Development of a compact multi-elements activation neutron spectrometer for BNCT

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on behalf of Enter_BNCT collaboration

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CONTENTS

INTRODUCTION

The project:

This work is conducted in the framework of the INFN Project ENTER_BNCT (2020-2022) by the Turin and the Frascati National Laboratories groups.
WP3: Diagnosis of the beam for quality assurance and dosimetric evaluations.

↓

- NCT-Wide Energy Spectrometer (NCT-WES) a new type of radiation-resistant, single moderator directional spectrometer
- COmpact NEutron Sensors (CONES) for in phantom field and dosimetric evaluations (with spectrometric capability)
- Ionization chamber with low sensitivity to neutrons for gamma dose measurements in BNCT clinical beams (in collaboration with CNAE)

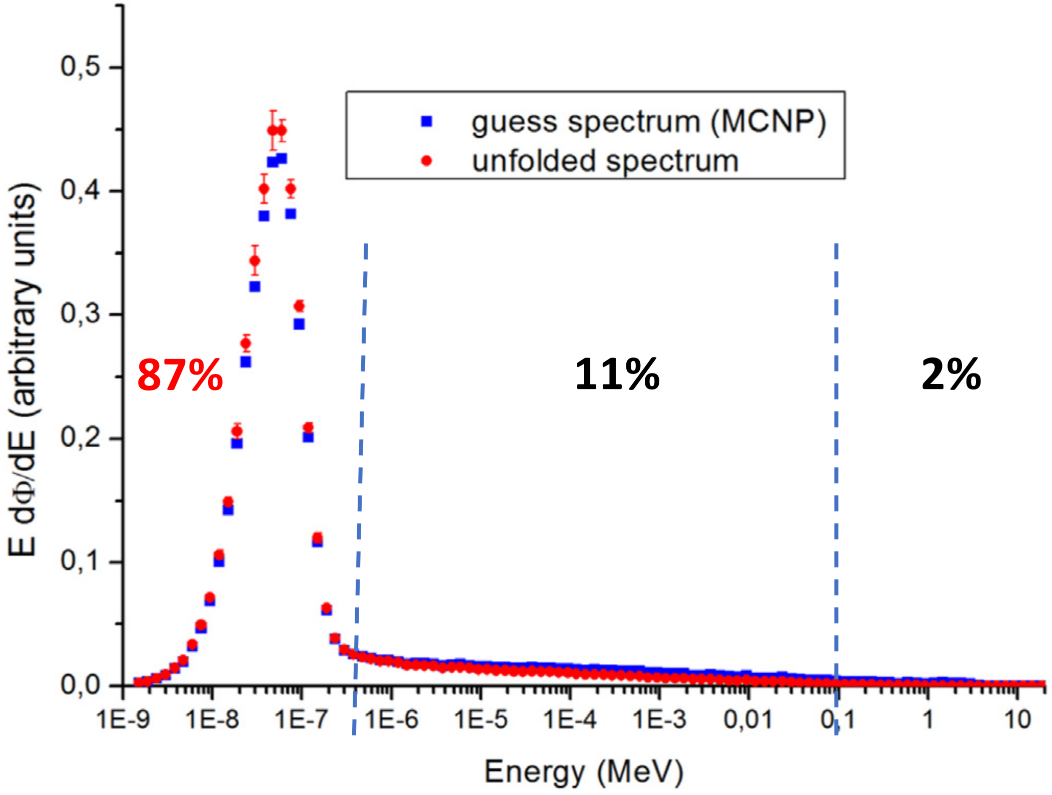
The Neutron facilities to test the detectors:

The TRIGA MARK II nuclear reactor in Pavia.

The e_LiBANS accelerator-based neutron source in Turin.

