NUCL SCI TECH (2017) 28:174
https://doi.org/10.1007/s41365-017-0328-2

Geant4 simulation of multi-sphere spectrometer response function and the detection of ^{241}Am–Be neutron spectrum

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Received: 8 September 2016 / Revised: 13 February 2017 / Accepted: 13 February 2017 / Published online: 16 November 2017
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Abstract This paper is aimed at detecting the neutron spectrum of ^{241}Am–Be, a widely used neutron source, with the SP9 ^{3}He proportional counter, which is a multi-sphere spectrometer system of eight thermal neutron detectors embedded in eight polyethylene (PE) spheres of varying diameters. The transport processes of a neutron in the multi-sphere spectrometer are simulated using the Geant4 code. Two sets of response functions of the PE spheres are obtained for calculating the ^{241}Am–Be neutron spectrum. Response Function 1 utilizes the thermal neutron scattering model G4NeutronHPThermalScattering for neutron energies of $\leq$ 4 eV, and Response Function 2 has no thermal treatment. Neutron spectra of an ^{241}Am–Be neutron source are measured and compared to those calculated by using the response functions. The results show that response function with thermal treatment is more accurate and closer to the real spectrum.

This work was supported by ITER Plan National Major Project (No. 2008GB109000) and the Introduces Talents Scientific Research Project of Guizhou University (2014, No. 32).

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Keywords Response function · Neutron energy spectrum · Multi-sphere · Geant4 · ^{241}Am–Be · G4NeutronHPThermalScattering

1 Introduction

Neutron spectrum spans a vast energy region from 10^{-7} to 10^{9} eV. The ^{241}Am–Be neutron source is a widely used neutron source [1]. The α particles emitted by ^{241}Am react with Be to generate neutrons. An ^{241}Am–Be neutron source is featured by its long life, simple protection, stable neutron emission, moderate size, and low γ-ray energy in the decay of ^{241}Am. It is of significance to detect the neutron spectrum of a ^{241}Am–Be source [2, 3], using the Bonner sphere made of polyethylene (PE) with copper or lead inlets [4–7]. Their responses to high-energy neutrons increase with the cross sections of copper and lead, but low-energy neutrons are absorbed after moderation. The pure PE spheres with thermal neutron detectors can detect lower-energy neutrons.

In this paper, we present a multi-sphere spectrometer system to detect the neutron spectrum of ^{241}Am–Be. This is the SP9 ^{3}He proportional counter consisting of eight thermal neutron detectors in eight pure PE spheres (PSs) of varying diameters [8–11]. Response functions of the eight PSs, as the key to calculating the ^{241}Am–Be neutron spectrum, are calculated by using Geant4 simulations with thermal neutron scattering model G4NeutronHPThermalScattering enabled and disabled. The counting rate is measured, and finally, the ^{241}Am–Be neutron spectrum is calculated.

2 The simulation

2.1 Theory

Neutrons are slowed down to thermal neutron by elastic collisions with hydrogen atoms of the PSs, as the cross section for hydrogen is larger than those for carbon. The reaction, ^{3}He(n, p)T ($Q = +764$ keV), has a good cross section to thermal neutrons. ^{3}He proportional counter is usually used for detecting the thermal neutrons because of its total cross sections [12] and low sensitivity to γ-rays. For the eight PSs of different diameters, the response function of the ith PS is $R_i(E)$ and the fluence of the neutron spectrum to be tested under different energy is $\Phi(E)$ [13–16]. The count value N_i of the ith PS is

$$N_i = \int \Phi(E)R_i(E)\mathrm{d}E, \quad i = 1, 2, \ldots, 8. \tag{1}$$

So, N_i can be obtained by the experiment and the response function $R_i(E)$ is obtained by Geant4 simulation, which is the key to calculating the ^{241}Am–Be neutron spectrum. The calculated response functions of the eight PSs are only applicable for the multi-sphere spectrometer in this paper.

2.2 Geant4 model

Geant4 [17–19] is a toolkit for simulating the passage of particles through matter. Its areas of application include high-energy, nuclear and accelerator physics, and studies in medical and space science as well. The Geant4 version Geant4.9.6 is used in this paper. The SP9 ^{3}He detector is sensitive to thermal neutrons. The corresponding Geant4 models [20–22] of interaction between neutron and matter are shown in Table 1. The G4NeutronHPThermalScattering model includes a thermal treatment below 4 eV. In all Geant4 versions, the user must first download the high-precision neutron data files from the Geant4 Web page to a local directory (G4NDL/) when they want to use the high-precision neutron models.

2.3 Simulation

The outside diameters of the eight PSs are 4″, 5″, 6″, 7″, 8″, 9″, 10″, and 12″. The SP9 ^{3}He proportional counter is 33 mm in diameter (the spherical part) and 134 mm in total length. It is operated at 800–900 V with a neutron sensitivity of 8 cps for 3.2 mrem/h. Figure 1 shows the arrangement of PS and the SP9 ^{3}He proportional counter.

