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RESEARCH
Section A

Evaluation and test of the response matrix of a multisphere neutron spectrometer in a wide energy range *
Part III. Validation

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A multisphere neutron spectrometer has been tested in well known neutron fields (two thermal beams and sources of americium–beryllium, californium and californium moderated with heavy water). The spectral distribution of the thermal neutron beams has been considered when comparing the measured sensitivity of the system to that established by calculation. These two values were found to be in good agreement. There is also a good agreement between the measured spectra and the ISO standards and between the measured and the reference dosimetric values for the three neutron sources used. The deviations on the dose equivalent are 0.4% for americium–beryllium, 3% for californium and 8% for californium moderated with heavy water. These satisfactory results contribute to the validation of the spectrometric system for thermal, intermediate and high energies.

1. Introduction

A neutron spectrometer of the Bonner spheres type, has been developped at the Institute for Radiation Physics in Lausanne and calibrated with thermal and monoenergetic neutrons [1]. Its response matrix has been established by calculation using the one-dimensional particle transport code ANISN and adjustment to the calibration data [2]. The spectrometer has been used in a large measurements campaign in a variety of neutron fields inside four Swiss nuclear power plants [3] and around particle accelerators [4].

Before using the spectrometer for the characterization of unknown neutron fields, its global performance has been tested in known neutron spectra. This test includes the measurements undertaken in a previous work in two reference thermal neutron beams [1] and those performed in the field of three reference neutron sources at the Paul Scherrer Institute (PSI) in Würenlingen (Switzerland). This paper describes the experimental conditions for the measurements at PSI, and presents the main results of the spectrometer's test. The aim of this test has been to validate both the spectrometer's response matrix and the unfolding procedure.

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2. Material and methods

2.1. The thermal neutron beams

The thermal neutron beam of the Centre for Nuclear Studies (CEN) in Cadarache (France) is produced by 12 calibrated americium–beryllium sources (592 GBq each) disposed around the central cavity of the SIGMA reference pile. The thermal neutron reference beam of the PTB research reactor is produced by placing a beryllium scatterer in the primary beam. The two facilities are briefly described in a previous publi-

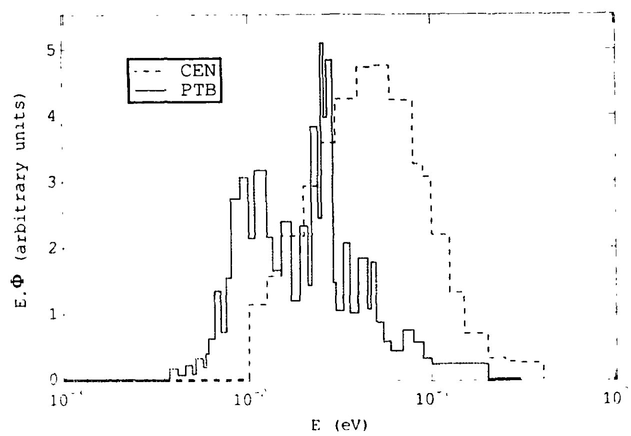

Fig. 1. Thermal neutron spectra at CEN (Cadarache) and PTB (Braunschweig).

cation [1]. Fig. 1 presents the spectral distribution of the sub-cadmium neutrons for the two thermal beams and shows that the two spectra have different shapes and mean energies.

2.2. The reference neutron sources

The irradiation hall at PSI is 13.24 m long, 6.70 m wide and 3.41 m high. It is provided with a 2.50 m deep pit that extends over more than half its area. The pit is covered with a grid which reduces the contribution of the radiation scattered by the floor. The reference neutron sources are americium–beryllium (Am–Be), californium-252 (Cf) and californium-252 moderated with a $\varnothing = 30$ cm sphere filled with heavy water ($Cf(D_2O)$). The emission of the Cf source is $3.52 \times 10^{+8} \pm 2.5\%$ n/s in 4π sr (10/11/1986); that of the Am–Be source is $9.15 \times 10^{+6}$ n/s in 4π sr. The Cf source presents an anisotropy of 1.01 in the horizontal plane. Concerning the $Cf(D_2O)$, the neutron loss in the sphere due to the moderation by heavy water and the capture in cadmium, is estimated at 11% for the moderating sphere used.

