

## Fast neutron spectrometry using thick threshold detectors

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### Abstract

This paper discusses the use of thick threshold activation detectors for the characterization of low intensity neutron fields. This technique has been applied to the determination of the spectral emission of a low activity (37 GBq) Am-Be source. The reaction rates induced by the neutrons emitted by this source in different thick metallic targets (Al, Si, Fe, In) have been measured in the following reactions:  $^{27}\text{Al}(n, p)^{27}\text{Mg}$ ,  $^{27}\text{Al}(n, \alpha)^{24}\text{Na}$ ,  $^{28}\text{Si}(n, p)^{28}\text{Al}$ ,  $^{56}\text{Fe}(n, p)^{56}\text{Mn}$ ,  $^{115}\text{In}(n, n')^{115\text{m}}\text{In}$  and  $^{115}\text{In}(n, \gamma)^{116\text{m}}\text{In}$ . Each measured reaction rate corresponding to a threshold detector response depends on the spectral emission of the source via a correcting factor. This factor, which takes into account the source detector geometry, the neutron attenuation and diffusion by the detectors, has been determined by Monte Carlo simulation using MCNP5 code. The spectral emission of the neutron source has been generated from the response matrix of the threshold detectors by using different neutron spectrum unfolding methods (Stayn<sup>1</sup>, Gravel and Maxed). A fairly good agreement with the assumed ISO spectrum has been achieved.

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## 1. Introduction

For environmental and personal safety, it is necessary to have adequate techniques to monitor environmental radioactivity. Neutrons are omnipresent in our environment, naturally or artificially, and are usually more dangerous for our safety than other radiation types. So, it is imperative to give great importance to the monitoring of environmental neutron radiation.

Since the biological effects of neutrons strongly depend on the neutron energy [1] measurements of environmental neutron energy spectra must be performed with great precision. In this work, we discuss the use of thick threshold activation foils to characterize low intensity neutron fields and by extension to measure environmental neutron energy spectra [2,3].

The threshold detectors are sensitive only to neutrons above threshold energies occurring in the region above 0.2 MeV and are thus classified as fast neutrons detectors.

The use of threshold detectors presents important advantages:

- they are robust, small and inexpensive; so, the detectors can be placed in difficult and hazardous environments.
- no electronic device is required at exposure.
- they present a good discrimination against gamma radiation.

However, their sensitivity is usually rather low because of the small size of the detectors commonly used. Fortunately, the sensitivity can be increased by increasing the thickness of the foils. The set of threshold detectors used in the present work, aimed for the characterization of lower fluxes, are, thus, thicker. They present different geometric configurations and their responses vary with neutron energy.

The neutron field characterization can be deduced after the application of the following process: the gamma-ray yields induced in the thick foils, exposed to the neutron field irradiation, are measured and a mathematical “unfolding” treatment of the experimental results is used to deduce the neutron energy spectrum in the measurement site.

Since the use of thick foils complicates the geometric configuration “sample- $\gamma$  detector”, a Monte Carlo simulation code is used to consider the neutron attenuation and diffusion by the thick targets and to determine the thick target gamma measurement efficiencies.

In the present work, the aforementioned approach is tested; it has been applied for the determination of the spectral emission of a low activity (37 GBq) Am-Be neutron source.

## 2. Experimental set-up

The experimental set-up includes:

- a cylindrical Am-Be source of low activity ( $\sim 37$  GBq)
- thick solid targets of Al, Si, Fe and In
- a classical electronic chain for gamma-ray spectrometry including either a cylindrical NaI(Tl) scintillator or a high purity germanium (HPGe) detector

The foils that are activated separately by the neutron field are placed perpendicularly to the horizontal axis of the Am-Be source cylinder at a distance of 5 mm. Endoenergetic reactions of type  $X(n, b)Y$  are produced in the irradiated foils at neutron energies above the threshold energy,  $E_{\text{threshold}}$ . The decay of an activation product is followed by at least one  $\gamma$ -ray emission. After an appropriate neutron time exposure, related to the half-life  $T_{1/2}$  of the activation product, the activated targets are transported from the activation site to the gamma-ray detector.