For smaller-diameter PSs, low-energy neutrons are slowed down after elastic scattering, but they still have high probabilities to reach the PS center and be detected, while high-energy neutrons still have high energy after moderating and tend to escape the PS. For larger-diameter PSs, a large number of low-energy neutrons are absorbed after moderation, while high-energy neutrons are slowed down to thermal energies, which still have high probabilities to reach the PS center and be detected. The degree of neutron moderation depends on the PS diameter. The neutron response of each PS is unique.

A general ^{241}Am–Be neutron source is used. The response functions can be obtained in the simulation by using a number of different concrete neutron energies. The response function simulation of Geant4 is shown schematically in Fig. 2. Eight SP9 ^{3}He proportional counters are arranged around the neutron source, with a distance of 40 cm between SP9 ^{3}He proportional counter and neutron source. In the Geant4 simulation, ten million neutrons are simulated for each energy point.

Eight sets of counts of PS at different energies are obtained by simulating the response function of the PSs. The response functions with and without thermal treatment

Table 1 Geant4 physics models including various models for high-energy physics processes

Process	Geant4 model	Energy (GeV)		Cross section data
		Minimum	Maximum	
Elastic	G4NeutronHPThermalScattering	0	4 eV	G4ThermalScatteringDataset
	G4NeutronHPElastic	0	0.02	G4HadronElasticDataSet
	G4hElasticCHIPS	0.0195	100,000	G4CHIPSElasticXS
Inelastic	G4NeutronHPInelastic	0	0.02	G4NeutronHPInelasticData G4HadronInelasticDataSet
	G4LENeutronInelastic	9.5	25	G4NeutronHPInelasticData G4HadronInelasticDataSet
Capture	G4NeutronHPCapture	0	0.02	G4HadronCaptureDataSet G4NeutronHPCaptureData
	G4LCapture	0.0199	20,000	G4HadronCaptureDataSet G4NeutronHPCaptureData
Fission	G4NeutronHPFission	0	0.02	G4HadronFissionDataSet G4NeutronHPFissionData
	G4LFission	0.0199	20,000	G4HadronFissionDataSet G4NeutronHPFissionData

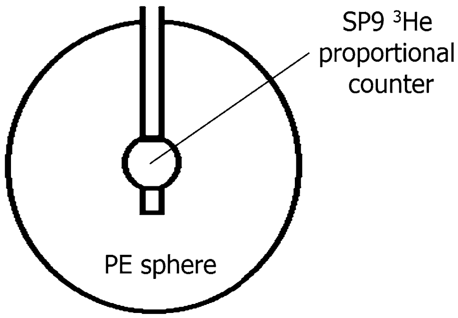

Fig. 1 Schematic of PS and SP9 ^{3}He proportional counter part

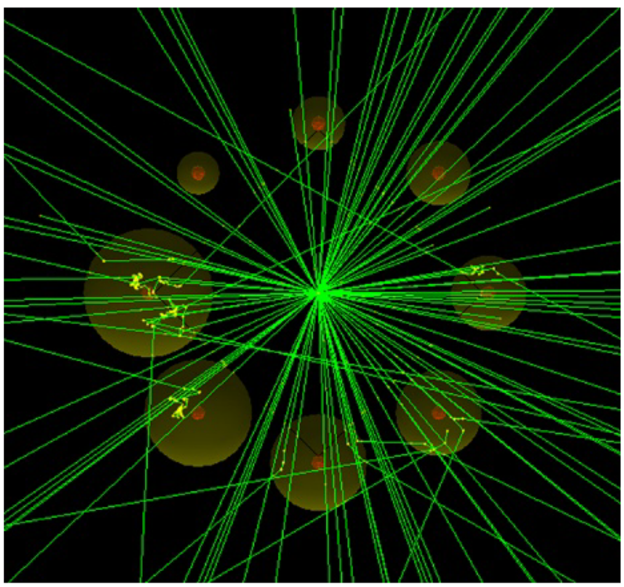

Fig. 2 (Color online) Schematic diagram of the Geant4 simulation

are shown in Fig. 3. The response functions of smaller-diameter PSs have a peak in the low-energy region, and the peak position moves toward high-energy region as the PS diameter increases.

Also, the response functions with thermal treatment have far higher counts than those without thermal treatment. The use of the G4NeutronHPThermalScattering thermal mode in Geant4 simulation slows down the neutrons in PS more effectively, which is critical for the neutron capture interaction that leads to different count measurements, hence the higher counts with the thermal treatment.

3 The measurement

The simulated response functions are usually validated by measuring an ^{241}Am–Be neutron source [23–26]. The ^{241}Am–Be neutron source we used was produced by Institute of Atomic Energy of China in 1978, numbered as 0078AB473395, with an activity of 2.0×10^{8} Bq. The neutron spectra specified by International Standard ISO 8529-1 were used (from thermal to 20 MeV) [27–29] for the ^{241}Am–Be simulation and measurement. Figure 4 shows the eight PSs surrounding the neutron source.

The SP9 ^{3}He detector had been tested with ^{137}Cs or ^{60}Co γ-ray sources by amplitude discrimination. No waveforms were viewed on an oscilloscope, indicating that the energy deposition of a γ-photon in the SP9 ^{3}He detector was much smaller than that of a neutron. So, we discriminated γ from neutrons only with the amplitude in the main electronics system.