The measurement point for the Bonner spheres is situated at a height of 1.42 m relative to the grid. This corresponds to the height of the sources in the irradiation position. The reference dosimetric values at the measurement points are established using an Andersson–Braun rem-meter calibrated at PTB with neutron sources of the same type [5].

2.3. Evaluation of the scattered radiation

In spite of the large dimensions of the irradiation hall and the presence of a very low scattering floor, the contribution of the scattered radiation can not be neglected. Its evaluation has been undertaken by the shadow cone technique [6]. The shadow cone used is 50 cm long and has a half angle α of 5.143°. For a correct use, it is recommended [6] that the cone shadows completely the instrument under investigation. The cone should not cover a solid angle greater than twice that subtended by the instrument, in order to avoid overshadowing problems. These considerations allowed the choice of an optimum source-detector distance of 190 cm. This provides a total shadowing of the biggest sphere used, but leads to an overshadowing of the small ones. Fortunately this is not so important in our case, since the measured spectra are quite hard and are determined mainly by the high diameter spheres' indications. The source–cone distance was 3 cm for the Cf source and 5 cm for the Am–Be one. These values are optimized and situated in a region where the source–cone distance is not critical [5]. In the case of $Cf(D_2O)$ the moderating sphere dimensions ($\varnothing = 30$ cm) prevented the use of the shadow cone. It has been replaced by a block of boron-loaded paraffin with the dimensions $40 \times 60 \times 30$ cm^3 placed at 56.5 cm from the centre of the sphere.

2.4. The unfolding of neutron spectra

The results obtained by the Bonner spheres are unfolded by a version of the code SAND [7] using a 640 energy groups structure. The unfolding code provides, in addition to the neutron spectrum and the total neutron fluence, different dosimetric quantities such as:

- $\hat{D}_n$ and $\hat{H}_n$ using conversion factors given in ICRP publication 21 [8];
- D_n^* (10), H_n^* (10), $Q_m = H_n^*(10)/D_n^*(10)$ and the effective dose equivalent, using conversion factors given in ICRP publication 51 [9];
- H_n^* (10), $Q_m = H_n^*(10)/D_n^*(10)$ using new conversion factors based on the recent recommendations of ICRP publication 60 [10].

Table 1
Difference between calculated and measured values of thermal neutrons sensitivity in cm^2, both at CEN (Cadarache) and PTB (Braunschweig)

Sphere diameter [in.]	Neutron sensitivity [cm^2]					
	At CEN			At PTB		
	Measured	Computed	Deviation [%]	Measured	Computed	Deviation [%]
2	0.18	0.18	<1	0.110	0.116	5
2.5	0.16	0.16	<1	0.097	0.099	2
3	0.14	0.15	7	0.084	0.087	4
4.2	0.096	0.102	6	0.057	0.057	<1
5	0.072	0.076	5	0.043	0.043	<1
6	0.048	0.053	10	0.030	0.029	−4
8	–	–	–	0.0126	0.0120	5
9	–	–	–	0.0083	0.0083	<1

Our version of SAND has given satisfactory spectrometric and dosimetric results in a recent European intercomparison of unfolding computer codes [11]. A detailed test of SAND and its comparison with two other codes will be given in a separate paper [12].

3. Results

3.1. The reference thermal neutron beams

The measured sensitivities of the Bonner spheres at thermal energies are compared to those obtained by convolution of the thermal neutron spectra (fig. 1) with the spheres' adjusted response functions. Concerning the results at PTB, this approach required an extrapolation of the response functions from the mean energy of the last thermal group to the low energy limit of the thermal spectrum. A linear extrapolation in a log–log scale has been performed. The results of the comparison between measurements and calculation for both CEN and PTB thermal neutron beams are presented in table 1. The mean adjustment factor adopted for the establishment of the response matrix (common multiplying factor for the energy response functions of all the spheres [2]) leads to a good agreement between measurements and calculation for thermal neutrons. The thermal beams can be considered as monoenergetic of equivalent energies 0.06 eV and 0.028 eV for CEN and PTB respectively. The deviation between measurements and calculation is reasonably low if these values are considered (< 10% for all the measurements).

