Measuring Underground Neutrons with the High-Efficiency Neutron Spectrometry Array (HENSA): Current Status and Future Prospects

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HENSA
High Efficiency Neutron Spectrometry Array

- **Bonner's Spheres spectrometer**
- **The HENSA project**
- **Previous activities underground**
- **HENSA @ LSC**
- **HENSA @ LNGS**
- **Remarks and future perspective**

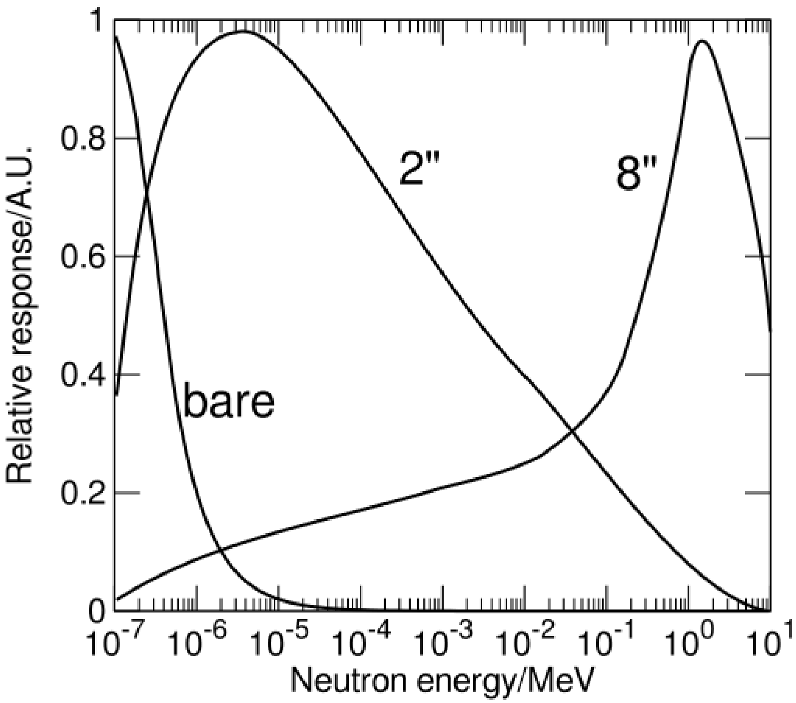
Neutron detection based on moderated thermal sensors

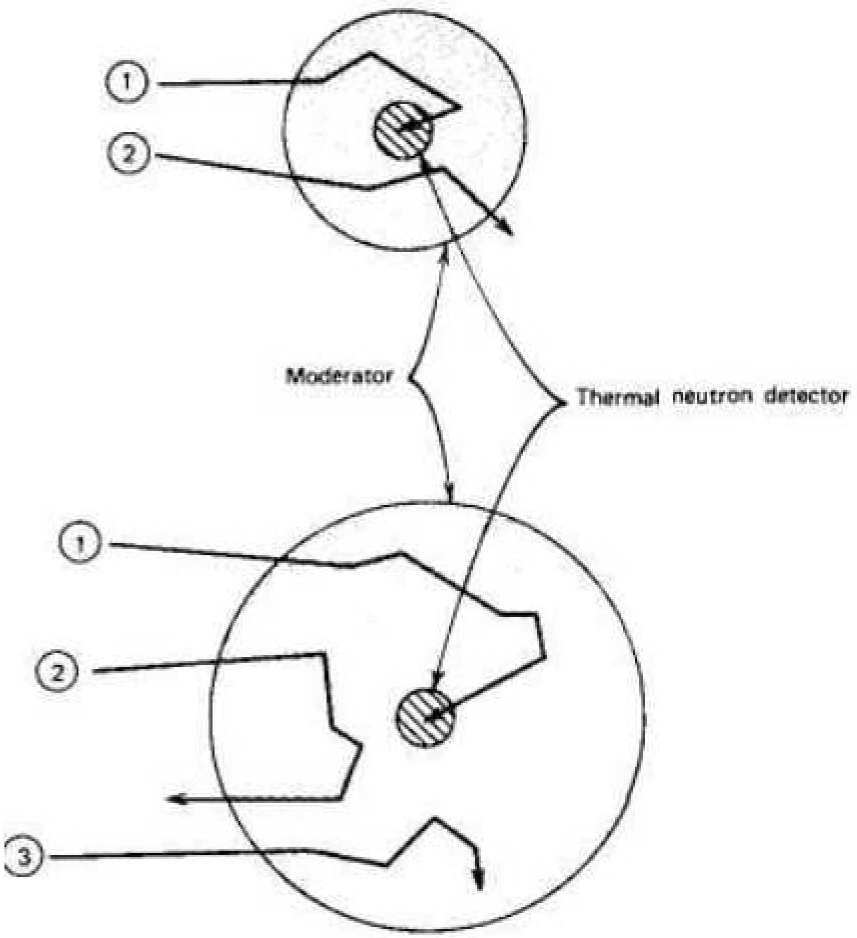
Detector response depends on:

- Moderator material: HDPE (H2O, graphite, etc)
  - → scattering cross section
- Moderator geometry:
  - → size or "effective thickness"

- Neutron energy:
  - → Simple moderator: meV – 20 MeV
  - → Moderator+multipliers: meV - GeV's

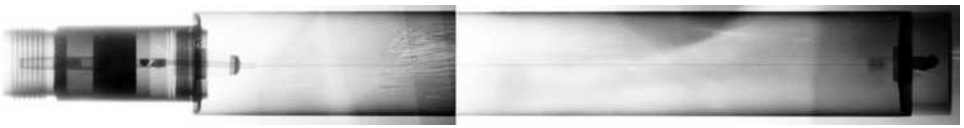
- Thermal sensors: 3He, BF3, 6LiI(Eu) scintillator
  - → Cross section
  - → Size





G. Knoll, Radiation detection and measurement, 3rd ed.

3He-filled proportional neutron counters: “thermal counters”



Detection reaction:

$$^{3}He + n \rightarrow {}^{3}H + p \qquad Q = 0.764\ MeV$$

High Thermal cross section: **5330 barns!!!**

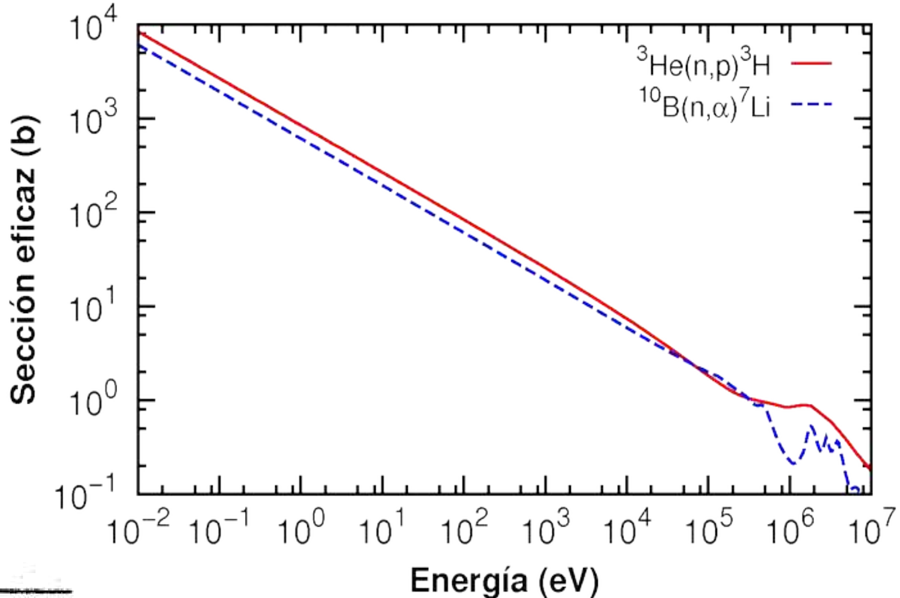


Table 13-1. Neutron and gamma-ray interaction probabilities in typical gas proportional counters and scintillators

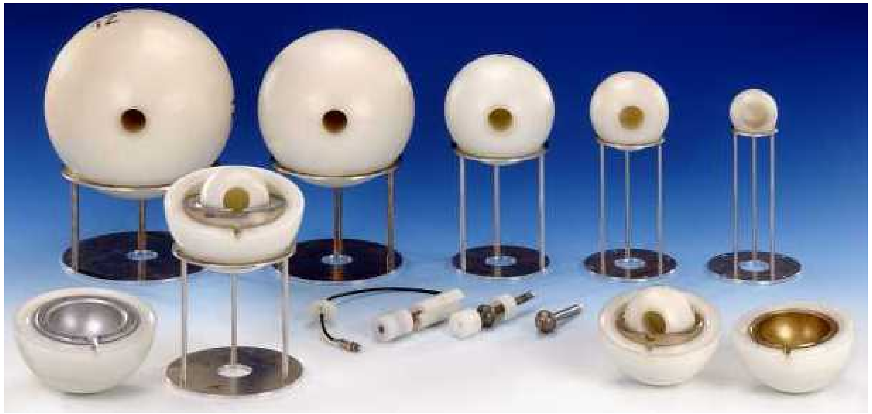
	Interaction Probability	
Thermal Detectors	Thermal Neutron	1-MeV Gamma Ray
^{3}He (2.5 cm diam, 4 atm)	0.77	0.0001
Ar (2.5 cm diam, 2 atm)	0.0	0.0005
BF_3 (5.0 cm diam, 0.66 atm)	0.29	0.0006
Al tube wall (0.8 mm)	0.0	0.014
	Interaction Probability	
Fast Detectors	1-MeV Neutron	1-MeV Gamma Ray
^{4}He (5.0 cm diam, 18 atm)	0.01	0.001
Al tube wall (0.8 mm)	0.0	0.014
Scintillator (5.0 cm thick)	0.78	0.26

*Extracted from Neutron Detectors, T. W. Crane and M. P. Baker

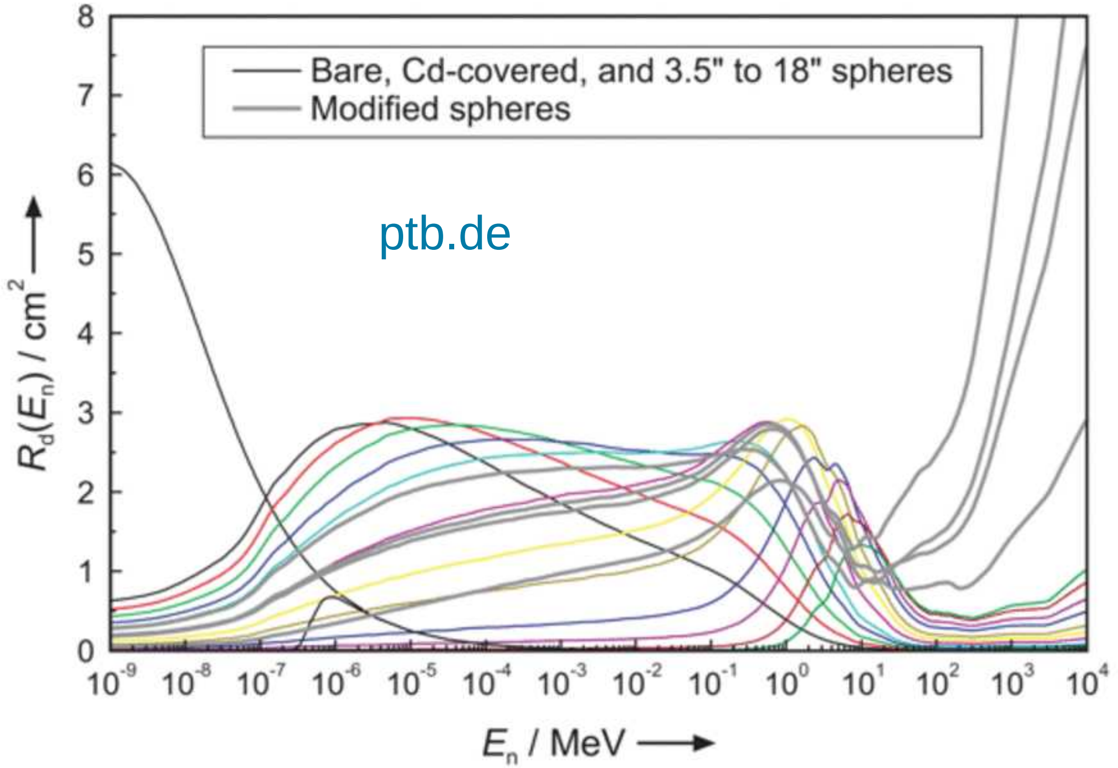
- These neutron counters are gaseous ionization detectors that use 3He as converting gas.
- Due to the **high thermal capture cross section**, 3He filled counters have a high neutron sensitivity.
- For non-thermal neutrons, the high efficiency can be exploited by using moderators.
- In addition, the l**ow gamma-ray sensitivity** makes these detectors very attractive for neutron spectroscopy (Bonner spheres) and dosimetry.

The Bonner Spheres neutron Spectrometer (BSS)

- **Bonner spheres Spectrometers (BSS) are among the most known and widespread technique for neutron spectrometry.**
- **Material:**
  - Moderator: HDPE (other options: paraffin wax, water,...)
  - Neutron filters: Cd foils
  - Extended energy range BSS use neutron multipliers (Pb, Cu, W, ...)
- **Thermal sensor:**
  - Active systems: 3He tubes (BF3 tubes, 6LiI(Eu) scintillators)
  - Passive systems: Activation foils (Au, Dy, ….), TLD-pairs 700/600

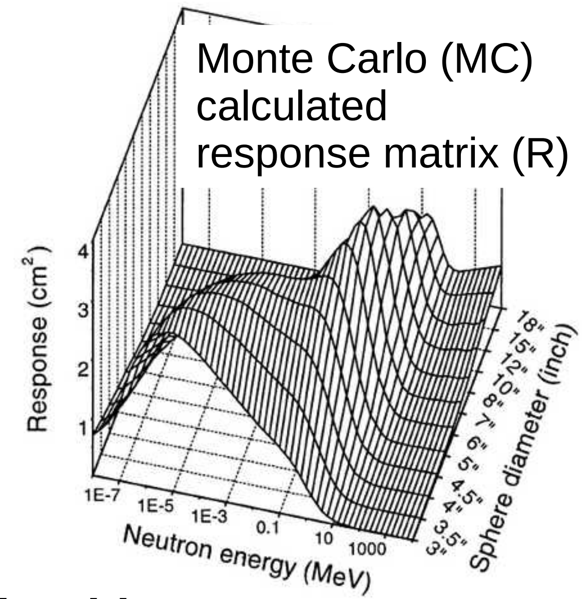


NEMUS (PTB)



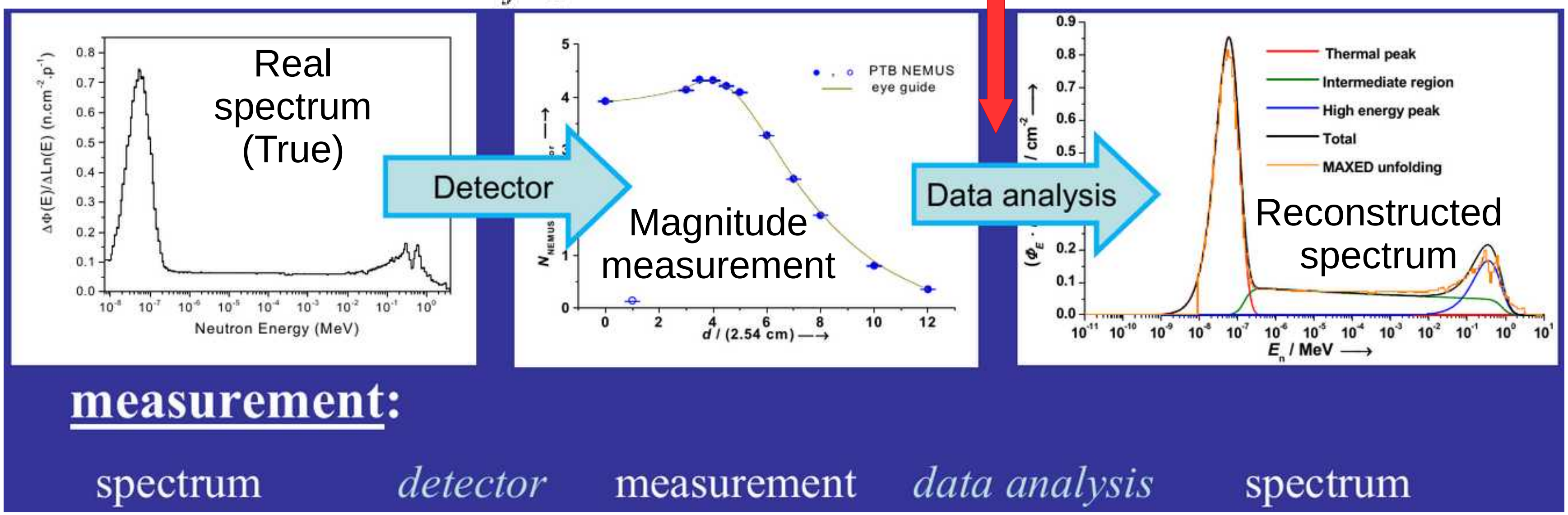
The Bonner Spheres neutron Spectrometer (BSS)

- **Number of detectors:** Typically 5 up to 16 spheres → ***ill-posed linear inverse problem*!**
  - Nasty connection with unfolding!
- **Detector responses:** calculated by using general purpose Monte Carlo codes. Requires:
  - Satisfactory geometrical model of the detector
  - High Precision nuclear data for neutron transport
  - Validation
- **Energy spectrum reconstruction (unfolding):** requires
  - A-priori information (again MC calcs!)
  - An unfolding algorithm
  - A well-trained user



$$M_i = \int R_i(E)\phi(E)\,\mathrm{d}E. \quad \rightarrow \quad M_i = \sum_{j=1}^{n} R_{ij}\phi_j$$

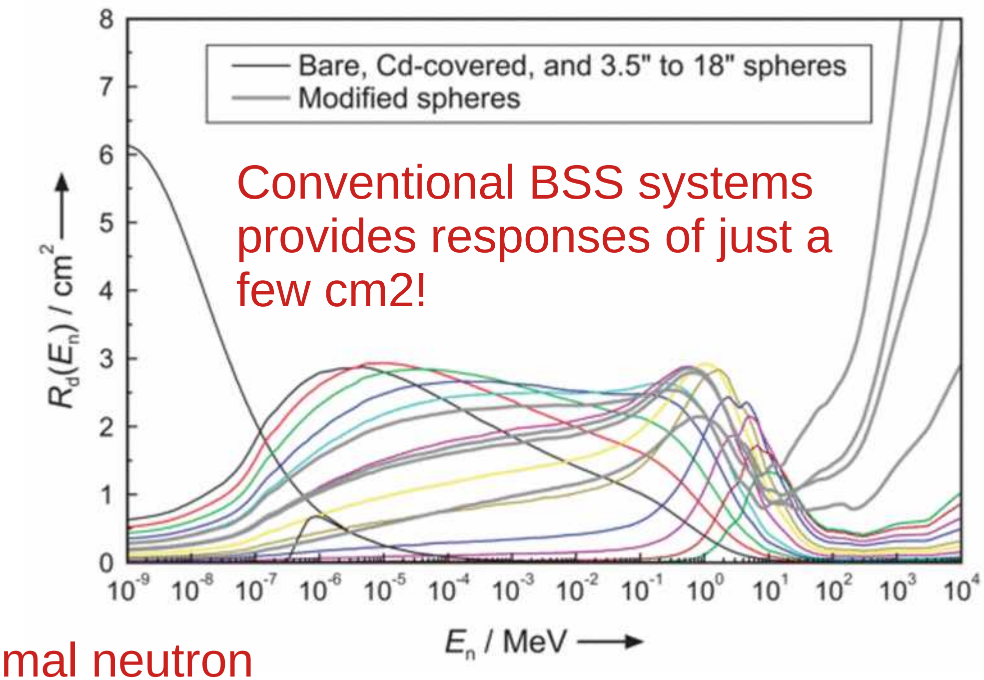
Unfolding algorithm



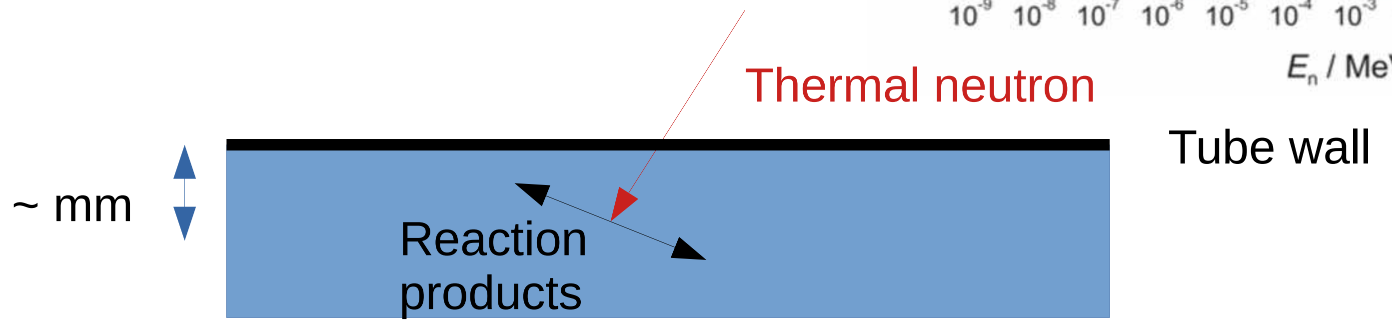
High efficiency BSS

Main applications:

- Nuclear safeguard
- Cosmic rays and space weather
- **Underground physics**



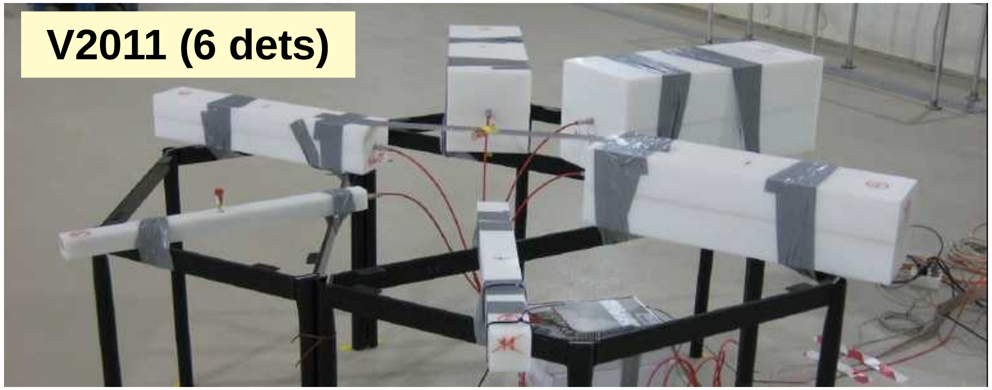
How to increase the efficiency?

