Response Matrix of a Bonner Spheres Spectrometer with $^3$He Detector

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Abstract

Using MCNP code the response matrix of a Bonner spheres spectrometer was calculated. The spectrometer has a 3.2 cm-diameter thermal neutron detector; this is a $^3$He-filled proportional counter that is located at the center of a set of polyethylene spheres. The response was calculated for 0, 3, 5, 6, 8, 10, 12 and 16 inches-diameter polyethylene spheres for neutrons whose energy goes from $10^{-9}$ to 20 MeV. The response matrix was compared with a set of responses measured with several monoenergetic neutron sources, from this comparison calculated matrix is in agreement with the experimental results. Also this matrix was compared against the response matrix calculated for the PTB C spectrometer. Nevertheless that calculation was carried out using a detailed model to describe the proportional counter both matrices were in agreement, small differences are observed in the bare case because the difference in the model used during calculations. Other differences are in some spheres for 14.8 and 20 MeV neutrons probable due to the differences in the cross sections used during both calculations.

1. INTRODUCTION

Since 1932 the development of nuclear physics was increased with the advances in neutron spectrometry, which also becomes an important tool in other fields like nuclear technology, fusion plasma diagnostics, radiotherapy and radiation protection. The introduction of multispheres spectrometer together with the achievements in computer unfolding methods
produced advances in neutron spectrometry from 1960 to 1979, in this period other notable developments were the applications of semiconductor detectors to neutron spectrometry and the introduction of superheated drop detectors [1].

Since its introduction in 1960, the Bonner sphere spectrometer (BSS) [2], also known as multisphere spectrometer, has been the only instrument, which allows the spectral neutron fluence to be measured in a wide range of energies from thermal up to at least 20 MeV [3]. By adding intermediate high mass number material shell the response of this spectrometer can be raised up to few GeV [4, 5].

BSS consists of a set of polyethylene spheres of different diameter, at the center of each sphere a thermal neutron detector is located. Fast neutrons impinging on a sphere are moderated during transport in the polyethylene arriving to the sphere’s center as thermal neutrons where are detected by the central counter [6]. In the original design BSS has a small cylindrical (0.4 $\Delta \times 0.4$ cm$^2$) $^6$LiI(Eu) scintillator, however thermoluminiscent dosimeters [7-9], gold [9] and other activation detectors [11], track detectors [12] and BF$_3$ [13] or $^3$He [14] filled proportional counters have been used as thermal neutron detectors.

The thermal neutron detector has a response that depends upon neutron energy that is modified when the detector is inserted in the polyethylene sphere. This give rise to an overall response function for each set of thermal neutron counter and moderating sphere, all response functions are also known as response matrix [5]. With the detector’s count rates ($C$) and matrix response ($R_\Phi(E)$) the neutron energy distribution or neutron spectrum ($\Phi_E$) can be obtained by solving the first kind Fredholm integro-differential equation,

$$C = \int R_\Phi(E) \Phi_E \, dE$$

Once neutron spectrum is obtained the dose equivalent quantities, $H$, can be obtained using equation (2),

$$H = \int h_\phi(E) \Phi_E \, dE$$

here, $h_\phi(E)$ are the fluence-to-dose equivalent conversion coefficients [15].

Is highly desirable that the response matrix be determined experimentally using monoenergetic neutrons, however, this is only practical for monoenergetic neutrons with energies greater than about a few keV and for thermal neutrons [6]. Therefore the responses have been determined through calculations using one dimensional discrete ordinates transport code (ANISN) [16] or Monte Carlo methods with MCNP code [17, 18] and high-energy codes [4, 5].

In this investigation the matrix response of a Bonner spectrometer with a $^3$He filled proportional counter has been calculated using Monte Carlo methods with updated cross section libraries. This matrix was compared against experimental and calculated responses.
2. MATERIALS AND METHODS

Counters that are most commonly used with BSS detect thermal neutrons through the following nuclear reactions: $^6$Li(n,α)$^3$H (Q = 4.78 MeV, $\sigma_{Th} = 940$ b), $^{10}$B(n,α)$^7$Li (Q = 2.31 MeV (93%) or 2.79 MeV (7%), $\sigma_{Th} = 3837$ b), and $^3$He(n, p)$^3$H (Q = 0.764 MeV, $\sigma_{Th} = 5333$ b). The high cross section makes $^3$He proportional counter a detector that can be used in areas where a high efficiency spectrometer is required. A commercially available proportional counter is the model SP90 $^3$He-filled spherical proportional counter. This is 3.2 cm in diameter and is made by Centronic Ltd, UK. This is used as thermal neutron detector in a Bonner sphere system and its response has been experimentally determined [19].

