Annals of Nuclear Energy 77 (2015) 369–375

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Neutron energy spectrum in a reactor exit channel with a single surface barrier sensor using GEANT4

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ARTICLE INFO

Article history:
Received 10 June 2014
Received in revised form 25 November 2014
Accepted 26 November 2014

Keywords:
Neutron spectrometry
GEANT4
Response functions
Nuclear reactor spectrum

ABSTRACT

A single surface barrier neutron spectrometer has been used to characterise the neutron energy spectrum at the neutron irradiation channel of a nuclear reactor. The response functions of a single surface barrier detector associated with a natural boron neutron-charged particle converter were calculated using the GEANT4 simulation toolkit. Calculations were performed for thermal, intermediate energy and fast neutrons and for four converter thicknesses from 50 $\mu g\ cm^{-2}$ to 3.26 $mg\ cm^{-2}$. The relationship between the response functions and the energy loss of the charged particles emitted by the $^{10}B(n,\alpha)^{7}Li$ reaction in the converter as a function of incident neutron energy is discussed. Finally, the neutron energy spectrum at the neutronography irradiation site of the Algerian Research Reactor NUR was determined using the experimentally determined pulse height spectrum of the single surface barrier spectrometer with the help of the calculated response functions and an efficient unfolding code.

1. Introduction

Knowledge of the neutron energy spectrum is of prime importance to evaluate neutron-induced reaction yields that are used in theoretical and experimental studies in various scientific disciplines ranging from fundamental sciences (Gould et al., 2006), nuclear physics, nuclear reactor physics and technology, radiation protection and dosimetry, to biological and medical sciences (Rouki, 2012). Furthermore at research nuclear reactors where the primary function is to provide intense and well characterised neutron flux densities, the determination of neutron flux and energy distributions is essential to fulfil proper neutron experiments at the operating irradiation channels and to correctly interpret their results.

Most often, the characterisation of neutron distributions at the irradiation sites in research nuclear reactors is achieved by means of neutron transport codes that simulate the neutrons behaviour from the reactor's core to the irradiation site taking into account all the interactions that neutrons undergo with the reactor structure materials. In addition, experimental measurements are usually fulfilled in order to verify and validate the simulation calculations especially when uncertainties on the results due to a lack of information about materials and their geometries are observed.

The algerian nuclear reactor NUR (Nuclear University Reactor) has several channels arranged in the reactor structure for neutron irradiations, including a neutronography channel. This channel is often devoted to material analysis by neutron imaging where the obtained neutron image is investigated according to the absorption and scattering process that neutrons undergo in the exposed sample. Since the quality of the obtained neutron radiography image is strongly dependent on the homogeneity of the neutron field and the image contrast is enhanced for thermal and sub-thermal neutrons, the neutron flux and energy spectral distributions at the irradiation site of this channel is of great importance for neutron radiography studies.

The neutron energy distribution at the exit of this channel has been previously established using a nuclear track detector (Seghour et al., 2008). Furthermore, the integral flux and the cadmium ratio are determined by means of the gold-foil activation technique which give valuable information about the hardness of the flux and provide a rough estimation of the neutron spectrum shape. For convenience, the shape of the neutron flux spectrum currently used for this channel is expressed according to the neutron distribution of a thermal reactor as a combination of a Maxwellian distribution for the thermal component of the spectrum and $1/E$ distribution for the epithermal component. The contribution of each component in the total shape of the neutron spectrum is adjusted to fit the experimental integral flux and the ratio measurements. However, the actual spectrum shape which is crucial for some experiments such as the absolute activation

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http://dx.doi.org/10.1016/j.anucene.2014.11.035
0306-4549/

measurements and structural effects in solids affected by neutrons, may present some differences from the semi-empirical formulation such as a deviation from the ideal $1/E$ distribution for the epithermal neutrons or a different temperature for the Maxwellian function.

Several neutron spectrometers have been developed. They differ mainly on the method used to measure neutron energy (Brooks and Klein, 2002). However, not all neutron spectrometers are suitable for neutron measurements in nuclear reactors due to the available space near the irradiation channels and the sensitivity of the neutron sensor to gamma radiations that are issued from fission products in the reactor core or from the neutron-activation of the reactor structure elements. Under these constraints, the most used techniques for measuring the neutron flux and the neutron energy spectra are the so-called multi-foil activation and Bonner sphere spectrometers.

Compact semi-conductor based detectors associated with neutron-charged particles converters have early been used to detect neutrons and measure their energies (Heijne, 2008). New detector sensor materials and new designs are continuously developed to enhance the detection efficiency of neutrons in mixed neutron-γ fields (Caruso, 2010). In neutron spectrometry, surface barrier detectors which are widely used in charged particle spectrometry due to their good energy resolution and high detection efficiency (Knoll, 2012), have been successfully used by association with special converters made of materials that present high cross sections for neutron-induced nuclear reactions (Brooks and Klein, 2002). The so-called sandwich spectrometer, where a thin neutron converter placed between two facing silicon surface barrier diodes allows measuring the incident neutron energy from the sum of the collected energies of the neutron-induced nuclear reaction particles detected in coincidence (Seghour and Sens, 1999). Unfortunately, with a more compact design of the spectrometer which consists of a single surface barrier detector and a neutron converter, the determination of the neutron energy is less straightforward because of the large angular acceptance of the detection system which approaches π. With such a simple detection system, and particularly for a polyenergetic neutron beam, charged particles produced by neutron-induced reactions in the converter can reach the active surface of the detector with the same energy even though they are produced by neutrons with different energies due to the angular dependence of the emitted particle's energy and the energy loss in the converter. Consequently, different neutron energy distributions could give rise to the same charged particle spectrum. To correctly unfold the actual neutron energy distribution from a charged particle spectrum, one must hold an accurate response function of the spectrometer that precisely describes the neutron and the induced charged particle interactions in the converter and the detector together with an efficient unfolding procedure.

