Neutron spectra from Neutron Standards Laboratory (LPN/CIEMAT) sources with two Bonner sphere spectrometers

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A B S T R A C T

The Neutron Standards Laboratory (LPN: Laboratorio de Patrones Neutrónicos) of the Ionizing Radiation Metrology Laboratory (LMRI) of the CIEMAT (Centro de Investigaciones Energéticas Medioambientales y Tecnológicas) has two calibration neutron sources, ^{241}Am-Be and ^{252}Cf. Studies to verify the shielding of the facility and to characterize the neutron field in the irradiation room have been carried out using Monte Carlo methods. However, spectral measurements were not performed yet. In this study, we measured the total and direct neutron spectra of both calibration neutron sources. Two different Bonner Sphere Spectrometers (BSS) systems were allocated to 115 cm from the sources, on the calibration bench, with and without the shadow cones (SC). From the count rates obtained with both BSS systems (BSS-^{6}LiI and BSS-^{3}He), the total neutron spectrum and direct neutron spectrum were unfolded. Total and direct spectra obtained for the ^{241}Am-Be and ^{252}Cf sources with the MCNPX and different BSS systems, unfold codes and response matrices presented similar shape and are consistent with each other.

1. Introduction

The Neutron Standards Laboratory (LPN: Laboratorio de Patrones Neutrónicos) is the newest facility of the Ionizing Radiation Metrology Laboratory (LMRI) of the CIEMAT (Centro de Investigaciones Energéticas Medioambientales y Tecnológicas). LPN has two calibration neutron sources, ^{241}Am-Be and ^{252}Cf, as recommended by International Organization for Standardization (ISO, 8529-1, 2001) for monitor and dosimeter calibration purposes. These sources are inside capsule holders to allow their remote manipulation, controlled from the control program in the Control Room.

The sources of the LPN are stored under at least 1 m of water in a pool. An automatic system assures the purification of the water and the maintenance of its level. Two manipulation systems are responsible to place the calibration sources in the irradiation position. The first one is a Cartesian coordinate manipulator that moves the chosen source from its storage position in the bottom of the water pool to the launching point. A second system launches the source to the irradiation point in the geometrical center of the room in less than one second.

The ^{241}Am-Be source was manufactured by Eckert & Ziegler Cesio s.r.o., Prague. The source is Am1. N20 type, ANSI/ISO classification C66646. It consists of a compacted mixture of ^{241}AmO$_2$ and ^{9}Be powder doubly encapsulated. This source has a nominal activity of 185 GBq and emits 1.11×10^7 s^{-1} ± 1.4% (2σ), traceable to the Czech Metrology Institute (CMI). ^{252}Cf source was manufactured by QSA Global, Inc. USA. It is X.1 model, ANSI/ISO classification C66545. This source has 236 µg of ^{252}Cf, dispersed in a ceramic matrix encapsulated in 2 mm thick A316 stainless steel. The nominal activity is 5 GBq emitting 5.471×10^8 s^{-1} ± 2.6% (2σ), traceable to the National Institute of Standards and Technology (NIST, USA).

