School of Applied Mathematical and Physical Sciences
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Neutron Flux Characterization of the n_TOF (CERN) NEAR Station via the SAND II Unfolding Code

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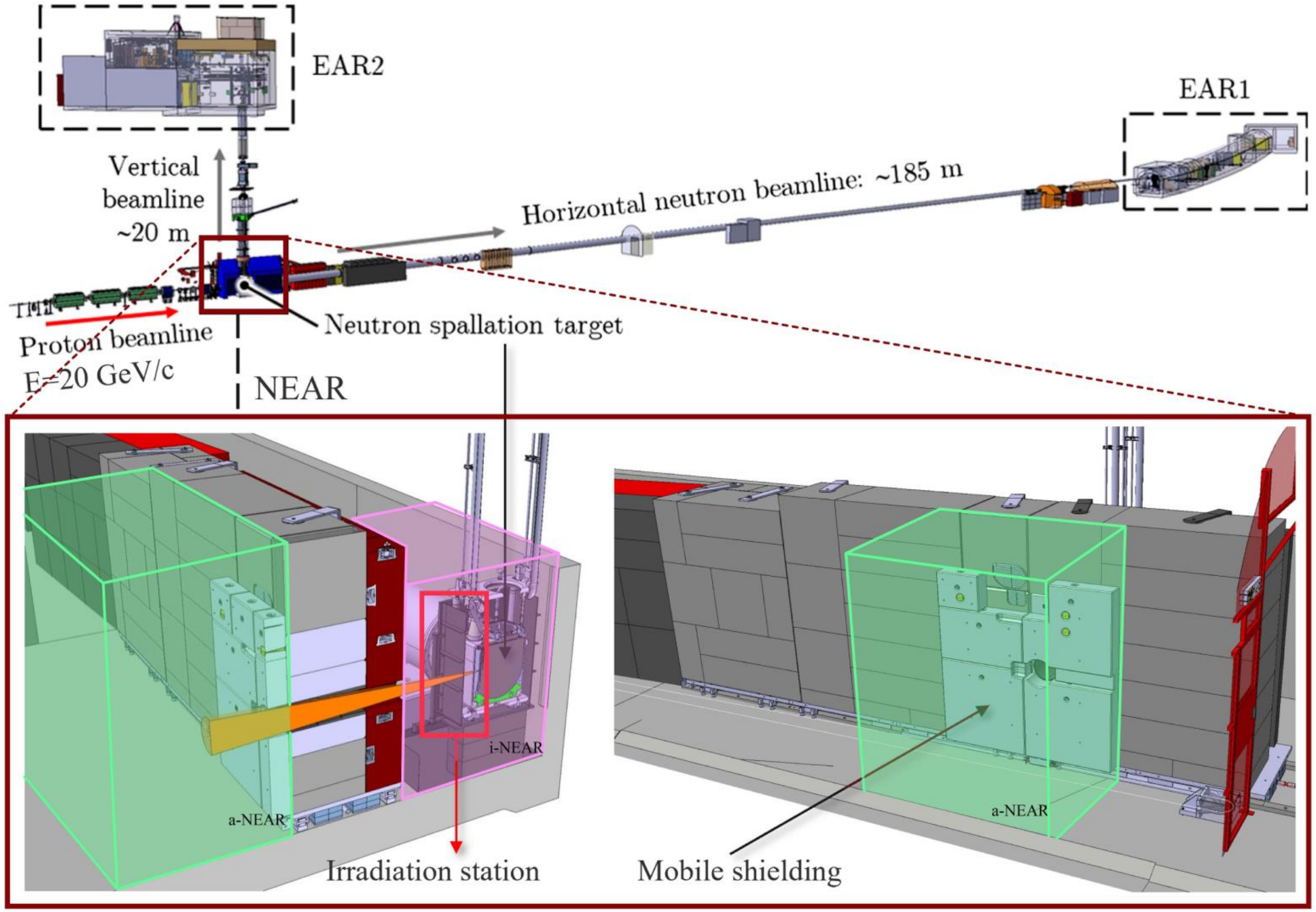
HINPw7 31/05 – 01/06/2024
7th Workshop of the Hellenic Institute of Nuclear Physics on Nuclear Structure, Astrophysics and Reaction Dynamics

Motivation



n_TOF
- Operational since 2001
- Neutron production via spallation (protons of 20 GeV impinge on a Pb target)

Motivation (NEAR station)
- High neutron flux values
- Radiation damage studies
- Cross-section measurements of astrophysical interest via the activation technique

Goal
- Characterization of the neutron flux

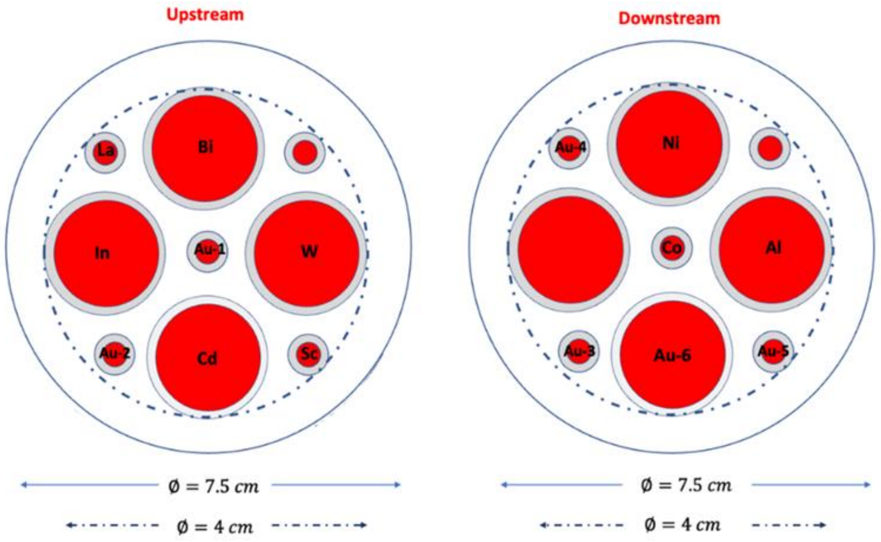
Neutron Flux Characterization - Overview

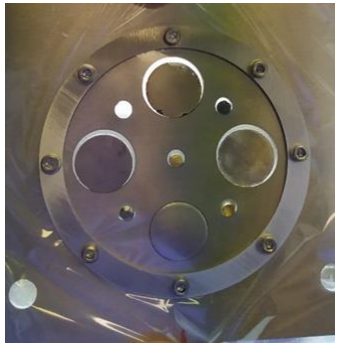
Goal
Characterization of the neutron flux

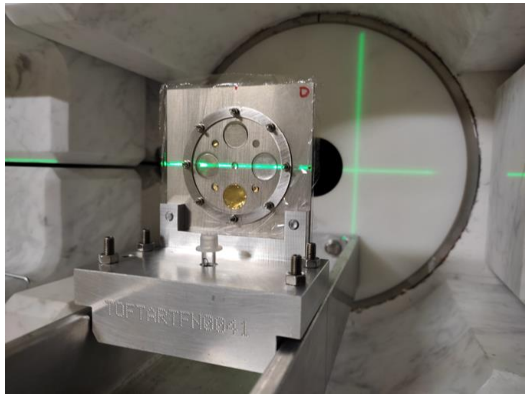
Activation technique on 14 samples

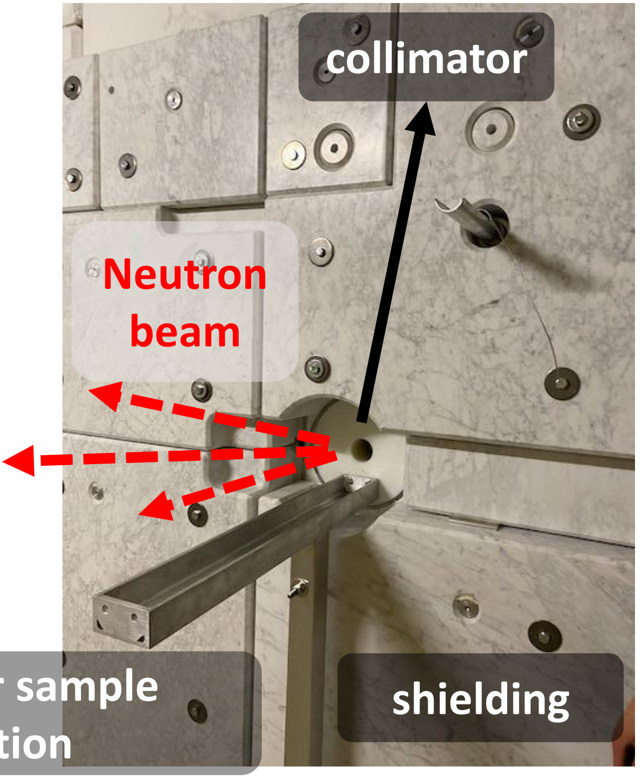
Experimental determination of **saturation activity**

