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Original Article

On the Possibility of the use of Tube Counters in Neutron Spectrometry

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Abstract *- Response matrices for ^{3}He proportional neutron counters of spherical and cylindrical form are simulated. It is shown that the latter can be converted to the former with a simple linear operation, which points to tube counters as a potential device for neutron spectrum observation.*

Keywords *- Atmospheric neutrons, Bonner sphere, Tube counter, Thermal neutrons, Monte carlo method.*

1. Introduction

Bonner Sphere Spectrometer (BSS) [1] is one of the systems most commonly used in neutron spectrometry [2] and dosimetry [3] and is a unique device suitable for spectral observation of the environment neutron background [4 - 32].

In its traditional configuration, BSS is a set of thermal neutron detectors like proportional counters of the spherical form filled with ^{3}He or BF_3 embedded in a thermalizer, i.e., a scattering material like polyethylene decreasing neutron energy down to thermal one (see Figure 1).

In the case of ^{3}He-filled counter, a neutron causes a breakup of the ^{3}He nucleus into a tritium nucleus ^{3}H and a proton. The triton and the proton share the reaction energy Q [9].

$$^3\mathrm{He} + n(\mathrm{thermal}) \rightarrow p + {}^3\mathrm{H} + Q, \quad Q = 764\ keV \qquad (1)$$

An increase in thermalizer thickness results in a decrease in the detection efficiency of less energetic neutrons and an increase in more energetic ones. This makes it possible to estimate the spectral composition of the neutron flux. That dependence is maximally pronounced for counters of a spherical form because it provides a maximum volume with minimum dimensions, which in turn leads to lower sensitivity.

To energetic neutrons with ranges exceeding the size of the sphere.

An important characteristic of spherical geometry is, of course, an isotropic response to an incident flux.
An output C_i that is a count rate of the i^{th} detector in a spectrometer with N detectors is [10]:

$$C_i = \int_{E_{min}}^{E_{max}} R_i(T_i, E)F(E)dE, \quad i = 1,2, \dots, N \quad (2)$$

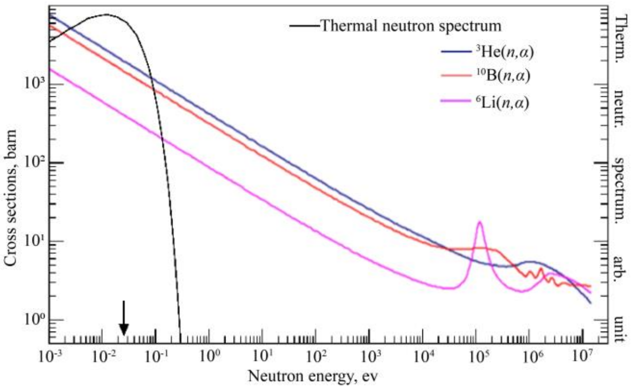

Fig. 1 Neutron capture cross sections of ^{3}He,^{10}B, ^{6}Li. [9]

Where $F(E)$ is a desired neutron flux of energy E and $R_i(T_i, E)$ describes the registration efficiency of a counter with a thermalizer thickness of T_i.

Equation 2 forms a system of N inhomogeneous Fredholm integral equations of the first kind [11] with no unique solution [12]. Due to that, to unfold (i.e. to restore) the spectrum from a set of the detector outputs, another problem is solved, namely, a search for a spectrum as close as possible to a predetermined one. For that Equation 2 is discretized with a tabulated spectrum $F(E)$: $F_k = F(E_k)$ k=1,…, M [13]:

$$C_i = \sum_{k=1}^{M} R_{i,k}\, F_k, \qquad i = 1,2, \dots, N \quad (3)$$

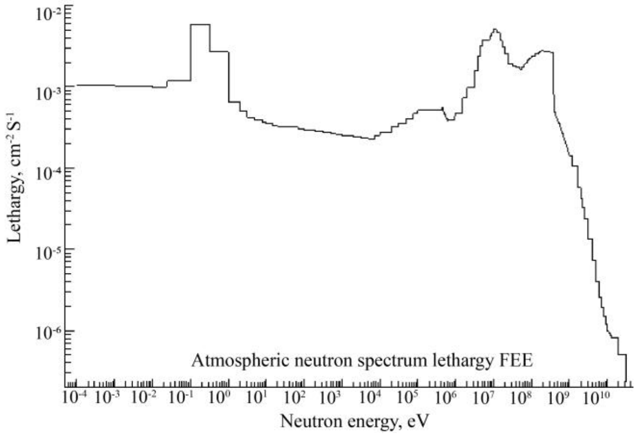

Fig. 2 A near-ground lethargy spectrum of atmospheric neutrons in Sao Jose dos Campos (Brazil, 23°10′44″S 45°53′13″W, 900 *m* altitude). It is a combination of an experimentally measured local spectrum (up to 10^8 *eV*) [3] and JEDEC JESD89A standard model [32] for higher energies

where $R_{i,k} = (T_i, E_k)$. is the so-called "response matrix of the spectrometer". When $M > N$, that discretization degree exceeds the number of detectors. Equation 2 is an ill-conditioned problem with an infinite number of solutions.