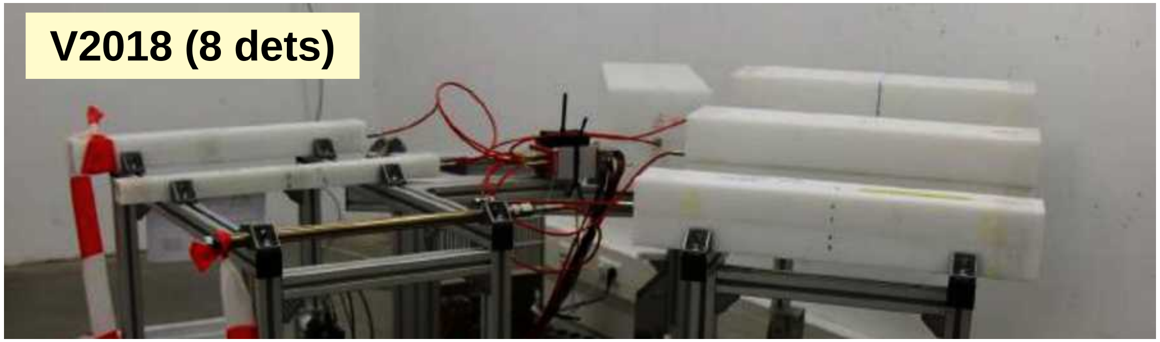


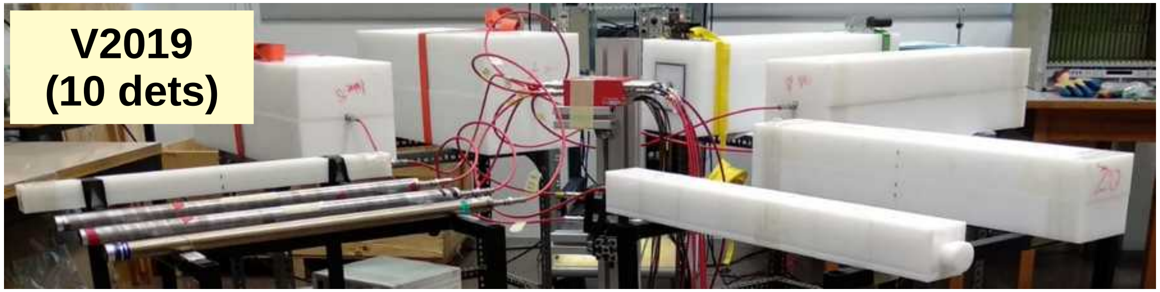
The efficiency is proportional to the active surface instead of the active volume

The High Efficiency Neutron Spectrometry Array (HENSA)

- HENSA is based on the Bonner Spheres Principle. Energy sensitivity from thermal to 10 GeV.
- **Research lines:** **neutron background in underground facilities**, cosmic rays neutrons and space weather, environmental radioactivity...

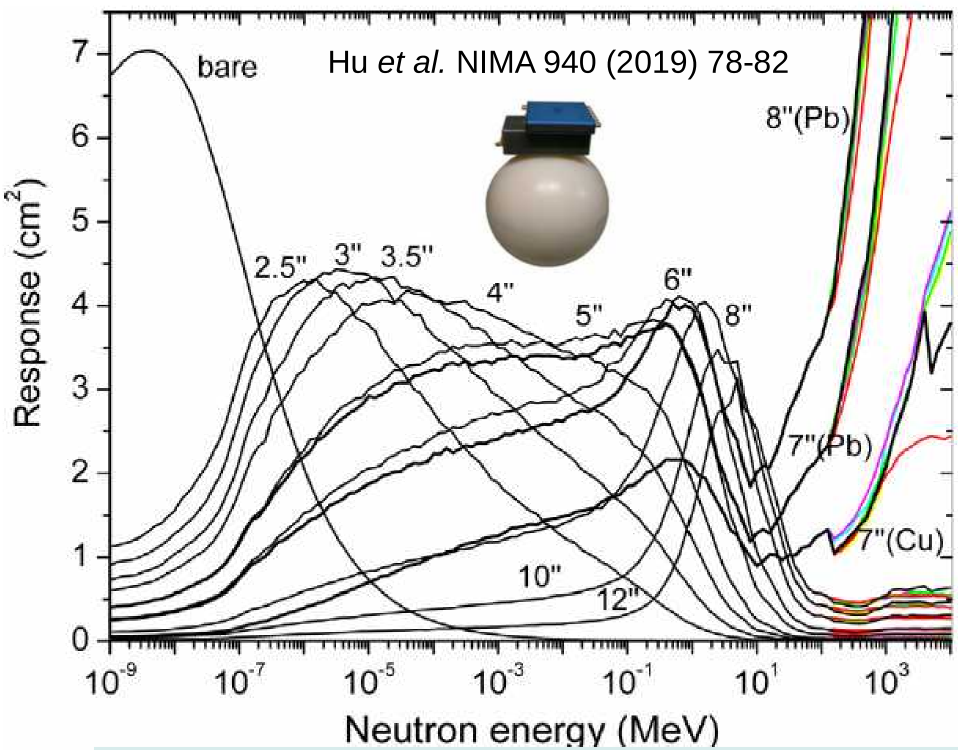




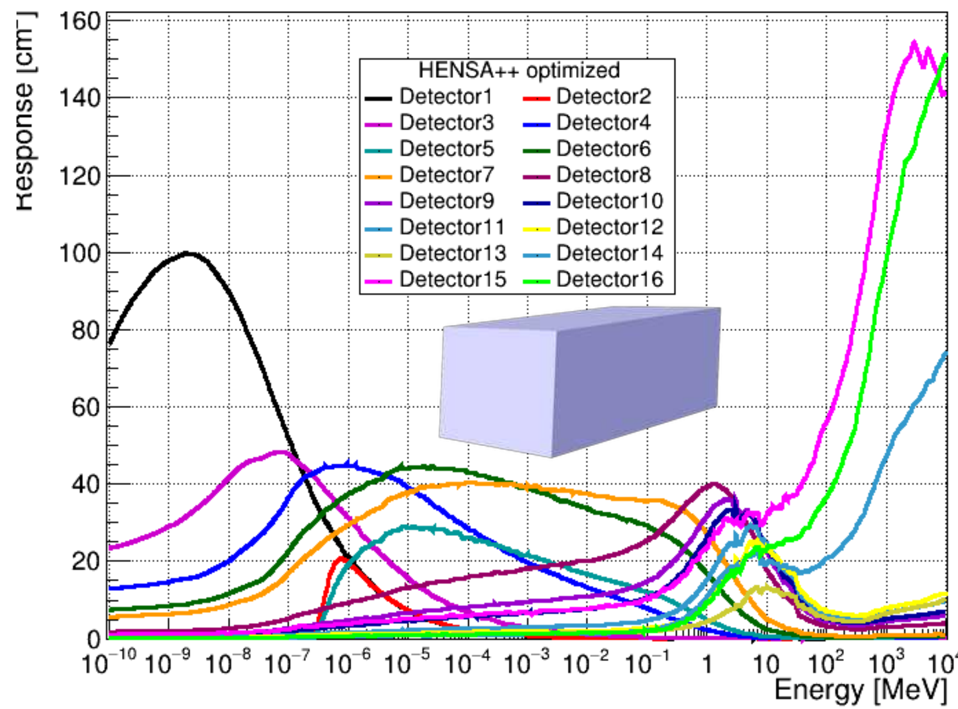


HENSA spectral sensitivity

Standard extended Bonner Spheres



A. Quero, PhD Thesis (UGR)



HENSA neutron response is **~5-15 times larger** than standard Bonner Spheres systems in the energy range from thermal up to 10 GeV.

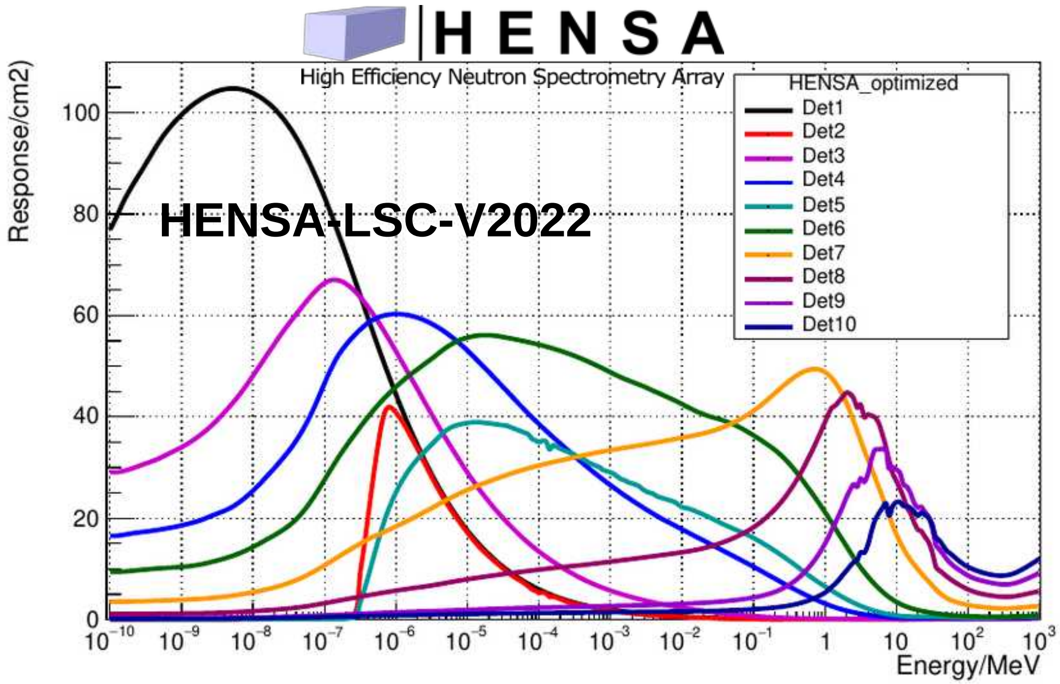
The higher neutron response means:

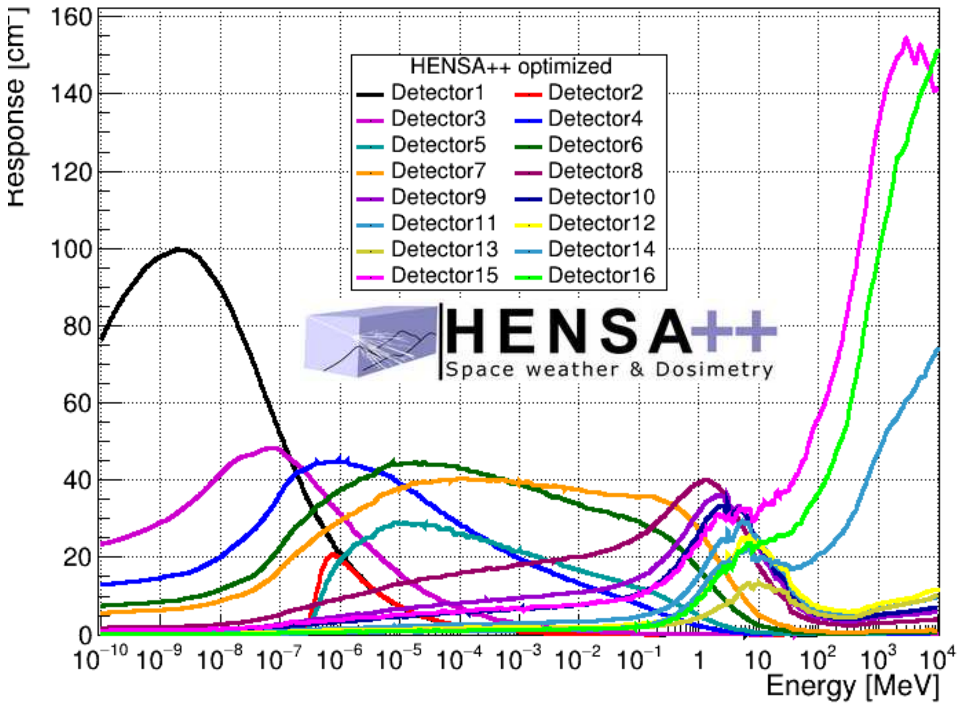
- Improved precision in low radioactivity or underground facilities.
- Temporal response in the scale of ten of minutes to hours for detecting fluctuations of cosmic-ray neutron flux at ground.

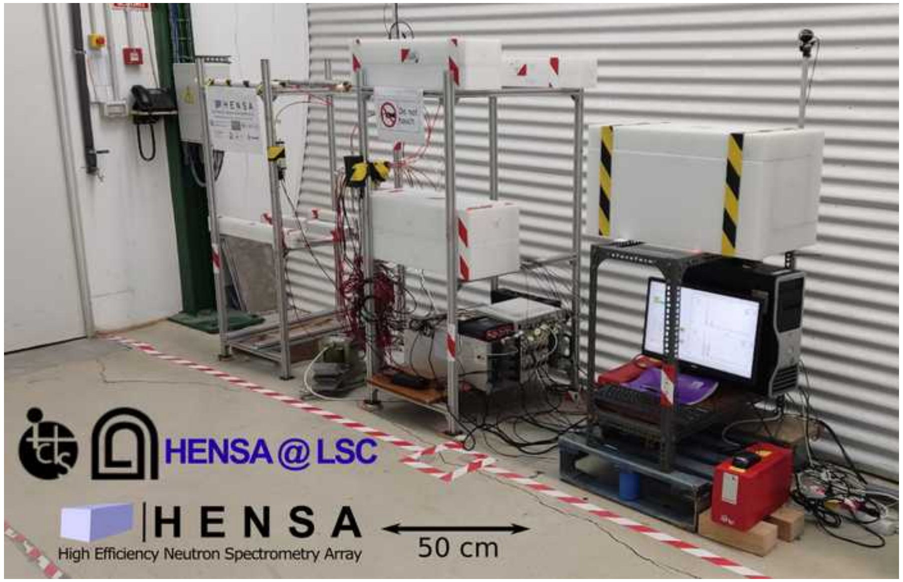
Currently two spectrometer designs: underground facilities & Cosmic-ray neutrons (HENSA++)

www.hensaproject.org

HENSA versions



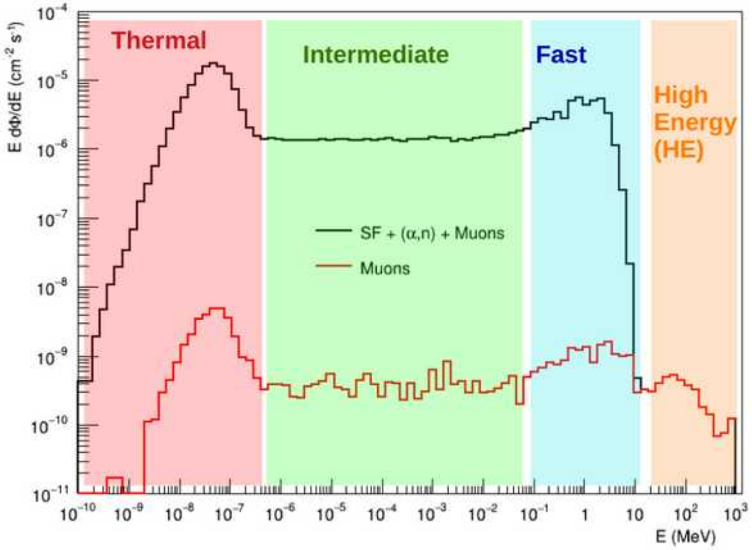




Neutrons in underground physics

- Underground research: **astroparticle physics**, **nuclear astrophysics experiments**, **biological** and geological studies.
- Neutron source: **(alpha,n) reactions**, **spontaneous fission** and muon contribution.
- **Neutron are a limiting factor** in many rare event experiments (e.g. neutrino searches, neutrino-less double-beta decay experiments and dark matter searches) and underground nuclear astrophysics experiments.
- Most of the measurements in underground facilities are based either on thermal neutron counters or scintillators sensitive to fast neutrons. **Fully spectrometric measurements are very scarce!**
- **HENSA is currently operating at LSC (Spain) and LNGS (Italy)**

MC simulation for LSC Hall A
N. Mont-Geli (PhD, UPC)



Underground lab	Depth (m.w.e)	Thermal neutron flux ($cm^{-2} s^{-1}$)	Fast neutron flux ($cm^{-2} s^{-1}$)
CPL	1000	No data	$(3.00 \pm 0.02 \pm 0.05)\times10^{-5}$
Yang Yang	2000	$(2.42 \pm 0.22)\times10^{-5}$	8×10^{-7}
Soudan	2090	$(0.7 \pm 0.08 \pm 0.08)\times10^{-6}$	No data
Canfranc	2450	$(1.13 \pm 0.02)\times10^{-6}$	$(0.66 \pm 0.01)\times10^{-6}$
Boulby	2800	No data	$(1.72 \pm 0.61 \pm 0.38)\times10^{-6}$
Gran Sasso	3600	$(1.08 \pm 0.02)\times10^{-6}$	$(0.23 \pm 0.07)\times10^{-6}$
Modane	4800	$(1.6 \pm 0.1)\times10^{-6}$	$(4.0 \pm 1.0)\times10^{-6}$
CJPL-I	6720	$(4.00 \pm 0.08)\times10^{-6}$	No data
CJPL-I	6720	$(7.03 \pm 1.81)\times10^{-6}$	$(3.63 \pm 2.77)\times10^{-6}$

Neutron flux at different underground facilities Compilation from Hu *et al*. NIMA 859 (2017) 37-40.

Neutron flux modulation in underground facilities

ISSN 1063-7796, Physics of Particles and Nuclei, 2017, Vol. 48, No. 1, pp. 34–37. © Pleiades Publishing, Ltd., 2017.

The Study of the Thermal Neutron Flux in the Deep Underground Laboratory DULB-4900[1, 2]

V. V. Alekseenko[a], Yu. M. Gavrilyuk[a], A. M. Gangapshev[a, *], A. M. Gezhaev[a], D. D. Dzhappuev[a], V. V. Kazalov[a], A. U. Kudzhaev[a], V. V. Kuzminov[a], S. I. Panasenko[b], S. S. Ratkevich[b], D. A. Tekueva[a], and S. P. Yakimenko[a]

[a]*Institute for Nuclear Research, RAS, Moscow, Russia*
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Abstract—We report on the study of thermal neutron flux using monitors based on mixture of ZnS(Ag) and LiF enriched with a lithium-6 isotope at the deep underground laboratory DULB-4900 at the Baksan Neutrino Observatory. An annual modulation of thermal neutron flux in DULB-4900 is observed. Experimental evidences were obtained of correlation between the long-term thermal neutron flux variations and the absolute humidity of the air in laboratory. The amplitude of the modulation exceed 5% of total neutron flux.

