Radiation Measurements 46 (2011) 1712–1715

Contents lists available at ScienceDirect

Radiation Measurements

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

Design and validation of a photon insensitive multidetector neutron spectrometer based on Dysprosium activation foils

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ARTICLE INFO

Article history:
Received 28 October 2010
Accepted 10 June 2011

Keywords:
Neutron spectrometry
Neutron dosimetry
Activation foils
Unfolding

ABSTRACT

This communication describes a photon insensitive passive neutron spectrometer consisting of Dysprosium (Dy) activation foils located along three perpendicular axes within a single moderating polyethylene sphere. The Monte Carlo code MCNPX 2.6 was used to optimize the spatial arrangement of the detectors and to derive the spectrometer response matrix. Nearly isotropic response in terms of neutron fluence for energies up to 20 MeV was obtained by combining the readings of the detectors located at the same radius value. The spectrometer was calibrated using a previously characterized 14 MeV neutron beam produced in the ENEA Frascati Neutron Generator (FNG). The overall uncertainty of the spectrometer response matrix at 14 MeV, assessed on the basis of this experiment, was ±3%.

1. Introduction

Intense neutron fields with an energy range from thermal up to hundreds MeV neutrons can be frequently encountered in accelerator facilities. In some applications, such as the accelerator-based cancer therapy, the neutron field is a parasitic effect due to the interaction of the primary beam with the structural materials, the equipments and the patient. In other applications, such as the irradiation of electronics equipments at neutron spectra reproducing the neutron component of the cosmic rays, dedicated high-energy spallation neutron beams have been set-up. This is the case of TRIUMF (Vancouver, www.triumf.ca), LANSCE (Los Alamos, lansce.lanl.gov), TSL (Uppsala, www.tsl.uu.se) and ISIS (RAL, www.isis.rl.ac.uk). In these and many other installations, the need exists to monitor the neutron fields. Because these fields are characterized by wide energy range (from thermal neutrons up to the maximum energy allowed for a given neutron production mechanism), the spectrum is a fundamental piece of information that monitoring systems should provide. To date, only the Bonner Sphere Spectrometer (BSS) has adequate response over the whole energy range. Nevertheless, the need to sequentially expose the spheres imposes time-consuming irradiation sessions and limits the applications of the BSS as routine monitoring system. As a possible solution, a new neutron spectrometer based on pairs of ^{6}LiF and ^{7}LiF thermoluminescent detectors allocated at different positions within a single polyethylene sphere has been assembled and experimentally tested (Gómez-Ros et al., 2010a, 2010b). By averaging the readings of the TLDs (after photon subtraction) located at the same radial distance from the sphere centre, a nearly isotropic fluence response was obtained up to 20 MeV. Nevertheless, the photon sensitivity of TLDs may be a problem, especially in workplaces where a large photon background is present. With the aim of providing a photon insensitive instrument for intense neutron fields, TLD pairs have been replaced with Dysprosium (Dy) activation foils that after irradiation are read out using a portable beta-counter. These detectors have been successfully used to replace gold foils in passive Bonner Sphere Spectrometers for measurement in intense neutron beams, resulting in an increased response, by two orders of magnitude in operational conditions (Bedogni et al., 2010a, 2010b).

This work describes the Dy-foils-based Single Sphere Spectrometer (Dy-SSS), its response matrix, and the calibration experiment performed in the previously characterized 14 MeV neutron beam produced in the ENEA Frascati Neutron Generator (FNG). The overall uncertainty of the spectrometer response matrix at 14 MeV, assessed on the basis of this experiment, was ±3%.

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1350-4487/$ – see front matter
doi:10.1016/j.radmeas.2011.06.037

2. Materials and methods

The design of the instrument is based on the previous studies performed using pairs of $^{6}LiF/^{7}LiF$ detector (Gómez-Ros et al., 2010a, 2010b). As it is shown in Fig. 1, it consists of two polyethylene semi-spheres of 30 cm diameter. The junction plane, conventionally called $X-Y$ plane, contains 24 activation foils (12 per axis). The semi-spheres were drilled to produce a 3 cm diameter cylindrical cavity along the Z-axis. This cavity is filled with a cylindrical piece formed by modules where 13 activation foils are located. As a result, 37 activation foils can be allocated at fixed radial distances ($r = 0$, 3, 6, 9, 10.5, 12, 14 cm) along the three axes.

