Neutron energy measurements of (α, xn) reactions with MONSTER

José Llanes Gamonoso

jose.llanes@ciemat.es

MONSTER collaboration; MANY collaboration

Unidad de Innovación Nuclear

Departamento de Fisión Nuclear

CIEMAT

Avda. Complutense 40, 28040 Madrid – España

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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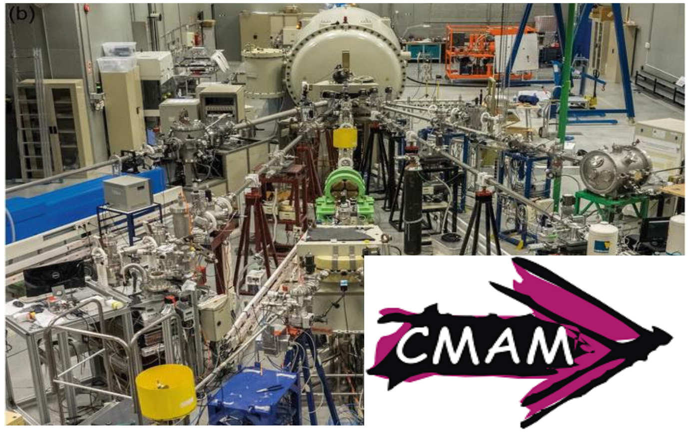
Motivation

- Nuclear data from (α,xn) reactions like yields, cross section, neutron spectra, angular distributions are relevant for: D. Cano-Ott et al., J. Phys. G: Nucl. Part. Phys., (2025)
  - Nuclear reactors and fuel cycles
  - Experiments in basic nuclear physics:
    - Dark matter
    - Neutrinos
  - Medical applications

- The available experimental data are outdated, incomplete, or have large uncertainties → New measurements (MANY collaboration) S.S. Westerdale et al., Summary report of the Technical Meeting, 8-12 Nov 2021 (virtual event)

Measurement of Alpha Neutron Yields and Spectra (MANY)

Two Spanish facilities



Universidad de Sevilla

IFIC
Institut de Física Corpuscular

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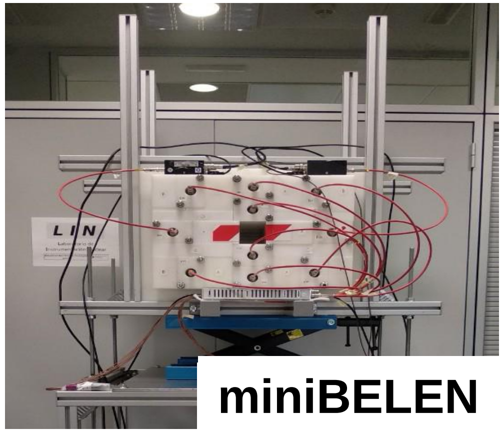
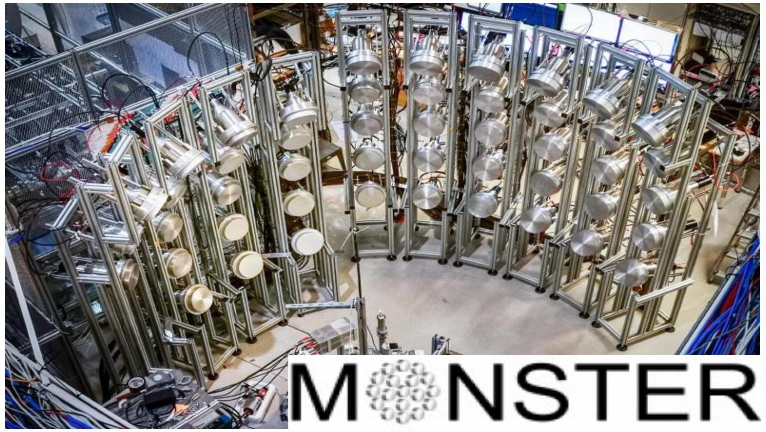
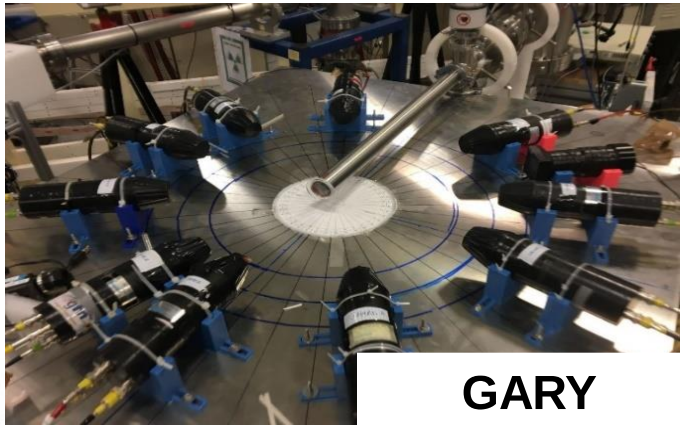
Three Spanish detectors







Measurement of neutron spectra in (α,xn) reactions

Within MANY collaboration, we are interested in:

- Neutron yields and cross sections → miniBELEN and GARY

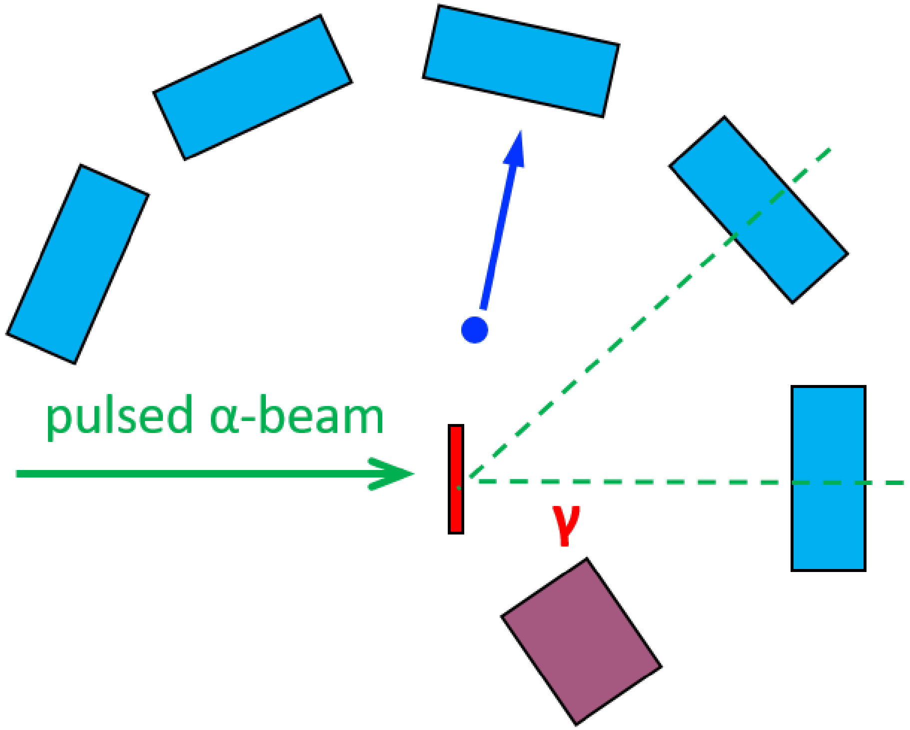
- **Neutron spectra and angular distribution → MONSTER**

TOF spectrometer:
- Requires a pulsed α-beam.
- Information for the eff correction $\varepsilon_n(E_n)$
- Measurements at different angles allows the study of angular distribution
- Low efficiency (~ 1%)
- Neutron/gamma discrimination and correlation with γ-rays

Our experimental setup

MONSTER

neutron detectors (liquid/plastic scintillators)



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Experimental setup

- HiSPANoS facility at the Centro Nacional de Aceleradores (CNA), Seville:
  - 3 MV tandem accelerator: to produce the α particles (between 5.5 and 8.5 MeV) (1)

- Five cells of MONSTER between 0° and 120° (2) A.R. Garcia et al., Journal of Instrumentation, 7, (2012) C05012
T. Martínez et al., Nucl. Data Sheets, 120, (2014) 78-80

