Simulation and calibration of the response function of multi-sphere neutron spectrometer

JIANG Xiaofei[1,2,*] CHEN Chao[1,2] CAO Jing[1,2] CAO Hongrui[1,2]
LI Shiping[1,2] SONG Xianying[3] YIN Zejie[1,2]

[1]*State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei 230026, China*

[2]*Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China*

[3]*Southwestern Institute of Physics, Chengdu 610041, China*

Abstract In order to realize the on-line real-time measurement of neutron spectrum of ITER fusion, this paper presents a multi-sphere spectrometer system which consists of eight thermal neutron detectors, namely SP9 ^{3}He proportional counter, embedded in eight different diameter polyethylene spheres. The response function of eight polyethylene spheres of multi-sphere neutron spectrometer was calculated after the simulation of the neutron transport processes in multi-sphere spectrometer by adopting software Geant4. The peak of the response function is in the low energy region for smaller diameter polyethylene sphere. As the polyethylene sphere diameter increased, the peak of the response function moves to the high energy region. The experimental calibration adopts ^{241}Am-Be neutron source. The relative error between normalized data of experiment 4π solid angle counts and normalized data of simulated detection efficiency of 4in to 8in polyethylene sphere is from 1.152% to 12.222%.The experimental results verify the response function of the simulation. All these results provide a theoretical and experimental basis for solving the on-line real-time neutron spectrum of ITER fusion.

Key words ITER, Multi-sphere spectrometer, Response function, Geant4, Simulation and calibration

1 Introduction

ITER (International Thermonuclear Experimental Reactor) is one of the world largest international scientific cooperation. ITER device is a super-conducting Tokamak to produce large-scale nuclear fusion reaction. Try to get advanced methods and technologies to measure the fusion neutron spectroscopy, and establish the characteristic neutron diagnostic system, then master neutron diagnostic techniques of Tokamak fusion are the part of ITER's study contents. ITER had presented new challenges for fusion neutron spectrum measurements. On-line real-time measurement of the dynamic and time-sharing fusion neutron spectroscopy is one of the major difficulties. BSS (Bonner sphere spectrometer) [1] was first introduced by Bramblett, Ewing and Bonner in 1960. This paper presents a multi-sphere spectrometer system which was based on BSS and suitable for the measurement of the dynamic and time-sharing fusion neutron spectroscopy of ITER fusion. The multi-sphere spectrometer system consists of eight different diameter pure polyethylene spheres (PS) and SP9 ^{3}He proportional counters which had larger neutron reaction cross sections[2] and lower sensitivity of γ. Simulate neutron response function of 8 PS with Monte Carlo method and calibrate the multi -sphere spectrometer with a neutron source, which was the key to measure the neutron spectrum precisely.

2 Basic measurement principle of multi-sphere spectrometer

The outside diameters of eight PS of multi-sphere spectrometer are 4, 5, 6, 7, 8, 9, 10, and 12 inches

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* Corresponding author. *E-mail address*: jxfqj@mail.ustc.edu.cn
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respectively. The SP9 3He proportional counter[3,4] was located in the center of the PS.

Neutrons were slowed down by elastic collisions with hydrogen atoms or carbon atoms after entering PS. For smaller diameter of PS, low energy neutrons were slowed down as thermal neutron after elastic scattering but they still have great chances to reach the center of PS to be detected. High energy neutrons still have high energy after moderated and tended to escape. For larger diameter of PS, a large number of low energy neutrons were absorbed after moderation. High energy neutrons were slowed down as thermal neutron but they still have great chances to reach the center of PS to be detected. Different energy neutrons in different diameter PS have different degree of moderation. The neutron response of each PS was unique. Response function[5,6] $R_i(E)$ defined as follows:

$$R_i(E) = {N_i}/{\phi(E)} \qquad (1)$$

Where i= 1, 2 ... 8 represented eight PS, N_i was the reading of i^{th} PS, $\phi(E)$ was the neutron fluence(cm^2) where SP9 detector located.

Neutron counts can meet the requirements of statistical error if we set a reasonable time-sharing time in the actual measurement. Measure time-sharing and real-time neutron spectrum continuously, finally, we can monitor the continuous neutron spectrum.

The neutron spectrum can be deduced by the reading of the eight SP9 ^{3}He detectors if we knew the response function $R_i(E)$ of each PS. So, the neutron response function of each PS was the key to solve the neutron spectrum accurately.