The assembly has been fabricated in polyethylene, $(CH2)_n$, 0.927 g cm^{-3} in density. The Dy activation foils have diameter 1.2 cm, thickness 0.01 cm and purity higher than 99.9%. Density of the foils is 8.55 g cm^{-3}. The isotope of interest, ^{164}Dy, has 28.2% abundance in natural Dysprosium. Taking advantage of the high (n,γ) activation cross section of ^{164}Dy (2700 b at thermal energy) and the reasonably short half life of ^{165}Dy (2.334 h), the specific activity reached in Dy foils in operation conditions (Bedogni et al., 2010a) is two order of magnitude higher than in the commonly used gold foils. Due to its high energy (end-point 1.287 MeV) and high yield (83%), the beta emission of ^{165}Dy is suited for in-situ measurements with a portable beta-counter. By correcting the counter signal for the time dependent accumulated activity, the exposure-to-count delay and the in-counting delay, the saturation count rate of the i-th Dy foil, C_i, is derived. The C_i values corresponding to the same radial distance are averaged and the results are used as input data for the FRUIT unfolding code (Bedogni et al., 2007b).

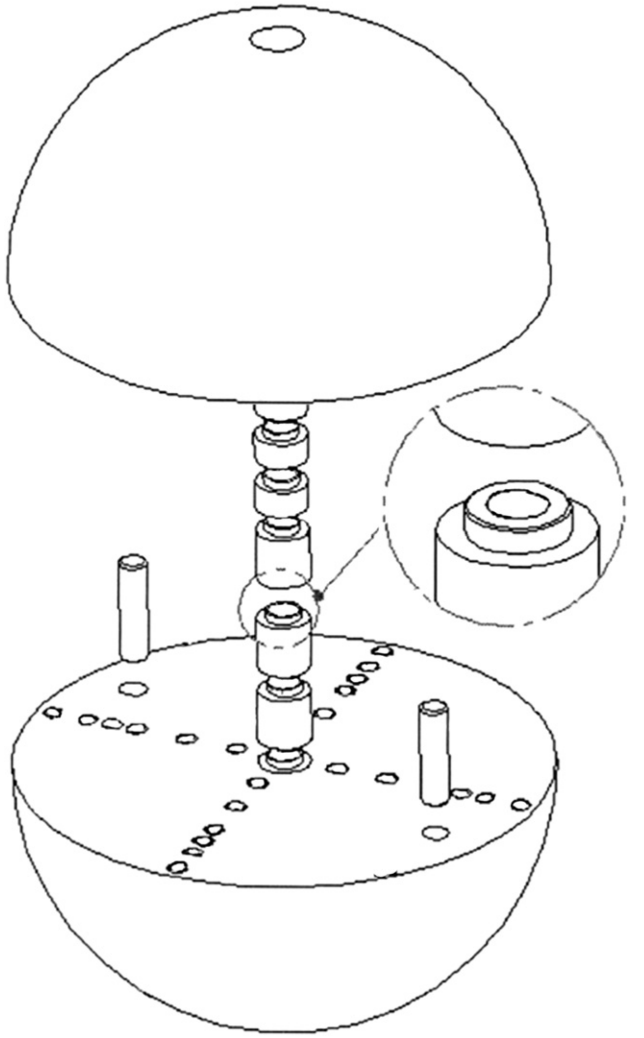

Fig. 1. Schematic design of the multidetector spectrometer, showing the arrangement of the thermoluminescent detectors along three perpendicular axes.

3. Response matrix

The response matrix has been calculated for 59 log-equidistant energies from 1.5×10^{-9} to 1.46×10^{2} MeV, using the Monte Carlo code MCNPX 2.6 (Pelowitz, 2008) and cross section data from the ENDF/B-VII nuclear library (Chadwick et al., 2006), including the corresponding room temperature cross section tables, S(α,β), for modeling the neutron scattering in polyethylene. Photonuclear reactions (γ,n) and the production of secondary neutrons have been also taken into account. A cut-off in the number of histories has been applied to obtain statistical uncertainties lower than 3% in all the cases. The simulated response matrix of the Dy-SSS was derived as the number of ^{164}Dy(n,γ)^{165}Dy reactions within the foil volume per unit incident fluence, as a function of the neutron energy and of the irradiation geometry. This was calculated for each position using, the track-length scoring option for the fluence (F4 tally), and is denoted $M_i^{(\mathrm{geom})}(E)$ The following irradiation geometries