- Four $LaBr_3$ detectors (3) and a HPGe detector (4)
  - (3) and (4) dedicated to γ measurements → γ/n correlated events

- ^{27}Al target: d = 2.5 cm, thickness = 150 μm, purity = 99.9 %

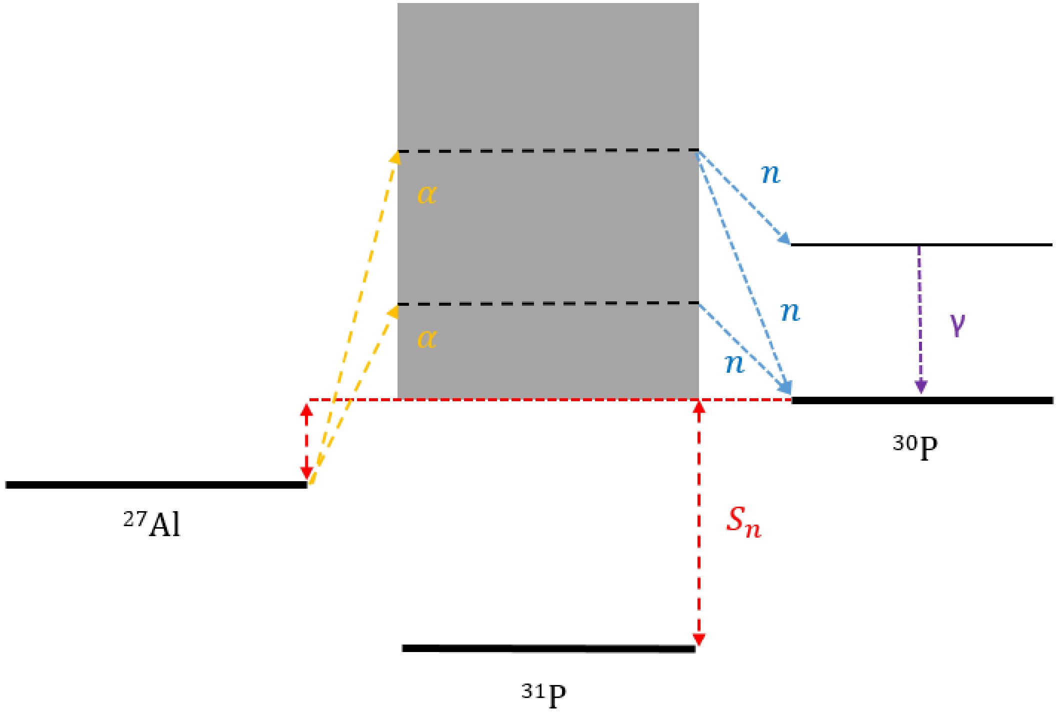
$^{27}Al(\alpha,n)^{30}P$ reaction

- IAEA suggests the use of this reaction as a benchmark A. Junghans et al., INDC International Nuclear Data Committee (IAEA), (2023)

- Aluminum is a very common element in structural materials

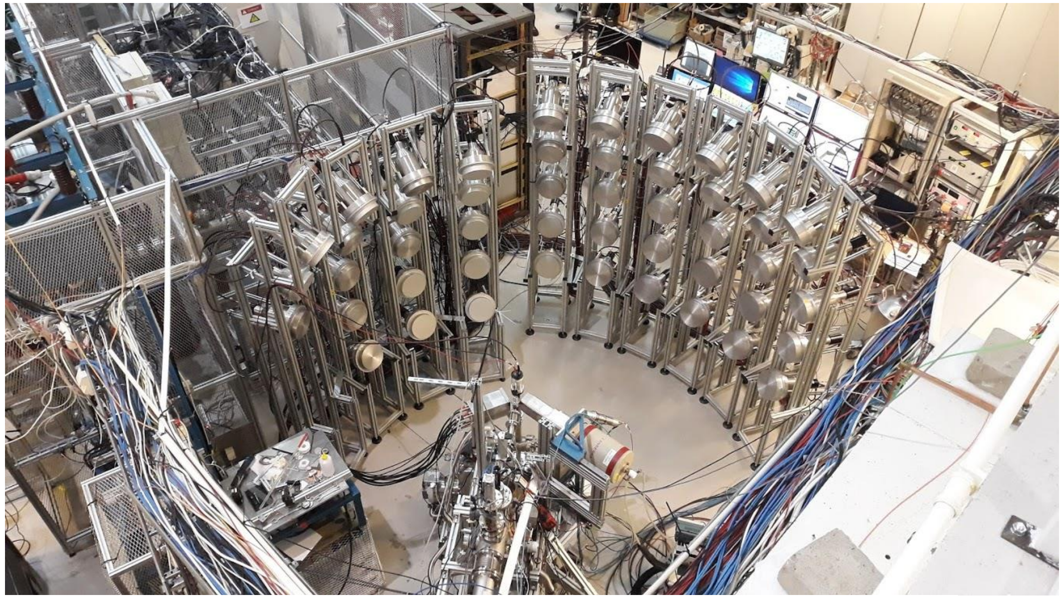
- There is available data for $^{27}Al(\alpha,n)^{30}P$ reaction G.J.H. Jacobs & Liskien, Annals of Nuclear Energy, 10, (1983) 541-552

- The reaction mechanism is well-known:
  - β^+ emission of ^{30}P allows the yield measurement

