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Application of Bonner spheres spectrometer in Californium-252 neutron field dosimetry

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Abstract. For the health physicist, it is a difficult problem to determine the neutron dose equivalent. There are several different procedures to solve such problem. In this paper the neutron fluence energy spectrum, the dose and the dose equivalent due to a Cf-252 neutron source are determined using a Bonner spheres spectrometer and the BUNKIUT computer code.

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1. Introduction

It is difficult for the health physicist to establish the dose equivalent for radiation fields where the major field component is neutrons [1,2]. In such cases several procedures have been proposed and many instruments have been built to detect the neutrons in complex radiation fields [2-6]. This problem becomes quite important in certain cases, where the neutron measurements are related with the neutron radiation cancer studies treatment [6-10] and with calibration-rooms characterization [11-16].

One of the most frequently used neutron detection system is the Bonner spheres spectrometer [17-22], which in its original design consisted of a small ^{6}LiI(Eu) crystal detector, which could be positioned at the center of any five polyethylene spherical moderators, 2 to 12 inches in diameter.

In this paper, the energy spectrum, the dose spectrum and the dose equivalent is presented for measurements for a Californium-252 neutron source obtained using a Bonner sphere spectrometer.

2. Theory

As the neutrons traversing a moderating material undergo elastic and/or inelastic scattering, they lose energy until they reach thermal equilibrium and eventually are absorbed or leave the moderator [22–25]. This process is known as neutron slowing down or moderation. Good moderating materials are hydrogen, deuterium, beryllium and carbon, since they have high scattering to absorption cross section ratios.

The response of a neutron detector system depends on the energy spectrum fluence at the center of a moderator. If a neutron detector system is placed at the center of a set of spherical moderators of different diameters, each detector-moderator combination will have a different response as a function of neutron energy.

The response of each detector to a neutron spectrum, $T(E)$, may be written as a inhomogeneous Fredholm equation,

$$M_j = \int_0^\infty T(E) R_j(E)\, dE, \tag{1}$$

where M_j is the spectrum measured by the j^{th} detector, $T(E)$ is the energy spectrum of the neutron field and $R_j(E)$ is the absolute response for jth detector as a function of neutron energy.

3. Experimental

The Bonner spheres spectrometer used in this experiment was a cylindrical shaped ^{6}LiI(Eu), 4 mm × 4 mm, scintillator crystal, which detects neutrons though the nuclear reaction,

$$^6\mathrm{Li}(n,\alpha)\,^3\mathrm{H}, \qquad Q = 4.8\ MeV,$$

the alpha particle produce a relatively large light output. This high Q-value nuclear reaction, the relatively low density of $^6LiI(Eu)$ and the small crystal dimension result in high neutron-photon discrimination.

We used six different diameter polyethylene spheres and the ^{6}LiI(Eu) scintillator detector positioned at the center of the spheres. For each diameter we got foreground and background measurements; for the last we used a set of shadowing cones. The shadow cones were made of a stainless steel section followed by a paraffin and borax mixture in order to attenuate all the neutrons coming directly from the neutron source.

In order to align the Cf-252 neutron source and the detector, a laser alignment system was used. In the Fig. 1 the experimental setup is shown.

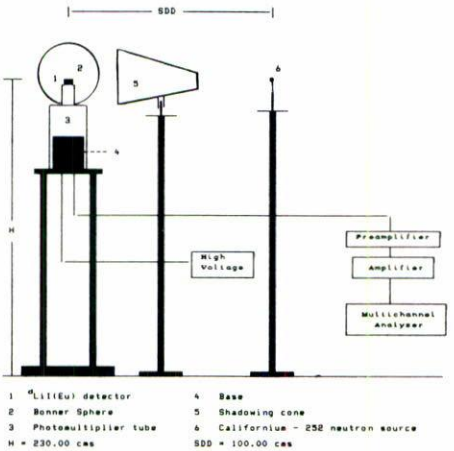

FIGURE 1. Experimental setup.

4. Results

In order to solve the inhomogeneous Fredholm equation in a discrete energy group a computer code named BUNKIUT, a PC version adapted by N.E. Hertel of the University of Texas [28] from the BUNKI by K. Lowry and T. Johnson [29], was used.

The BUNKIUT code solves the next M linear equations in N unknowns, where M is the number of detectors utilized and N is the number of points or intervals, needed to define the spectrum. Thus Eq. (1) becomes

$$a_j = \sum_{i=1}^{N} \sigma_{ij} X_i \qquad (j = 1, 2, 3, \ldots, M), \tag{2}$$

where a_j is the count for the j^{th} detector, σ_{ij} is the response of the j^{th} detector to the neutrons in the i^{th} energy interval and X_i is the neutron fluence in the i^{th} energy interval.

To solve Eq. (2), BUNKIUT uses a 31-group response matrix, and outputs a percent error that is the difference between the count rates predicted with the flux solution and the measured count rates for each sphere added in quadrature. This error is indicative of the consistency between the solution generated in the code and the input data.

The experimental results are shown in the Table I, here the corrected count rate was obtained by measuring the pulse height spectrum three times for each sphere, obtaining the average and doing the correction for the background measured three times as well. The total calculated fluence was 1.281×10^4 neutrons/cm^2, the total dose was 3.563×10^{-5} ad while the total dose equivalent was 3.721×10^{-4} rem. In Table II, the data are were obtained from the computer code. In Fig. 2 the unfolded

Detector	Bonner sphere diameter (cm)	Corrected count rate (counts/sec)
Bare	0.00	9.50 ± 3.08
1	5.08	117.35 ± 10.83
2	7.62	761.20 ± 27.59
3	12.70	2819.20 ± 53.10
4	20.32	3368.60 ± 58.04
5	25.40	2672.40 ± 51.70
6	30.48	769.42 ± 27.74

TABLE I. Experimental measurements obtained with different detector-neutron source combination.

