β-delayed neutron spectroscopy opportunities with MONSTER

Alberto Pérez de Rada Fiol

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

MONSTER Collaboration

GOBIERNO
DE ESPAÑA

MINISTERIO
DE CIENCIA, INNOVACIÓN
Y UNIVERSIDADES

Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

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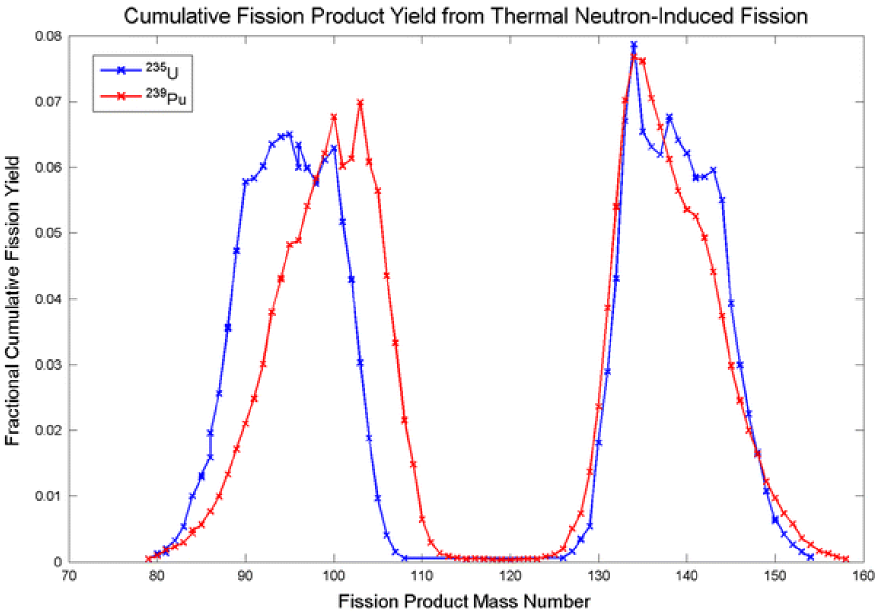
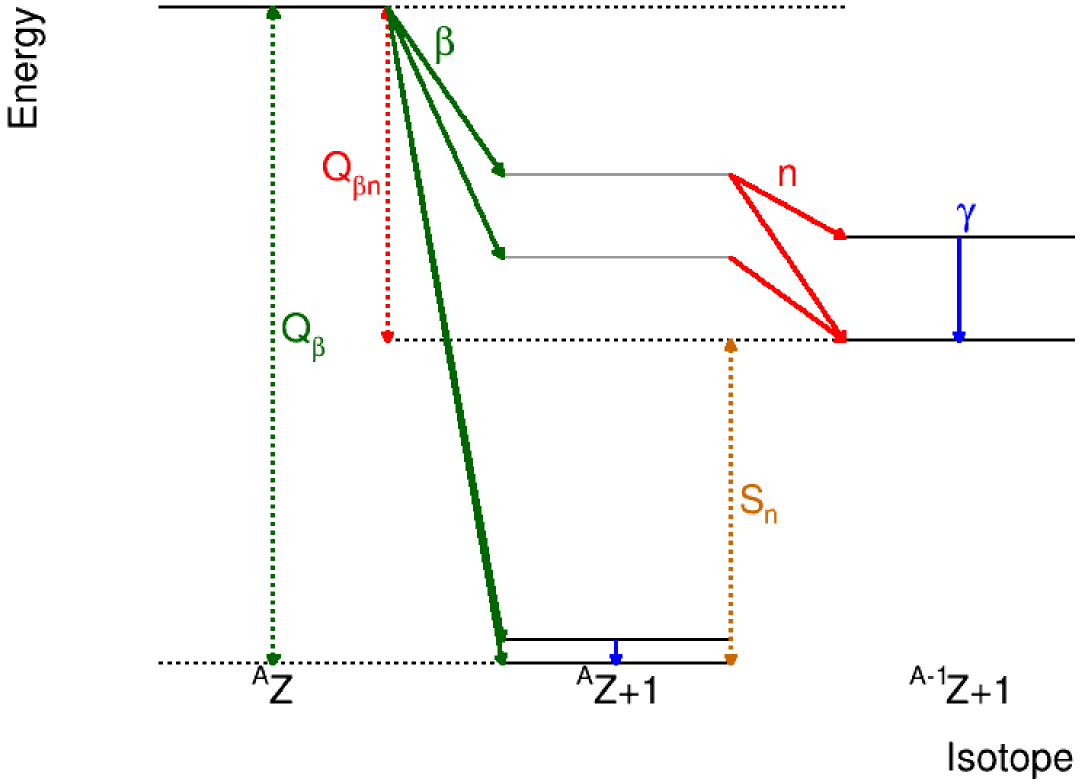
β-delayed neutron emission