3.2. The reference neutron fields

The spectrometric results are presented in figs. 2 and 3. Fig. 2 shows a comparison between the count rates measured by the spheres and those obtained by convolution of the spheres' response functions with the neutron spectra associated with the three sources. The standard spectra are those recommended by ISO [13]. The measurements and the calculation are in good agreement if we consider the experimental errors and those associated with the response matrix. For small and intermediate spheres and for Am–Be and Cf sources the measured count rates are slightly greater than the values established by calculation. This high contribution of intermediate energies neutrons in the measured spectra can be attributed to the overshadowing of the small and intermediate spheres during the measurement.

Fig. 3 presents the experimental neutron spectra unfolded by the program SAND in comparison with the ISO standard spectra. A satisfactory agreement has been obtained for the fast-neutron sources, taking into account the low energy resolution of the Bonner spheres system. For the Cf(D_2O) source the agreement is poorer, due to the fact that the correction of scattered radiation has been performed by a large paraffin block instead of a shadow cone.

Table 2 presents the dosimetric results corresponding to pure spectra (corrected for scattered radiation) obtained by Bonner spheres and compares them to the reference values. The results are in good agreement, the deviations on the dose equivalent being 0.4% for Am–Be, 3% for Cf and 8% for the Cf(D_2O) source.

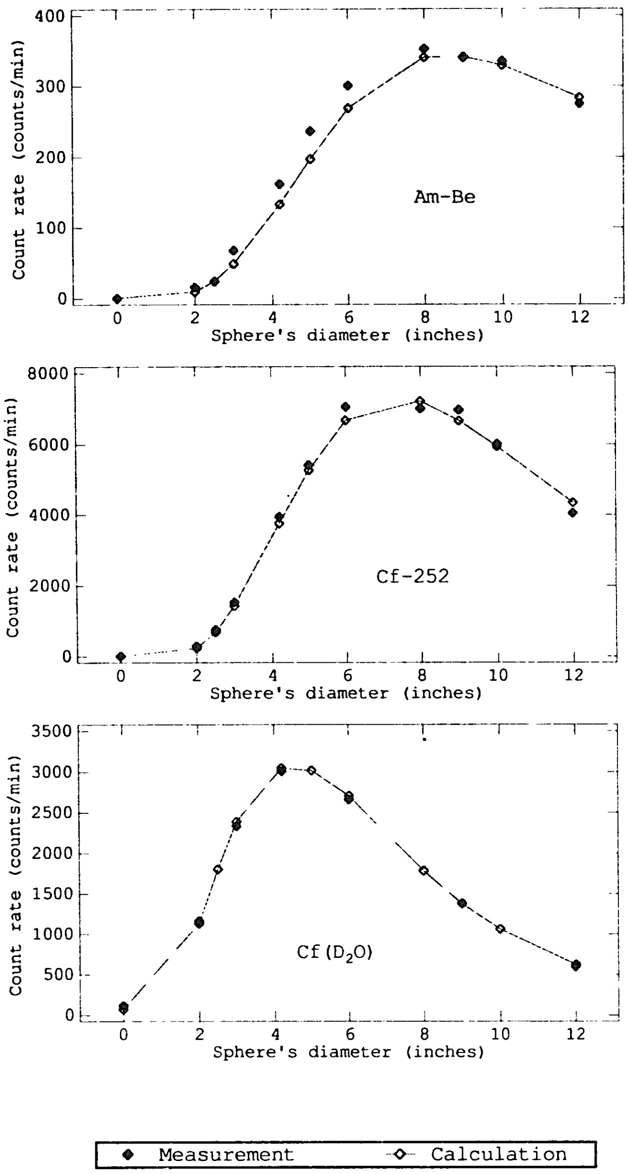

Fig. 2. Comparison of the count rates measured by Bonner spheres and those calculated from the ISO standard neutron spectra for Am–Be, ^{252}Cf, and D_2O-moderated ^{252}Cf sources. The standard error on the experimental data is comparable to the size of the graphic symbols.