The unfolding spectrum [14] is obtained using various iterative [15, 31] and non-iterative [17] procedures, including neuron networks [18]. For this reason, the number of modern experimental detectors exceeds a dozen [19]. Obviously that the more detectors are used and statistics accumulated, the more accurate approximation is obtained.

As for atmospheric neutrons, their specific problem is quite low flux (see Figure 2) that needs a long exposition time or/and a detector with a large sensitive surface. However, the maximal diameter of commercially produced spherical counters does not exceed 5 *cm* [20]. That impedes the accumulation of statistics needed for accurate spectrum determination and reliable detection of actual changes in it.

In this work, we consider the possibility of using cylindrical counters for spectral observation. That type of counters of sizes up to 2 *m* long and 30 *cm* diameter are widely used in cosmic ray monitors [21] and soil moisture monitoring [22]. To this end, response matrices for spherical and cylindrical counters were simulated. The modern toolkits for numeric simulation of the passage of particles through matter allow us to perform such a simulation with any needed accuracy.

2. Simulation Model

The simulation was performed with Geant4 [23] – a large-scale particle physics package based on the Monte Carlo method. Data on reaction cross sections, neutron multiple scattering and particle propagation through the matter were taken from the QGSP_BIC_HP Physics list[24] containing a high precision model for neutrons below 20 *MeV* energy. Edition and compilation of the program code were performed in Windows Visual C++ environment [25]. Executable code was produced with the CMake tool [26].

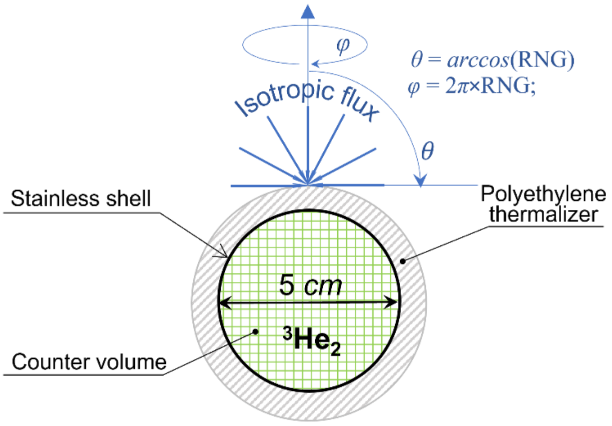

Fig. 3 A geometry considered in the simulation. RNG is a Random Number Generator from 0 up to 1

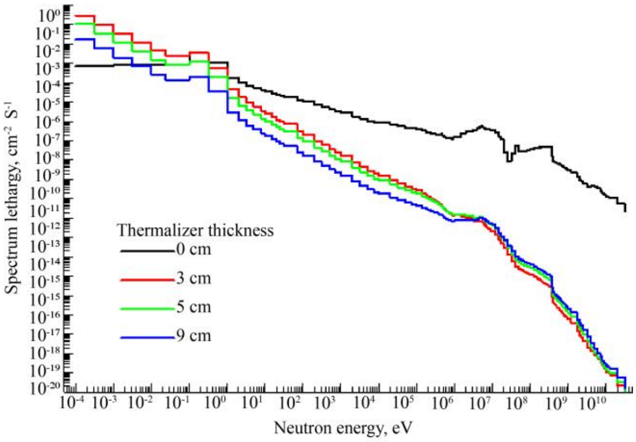

Fig. 4 The integrands used in Eq.1 for spherical detectors

The model's configuration is presented in Fig.3. Contrary to tube counters, the efficiency of spherical counters is isotropic. However, because the neutron ground level background is known to be isotropic also [27, 28], both geometries are adequate in this case. The response matrices were simulated for a spherical counter of 5 *cm* diameter (like in [29]) and a cylindrical counter of the same diameter and of 30 *cm* length (like in [22]) with bare counters and those with polyethylene thermalizers of 3, 5, and 9 *cm* thickness. The simulation was performed for neutrons in the 10^4–$3{\cdot}10^{11}$ *eV* energy range. The number of samplings varied from 10^3 to $3{\cdot}10^9$ depending on the reaction cross-section for tested neutron energy (see Figure 1). Integrands in Equation 2 were calculated using the spectrum in Figure 2.

3. Results and discussion

Figure 4 presents simulated integrands $F(E)R_i(T_i, E)$ in Figure 2 that is the detector responses for the spectrum in the same figure. The response matrices themselves for spherical and cylindrical detectors are shown in Figure 5. The curves for the cylindrical detector outputs C_{tube_i} are normalized for the ratio of the corresponding outputs $C_{\text{tube}_i}/C_{\text{sphere}_i}$.(see line 4 in Table 1).