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



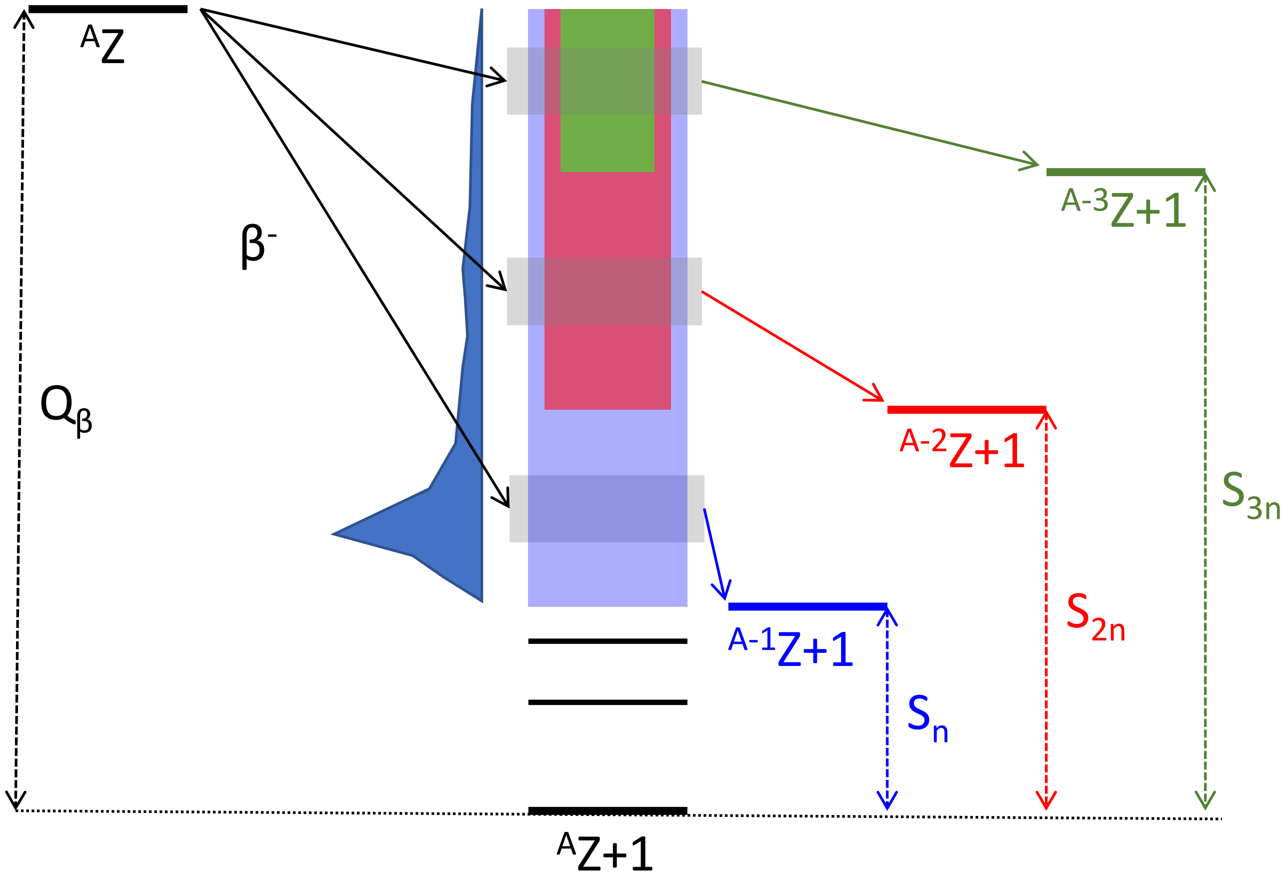


Priority list for reactor studies:

^{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 $\Gamma_n(E) >> \Gamma_\gamma(E)$

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

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

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

MONSTER

MOdular Neutron time-of-flight SpectromeTER is a detection system designed for DESPEC

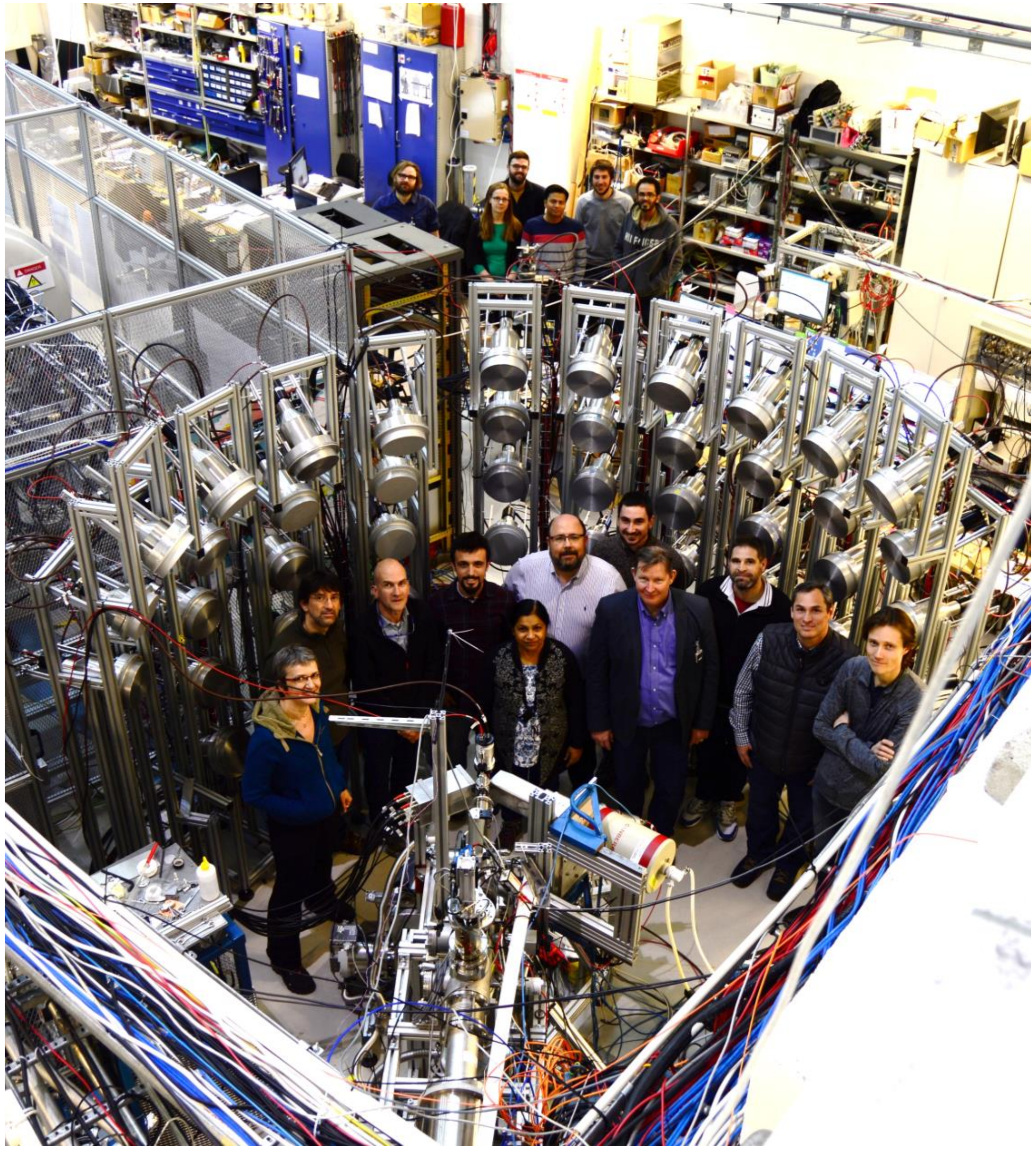
MONSTER TDR, (2013)