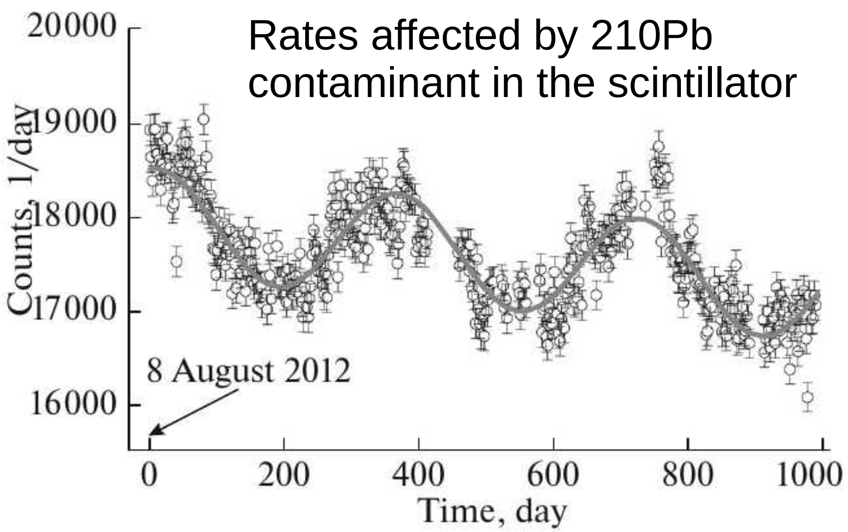
DOI: 10.1134/S1063779616060022

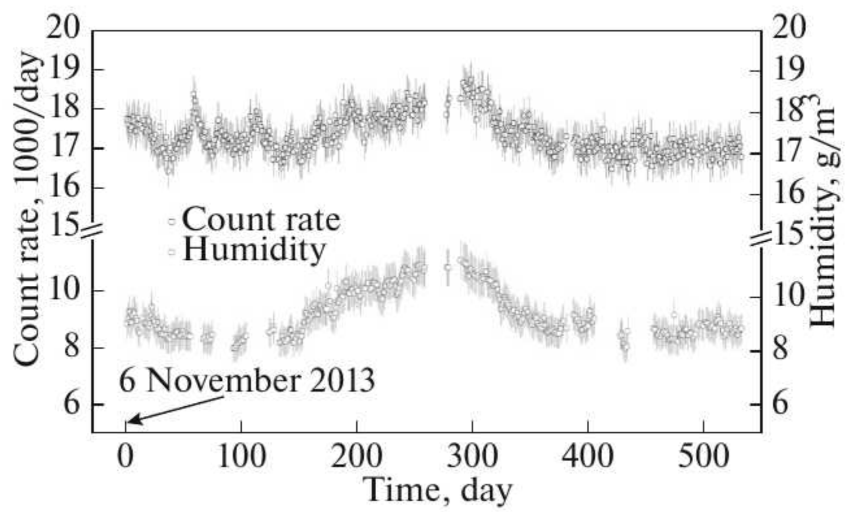
Large volume detectors (6LiF + ZnS(Ag))

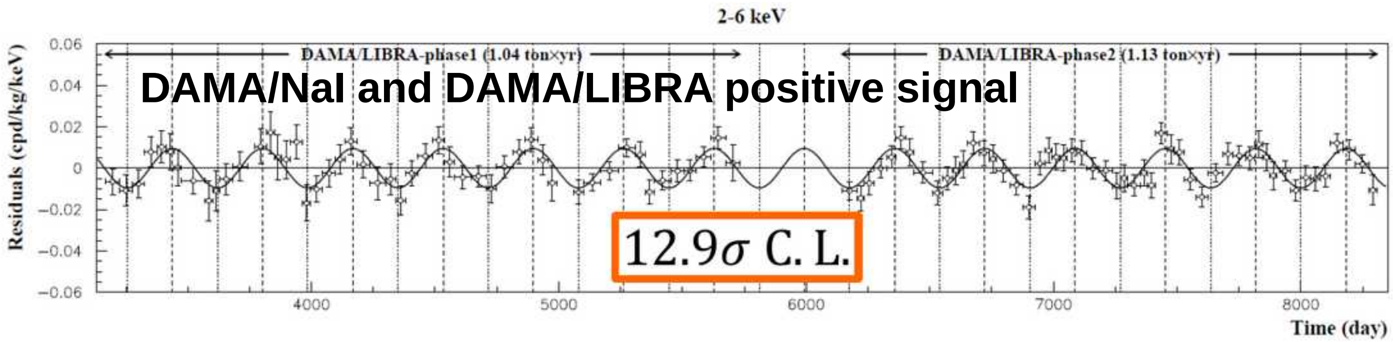
Themal flux:
~ 10^{-9} – 10^{-6} MeV

No fully spectrometric studies yet!

Rates affected by 210Pb contaminant in the scintillator





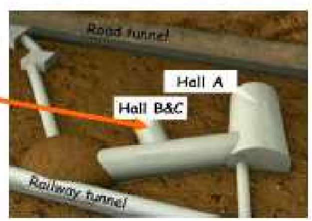


Goal

ANAIS (*Annual modulation with NaI(Tl) scintillators*) intends to provide a **model independent** test of the signal reported by DAMA/LIBRA, using the **same target and technique** at the **Canfranc Underground Laboratory** (Spain)

LSC
Laboratorio Subterráneo de Canfranc

ANAIS



Experimental goals

- Energy **threshold** at 1 keV_{ee}
- **Background** level below 10 keV_{ee} at a few $cpd/kg/keV_{ee}$
- Very **stable** operation conditions

Courtesy ANAIS team

For ANAIS is relevant the measurements of:

I) total neutron flux and spectral distribution at LSC (Hall B).

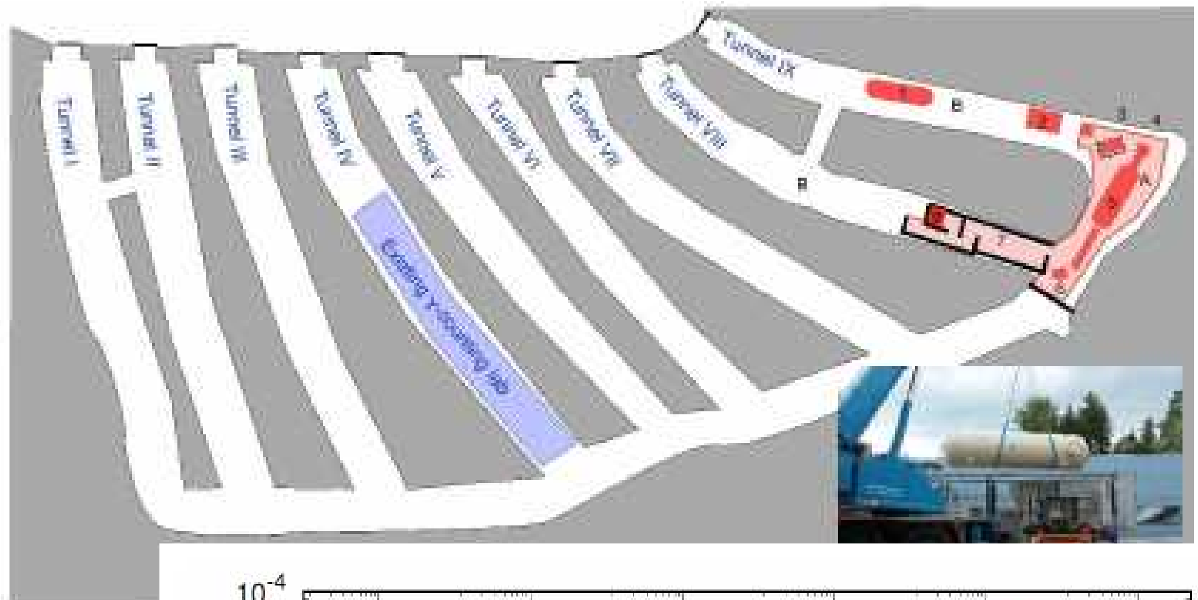
II) Possible long-term variations of the neutron flux. Required in order to set a limit on the corresponding effect in ANAIS background and annual modulation analysis.

HENSA/ANAIS collaboration at LSC

Previous activities: shallow-underground laboratory Felsenkeller

Two measurement campaigns (2014 & 2018)

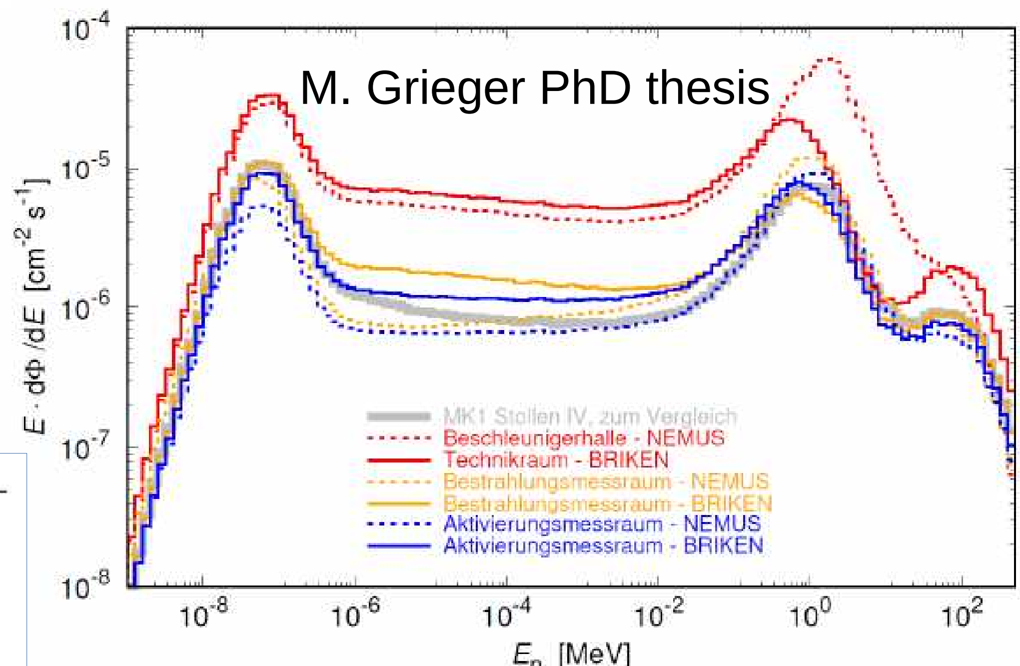
- System of nine tunnels built for Felsenkeller brewery in 1856-59
- 5 MV Pelletron ion accelerator for ^{1}H, ^{4}He, ^{12}C beams
- Combination of µ attenuation by 45 m rock and active µ veto



PHYSICAL REVIEW D **101**, 123027 (2020)

Neutron flux and spectrum in the Dresden Felsenkeller underground facility studied by moderated ^{3}He counters

M. Grieger,[1,2] T. Hensel,[1,2] J. Agramunt,[3] D. Bemmerer,[1,*] D. Degering,[4] I. Dillmann,[5] L. M. Fraile,[6] D. Jordan,[3] U. Köster,[7] M. Marta,[5] S. E. Müller,[1] T. Szücs,[1] J. L. Taín,[3] and K. Zuber[2]

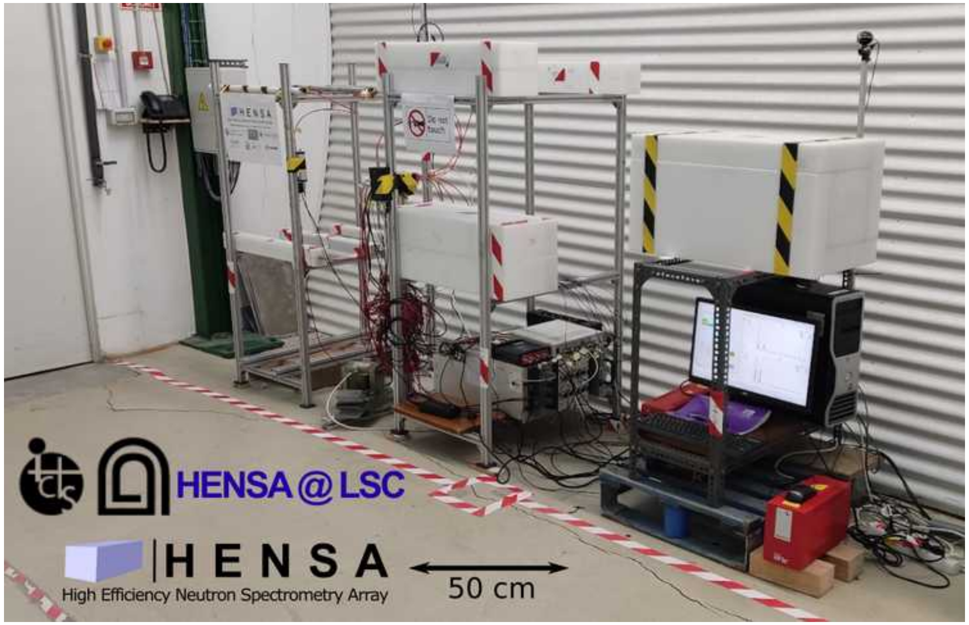


HENSA @ LSC: Experiment at the Canfranc Underground Laboratory

New measurement at **Hall A** @ LSC:
- Data acquisition from **Oct 2019 until March 2021.** Using previous version of HENSA for LSC.

- S. Orrigo et al. Eur. Phys. J. C 82, 814 (2022).
- Final results, draft in preparation.

- Continuous monitoring based on a reduced HENSA setup (4 dets), **PhD thesis J. Plaza (CIEMAT).**

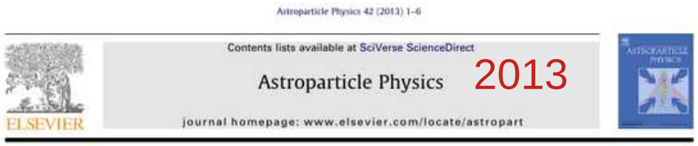


New measurement at **Hall B** @ LSC:
In collaboration with **ANAIS** experiment (**dark matter search**):
- Measurements started in **March 2021**, Planned until **2025.** Using optimized version for underground (HENSA-V2022) **PhD thesis N. Mont, UPC**

- **Collaboration with ANAIS-112**: assessment of the neutron flux long-term evolution and background component affecting the ANAIS-112 experiment (*Marisa Sarsa/María Martínez, UNIZAR)*

- **Development of a dedicated facility** for characterization of internal radiactivity in proportional neutron counters.

HENSA @ LSC: Hall A


Astroparticle Physics 42 (2013) 1–6

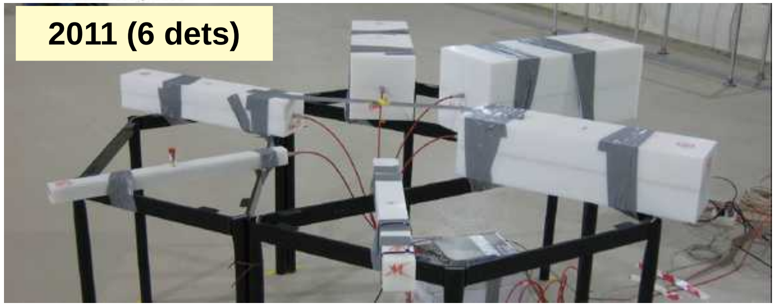
Contents lists available at SciVerse ScienceDirect

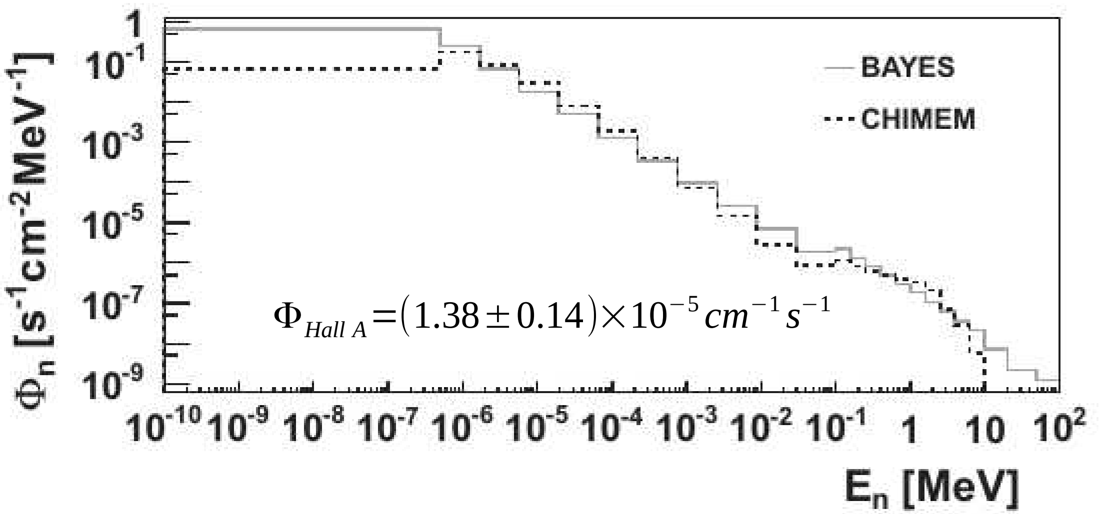
Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

Measurement of the neutron background at the Canfranc Underground Laboratory LSC

2013





Hall A


Eur. Phys. J. C (2022) 82:814

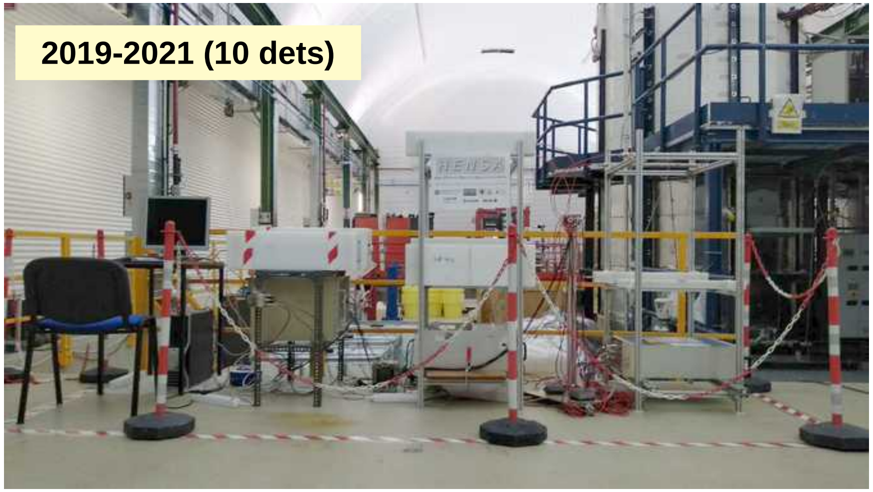
https://doi.org/10.1140/epjc/s10052-022-10755-6

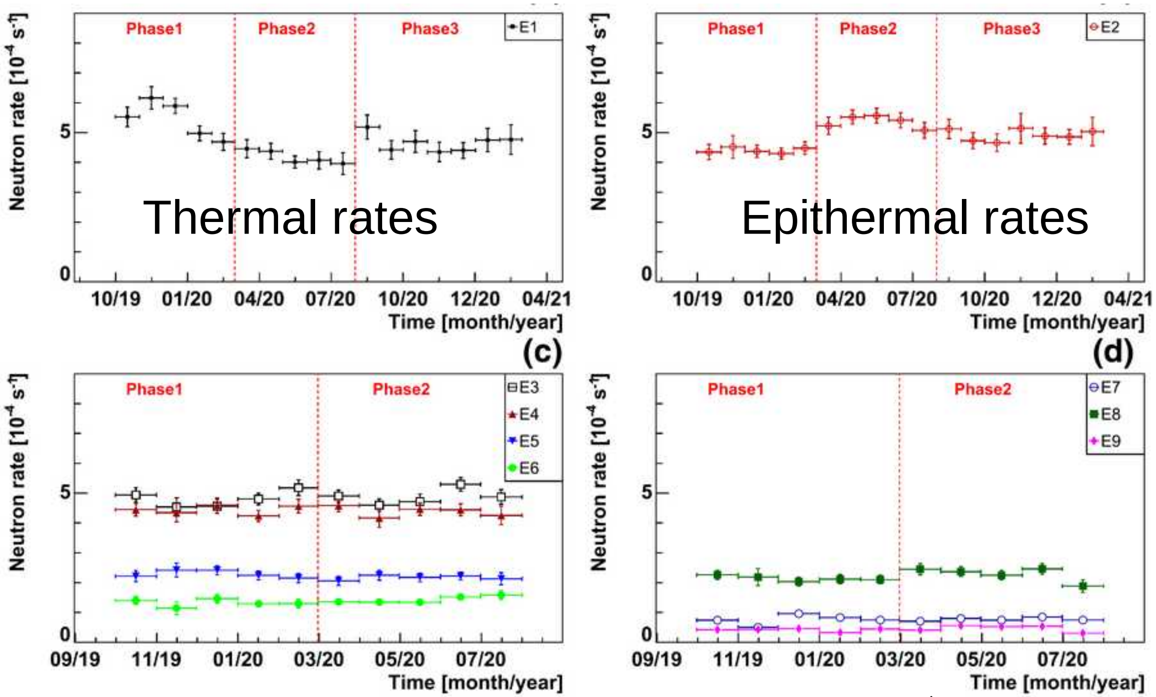
THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Long-term evolution of the neutron rate at the Canfranc Underground Laboratory

2022





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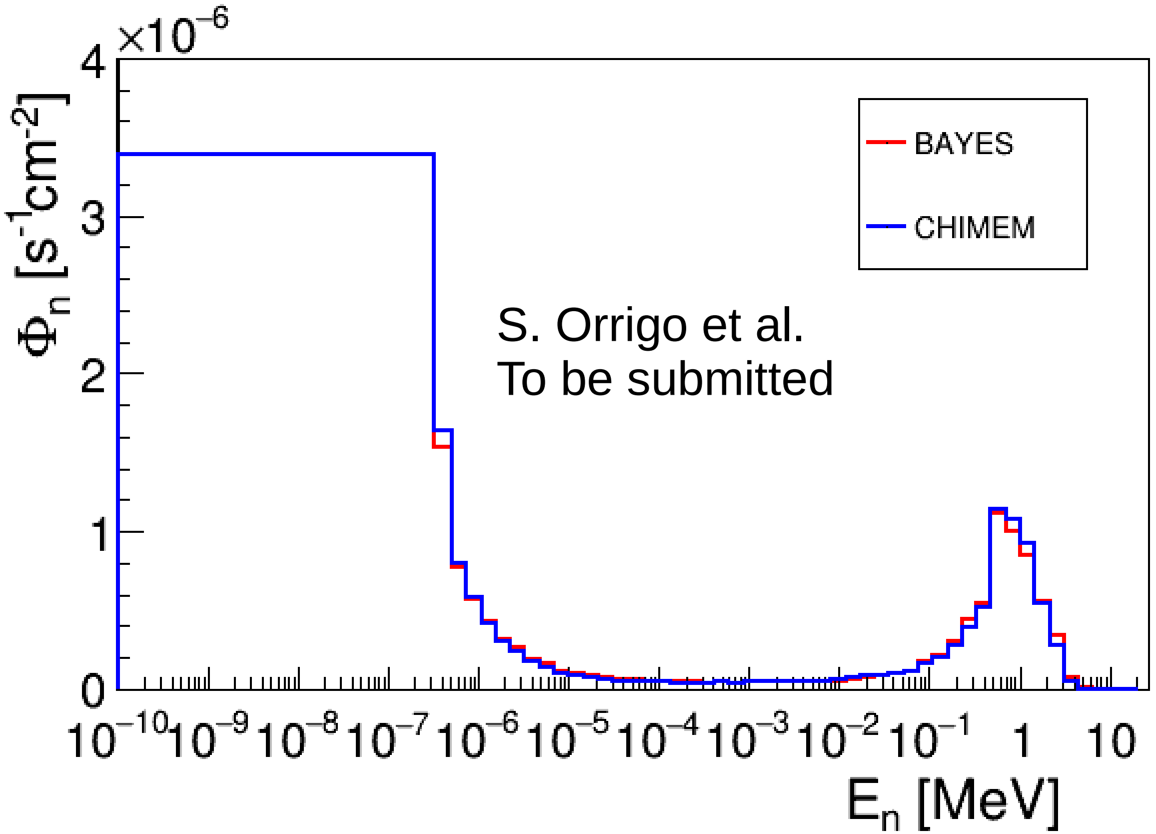
HENSA @ LSC: Hall A



2019 Campaign
Detector HENSA-V2019

$$\Phi_{Hall\,A} = (1.48 \pm 0.02) \times 10^{-5}\, cm^{-1}\, s^{-1}$$

Thermal flux estimated independently from bare tube + Cd-lined measurement.