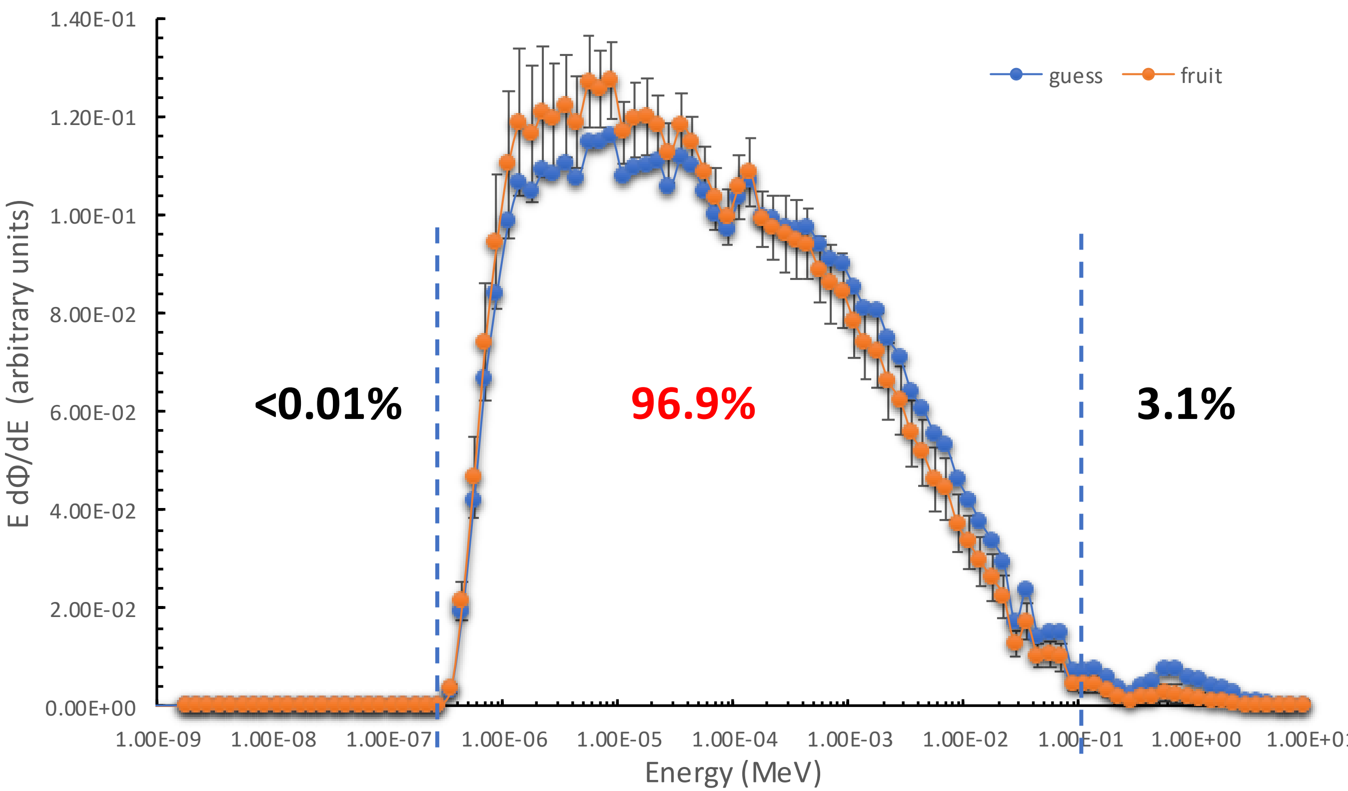
The accelerator-based neutron source in Turin

Thermal-mode



Thermal neutron fluence rate @ 400MU/min:
$\dot{\Phi}_{th} = (1.46 \pm 0.05)10^6\ cm^{-2}\ s^{-1}$
Irradiation cavity: 30 x 30 x 40 cm³

Epithermal-mode

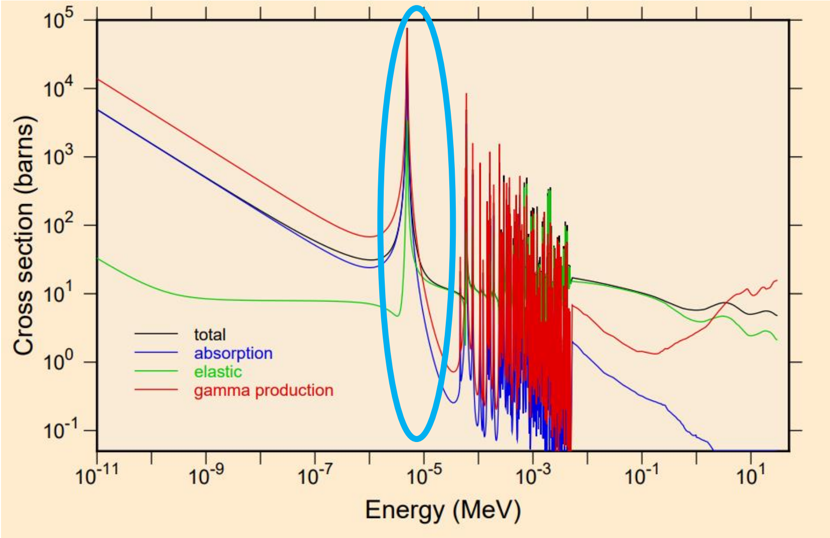


Epithermal neutron fluence rate @ 400MU/min:
$\dot{\Phi}_{epi} = (2.46 \pm 0.30)10^5\ cm^{-2}\ s^{-1}$
Irradiation cavity: 30 x 30 x 20 cm³