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



DAISY

Digital data AcquIsition SYstem

Custom DAQ software developed at CIEMAT

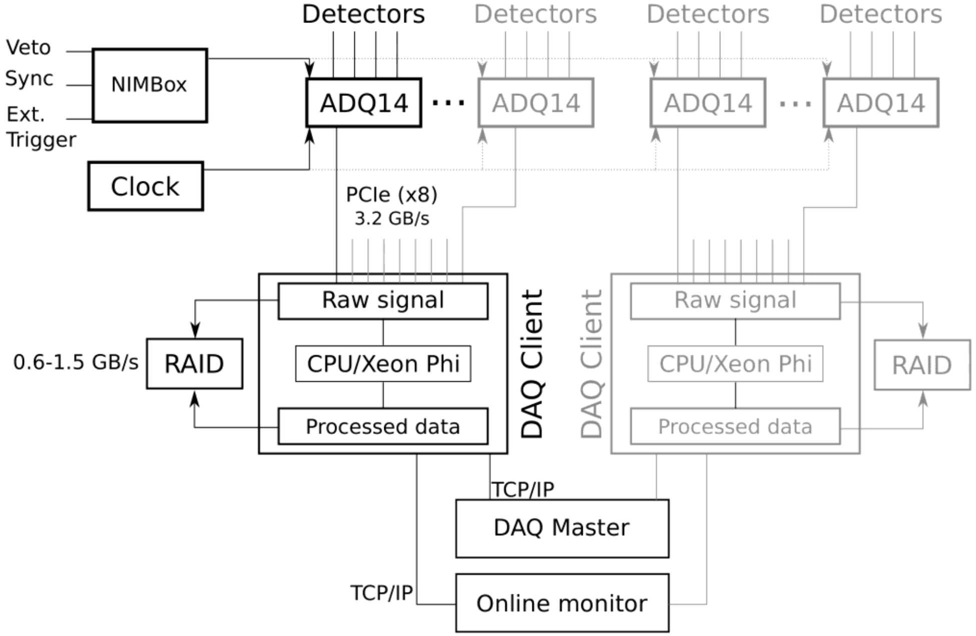
D. Vilamarín, Nucl. Instrum. and Methods A, **1055**, (2023) 168526

Hardware:

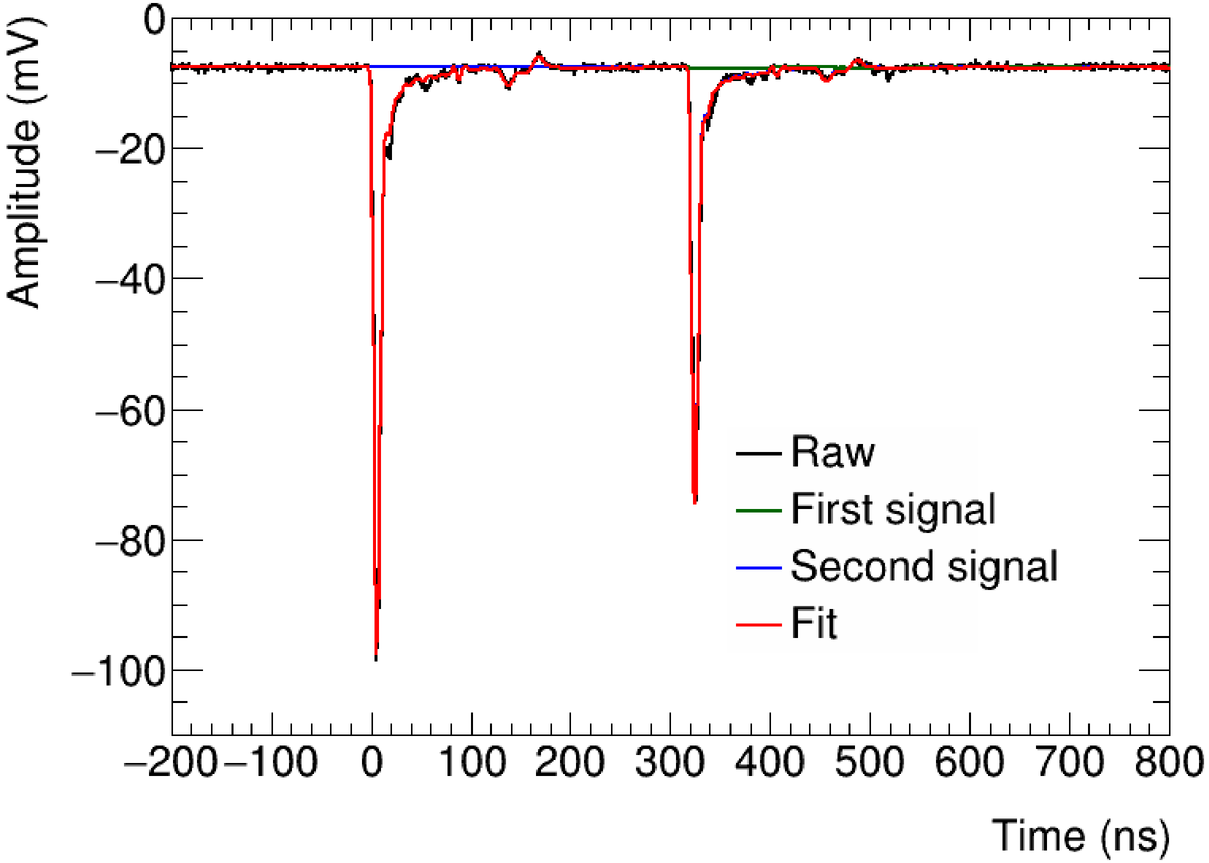
- 15 x ADQ14DC Teledyne SP Devices cards (14 bits, 1 GS/s, 4 ch)
- 2 x Counter/Timer PCIe6612 National Instruments
- NI Octoclock CDA-2990 (10 MHz, 8 ch)
- Wiener NIM/TTL Programmable modules
- 2 x PCs + 2 x PCIe crates
- 3 x 96 TB RAID 6