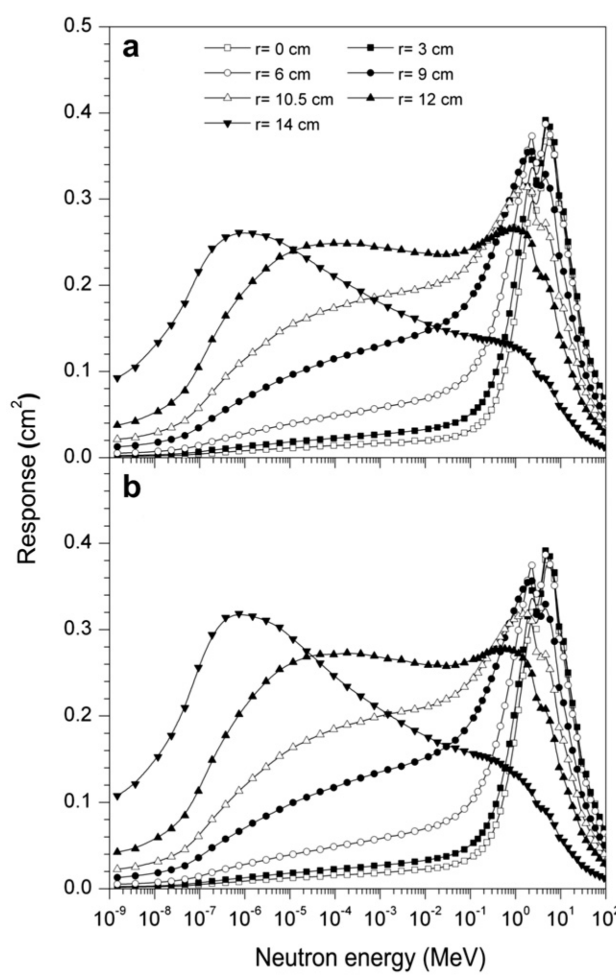

Fig. 2. Energy response functions to mono-energetic incident neutrons, averaged over the detectors located at the same distance, d, from the centre, for a) irradiation along a detectors axis; b) isotropic irradiation.

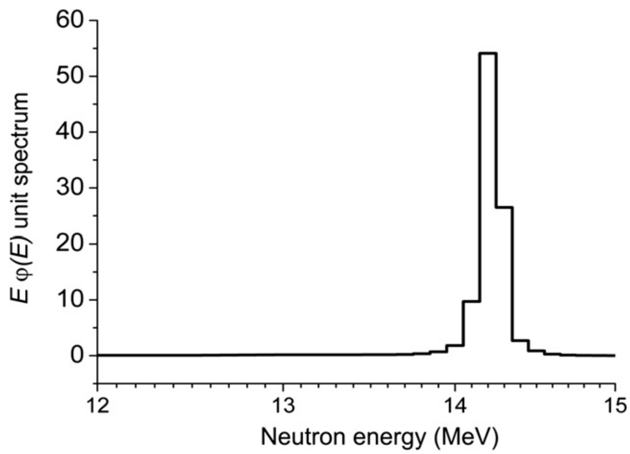

Fig. 3. Reference spectrum of FNG normalized to the unit fluence and in equi-lethargy representation.

(Gómez-Ros et al., 2010a) were considered: uni-directional along one axis, namely (1,0,0), uni-directional along (1,1,1) direction and isotropic (ISO). For a given geometry and energy, the M_i values obtained at the same radial distance were averaged obtaining the average response matrix $M^{(\text{geom})}(r,E)$. In the present configuration, r values are 0, 3, 6, 9, 10.5, 12 and 14 cm.

Fig. 2 shows the calculated response matrix for the irradiation geometries (1,0,0) and ISO. As previously discussed (Gómez-Ros et al., 2010a), the average of six positions for each radial distance provides a nearly isotropic response for neutrons above 1 keV. The differences in the response functions for the shallowest position (d = 14 cm), depending on the irradiation geometry (Fig. 2, down triangles), will only affect the thermal part of the neutron field. This is not expected to be significant in most of the practical situations, where the thermal fluence can be considered as isotropic.

4. Calibration of the Dy-SSS

The Dy-SSS was calibrated in the quasi mono-energetic 14 MeV neutron beam of the ENEA Frascati Neutron Generator (see Fig. 3) (Angelone et al., 1996). The centre of the sphere was placed at 95 cm from the neutron emitting tritiated target, in a normal direction with respect to the incident deuterons. This neutron beam is monitored by means of an NE213 neutron scintillator and of an alpha counter. It is characterized by continuous emission and high reproducibility (within 1% in terms of neutron fluence per NE213 count). The reference fluence was measured using a well-established Bonner sphere spectrometer equipped with a 4 mm × 4 mm ^{6}Li(Eu) scintillation detector (Esposito et al., 2010) and a set of seven polyethylene spheres plus three extended range spheres (with lead and copper inserts). A special gradient method (Matzke, 2003), available as "non parametric" option in the FRUIT unfolding code, was used to obtain the reference spectrum. A detailed spectrum generated with MCNPX (Bedogni et al., 2007a) was used as pre-information.