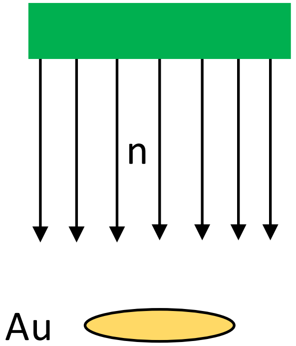
The two spectra were unfolded using the FRUIT algorithm [1]

BNCT measurements using activation

Some elements present an n-γ absorption cross section with resonances in the epithermal range (0.4 eV – 100 keV).
Au shows a high resonance for neutron with energy around 5.65 eV



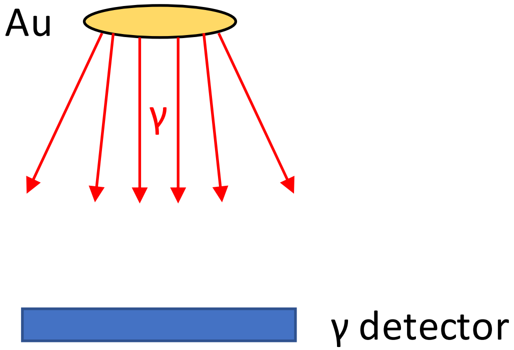
Phase 1:



Foil irradiation with neutrons.

+

Phase 2:



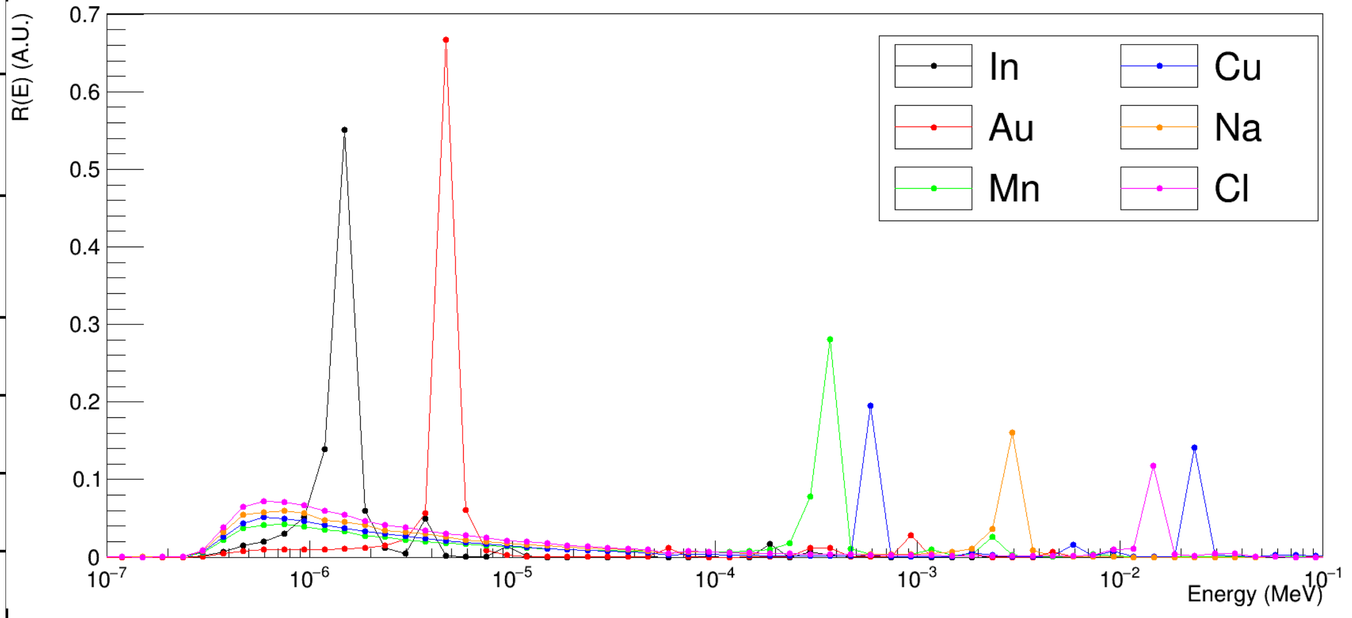
Gamma reading via a HPGe detectors

- In BNCT foils of different elements are used to make beam quality assurance and to define the normalization coefficients of MC simulations.
- Activation foils are also used for spectrometric evaluation, but many irradiation and reading phases are necessary
- The project goal: develop a compact spectrometer with isotropic response (**NCT**- **A**ctivation **C**ompact **S**pectrometer) to provide an increased number of measured points in the epithermal range in a single exposure and in a single gamma reading measurement.

Sensitivity in the epithermal range (0.5 eV – 100 keV)

Elements selection critheria:

PARAMETER	SELECTION
Natural state	Solid
Neutron energy of main resonance peak	1 eV – 100 keV (epithermal)
Half life time of the activated nucleus	3 min $< t_{1/2} <$ 3 d
Decay chain	Not more than 2 cascade decays
Energy of the emitted γ	100 keV $< E_\gamma <$ 3000 keV
B.R. for the γ emission	B.R. > 1%
Toxicity /dangeourous aspects	No



Response curves for some of the selected elements.

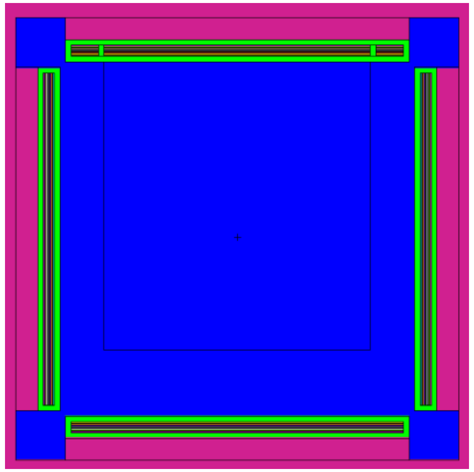
List of **8 elements** suitable for the NCT-ACS:
In, Au, Mn, Cu, Cl, Na, V, Ti

Choice of the geometry

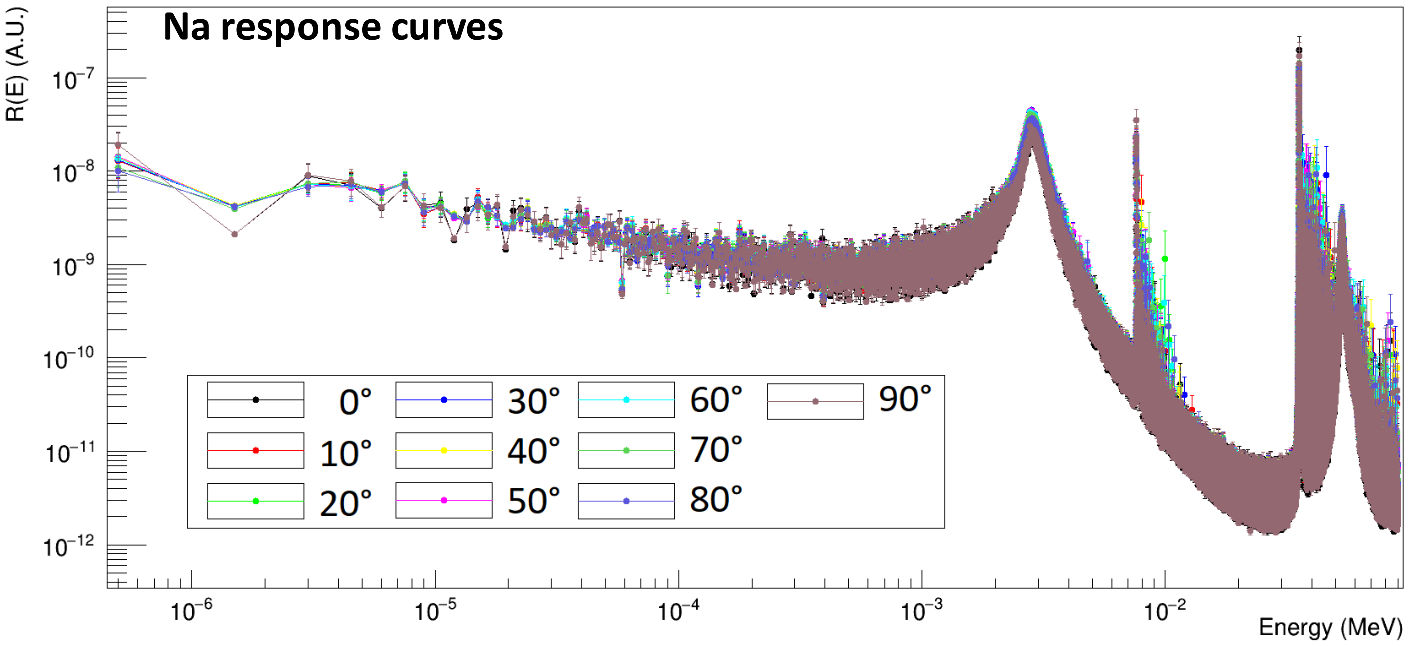
Many **geometries** have been simulated with **MCNP6.**