Response or calibration factor of a device shall not be a function of the characteristics of the calibration facility. It shall be a unique property of the instrument type and neutron-source spectrum (ISO, 8529-2, 2000). Studies to verify the shielding of the facility (Mendez-Villafañe et al., 2014) and to characterize the neutron field in the irradiation room have been carried out using Monte Carlo methods (Guzman-Garcia et al., 2015). However, spectral measurements were not performed yet.
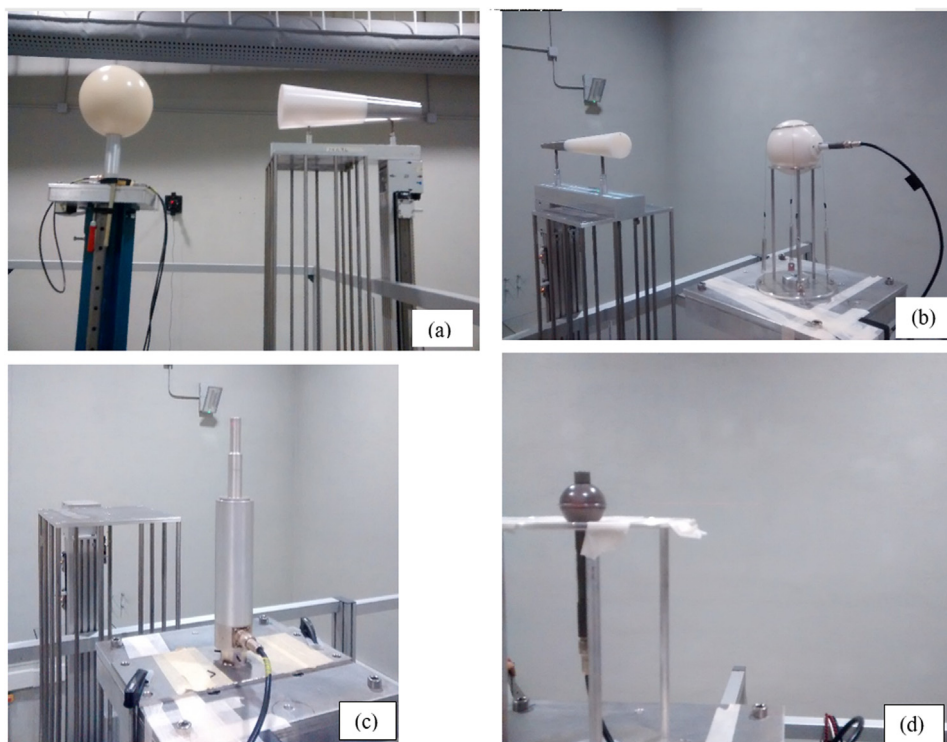
Fig. 1. Different BSS systems on the calibration bench: (a) 10 in. sphere of the BSS-^{6}LiI with the respective shadow cone for Am-Be source; (b) 3 in. sphere of the BSS-^{3}He system, with the respective shadow cone for the Cf source; (c) BSS-^{6}LiI (bare detector) and; (d) BSS-^{3}He (bare detector).

The aim of this work was to measure the neutron spectra of both calibration neutron sources using two different Bonner Sphere Spectrometers (BSS) and different unfolding codes/response matrices.

2. Materials and methods

Measurements were performed with two BSS, the LPN/CIEMAT BSS system and the BSS system of the Neutron Measurements Laboratory of Universidad Politécnica de Madrid (LMN-UPM).

The LPN/CIEMAT BSS is 12 spheres (bare, 3″, 3.5″, 4″, 4.5″, 5″, 6″, 7″, 8″, 9″, 9.5″, 10″ and 12″) with a spherical ^{3}He SP9 counter (Centronic Ltd., UK),. The LMN-UPM BSS has 6 spheres (2″, 3″, 5″, 7″, 8″, 10″, 12″ diameter) and the bare detector (a small cylindrical 4 mm x 4 mm ^{6}LiI(Eu) scintillator, Ludlum Measurements).

BSS systems were allocated to 115 cm from the sources, on the calibration bench, with and without the shadow cones (SC), as showed in the Fig. 1. From the count rates obtained with both BSS systems (BSS-^{6}LiI and BSS-^{3}He), the total neutron spectrum (Φ_{tot}) and direct neutron spectrum ($\Phi_{dir} = \Phi_{tot} - \Phi_{SC}$), where Φ_{SC} is the neutron spectrum measured with the SC, were unfolded. Total neutron spectrum (Φ_{tot}) includes the room-return neutrons and background contribution. Direct neutron spectrum (Φ_{dir}) includes only neutrons from the direct source-to-detector path (ISO, 8529-2, 2000). Neutron background above calibration bench is negligible ($< 0.02\,\mu Sv/h$) (Méndez-Villafañe et al., 2014).

Data obtained with the CIEMAT BSS system (BSS-^{3}He) were unfolded with the MAXED computer code, from the UMG 3.3 package (Reginatto et al., 2004) and specific response matrix, with 221 energy bins, determined in the Physikalisch-Technische Bundesanstalt (PTB) (PTB-Physikalisch-Technische Bundesanstalt, 2008). Data obtained with the LMN-UPM BSS system (BSS-^{6}LiI) were unfolded with the BUNKIUT code (Lowry and Johnson, 1984) and three different response matrices: (a) response matrix UTA-4, with 31 energy bins (collapsed from 171) (Hertel and Davidson, 1985); (b) a new response matrix, with 221 energy bins, published by Lacerda et al. Lacerda et al. (2017) and;

(c) response matrix of Mares & Schraube (Mares and Schraube, 1994; Mares and Schraube).