One can see in Figure 5 that response matrices for the spherical and cylindrical counters match well after the above linear transformation. It means that Equation 2 or some unfolding procedure will give the same result for both geometries, and the matrices are equivalent at this point. Another crucial point is the accuracy of an unfolded spectrum. Obviously, the stronger an output dependence on thermalizer thickness and the larger the statistic accumulated, the higher accuracy of the result. As it should be expected that dependence (see line 5 in Table 1) is stronger for the spherical geometry as compared with the cylindrical one (although this difference does not even reach 2). That should result in a less accurate determination of an unfolded spectrum. However, this shortage, at least partially, could be offset by increased statistics accumulated with larger tube counters. For example, the sensitive surface of the spherical detector considered here is $25\pi\ cm^{2}$, and that of the cylindrical one is $150\pi\ cm^{2}$, which is 6 times more. The registration efficiency of the latter detector with a 3 *cm* thermalizer is 2.4 higher, and for the 5 *cm* one is 3.3 higher. The corresponding narrowing of error margins [27] is $\sqrt{6\cdot 2.4}\approx 3.8$ and $\sqrt{6\cdot 3.3}\approx 4.4$ times in comparison with those of the spherical counters that quite compensates a weaker dependence in the case of tube counter.

Table 1. Simulated output of tube and spheric detectors

	Detector number *i*		1	2	3	4
1	**Thermalizer thickness, *cm***		0	3	5	9
2	**Detector output C_i, cm^{-2}**	**Tube**	$1.2\cdot10^{-2}$	$.32\cdot10^{-2}$	$2.7\cdot10^{-2}$	$.09\cdot10^{-2}$
		Sphere	$2.7\cdot10^{-2}$	$.13\cdot10^{-2}$	$.82\cdot10^{-2}$	$.02\cdot10^{-2}$
3	$C_{\text{tube } i}/C_{\text{sphere } i}$		1.26	2.43	3.30	4.57
4	**Detector output ratio $C_{\text{tube}_i}/C_{\text{sphere } i-1}$**	**Tube**		3.66	0.12	30.1
		Sphere		7.1	0.16	41.6

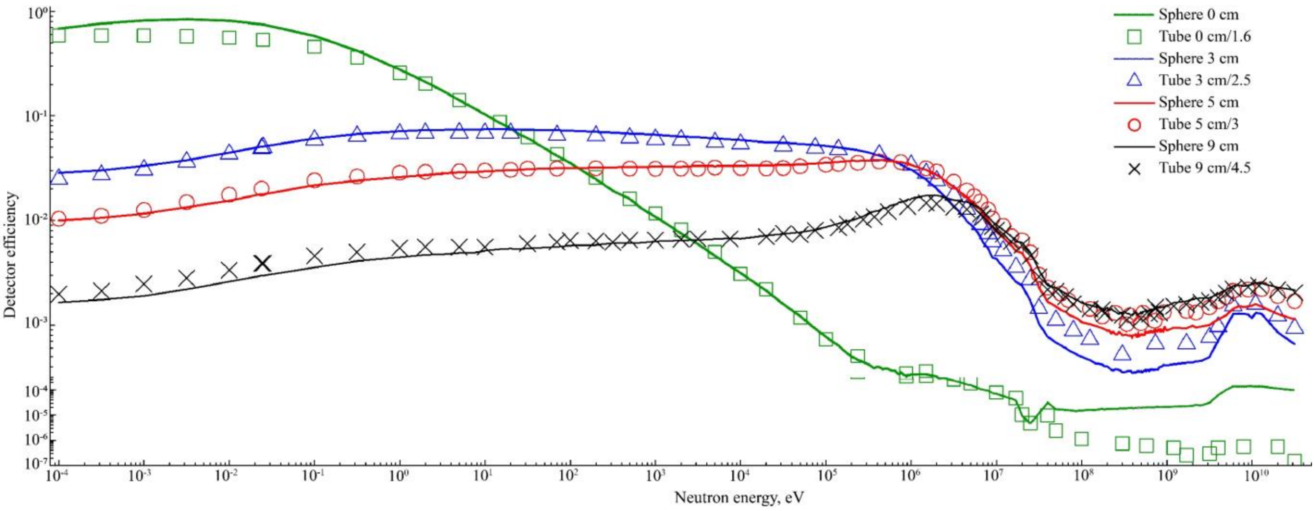

Fig. 5 The simulated response matrices (i.t. energy dependences of registration efficiencies) of the spherical and cylindrical counters with different thermalize thicknesses for an isotropic neutron flux

4. Conclusion

Response matrices for neutron detectors of spherical and cylindrical geometries for the atmospheric ground-level isotropic neutron spectrum were simulated using the Geant4 package. A comparison of response matrices of the two geometries demonstrated their identity up to a linear transformation. This, in turn, should result in identical unfolded spectra. At the same time, the cylindrical geometry demonstrated a weaker dependence on the thermalizer thickness compared to the spherical one. That may result in lower accuracy of an unfolding procedure. Still, it is shown that this shortage can be compensated at list partially by increased registration efficiency and the sensitive surface of cylindrical counters. Thus, the result of the simulation allows tube neutron counters to be considered as a potential device for spectral monitoring of the radiation environment.

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