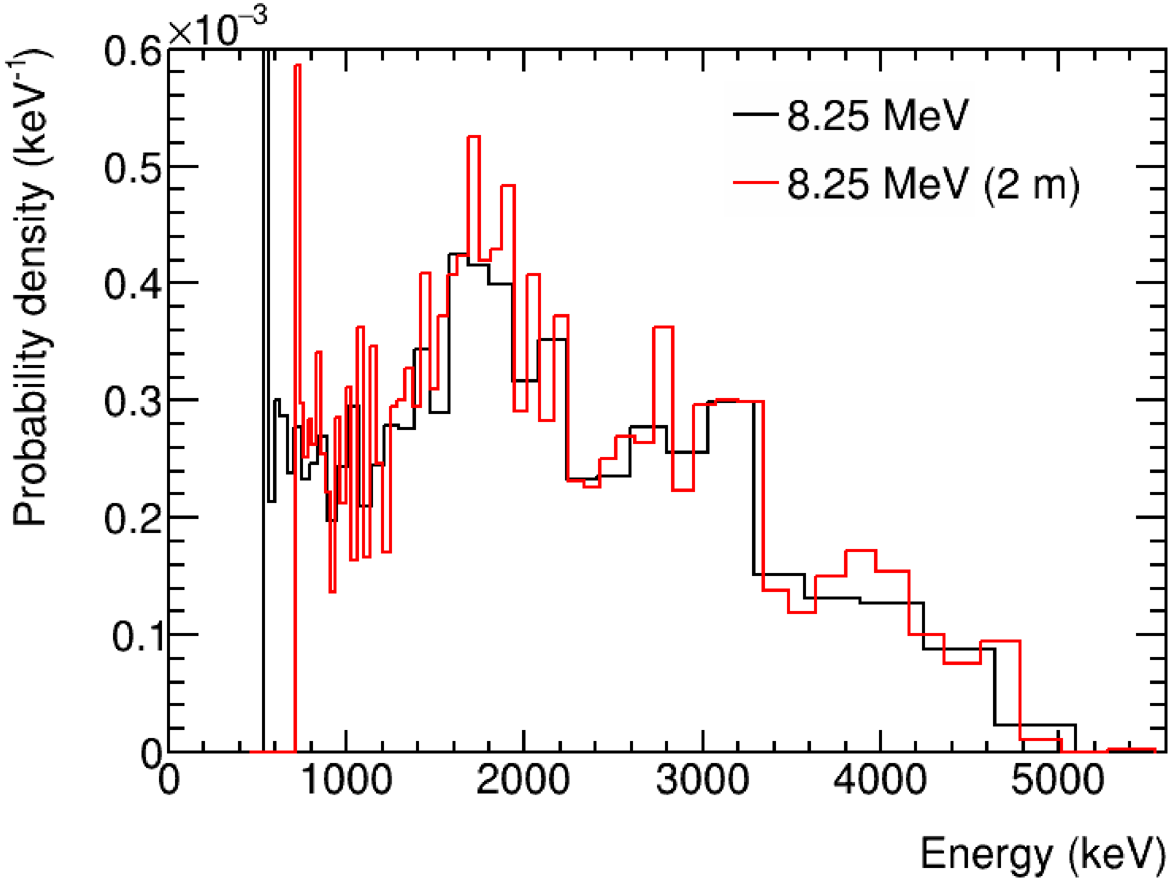
Clean neutron TOF spectra applying MONSTER's neutron/γ-ray discrimination capabilities