A cylindrical NaI(Tl) scintillator is used to measure the low radioactivity induced in the Al, Si and Fe targets. Activated detectors were positioned on the scintillator axis at a distance of 5 mm of its entry window. Furthermore, a HPGe detector is used to measure the  $\gamma$ -rays induced in the activated indium foil placed at 4.5 cm in front of the detector.

It is difficult to perform an experimental calibration of the  $\gamma$ -detectors in the present case where thick samples and different geometric configurations are used. The solid angle subtended by the  $\gamma$ -detector and the self-absorption effects of the emitted photons within the sample are among the parameters that should be accounted for in a thick sample radioactivity measurement.

To overcome these difficulties, a possible solution would be a Monte Carlo simulation of NaI(Tl) scintillator and HPGe detector responses [4, 5] to the photons emitted by the activated foils.

Monte Carlo N-particle Code, version 2005 (MCNP5) [6] is a simulation code to solve transport problems of neutrons, photons, electrons and coupled particles.

In the present work, the MCNP5 code has been used to evaluate the NaI(Tl) scintillator and HPGe detector responses as a function of the incident photons energy for the different geometric configurations studied.

Table I: Experimental data for the induced reactions [8].

Reaction	$^{27}\text{Al}(n, p)^{27}\text{Mg}$	$^{27}\text{Al}(n, \alpha)^{24}\text{Na}$	$^{28}\text{Si}(n, p)^{28}\text{Al}$	$^{56}\text{Fe}(n, p)^{56}\text{Mn}$	$^{115}\text{In}(n, n')^{115}\text{In}^m$	$^{115}\text{In}(n, \gamma)^{116}\text{In}$
$\xi$	0.98	0.98	0.92	0.47	0.95	0.95
Geometric configuration	parallelepiped of 1 cm <sup>2</sup> area and 0.6 cm thickness	parallelepiped of 2 cm <sup>2</sup> area and 0.6 cm thickness	Cylinder of 2.4 cm diameter and 0.5 cm thickness	Cylinder of 3.18 cm diameter and 1.27 cm long	Cylinder of 1.03 cm diameter and 0.47 cm thickness	Cylinder of 1.03 cm diameter and 0.47 cm thickness
$T_{1/2}$ (half-life)	9.458 min	14.9574 h	2.2414 min	2.57878 h	4.486 h	54.29 min
$E_\gamma$ (keV)( $I_\gamma$ (%))	846.8(72)	1368.5(100)	1779(100)	846.8(98.9)	336.0(45.8)	1293.0(84.4)
$E_{\text{threshold}}$ (MeV)	2.0	5.1	5.01	3.2	0.336	0.0
$N_\gamma (\pm \Delta N_\gamma)$	1103 $\pm$ 130	5284 $\pm$ 218	865 $\pm$ 45	25049 $\pm$ 480	2762 $\pm$ 59	690 $\pm$ 29
$t_i$	30 min	17 h	7 min	3 h	3 h	3 h
$t_d$	1 min	5 min	18 s	5 min	3 min	3 min
$t_c$	30 min	2 h	7 min	2 h	2 h	2 h

### 3. Reaction rates measurements

The reaction rate  $a_i$  induced in a threshold detector irradiated by the neutron source during  $t_i$  and measured during  $t_m$  after decay time  $t_d$  was determined from the following expression:

$$a_i = \frac{\lambda N_\gamma}{I_\gamma \xi \varepsilon(E_\gamma) (1 - e^{-\lambda t_i}) e^{-\lambda t_d} (1 - e^{-\lambda t_c})}, \quad (1)$$

where  $N_\gamma$  is the number of counts in the full energy peak (FEP) of energy  $E_\gamma$ , emitted with the probability  $I_\gamma$  by the radionuclide formed and registered by the detector with the FEP efficiency  $\varepsilon(E_\gamma)$ .  $\lambda$  is the decay constant of the formed radionuclide and  $\xi$  the fraction of the isotope of interest in the irradiated target. The experimental data [7,8] for the induced reactions are listed in table I.