Deconvolution code **SAND-II**: Tuning of input Flux (seed spectrum) to **reproduce the experimental saturation activity values**

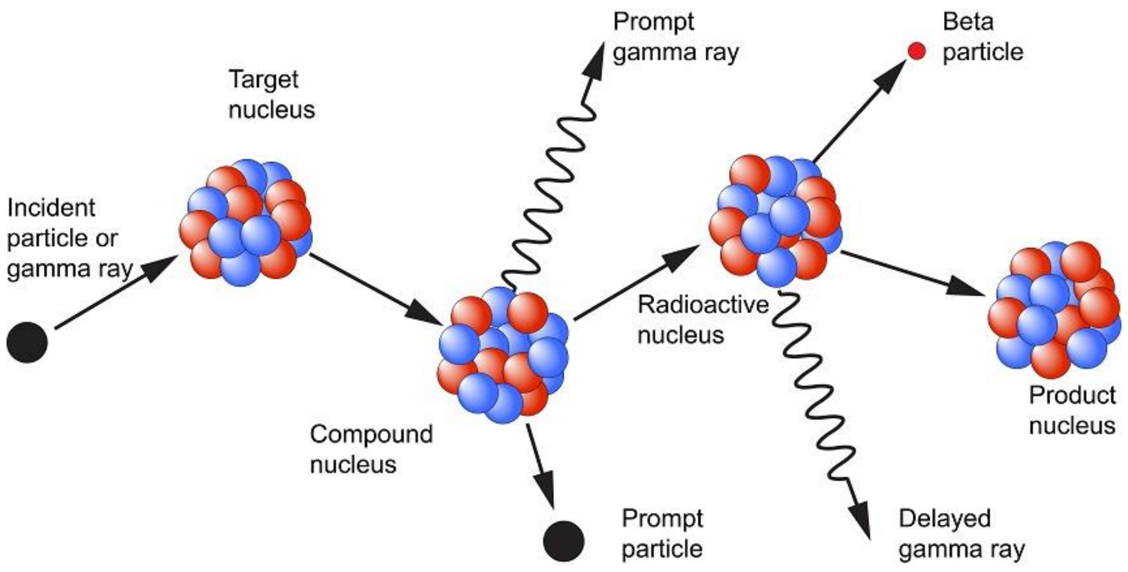


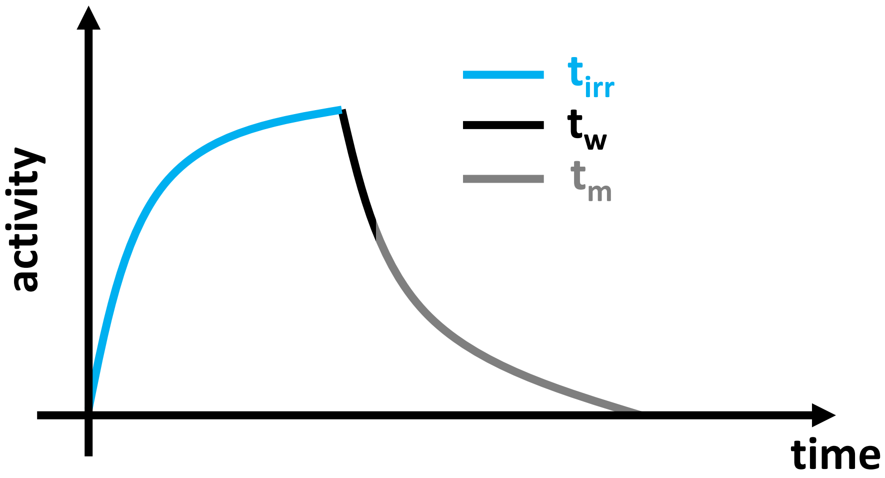


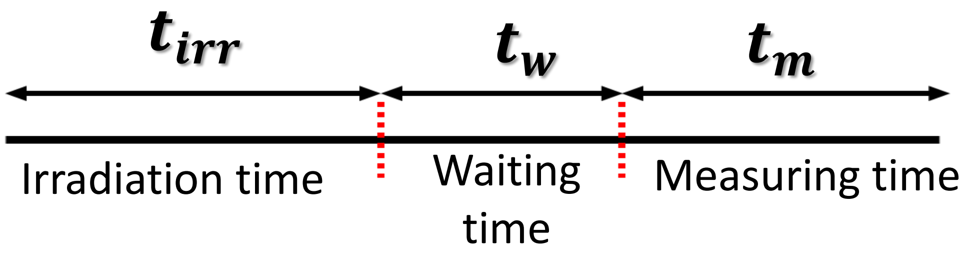




Multiple Foil Activation Technique







$$\int_0^\infty \sigma_i(E) \cdot \Phi(E,t)\, dE \cdot N_i(0) = SA_i$$

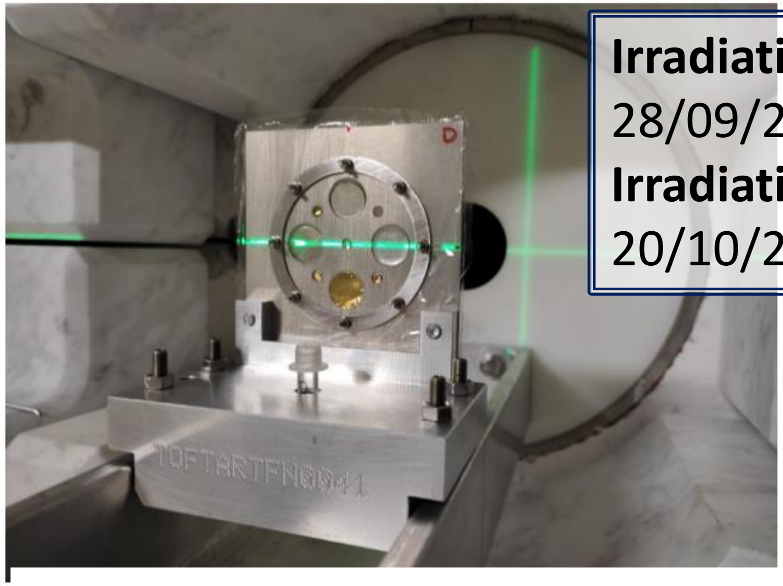
$\Phi(E,t)$: neutron flux$[n/cm^2/sec]$

$\sigma_i(E)$: cross section

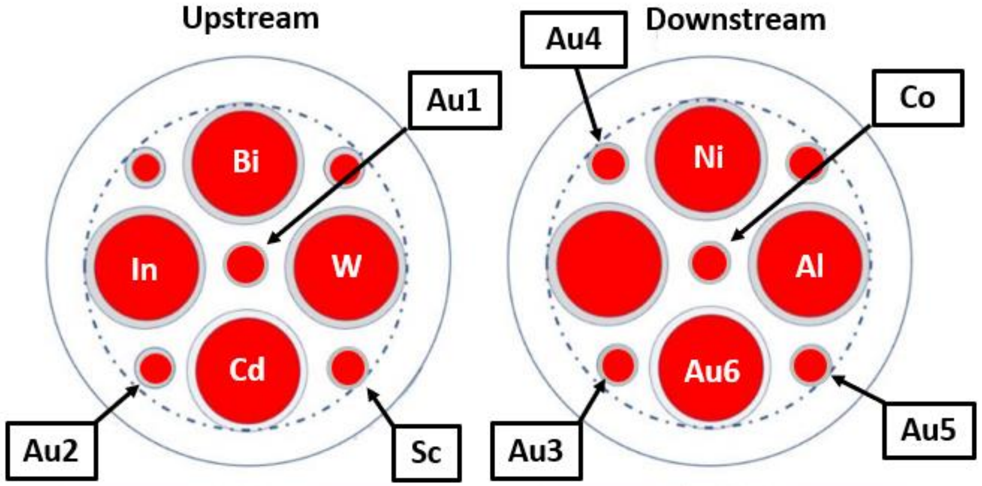
$N_i(0)$: number of target nuclei

SA_i: saturation activity

