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Calculation of response functions for cylindrical nested neutron spectrometer

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Abstract: In a recent work, a new neutron spectrometer, namely Cylindrical Nested Neutron Spectrometer (CNNS). It works under the same principles as a Bonner Sphere Spectrometer (BSS), except that different amounts of moderator around a thermal neutron detector are configured by adding or removing cylindrical shells. The CNNS consists of a 4mm x 4mm ^{6}LiI(Eu) scintillator crystal and nested cylindrical polyethylene moderators. The objective of this paper is describing the use of MCNPX code for determining a optimal ratio between height and diameter of the moderators in order to remain isotropic angular response to neutrons like BSS and determining of response functions for moderators of different diameters at 104 energy points from 0.001 eV to 19.95 MeV.

Keywords: *cylindrical nested neutron spectrometer, response function, MCNPX code.*

I. INTRODUCTION

From the point of view of radiation protection, neutron dosimetry is the most difficult and complicated task due to the fact that there are almost no neutron-induced reaction mechanisms in sensors that exactly match those in tissue. Neutrons deposit energy by means of producing complex spectra of secondary charged particles. In addition, the energies of neutrons encountered in the workplace can range from thermal to many GeV.0

In order to overcome the defects of REM (Roentgen Equivalent Man) counters, i.e over-response and under-response happened in the low energy and high energy, and to characterize the neutron field better, it is recommended to measure the energy differential neutron fluence. The ambient dose equivalent can be calculated by folding the measured energy fluence spectrum with fluence to dose equivalent conversion factors such as those found in the ICRP74 [1].

Among many types of neutron spectrometer, BSS that was first introduced in 1960 by Bramblett et al [2] has been used by more laboratories than others [3], due to some avantages (e.g. excellent energy range, good photon discrimination, isotropic angular response ...). Howerver, the cumbersomeness of the whole system makes it unsuitable for measurement in the neutron workplace field. A new neutron spectrometer, which preserves the advantages of the BSS system while improving the usability of this technique in the working field, has been developing at Institute for the Nuclear Science and Technology (INST). It comprises of a 4mm x 4mm ^{6}LiI(Eu) scintillator crystal which could be positioned at

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the center of cylindrical nested polyethylene moderators. These moderators can be nested, like a Russian nesting doll.

The origin BSS was built around spherically shaped moderators so as to make sure that the instrument would have a response independent of the direction of incidence of the neutrons. In the case of the CNNS, the most important feature of the set of shells is that, for each configuration, the ratio of diameter and height have been optimised to offer a nearly isotropic angular response to the neutron. Similarity to BSS, for the proper use of the CNSS, an accurate determination of the response function is thus of primary importance [4]. The BSS's responses have been widely studied since 1960 and published in the literatures [5] for some common thermal detectors like ^{6}LiI scintillators or ^{3}He proportional counters.

In order to determine the response functions, the Monte Carlo method was adopted in the present work, which is the most appropriate approach [3]. It relies on simulating the system, computing its response and adjusting the results to the experimental calibration points. However, due to difficulty in Viet Nam and limited time, the validation of simulated responses was carried out by applying this model of simulation into BSS and making a comparision between calculated matrix and the one reported by Mares and Schraube [6]. MCNPX code [7] was used to optimize the ratio between height and diameter of the moderators so as to preserve the angular isotropic response to neutrons like BSS and to establish response functions for moderators of different diameters at 104 energy points from 0.001 eV to 20 MeV.

II. MODEL OF SIMULATION

A. Geometrical and physical parameters

A ^{6}LiI(Eu) scintillator is placed at the center of the cylindrical polyethylene moderator of density 0.95 g/cm^{3}. The scintillator is 4mm x 4mm cylindrical, and its density is 3.84 g/cm^{3}. Although there exist ^{7}Li and Eu isotopes in the crystal, but only ^{6}Li and ^{127}I isotopes are present in model of simulation.