3 Simulation

Geant4(GEometry ANd Tracking)[7-9] is a Monte Carlo application package for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science.

According to the simulation of the transmission process of the neutron in spectrometer system by software Geant4, we can get eight neutron response curves of the 8 PS. Figs (1) and (2) showed the Geant4 simulation results of 4, 8 and 12 inches PS, which respectively correspond to low-energy neutrons and high-energy neutrons. Neutron source was launched into polyethylene from the left side of PS by the way of solid angle divergence. Green rays in figure are neutron trajectory. Red sphere located in the center is the SP9 ^{3}He proportional counter which was embedded in PS. The distance between the neutron source and SP9 ^{3}He proportional counter was 24 cm.

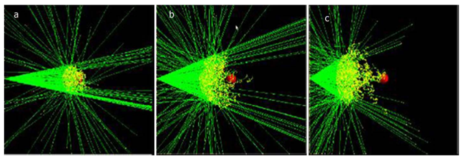

Fig.1 4, 8, and 12 inches Geant4 simulation of low energy.

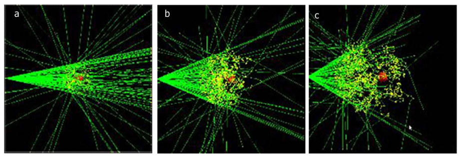

Fig.2 4, 8, and 12 inches Geant4 simulation of high energy.

Comparing Fig.1(a) with Fig.2(a): For smaller diameter of PS, most of the low-energy neutrons stopped in PS after moderation, therefore, there was a great chance for them to reach the center of PS to be detected by the SP9 ^{3}He proportional counter. Most of high-energy neutrons escaped through the PS because the energy of high-energy neutron was still high after moderation. From Fig.1(c) and Fig.2(c), for lager diameter of PS, most of the low-energy neutrons had completely lost their energy before reaching the center of the detector because of deep slow degree, so they cannot be detected. High-energy neutrons still had great chance to reach the PS center to be detected by SP9 ^{3}He proportional counter after moderation.

The two-dimensional response-energy curves of 8 PS calculated by Geant4 were shown in Fig.3.

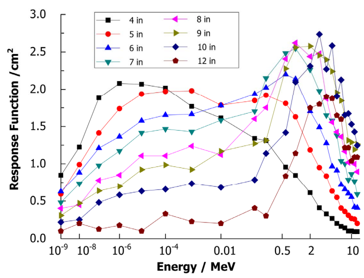

Fig.3 Two-dimensional response-energy curves of 8 PS.

The abscissa was the energy (MeV) and the ordinate was the response (cm^2). The three-dimensional response-energy curves of 8 PS were shown in Fig.4.

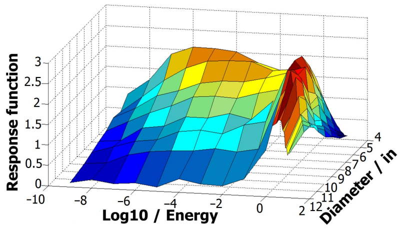

Fig.4 Three-dimensional response-energy curves of 8 PS

We can conclude from Figs.(3) and (4) that each PS has a unique neutron response function. The peak of the response function was in the low energy region for smaller diameter PS (e.g., 4 inch). With increasing of the diameter of PS, the peak of the response function moved to the high energy region. The response function of the small size PS was 4 to 15 times of the large size PS in the low-energy region. The response function of the large size PS was 3 to 12 times of the small size PS in the high-energy region.

4 Experimental calibration

The experimental calibration[10] adopted The ^{241}Am-Be neutron source was produced in 1978 and the product number was 0078AB473395. The radio-activity of the ^{241}Am-Be neutron source was 2.0×10^8 [11–13]. Experimental environment diagram was shown in Figs.5 and 6. The experimental devices were placed on one mobile table. PS (3) was placed on a small table (7) which was next to neutron source (1).

The distance between the neutron source and the sliding bar (5) was 1 meter when neutron source located in the bottom of the shielding barrel (2).The sliding bar can control the height of source precisely. The center of neutron source and PS were located in the same horizontal plane and the distance between the neutron source and the PS was 24 cm.

