Neutron TOF measurements with MONSTER: from β-decay to (α,n) reactions and beyond

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MONSTER Collaboration

MANY Collaboration

Index

- Introduction
- Methodology
- ^{85,86}As β-decays @ IGISOL
- $^{27}Al(\alpha,n)^{30}P$ reaction @ HiSPANoS
- $^{140}Ce(n,n')^{140}Ce^{*}(\gamma)^{140}Ce$ reaction @ NFS
- Summary and conclusions

Index

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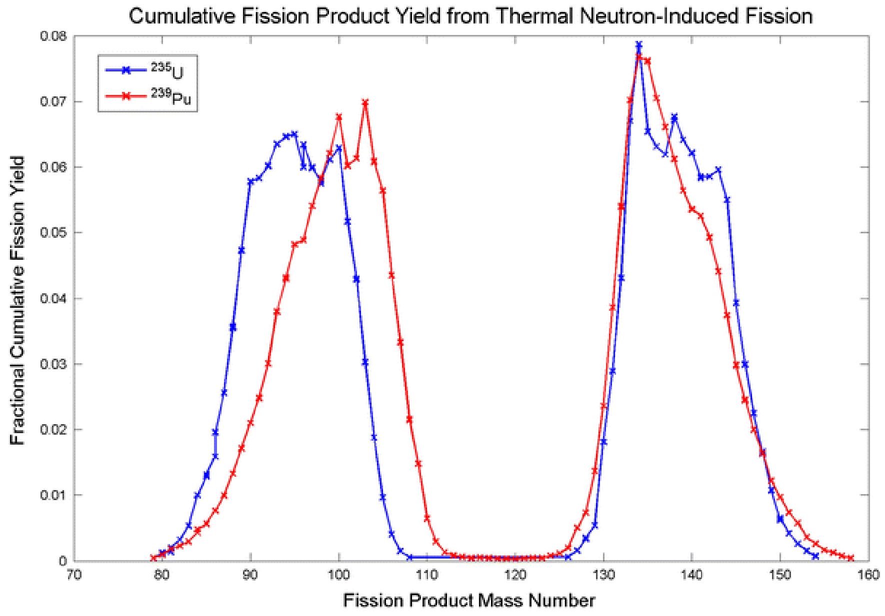
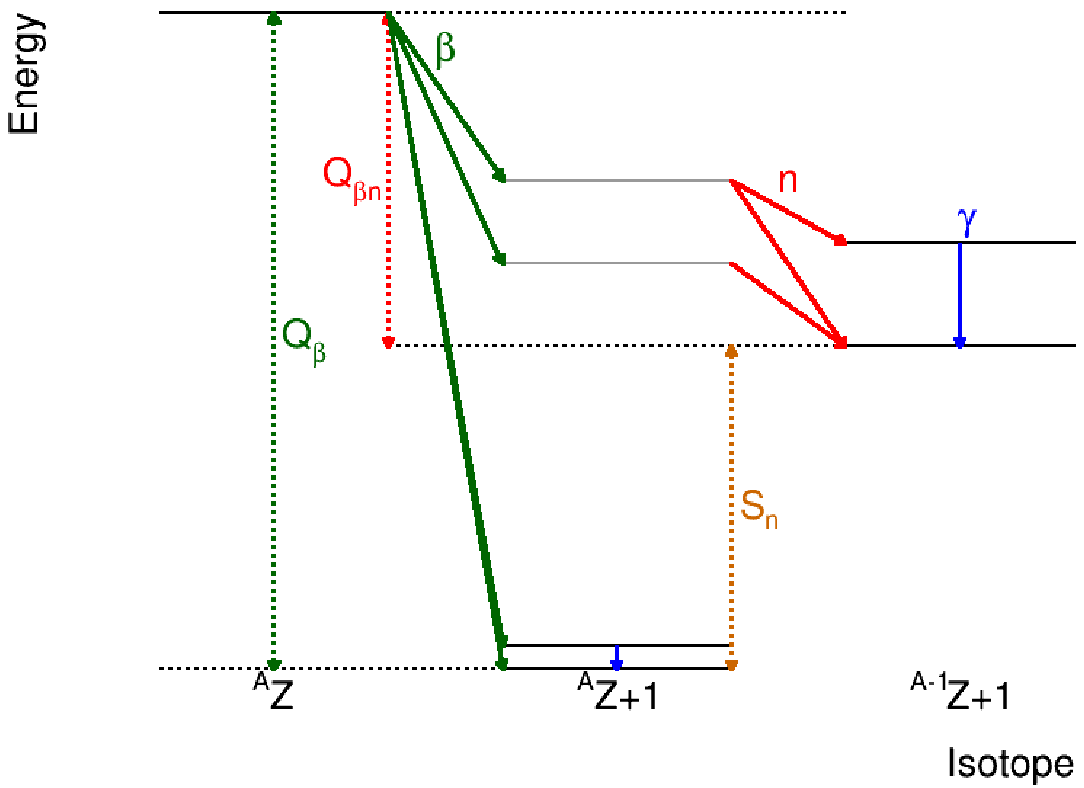
β-delayed neutron emission