A broad parallel neutron beam was assumed during all the calculations in order to ensure a uniform irradiation of the exposed detector. The irradiation source has the same area as the cross section area of the cylindrical detector. The response functions were calculated in two cases of neutron beam direction: angle 0^{o} (i.e. parallel to cylindrical axe), angle 90^{o} (i.e. normal to cylindrical axe). The environment between the source and the detector was treated as void. Thus, neutrons reach the detector on the straight path without any interaction.

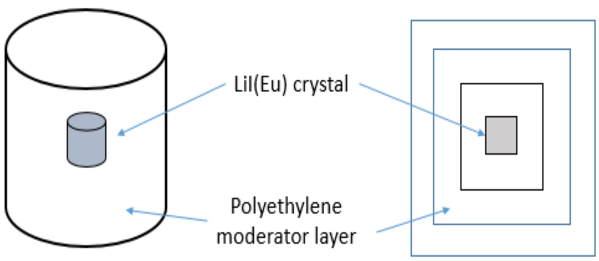

Fig. 1. Geometrical view of cylindrical nested neutron spectrometer

B. MCNPX parameters

Neutron cross-section libraries ENDF-B/VI were taken from MCNP5 [9] data. The S(α,β) cross-section table "*poly.60t*" [8] was used in order to take into account the chemical binding of hydrogen in polyethylene at thermal region.

The response was defined as the number of the $^{6}Li(n,t)^{4}He$ reaction within sensitive $^{6}LiI(Eu)$ crystal volume per unit fluence. This was done by using tally F4 and FM card.

Among existing methods in MCNPX to reduce the variance of the tallies and to speed up the computational time, the only method "geometry splitting and Russian roulette" was applied to the moderators larger than 15cm in diameter. This technique is the easiest to use and very effective, but care was taken to avoid the splitting "all at one" [9]. In all simulations, the neutron capture was treated explicitly as analog rather implicitly.

C. Model verification

The calculated response function of the CNNS need to be experimentally validated [4]. However, in the present study, another approach was used. The CNNS model was verified by using the model as described above with spherical moderator instead of cylindrical moderator. The response function of this spherical model (BSS model) was then compared to the one published by [6] by a χ^2 goodness of fit test. This involved adopting the hypothesis that both response functions were statistically identical and any deviation in value as a result of random fluctuations.

To evaluate the hypothesis, two response functions were compared using the following equation:

$$\chi^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \quad (1)$$

where k represents number of energy point (in this case, k = 48), O are observed values (response function of the BSS model in this study), and E are expected values (i.e. response function in [6]).

Table I. Calculated χ^2 values for each sphere

Bonner sphere	2 inch	5 inch	8 inch	10 inch
χ^2	5.19 x 10^{-3}	1.01 x 10^{-2}	4.95 x 10^{-3}	3.84 x 10^{-3}

The χ^2 values for 2, 5, 8 and 10 inch spheres are presented in table 1. The calculated χ^2 values fall far short of the 27.4 critical value for 47 degrees of freedom and an alpha of 0.99. Therefore, the calculated BSS response values are valid as those published by [6]. In other words, the physics parameters and MCNPX parameters were verified. The model can be used to determine response function of the CNNS system

III. RERULTS AND DISCUSSION

A. Optimized ratio between height and diameter of the moderator

The response functions of CNNS for different neutron beam directions (0° and 90°) and for different ratios were calculated, then were compared. For small moderators (5.08 cm and 12.7 cm diameters) , response functions were calculated with ratios of 0.8, 0.9, 1.0 and 1.1. The results show that the ratio of 0.9 gives the best angular response. After that, ratios of 0.88, 0.90 and 0.92 were selected to compute response for the larger moderator (30.48 cm diameter). The ratio of 0.90 still gives a nearly isotropic angular response than the other ratios (Fig. 2). In this case, the maximum difference between 2 response functions was 3.8%. Thus, the ratio of 0.90 was optimized value for CNNS system.