Experimental Setup – MAM1



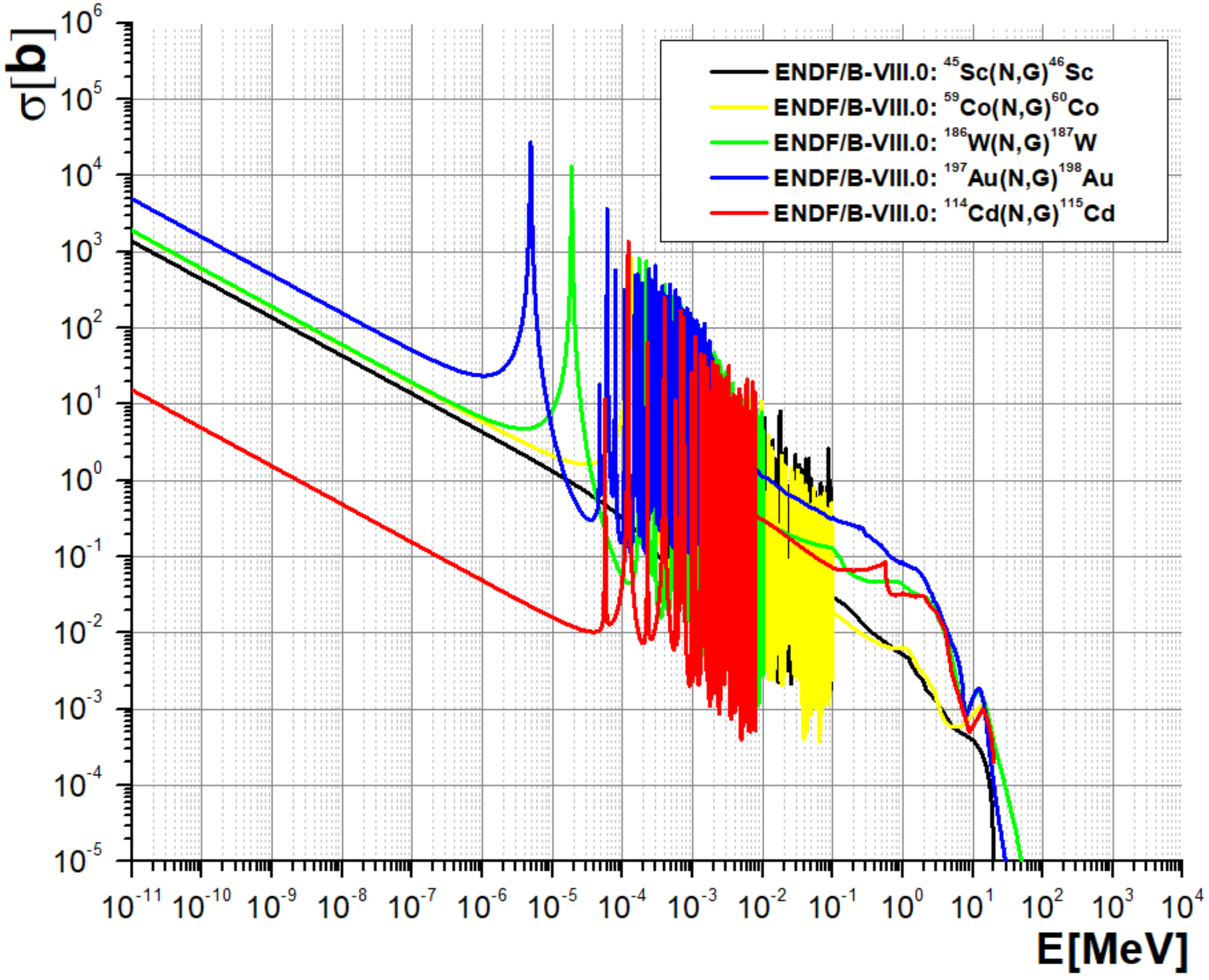
Irradiation start:
28/09/21
Irradiation end:
20/10/21



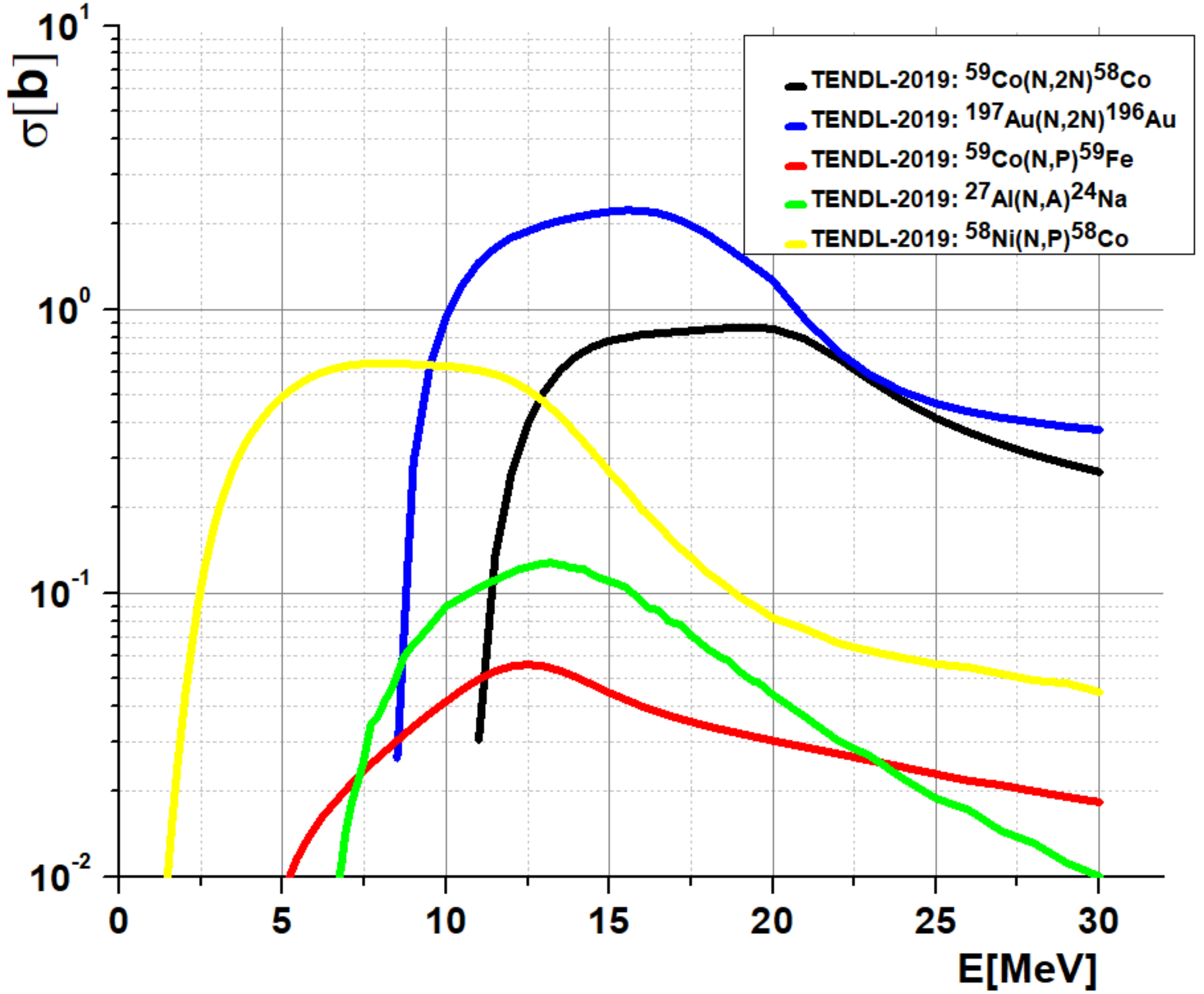
Foil	Thickness [mm]	Diameter [mm]	Mass [g]	Foil	Thickness [mm]	Diameter [mm]	Mass [g]
In	0.5	13	0.4675± 0.0002	*Au3*	0.1	3	0.0142± 0.0003
Sc	0.3	3	0.0073± 0.0001	*Au4*	0.1	3	0.0149± 0.0003
W	0.5	12.7	1.2349± 0.0001	*Au5*	0.1	3	0.0148± 0.0002
Bi	1	13	1.1070± 0.0003	*Au6*	0.025	13	0.0550± 0.0002
Cd	1	12.7	1.0714± 0.0002	*Co*	0.5	3	0.0348± 0.0001
Au1	0.5	3	0.0709± 0.0002	*Al*	0.5	13	0.1694± 0.0003
Au2	0.5	3	0.0712± 0.0003	*Ni*	0.5	13	0.5624± 0.0001