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



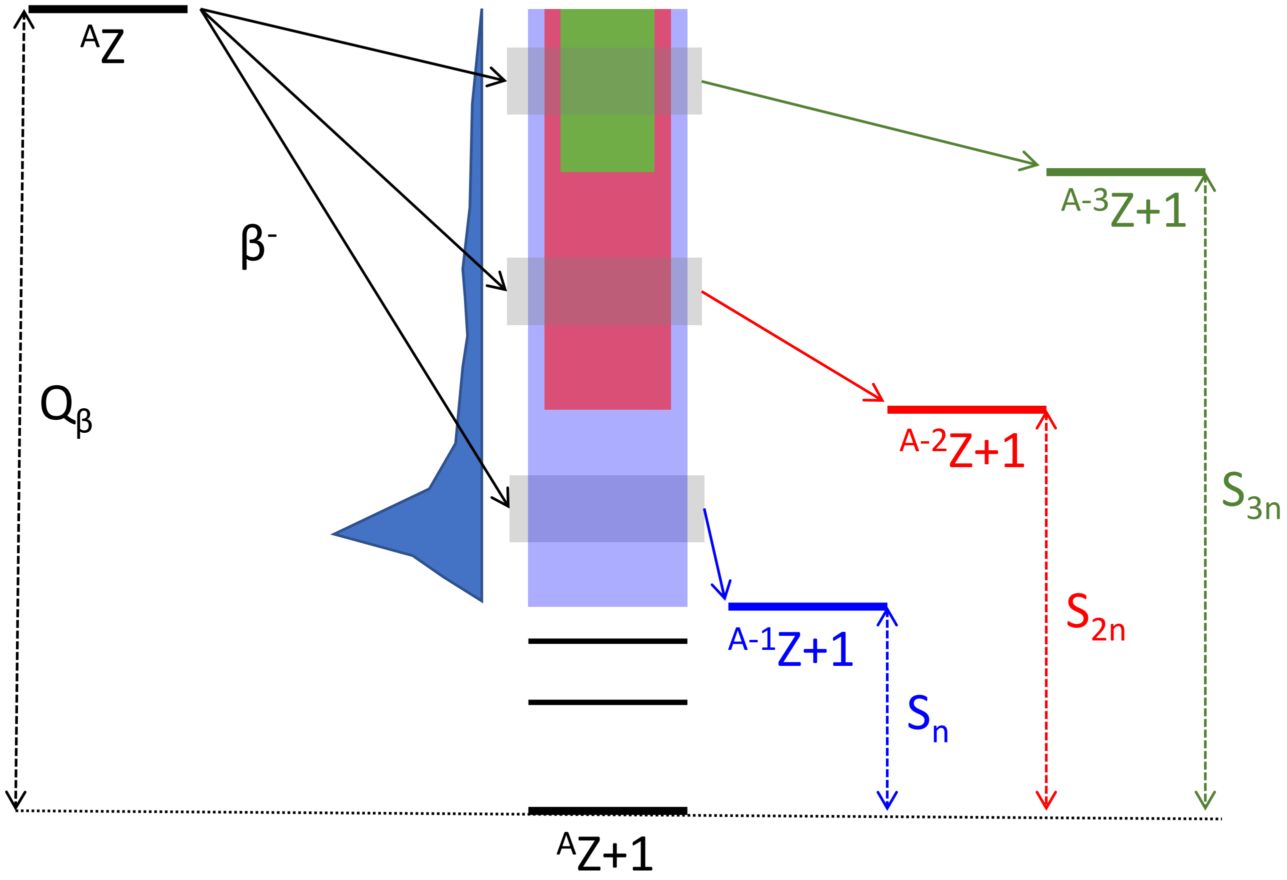


Priority list for reactor studies:

^{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



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

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

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

MONSTER

M⁘NSTER

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

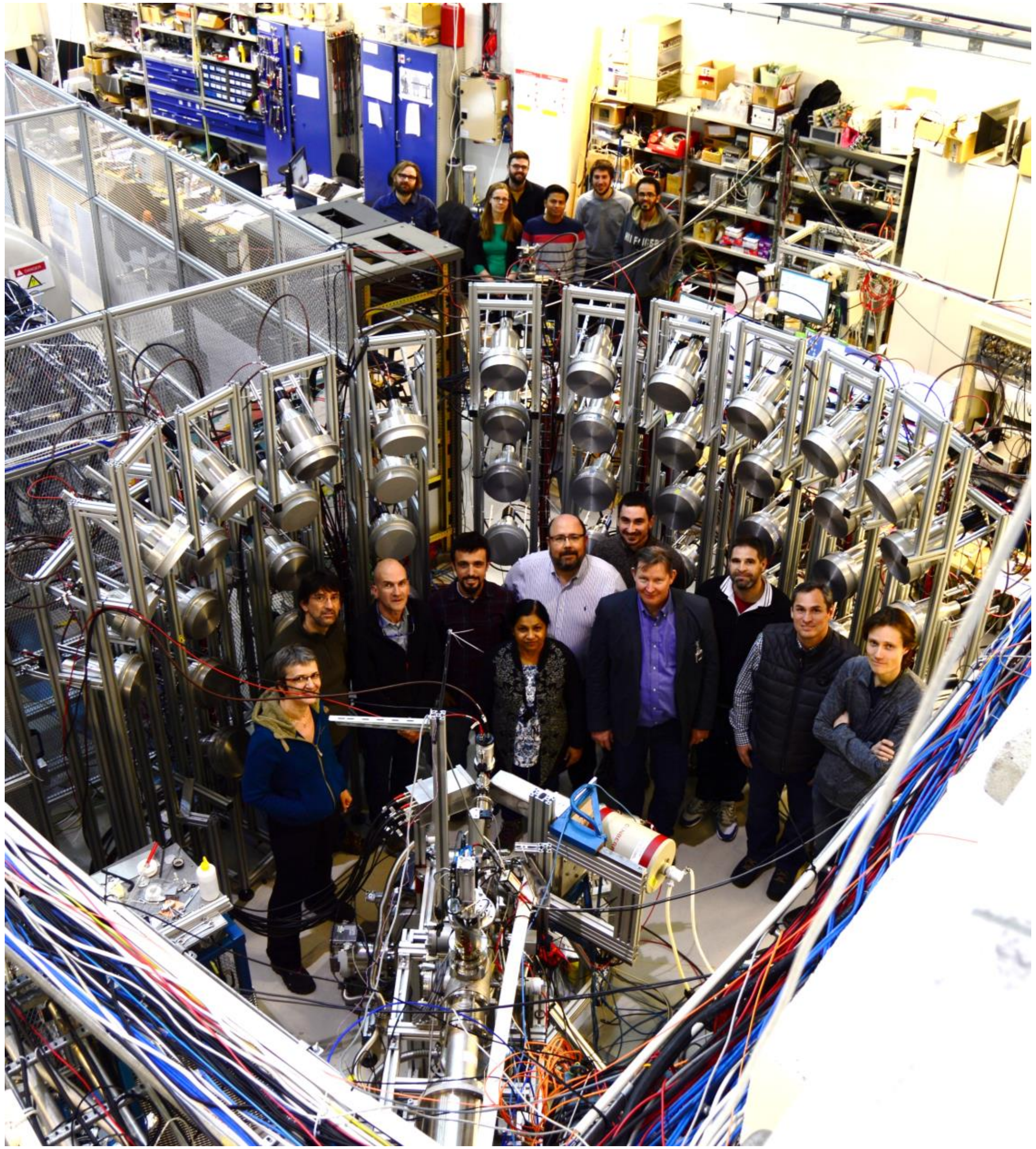
MONSTER TDR, (2013)