Reconstruction constrained by the thermal flux

Table 1. Integral values of the neutron flux obtained in different energy regions from deconvolution algorithms codes BAYES and CHIMEM. Neutron flux in units of 10^{-6} n/cm^2/s

NEUTRON FLUX	Thermal	Epithermal	Fast	Total
Energy range [MeV]	10^{-10} – $3.2 \cdot 10^{-7}$	$3.2 \cdot 10^{-7}$-0.1	0.1-20	10^{-10} - 20
Φ_n (BAYES)	3.4(2)	5.96(8)	5.45(8)	14.8(2)
Φ_n (CHIMEM)	3.4(2)	5.94(8)	5.42(9)	14.8(2)

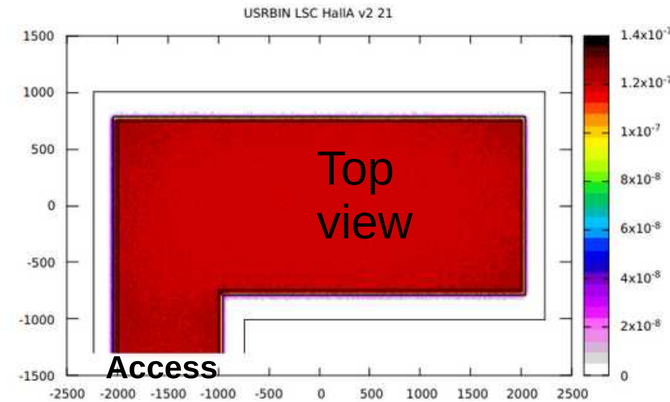
Neutron source in hall A

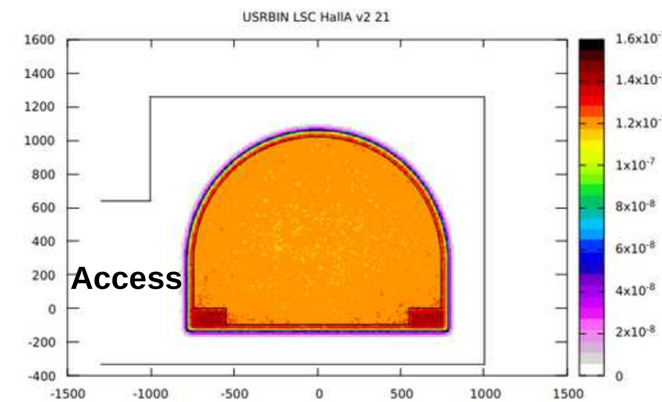
Monte Carlo FLUKA (v. 4.3.2) calculations used to estimate the neutron flux **in Canfranc**.

- **(α,n) reactions.**
- **Spontaneous fission.**
- **Muon-induced neutrons**

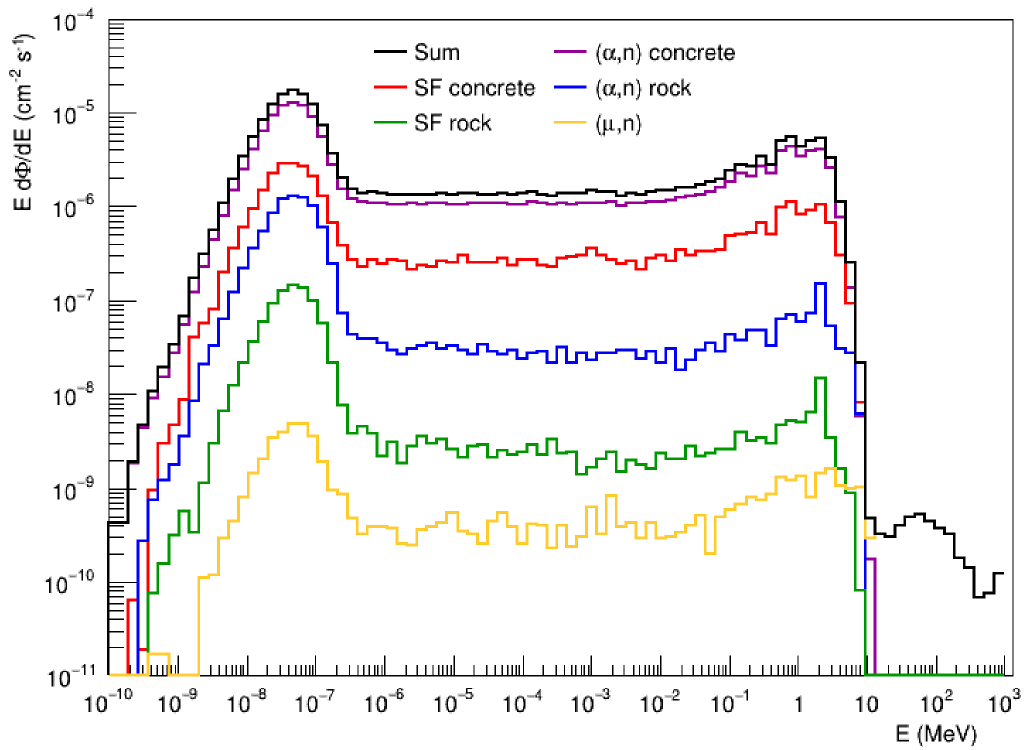
Thermal peak ~ 4.5 – 6.5 · 10^{-8} MeV
Isolethargic intermediate region
Fast peak ~ 0.5 – 3 MeV
HE peak ~ 50 MeV

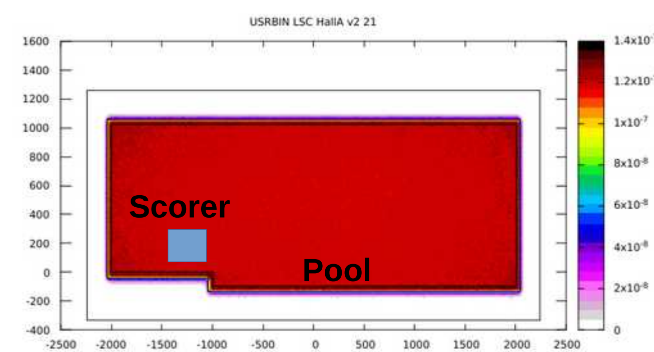
PhD thesis N. Mont, UPC





Contributions:
Concrete: 94%
Rock: 6%
Muons: 0.03%

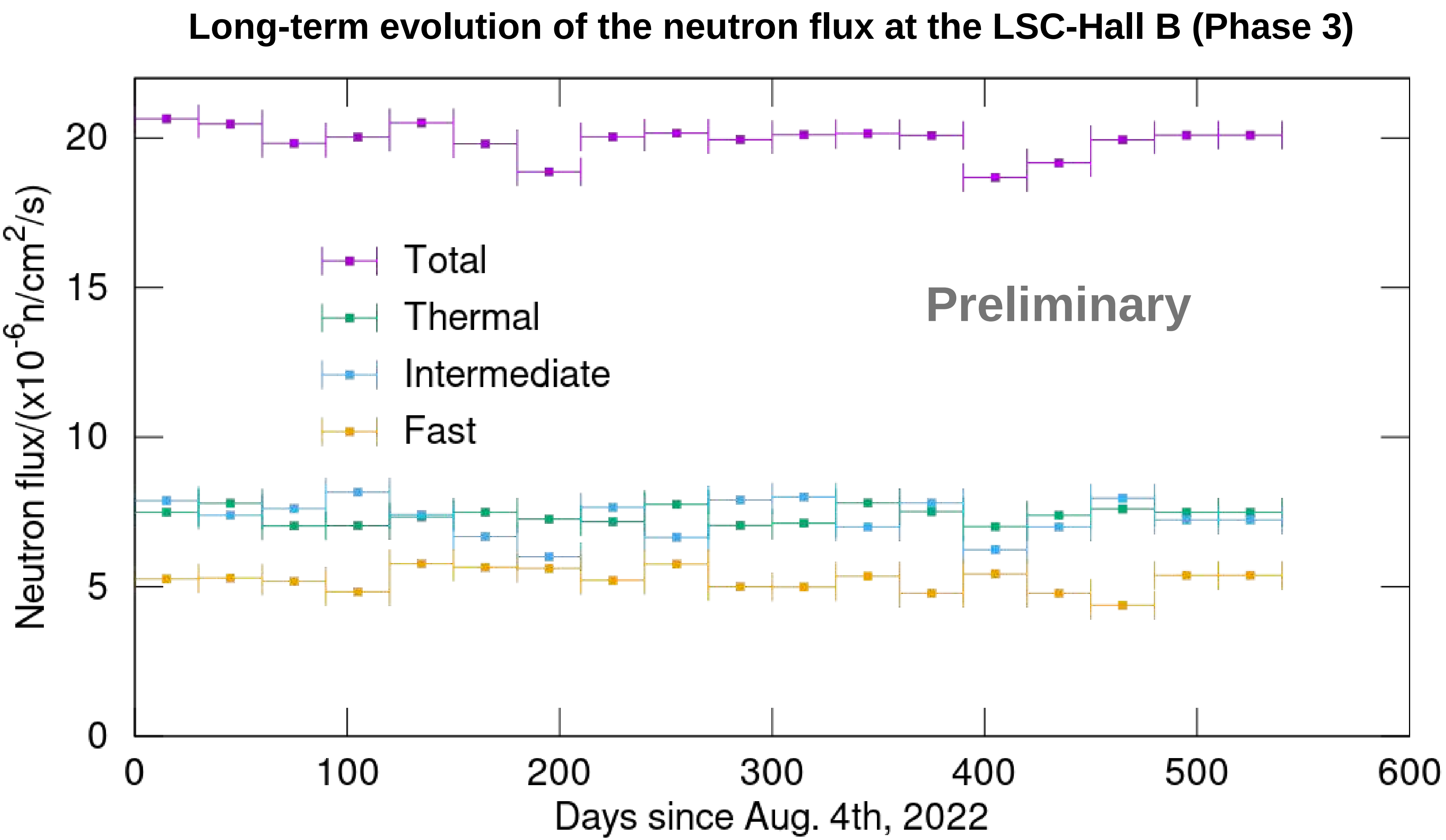




N. Mont-Geli *et al* 2021, J. Phys.: Conf. Ser. 2156, 01223
N. Mont-Geli *et al* 2023, Proceedings of Science 441, 312

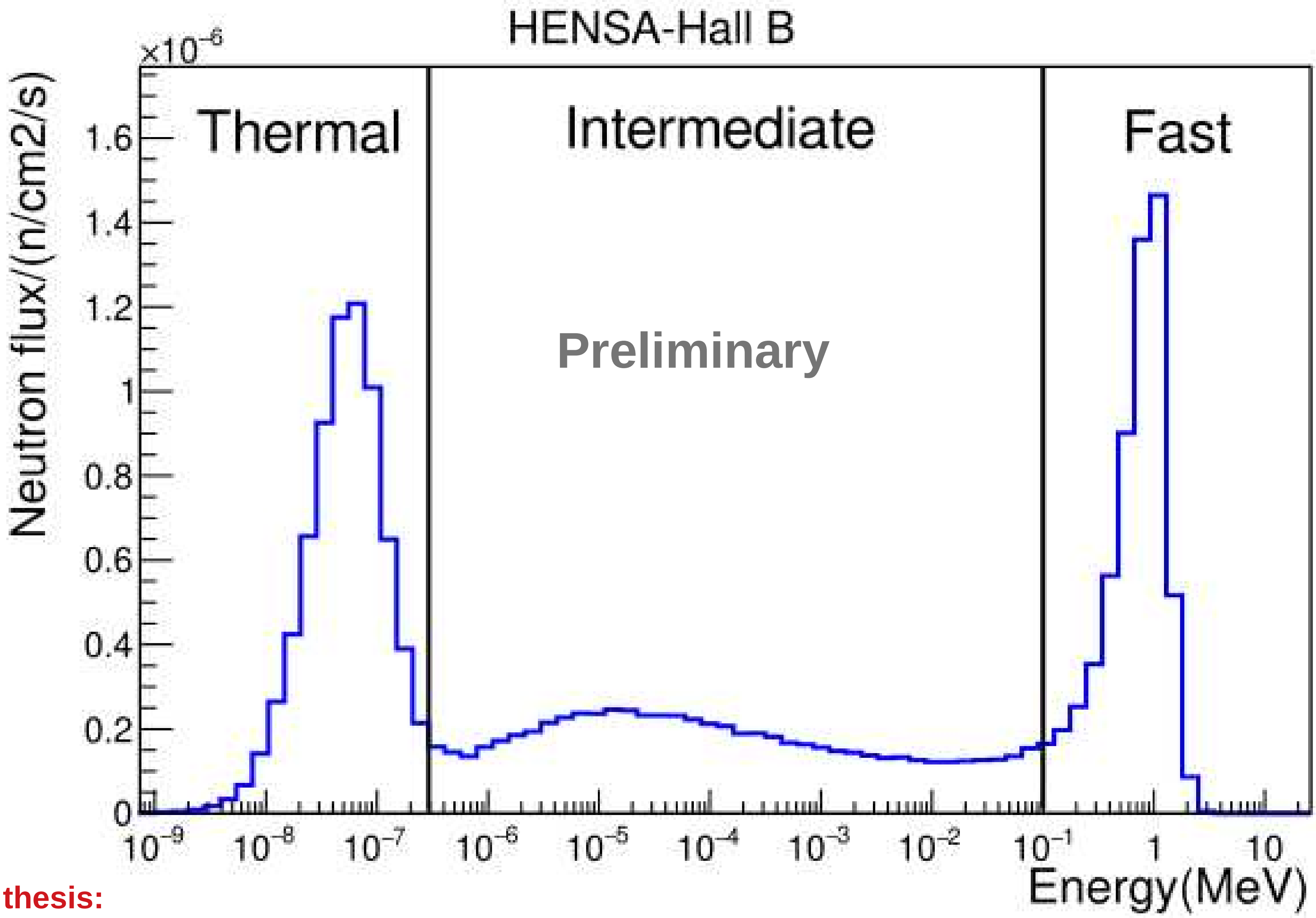
Long-term measurement in hall B
Two setups:
HENSA-v2019 (hall B, February 2022 – August 2022).
HENSA-v2022 (hall B, since August 2022) – **Better spectral resolution**