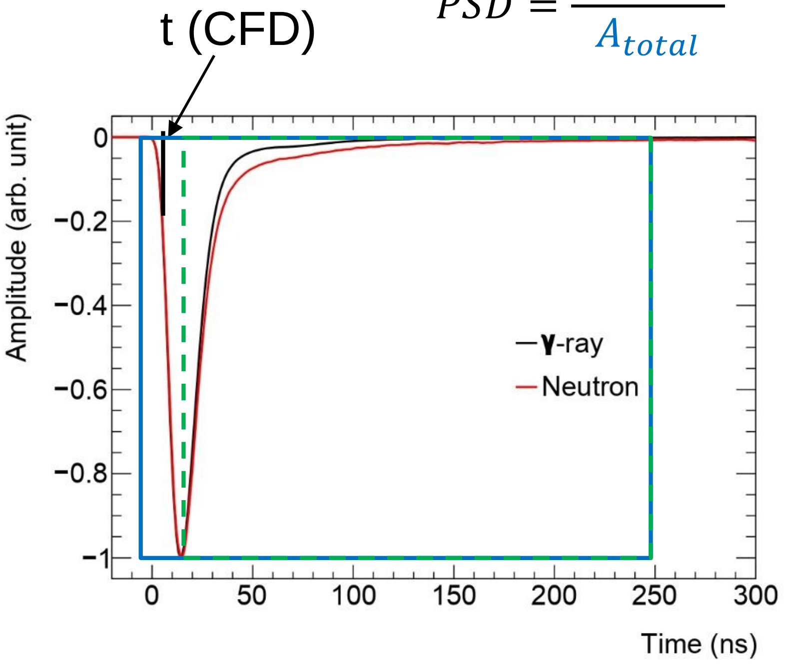


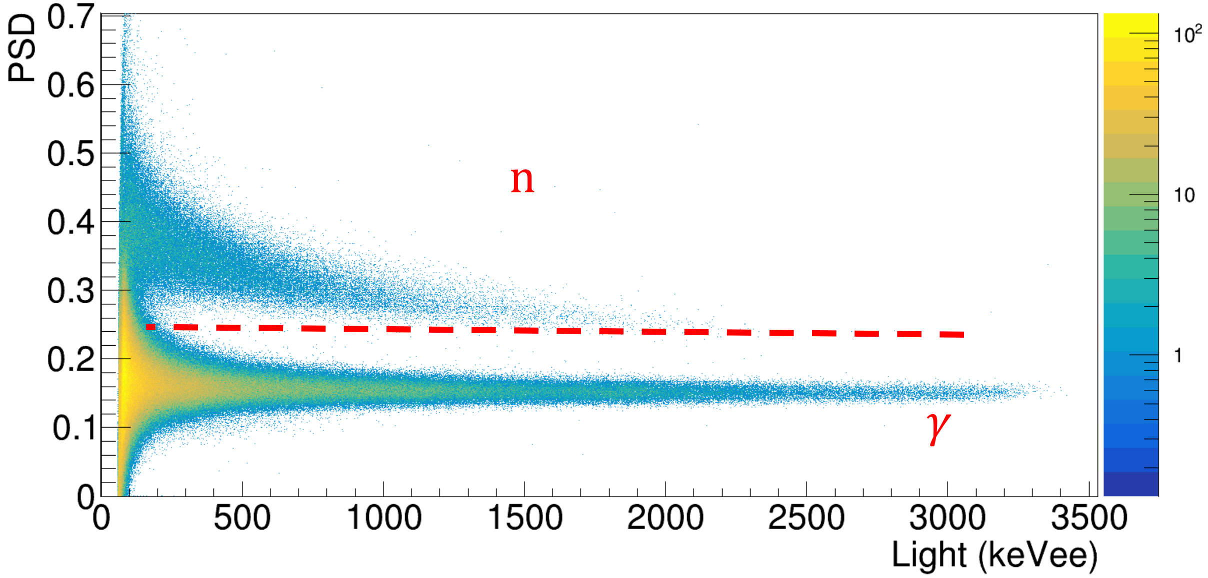
MONSTER spectrometer

- Cells are filled with a scintillating liquid (BC501A or EJ301)
- Good time resolution (< 1 ns)
- These detectors have a good neutron/γ-ray discrimination capability → Pulse Shape Discrimination (PSD)



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





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Inverse problem

$$TOF = R \cdot E_n$$

Measured neutron TOF spectrum

Response matrix

Neutron energy distribution

- Measured neutron TOF spectrum → Neutron selection over raw data
- Response matrix → Accurate Monte Carlo simulations with Geant4

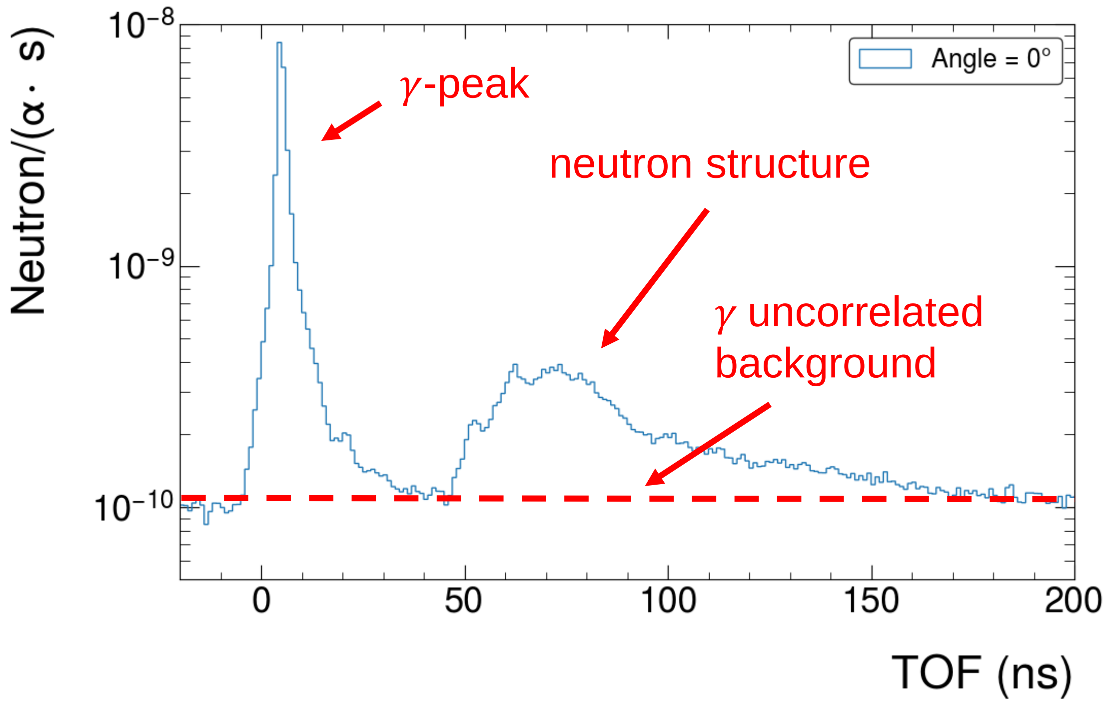
S. Agostinelli et al., Nucl. Inst. and Meth. A, 506, (2003) 250-303

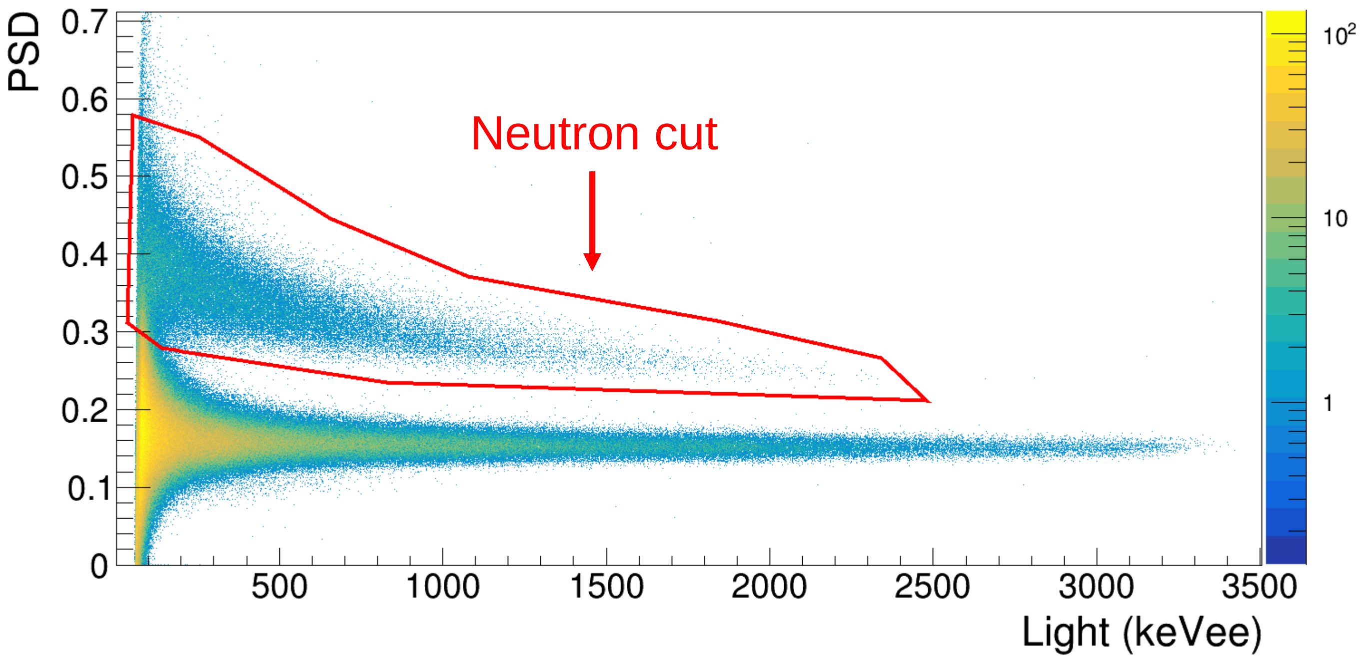
- Neutron energy distribution → Solving the inverse problem by an unfolding algorithm

Neutron Selection

$E_\alpha = 8.5$ MeV

Raw TOF spectra





- Difficult to see the neutrons due to high γ contribution → γ-peak and uncorrelated background → → Necessity of a neutron cut