Reactions - Cross Sections

Capture reactions

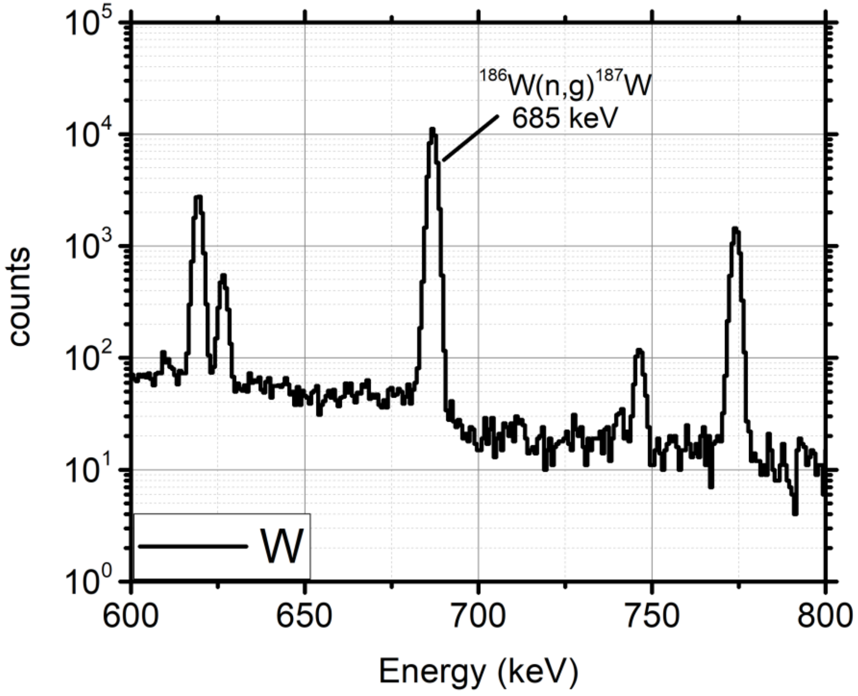


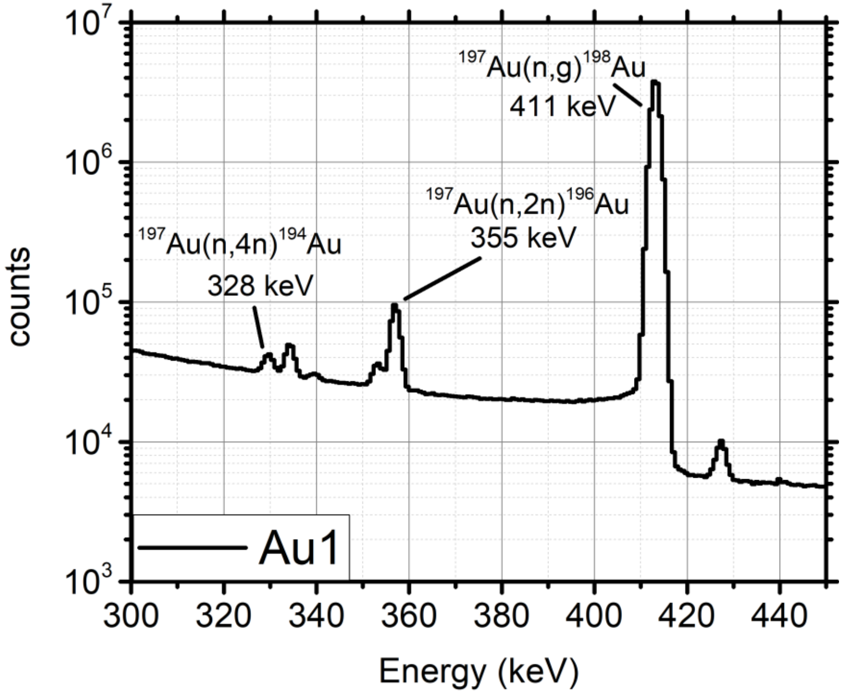
Threshold reactions

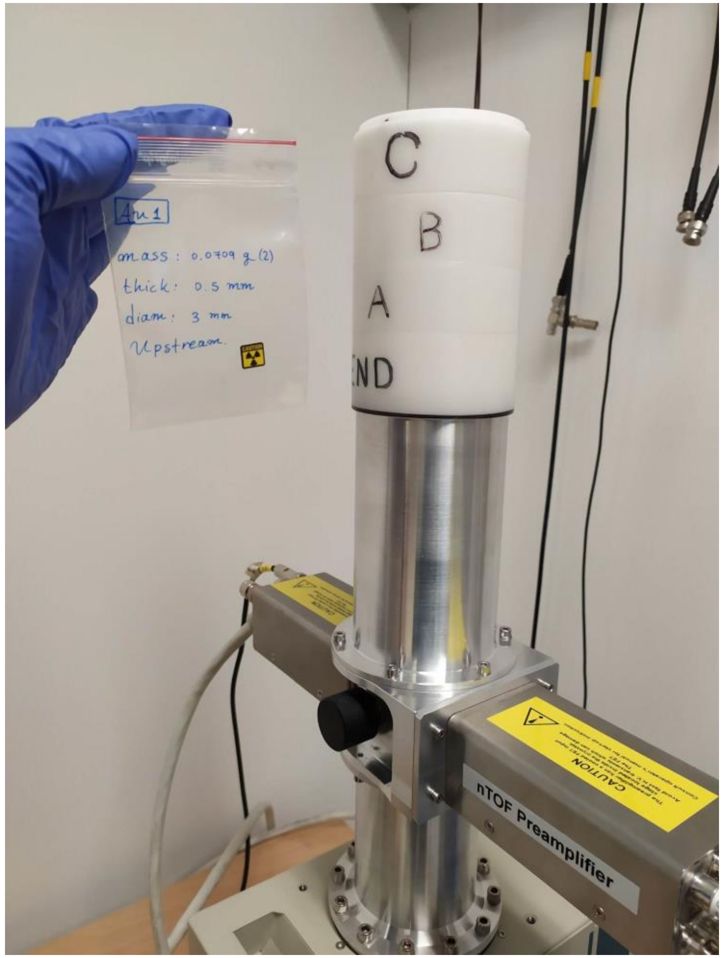


Data Analysis

- The induced radioactivity was measured via **γ-ray spectroscopy** after the end of the irradiation
- A HPGe detector of **30% relative efficiency** was used
- The γ-ray yield was calculated by integrating the photopeaks of interest (SPECTRW code)







Experimental Saturation Activity (S.A.) Values

$$\mathrm{SA_i} = \frac{\mathrm{N_\gamma}}{\mathrm{I_\gamma \cdot \varepsilon \cdot (1 - e^{-\lambda t_m}) \cdot e^{-\lambda t_w} \cdot t_{irr} \cdot f_c \cdot f_s \cdot f_\Omega}}$$

N_γ : γ-ray yield
I_γ : γ-ray Intensity
ε : HPGe detector efficiency
t_{irr}: irradiation time
t_w : waiting time
t_m : measurement time
f_c : correction factor for the de-excitation of nuclei during the irradiation
f_s : γ-ray self absorption correction factor
f_Ω : solid angle correction factor

Correction Factors
Shielding & Self shielding
Activity correction for threshold reactions

Target	Reaction	E_γ [MeV]	S.A. [Bq/TN]	δS.A. [Bq/TN]
Au1	(n,g)	0.412	2.99E-16	1.43E-17
	(n,2n)	0.356	3.59E-18	1.81E-19
Au2	(n,g)	0.412	2.74E-16	1.31E-17
Au3	(n,g)	0.412	2.78E-16	1.45E-17
Au4	(n,g)	0.412	5.04E-16	2.61E-17
Au5	(n,g)	0.412	4.67E-16	2.33E-17
Au6	(n,g)	0.412	7.18E-16	3.55E-17
Cd-114	(n,g)	0.528	1.43E-17	6.73E-19
Sc-45	(n,g)	1.121	4.42E-17	2.33E-18
W-186	(n,g)	0.686	1.85E-16	8.45E-18
Ni-58	(n,p)	0.812	4.03E-18	1.95E-19
Co-59	(n,2n)	0.811	1.89E-18	9.32E-20
	(n,g)	1.173	7.21E-17	3.55E-18
	(n,p)	1.099	2.71E-19	1.95E-20
Al-27	(n,a)	1.369	2.99E-19	1.50E-20

