Evaluation of the Response of a Bonner Sphere Spectrometer with a ^{6}LiI detector using 3D meshed MCNP6.1.1 models

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Abstract

In order to undertake further studies on neutron spectra deconvolution in radiotherapy LinAc bunkers after using high megavolts treatment beams, it has been calculated the theoretical Response Function for a widespread neutron Bonner Sphere Spectrometer (BSS) exposed to arbitrary neutron sources. The neutron response function of the Bonner spectrometer is of essential importance for its neutron spectrum unfolding procedure and is directly related to the quality of the unfolded spectrum. Response detector curves from 10 keV to 20 MeV have been obtained by Monte Carlo (MC) simulation with MCNP6.1.1, where the use of unstructured mesh geometries is introduced as a novelty. In order to validate the accuracy of the MCNP6 simulation, we have used the detector model to measure an ^{241}Am-Be neutron source, and the obtained neutron counts of the spectrometer and simulated counts are found to be very consistent, with a relative error below 10%. This comparison shows that the estimation of the Bonner sphere neutron response by MCNP6 is highly precise.

Keywords: Response function, Bonner sphere spectrometer, BSS, MCNP6, Monte Carlo, ^{241}Am-Be neutron source

1. INTRODUCTION

Neutron spectrum study is of great significance in measuring the potential overdose received by patients undergoing radiotherapy treatments with high energy beams. The present work completes the previous step to determine neutron spectrum generated by a Medical Linear Accelerator (LinAc) Varian TrueBeam using a multisphere spectrometer. The quality factor of neutrons depends upon the neutron energy; also, the response of neutron monitors and dosimeters depend upon the energy of neutrons. So, spectrometric information on the neutron radiation field is very important in radiation protection [1].

The Bonner Sphere Spectrometer (BSS) is a device used to determine the energy distribution, also known as spectrum, of neutrons. The method was first described in 1960 by *Bramblett*, *Ewing* and *Bonner* [2] and it is widely used nowadays for radiation protection purposes since it is the only device that can detect a wide neutron energy range from thermal to hundreds of MeV. The spectrometer is a set of different-diameter moderating spheres, with a thermal neutron in the center. It has a poor resolution but offers an isotropic response.

In this case, the BSS used is based on a thermal detector, the associated electronics of a scintillator as ^{6}LiI(Eu) and a set of polyethylene spheres. These spheres act as moderators for higher energy neutrons and they thermalize the neutrons to a degree depending on the initial energy and the sphere diameter. Fast neutrons slowdown in the moderator and they arrive at the detector in thermal state, while initially thermal neutrons are partially absorbed and these neutrons do not reach the detector.

The main objective of this work is to estimate the neutron response of a neutron multisphere spectrometer equipped with a ^{6}LiI(Eu) detector, using Monte Carlo simulations [3, 4]. Given the response matrix of the BSS and an unfolding algorithm, the system will be used to evaluate the neutron spectrum generated by a radiotherapy bunker facility. The validation of the response matrix obtained by simulation represents the first step to perform the necessary deconvolution to obtain the neutron energy spectrum, since a good knowledge of the response matrix of the BSS is crucial for obtaining reliable spectrometric results.

According to this, the obtained response function was compared with other response functions found in literature, and we also employ ^{241}Am-Be neutron source experimental measurements to test the simulation accuracy.

Moreover, this work presents two novelties, the use of the new cross section tables ENDF/B-VII and the generation of unstructured meshed geometries in the simulation. The use of meshed geometries allows refine the mesh in the interest zones of the detector.

2. METHODS AND MATERIALS

2.1 Description of the BSS system

The neutron detector device used in this work has been selected for its good quality. It is formed by a multispheres spectrometer (BSS) that uses 6 high-density polyethylene spheres with different diameters. Concretely, the BSS consists of a set of 0.95 g/cm^3 [5] high-density polyethylene spheres. The 6 spheres diameters: 0 inch (bare detector), 2, 3, 5, 8, 10 and 12 inches. Such configuration allows getting neutron spectral information from thermal to hundreds of MeV.

The detector is composed of a lithium iodide (^{6}LiI-Eu) cylindrical scintillator crystal 4mm x 4mm size (LUDLUM Model 42-5) [6] coupled to a photomultiplier tube. The scaler LUDLUM 2200 is coupled for neutron counting.

A cross sectional view of the central detector is shown in Figure 1. As it can be seen, the whole assembly has a cylindrical geometry and the active part corresponding to the ^{6}LiI crystal is located at 0.9 cm from the right external surface of the Aluminum assembly. Detector inside is vacuum and the light pipe connecting the scintillator to the photomultiplier (green part in figure) is Plexiglas.