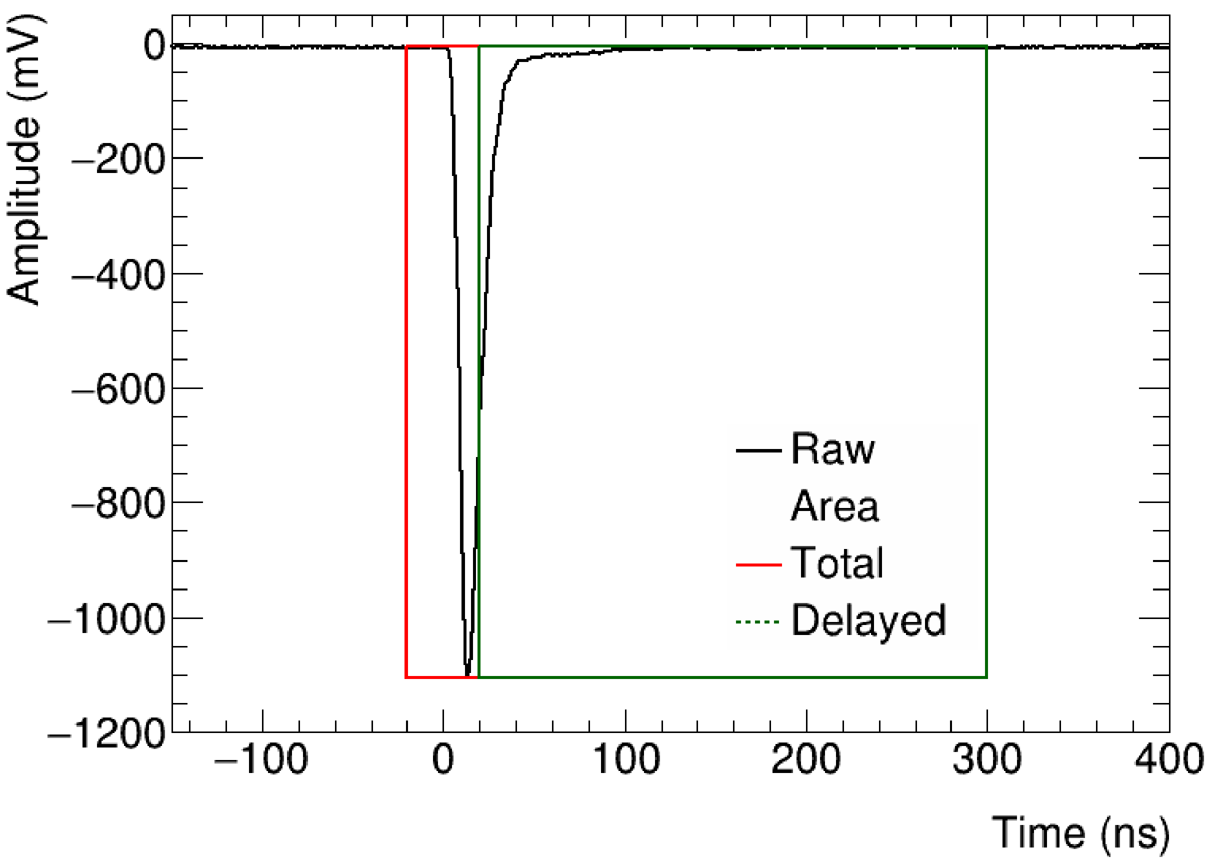
Integrates custom pulse shape analysis software developed at CIEMAT to analyze signals online:

- 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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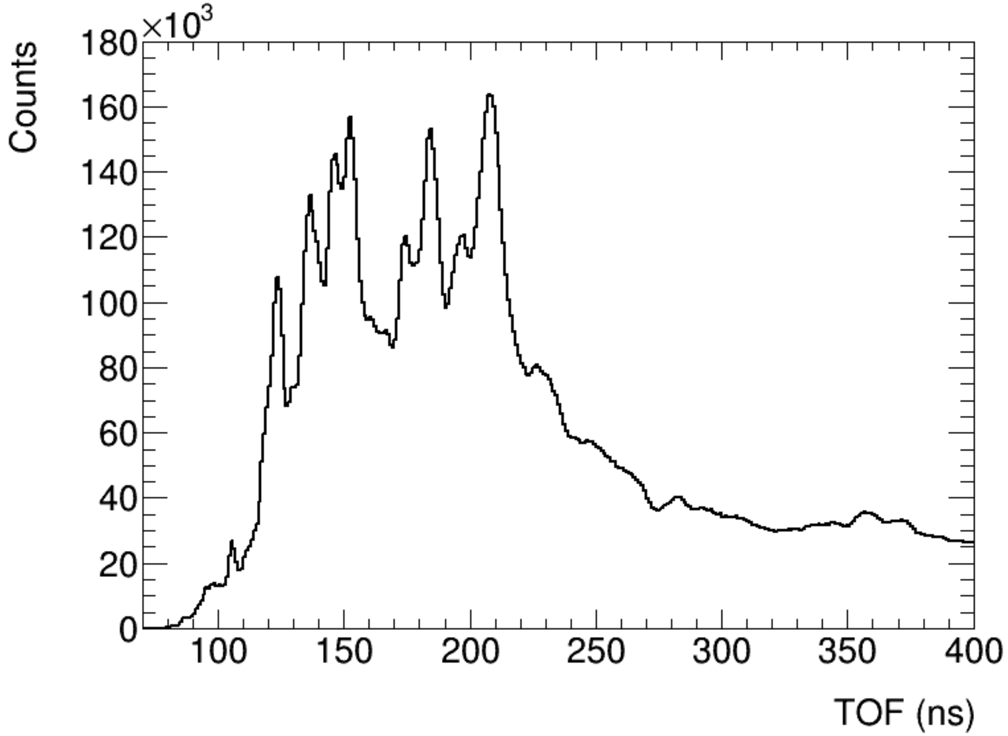
Inverse problem

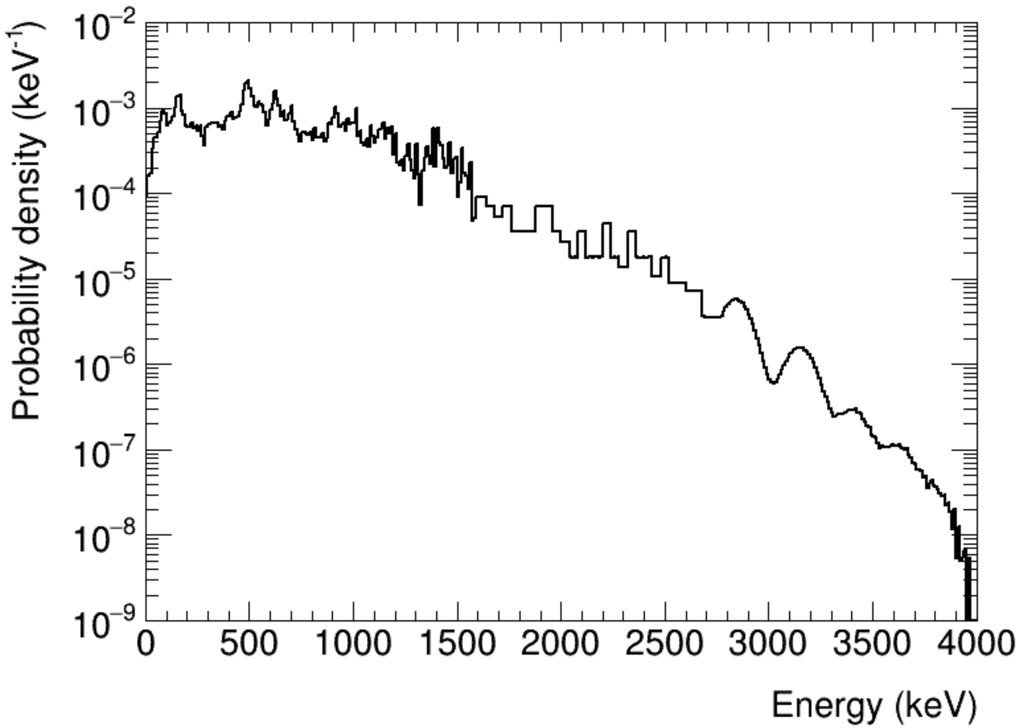
$$TOF = R \cdot E_n$$

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:

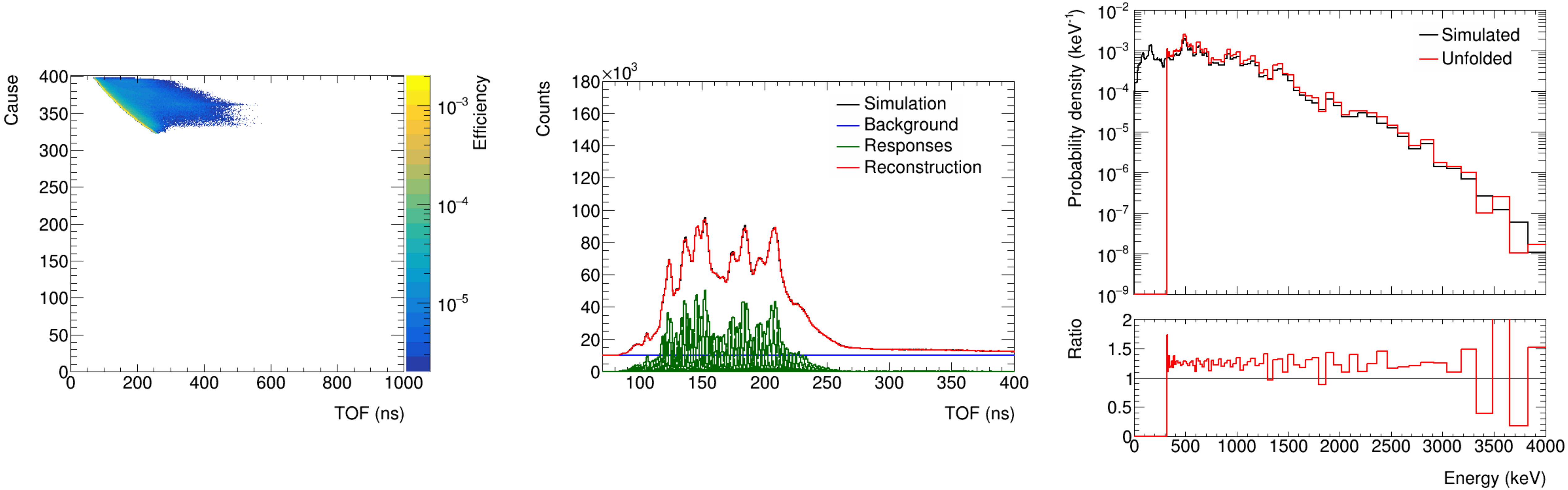
- Method for solving the inverse problem -> Iterative Bayesian method G. D'Agostini, Nucl. Instrum. and Methods A, **362**, (1995) 487
- Construction of the response matrix R covering the whole neutron energy range and providing the TOF response for each considered neutron energy -> Accurate Monte Carlo 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.*, "Analysis methodology of neutron time-of-flight spectra based on Bayesian unfolding and accurate Monte Carlo simulations", Submitted for publication

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Analysis scheme

Fit of the β-activity curve -> Number of decays N_d

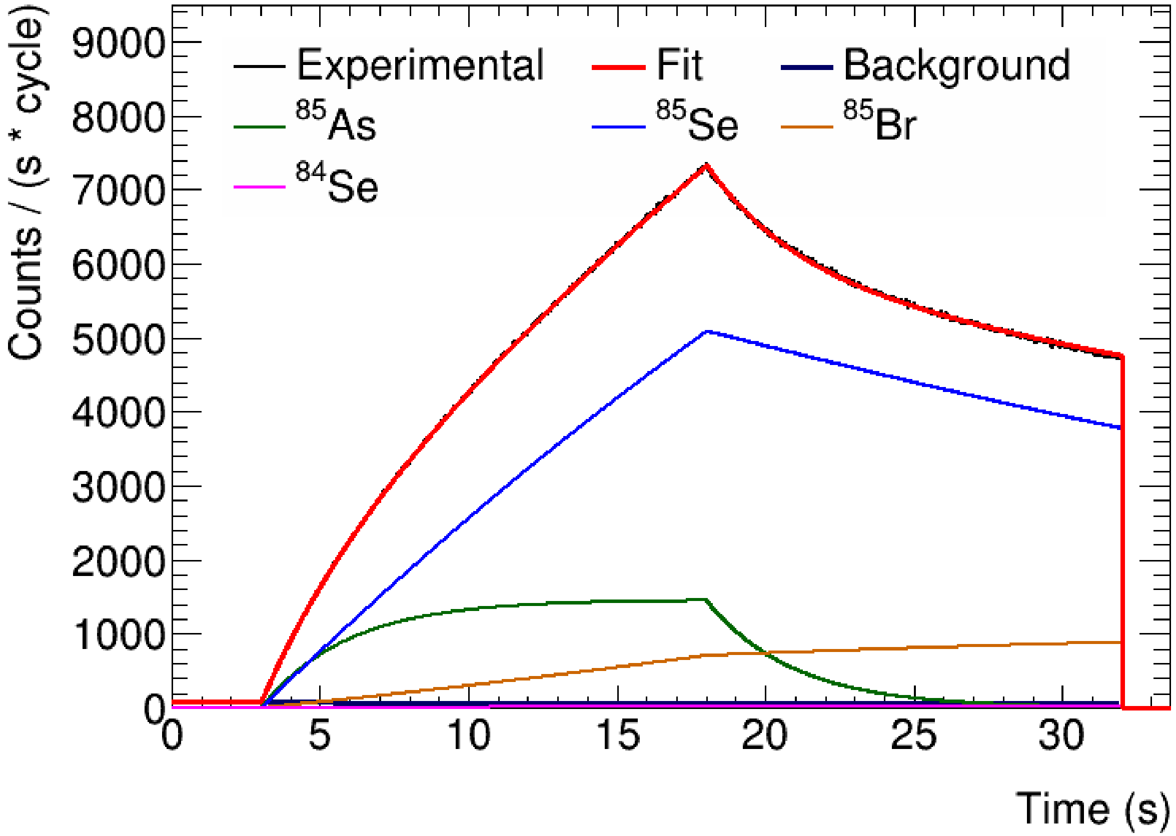
Unfolding of the TOF spectrum ->

- Neutron energy distribution
- Total number of neutrons N_n emitted above the detection threshold