The response matrix of each single geometry has been evaluated.

- A single 2-D geometry formed by a sandwich of 8 foils.
- A cubic geometry, with a sandwich of 8 foils for each face.
- An octagonal geometry, with a sandwich for each vertex
- A double-pyramidal geometry, with a sandwich for each vertex.



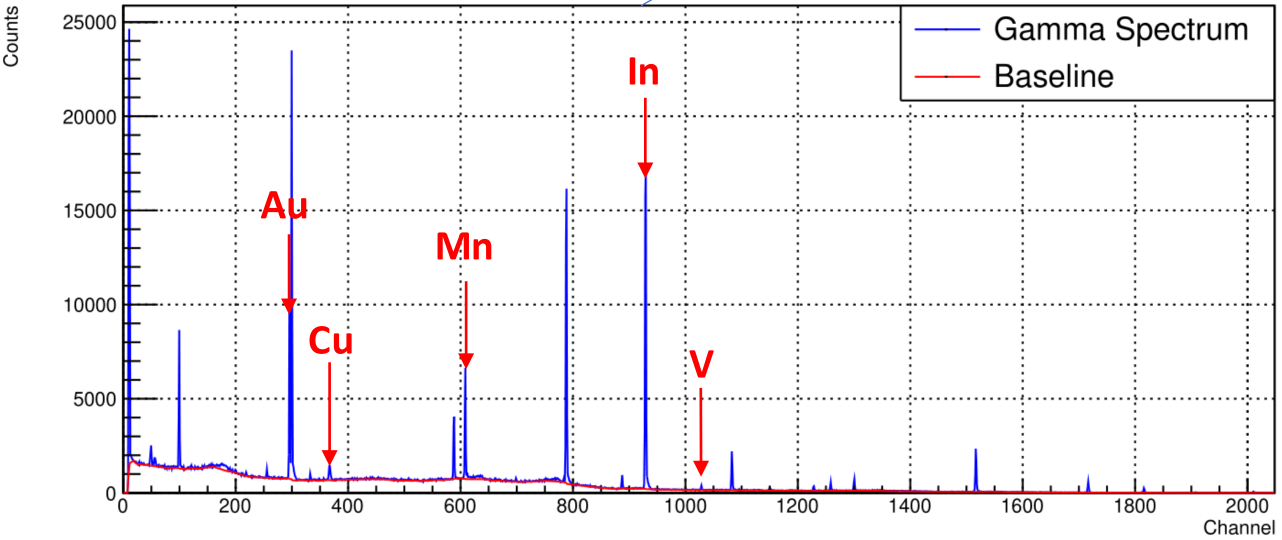
Section of the chosen cubic geometry.
***Green = Cadmium cover**, **Blue = Al structure**,*
***Purple = Air**.*
The overall size is less than 2 cm, suitable also for in phantom measurements