The quantities: total fluence and fluence components (thermal, epithermal and fast), ambient dose equivalent (H*(10)) rates and average energy were determined from the unfolded spectra. H*(10) values were calculated using fluence-to-ambient dose equivalent conversion coefficients, in pSv.cm^2, from the ICRP 74 (Pelowitz, 2011). Average energies (E_{Av}) were calculated using the Eq. (1).

$$E_{Av} = \frac{\sum_1^n E_{ci} \cdot \Phi(E_i)}{\sum_1^n \Phi(E_i)} \tag{1}$$

Where, "n" is the number of energy bins, which is 31 for response matrix UTA-4 (Hertel and Davidson, 1985), and 101 and 221 for the matrices Mares & Schraube (Mares and Schraube, 1994; Mares and Schraube) and Lacerda et al. Lacerda et al. (2017), respectively. E_{ci} is given by Eq. (2).

$$E_{ci} = \frac{(E_{upper} + E_{lower})}{2} \tag{2}$$

Here, E_{upper} is the energy in the upper class interval and E_{lower} is the energy in the lower class interval of the energy bin.

The initial guess spectra used in all cases were those obtained with Monte Carlo calculations performed with MCNPX code, version 2.7.0, with ENDF/B-VII.0 nuclear data library (International Commission on Radiological Protection, 1996). To unfold direct spectra we used the Monte Carlo model replacing the concrete of the walls with the air, to exclude room scattering.

3. Results and discussions

Figs. 2–5 show, respectively, the total and direct spectra measured at 115 cm from the ^{241}Am-Be and ^{252}Cf sources, obtained with the MCNPX and the different BSS systems, unfold codes and response matrices. Table 1 shows a comparison of the quantities: total fluence and fluence components (thermal, epithermal and fast), ambient dose
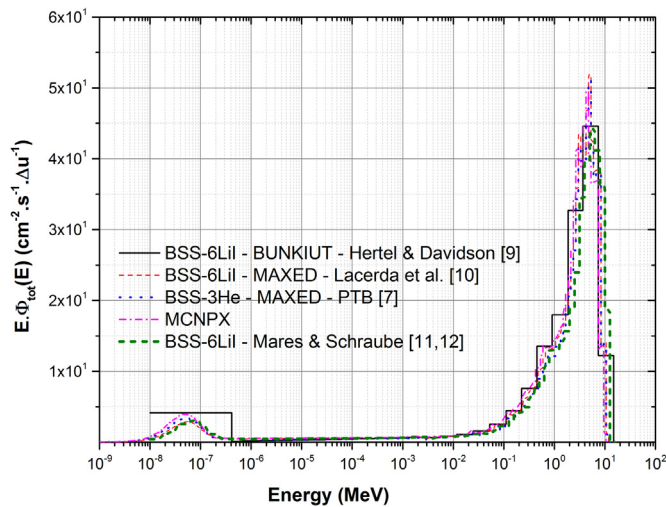
Fig. 2. Total spectra measured at 115 cm from the ^{241}Am-Be source, obtained with the MCNPX and the different BSS systems, unfold codes and response matrices.
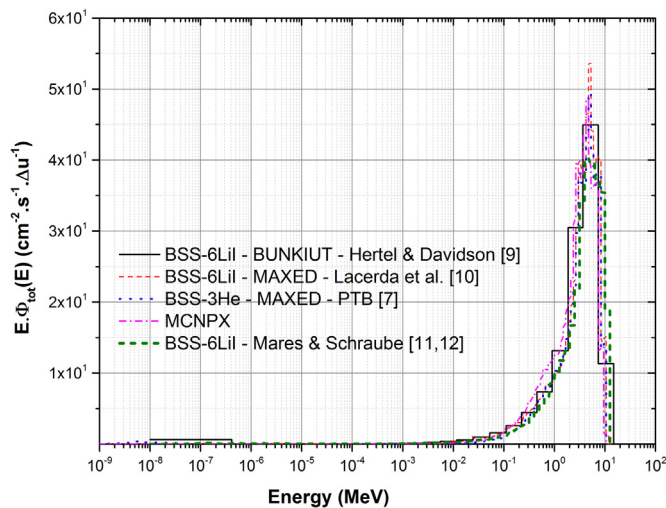

Fig. 3. Direct spectrum measured at 115 cm from the ^{241}Am-Be source, obtained with the MCNPX and the different BSS systems, unfold codes and response matrices.

Fig. 4. Total spectrum measured at 115 cm from the ^{252}Cf source, obtained with the MCNPX and the different BSS systems, unfold codes and response matrices.