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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Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Index

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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:

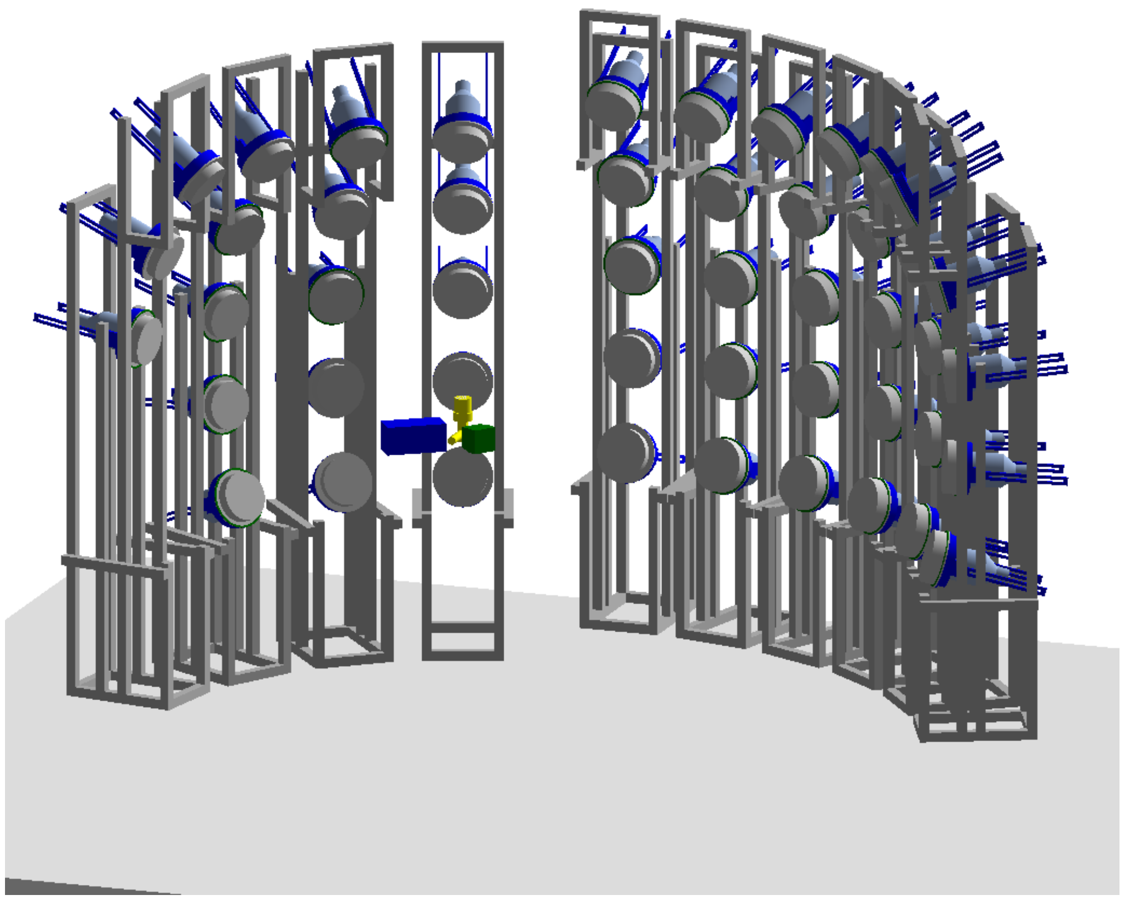
- C_i: independent causes -> neutron energy distribution
- E_j: effects -> TOF spectrum
- $P(E_j|C_i)$: response matrix