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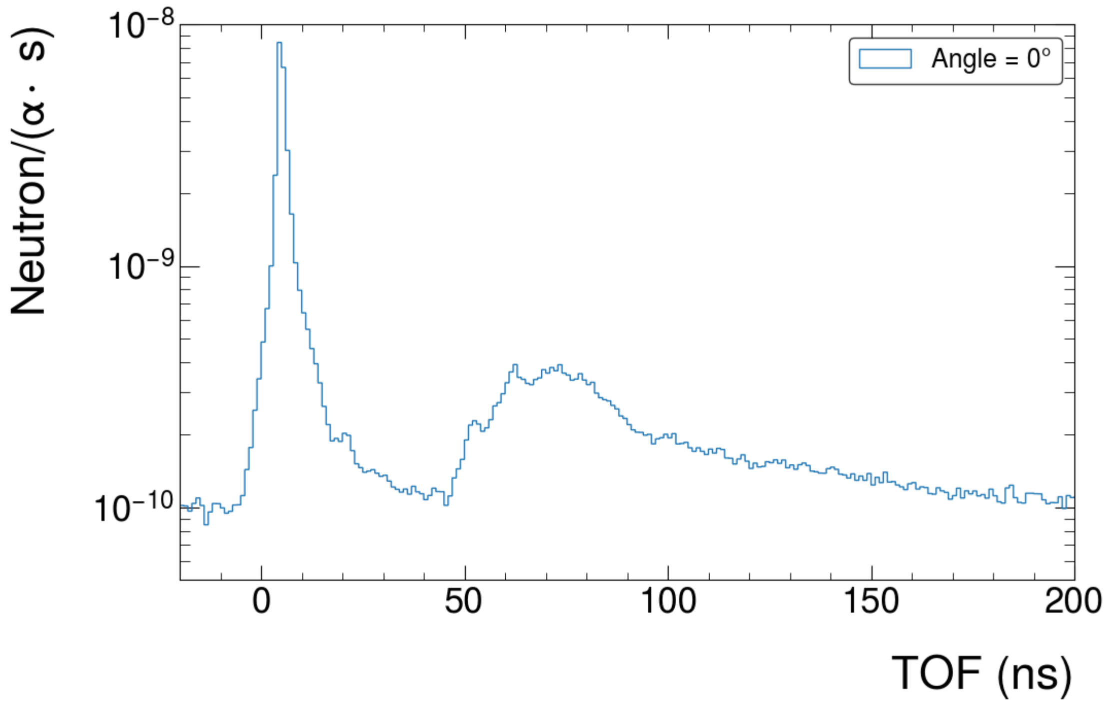
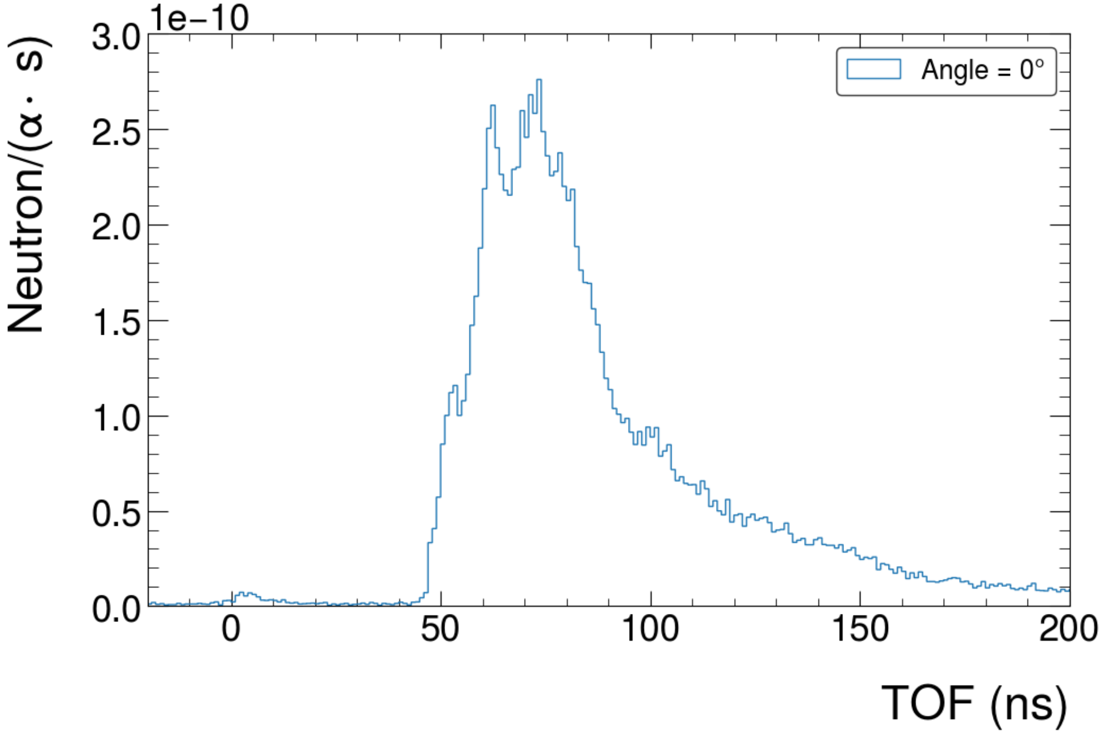
Neutron Selection

$\boldsymbol{E_\alpha = 8.5}$ **MeV**

Raw TOF spectra



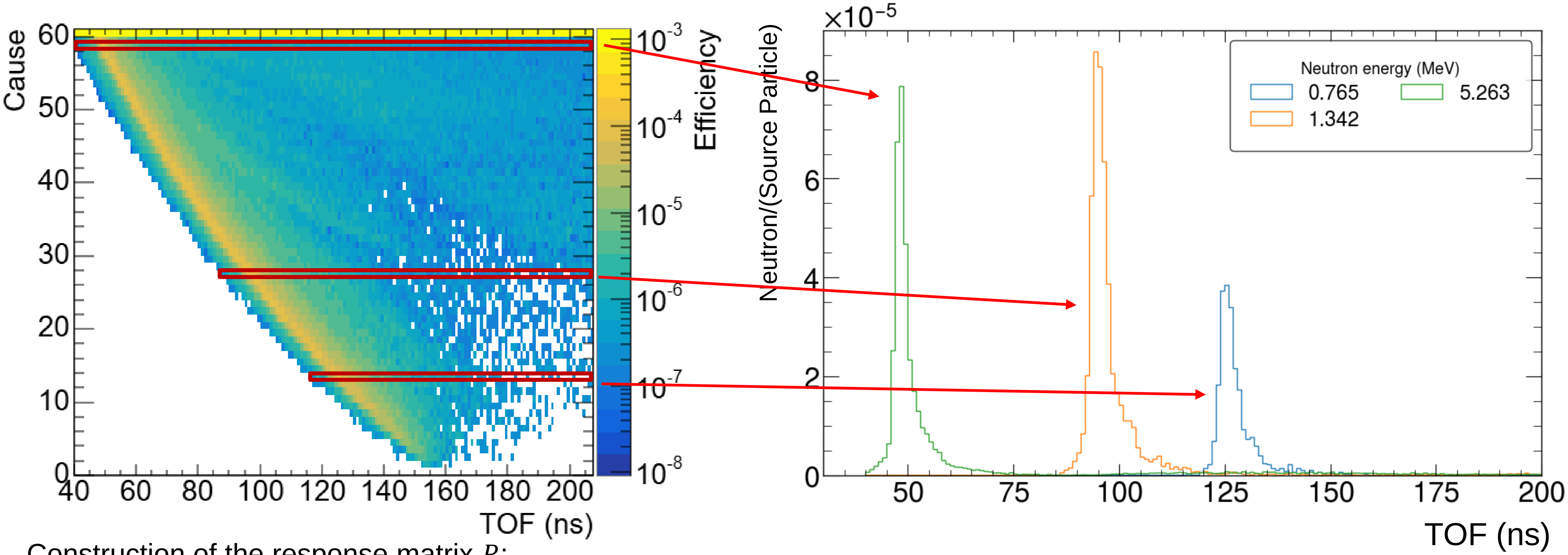
Neutron cut



- No γ contribution → Neutron TOF obtained
- Neutron structures are now highlighted

Response matrix

0º MONSTER cell



- Construction of the response matrix R:
  - Cover the whole neutron energy range
  - Provide TOF response for each considered neutron energy
  - The energy bin width is according to MONSTER resolution: $\frac{\Delta E}{E} = \gamma(\gamma+1)\sqrt{\left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta d}{d}\right)^2}, \Delta t < 1$ ns