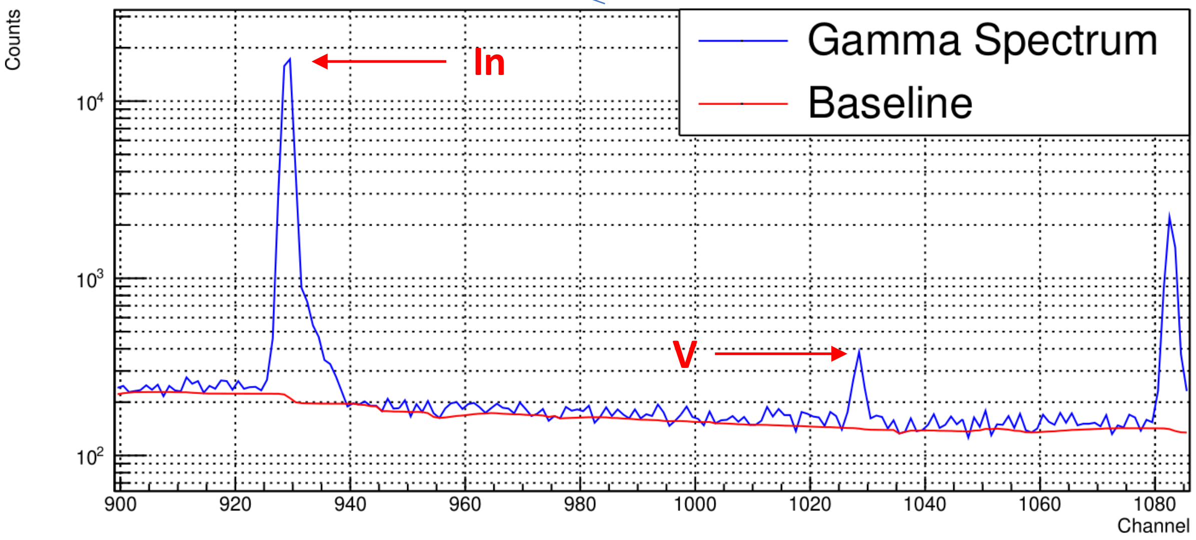
Response curves varying the neutron incoming angle between 0° and 90°.
*The **anisotropies** are **within 3%.***

NCT-ACS work flow

A **single neutron irradiation** generates foils activation. → A **single gamma reading** produces a complex γ spectrum. → A fine analysis is used to calculate the activity extracting the peaks area. → Unfolding method will be used to rencostruct the neutron energy spectrum.



*Overall γ spectrum obtained exposing 5 foils in the **thermal cavity.***



*Zoom over the In and V reference peaks region. Baseline extimation using **SNIP algorithm** [2].*

Integrated fluence: $4.6 \cdot 10^{9} \mathrm{cm}^{-2}$
Irradiation time: 38 min
Waiting time: 10 min

Thermal field measurements

Useful to:

1. Exeperimentally evaluate the impact of the foils geometry;
2. Validate the MC simulations for the corrective factors calculation;
3. Validate the procedure of the gamma spectrum analysis;
4. Evaluate the data from the multiple foil irradiation.

Single foil irradiation (1-2-3):

- Two couple of foils were irradiated at the same time.
- One couple was bare
- One couple was covered by a Cd shield

Multiple foil irradiation (4):

- A couple of basic set was irradiated at the same time.
- One set was bare
- One set was covered by a Cd shield

The Cd subtraction technique was used to derive the sub-Cd Westcott fluence rate [3]:

$$\dot{\Phi}_{th} = \frac{\left(A_{bare} - \frac{F_b}{F_a} A_{Cd}\right)}{\rho \sigma_0 g} F_c F_d = \frac{A_{th}}{\rho \sigma_0 g}$$

Corrective factors:

F_a = survived thermal compenent in Cd
F_b = absorbed epithermal component in Cd
F_c = self attenuation of neutron beam in the foil
F_d = self gamma absorption in the foil

Easy comparison with the measurement of a a calibrated 6LiF+Silicon detector (TNRD) [4].

Validation in Thermal field (both single foil or sandwich)

- A pair of foil/sandwiches, bare and under Cd, are irradiated
- The Cd subtraction technique was used to derive the sub-Cd Westcott thermal fluence rate
- The results were compared with the TNRD reference value

Single foil irradiation

Foil	Experimental $\dot{\Phi}_{th}$ $(\cdot 10^6\ \mathrm{cm^{-2}s^{-1}})$	Reference $\dot{\Phi}_{th}$ $(\cdot 10^6\ \mathrm{cm^{-2}s^{-1}})$
In	1.40 ± 0.02	1.39 ± 0.03
Au	1.43 ± 0.03	1.45 ± 0.04
Mn	1.43 ± 0.03	1.47 ± 0.04
Cu	1.49 ± 0.04	1.44 ± 0.04
V	1.57 ± 0.06	1.48 ± 0.04

Sandwich foil irradiation:

<table>
<tr><th>Foil</th><th>Experimental $\dot{\Phi}_{th}$ $(\cdot 10^6\ \mathrm{cm^{-2}s^{-1}})$</th><th>Reference $\dot{\Phi}_{th}$ $(\cdot 10^6\ \mathrm{cm^{-2}s^{-1}})$</th></tr>
<tr><td>In</td><td>1.26 ± 0.02</td><td rowspan="5">1.36 ± 0.04</td></tr>
<tr><td>Au</td><td>1.33 ± 0.05</td></tr>
<tr><td>Mn</td><td>1.25 ± 0.03</td></tr>
<tr><td>Cu</td><td>1.41 ± 0.06</td></tr>
<tr><td>V</td><td>1.53 ± 0.08</td></tr>
</table>

- Good reproducibility with different elements.
- Good compatibility with the reference TNRD values

Validation in Epithermal field (sandwich)

- A sandwich under Cd was irradiated
- The saturation activities were measured
- The results were compared with expected value (folding)

Element	$E_{resonance}$ (eV)	Expected Saturation Activity (Bq/g)	Experimental Saturation Activity (Bq/g)
In	1.56	$(9.70 \pm 0.87) \cdot 10^4$	$(8.69 \pm 0.23) \cdot 10^4$
Au	5.65	$(2.91 \pm 0.32) \cdot 10^4$	$(3.70 \pm 0.12) \cdot 10^4$
Mn	468	$(4.56 \pm 0.37) \cdot 10^3$	$(4.53 \pm 0.13) \cdot 10^3$
Cu	766	$(0.75 \pm 0.10) \cdot 10^3$	$(0.71 \pm 0.04) \cdot 10^3$
V	7230	$(0.68 \pm 0.09) \cdot 10^3$	$(1.02 \pm 0.09) \cdot 10^3$

The expected values are obtained folding the response curves with the measured spectrum.

Conclusions

- A **compact neutron spectrometer**, based on activation, able to cover **8 order of magnitude** in energy is under study in Turin;
- It is composed by many ‘’basic-set’’ of 8 elements ditributed on a cubic geometry to guarantee **isotropic response**;
- Its compact size will allow to perform **single exposure measurements** both in **air** or in **phantom**;
- The spectormeter allow to perform **fast spectrum measurements**;
- A SNIP was used to evaluate the peks counts and extract the different elements activation;
- The measurements in the thermal cavity shown a **good agreement** between the foil and the **TNRD** measurements both for a single foil irradiation and a multiple foil irradiation;
- The measurements in the epitheraml cavity shown a **good agreement** between experimental data and **expected values** for the multiple foil irradiation.;

Upcoming steps:

1. Develop of an unfolding algorithm to reconstruct the neutron energy spectrum (now under study).
2. Construct the cubic geometry (now in elaboration).
3. Irradiation of NCT ACS at the Turin facility
4. Irradiation of NCT ACS at a higher flux facility

References

[1] R. Bedogni, C. Domingo, A. Esposito, F. Fernandez. FRUIT: An operational tool for multisphere neutron spectrometry in workplaces. Nucl. Instrum. Methods A 580 1301, 2007.

[2] Morhác, Miroslav & Matoušek, Vladislav. (2008). Peak Clipping Algorithms for Background Estimation in Spectroscopic Data. Applied spectroscopy. 62. 91-106. 10.1366/000370208783412762.

[3] D. Thomas and P. Kolkowski. Thermal fluence and dose equivalent standards at NPL. DQL-RN 008, 2005.

