Monte Carlo calculation of the response matrix of a Bonner spheres spectrometer

Hector Rene Vega-Carrillo[a*], Eduardo Gallego[b], Eduardo Manzanares-Acuña[a], Alfredo Lorente[b],

[a]Universidad Autónoma de Zacatecas, Unidad Académica de Estudios Nucleares, Ciprés 10, Fracc. La Peñuela, 98068 Zacatecas, Zac. México

[b]Polytechnic University of Madrid, Nuclear Engineering Department, José Gutierrez Abascal, 2, E-28006, Madrid, Spain.

Abstract. The Bonner spheres spectrometer is utilized to estimate the neutron spectrum of neutrons from thermal up to several MeV neutrons. Its response is increased to few GeV neutrons by introducing large Z materials as inner shells. To use the spectrometer a matrix response and an unfolding method are required; these are crucial to assure the quality of spectrometer output. The response matrix of a Bonner sphere spectrometer was calculated by use of the MCNP code. As thermal neutron counter the spectrometer has a 0.4 Ø × 0.4 cm2 ^{6}LiI(Eu) scintillator which is located at the centre of a set of polyethylene spheres. The response functions were calculated for 0, 2, 3, 5, 8, 10, and 12 inches-diameter polyethylene spheres for neutrons whose energy goes from 10^{-8} to 100 MeV. For energies from 10^{-8} to 20 MeV the MCNP4C code was utilized while for neutrons from 20 to 100 MeV calculations were carried out with MCNPX code. The response functions were compared with those reported in the literature.

KEYWORDS: Monte Carlo, Bonner spheres spectrometer, Matrix response, neutrons

1. Introduction

In 1932 Chadwick did prove the existence of neutrons [1], since then neutrons have become an important tool in several fields. In 1960 the multisphere spectrometer, also known as Bonner sphere spectrometer (BSS), was introduced in the aim to measure the neutron energy distribution, known as neutron spectrum [2]. BSS is a set of different sizes polyethylene spheres where alternatively a thermal neutron detector is located at their centre. From 1960 to 1979 several advances in computer unfolding methods, the application of semiconductor detectors to neutron spectrometry and the introduction of superheated drop detectors contributed to progress in neutron spectrometry [3].

With the BSS the neutron spectra is obtained from thermal up to at least 20 MeV [4]. By adding intermediate shells of lead to the moderator spheres the BSS is utilized to measure neutrons reaching few GeV [5, 6].

Different materials had been utilized as thermal neutron detector in the BSS such as, ^{6}LiI(Eu) scintillator [2, 7], pairs of thermoluminiscent dosimeters (TLD600-TLD700) [8-10], gold and other activation foils [11], track detectors [12], and BF_3 [13] or ^{3}He [14] filled proportional counters. When the detector is located inside the polyethylene spheres the response is modified due to the moderating effect of the spheres. The set of response functions is named response matrix [6, 15].

Inside a neutron field the detector, bare o inside of any sphere, produces a count rate (C). The set of detector's count rates (C), the response matrix (R_Φ (E)), and the neutron spectrum (Φ_E (E)), are related through the Fredholm integral equation of the first kind, shown in equation 1.

[*] Presenting author, E-mail: fermineutron@yahoo.com

$$C = \int_{E_i}^{E_f} R_\Phi(E)\, \Phi_E(E)\ dE \qquad (1)$$

Having the neutron spectrum the neutron dose, Δ, can be estimated using equation 2 [16].

$$\Delta = \int_{E_i}^{E_f} \delta_\Phi(E)\ \Phi_E(E)\ \ dE \qquad (2)$$

Here, δ_Φ (E) are the fluence-to-dose conversion coefficients. Depending of the type of δ_Φ (E) utilized any type of neutron dose can be estimated.

Technological limitations prevent the experimental determination of the response functions using monoenergetic neutrons. This is only practical for few monoenergetic neutrons with energies greater than about a few keV and for thermal neutrons [6]. Therefore the responses have been calculated; this has been realized using the one-dimensional discrete ordinates transport code ANISN [17], Monte Carlo methods with the MCNP code [18, 19], MCNPX code [14], and high-energy codes [5].