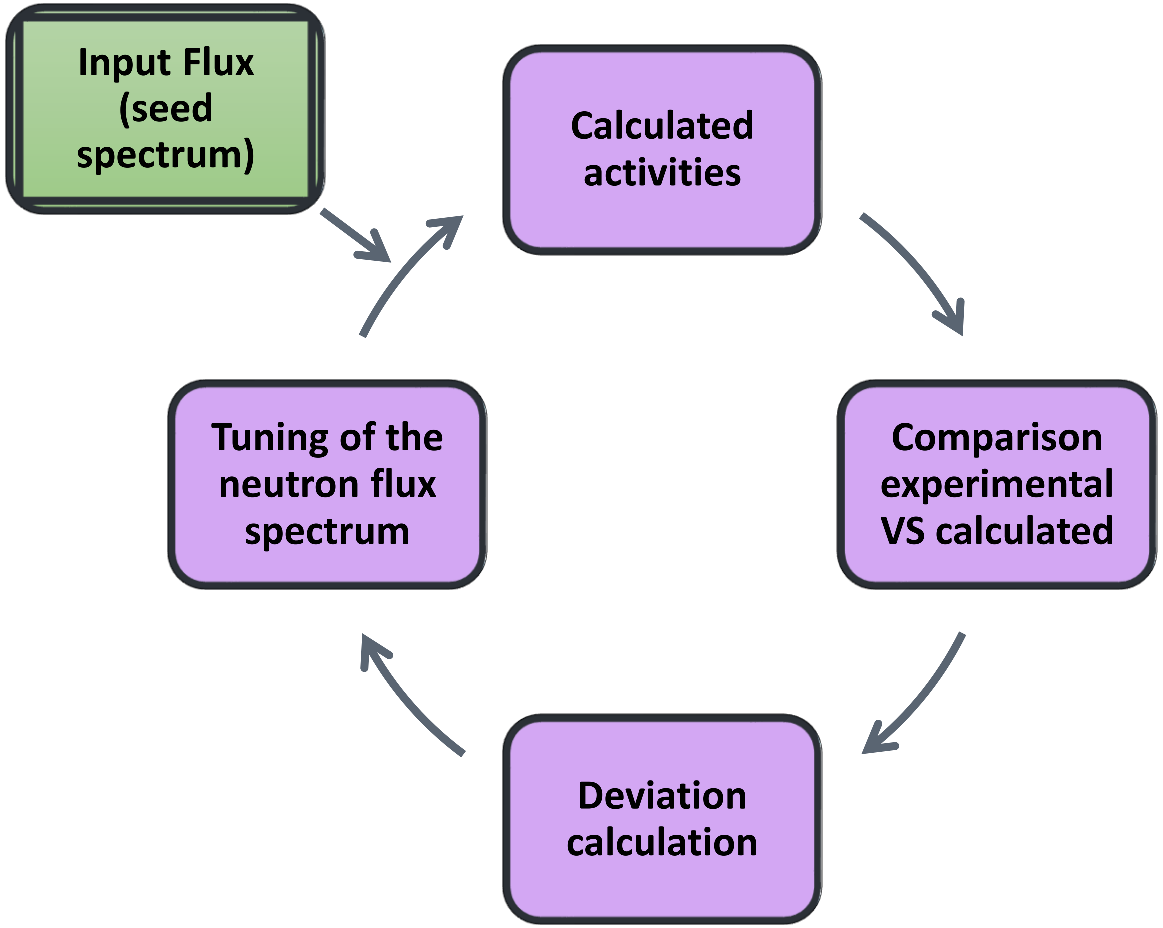
SAND II code (I)

SAND-II

- Experimental Saturation Activity values
- Input flux (seed spectrum) in the energy range of 10^{-10} – 18 MeV in 200 energy points
- “smoothing” parameter N_s

CSTAPE

- Cross-section values obtained from the IRDFF and ENDF/B-VIII.0 libraries
- Calculates average cross section values ($\overline{\sigma}_{i,j}$) for each energy bin (E_j,E_{j+1}) in the range between 10^{-10} – 18 MeV



SAND II code (II)

SAND II Recursive formulas

- For each iteration [k] the individual activities $A_{i,j}^{[k]}$ are calculated as well as the total activity $A_i^{[k]}$ for all the available reactions (i):

$$A_{i,j}^{[k]} = \Phi_j^{[k]}(E,t) \cdot \overline{\sigma}_{i,j} \cdot \left(E_{j+1} - E_j\right)$$

$$A_i^{[k]} = \sum_{j=1}^{620} \Phi_j^{[k]}(E,t) \cdot \overline{\sigma}_{i,j} \cdot \left(E_{j+1} - E_j\right)$$

- The experimental activities (A_i) are compared with the calculated ones $A_i^{[k]}$:

$$R_i^{[k]} \approx {A_i}\Big/{A_i^{[k]}}$$

- A weight is calculated as a function of the smoothing parameter N_S for the calculated activities $A_{i,j}^{[k]}$:

$$w_{i,j}^{[k]} = \frac{\sum_{Ns} A_{i,j}^{[k]}}{(l_2 - l_1 + 1) \cdot A_i^{[k]}}$$

- The neutron flux for the (j) bin is calculated for the [k+1] iteration: $\Phi_j^{[k+1]} = \Phi_j^{[k]} \, e^{C_j^{[k]}}$, $C_j^{[k]} = \frac{\sum_{i=1}^{n} W_{i,j}^{[k]} \cdot \ln(R_i^{[k]})}{\sum_{i=1}^{n} W_{i,j}^{[k]}}$

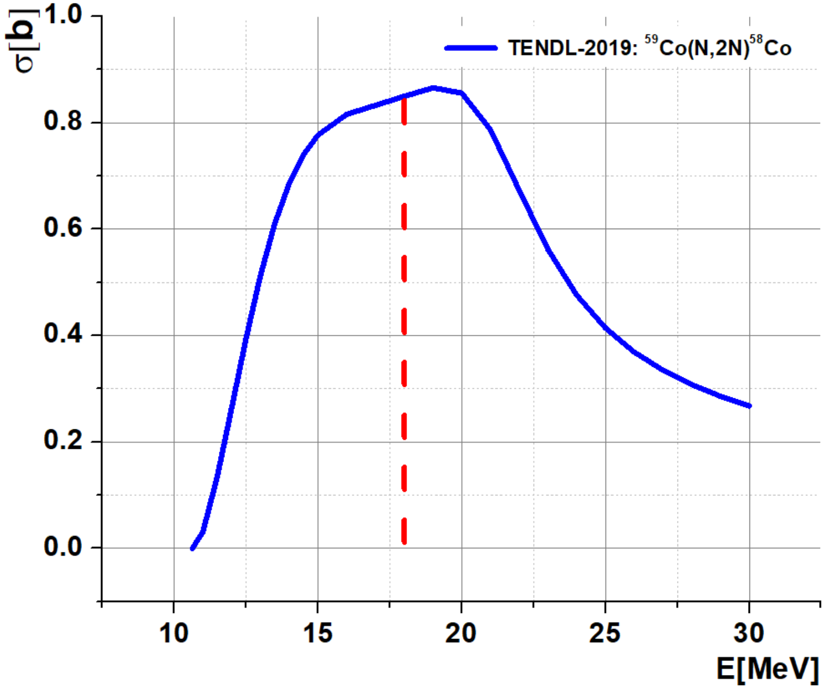
Correction Factors in the Input Data

Problem

The experimentally calculated S.A. values are due to a neutron spectrum with a **wider energy range**, than the one calculated from the SAND-II deconvolution code:

- SAND-II → 10^{-10} – **18** MeV
- NEAR Station → 10^{-10} – 450 MeV

> Possibility for **overestimation of the flux** in the energy range **1 – 18 MeV**



Solution

The **simulated FLUKA flux** was used, along with the cross-section values from the **IRDFF library** for each studied reaction (i):

$E_{threshold}$ - E_{max}

$$A_1 = \sum \sigma_i \cdot \Phi_i \cdot (E_{i+1} - E_i)$$

$E_{threshold}$ - 18 MeV

$$A_2 = \sum \sigma_i \cdot \Phi_i \cdot (E_{i+1} - E_i)$$

$$\frac{A_2}{A_1} \cdot A_{measured} = A_{SAND}\ (\text{input})$$

Reaction	Correction (%)
$^{59}Co(n,2n)^{58}Co$	38.6%
$^{197}Au(n,2n)^{196}Au$	65.6%
$^{59}Co(n,p)^{59}Fe$	67.8%
$^{58}Ni(n,p)^{58}Co$	95.9%
$^{27}Al(n,a)^{24}Na$	87.3%