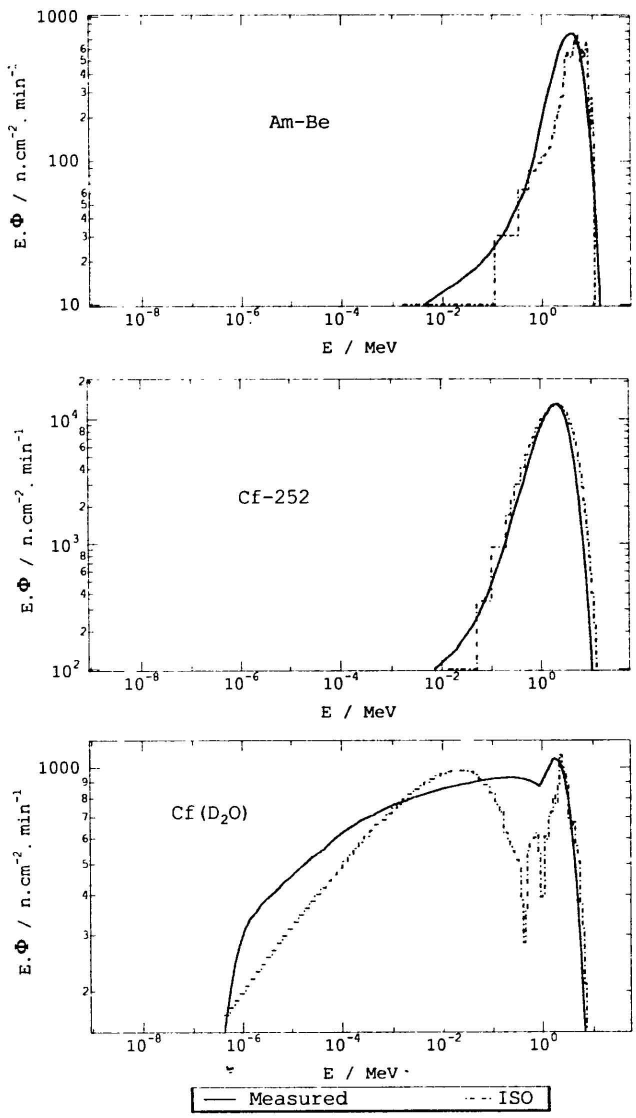

Fig. 3. Comparison between the experimental neutron spectra (scatter subtracted) and the ISO standard spectra for Am–Be, ^{252}Cf, and D_2O-moderated ^{252}Cf sources.

The origin of the larger deviation for the moderated Cf source has been explained before.

Our result for Cf can be compared with the work reported recently [14] where four multisphere spectrometers have been evaluated. The intercomparison of the systems was performed in seven reference neutron fields of different hardness. The dosimetric results reported for Cf show deviations from reference values of −2.4% to −5.7%. The authors showed that these deviations can reach about 30% in the case of soft reference neutron spectra and attributed this to the uncertainty on the response matrix used and to the insufficient energy resolution of the system, especially in the intermediate energy range.

The results presented in fig. 3 and table 2 represent a validation of the performance of the Bonner spheres system concerning:

– the response matrix (both shape and absolute value) for the energy range considered in this test;

– the unfolding procedure [both differential (spectral) and integral (fluence, dose equivalent) results].

Due to the complex interdependence of these factors, the experimental assessment does not allow to draw quantitative conclusions about the individual influence of each of them on the final result. However, the good agreement between the experimental results and the reference values (both spectral and dosimetric ones) is interpreted as a global validation of the system's performance.

Table 2
Neutron dose equivalent rate at 190 cm from the source

Source	Reference value [μSv h^{-1}]	Bonner spheres [μSv h^{-1}]
Am–Be	27.3	27.4
Cf	450	465
Cf(D_2O)	68	63

4. Conclusion

A multisphere neutron spectrometer has been tested in well known neutron fields. The overall results obtained with the thermal neutron beams are satisfactory. For the Am–Be, Cf and Cf(D_2O) sources, the neutron spectra unfolded from the spheres' measurements agree well with ISO standards and the deviation of the dose equivalent rates from the reference values is low. The work presented in this paper allowed a good evaluation of the spectrometric system and increased the confidence in the accuracy of its response matrix and in the unfolding method for thermal, intermediate and high energies.

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