The Dy-SSS was exposed for about 15 min in the point of test in mono-directional irradiation geometry, (1,0,0). The Dy foils were counted and the corresponding readings were corrected for the time dependent accumulated activity (saturation correction factor), the exposure-to-count delay and the in-counting delay to get the saturation count rate C_i. Due to the time variability of the neutron source, the saturation correction factor F_{sat} was determined on the basis of the instantaneous intensity of the neutron beam, which is proportional to the time variation of the NE213 count rate. This is shown in Fig. 4.

The spectrometer calibration factor, F_i, was derived on the basis of the readings of 11 foils located in different positions indicated in Table 1, using the following equation:

$$F_i = \frac{C_i}{\dot{\phi}_{\text{ref}} \cdot \int \mathrm{d}E \cdot M_i^{(1,0,0)}(E) \cdot \varphi(E)} \quad (1)$$

where $M_i^{(1,0,0)}(E)$ is the response matrix in mono-directional irradiation geometry; φ(E) is the reference neutron spectrum, determined with the BSS and normalized to the unit fluence (unit spectrum); and $\dot{\phi}_{\text{ref}}$ is the reference fluence rate, i.e. the neutron fluence rate corresponding to the reference value of NE213 count rate. This was determined with the BSS and its value is $(1.83 \pm 0.03) \cdot 10^5$ cm^{-2} s^{-1} at a reference NE213 count rate of $(3.33 \pm 0.03) \cdot 10^3$ s^{-1}.

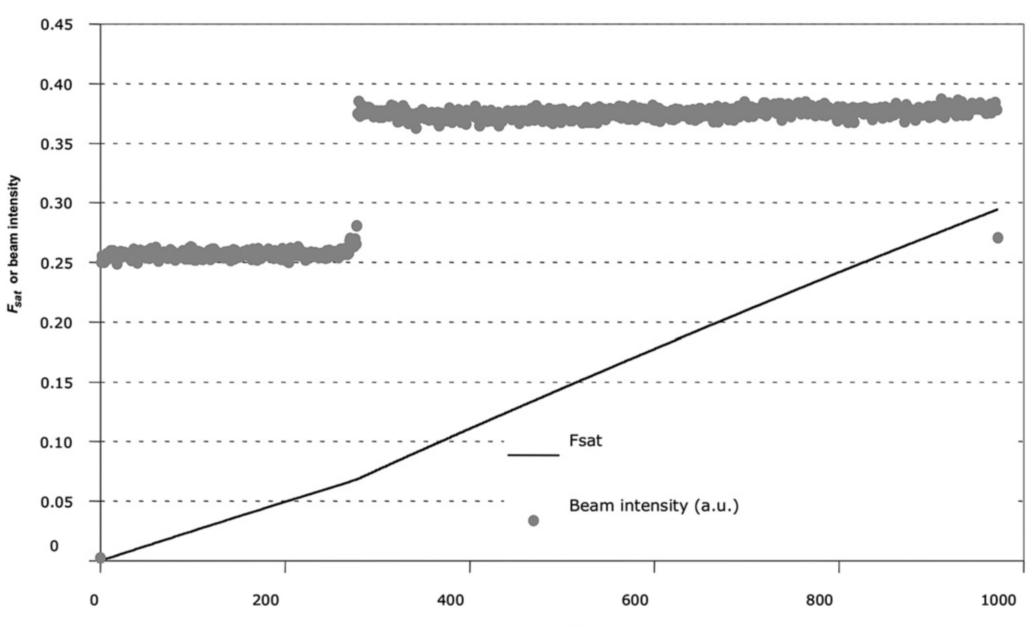

Fig. 4. Time variability of the FNG beam during the Dy-SSS irradiation and corresponding variability of the Dy foils saturation correction factor.

Table 1
Calibration table of the Dy-SSS. The *X*-axis corresponds to the beam direction. The *X* points with (−) sign are located along the radius opposing the beam. For *Y*-axis, the points at the same radius have been averaged. For *Z*-axis, only the points of the upper half-sphere were considered because those located in the lower half were significantly perturbed by the scattering from the support materials. Uncertainties of the F_i values are below ±2%.