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

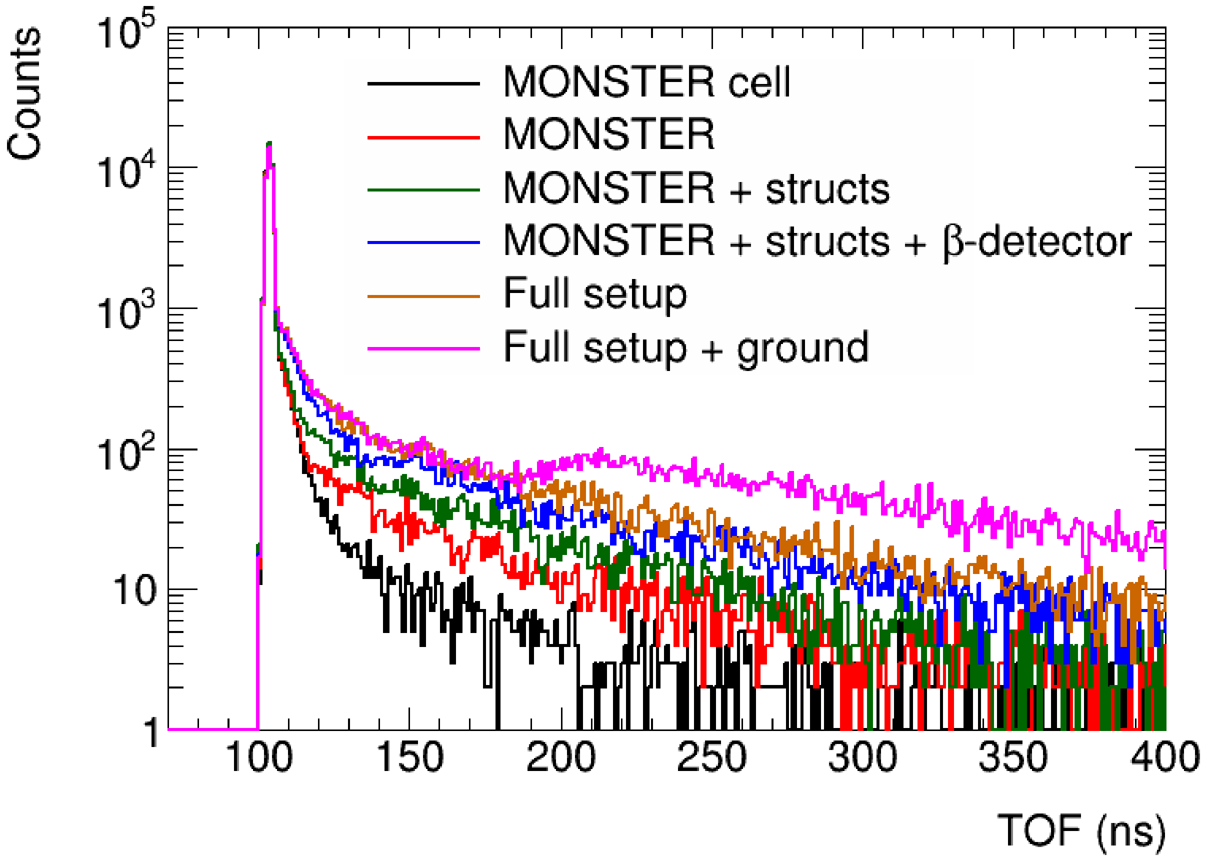
Unfolding applying an iterative Bayesian method to obtain the neutron energy spectrum

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

Monte Carlo simulation of the TOF response function



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

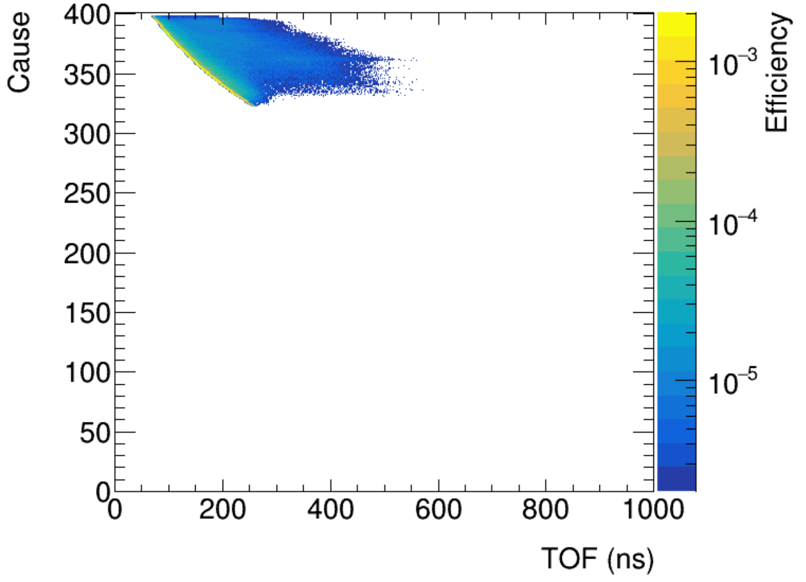


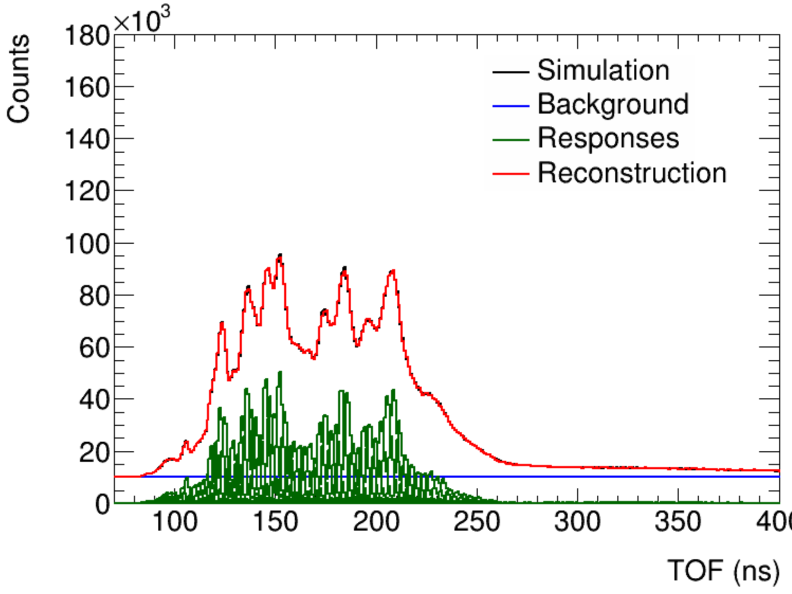
TOF response to 2 MeV neutrons for different setups, including effects due to time and spatial resolutions