PhD thesis N. Mont, UPC



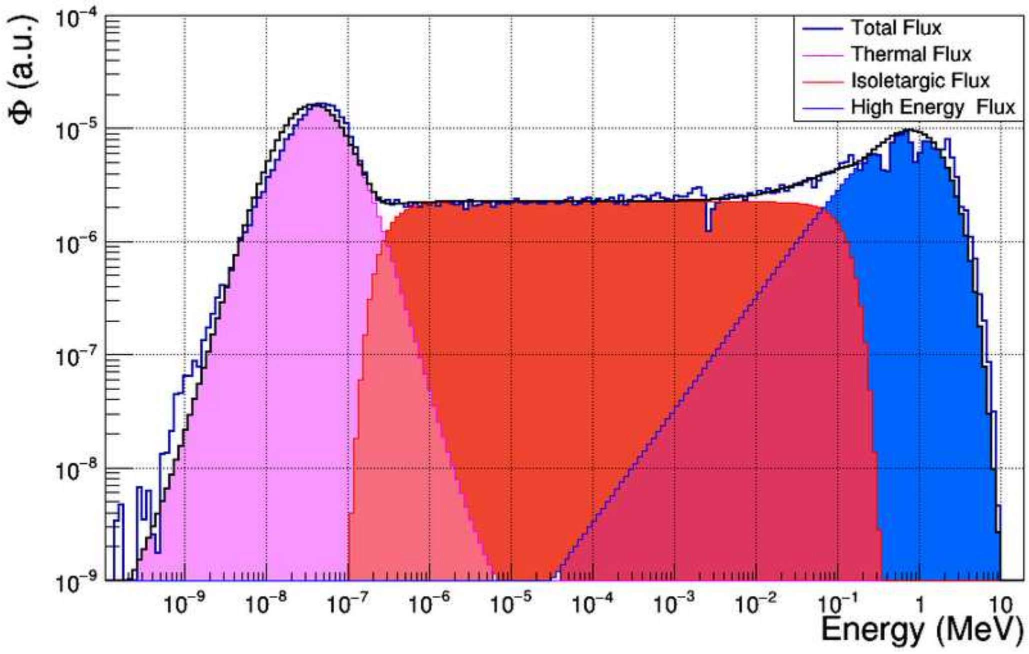
PhD thesis N. Mont, UPC

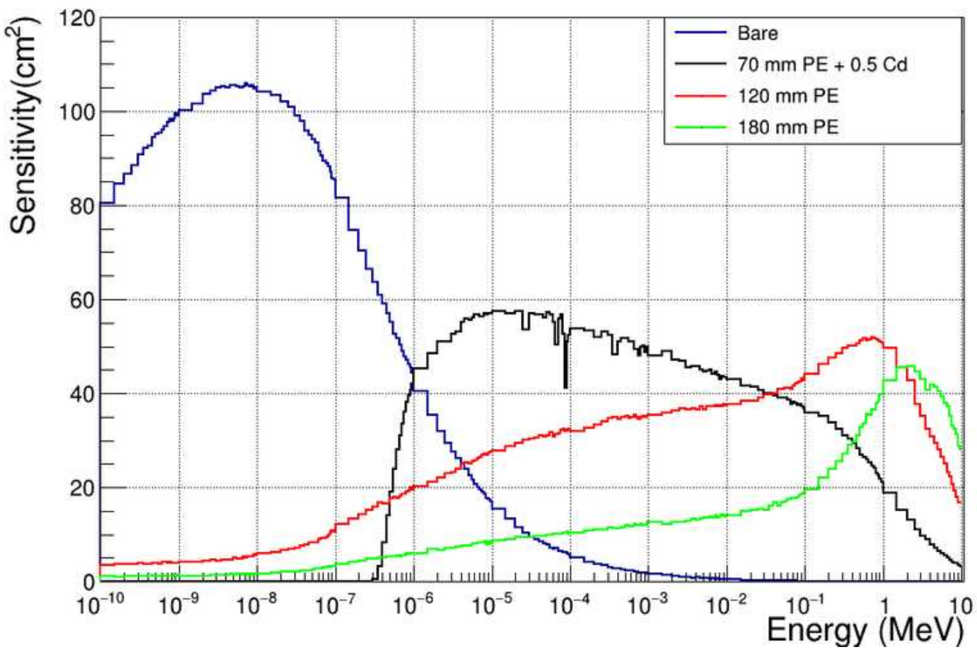
HENSA @ LSC: Hall B



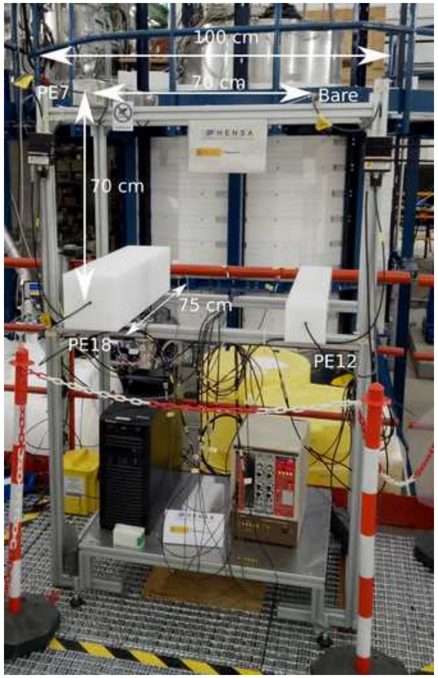
PhD thesis:
N. Mont, UPC
A. Quero, UGR

HENSA @ LSC: Neutron monitor setup





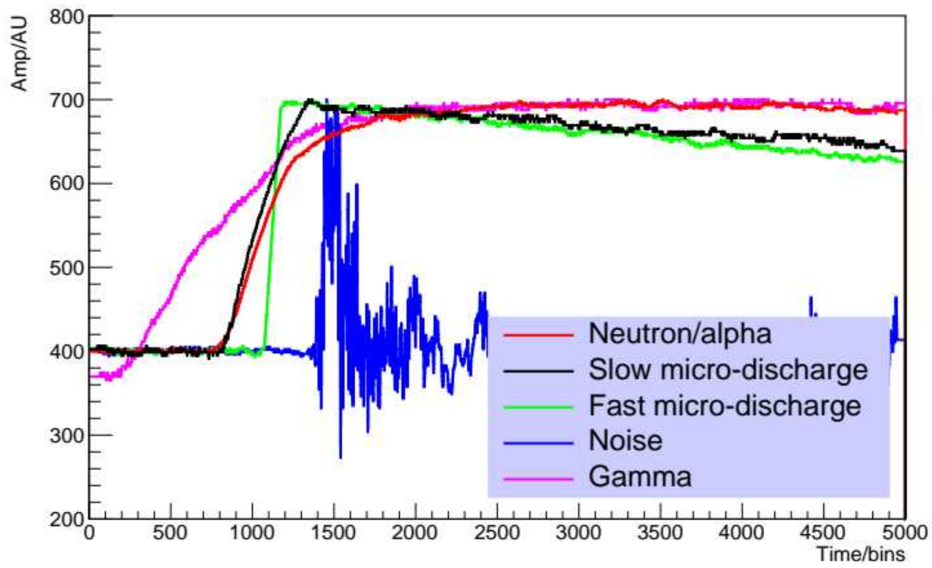
J. Plaza, PhD thesis, CIEMAT

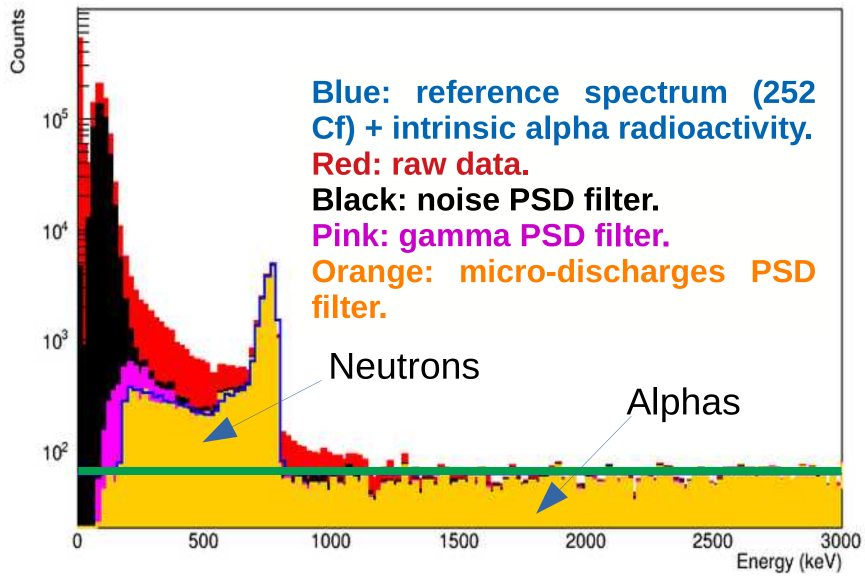


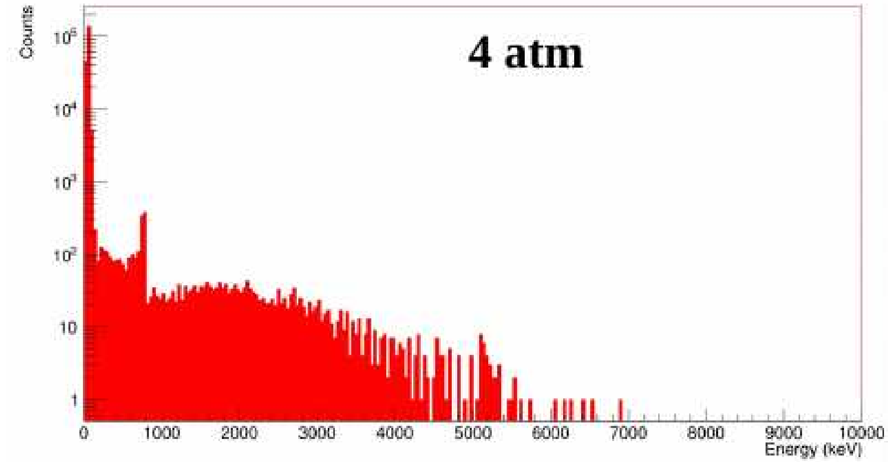
- Division of the flux in three components.
- Design of polyethylene moderators to modify the response of ^3He detectors.
- Maximize detector response to a particular component.
- Minimization of sensitivity to the other components.

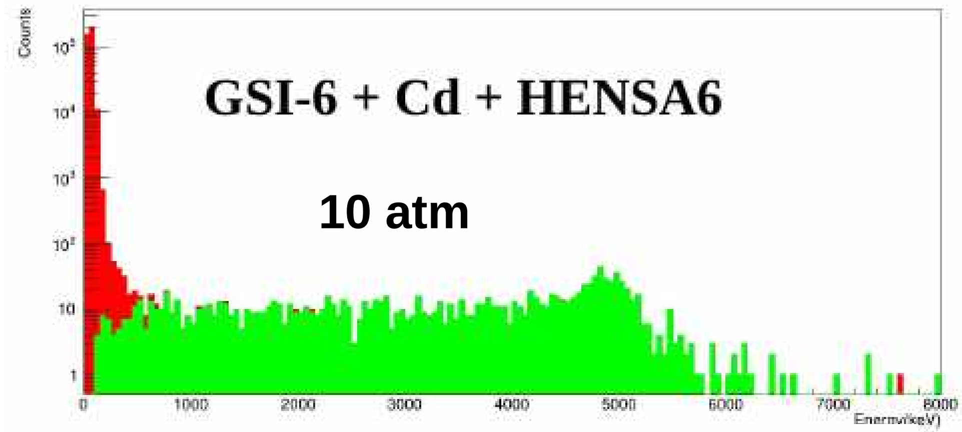
- Small changes in count rate in one detector, directly proportional to changes in its flux range.
- *Expected sensitivity ~4% variations of the flux.*

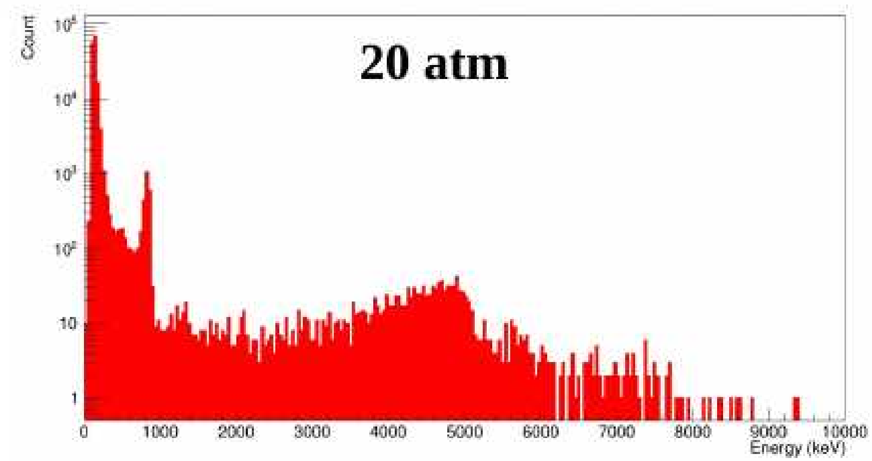
HENSA @ LSC: alpha background in neutron counters





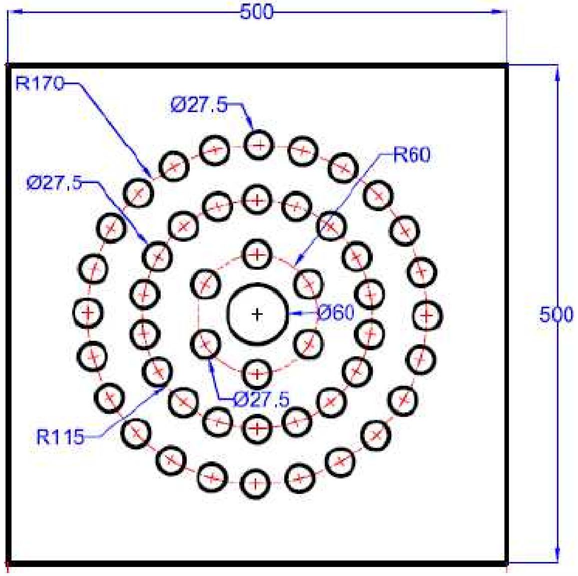


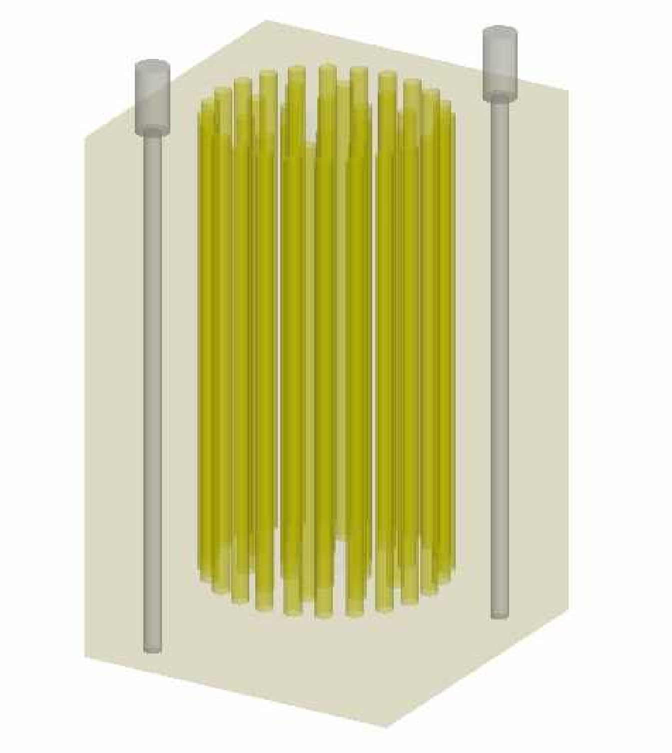




Need of a low neutron background facility for characterizing neutron counters!

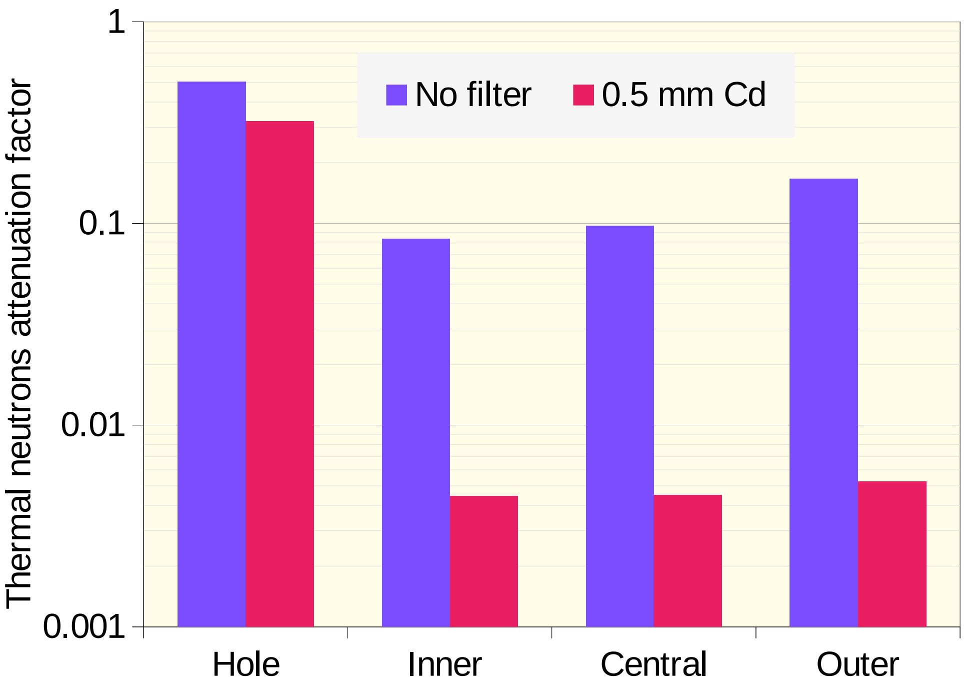
Detector test station at LSC

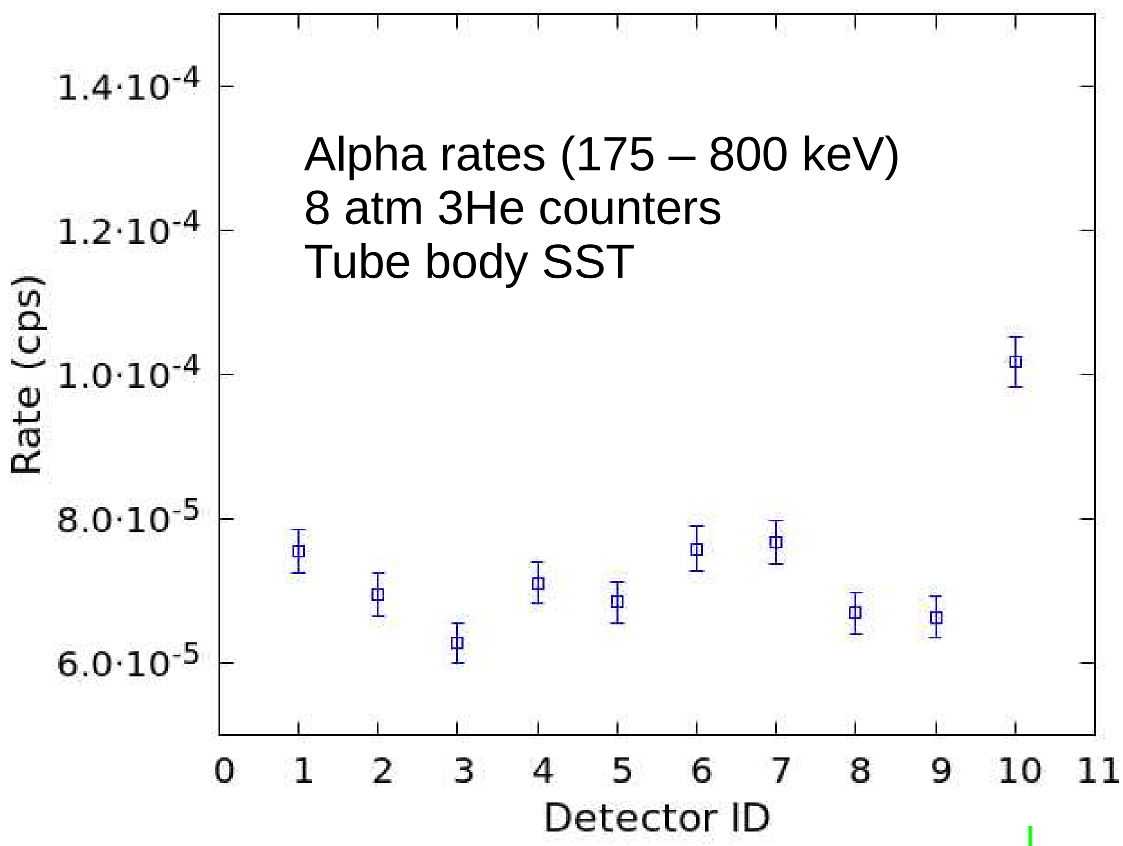




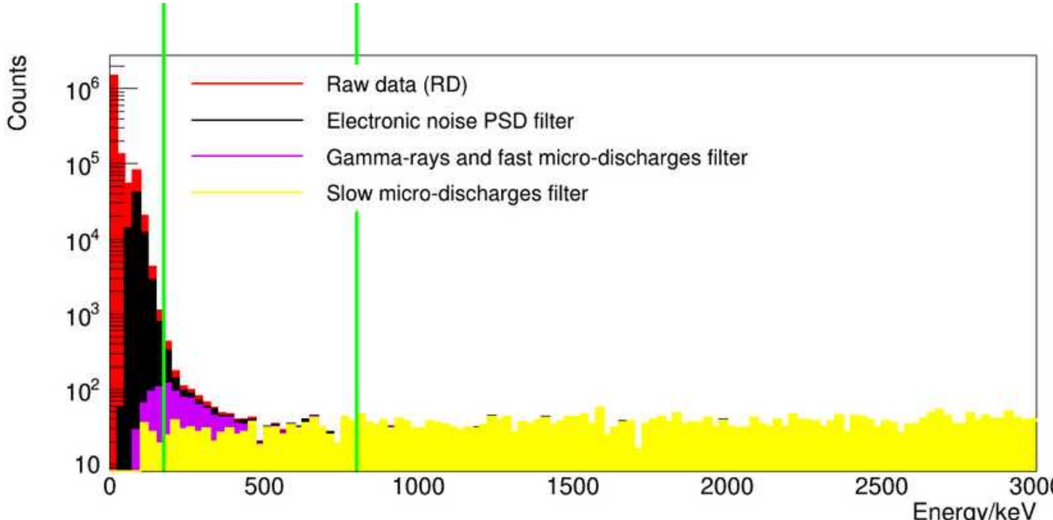
Shielding station for characterization of alpha-background in neutron counters

- Based on HDPE moderator (50x50x80cm3) + Cd filter (0.5 mm thickness).
- 48 positions for 1” counters, up to 70 cm length (can be adapted to other diameters).
- More than two orders of magnitude thermal flux attenuation factor





- In operation at LSC since Sep 2023.
- A first batch of detectors already characterized.
- Characterization of a second batch of detectors is ongoing.



Status of the neutron data at LNGS

Work	Hall	Technique
Belli (1989)	A	BF3 counters + 7 variable size moderators (Spec.)
Aleskan (1989)	A	Li-6 scintillator (> 3 MeV)
Arneodo (1999)	C	Proton recoil scintillation detector (> 1 MeV)
Belloti (1985)	B	3He counters, bare + 1 paraffin (thermal and fast)
Debicki (2009)	-	3He bare counters (thermal)
Cribier (1995)	A	CaNO3 radiochemical detector (> 2.5 MeV)
Rindi (1988)	-	3He counters, bare + paraffin + bare and cd
Best (2016)	Interferometer tunnel	3He bare counters (thermal)
Debicki (2018)	(same 2009)	3He counters + long counter for fast neutrons
Bruno (2019)	A (LVD)	Liquid scintillators (above 10 MeV)
Bertoni (2023)	C	Bubble chamber (> 1MeV)

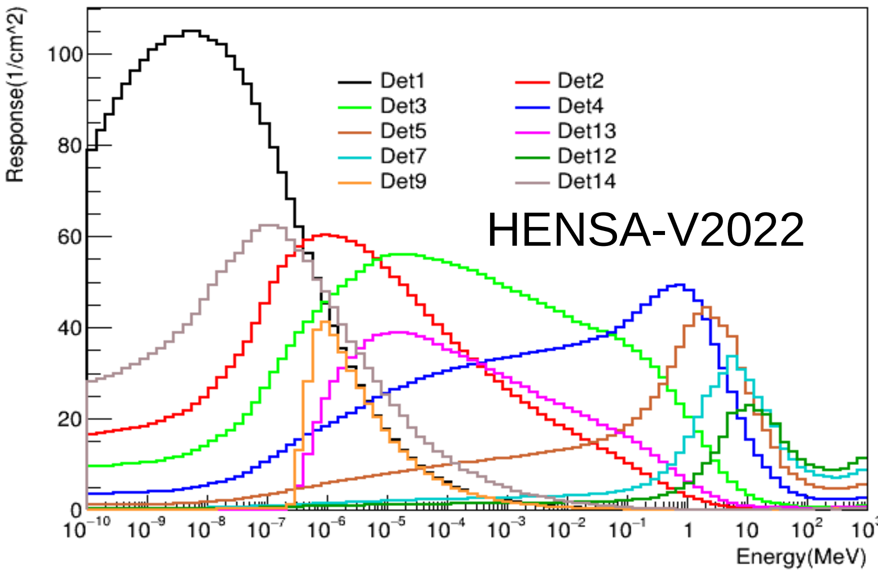
HENSA @ LNGS: Experiment at INFN Gran Sasso National Laboratory

- Detector HENSA-V2022 (8 atm)
- Measurement at **Hall A** @ LNGS has started in April 2024.
- Foreseen activities up to 2026.