The aim of this study was to calculate the response functions of a Bonner spectrometer with a 0.4 ∅ × 0.4 cm^2 ^{6}LiI scintillator. The response matrix includes the 0, 2, 3, 5, 8, 10, and 12 inches-diameter spheres, was compared with the matrix reported in literature. Calculations were carried out using Monte Carlo methods and updated cross section libraries.

2. Materials and Methods

Naturally occurring lithium isotopes are 92.5% ^{7}Li and 7.5% ^{6}Li, while the I has only one natural isotope, ^{127}I; all those isotopes are stable. The ^{6}LiI(Eu) scintillator has ^{6}Li, ^{7}Li, ^{127}I isotopes with smaller amounts of Eu added as impurities. The cross sections of these isotopes are well known [20]. When neutrons reach the scintillator some are absorbed by the different nuclei in the detector. For each type of isotope the amount of neutron absorptions, n_a, are estimated with equation 3.

A realistic model of the detector, including the 0.4 cm × 0.4 ∅ cm ^{6}LiI scintillator, the light pipes, the detector's cask, and the polyethylene spheres was designed. Cases included in the calculations were the bare detector (Ball 0) and those with the detector inserted in the spheres of 2" (Ball 2), 3" (Ball 3), 5" (Ball 5), 8" (Ball 8), 10" (Ball 10), and 12 inches-diameter (Ball 12). In the model design was used polymethyl methacrylate to define the detector's light pipes, the cask was modeled as made of aluminum, and the scintillator was modeled as made of ^{6}Li, ^{7}Li and I; the Eu impurities were excluded.

Each model was irradiated with a parallel neutron beam produced by a disk-shaped neutron source; irradiations were carried out using 20 monoenergetic neutrons for each detector. The energy of the monoenergetic neutron sources varied from 2.50E(-8) to 20 MeV. These calculations were performed with the Monte Carlo code MCNP 4C [21] and the ENDF/B-VI cross section library [22]. Using MCNPX [23], version 2.4.0, the response calculations were extended until 100 MeV neutrons using the LA150 cross section library [24]. In all calculations the response was defined as the number of ^{6}Li(n, α)^{3}H reactions occurring in the scintillator per each neutron emitted by the disk-shaped monoenergetic neutron source.

In calculations reported in literature the scintillator has been modeled with different mass densities: 3.84 g-cm^3 [18], 4.08 g-cm^3 [25]. Also, has been assumed two different values for the ^{6}Li enrichment: 100% [18] and 96.1% [25], resulting in two distinct atomic densities in the scintillator: 1.74E(22) [18] and 1.848E(22) [25] atoms-cm^{-3}.

In this investigation the scintillator was modeled using a density of 3.494 g-cm^{-3} containing weight fractions of 4.36, 0.18, and 95.46 w/o for ^{6}Li, ^{7}Li, and I respectively. These characteristics give a scintillator with an atomic density of 3.162E(22) atoms-cm^{-3}. Moderating spheres were modeled as made of polyethylene with a mass density of 0.95 g-cm^{-3}. Atomic composition and physical data of different elements utilized to build the model were obtained from Seltzer and Berger [26].

Chemical binding and crystalline effects of polyethylene during thermal neutron scattering were taken into account using the S(α, β) treatment [21]. A disk-shaped source term with the same diameter as the moderating sphere was used to represent a monoenergetic neutron source whose neutrons were directed toward the polyethylene sphere.

Polyethylene spheres were modeled as a series of concentric polyethylene shells, each with a different neutron importance, increasing as the sphere center was approached. This was the only variance reduction technique used in the calculations. Throughout the MCNP 4C and MCNPX calculations the number of histories used for each sphere was large enough to have uncertainties less than 3%. The calculated responses were interpolated to include a larger number of energy bins and were compared with the response functions reported in literature.

3. Results and Discussion

In figure 1 the response functions for 0, 2, and 3 inches-diameter polyethylene spheres, as a function of neutron energy, are shown. The bare detector (Ball 0) has the shape of ^{6}Li cross section. As the sphere's diameter is increased the response tends to decrease for thermal and epithermal neutrons. On the other hand, the maximum in the responses is shifted to higher energies for large spheres. This is in agreement with the response matrix reported in the literature [17, 18] even regardless the type of thermal neutron detector [12, 15].