Using Monte Carlo code MCNP 4C [20] the thermal neutron detector and polyethylene spheres were modeled. The proportional counter was modeled as a sphere filled with $^3$He at 200 kPa, assuming an operation temperature of 293.15 K the atomic density was 4.9418 x 10$^{19}$ cm$^{-3}$, gas enclosure was modeled as a 1.6 cm inner radius and 1.65 cm outer radius made of steel.

Moderating spheres were modeled as polyethylene with a density of 0.946 g-cm$^{-3}$. Chemical binding and crystalline effects of polyethylene during thermal neutron scattering were taken into account by using S(α,β) treatment. 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 through the polyethylene sphere.

During neutron transport calculation three nuclear reactions (n, total), (n, n’) and (n, p) occurring inside the detector active volume were determined, as spectrometer response only the (n, p) reaction per neutron emitted by the source term was considered. The only variance reduction technique used along the calculations was to model the moderating spheres as spherical shells whose importance was increased as the detectors was approached. The number of histories utilized was long enough to have uncertainties less than 1%.

The responses were calculated for 27 neutron energies ranging from 10$^{-9}$ to 20 MeV. Diameters of moderating spheres were 0, 7.62, 12.70, 15.24, 20.32, 25.40, 30.48 and 40.64 cm, this mean 0, 3, 5, 6, 8, 10, 12 and 16 inches-diameter respectively.

3. RESULTS

In Figure 1 the response functions for 0, 3, 5, 6, 8, 10, 12, and 16 inches-diameter polyethylene spheres in function of neutron energy are shown. Bare detector ($^3$He proportional counter without moderator) has the maximum response for 10$^{-9}$ MeV neutrons, this also has the minimum response for 20 MeV neutrons; between this two extremes the response has 1/v behavior.

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. The calculated discrete set of responses is shown in Table I.

In general response functions are similar in shape regardless the thermal neutron detector except for bare case whose response is strongly characterized by the cross section. Thus for $^6$LiI(Eu) and
TLDs there is a resonance around 0.1 MeV. Nevertheless these detectors are solid and their responses go from $10^{-5}$ up to 0.2 cm$^2$ that are smaller to BSS with $^3$He detector whose responses go from $10^{-4}$ up to approximately 7 cm$^2$. This is mainly due to the differences between the $^6$Li(n,$\alpha$)$^3$H and $^3$He(n, p)$^3$H cross section.

Calculated matrix was compared against a set of experimental values reported for a BSS with $^3$He [19]. This comparison is shown in Figure 2, here the 16 inches-diameter sphere was not included because no experimental data are reported. For bare detector there is only a single response experimentally reported. By analyzing calculated and measured responses a good agreement was found. Calculated matrix is better to the set of calculated responses used originally by Alevra et al. [19] to compare their experimental data.

![Figure 1. Calculated response matrix for BSS with $^3$He detector](image-url)
The International Atomic Energy Agency has published two technical reports [21, 22] where the updated data about detector responses using a consistent energy structure were compiled. In this data set the response of a BSS with $^3$He, known as PTB C, is shown. That response was calculated in 1994 using an older MCNP code version, it was also used a realistic detector model. That response was taken here to compare with the responses obtained in this work. In Figure 3 continuous lines are the calculated responses compiled by the IAEA and discrete dots are the responses calculated in this study.

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Figure 2. Calculated and measured responses for BSS with $^3\text{He}$ detector
From Figure 3 can be noticed that there are small differences between both calculated responses in the case of bare detector. For other spheres there is a good agreement between both responses except for the two last neutron energies. In the case of bare detector the differences are attributed to the details included in the model used in the PTB C calculations. For other spheres the differences observed are attributed to neutron cross sections used here in comparison with those used in the PTB C calculations.
4. CONCLUSIONS

The fluence responses for eight Bonner sphere sets have been calculated for neutron from $10^{-9}$ to 20 MeV. Calculations have been performed with MCNP 4C code. Response matrix has been compared with experimentally determined responses and with calculated responses. From this comparison there is a good agreement between the measured responses and the correspondent responses here calculated. The agreement is also observed between both calculated responses even when in this work a simple model of $^3$He proportional counter was utilized, therefore small differences are observed for bare detector in both calculated responses, also differences are noticed in both calculated responses for 14.9 and 20 MeV neutrons which is attributed to the cross sections used during calculations.

REFERENCES