$$P_n^* = \frac{N_n}{N_d}$$

Lower estimate of the P_n value

Solving the Bateman equations for ^{85}As



Simulated from experimental data

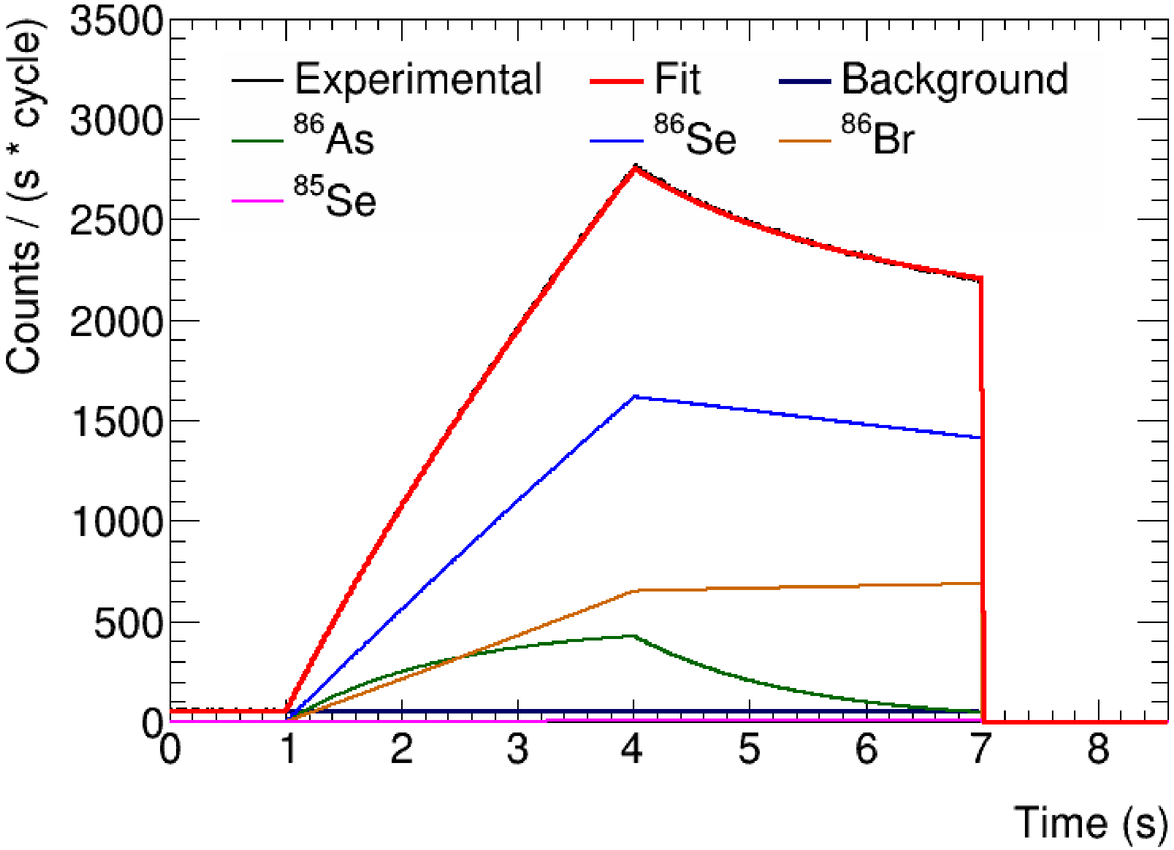
^{A}Z	$\overline{\epsilon}$ (%)	R (ions/s)	Decays
^{85}As	80.8	1800 ± 100	$(4.8 \pm 0.3) \times 10^7$
^{85}Se	76.0	23300 ± 900	$(2.39 \pm 0.09) \times 10^8$
^{85}Br	69.7	13900 ± 2500	$(4.2 \pm 0.5) \times 10^7$
^{84}Se	55.1	0 ± 0	$(1.8 \pm 0.1) \times 10^6$

$$N_n(t) = \sum_{i=1}^{n} N_i(t_0) \left(\prod_{j=i}^{n-1} (\lambda_j b_{j,j+1}) \sum_{j=i}^{n} \frac{e^{-\lambda_j (t-t_0)}}{\prod_{p=i,p\neq j}^{n} (\lambda_p - \lambda_j)} \right) + \sum_{i=1}^{n} R_i \left(\prod_{j=i}^{n-1} (\lambda_j b_{j,j+1}) \sum_{j=i}^{n} \frac{1 - e^{-\lambda_j (t-t_0)}}{\lambda_j \prod_{p=i,p\neq j}^{n} (\lambda_p - \lambda_j)} \right)$$

$$A(t) = \sum_{i=1}^{n} \overline{\epsilon_i} \lambda_i N_i(t)$$

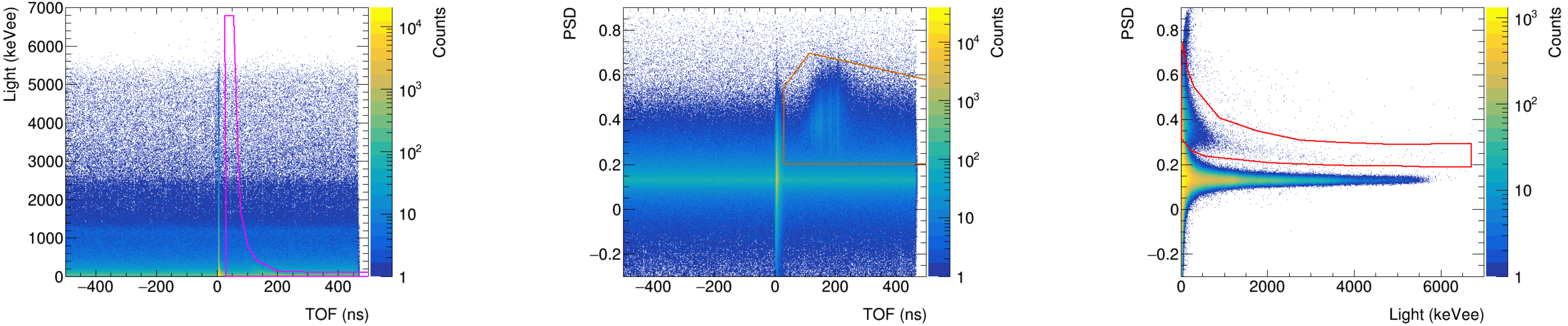
K. Skrable *et al.*, Health Physics, **27**, (1974) 155