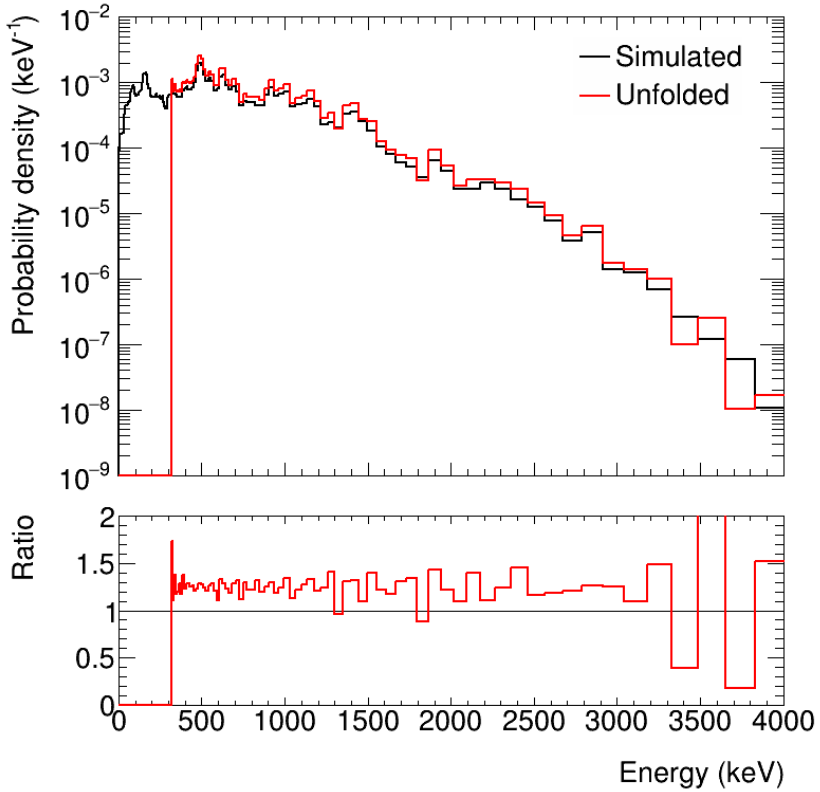
Only the array at 2 m is considered in this analysis

Analysis of a realistic β-decay experiment

The realistic experiment combines all previously studied effects and includes the effect of the β-detector threshold