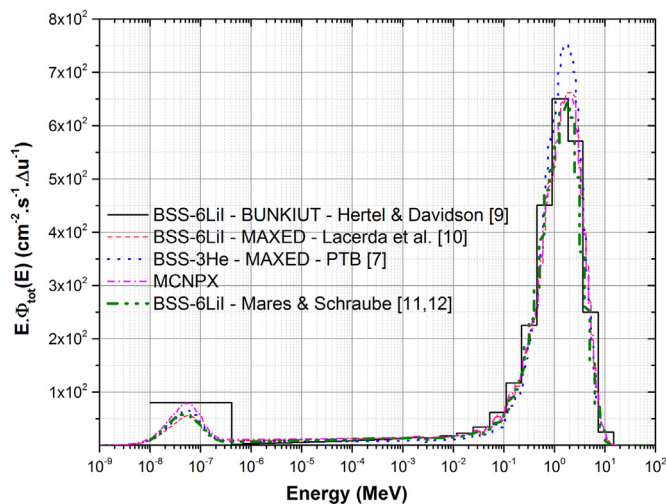**Fig. 5.** Direct spectrum measured at 115 cm from the ^{252}Cf source, obtained with the MCNPX and the different BSS systems, unfold codes and response matrices.

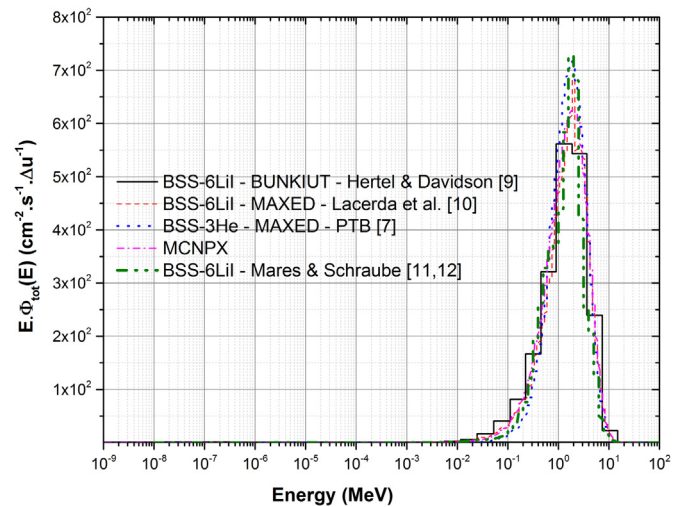equivalent (H*(10)) rates and average energy, determined from Monte Carlo calculations and measured spectra.

Figs. 2 and 4 show that total spectra obtained for the ^{241}Am-Be and ^{252}Cf sources with the MCNPX and different BSS systems, unfold codes and response matrices present similar shape and relatively good agreement. Table 1 shows that fast neutron fractions agree within 7.1%. MCNPX calculations showed the lowest values in this case. Average energies agree within 11.7% and 11.5%, respectively, for ^{241}Am-Be and ^{252}Cf sources.

Figs. 3 and 5 also show that direct spectra obtained for the ^{241}Am-Be and ^{252}Cf sources with MCNPX and the different BSS systems, unfold codes and response matrices present similar shape and relatively good agreement. Fast neutron fractions agree within 2.0%. Average energies agree within 11.6% and 17.8%, respectively, for ^{241}Am-Be and ^{252}Cf sources.

Table 1 shows that for ^{241}Am-Be source, the mean value obtained for the thermal fraction drops from 6.9% for the total spectrum, to 0.6%, for the direct spectrum. For ^{252}Cf source, the decreasing is more significant (from 7.3% to 0.1%).

Table 1 shows an agreement better than 12.5% and 9.9%, respectively, for the total fluence obtained from the total spectra. The agreement for the total fluence, obtained from the direct spectra, were within 13.1%. H*(10) values obtained from the total and direct spectra agree within about 14.1% and 14.7%, respectively, for the ^{241}Am-Be and ^{252}Cf sources, respectively.

The lowest values of fluence and H*(10) were obtained with the Mares & Schraube response matrix (Mares and Schraube, 1994; Mares and Schraube). For the ^{241}Am-Be source, the highest values of fluence and H*(10) were obtained with the Hertel & Davidson matrix (Hertel and Davidson, 1985) along with the BUNKIUT code. For the ^{252}Cf source, the highest values for these quantities were obtained through MCNPX calculations.