### 4. Analysis approach

The reaction rate  $a_i$  induced in a threshold detector  $i$  by neutrons of energy  $E$  can also be calculated from the expression:

$$a_i = n_i \int_{E_{\text{threshold}}}^{E_{\text{max}}} \sigma_i(E) \bar{\varphi}_{iV}(E) dE, \quad (2)$$

where  $n_i$  is the number of the activated nuclei present in the threshold detector  $i$ ,  $\sigma_i(E)$  is the cross section of the induced reaction at neutron

energy  $E$  taken from the ENDF library [9] and  $\bar{\varphi}_{iV}(E)$  the neutron flux at energy  $E$  averaged over a detector volume  $V$ , whereas  $E_{\max}$  is the maximal energy of the neutrons emitted by an Am-Be source ( $E_{\max} \sim 12$  MeV).

$\bar{\varphi}_{iV}(E)$  can be expressed as a function of the spectral emission  $\varphi_E(E)$  of the neutron Am-Be source as:

$$\bar{\varphi}_{iV}(E) = G_i(E)\varphi_E(E), \quad (3)$$

where  $G_i(E)$  is a correcting factor, which takes into account the source-detector geometry, the neutron attenuation and the diffusion by the detectors.

$G_i(E)$  is evaluated by simulation using the MCNP5 code. Assuming a threshold detector  $i$  of volume  $V$  exposed to a neutron spectrum  $\varphi_{E_{ISO}}(E)$  emitted by an ISO Am-Be source [10,11] of similar geometric configuration as the laboratory source, one calculates the neutron fluence  $\bar{\varphi}_{iV_{ISO}}(E)$  at energy  $E$  averaged over the detector volume. The correction factor can then be expressed as:

$$G_i(E) = \frac{\bar{\varphi}_{iV_{ISO}}(E)}{\varphi_{E_{ISO}}(E)} = \frac{\bar{\varphi}_{iV}(E)}{\varphi_E(E)}. \quad (4)$$

Using eq. (4), eq. (2) can be rewritten as:

$$a_i = n_i \int_{E_{\text{threshold}}}^{E_{\max}} \sigma_i(E) G_i(E) \varphi_E(E) dE. \quad (5)$$

The measured reaction rate  $a_i$  is linked to the spectral emission  $\varphi_E(E)$  of the neutron source by the relation

$$a_i = \int_{E_{\text{threshold}}}^{E_{\max}} R_i(E) \varphi_E(E) dE, \quad (6)$$

where  $R_i(E) = n_i \sigma_i(E) G_i(E)$ , is the response function of the  $i^{\text{th}}$  detector. The set of response functions determined for all the threshold detectors forms the response matrix.

The spectral emission of the Am-Be source  $\varphi_E(E)$  can then be determined by deconvolution of eq. (6). This equation is known as ‘‘Fredholm’s integral equation of the first kind’’ [12], which can be expressed for computational purposes in a discrete form as follows:

$$a_i = \sum_{j=1}^m R_{ij} \varphi_{E_j}, \quad (7)$$

where  $i = 1, \dots, n$  ( $n$  is the number of the detectors and equal to the number of measurements) and  $j = 1, \dots, m$  ( $m$  is the number of energy groups).  $\varphi_{E_j} = \int_{E_j}^{E_{j+1}} \varphi_E(E) dE$  is the spectral emission of the source in the interval  $E_j, E_{j+1}$  and  $R_{ij}$  is the response function of the  $i^{\text{th}}$  detector in the interval  $E_j, E_{j+1}$ .

Since the number of detectors  $n$  is usually less than the number of unknown energy bins  $m$ , the unfolding algorithms [13] based on different methods like least square, iterative, maximum entropy etc., can be used to obtain only the physical solutions out of an infinite number of solutions to eq. (7). Some of the well-established codes such as Stayn'l [14], Maxed [15] and Gravel [16] are used frequently to unfold the spectral information from these detector responses. These methods require a guess spectrum or a-priori information to start the unfolding procedure.