Response matrix and unfolding algorithm

- Iterative Bayesian method : [G. D'Agostini, Nucl. Instrum. and Methods A, 362 (1995) 487-498]
  - Bayes formula

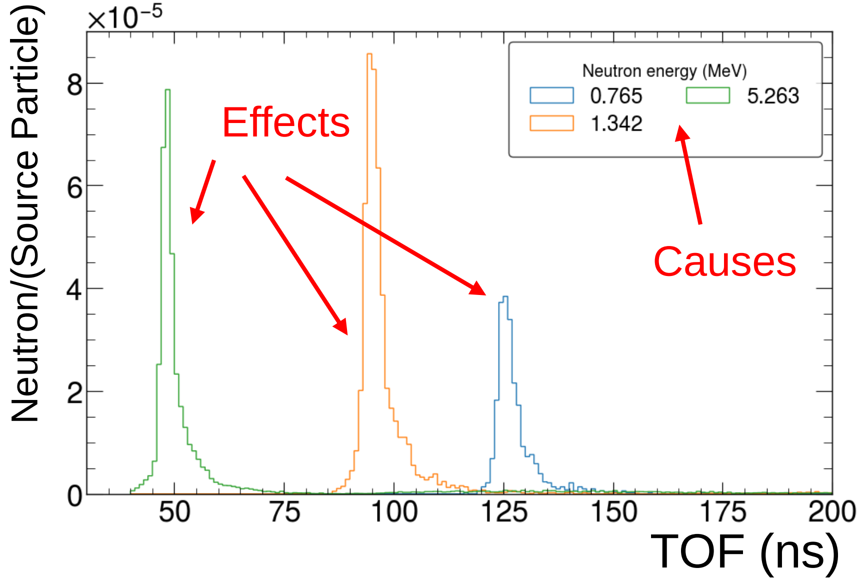
independent causes

effects

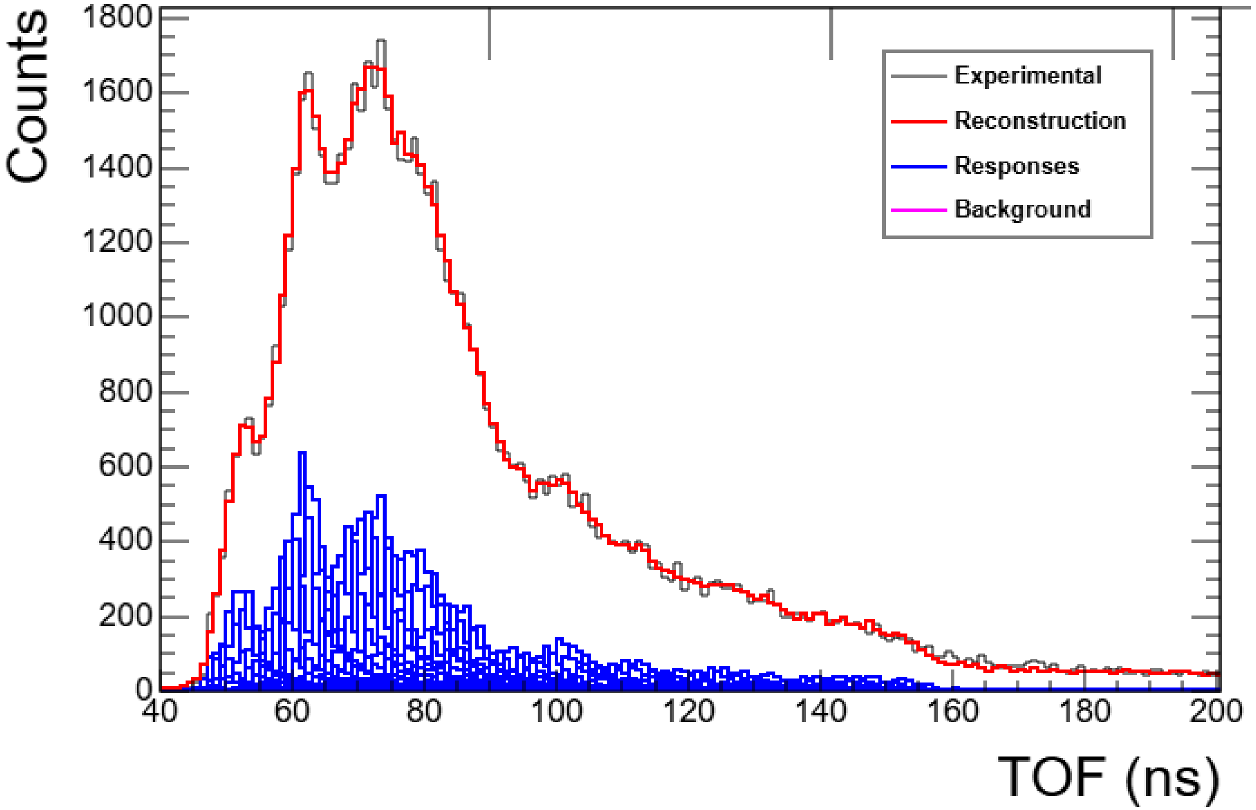
response matrix

initial guess

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



$E_\alpha = 8.5$ MeV, 0º MONSTER cell



- This methodology is validated with simulations (1) and real experiments (2)

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

(2) A. Pérez de Rada Fiol et al., Phys. Rev. C, 111, (2025), 044312

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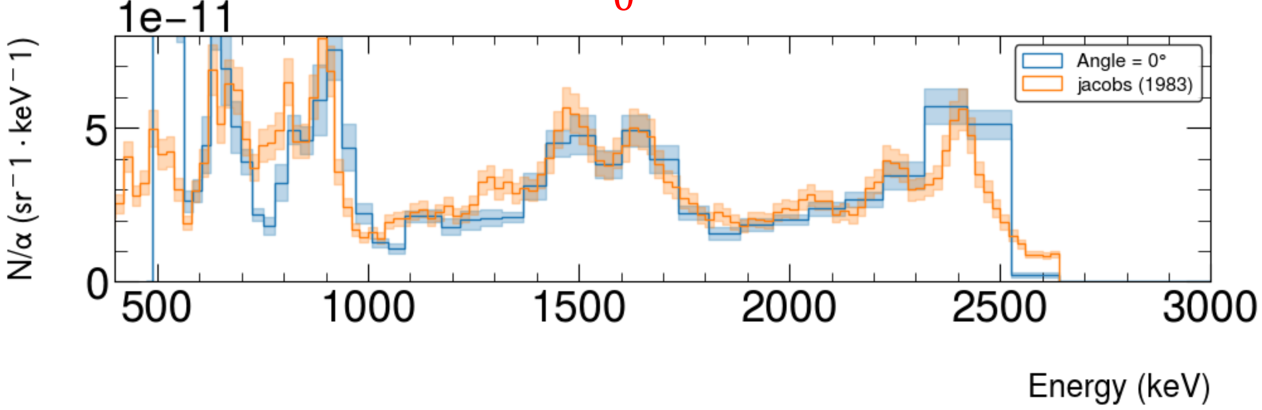
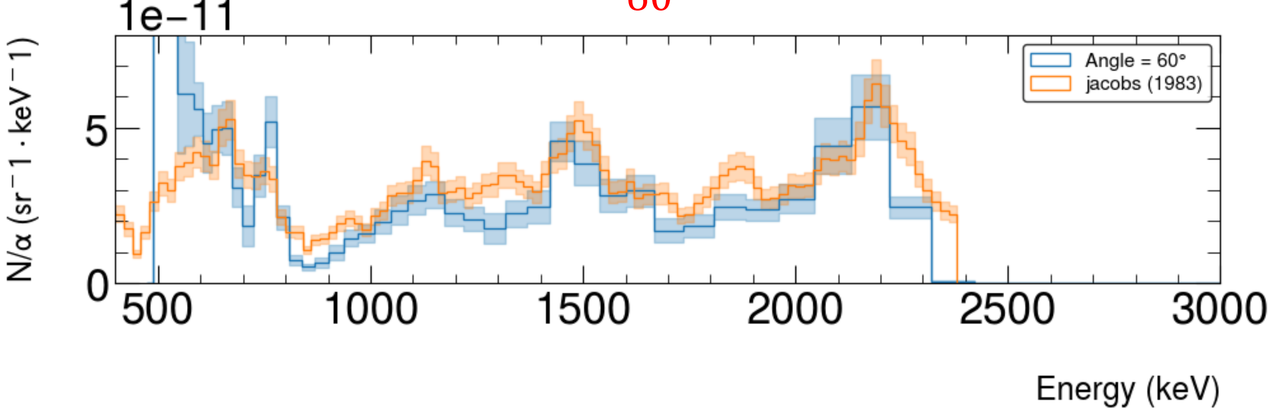
Neutron energy distributions: comparison with previous data ($E_\alpha = 5.5$ MeV)