4. Conclusions

In this study, we measured the total and direct neutron spectra of both calibration neutron sources of the LPN/LMRI/CIEMAT. Total and direct spectra obtained for the ^{241}Am-Be and ^{252}Cf sources with the MCNPX and different BSS systems, unfold codes and response matrices presented similar shape and are consistent with each other. Fast neutron fractions, average energies, total fluence and ambient dose equivalent, H*(10), values were also consistent. Lowest values of fluence and H*(10) were obtained with the BSS-^{6}LiI system and MAXED

Table 1

Comparison of the quantities: total fluence and fluence components (thermal, epithermal and fast), ambient dose equivalent rate (H*(10)) and average energy, determined from Monte Carlo calculations and measured spectra.

	Fluence rate[a] (n/cm^2.s)	H[a](10) rate[a] (μSv/h)	Average energy (MeV)	Thermal (%)	Epithermal (%)	Fast (%)
^{241}Am-Be - Total spectra data						
BSS-^{3}He -MAXED - PTB (PTB-Physikalisch-Technische Bundesanstalt, 2008)	97.2 ± 0.2	117.4 ± 0.4	3.1	7.1	7.4	85.5
BSS-^{6}LiI - MAXED - Lacerda et al. Lacerda et al. (2017)	102.4 ± 0.4	122.8 ± 0.8	3.0	5.8	9.0	85.2
BSS-^{6}LiI - MAXED - Mares & Schraube (Mares and Schraube, 1994; Mares and Schraube)	93.6 ± 0.4	111.7 ± 0.9	2.9	6.0	9.1	84.8
BSS-^{6}LiI- BUNKIUT - Hertel & Davidson (Hertel and Davidson, 1985)	105.3 ± 0.9	127.4	3.3	7.6	5.9	86.5
MCNPX	103.1	119.7	2.9	7.9	9.6	82.5
^{241}Am-Be - Direct spectra data						
BSS-^{3}He -MAXED - PTB (PTB-Physikalisch-Technische Bundesanstalt, 2008)	73.8 ± 0.3	103.0 ± 0.5	3.9	0.9	1.5	97.6
BSS-^{6}LiI - MAXED - Lacerda et al. Lacerda et al. (2017)	79.1 ± 0.5	108.4 ± 0.7	3.9	0.2	3.5	96.3
BSS-^{6}LiI - MAXED - Mares & Schraube (Mares and Schraube, 1994; Mares and Schraube)	71.1 ± 0.6	97.9 ± 0.7	3.6	0.3	3.3	96.4
BSS-^{6}LiI- BUNKIUT - Hertel & Davidson (Hertel and Davidson, 1985)	80.6 ± 0.7	110.6	4.0	1.5	2.2	96.3
MCNPX	78.3	109.0	3.7	0.0	1.8	98.2
^{252}Cf - Total spectra data						
BSS-^{3}He -MAXED - PTB (PTB-Physikalisch-Technische Bundesanstalt, 2008)	1895 ± 4	2262 ± 4	1.6	7.0	7.0	86.0
BSS-^{6}LiI - MAXED - Lacerda et al. Lacerda et al. (2017)	1833 ± 7	2104 ± 13	1.6	6.2	10.2	83.6
BSS-^{6}LiI - MAXED - Mares & Schraube (Mares and Schraube, 1994; Mares and Schraube)	1732 ± 30	2018 ± 75	1.5	6.5	9.9	83.6
BSS-^{6}LiI- BUNKIUT - Hertel & Davidson (Hertel and Davidson, 1985)	1871 ± 19	2121	1.6	8.2	6.9	84.8
MCNPX	1904	2100	1.5	8.6	11.0	80.4
^{252}Cf - Direct spectra data						
BSS-^{3}He -MAXED - PTB (PTB-Physikalisch-Technische Bundesanstalt, 2008)	1399 ± 9	1977 ± 21	2.0	0.0	0.6	99.4
BSS-^{6}LiI - MAXED - Lacerda et al. Lacerda et al. (2017)	1331 ± 7	1812 ± 12	2.0	0.1	2.4	97.5
BSS-^{6}LiI - MAXED - Mares & Schraube (Mares and Schraube, 1994; Mares and Schraube)	1243 ± 6	1722 ± 10	1.7	0.2	1.8	98.0
BSS-^{6}LiI- BUNKIUT - Hertel & Davidson (Hertel and Davidson, 1985)	1355 ± 13	1807	2.1	0.2	1.5	98.3
MCNPX	1405	1913	2.0	0.0	1.8	98.2

[a] Uncertainties in the unfolding. It is not included uncertainties in the response matrix and calibration of the spectrometer.

code along with Mares & Schraube response matrix (Mares and Schraube, 1994; Mares and Schraube).

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