Energy-interpolated response functions are compared with those reported by Mares and Schraube [18]. It can be noticed that the response function for the bare detector is strongly influenced by the (n, α) ^{6}Li cross section, and how this is modified by the presence of the sphere moderators.

In figure 2 are shown the response functions for 5, 8, 10 and 12 inches-diameter, together with the Mares and Schraube response functions. Here can be noticed that both agrees well.

For Ball 2 to Ball 12 the main differences are in the low energy region and for neutrons whose energy is larger to 20 MeV, i.e. those values calculated using MCNPX. Probable explanation of this difference is attributed to the cross sections utilized by Mares and Schraube for neutrons beyond 20 MeV. They utilized the HIGH library [18], while in this study the LA150 cross section library was utilized in the MCNPX code.

The χ^2 test was applied to compare the response functions here calculated with those reported by Mares and Schraube. The test was applied using α = 0.95 and 22 degrees of freedom; for these parameters the χ^2-critical value is 12.338. The calculated chi-square values for each detector are smaller than the critical chi-value. Meaning that there is not significant difference between the response functions calculated in this work and those reported by Mares and Schraube.

Figure 1: Response functions for 0, 2 and 3 inches Bonner spheres.

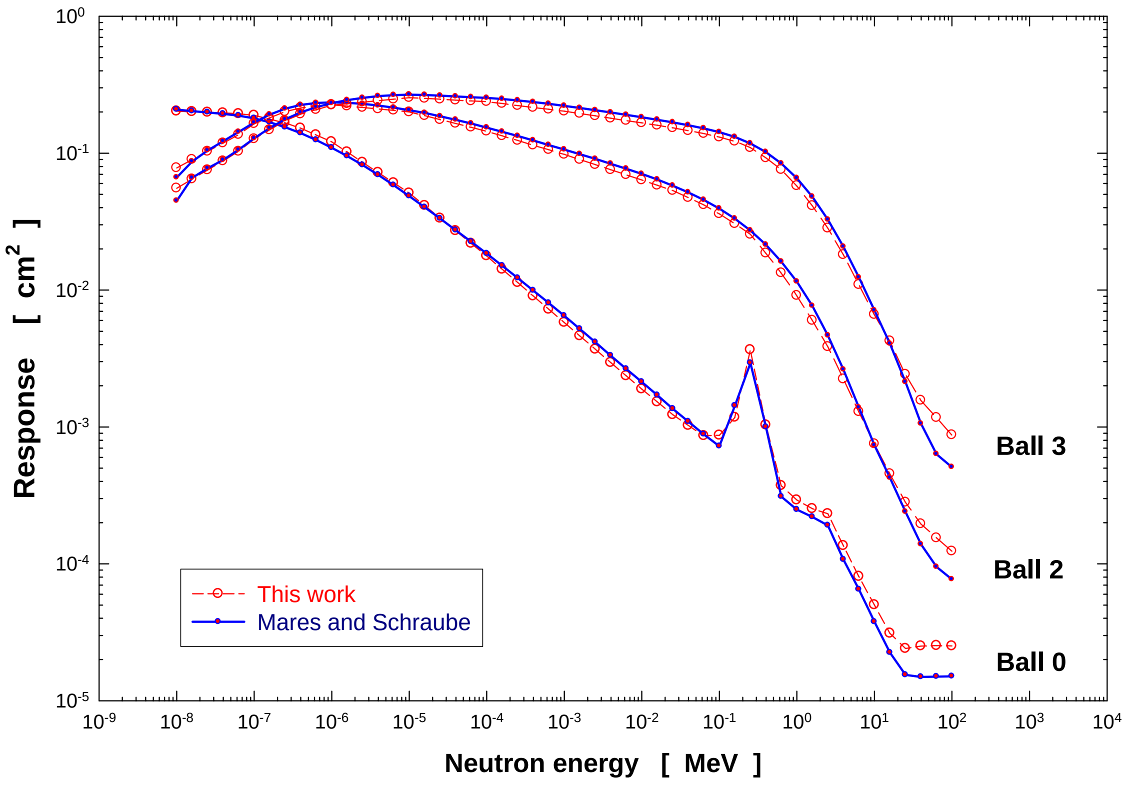
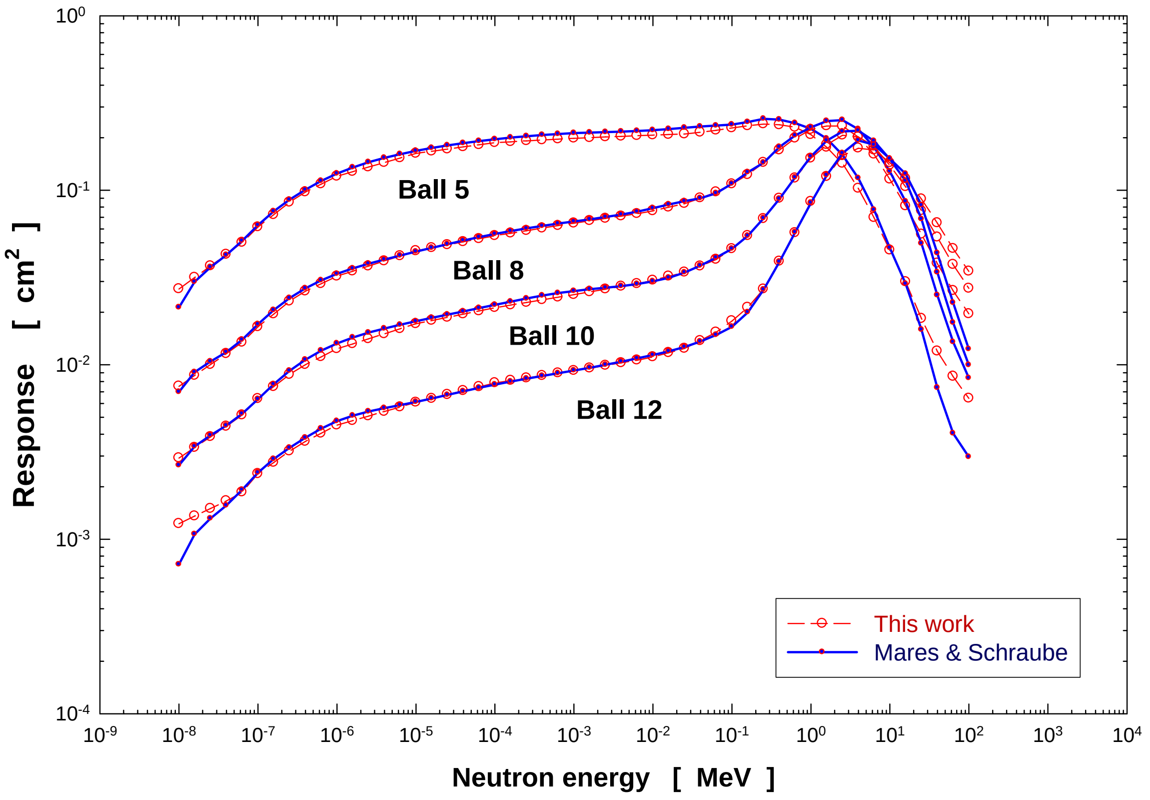