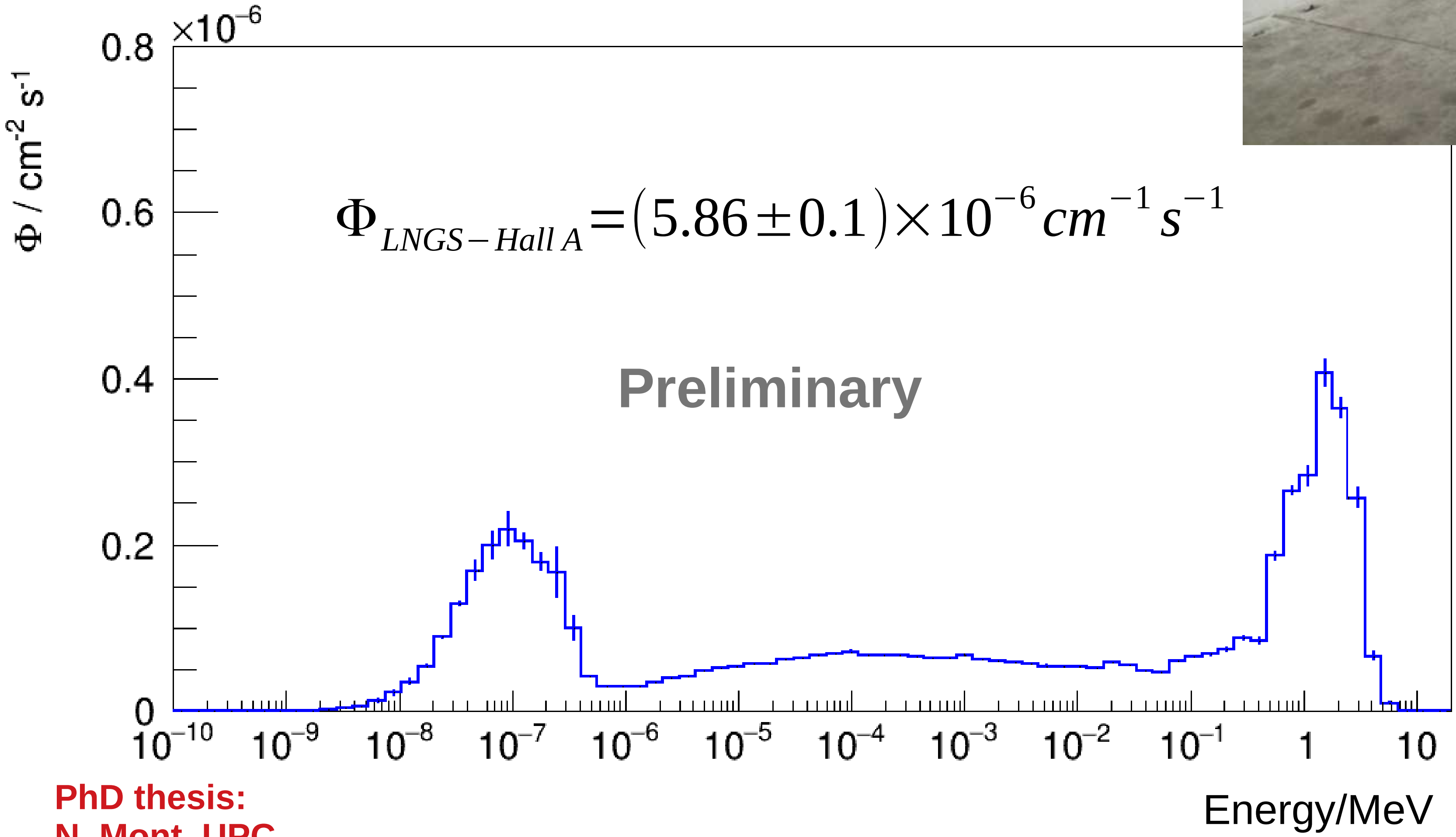
Collaborators:
Matthias Laubenstein, Chiara Ghiano, Roberto Cerroni (Special Techniques for detection of rare events, INFN)

Goals:
1) Determination of the neutron flux in a wide energy range (thermal – 20 MeV) in Hall A, B & C + new STELLA facility.

2) Assessment of potential modulation of the neutron background.

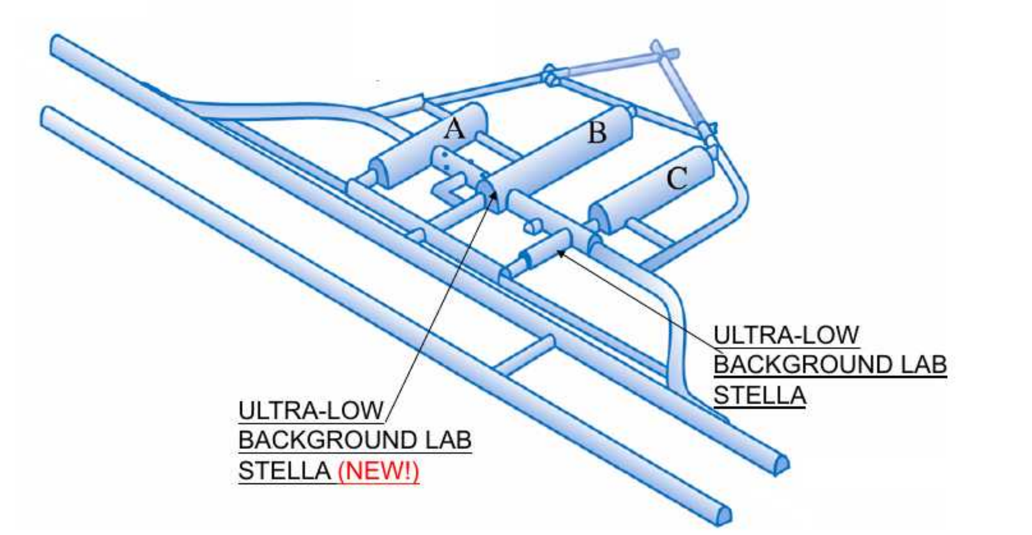


- **Setup assembled in hall A from 17 - 20 April 2024.**
- **Data acquisition from April 20th up to mid June 2024.**
- **Data analysis is on-going.**



PhD thesis:
N. Mont, UPC

HENSA @ LNGS: STELLA



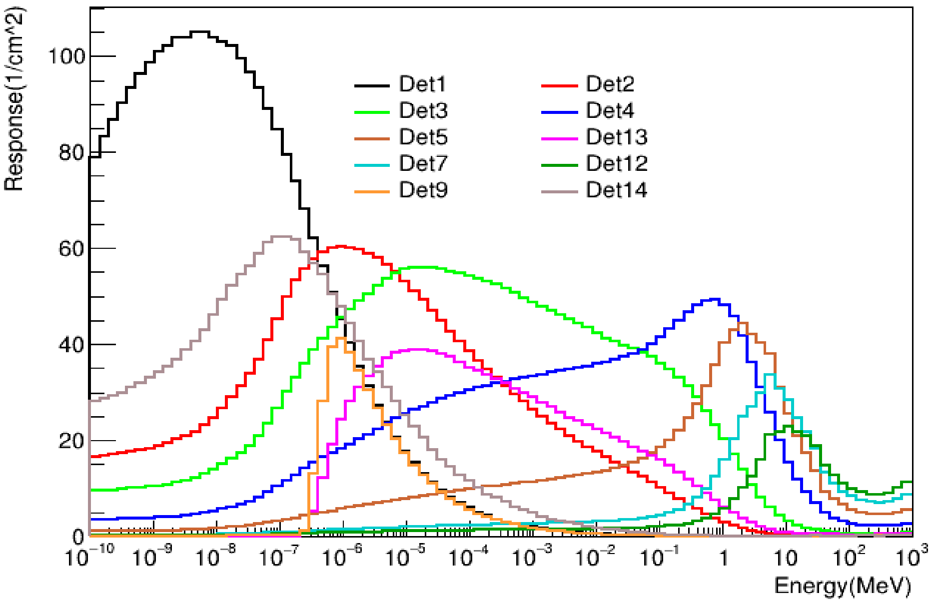
Courtesy of M. Laubenstein

HENSA setup installed inside STELLA (hall B)

Data acquisition in progress, it started by the end of July.

Preliminary analysis of the counting rates inside STELLA@LNGS

Detector ID	Neutron rate/(10^{-4} cps)	% error
1	0.102	54.7%
2	0.145	36.7%
3	0.105	63.2%
4	0.190	31.5%
5	0.334	18.2%
7	**0.012**	**428.9%**
9	**0.019**	**273.5%**
12	**0.055**	**96.7%**
13	**0.017**	**301.9%**
14	0.095	57.8%



Counting time used to extract the rates at LNGS: 49.79 days (from July 26th to August 25th).

- **We are reaching the limit of sensitivity inside STELLA.**
- Counting uncertainties are fully dominated by alpha-background subtraction
- *Rough estimation: neutron flux in STELLA aprox. 10 times lower than Hall A*
- **STELLA is a good case for low-background 3He detectors!**

Remarks and future perspective

- HENSA is able to provide valuable information about the neutron flux and its temporal evolution in underground laboratories.

- A study of the neutron flux, using the same instrument design, in underground facilities is ongoing (Felsenkeller-Germany, LSC-Spain, LNGS-Italy).

- Current activities:

LSC:
- Long-term study in Hall B to be finished next year.
- Monitoring task using reduced setup will continue supported by LSC.

LNGS:
- Data taking at the new STELLA facility will continue until Nov. 2024.
- Next measurement will be performed in Hall B (to be confirmed).
- Long-term characterization study will be started next year.

- By 2026, an additional HENSA spectrometer would be available to be installed in other underground facility (potential interest?)

Thanks!

PEOPLE

- Instituto de Física Corpuscular (IFIC), CSIC-UV, Spain

A. Tarifeño-Sadivia, J.L. Tain, S.E.A. Orrigo, B. Rubio, E. Nácher.

- Institute of Energy Technologies (UPC)

*F. Calviño, **N. Mont i Geli**, A. Casanovas, G. Cortés, A. De Blas, R. García, **M. Pallàs**, **B. Brusasco**.*

- Universidad Complutense de Madrid (UCM)

*L.M. Fraile, **V. Martínez Nouvillas***

- Helmholtz-Zentrum Dresden-Rossendorf (HZDR)

D. Bemmerer, M. Grieger

- TRIUMF

I. Dillmann

HENSA collaboration at LSC

- CIEMAT

*D. Cano-ott, T. Martínez, **J. Plaza del Olmo***

- Centro de Astropartículas y Física de Altas Energías

M. Martínez, M.L. Sarsa, A. Ortiz de Solórzano

HENSA collaboration for cosmic-rays & space weather

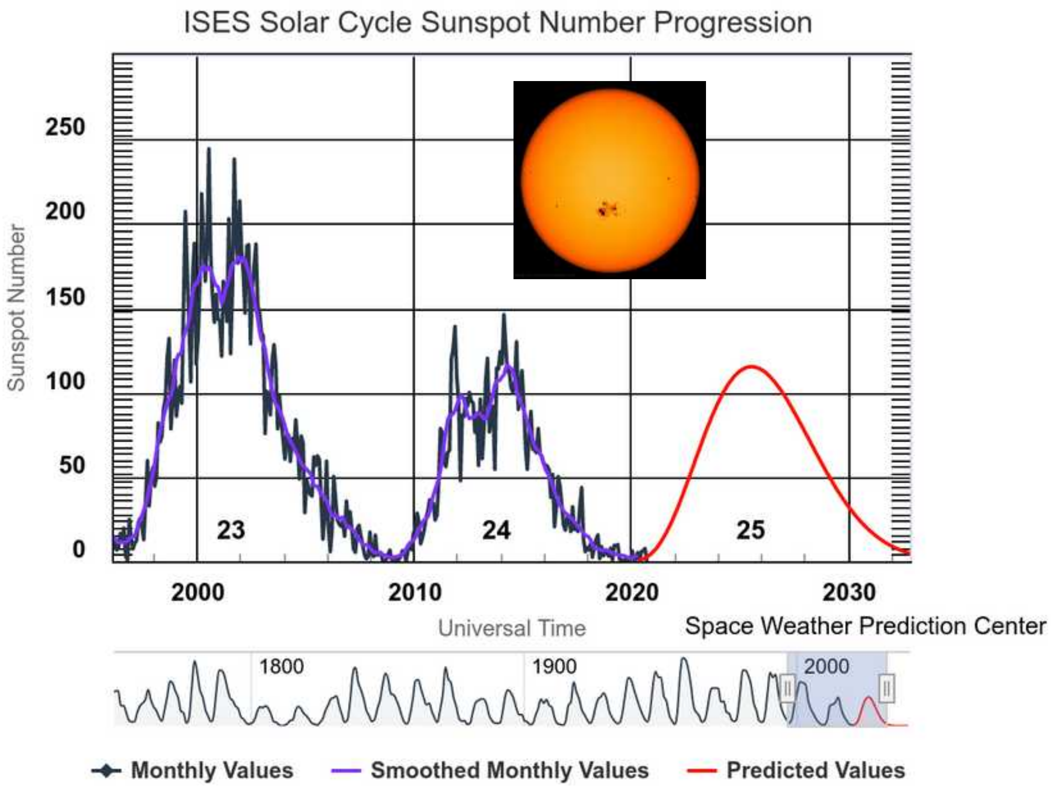
- Universidad de Granada

*A. Lallena, **A. Quero***

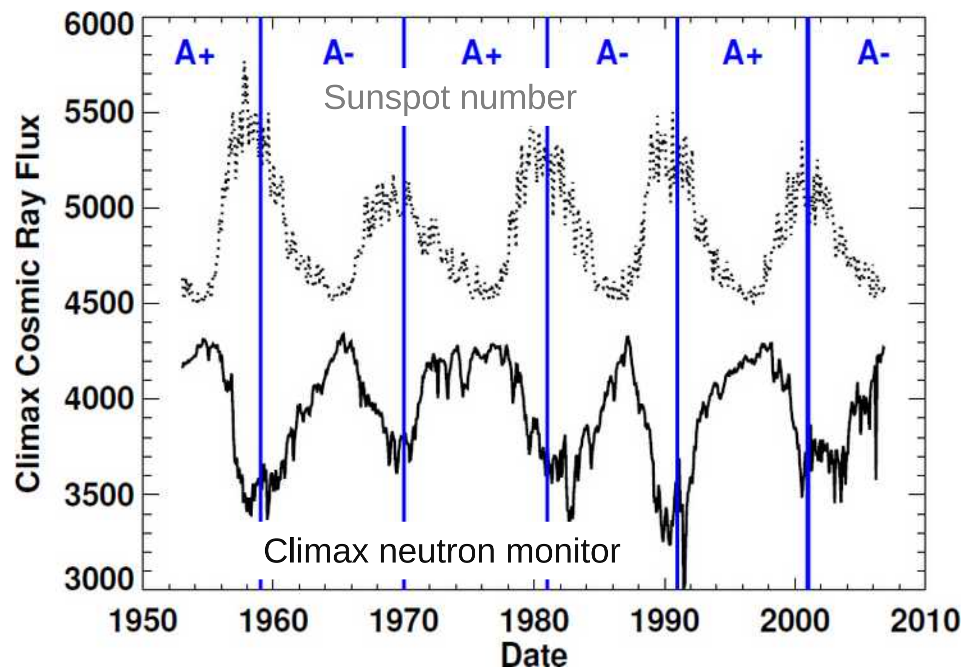
www.hensaproject.org

BACKUP SLIDES

Physics of cosmic rays and space weather



NOAA/NASA forecast for Solar Cycle 25. Maximum solar activity expected for July, 2025 (+/- 8 months). Solar minimum between Cycles 24 and 25 was observed around Dec. 2019 (+/- 6 months).



Neutron background anti-correlation with solar cycle. Cosmic Ray flux from the Climax Neutron Monitor and rescaled Sunspot Number.

Reference data from Neutron Monitors (www.nmdb.eu)

See poster by F. López-Usquiano (CCHEN)!

Secondary neutrons by cosmic-rays

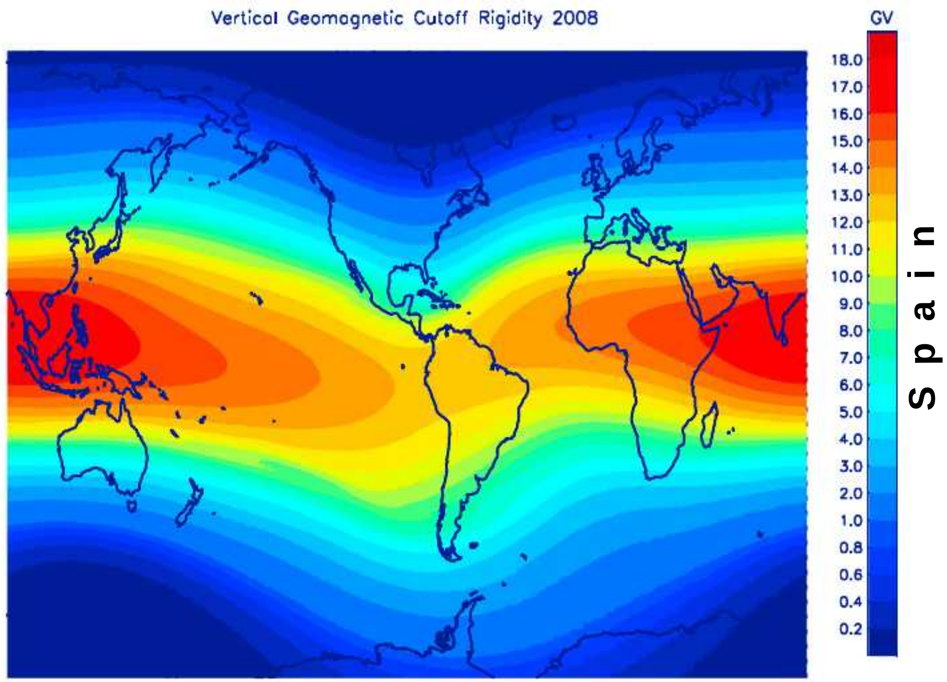


Figure 3. Global grid of vertical geomagnetic cutoff rigidities (GV) calculated from charged particle trajectory simulations in the IGRF field for 2008.

Martens *et al*. Space Weather 11 (2013) 603–635.

Secondary neutrons produced by cosmic rays depends mainly on:
- Solar cycle.
- Geomagnetic cutoff rigidity.
- Altitude.

- Peninsular spanish territory covers a range of cosmic rays vertical cutoff rigidity (Rc) values from 5 GV to 9 GV. In Ceuta and Melilla, Rc-values are 9.15 GV and 9.6 GV, respectively. In Canary Islands Rc is ~11.7 GV.
- Thus, the whole spanish territory covers a relatively ample range of Rc-values compared to other larger countries (for instance USA with 1.5 GV < Rc < 4.7 GV).