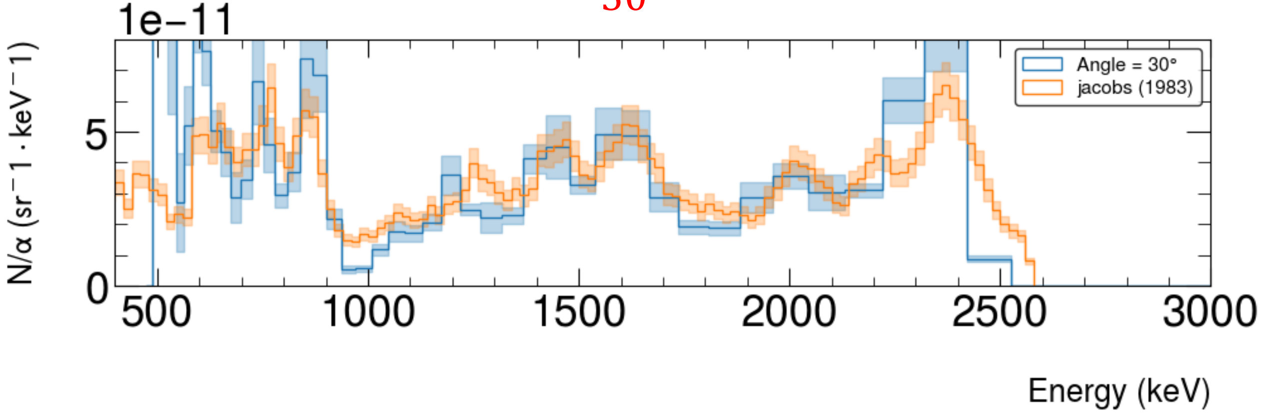
0°



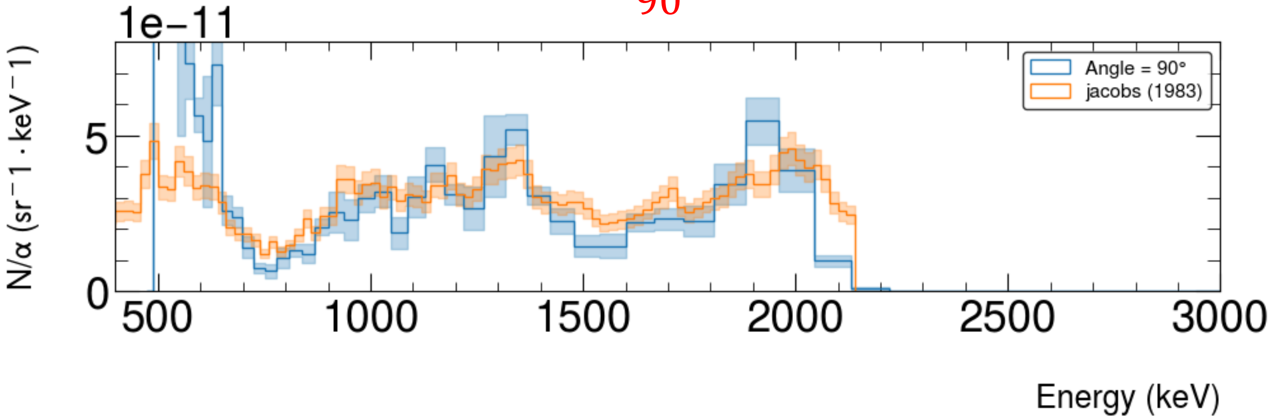
60°



30°



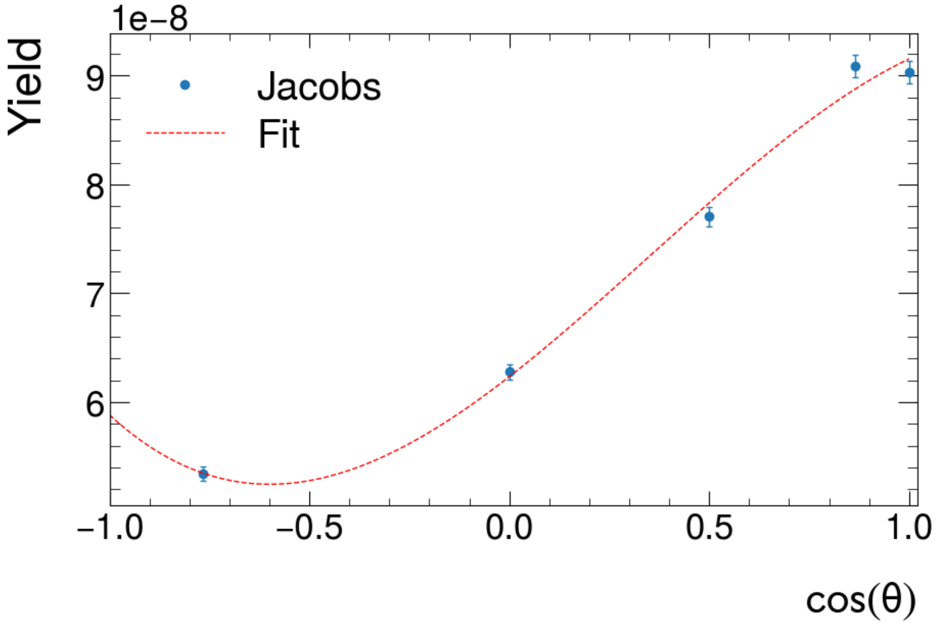
90°

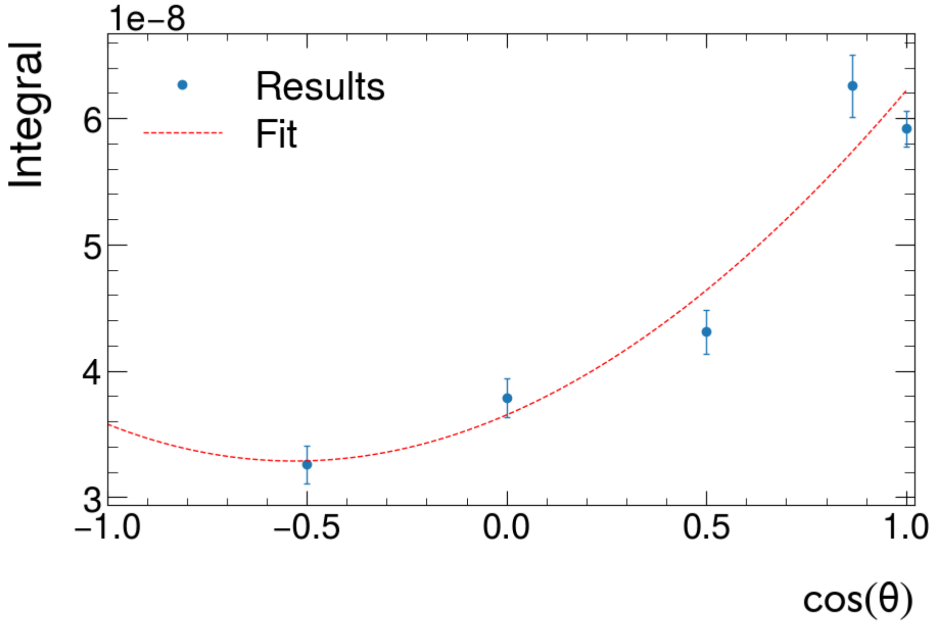


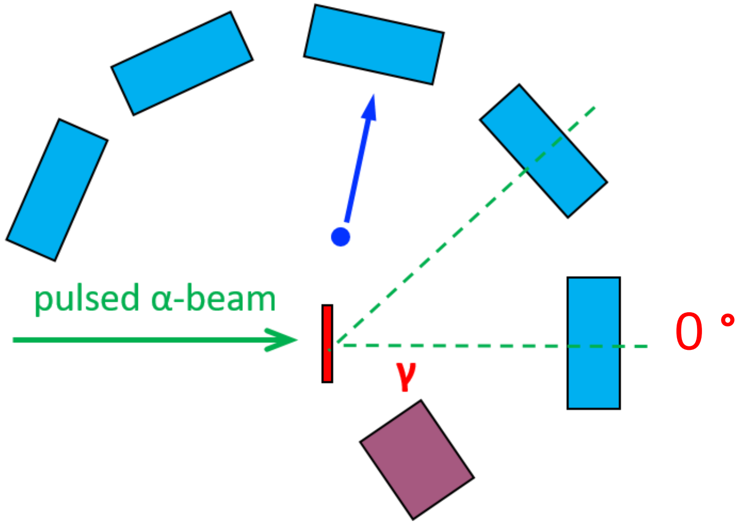
- Good agreement with previous data (within 10 %)

[G.J.H. Jacobs & Liskien, Annals of Nuclear Energy, 10, (1983) 541-552]

Angular distribution ($E_\alpha = 5.5$ MeV)