Figure 2: Response functions for5, 8, 10 and 12 inches Bonner spheres.



4. Conclusions

Response functions for seven Bonner spheres have been calculated for neutrons from 2.50E(-8) to 100 MeV. The calculations have been performed using the MCNP 4C for neutrons from 2.50E(-8) to 20 MeV using the ENDF/B-VI cross-section library, while for neutrons between 30 to 100 MeV the response was obtained using the MCNPX code and the LA150 cross section library [23, 24]. For all the calculated cases with the spheres the $S(\alpha, \beta)$ scattering model was utilized during the transport of low energy neutrons.

Response matrix was calculated for 23 energy bins and the response functions were interpolated to include a larger number, 51, energy bins. Full matrix is available upon request from corresponding author.

The response functions were compared with those reported by Mares and Schraube. Good agreement was also observed between our response matrix and the matrix calculated by other scientists. Response functions are similar in shape regardless of thermal neutron detector except for the B0 case whose response is strongly influenced by the type of thermal neutron detector.

Differences are mainly observed in the low energy region and in the case of neutrons whose energy is larger to 20 MeV; this is attributed to the different cross sections libraries utilized in both studies. The chi-square test was applied to determine if there are significant differences between our response functions and those reported by Mares and Schraube. From this test no significant differences were observed.

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