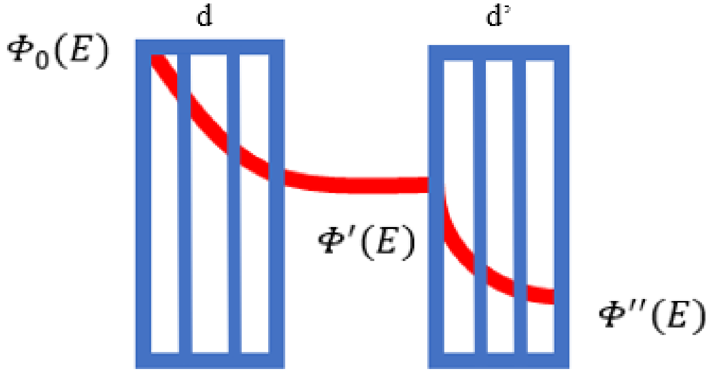
Shielding & Self Shielding Effects

Shielding

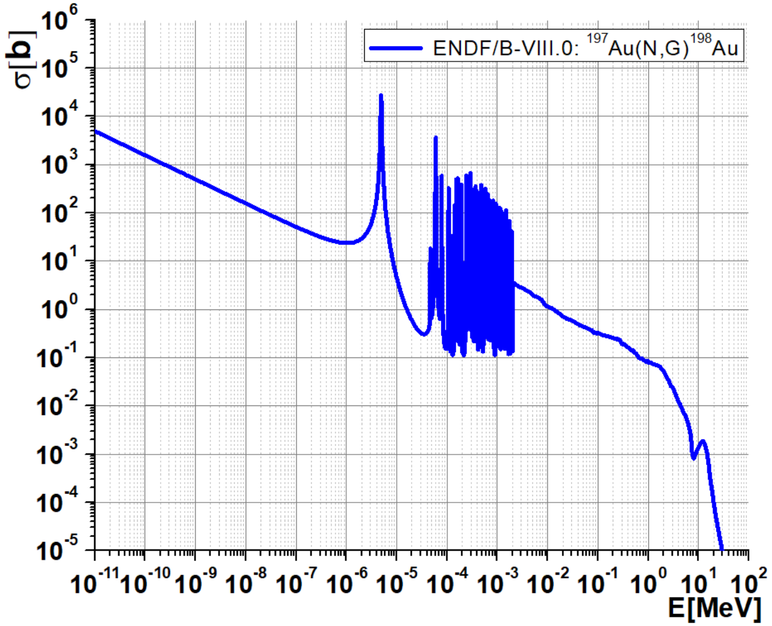
Targets (upstream) absorb enough neutrons due to a large cross section of certain reactions and thus targets (downstream) are irradiated by a different neutron flux.

Self-Shielding

A phenomenon observed in thick targets and a large cross section in a specific reaction. Each elementary surface dS is activated by a different flux

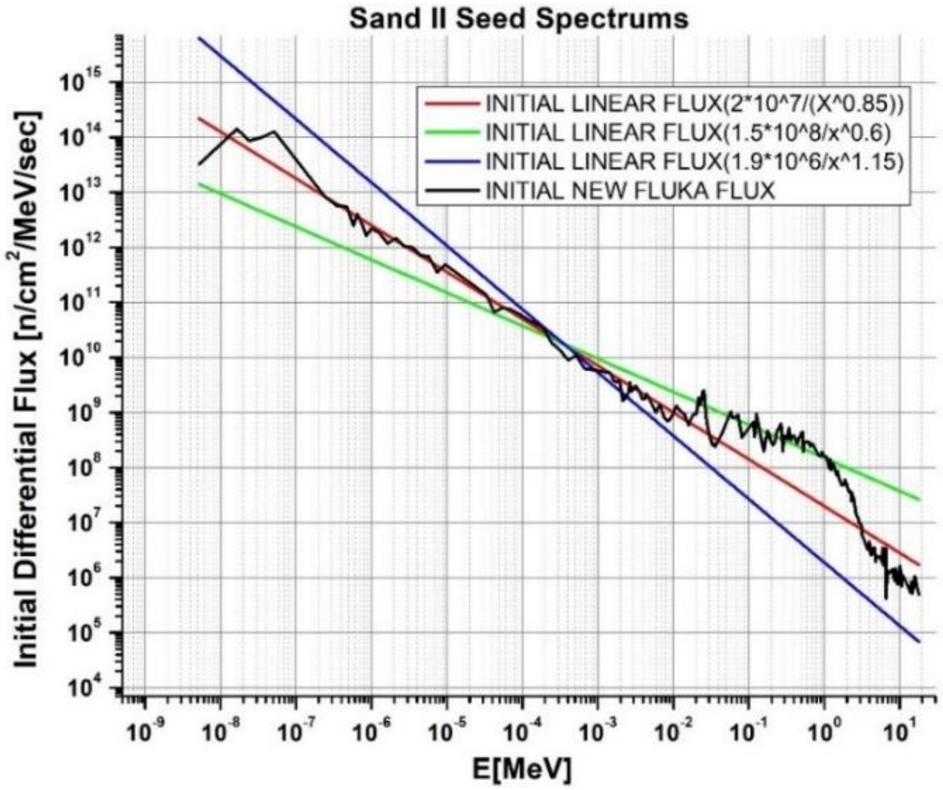


The activities used correspond to a different neutron flux. This phenomenon is observed mainly in absorption reactions where we have large cross section values. Corrections were obtained via MCNP5



SAND-II Input Data

Reaction	S.A. (Bq/TN)
$^{59}Co(n,2n)^{58}Co$	7.307360E-19
$^{197}Au(n,2n)^{196}Au$ (Au1)	3.034668E-18
$^{59}Co(n,p)^{59}Fe$	1.835672E-19
$^{58}Ni(n,p)^{58}Co$	3.882956E-18
$^{27}Al(n,a)^{24}Na$	2.609563E-19
$^{197}Au(n,\gamma)^{198}Au$ (Au6)	7.189125E-16
$^{197}Au(n,\gamma)^{198}Au$ (Au1)	2.994515E-16
$^{197}Au(n,\gamma)^{198}Au$ (Au5)	4.678819E-16
$^{114}Cd(n,\gamma)^{115}Cd$	1.432550E-17
$^{59}Co(n,\gamma)^{60}Co$	7.217970E-17
$^{45}Sc(n,\gamma)^{46}Sc$	4.425686E-17
$^{186}W(n,\gamma)^{187}W$	1.852110E-16



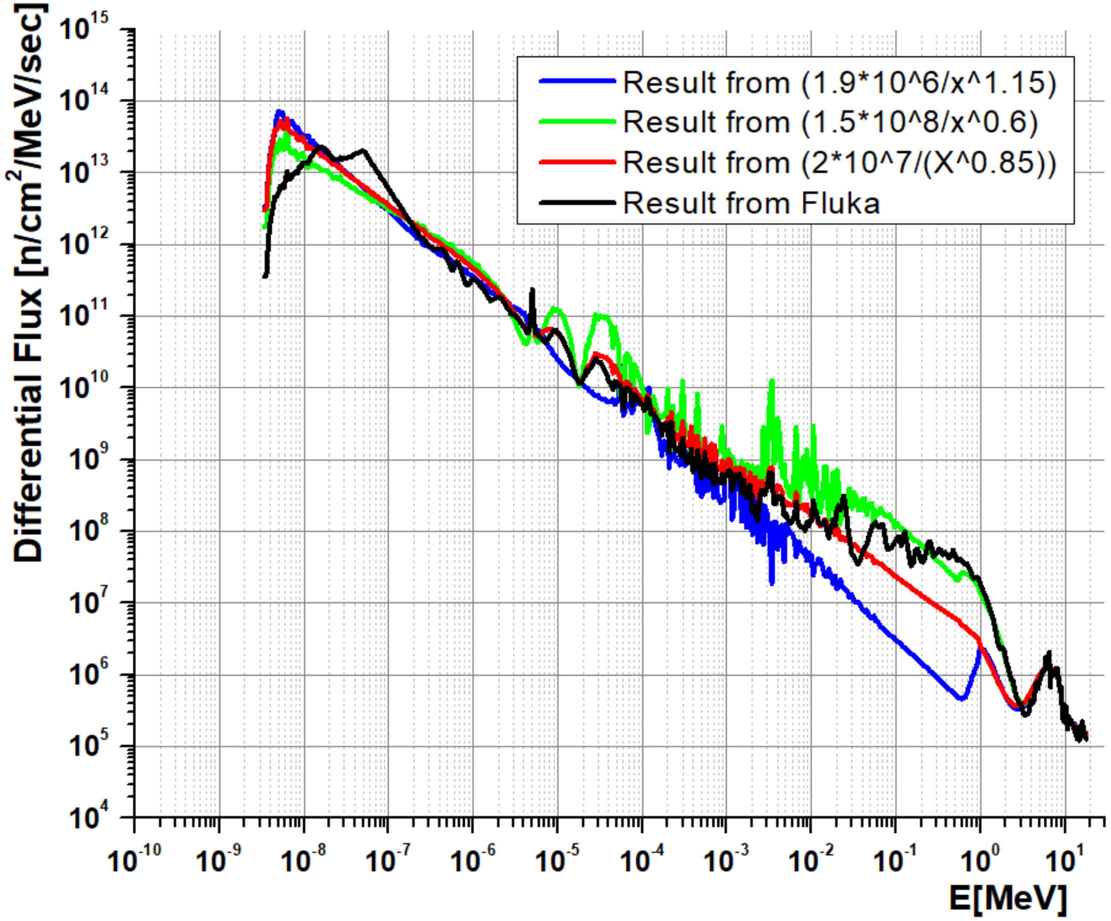
Problem: Only 12 reactions were used for the determination of the neutron flux in 620 bins