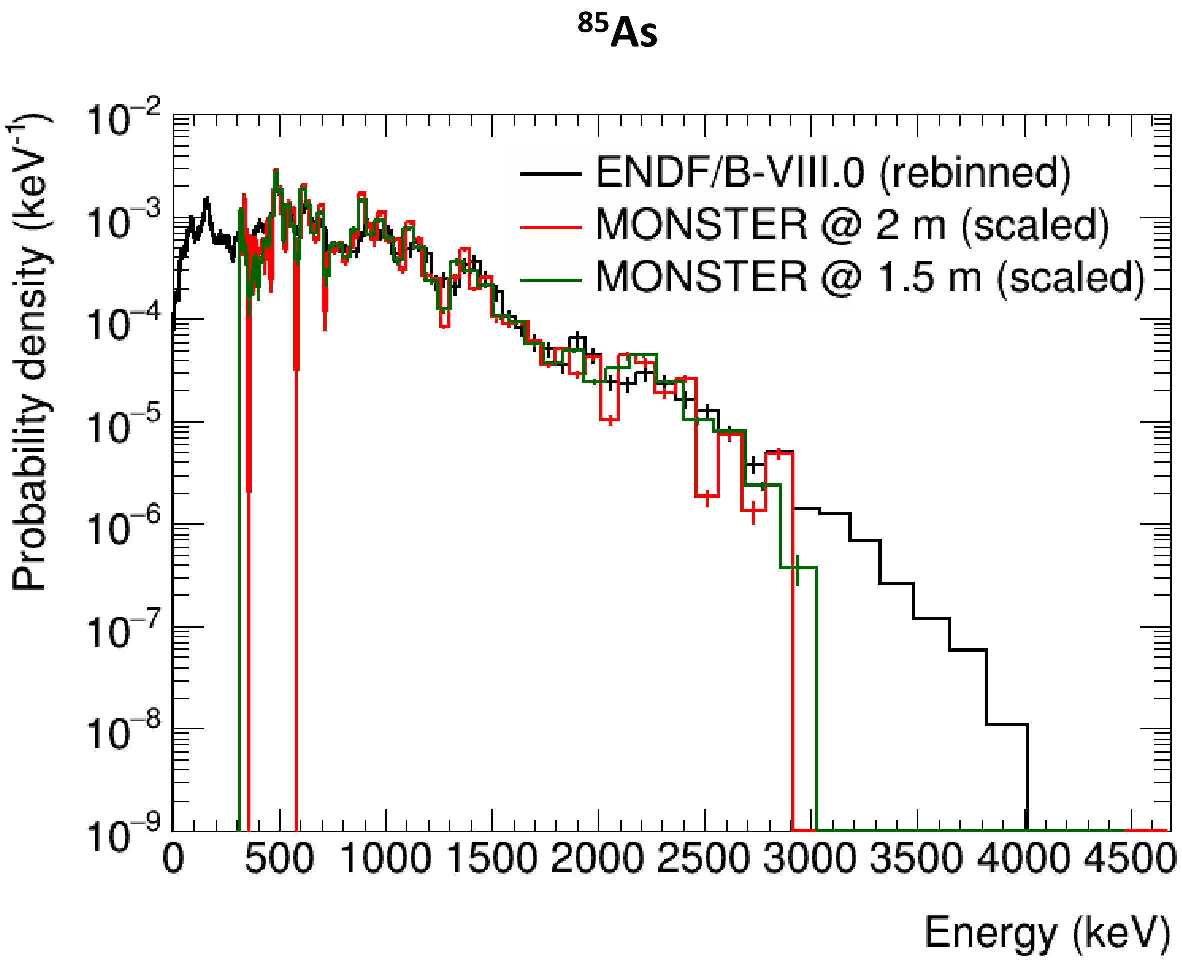


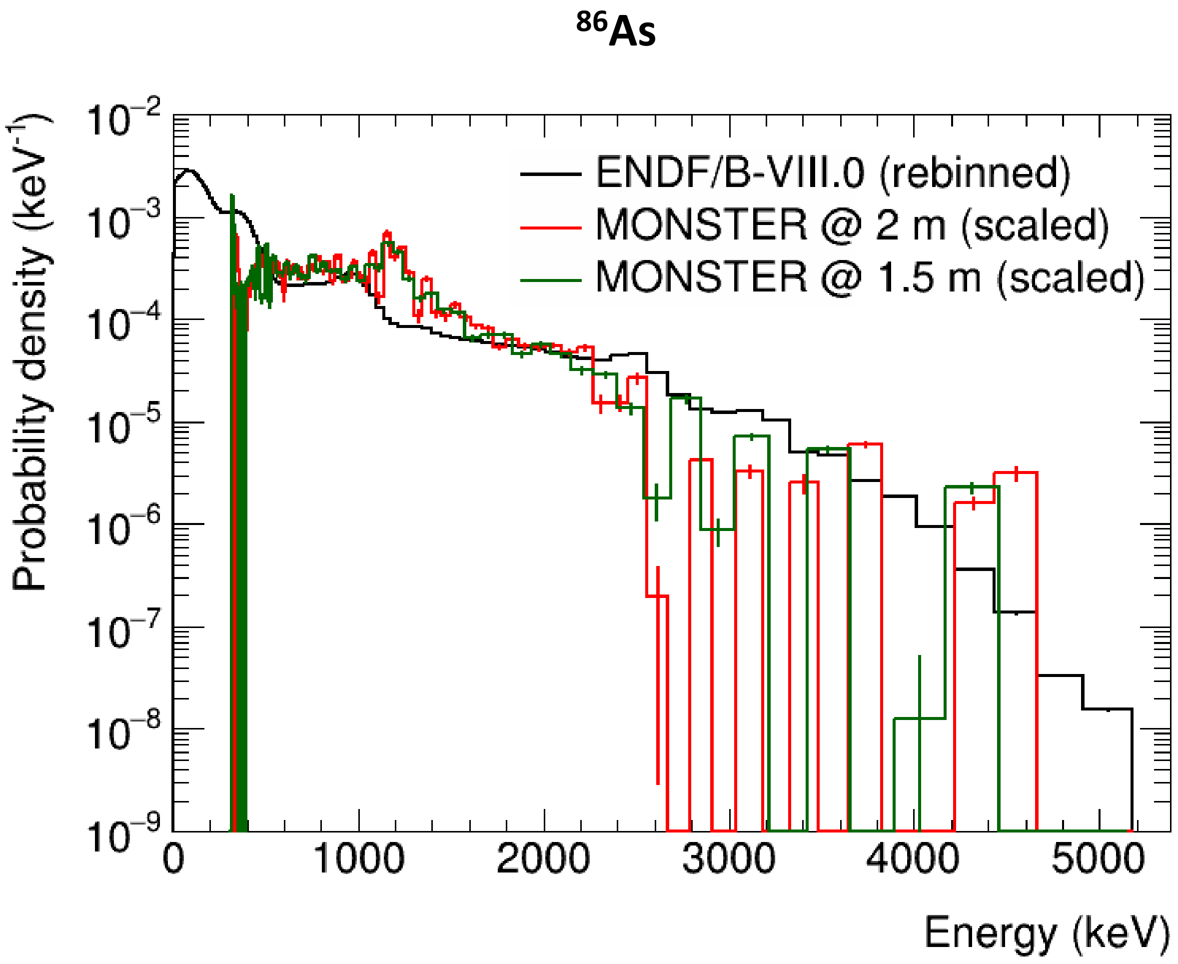


A very accurate reproduction of the neutron energy distribution is achieved over a large energy range