Most of the calculations models are based on data taken in US ~15 years ago! (Gordon et al. IEEE Trans. Nucl. Sci. 51:6 (2004) 3427-3434)

Mapping cosmic-ray induced neutron background in Spain with HENSA

HENSA-CR @ 2020
UPC / IFIC / UCM / HZDR

Spain is a good lab for cosmic-ray neutrons in pandemic times

HENSA campaign along the Spanish territory close to the minimum of solar activity (2020, solar cycle #25)

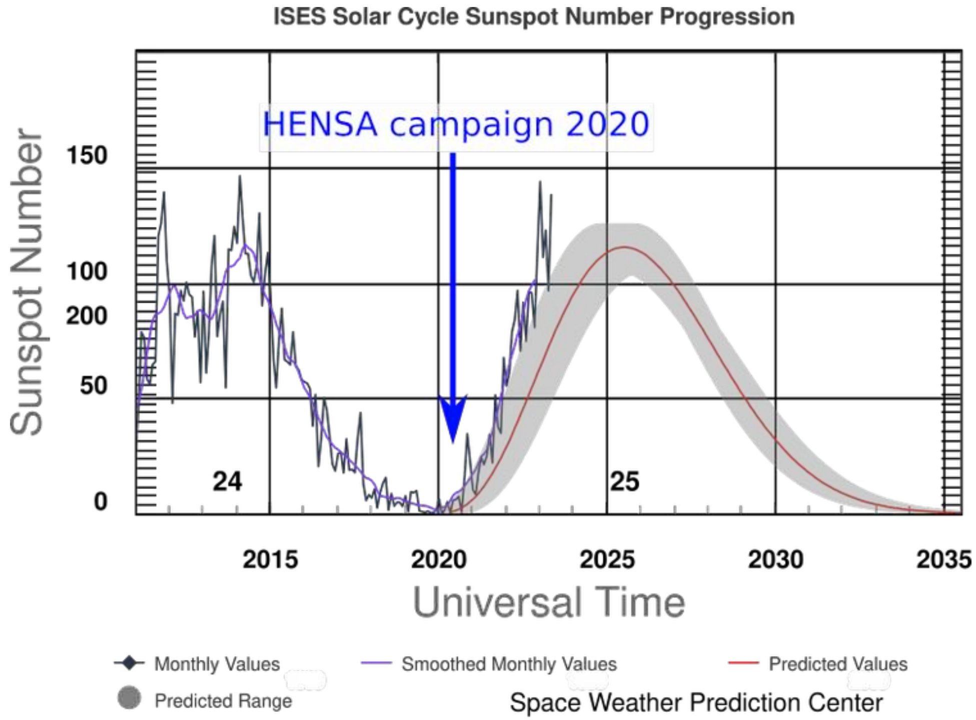
Cosmic ray induced neutron background

+ Cosmic ray physics and space weather
+ Environmental radiation dosimetry
+ Single-event upsets in microelectronics

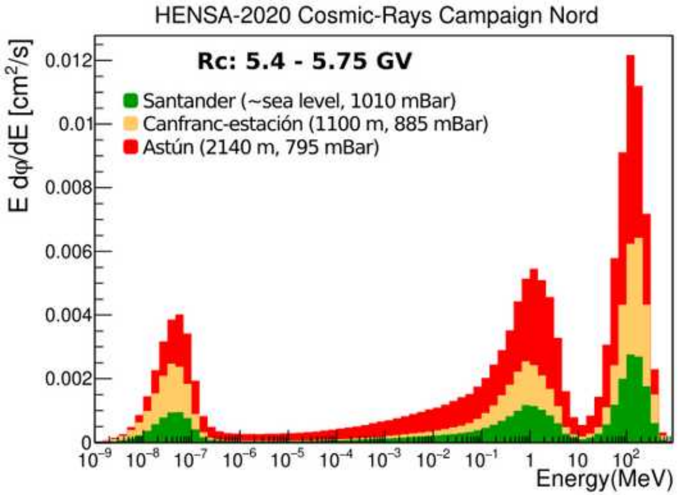
www.hensaproject.org

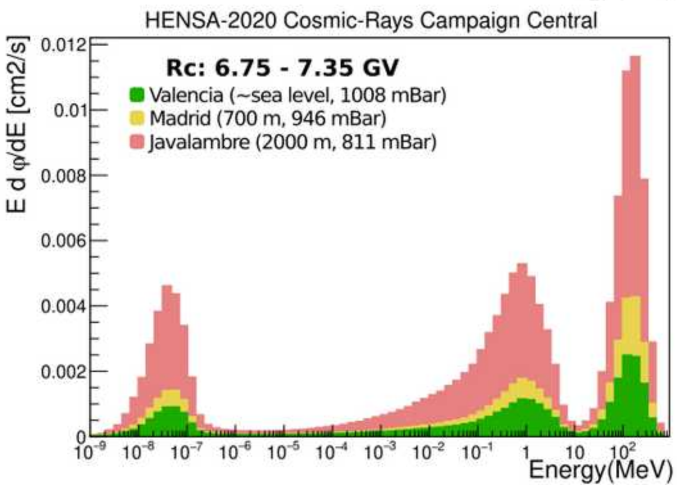
HENSA
High Efficiency Neutron Spectrometry Array

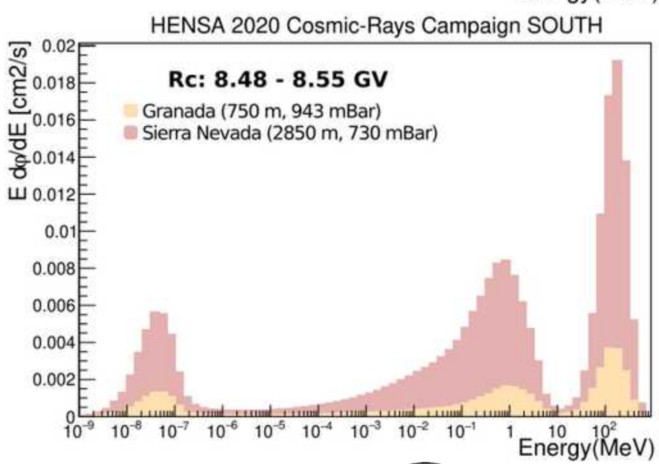
HENSA campaign 2020: July-August, October

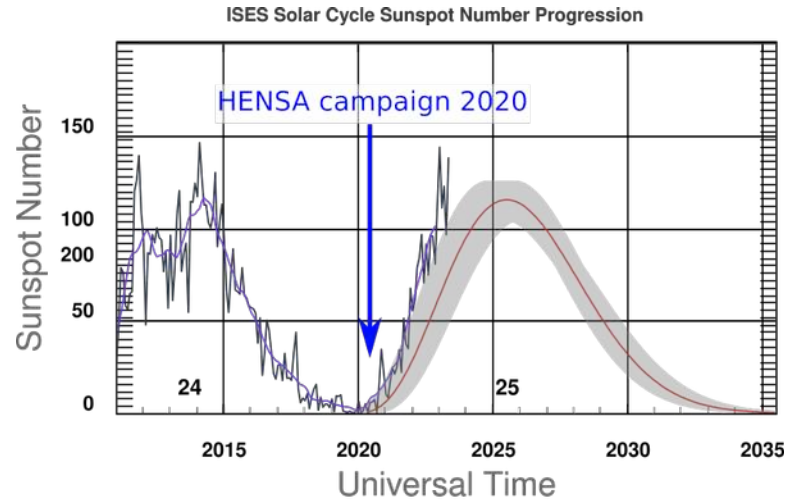


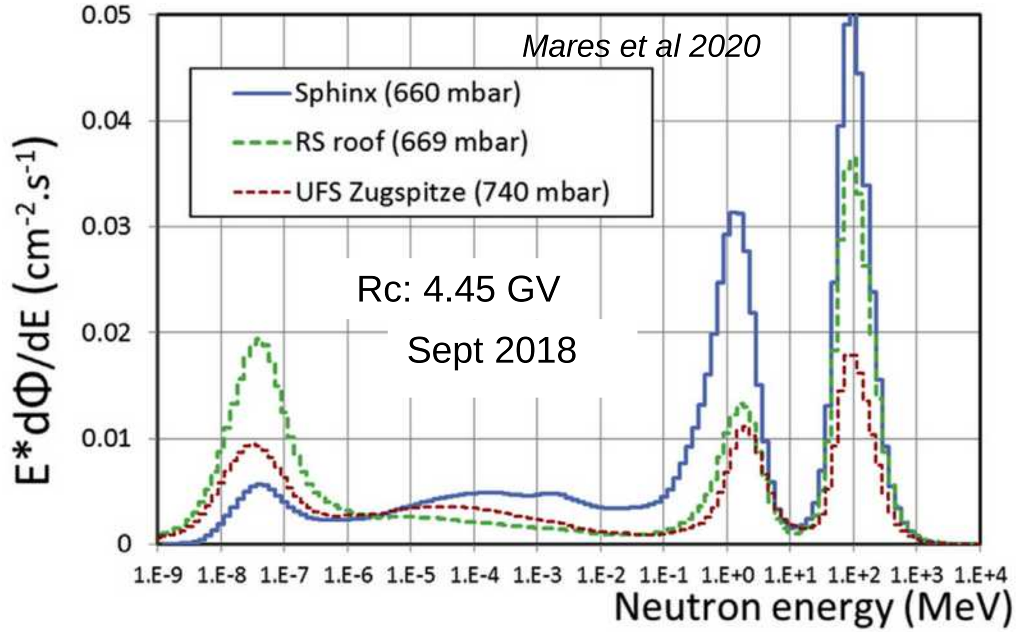
- 9 weeks of field campaign
- 4000 km in the route
- 9 different sites in Spain
- From sea level up to 2850 m
- Rc: 5.4-8.9 GV (complementary data to Gordon+2004)









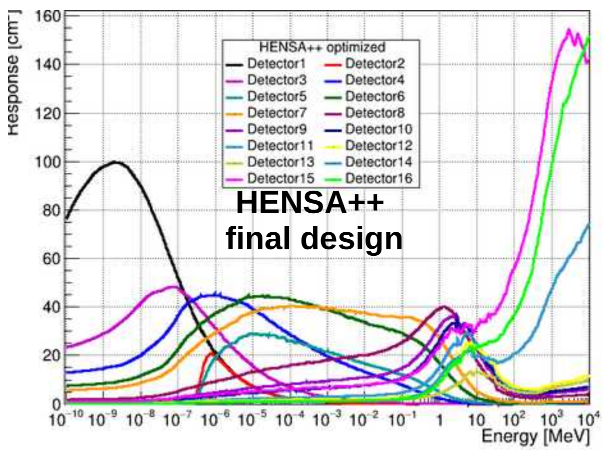


- Confirmed structure and flux magnitude with HENSA
- Confirmed effect of higher sensitivity of HENSA with respect to conventional BSS.
- Over 2000 m altitude, relative uncertainty in count rates at 1h time window is ~2% or less.

HENSA++: dedicated to CR applications

- **High efficiency spectrometer for space weather applications:**

- Array of 16 detectors (3He, 4 atm, 60 cm AL) for measurements of cosmic-ray neutrons.
- **Sensitivity from thermal neutrons up to 10 GeV.**
- Focus on monitoring **solar activity** and **environmental radioactivity**.
- System assembled and **commissioning during 2024** (detector array, electronics and auxiliary systems).
- Final deployment for **first experimental run planned during 2024** at the Observatorio Astrofísico de Javalambre (***A. Quero, PhD Thesis***).



Proyecto: IDIFEDER/2021/002

INSTRUMENTACIÓN AVANZADA EN DETECCIÓN DE NEUTRONES PARA LA VIDA Y EL CLIMA ESPACIAL: HENSA++

Programa Comunitat Valenciana Fondo Europeo de Desarrollo regional (FEDER) 2021 - 2027

Subvención: 260.199,21 €

Beneficiario: CSIC – Instituto de Fisica Corpuscular

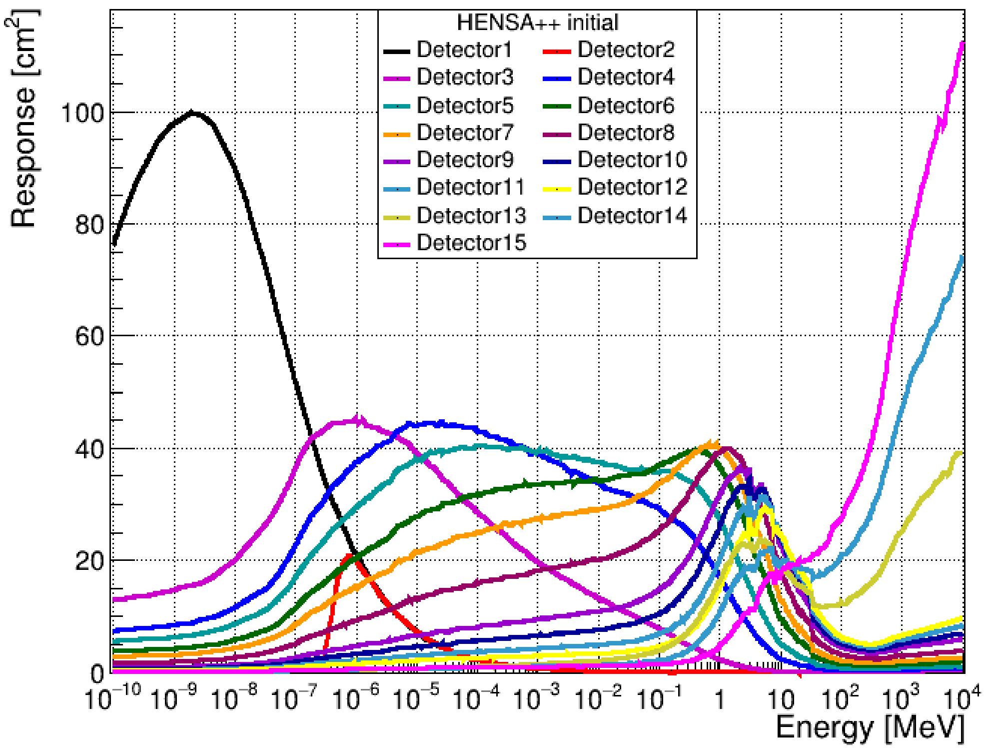
IFIC INSTITUT DE FÍSICA CORPUSCULAR

GENERALITAT VALENCIANA Conselleria d'Innovació, Universitats, Ciència i Societat Digital

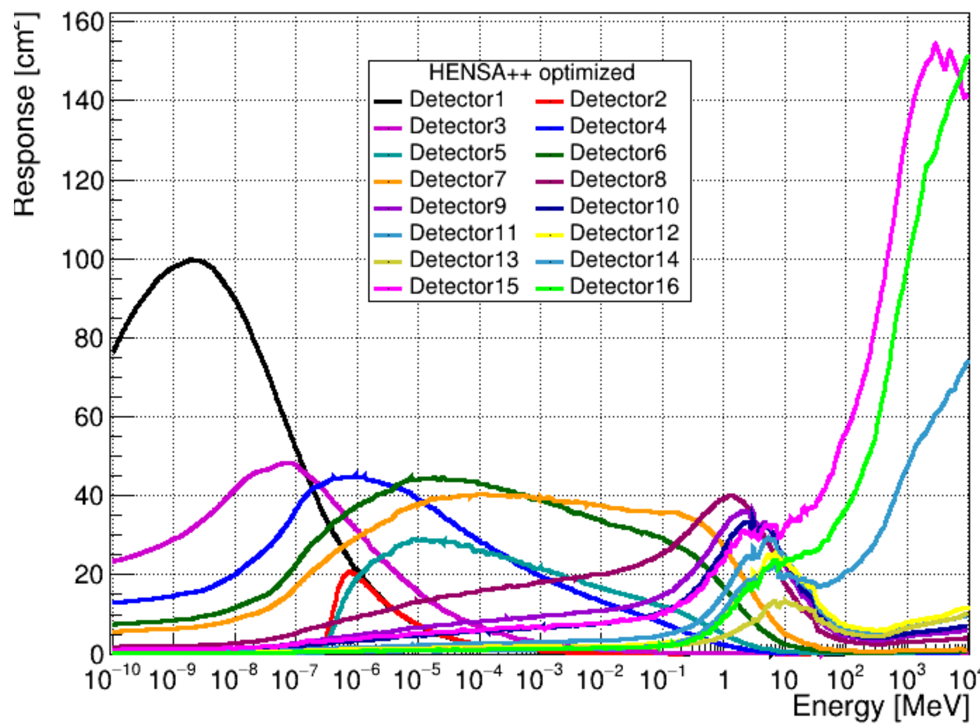
Financiado por la Unión Europea

Optimization of responses for HENSA++

HENSA++ proposal design



HENSA++ Optimized version



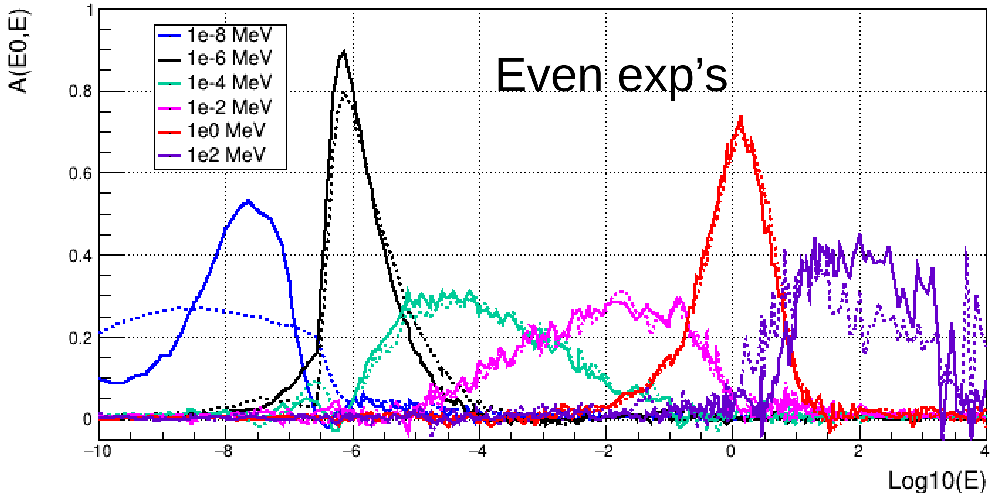
+ Intensive MC calculations have been performed.
+ Explored hundreds of possible detector configurations.
+ Optimization based on improving the resolving power of the array & tradeoff with technical viability (construction & weight).

MC simulations by the Geant4 application ***ParticleCounter***.

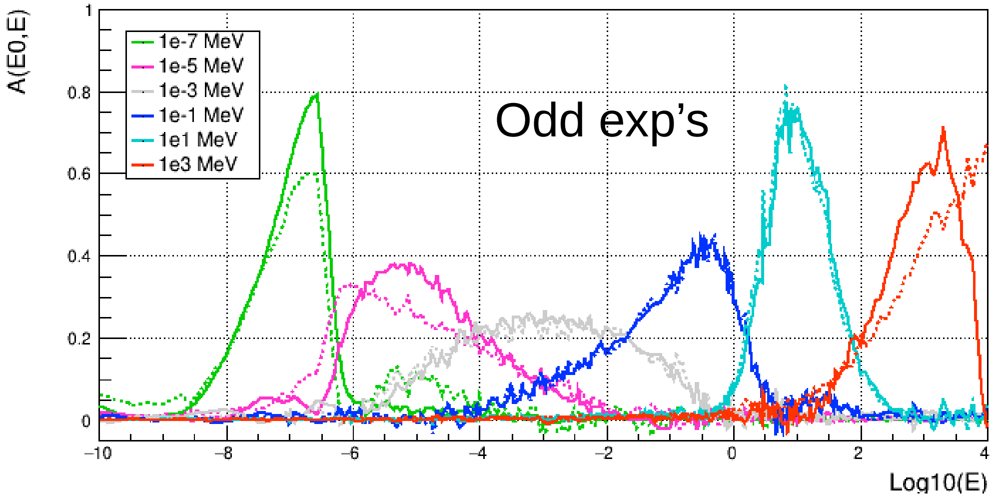
A. Quero, PhD thesis, UGR (Granada)

Final solution: resolving power

A. Quero, PhD thesis, UGR (Granada)



Dotted: Initial | Continuous: Optimized



Comparison of the resolving power moments

LogE	Mean(vInit)	Mean(vOpt)	SD(vOpt)/SD(vInit)-1
-8	-7.72	-7.69	-44.20%
-7	-6.76	-6.86	-51.11%
-6	-5.76	-5.89	-20.37%
-5	-4.93	-4.86	-24.11%
-4	-3.93	-3.98	-4.65%
-3	-3.00	-2.98	-8.27%
-2	-2.07	-2.08	-2.13%
-1	-1.12	-1.09	2.56%
0	-0.08	-0.09	-1.71%
1	0.91	0.94	-2.15%
2	1.43	1.72	-38.90%
3	2.71	2.73	-39.72%

Nuclear Instruments and Methods in Physics Research A 480 (2002) 690–695

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

Resolving power of a multisphere neutron spectrometer

Marcel Reginatto*

$$< \phi >_{E_0} = \int A(E_0, E)\phi(E)dE$$

Final version will use 60 cm counters at 4, 8 and a small one (30 cm) at 20 atm.