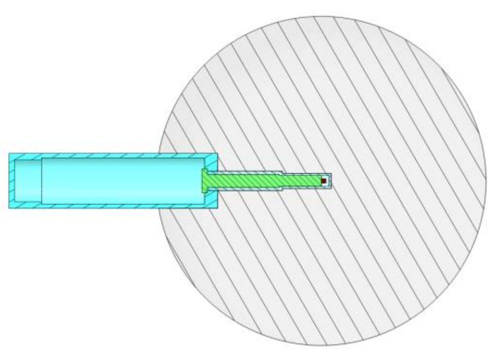

Figure 1. Central axis cross sectional view of the BSS detector.

Its measurement technique is quite simple [7]. The thermal neutron detector is set inside spheres being sensitive to higher energy neutrons depending on the thickness of the moderator sphere. With a sequence of different spheres sizes (Figure 2), the inner scintillator can register neutrons over a wide energy range, and information about the neutron spectrum can be gained from the counts rate corresponding to each sphere. The neutron spectrum can be unfolded then using a specific energy unfolding mathematic algorithm.

Figure 2. BSS detector measuring neutrons in a radiotherapy Linac room.

2.2.BSS response function

The normalized response (in cm^2) of a Bonner Sphere is defined as the expected number of reaction counts caused by the incident neutrons of a unit flux from a parallel source divided by the neutron fluence at the point where the center of the sphere is placed in the absence of the sphere [8]:

$$R(E) = \frac{N}{\Phi(E)} \qquad \Phi(E) = \frac{1}{S_{si}}\left(\frac{neutrons}{s \cdot cm^2}\right) \qquad N\left(\frac{counts}{s}\right)$$

where N is the number of detector counts, and $\Phi(E)$ is the neutron flux at energy E (n/cm^2). Assuming both an isotropic neutron field and BSS response, $R(E)$ for each sphere configuration is given by the equation:

$$R_i(E) = \Phi i\,(E) \cdot S_{si} \cdot\ N_{Li-6} \cdot\ V_{Cristal} \cdot\ \sigma_{(n,\alpha)}(E)$$

where Φ is the particle fluence (cm^{-2}/s), S_S is the area of the neutron disk source (cm^2), $N_{Li} = 1.525 \cdot 10^{-2}$ atoms/barn·cm is the ^6Li atomic density (in $10^{24}/cm^3$), $V_{Cristal}$ is the volume of the counter (cm^3) and $\sigma_{(n,\alpha)}$ is $^6Li(n,\alpha)^3H$ cross section (barn).

2.3. BSS theoretical response by Monte Carlo simulation

Simulations have been performed with general-purpose Monte Carlo N-Particle code version 6.1.1 (Los Alamos National Laboratory). Particularly, this new version introduces as a novelty the use of non-structured meshed geometries designed by means of CAD-CAE software improving the accuracy of models geometry definition that could lead to a calculation accuracy improvement [9].
A detailed detector model was created according to the detector layout and manufacturer´s information using meshed geometries and the different spheres were modeled to perform the six simulations corresponding to each of them.
Next image (*figure 3*) shows the 3D meshed model and the neutron flux distribution registered inside the 10-inch moderator sphere.

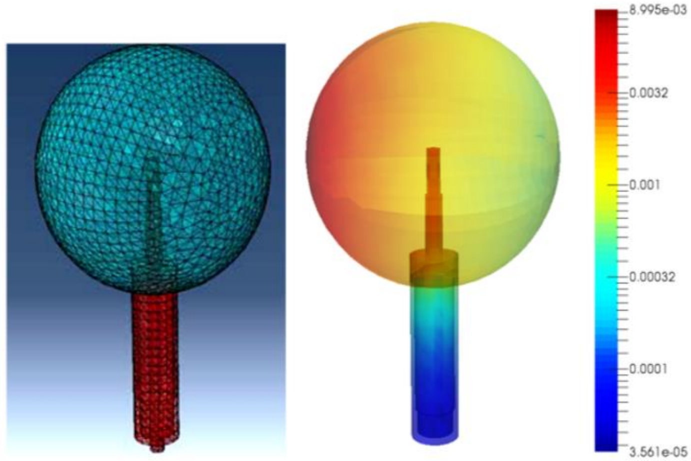

Figure 3. Meshed model and three-dimensional Neutron Flux distribution inside the moderator sphere (part/cm^2).

To obtain the BSS response function, incident monoenergetic neutron beams from 10 keV to 20 MeV using 29 energy bins have been used for each sphere and without it (a total of 203 simulations).
All the spheres are irradiated in vacuum by a parallel discrete neutron beam of the same cross sectional area of the corresponding sphere.