Neutron energy (MeV)	Fluence (Neut/cm^2)	Dose (Rad)	Dose equivalent (Rem)
4.140×10^{-7}	3.802×10^{-1}	2.000×10^{-8}	$.376 \times 10^{-8}$
6.826×10^{-7}	7.053×10^{-4}	4.294×10^{-13}	8.689×10^{-13}
1.445×10^{-6}	1.315×10^{-4}	8.121×10^{-14}	1.649×10^{-13}
3.059×10^{-6}	7.971×10^{-6}	4.890×10^{-15}	9.916×10^{-15}
6.476×10^{-6}	3.160×10^{-7}	1.918×10^{-16}	3.877×10^{-16}
1.371×10^{-5}	8.137×10^{-9}	4.889×10^{-18}	9.854×10^{-18}
2.902×10^{-5}	1.518×10^{-10}	9.063×10^{-20}	1.814×10^{-19}
6.144×10^{-5}	2.664×10^{-12}	1.582×10^{-21}	3.141×10^{-21}
1.301×10^{-4}	7.215×10^{-14}	4.251×10^{-23}	8.377×10^{-23}
2.754×10^{-4}	2.819×10^{-15}	1.606×10^{-24}	3.166×10^{-24}
5.929×10^{-4}	1.786×10^{-16}	9.759×10^{-26}	1.929×10^{-25}
1.234×10^{-3}	2.268×10^{-17}	1.191×10^{-26}	2.359×10^{-26}
2.613×10^{-3}	7.379×10^{-18}	3.800×10^{-27}	7.527×10^{-27}
5.531×10^{-3}	6.300×10^{-18}	3.202×10^{-27}	6.350×10^{-27}
1.71×10^{-2}	1.671×10^{-17}	8.422×10^{-27}	1.686×10^{-26}
2.479×10^{-2}	1.599×10^{-16}	8.999×10^{-26}	2.421×10^{-25}
5.247×10^{-2}	8.187×10^{-15}	5.435×10^{-24}	2.200×10^{-23}
1.111×10^{-1}	9.150×10^{-12}	7.180×10^{-21}	4.369×10^{-20}
2.237×10^{-1}	9.381×10^{-6}	9.738×10^{-15}	7.785×10^{-14}
4.508×10^{-1}	5.087×10^{0}	7.397×10^{-9}	7.203×10^{-8}
9.072×10^{-1}	6.785×10^{3}	1.523×10^{-5}	1.622×10^{-4}
1.872×10^{0}	5.982×10^{3}	2.038×10^{-5}	2.097×10^{-4}
3.679×10^{0}	2.149×10^{-3}	9.067×10^{-12}	8.584×10^{-11}
7.408×10^{0}	7.595×10^{-14}	4.388×10^{-22}	3.093×10^{-21}
1.492×10^{-1}	1.561×10^{-23}	1.034×10^{-31}	6.417×10^{-31}
2.81×10^{1}	7.436×10^{-27}	6.765×10^{-35}	3.239×10^{-34}

TABLE II. Fluence, dose and dose equivalent spectra calculated, from the experimental data, using the Bunkiut computer code.

Californium-252 neutron energy spectrum is plotted. In Fig. 3 the dose and the dose equivalent spectrum due to the neutron source are plotted.

5. Conclusions

Although the Bonner spheres spectrometer has inherently poor energy resolution, the results shown herein indicate that it can reliably be used as neutron spectro-

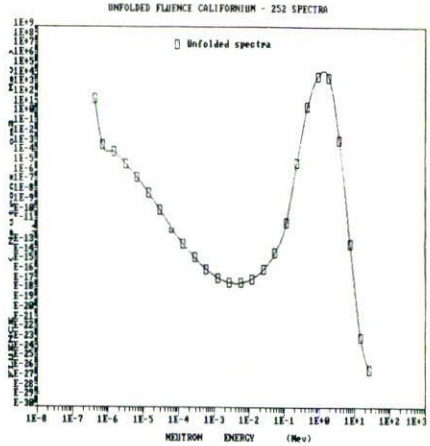

FIGURE 2. Unfolded fluence energy spectrum of 6 cm Californium-252 neutron source.

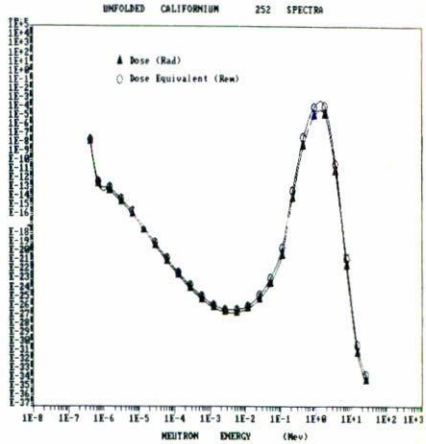

FIGURE 3. Dose and dose equivalent spectrum of a Californium-252 neutron source.

meter. Compared with other detection systems such as foil activation detectors and NE-213 spectrometers, for instance, the Bonner spheres spectrometer is easy to use. The dose equivalent for any neutron source can also easily determined use Bonner sphere spectrometers using the same procedure discussed here.

Acknowledgments

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Resumen. Existen diferentes procedimientos que se emplean en la dosimetría de un campo mixto de radiaciones, pero el problema reviste especial interés cuando el campo de radiación es debido a neutrones. Aquí se presentan los resultados obtenidos al determinar el espectro en energía de la fluencia de neutrones, la dosis y la dosis equivalente debida a una fuente de Californio-252 mediante el empleo del sistema espectrométrico llamado esferas de Bonner y el uso de un programa de cómputo denominado BUNKIUT.