Acceptance criteria for solutions

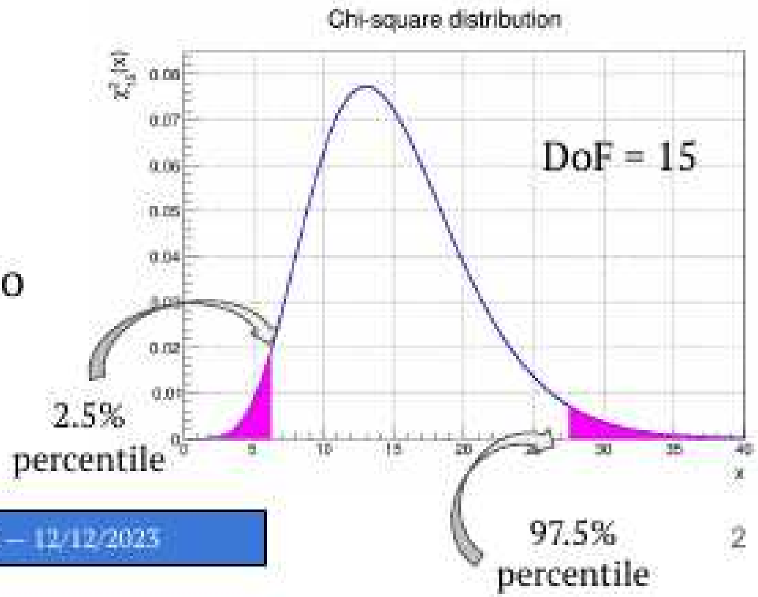
- Null hypothesis:

$$H_0: \{C_i^{unfold}\}_{i=1}^{n} \sim \{C_i^{true}\}_{i=1}^{n}$$

- Set a Confidence Interval for the chi-square statistic (Ex: 95%)

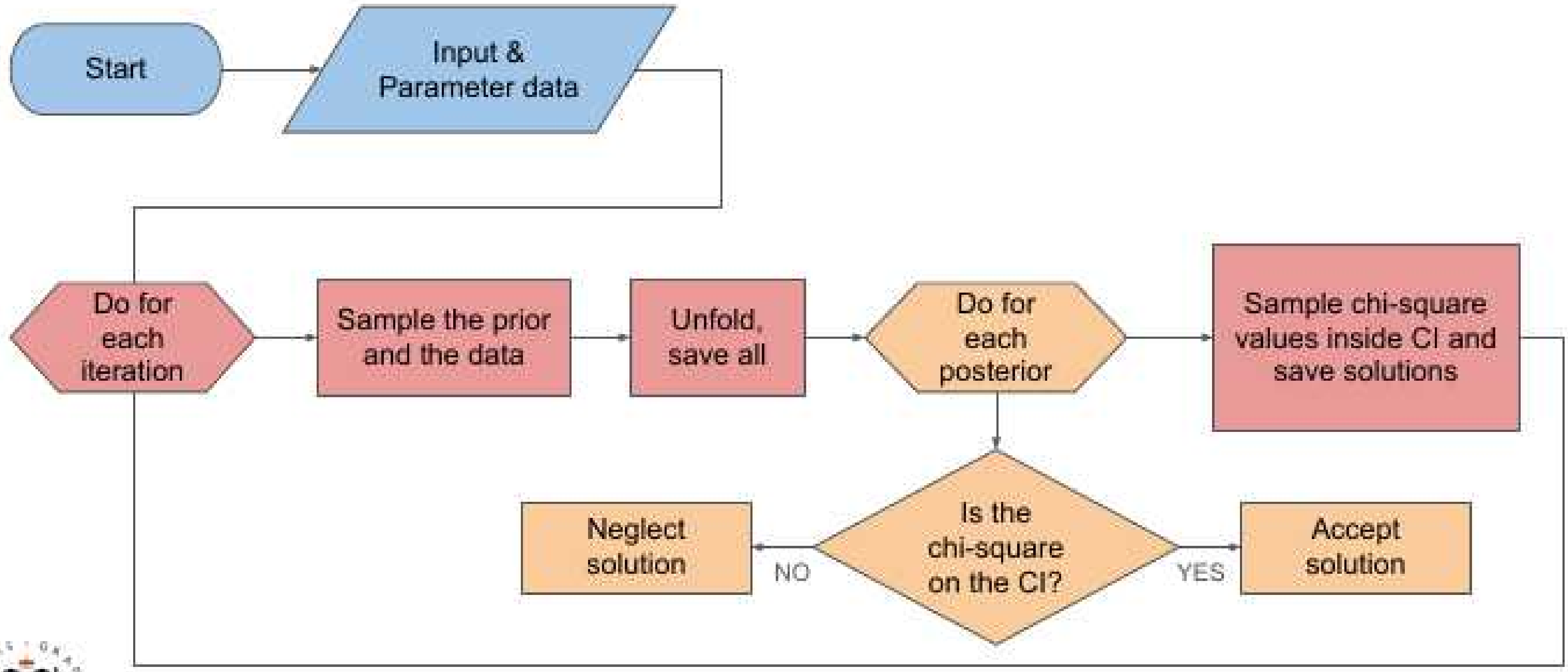
$$\chi^2 = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{C_i^{input} - C_i^{output}}{\sigma_i^{input}}\right)^2$$

- If the chi-square value of the unfolding is in the CI, Ho can't be rejected so the solution is accepted



Chi-squared Analysis for POU – A Quero-Ballesteros – 12/12/2023 2

Methodology of POU

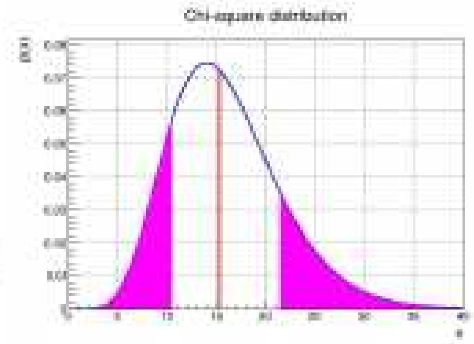


Chi-squared Analysis for POU – A Quero-Ballesteros – 12/12/2023

3

Treatment of the solutions

- For each energy bin, we'll obtain a set of solutions $[\phi_i]_{i=1}^{n}$ that constitute a distribution of fluence.



- We want to give a final spectrum with its uncertainty, so:
  - The central value selected is the median of the distribution
  - The uncertainty is given by a Confidence Interval of $1\sigma\ (68\%)$

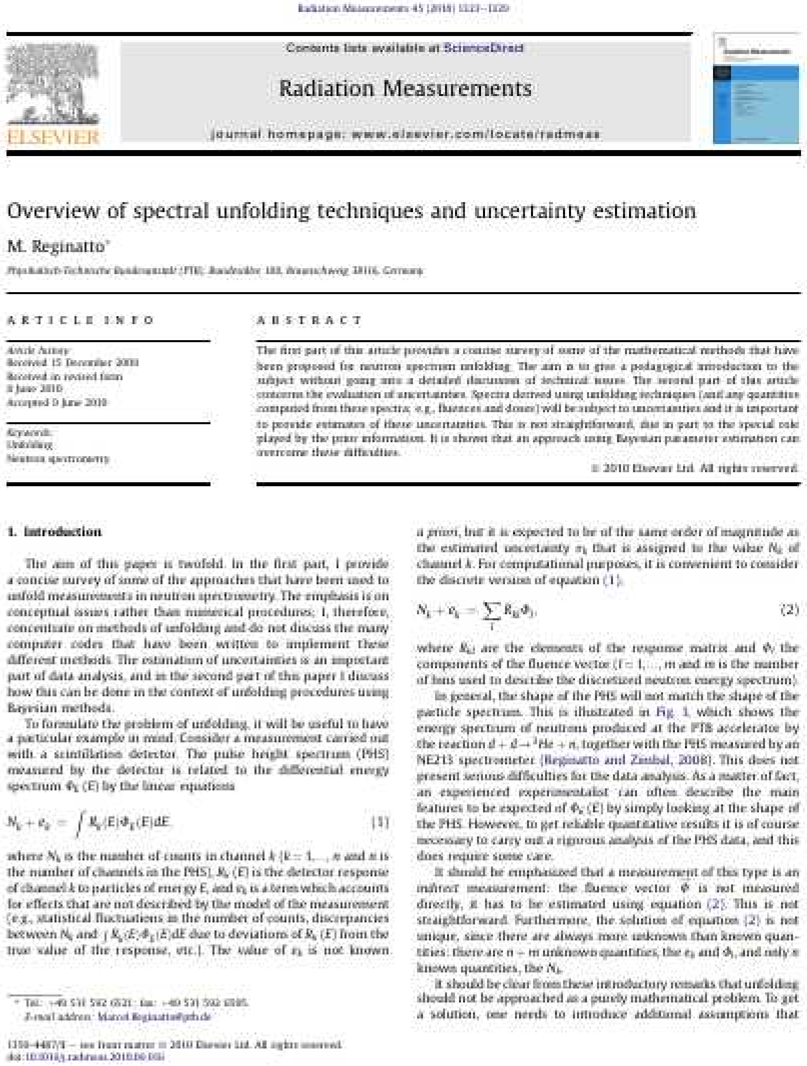
- The same process is employed for the integral values of the fluence and doses in the desired regions.

- With the code, we can calculate: space of solutions, chi-square distribution, covariance matrix, distribution of solutions, chi-square maps for the parameters…

Energy spectrum reconstruction: algorithms

- **Iterative procedures**: usually black-magic recipes!
- **Stochastic methods**: Monte Carlo, genetic algorithms, ...
- **Regularisation**: add constraints to enforce smoothness
- **Least-squares adjustment**
- **Bayesian parameter estimation**: requires an analytical model for fitting
- **Maximum entropy principle:** justifiable from information theory consistent treatment of prior information and uncertainties
- **Machine learning...**

Most of this methods require a-priori information that is retrieved from MC calculations



Radiation Measurements 45 (2010) 1323–1329

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Overview of spectral unfolding techniques and uncertainty estimation

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ABSTRACT

The first part of this article provides a concise survey of some of the mathematical methods that have been proposed for neutron spectrum unfolding. The aim is to give a pedagogical introduction to the subject without going into a detailed discussion of technical issues. The second part of this article concerns the evaluation of uncertainties. Spectra derived using unfolding techniques (and any quantities computed from these spectra, e.g., fluences and doses) will be subject to uncertainties and it is important to provide estimates of these uncertainties. This is not straightforward, due in part to the special role played by the prior information. It is shown that an approach using Bayesian parameter estimation can overcome these difficulties.

1. Introduction

The aim of this paper is twofold. In the first part, I provide a concise survey of some of the approaches that have been used to unfold measurements in neutron spectrometry. The emphasis is on conceptual issues rather than numerical procedures; I, therefore, concentrate on methods of unfolding and do not discuss the many computer codes that have been written to implement these different methods. The estimation of uncertainties is an important part of data analysis, and in the second part of this paper I discuss how this can be done in the context of unfolding procedures using Bayesian methods.

To formulate the problem of unfolding, it will be useful to have a particular example in mind. Consider a measurement carried out with a scintillation detector. The pulse height spectrum (PHS) measured by the detector is related to the differential energy spectrum $\Phi_E(E)$ by the linear equations

$$N_k + \epsilon_k = \int R_k(E)\Phi_E(E)\mathrm{d}E \qquad (1)$$

where N_k is the number of counts in channel k ($k = 1, \ldots, n$ and n is the number of channels in the PHS), $R_k(E)$ is the detector response of channel k to particles of energy E, and ϵ_k is a term which accounts for effects that are not described by the model of the measurement (e.g., statistical fluctuations in the number of counts, discrepancies between N_k and $\int R_k(E)\Phi_E(E)\mathrm{d}E$ due to deviations of $R_k(E)$ from the true value of the response, etc.). The value of ϵ_k is not known a priori, but it is expected to be of the same order of magnitude as the estimated uncertainty σ_k that is assigned to the value N_k of channel k. For computational purposes, it is convenient to consider the discrete version of equation (1),

$$N_k + \epsilon_k = \sum_i R_{ki}\Phi_i \qquad (2)$$

where R_{ki} are the elements of the response matrix and Φ_i the components of the fluence vector ($i = 1, \ldots, m$ and m is the number of bins used to describe the discretized neutron energy spectrum).

In general, the shape of the PHS will not match the shape of the particle spectrum. This is illustrated in Fig. 1, which shows the energy spectrum of neutrons produced at the PTB accelerator by the reaction $d + d \rightarrow {}^3He + n$, together with the PHS measured by an NE213 spectrometer (Reginatto and Zimbal, 2008). This does not present serious difficulties for the data analysis. As a matter of fact, an experienced experimentalist can often describe the main features to be expected of $\Phi_E(E)$ by simply looking at the shape of the PHS. However, to get reliable quantitative results it is of course necessary to carry out a rigorous analysis of the PHS data, and this does require some care.

It should be emphasized that a measurement of this type is an indirect measurement: the fluence vector Φ is not measured directly, it has to be estimated using equation (2). This is not straightforward. Furthermore, the solution of equation (2) is not unique, since there are always more unknowns than known quantities: there are $n + m$ unknown quantities, the ϵ_k and Φ_i, and only n known quantities, the N_k.

It should be clear from these introductory remarks that unfolding should not be approached as a purely mathematical problem. To get a solution, one needs to introduce additional assumptions that

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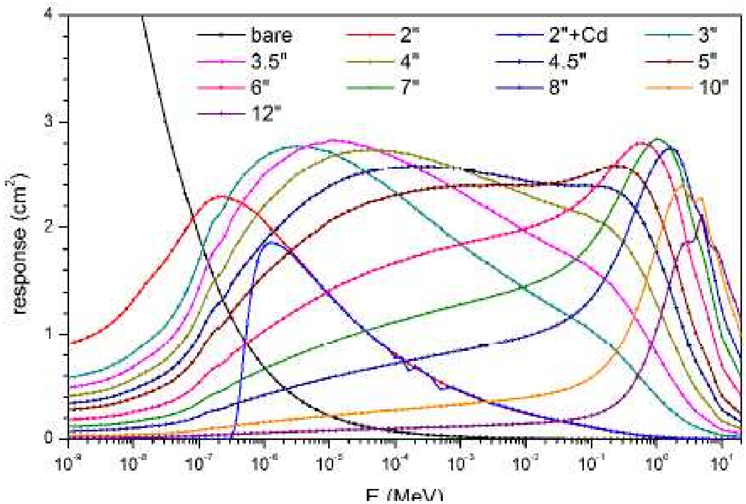
M. Reginatto, Rad. Meas. 45 (2010) 1323-1329

Energy spectrum reconstruction: trained users



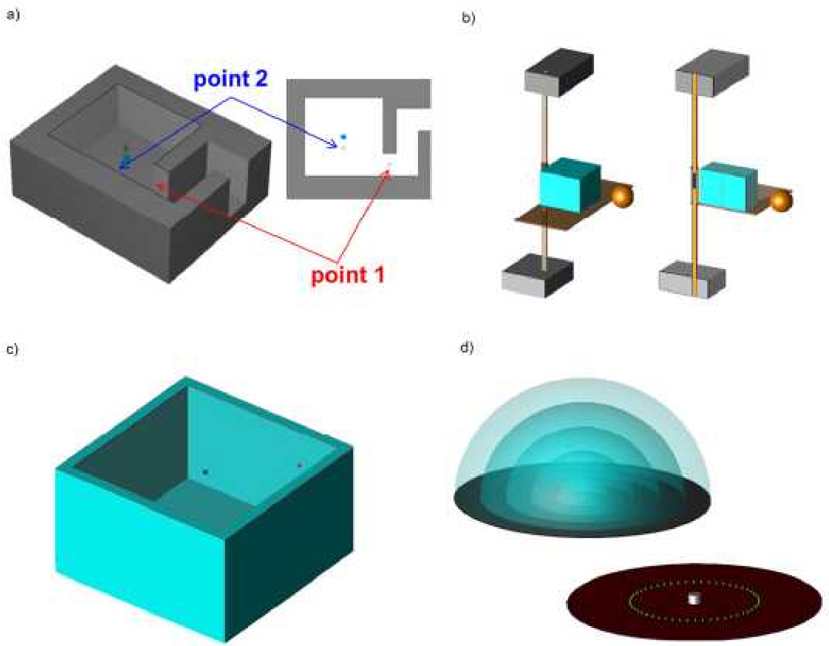


Fig. 2: Irradiation scenarios: a) medical LINAC (2 measurement points); b) workplace; c) calibration facility; d) skyshine

Results of the EURADOS international comparison exercise on neutron spectra unfolding in Bonner spheres spectrometry

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Table 1 Summary of participants unfolded codes, solved scenarios and pre-information method.

participant	unfolding method	LINAC	workplace	calibration room	skyshine	pre-information
a	B-UNCLE	x	x	x	x	not clearly indicated
b	FRUIT	x	x	x	x	choice of parametric model
c	FRUIT	x	x	x	x	choice of parametric model
d	FRUIT	x	x	x	x	missing information
e	GRUPINT, ANGELO, ZOTT99	x	x	x	x	MCNP6
f	UMG 3.3	x		x		MCNP6
g	UMG 3.3	x				default spectrum from literature
h	UMG 3.3	x	x	x	x	MCNPX 2.5
i	UMG 3.3		x	x	x	MCNP6
j	UMG package: MXD_FC33		x	x		MCNP6
k	MAXED	x	x	x	x	problem dependent
l	GRAVEL	x	x	x	x	problem dependent
m	MXD_FC33 and IQU_FC33	x	x	x	x	problem dependent
n	MAXED	x	x	x	x	MCNP5
o	MAXED / UMG			x		MCNP5
p	MAXED 2000			x		not clearly indicated
q	MSITER / MIEKE		x	x		MCNP5
r	WinBUGS	x	x	x	x	choice of parametric model
s	basic Tykhonov method	x	x	x	x	none
t	self-made	x	x	x	x	none
u	self-made			x		none

Energy spectrum reconstruction: trained users

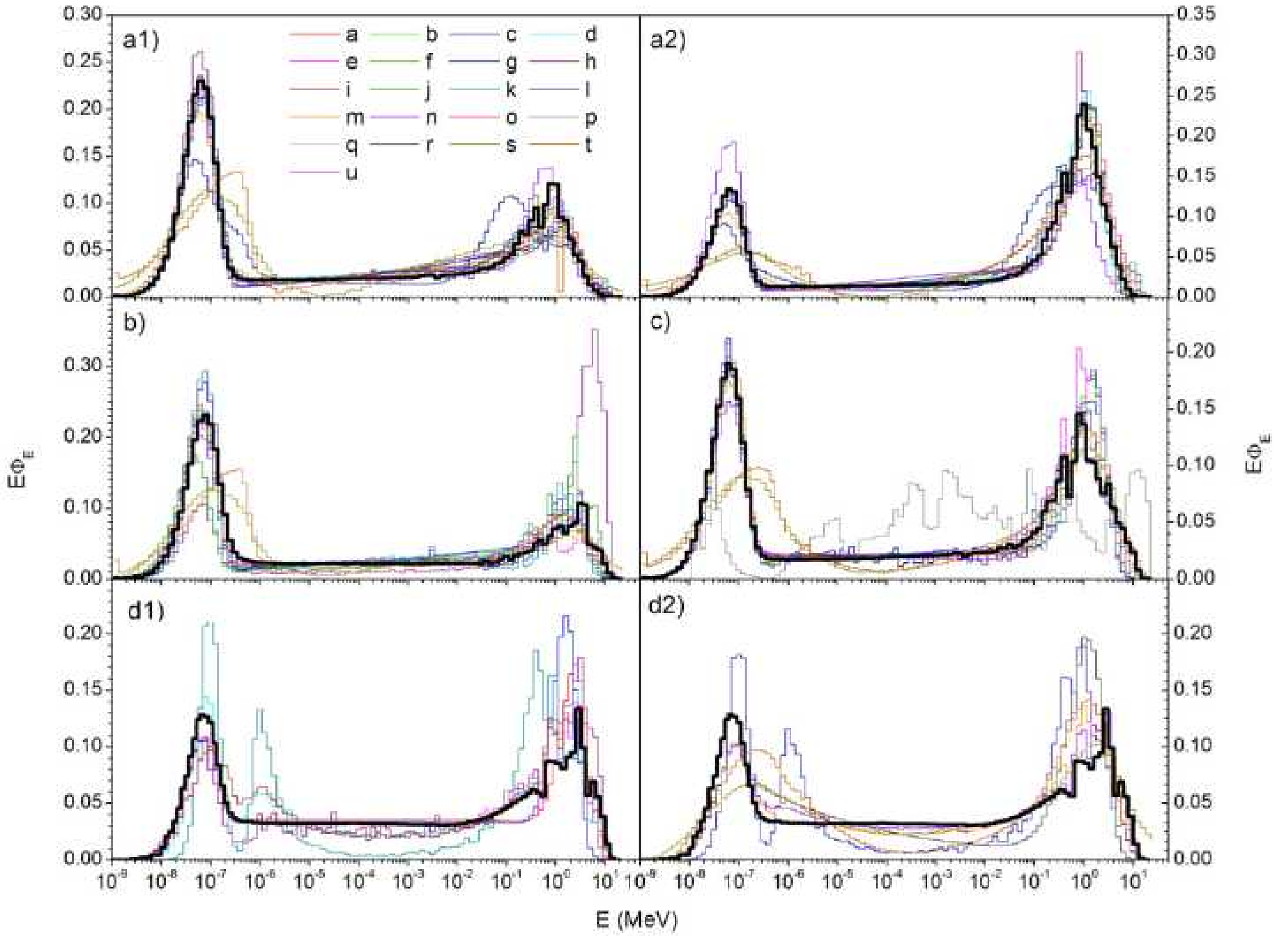

Fig. 3: Participants unfolded spectra (in colour) compared with the reference spectra for: a1) LINAC scenario, point 1 (at the entrance of the maze); a2) LINAC, point 2 (1 m from the isocentre); b) workplace; c) calibration facility; d) skyshine.