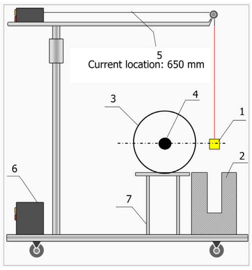

Fig.5 Experimental environment principle diagram. (1) ^{241}Am-Be neutron source; (2) Shielding barrel; (3) Polyethylene sphere; (4) SP9 3He proportional counter; (5) Sliding rod; (6) Power of Sliding rod; (7) Table.

Fig.6 Actual experimental environment photograph.

We can obtain by Eq.(1)

$$N_i = \int R_i(E)\cdot\phi(E)\,\mathrm{d}E \qquad (2)$$

If energy spectrum E fixed, the count N_i and the detection efficiency were proportional to response $R_i(E)$. We can verify the response function of simulation by comparing the detection efficiency of simulation and experimental 4π solid angle counts. The normalized data of detection efficiency by simulation and experimental 4π solid angle counts were shown in Table1. Statistics error is $1/N^{0.5}$, where N is 4π solid angle count.

Table 1 Compare normalized data

PS diameter / in	Simulate detect efficiency	Measure 4π Solid angle count	normalized data: Simulate	normalized data: Measure	Relative Error / %	Statistics Error / %
4	0.6646	6333.2810	0.956355	0.927578	–3.0090	1.2566
5	0.6949	6749.1320	1.000000	0.988484	–1.1516	1.2172
6	0.6296	6827.7580	0.905991	1.000000	10.3764	1.2102
7	0.5681	5251.7560	0.817536	0.769177	–5.9151	1.3799
8	0.4696	4049.9440	0.675752	0.593159	–12.2224	1.5714
9	0.4240	3155.8520	0.610133	0.462209	–24.2446	1.7801
10	0.3390	2562.8110	0.487819	0.375352	–23.0551	1.9753
12	0.2393	1396.2060	0.344394	0.204490	–40.6234	2.6762

The normalized curve of simulation and experimental were drawn in the same coordinate system, as shown in Fig.7.

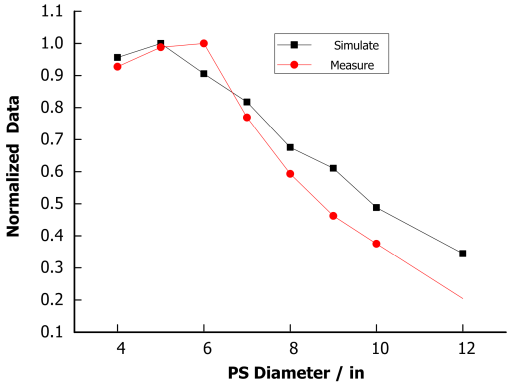

Fig.7 Compare simulate and experiment normalized data.

The variation of experimental data and simulation data were entirely consistent in Table 1 and Figure 5. The relative error of 4 in, 5 in, 6 in, 7 in and 8 in PS were relatively small but 9 in, 10 in and 12 in PS's were relatively large. The corresponding neutron energy of each ball in simulation was from 0.001 eV to 12 MeV but the energy of ^{241}Am-Be neutron source was 5MeV. The peak of response function of large-size PS was in the high energy region, most of the low energy and medium energy neutrons were moderated and captured after entering the PS. Therefore, the experiment count of large size PS was smaller than the simulation data, and the relative error was large. This proved the correctness of the response function obtained by simulation. Combined the response function with multi-sphere spectrometer readings of 8 SP9 ^{3}He detectors can solve the neutron spectrum.

5 Conclusion

The response function of multi-sphere was simulated and calculated by Geant4. The multi-sphere was calibrated using ^{241}Am-Be neutron source. The absolute values of the relative error of PS from 4in to 8 in were less than 12.5%. The good agreement between the measured and simulated response functions confirmed the Monte Carlo model adopted for the multi-sphere simulation. The response function of multi-sphere was the key to solve the real-time neutron spectrum precisely. We can obtain the response function of each PS by Monte Carlo simulation and experimental calibration. This laid the foundation for solving online real-time neutron spectrum of ITER fusion. Future research will include similar experiments for mono energetic beams to improve the response function of multi-sphere, specifically for high energy mono energetic neutron beam greater than 5 MeV. Future work will focus on using the multi-sphere to measure neutron spectra.

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