Index

^{85,86}As β-decays @ IGISOL





Excellent agreement with previous data and evaluations

Index

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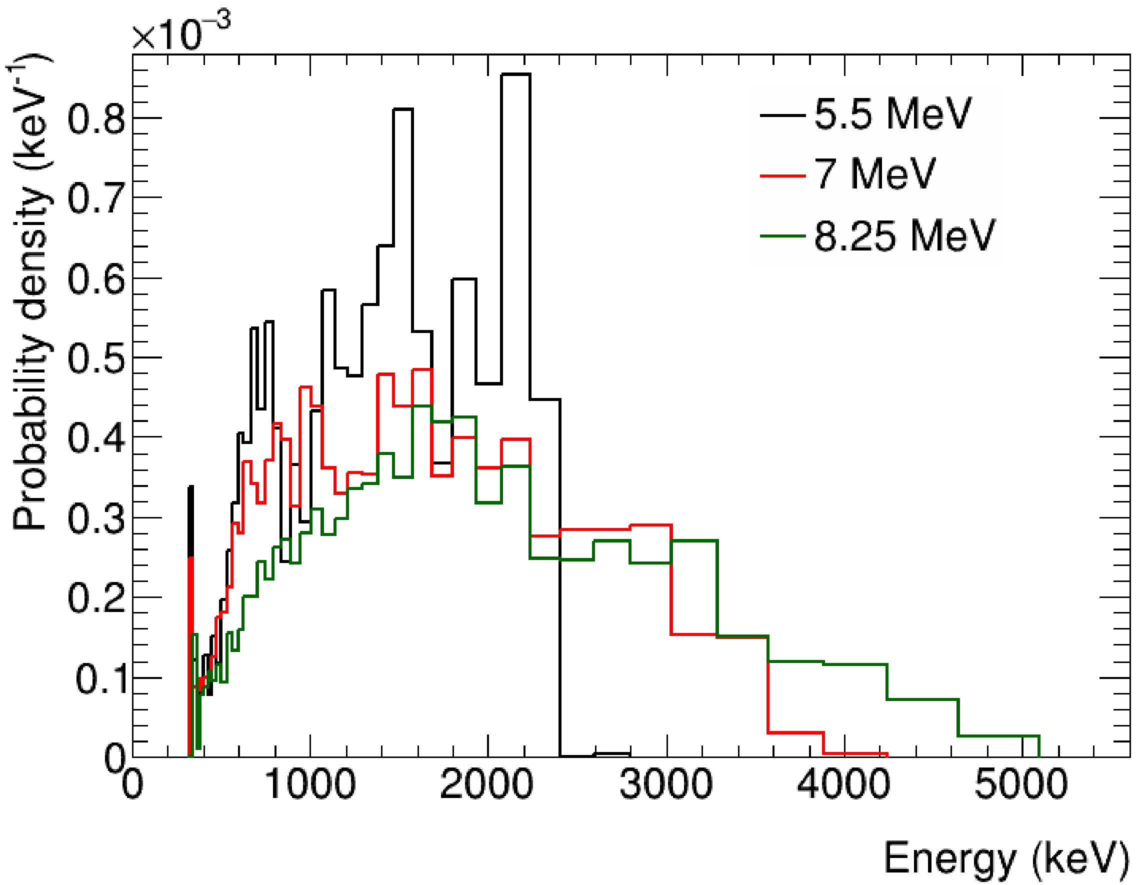
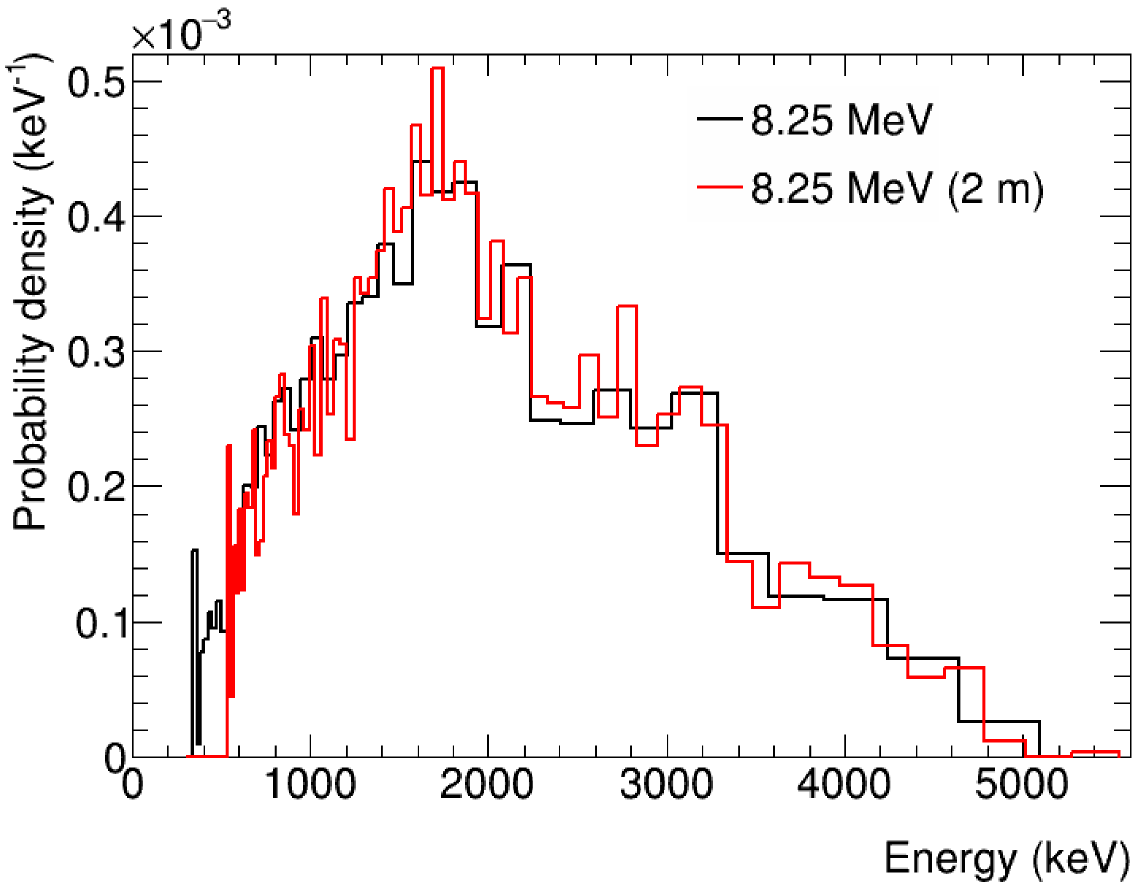
$^{27}Al(\alpha,n)^{30}P$ reaction @ HiSPANoS