## 5. Unfolding results and discussion

A total of 6 detector responses (reaction rate measurements) have been obtained. These values together with the response matrix  $R_i(E)$  have served as inputs to the unfolding procedures.

Three unfolding algorithms have been used:

- Stayn'l code based on a least squares generalized method;
- Maxed code based on the maximum entropy method;
- Gravel code based on a non linear least squares method;

These unfolding codes require an input default spectrum representing a first “guess” of the spectral emission source. The reference spectrum recommended by an ISO-8529 Am-Be source has been introduced as “default spectrum”. Fig. 1 gives the resulting unfolded spectra obtained with the above listed codes. The spectra have also been compared to the ISO-8529 Am-Be spectrum.

From fig. 1 it is apparent that the shape of Am-Be neutron spectra generated by the different unfolding methods are comparable to the ISO one with the exception of neutron energies below 0.4 MeV. This can be explained by the contribution of a plausible low-energy part in the spectrum, irradiating the threshold foils, not included in the ISO spectrum.

The areas under the unfolded spectra (before normalization) measure the source activity. The discrepancy between the different calculated activities and that given by the manufacturer,  $A_{\text{manufacturer}} = 2.2 \cdot 10^6 \text{ s}^{-1}$ , do

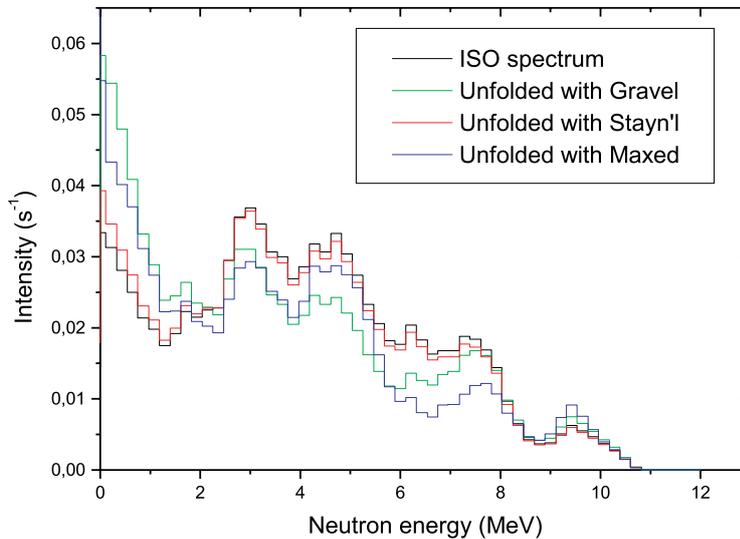


Figure 1: Am-Be neutron spectra unfolded using three different methods (Stayn'l, Gravel and Maxed). The spectra are compared to a typical standard spectrum (ISO spectrum).

not exceed 15%. This uncertainty remains comparable to that tolerated in neutron measurements for radioprotection purposes, validating thereby the proposed method.

## 6. Conclusion

In this paper, we have proposed a method to characterize low neutron fields using thick threshold activation detectors. This technique has been applied for the measurement of neutron energy distribution of low activity ( $\sim 37$  GBq) Am-Be source.

The induced radioactivity in activated thick detectors has been measured using a classical detection chain for gamma-ray spectrometry including either a NaI(Tl) scintillator or a HPGe detector.

A mathematical treatment of the threshold detector responses using different unfolding codes has been applied to determine the spectral emission of the Am-Be source. The results obtained are encouraging for the use of

these detectors in the characterization of low intensity neutron fields.

The proposed technique is convenient for measurements of environmental neutron fields. The detectors can be placed anywhere, even in hazardous environments or in areas difficult to access, as they are cheap, robust and need no electric power. These detectors can also be used to monitor undesirable neutrons generated around nuclear installations (*e.g.* medical accelerator, Van de Graff).

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