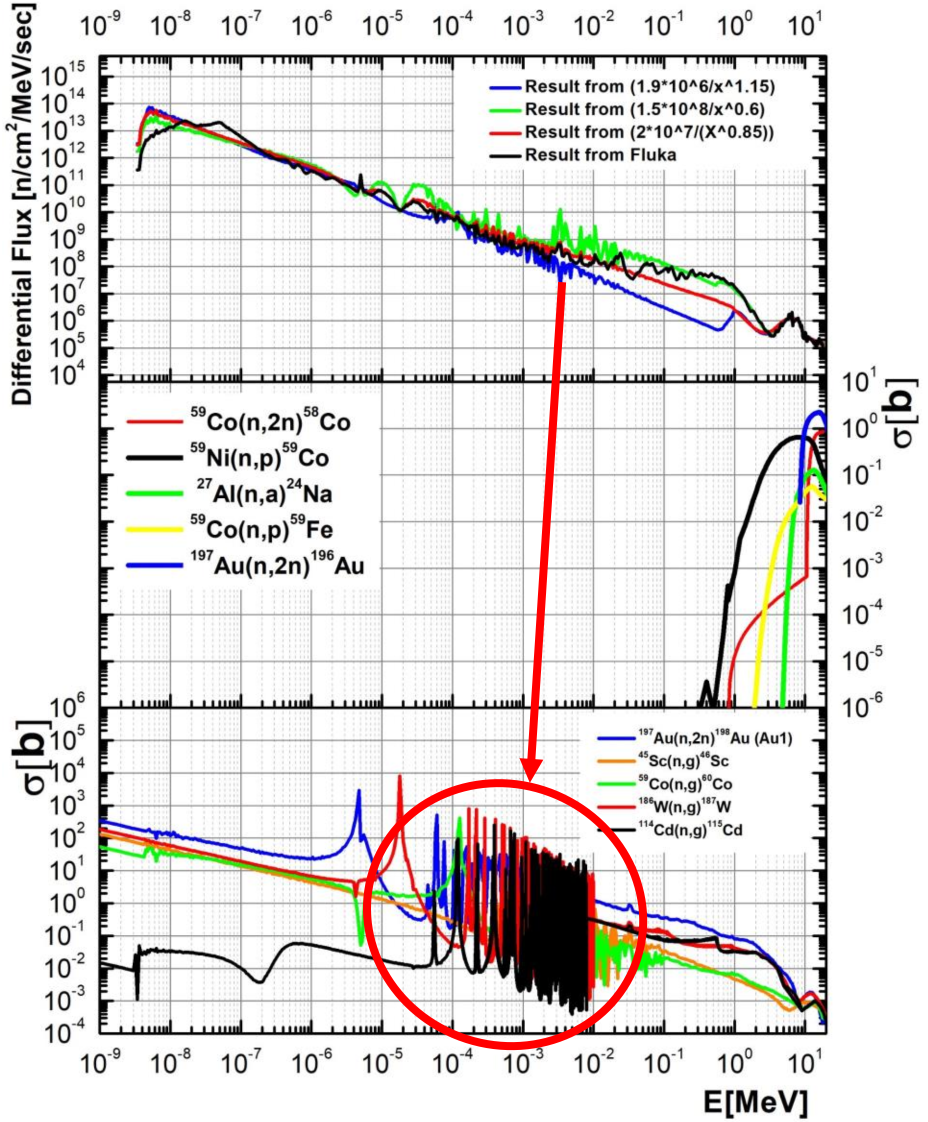
Solution

1) Four different input seed fluxes were tested
2) Reduction of the degrees of freedom using the N_s parameter

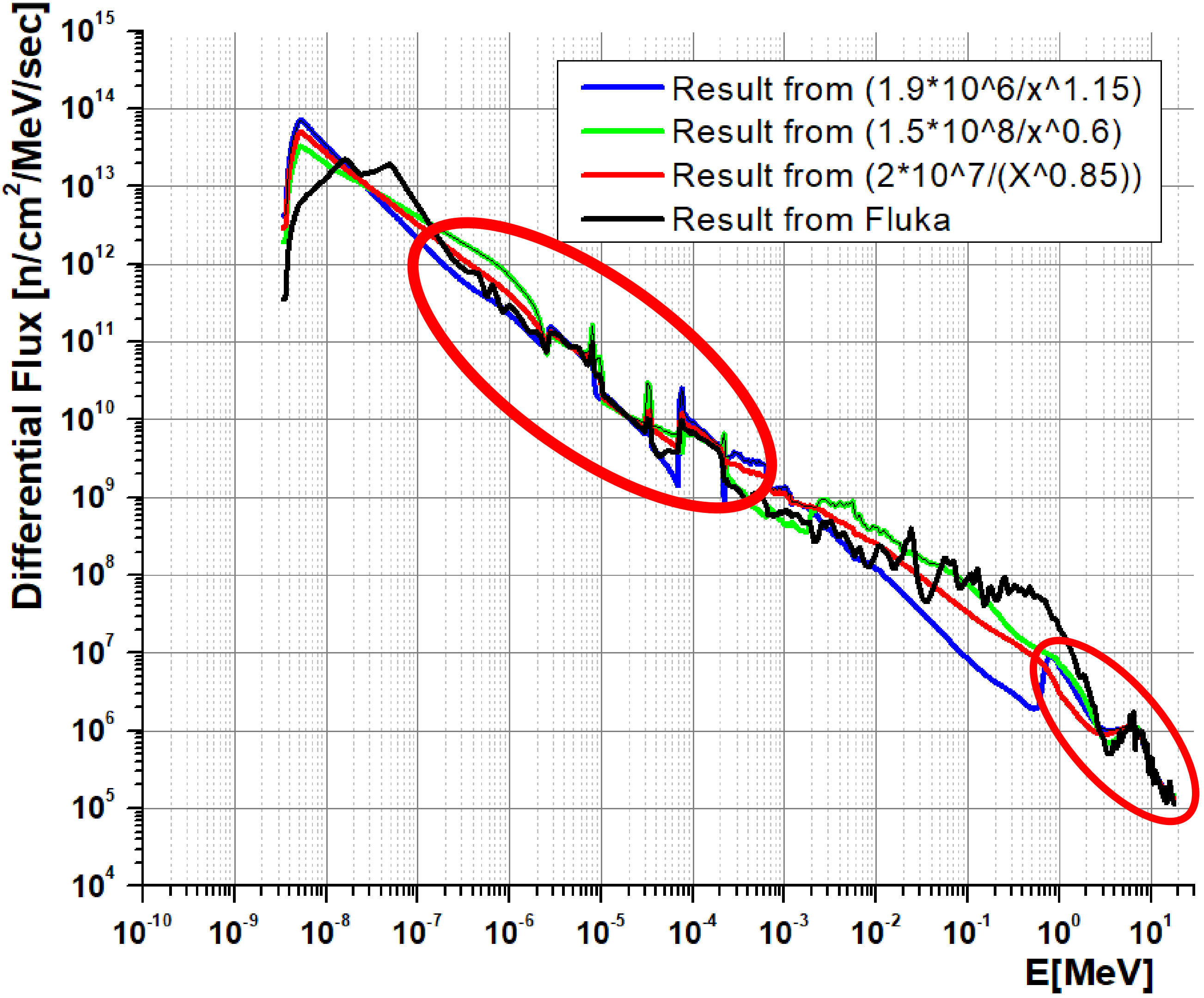
Parameter N_s=1

$$w_{i,j}^{[k]} = \frac{A_{i,j}^{[k]}}{A_i^{[k]}} = \frac{\Phi_j^{[k]}(E,t)\cdot\bar{\sigma}_{i,j}\cdot(E_{j+1}-E_j)}{A_i^{[k]}}$$