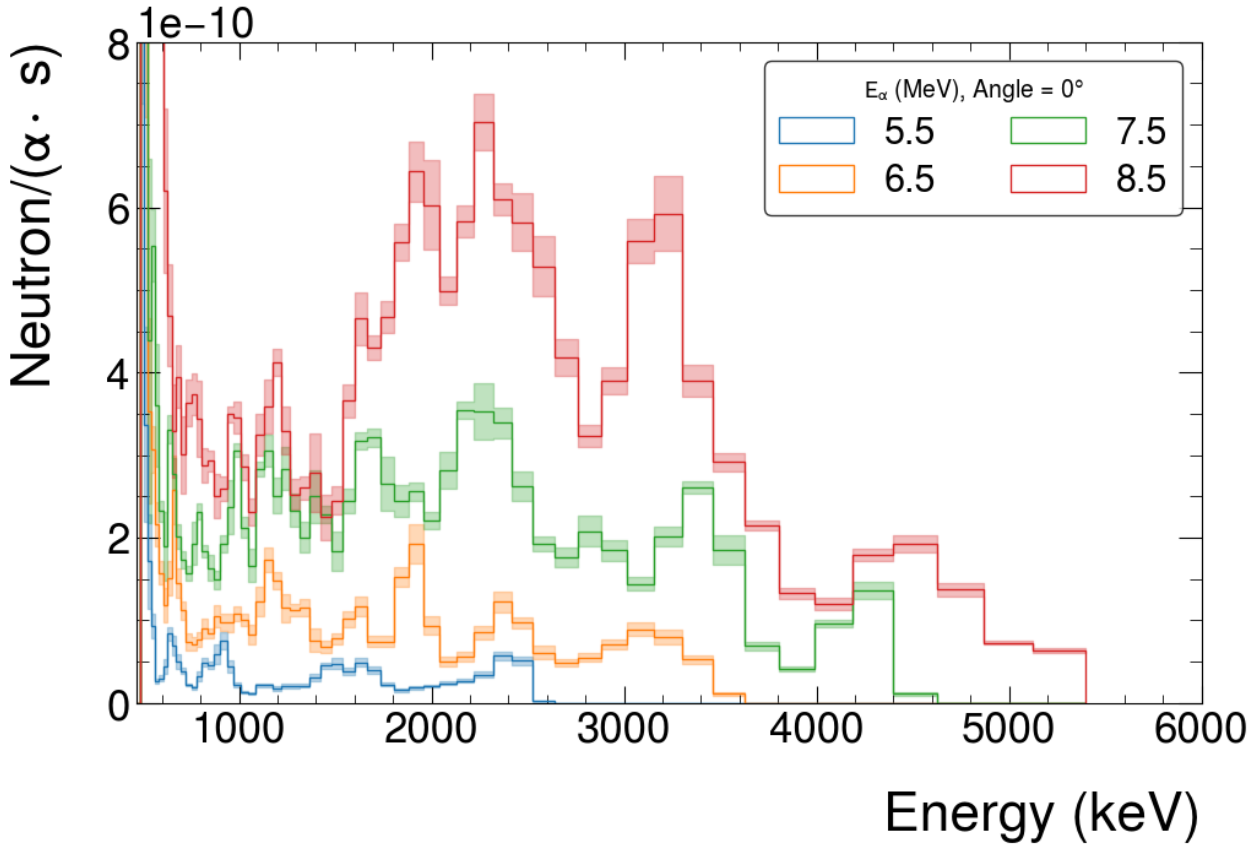


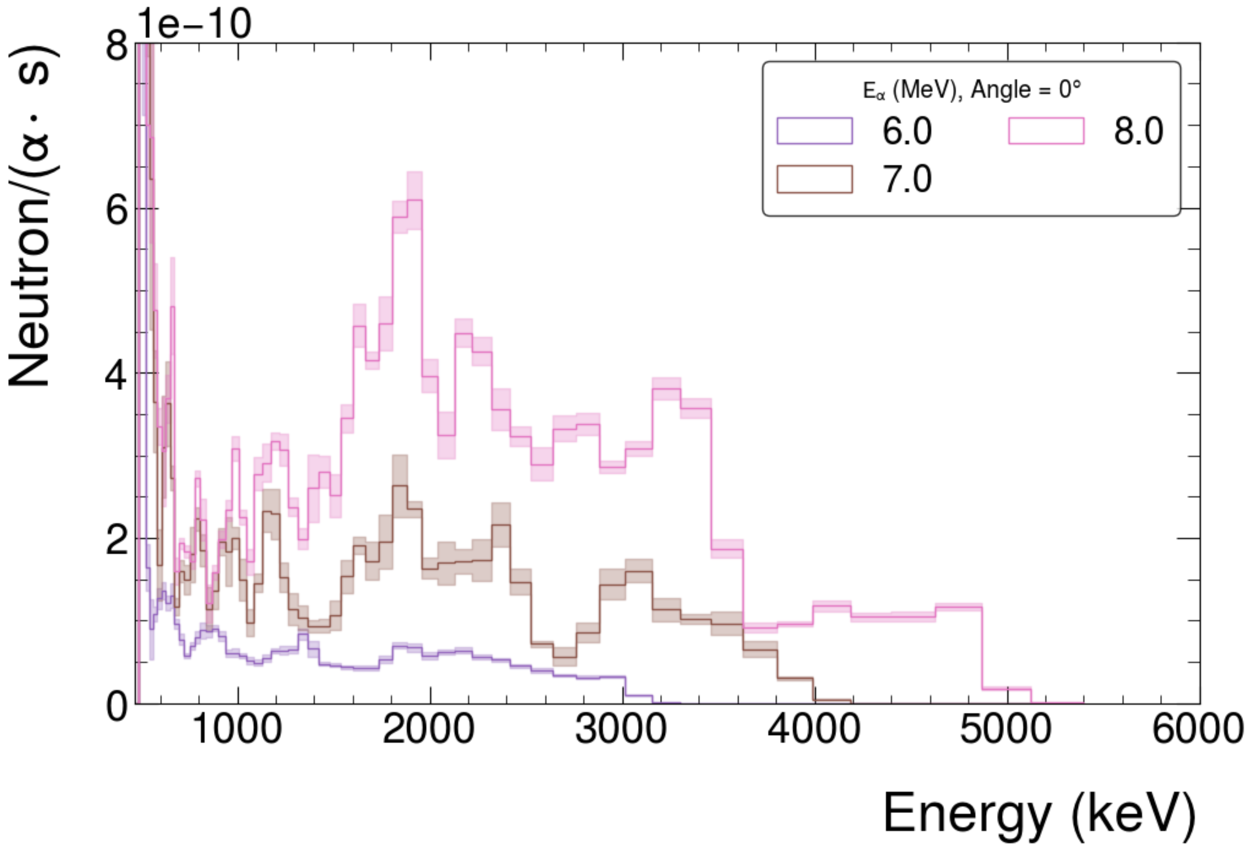
- Fit function: [R. M. Sealock, Nuc. Phys. A, **357**, (1980) 279-292]

$$f(\theta) = a_0 + a_1 \cos(\theta) + a_2 \cos^2(\theta) + a_3 \cos^3(\theta)$$

- Reaction kinematics:
  - Higher neutron yield/integral with decreasing angle → Maximum in the direction of the α beam line