Axis	Radius	F_i
X-axis	−10.5 cm	0.146
	−6 cm	0.143
	−3 cm	0.142
	Centre sphere	0.149
	+3 cm	0.143
Y-axis	3 cm average	0.136
	6 cm average	0.135
	9 cm average	0.140
Z-axis	+3 cm	0.142
	+6 cm	0.138
	+ 9 cm	0.140

The best estimation of the calibration factor was calculated as the mean of the F_i values listed in Table 1, thus obtaining (0.141 ± 0.003). The standard deviation of the F_i values reported in Table 1 can be regarded as an estimation for the uncertainty of the Dy-SSS response matrix at 14 MeV. This is 3%, which is fully comparable with the corresponding figure obtained for well-established devices such the BSS (Bedogni et al., 2010c).

5. Conclusions

A passive neutron spectrometer based on Dy activation foils symmetrically arranged at 6 radial distances within a single moderating sphere (Dy-SSS), has been developed in the framework of the INFN-CIEMAT collaboration. The response matrix, accurately generated with MCNPX 2.6 for different irradiation geometries and for energies from thermal up to 146 MeV neutrons, was partially validated at 14 MeV quasi mono-energetic neutrons obtaining a figure of ±3% as overall uncertainty. This value is fully comparable with the uncertainty of the response matrix of well-established spectrometers like the BSS.

Additional experiments are needed to extend this validation to a larger variety of energies and to study the systematic errors that may be induced by non-uniform irradiation and irradiation with thermal to keV neutrons, where the average response of the shallowest detectors (r = 14 cm) can be different for different irradiation geometries. Nevertheless, the results of this paper indicate that the Dy-SSS could constitute a valuable monitor instrument with many potential applications in neutron producing facilities.

Acknowledgments

This work has been partially supported by ACI2009-0992 and INFN-MICINN-2010 collaboration projects between INFN-Frascati (Italy) and CIEMAT (Spain).

References

Angelone, M., Pillon, M., Batistoni, P., Martini, M., Marton, M., Rado, V.M., 1996. Absolute experimental and numerical calibration of the 14 MeV neutron source at the Frascati neutron generator. Rev. Sci. Instrum 67, 2189–2196.
Bedogni, R., Esposito, A., Domingo, C., Fernandez, F., García, M.J., Angelone, M., 2007a. Performance of the UAB and the INFN-LNF Bonner sphere spectrometers in quasi mono-energetic neutron fields. Radiat. Prot. Dosim. 126, 342–345.
Bedogni, R., Domingo, C., Esposito, A., Fernández, F., 2007b. FRUIT: an operational tool for multisphere neutron spectrometry in workplaces. Nucl. Instrum. Meth. A 580, 1301–1309.
Bedogni, R., Ferrari, P., Gualdrini, G., Esposito, A., 2010a. Design and experimental validation of a Bonner Sphere Spectrometer based on Dysprosium activation foils. Radiat. Meas. 45, 1201–1204.
Bedogni, R., Esposito, A., Gomez-Ros, J.M., 2010b. Response matrix of an extended range Bonner Sphere Spectrometer for the characterization of collimated neutron fields. Radiat. Meas. 45, 1205–1212.
Bedogni, R., Domingo, C., Esposito, A., Chiti, M., Garcia Fusté, M.J., Lovestam, G., 2010c. Testing Bonner Sphere Spectrometers in the JRC-IRMM mono-energetic neutron beams. Nucl. Instr. Meth. A 620, 391–396.
Chadwick, M.B., Oblozinsky, P., Herman, M., et al., 2006. ENDF/B-VII.0: Next generation evaluated nuclear data library for nuclear science and technology. Nucl. Data Sheets 107, 2931–3060.
Esposito, A., Bedogni, R., Domingo, C., García, M.J., Amgarou, K., 2010. Measurements of leakage neutron spectra from a high-energy positron accumulation ring using extended-range Bonner Sphere Spectrometers. Radiat. Meas. 45, 1522–1525.
Gómez-Ros, J.M., Bedogni, R., Moraleda, M., Delgado, A., Romero, A., Esposito, A., 2010a. A multi-detector neutron spectrometer with nearly isotropic response for environmental and workplace monitoring. Nucl. Instrum. Meth. A 613, 127–133.
Gómez-Ros, J.M., Bedogni, R., Moraleda, M., Romero, A., Delgado, A., Esposito, A., 2010b. Design and validation of a single sphere multidetector neutron spectrometer based on LiF: Mg, Cu, P thermoluminescent dosimeters. Radiat. Meas. 45, 1220–1223.
Matzke, M., 2003. Neutron spectrometry in mixed fields: unfolding procedures. Radiat. Prot. Dosim. 107, 37–72.
Pelowitz, D.B. (Ed.), 2008. MCNPX User's Manual Version 2.6 Report LA-CP-07–1473.