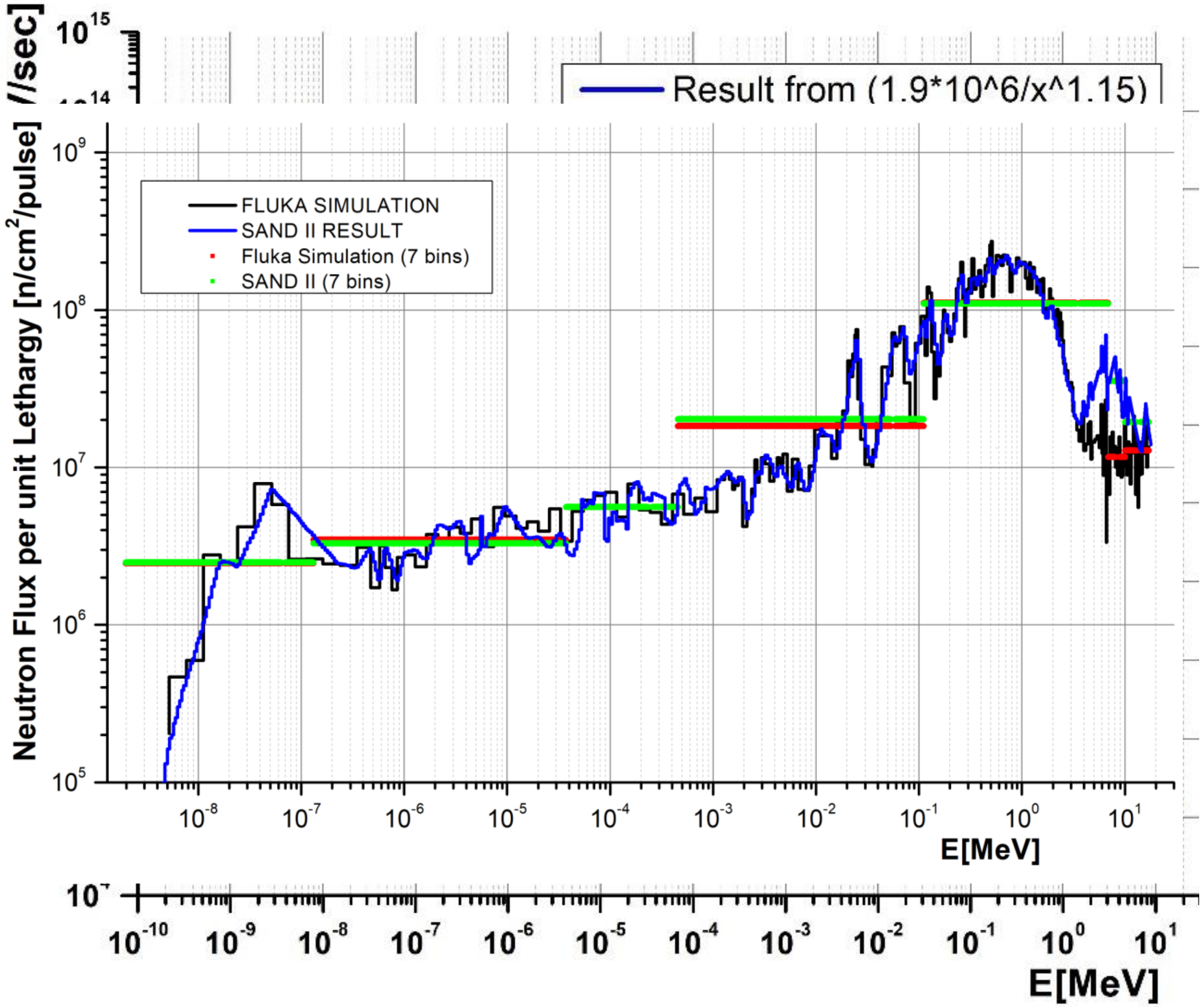
Parameter N_S=20

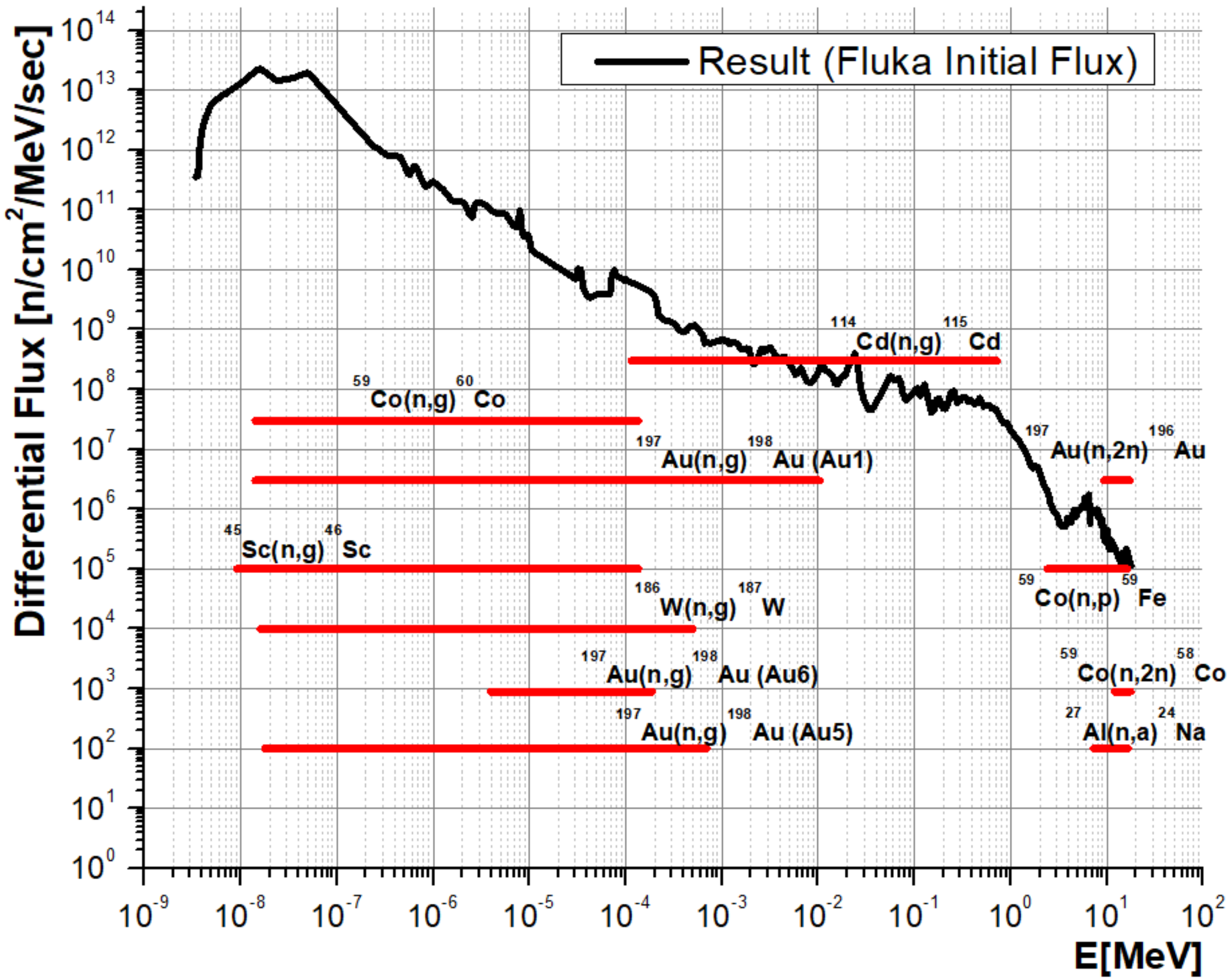


Convergence between the different seed fluxes in the energy ranges 10^{-7} – 2 10^{-4} and 2 – 18 MeV, ranges with **many available reactions** providing valuable information

Target	Reaction	S.A. exp (Bq/TN)	S.A. calc (Bq/TN)	std (%)
Au-1	(n,g)	2.995×10^{-16}	3.152×10^{-16}	-4.99
Au-5	(n,g)	4.679×10^{-16}	5.082×10^{-16}	-7.93
Au-6	(n,g)	7.189×10^{-16}	6.643×10^{-16}	8.22
Au-1	(n,2n)	2.958×10^{-18}	3.125×10^{-18}	-5.36
Sc	(n,g)	4.426×10^{-17}	4.204×10^{-17}	5.27
Co	(n,g)	7.218×10^{-17}	7.328×10^{-17}	1.50
Co	(n,2n)	7.307×10^{-19}	7.146×10^{-19}	2.26
Co	(n,p)	1.836×10^{-19}	1.699×10^{-19}	-1.50
W	(n,g)	1.836×10^{-16}	1.855×10^{-16}	-0.14
Ni	(n,p)	3.871×10^{-18}	4.029×10^{-18}	-3.93
Al	(n,a)	2.610×10^{-19}	2.641×10^{-19}	-1.20
Cd114	(n,g)	1.433×10^{-17}	1.414×10^{-17}	1.28

Neutron Flux Result





Summary/Perspectives

- The **Multiple Foil Activation Technique** was used for the experimental determination of the **saturation activity** values of 13 reactions (**MAM1**)
- Correction factors were employed (e.g. to take into account shielding effects)
- The results were used by the SAND-II deconvolution code
- The neutron flux spectrum was calculated for the NEAR station and compared with the one from the FLUKA simulations

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- **Comparison** with the respective results from other n_TOF groups that employed different deconvolution codes (**MAM2, ANTILOPE**)
- A **final publication** by the n_TOF collaboration taking into account all the available results

Thank you for your attention!