In this work, GEANT4 is used to calculate the response functions of the single surface barrier neutron spectrometer with a neutron converter made of natural boron. The response functions are then used by an unfolding program to characterise the neutron energy spectrum at the neutronography channel of the Algerian Research Reactor NUR.

2. Single surface barrier neutron spectrometer

The neutron spectrometer consists of a surface barrier detector and a neutron converter layer in close contact with the active surface of the detector (Fig. 1).

^{10}B and ^{6}Li based materials are most often used as neutron converter since they are highly sensitive to neutrons via the following reactions:

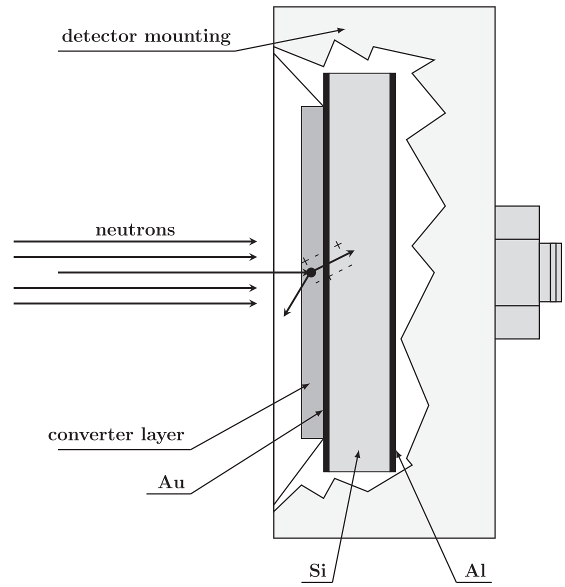

Fig. 1. Single surface barrier neutron spectrometer.

$$^{10}\mathrm{B} + n \longrightarrow \begin{cases} \alpha + {}^{7}\mathrm{Li} + 2.79\ \mathrm{MeV} & (6.3\%) \\ \alpha + {}^{7}\mathrm{Li}^{*} + 2.31\ \mathrm{MeV} & (93.7\%) \end{cases} \tag{1}$$

and:

$$^{6}\mathrm{Li} + \mathrm{n} \longrightarrow \mathrm{t} + \alpha + 4.78\ \mathrm{MeV} \tag{2}$$

Charged particles resulting from the $^{10}\mathrm{B(n,\alpha)^{7}Li}$ or $^{6}\mathrm{Li(n,t)\alpha}$ reactions lose part or all their energies in the converter material. Only particles that reach the detector's entrance window deposit their remaining energy in the sensitive layer of the surface barrier detector. The number of collected particles in the detector is strongly dependent on the neutron reaction cross section and on the range of the emitted particles in the converter.

The choice of using either a ^{6}Li or ^{10}B based converter is related to the advantages that each isotope offers for neutron spectrometry measurements. On the one hand, the high Q-value (4.78 MeV) of the $^{6}\mathrm{Li(n,t)\alpha}$ reaction usually allows a good separation of the t and α peaks. The fact that there is only one decay channel for reaction (2) gives the ^{6}Li converter an advantage over ^{10}B, especially for monoenergetic neutrons. However, in the presence of polyenergetic neutrons, where the emitted charged particles do not necessarily appear in resolved peaks, the advantage would be with a ^{10}B-based converter. This is due to the fact that the $^{10}\mathrm{B(n,\alpha)^{7}Li}$ cross section is roughly four times the $^{6}\mathrm{Li(n,t)\alpha}$ cross section for thermal and intermediate energy neutrons except in the vicinity of 250 keV, where a strong resonance is observed for ^{6}Li (Fig. 2).

Neutrons that cross the converter layer without interacting with boron or lithium may induce nuclear reactions with the surface barrier detector materials. When these reactions occur within or close to the sensitive layer of the detector, the reaction products deposit their energies in the active zone and generate an unwanted background which is added to the useful pulse height spectrum of $^{10}\mathrm{B(n,\alpha)^{7}Li}$ or $^{6}\mathrm{Li(n,t)\alpha}$ reactions. The most relevant neutron induced reactions induced in silicon are reported in Table 1 and one can see that all the considered reactions occur only with fast neutrons in the energy range greater than 2.75 MeV except the $^{29}\mathrm{Si(n,\alpha)^{26}Mg}$ reaction which can be induced with intermediate neutrons. However, since the natural abundance of ^{29}Si is low and the neutron cross section of the $^{29}\mathrm{Si(n,\alpha)^{26}Mg}$ reaction does not exceed few tenths of b, the contribution of this reaction to the background can be ignored. Moreover, by observing that fast