Neutron energy distributions

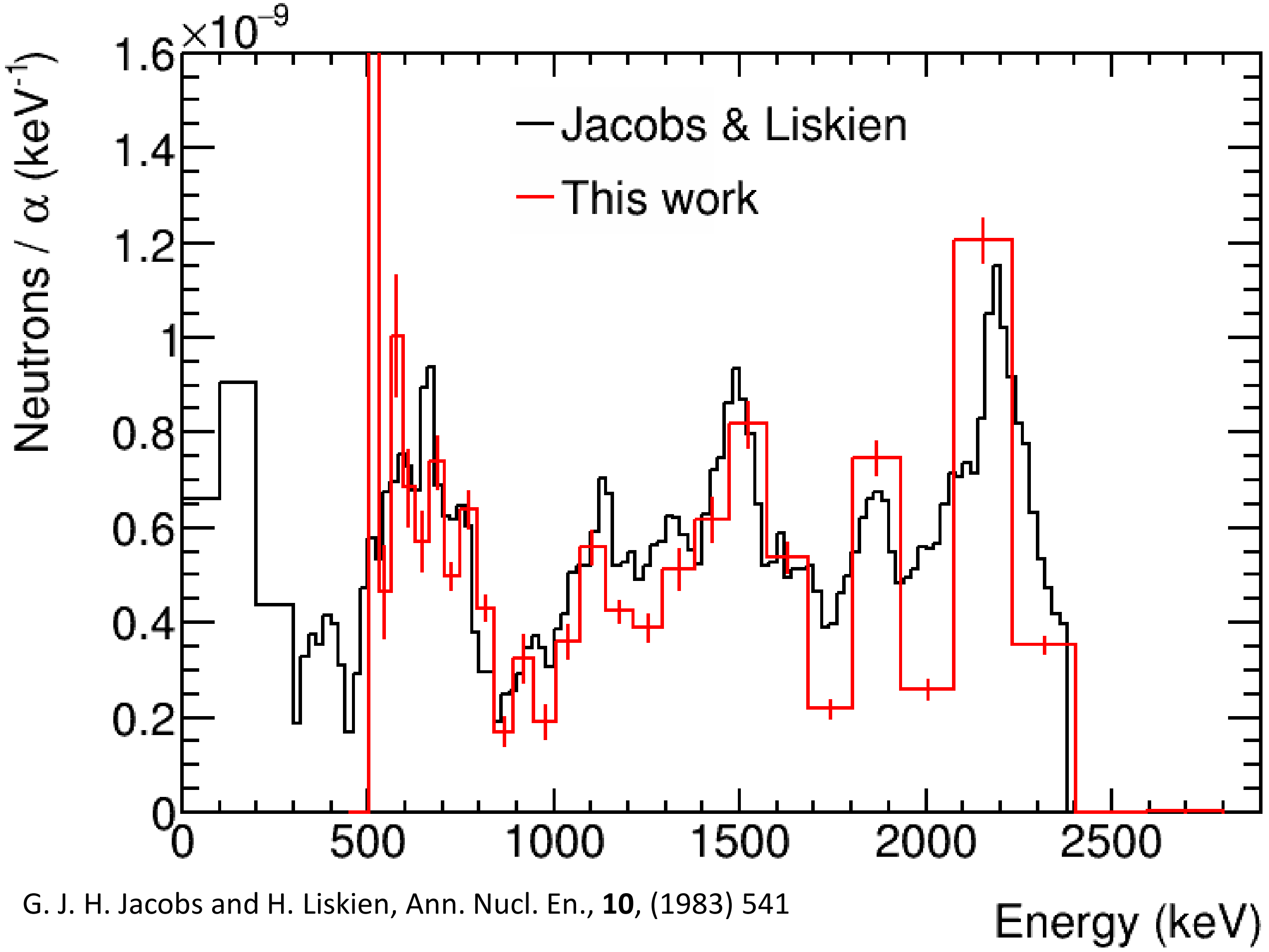
1 m



2 m



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

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Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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- $^{85,86}As$ β-decays @ IGISOL
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- Summary and conclusions

Summary and conclusions

The main takeaways from this presentation are:

- Commissioning of MONSTER and its DAQ system DAISY:
  - Successful commissioning of MONSTER
  - Good neutron/γ-ray discrimination capabilities
  - Excellent energy resolution
- New data analysis methodology for neutron TOF spectroscopy:
  - Unfolding of the TOF spectrum with the iterative Bayesian unfolding method based on accurate Monte Carlo simulations
  - Validation of the unfolding methodology with a simulated experiment
- Experimental validation:
  - Procurement of the ^{85}As β-delayed neutron spectrum and the “first” ^{86}As β-delayed neutron spectrum
  - First successful test at CNA for (α,n) reaction measurements with MONSTER
- New experiments are being planned at CNA and CMAM

Thank you!