Solving the Bateman equations for ^{86}As



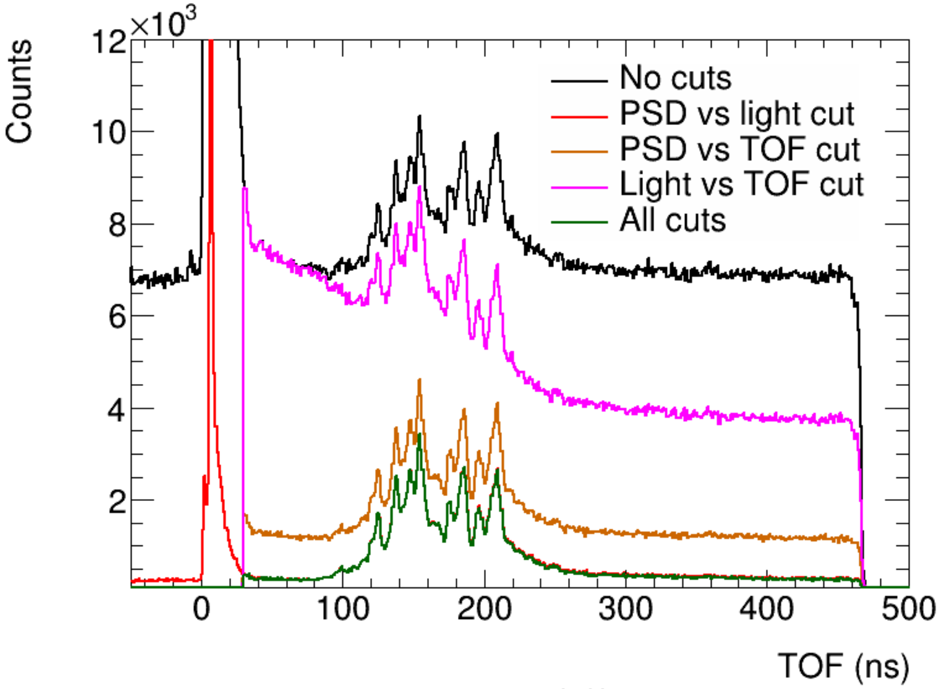
^{A}Z	$\bar{\epsilon}$ (%)	R (ions/s)	Decays
^{86}As	83.5	570 ± 40	$(1.27 \pm 0.08) \times 10^{7}$
^{86}Se	72.9	16100 ± 400	$(7.4 \pm 0.2) \times 10^{7}$
^{86}Br	77.5	21500 ± 2100	$(3.0 \pm 0.3) \times 10^{7}$
^{85}Se	76.0	0 ± 0	$(3.2 \pm 0.2) \times 10^{5}$

Analysis of the TOF data



Neutron cut used in plastic scintillators

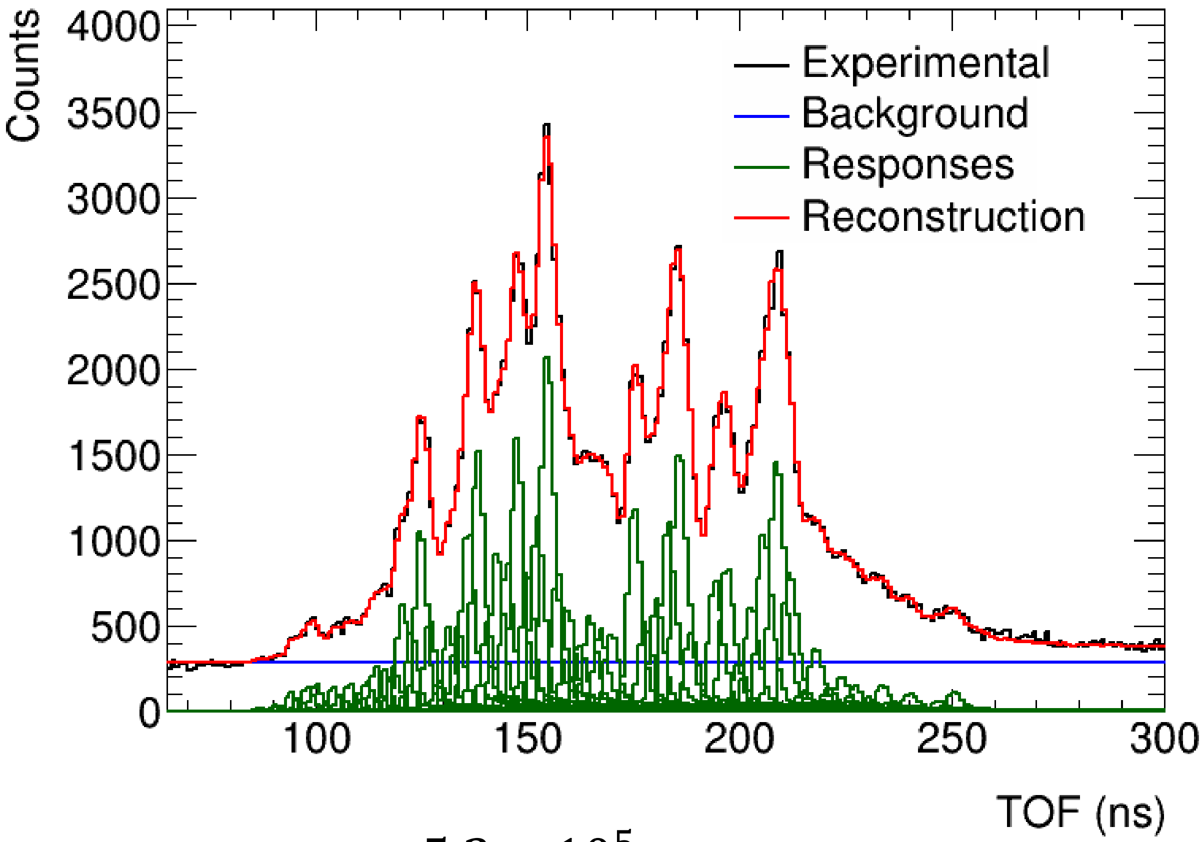
Different neutron cuts were studied to obtain a “clean” TOF spectrum