1 m



2 m



Demonstrated viability of (α,n) reaction measurements

Index

- Introduction
- Methodology
- ^{85,86}As β-decays @ IGISOL
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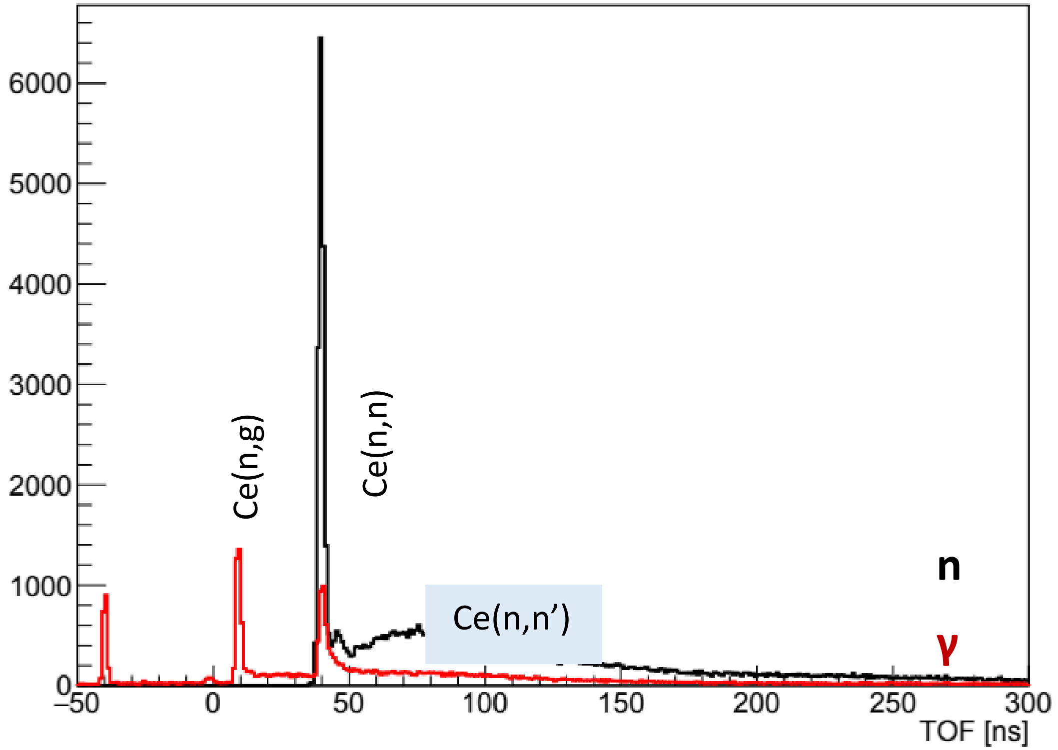
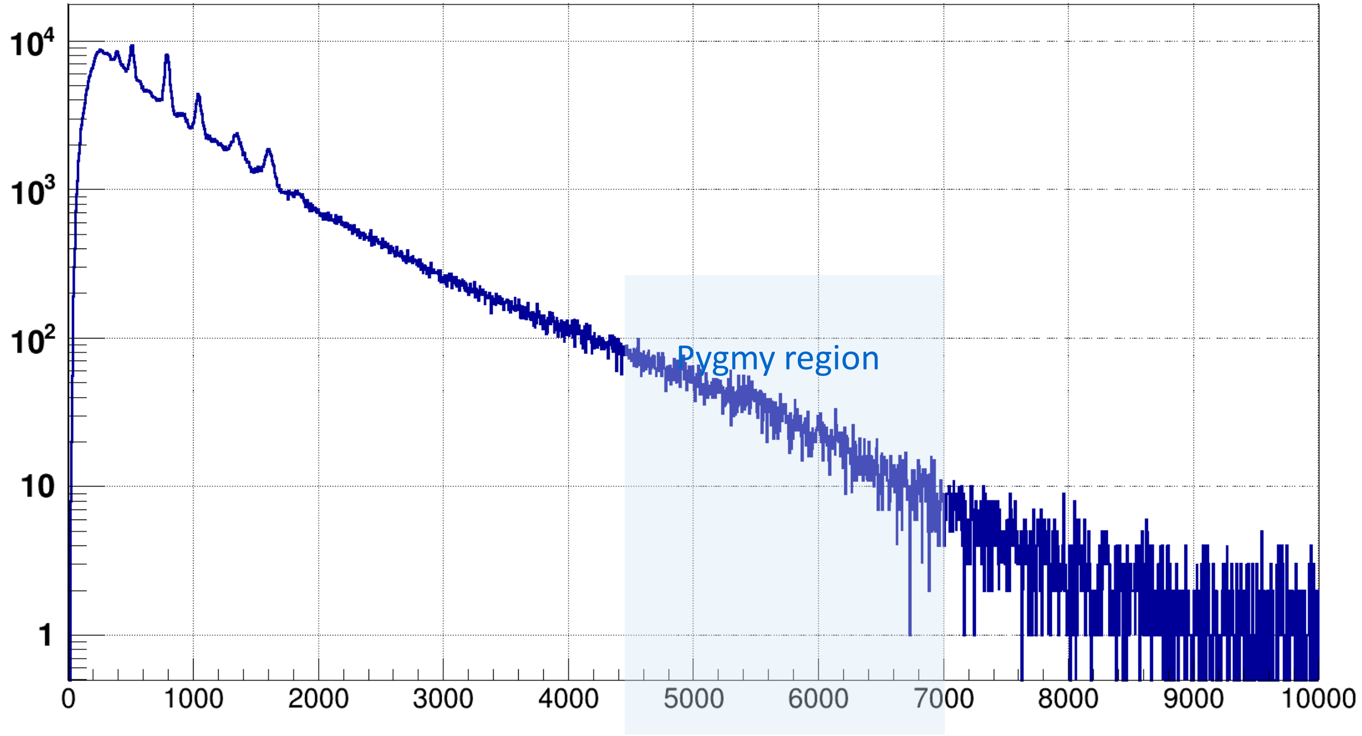
MONSTER



PARIS (coin. MONSTER)



Other kind of reaction studies are also possible

M. Vandebrouck, I. Matea, et al.

Characterization of MONSTER cells at high energies (20-40 MeV) is ongoing

Index

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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
- Validation of a 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
- Results:
  - Procurement of the ^{85}As β-delayed neutron spectrum and the “first” ^{86}As β-delayed neutron spectrum
  - Demonstrated viability of MONSTER for reaction measurements

Thank you!