Thermal S(α,β) tables are required to polyethylene cross section since they are absolutely essential to get correct answers in problems involving neutron thermalizations. Chemical binding and crystalline effects of polyethylene spheres during thermal neutron scattering were taken into account using the S(α,β) treatment [10]. The detector modeled has a density of 3.494 g/cm^3 and it is composed by 4.36 w/o of ^{6}Li, 0.18 w/o of ^{7}Li and 95.46 w/o of I [11].
The MCNP6 cross section treatment is continuous, with linear interpolation between energy points. The continuous energy neutron cross sections used are those available in the standard package, and extracted from Evaluated Nuclear Data Files: ENDF/B-VII. For the case of polyethylene, poly.20t has been used.

The tally used in these MCNP6 simulations was the neutron fluence (as a function of energy) within the scintillator detector, and using adequate cross sections, the number of ^{6}Li(n,α)^{3}H reactions per incident neutron is obtained. In this work, the response is calculated in terms of number of reactions per unit fluence (i.e. cm^2 as unit) expressed as a function of neutron energy.
The simulations run 10^8 neutrons to achieve relative statistical uncertainties under 3%.
Figure 4 presents the neutron response function of the BSS system after applying the procedure to all six spheres.

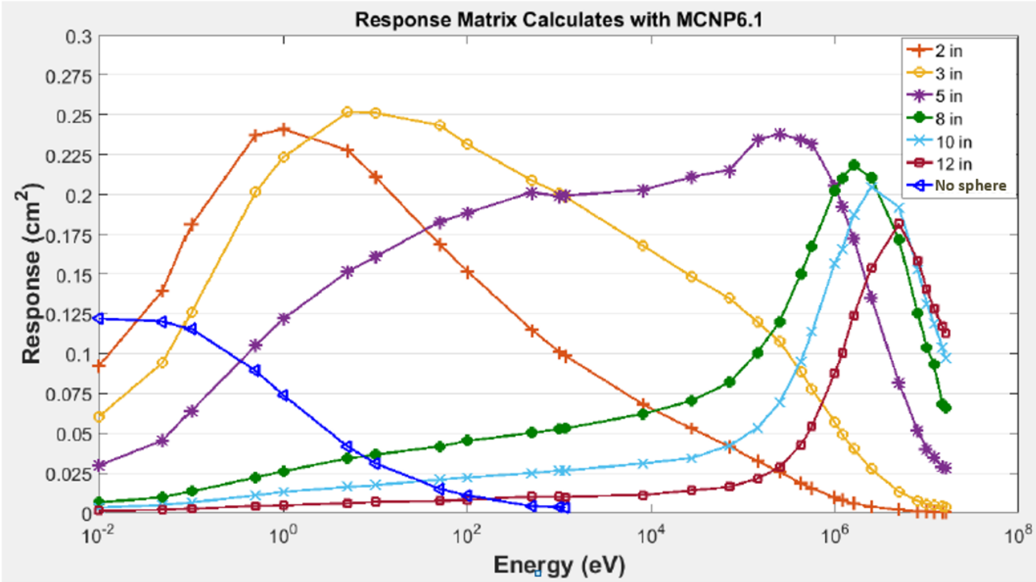

Figure 4. Neutron response of the BSS system as function of energy calculated with MCNP6.

From the figure, we can obviously find that as the sphere size increases, the peak of the response function gradually moves to the high-energy range, the larger sphere tend to be more sensitive to higher energy neutrons.

We compared this response matrix with the other response function of the same type taken from the published literature [11, 12, 13, 5], and found they fit very precisely (less than 3% maximum error). An example of this comparison is shown in Figure 5.

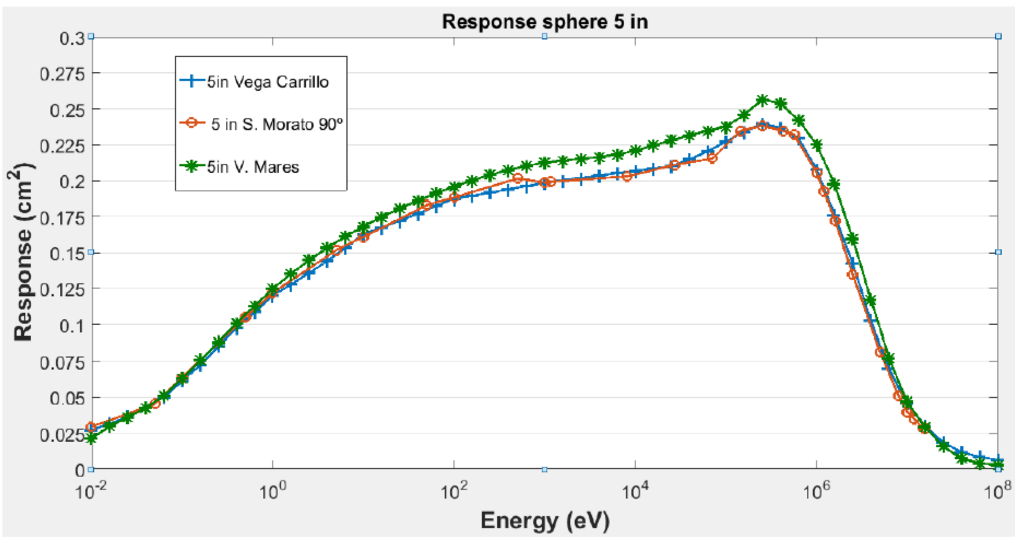

Figure 5. Response using the sphere 5 compared with literature.