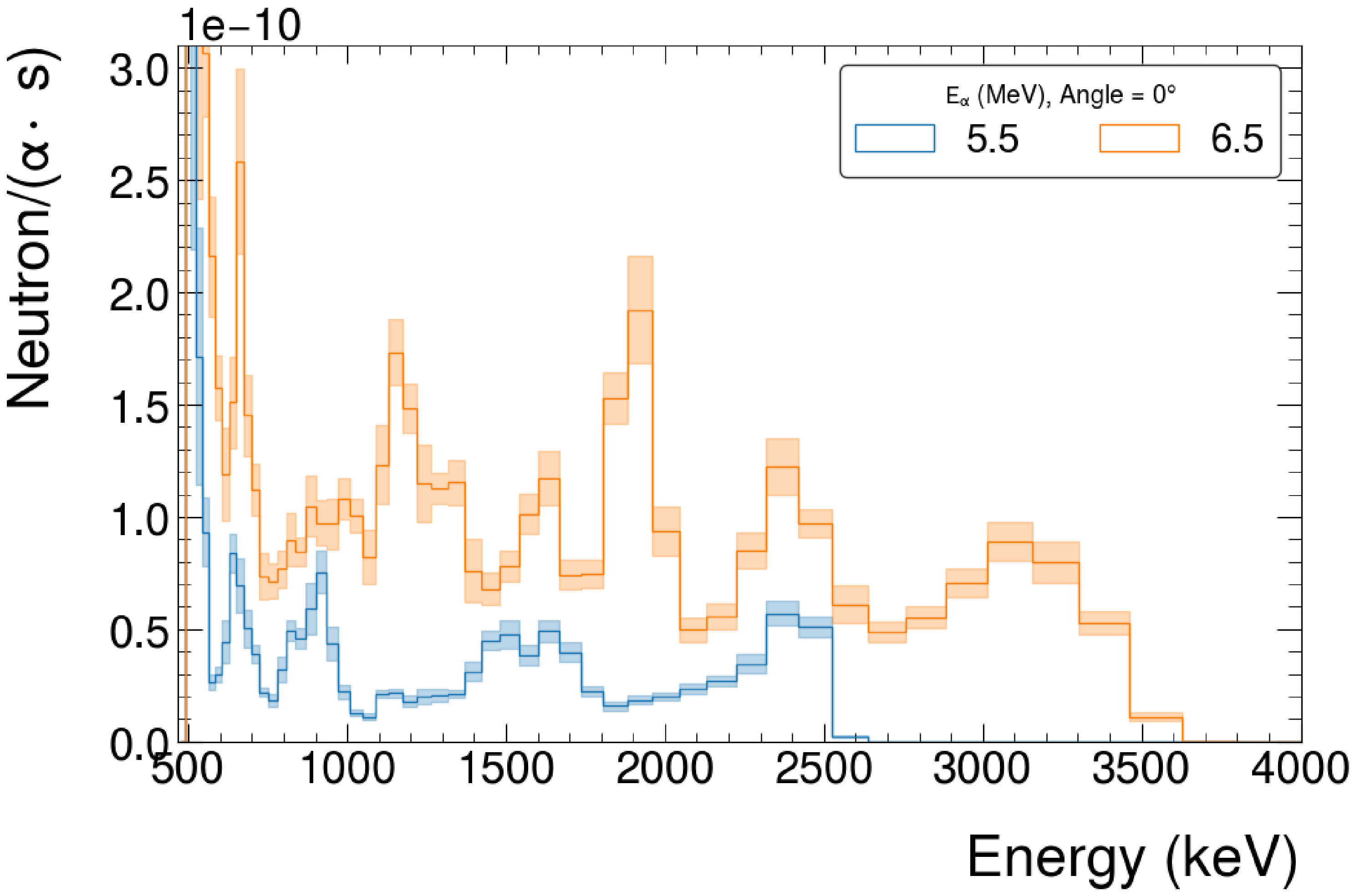
Neutron energy distributions: all energies (angle = 0º)





- Higher neutron energy and yield with higher E_α
- Maximum neutron energy corresponds with the minimun TOF per each E_α

Neutron energy distributions: structures (angle = 0º)



- Different structures due to the population of different excited states of ^{30}P for different E_{α}

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Final remarks

- First measurements of the (α,xn) reaction on a thick ^{27}Al target with MONSTER at the Centro Nacional de Aceleradores (CNA)
    - α energies from 5.5 MeV to 8.5 MeV → 6 new energy spectra measured!
- Clean TOF spectra obtained after neutron selection
- Neutron spectra have been obtained and compared to existing data
- Study of the angular distribution started
- Uncertainty analysis of the results is ongoing

- Future work:
    - Repeat the experiment at CMAM
    - Study other (α,xn) reactions with other isotope targets, e.g., ^{9}Be

Thanks for your attention

José Llanes Gamonoso
jose.llanes@ciemat.es

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MANY collaborators

V. Alcayne[6], A. Algora[2], O. Alonso-Sañudo[3], G. Auñón[7,8], D. Bachiller-Perea[6], J. Balibrea-Correa[2], J. Benito[3], M. J. G. Borge[5,4], J. A. Briz[3], F. Calviño[1], D. Cano-Ott[6], G. Cortés[1], A. De Blas[1], C. Domingo-Pardo[2], A. Espinosa[3], B. Fernández[7,8], L. M. Fraile[3], G. Garcia[4], R. García[1], V. García Tavora[4], J Gómez-Camacho[7,8], E. M. González-Romero[6], C. Guerrero[7,8], A. Illana[3], J. Lerendegui-Marco[2], **J. Llanes-Gamonoso[6]**, M. Llanos[3], T. Martínez[6], V. Martínez-Nouvilas[3], E. Mendoza[6], N. Mont-Geli[1], J. R. Murias[3], E. Nácher[2], A. Nerio Aguirre[5], V. V. O. Onecha[3], S. E. A. Orrigo[2], M. Pallàs[1], A. Perea[5], A. Pérez de Rada Fiol[6], V. Pesudo[6], J. Plaza[6], J. M. Quesada[7], A. Sanchez-Caballero[6], V. Sánchez-Tembleque[3], R. Santorelli[6], J. L. Tain[2], A. Tarifeño-Saldivia[2], O. Tengblad[5], J. M. Udías[3], D. Villamarín[6], S. Viñals[4]

[1]Institut de Tècniques Energètiques (INTE), Universitat Politècnica de Catalunya (UPC), E-08028, Barcelona, Spain
[2]Instituto de Física Corpuscular (IFIC), CSIC – Univ. Valencia (UV), E-46071, Valencia, Spain
[3]Grupo de Física Nuclear (GFN) and IPARCOS, Universidad Complutense de Madrid (UCM), E-28040, Madrid, Spain
[4]Centro de Micro-Análisis de Materiales (CMAM), Universidad Autónoma de Madrid (UAM), E-28049, Madrid, Spain
[5]Instituto de Estructura de la Materia (IEM), CSIC, E-28006 Madrid, Spain
[6]Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), E-28040, Madrid, Spain
[7]Departamento de Física Atómica, Molecular y Nuclear, Universidad de Sevilla (US), E-41012 Sevilla, Spain
[8]Centro Nacional de Aceleradores (CNA) (Universidad de Sevilla (US) - Junta de Andalucía - CSIC), E-41092, Sevilla, Spain