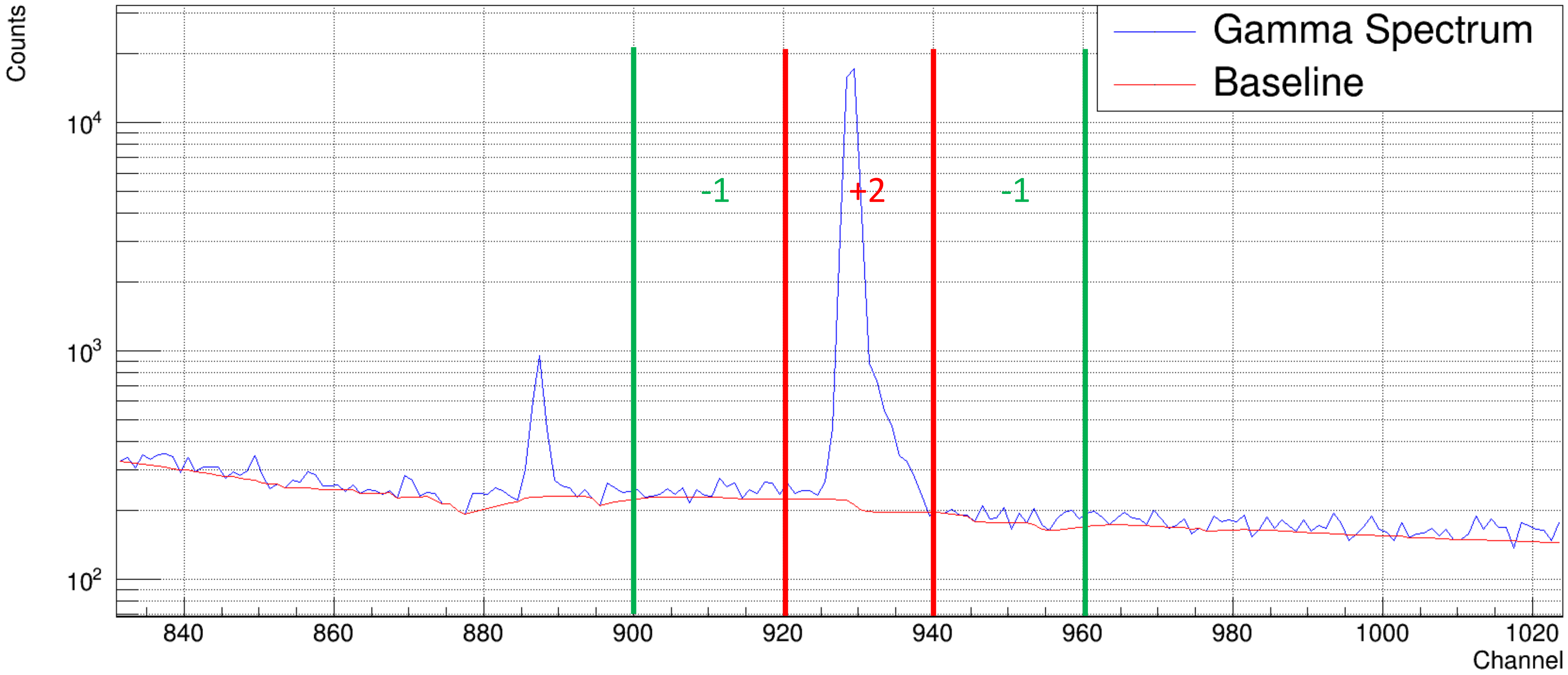
[4] R. Bedogni, D. Bortot, A. Pola, M. V. Introini, A. Gentile, A. Esposito, J. M. Gomez-Ros, M. Palomba, A. Grossi. A new active thermal neutron detector. Radiation Protection Dosimetry 161 1-4 241-244, 2014.

BACKUP

Some hints about SNIP algorithm

It subdivides the peak region into 3 part (lower baseline, higher baseline and peak region) with different weights, then it operates a weighted sum to determine the baseline under the peaks region.
Many parameters can be modified:

- **Width of the clipping filter**: normally 4-5 times the FWHM of the peaks;
- **Order of the clipping filter**: to properly estimate the physics shape of the spectrum (compton scattering, backscatter…);
- **Direction of the clipping window**: from 1 to W or vice-versa;
- **Gaussian smoothing**: For noisy or low-statistics data.



FWHM=4
W=20

In red: the weight of the peak region.
In green: the weight of the baselines region.

SOURCES OF UNCERTAINTIES:

Systematic:

1. SNIP algorithm
2. Detector geometry
3. Measurments conditions
4. Response curves
5. Unfolding algorithm

Solution:

1. Optimization of the algorithm parameters.
2. Calculating corrective factors for the cubic geometry.
3. Non-contact measurments allow to low the dead time and to assume the point-source approximation.
4. Very precise MC simulations with low uncertainties.
5. Choice of the correct unfolding procedure and optimization of the algoritmh

Goal/expectation: below 5%

Statiscal:

Poissonian uncertanty due to the total area below the activation peaks in the γ spectrum.

Solution:

Higher fluence or longer acquisition time can reduce this uncertainty. The higher fluence means higher activity and counts under the peaks.
Not for alla the elements is possible to extend the acquisition time (e.g. V or Ti).

Goal/expectation: below 2%