3. RESULTS AND VALIDATION

To verify the accuracy of the MCNP6 simulation in calculating the BSS response function, we carried out an experiment using BSS to measure the ^{241}Am-Be neutron source from a surface moisture-density gauge (Troxler 3430 Plus®). This neutron source belongs to the unique radioactive facility of the *Universitat Politècnica de València* and its activity is 1.48 GBq and presents a neutron emission rate of $7 \cdot 10^4$ neutrons per second.

Figure 6 shows the experiment environment with different sphere sizes. The ^{6}LiI crystal was located at 20 cm distance from neutron source. We measured the neutron count rates for each sphere applying a gamma rejection methodology according to LUDLUM methodologies recommended [6].

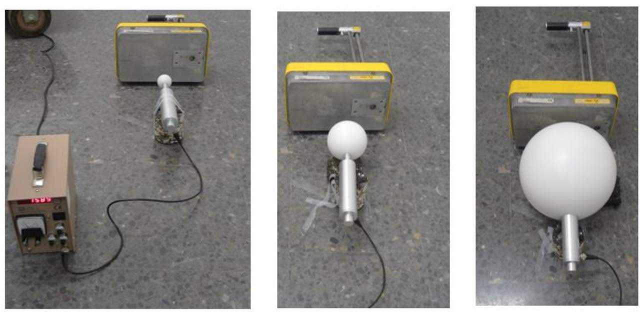

Figure 6. 241Am-Be neutron source measuring with the BSS system

On the other hand, we undertook MCNP6 simulations to reproduce closely the real experiment process, although for simplifying simulations the floor was not included. In this case, the neutrons were emitted for diverging instead of parallel. The spectrum of the emitted neutron was obtained from the ISO 8529-1 standard ^{241}Am-Be spectrum [14]. In the simulation, 10^7 neutrons were emitted for each sphere (bare detector is not necessary for spectrum reconstruction), and we normalized the simulated counts and the real-measured counts and then compare them in Figure 7, where the error bars of the simulated results are plotted. As it can be seen, the detector response is expressed in relative counts normalized to 10" sphere response.

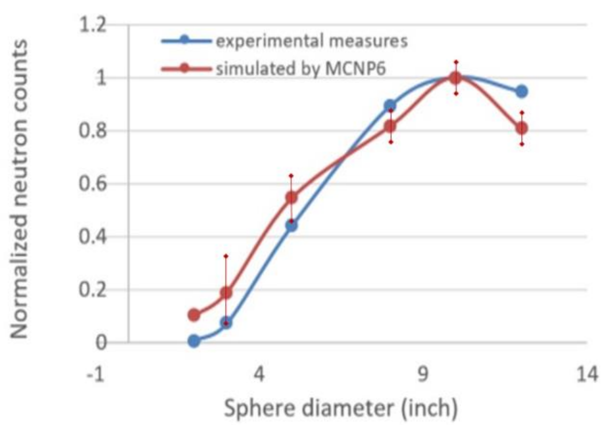

Figure 7. 241Am-Be measured neutron counts compared with simulated neutron counts after normalization.

The comparison shows that MCNP6 results are highly consistent with measures, and the greatest relative error between the two curves was 10 %. In the next future, this process will be applied for the reconstruction of neutrons spectra emitted in facilities with medical linear accelerators, and in these cases the experimental measures to be carried out will be much more detailed, thus reducing the discrepancies between simulation and experimental measures.

4. CONCLUSIONS

The response function of a neutron Bonner Sphere Spectrometer, (planned to be set inside a medical LinAc facility), was carefully calculated with 29 discrete energy beams from 10 keV to 20 MeV with an uncertainty of less than 3%, which was done by simulation based on MCNP6. We also simulated the response of the BSS to the emitted neutrons by an ^{241}Am-Be neutron source from a Troxler® device, and the simulated BSS counts were quite close to the experimental measured counts with errors up to 10%, which has proven the simulation of the BSS's response to neutrons by MCNP6 to be quite accurate. This calculated response function will play a fundamental role in using BSS around a medical LinAc emitting photon beams with energies between 10 and 15 MeV (which are able to generate neutrons because of photonuclear reactions).

This work is just a previous step to achieve the neutron reconstructed energy spectrum that will allow calculate the effective dose due to neutrons in patients and medical staff in radiotherapy facilities.

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