Neutron counts of the eight PSs were measured at 662, 1959, 2367, 1768, 1717, 1161, 1077, and 534 for 12″, 10″, 9″, 8″, 7″, 6″, 5″, and 4″ PSs, respectively.

With the simulated response functions, the ^{241}Am–Be neutron source spectra were calculated by Eq. (1). Two spectra calculated by the two sets of response functions are shown in Fig. 5. (The inset shows the neutron spectra of 2–11 MeV).

The RMS difference is 0.666 between the spectra calculated with thermal treatment and evaluated with ISO8529-1, and the RMS difference is 1.323 between spectra calculated without thermal treatment and evaluated with ISO8529-1. In Fig. 5, the spectrum calculated with thermal treatment is more accurate in high-energy region.

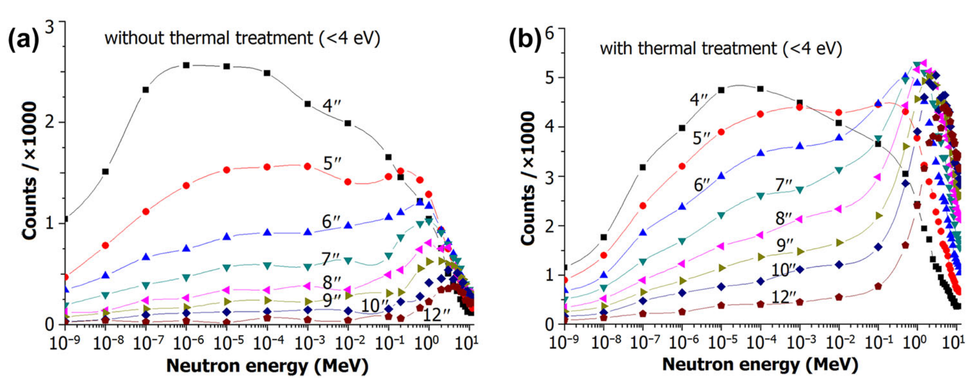

Fig. 3 (Color online) Response function without (**a**) and with (**b**) thermal neutron scattering model G4NeutronHPThermalScattering

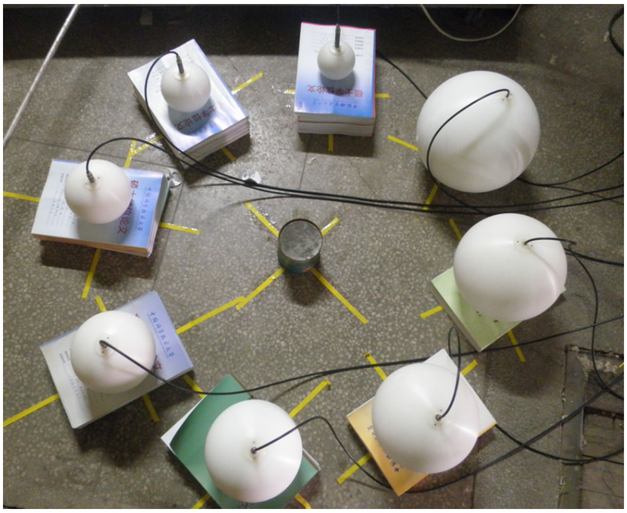

Fig. 4 (Color online) Experimental arrangement

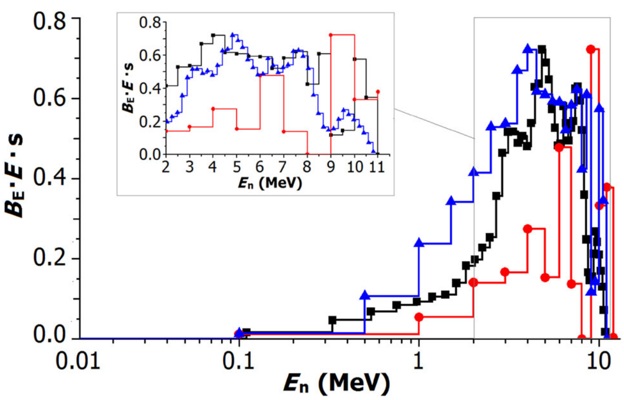

Fig. 5 (Color online) Neutron source spectra of the ^{241}Am–Be evaluated by ISO 8529-1 (filled square), and simulated with (filled triangle) and without (filled circle) 4 eV neutron process. B_E is the spectral source strength, and E_n is neutron energy

The results indicate that neutron scattering model G4NeutronHPThermalScattering below 4 eV is indispensable for the response function simulation.

4 Conclusion

Two sets of response functions for an eight-PE-sphere spectrometer to detect neutron spectrum of ^{241}Am–Be are simulated, by using the scattering model of G4NeutronHPThermalScattering with and without thermal treatment (< 4 eV). From the neutron spectra of ^{241}Am–Be measured with the eight PSs, the response function with thermal treatment is closer to the spectrum evaluated by ISO 8529-1. Therefore, the thermal model of G4NeutronHPThermalScattering is more appropriate within the limits of this particular response function in this paper.

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