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

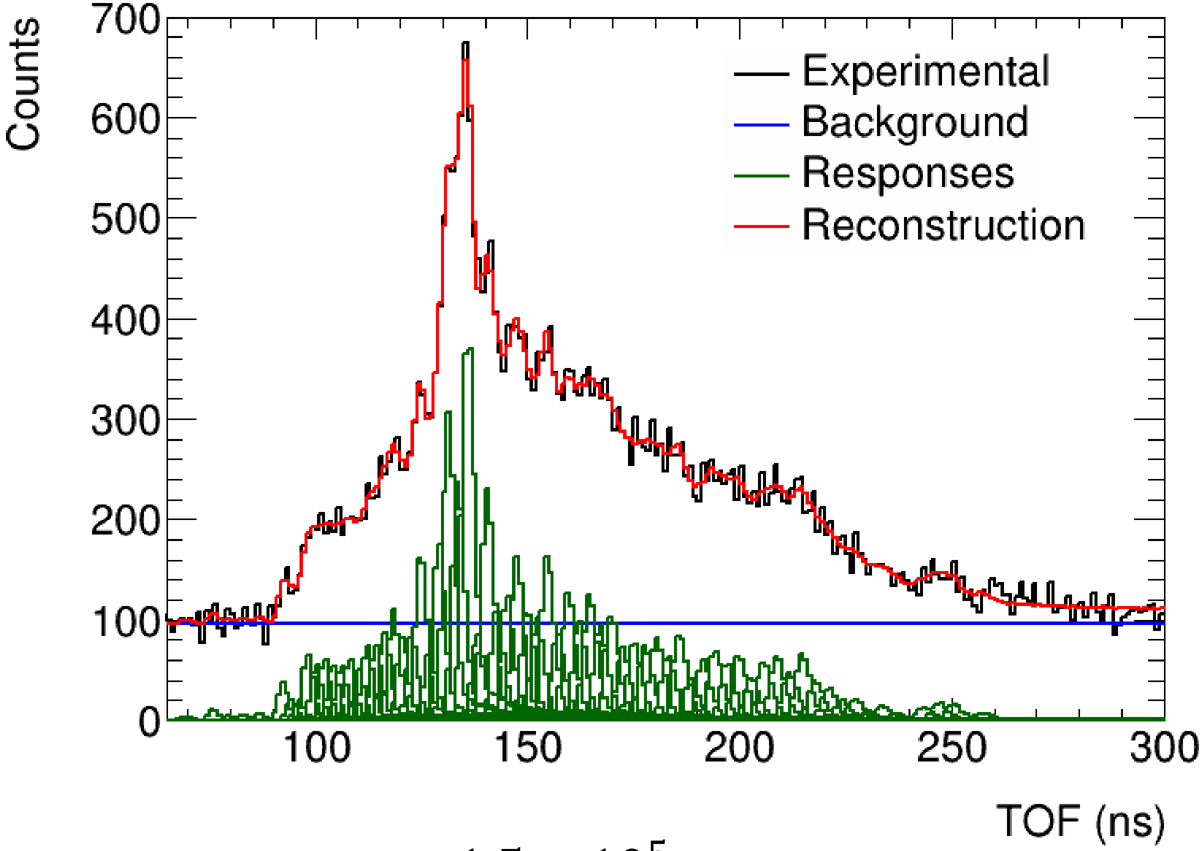
Neutron TOF data unfolding

^{85}As



5.2×10^5counts

^{86}As

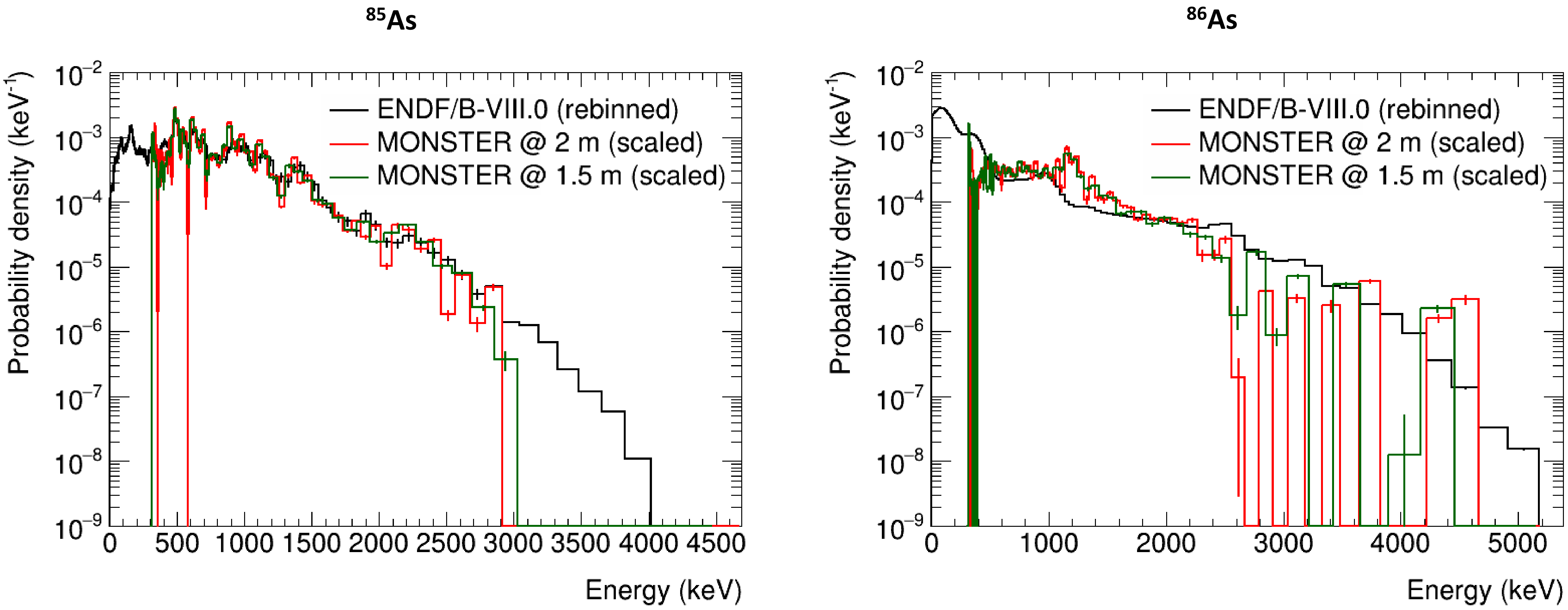


1.5×10^5counts

^{85,86}As β-decays @ IGISOL

^{85}As

^{86}As



Excellent agreement with previous data and evaluations

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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

The MONSTER Collaboration today

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