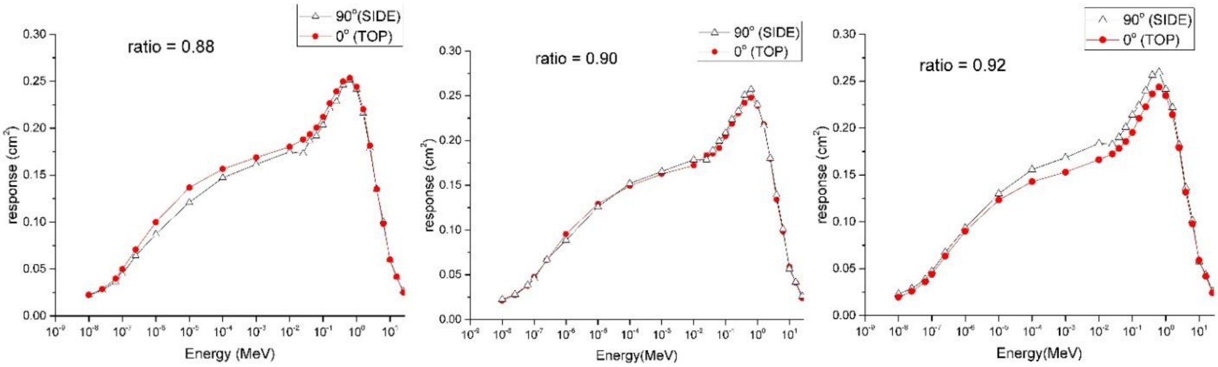

Fig.2. Response functions of the CNNS model with ratios of 0.88, 0.90 and 0.92 in two cases of neutron beam direction (0^o and 90^o)

B. Response of the CNNS system

The response matrix was calculated with cylindrical diameters of 2, 3, 5, 6, 8, 10, 12, 15, 18 and 20 cm. Energy points from 10^{-9} MeV to 19.95 MeV were equidistant on log scale. The response function of the bare detector was interpolated from [6].

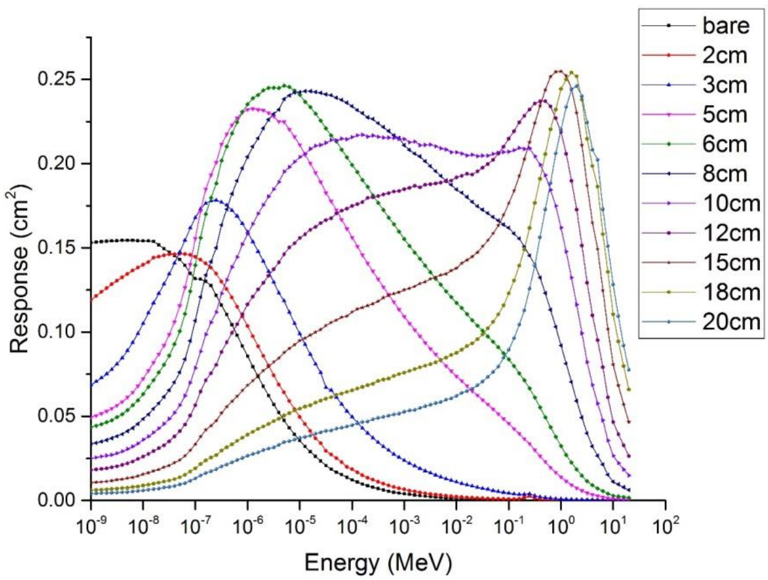

Fig.3. Response function of CNNS system as function of energy and cylindrical diameter. The optimized ratio between height and diameter of the moderator is 0.90.

The response function of the CNNS system is similar to that of the conventional Bonner system. For the small moderators, response function has maximum value at low energy. For the bigger moderators, response function peaks in the higher energy region.

The response at any energy from 10^{-9} MeV to 19.95 MeV with a different diameter (smaller than 20 cm) can be obtained by interpolation. In the case of neutron energy above 20 MeV or diameter of the moderator bigger than 20cm, extrapolation technique can be used but must be carefully examined.

IV. CONCLUSIONS

The response functions with optimized ratio between height and diameter of cylindrical moderator were calculated. Although these values were not validated by experimental measurement, but the model used was verified. The result of this study is an important part of developing a new cylindrical nested neutron spectrometer at INST.

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