Simulation and Calibration of the Response Function of Multi-Sphere Neutron Spectrometer Postprint

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Abstract

To achieve online real-time measurement of the neutron spectrum for ITER fusion, this paper presents a multi-sphere spectrometer system comprising eight thermal neutron detectors (SP9 3He proportional counters) embedded in eight polyethylene spheres of varying diameters. The response functions of the eight polyethylene spheres were calculated through simulation of neutron transport processes in the multi-sphere spectrometer using Geant4 software. For polyethylene spheres with smaller diameters, the peak of the response function is located in the low-energy region; as the polyethylene sphere diameter increases, the peak shifts to the high-energy region. Experimental calibration was conducted using a 241Am-Be neutron source. The relative error between normalized experimental 4π solid-angle count data and normalized simulated detection efficiency data for 4-inch to 8-inch polyethylene spheres ranges from 1.152% to 12.222%. The experimental results verify the simulated response functions. These results collectively provide a theoretical and experimental basis for enabling online real-time neutron spectrum measurement in ITER fusion.

Full Text

Simulation and Calibration of the Response Function of a Multi-Sphere Neutron Spectrometer

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Abstract

To enable online real-time measurement of the neutron spectrum in ITER fusion experiments, this paper presents a multi-sphere spectrometer system consisting of eight thermal neutron detectors (SP9 ^{3}He proportional counters) embedded in polyethylene spheres of eight different diameters. The response functions of the eight polyethylene spheres were calculated by simulating neutron transport processes in the multi-sphere spectrometer using the Geant4 software package. For smaller-diameter polyethylene spheres, the peak of the response function appears in the low-energy region, and as the sphere diameter increases, this peak shifts to higher energy regions. Experimental calibration was performed using a ^{241}Am-Be neutron source.

The relative error between normalized experimental data from 4π solid angle counts and normalized simulated detection efficiency data for polyethylene spheres ranging from 4 to 8 inches varies from 1.152% to 12.222%. These experimental results verify the simulated response functions. All these findings provide both theoretical and experimental foundations for achieving online real-time neutron spectrum measurement in ITER fusion experiments.

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

Introduction

The International Thermonuclear Experimental Reactor (ITER) represents one of the world's largest international scientific collaborations. The ITER device is a tokamak designed to produce large-scale nuclear fusion reactions. Developing advanced methods and technologies for fusion neutron spectroscopy, establishing characteristic neutron diagnostic systems, and mastering neutron diagnostic techniques for tokamak fusion devices constitute important components of ITER's research program. ITER has presented new challenges for fusion neutron spectrum measurements, with online real-time measurement of dynamic and time-sharing fusion neutron spectroscopy being among the major difficulties.

The Bonner Sphere Spectrometer (BSS) was first introduced by Bramblett, Ewing, and Bonner in 1960 [1]. This paper presents a multi-sphere spectrometer system based on the BSS principle and specifically designed for measuring

the dynamic and time-sharing fusion neutron spectroscopy of ITER. The system consists of eight pure polyethylene spheres (PS) of different diameters and SP9 ^{3}He proportional counters, which feature large neutron reaction cross sections [2] and low gamma sensitivity. Monte Carlo simulation of the neutron response function for eight polyethylene spheres and calibration of the multi-sphere spectrometer with a neutron source are key to precise neutron spectrum measurement.

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2. Basic Measurement Principle of the Multi-Sphere Spectrometer

The eight polyethylene spheres in the multi-sphere spectrometer have outer diameters of 4, 5, 6, 7, 8, 9, 10, and 12 inches, respectively. An SP9 ^{3}He proportional counter [3,4] is positioned at the center of each sphere.

Neutrons entering a polyethylene sphere are slowed down through elastic collisions with hydrogen and carbon atoms. For smaller-diameter spheres, low-energy neutrons can be moderated to thermal energies and still have a high probability of reaching the sphere's center to be detected. However, high-energy neutrons retain significant energy after moderation and tend to escape. For larger-diameter spheres, numerous low-energy neutrons are absorbed during the moderation process, while high-energy neutrons can be slowed to thermal energies and still have a good chance of reaching the center for detection. Thus, neutrons of different energies experience different degrees of moderation in spheres of different diameters, giving each sphere a unique neutron response function [5,6] defined as R (E):

Where i = 1, 2, …, 8 represents the eight spheres, N is the reading of the i-th sphere, and ϕ(E) is the neutron fluence (cm^{-2}) at the location of the SP9 detector.

In actual measurements, neutron counts can meet statistical error requirements if we set a reasonable time-sharing interval. By continuously measuring time-sharing and real-time neutron spectra, we can monitor the neutron spectrum continuously.

The neutron spectrum can be deduced from the readings of the eight SP9 ^{3}He detectors if the response function R (E) of each sphere is known. Therefore, the neutron response function of each sphere is the key to accurately determining the neutron spectrum.

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3. Simulation

Geant4 (GEometry ANd Tracking) [7-9] is a Monte Carlo application package for simulating the passage of particles through matter, with applications in high-

energy physics, nuclear physics, accelerator physics, as well as medical and space science studies.

By simulating the neutron transmission process in the spectrometer system using Geant4, we obtained eight neutron response curves for the eight polyethylene spheres. Figs. 1 and 2 show the Geant4 simulation results for 4, 8, and 12-inch spheres, corresponding to low-energy and high-energy neutrons, respectively. The neutron source was launched into the polyethylene from the left side of the sphere with solid angle divergence. Green rays in the figures represent neutron trajectories, while the red sphere at the center represents the SP9 ^{3}He proportional counter embedded in the polyethylene sphere. The distance between the neutron source and the 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 spheres, most low-energy neutrons are stopped in the sphere after moderation, giving them a high probability of reaching the center to be detected by the SP9 ^{3}He proportional counter. Most high-energy neutrons escape through the sphere because their energy remains high after moderation. From Figs. 1(c) and 2(c), for larger-diameter spheres, most low-energy neutrons completely lose their energy before reaching the detector center due to deep moderation and thus cannot be detected. High-energy neutrons still have a good chance of reaching the sphere center to be detected by the SP9 ^{3}He proportional counter after moderation.

The two-dimensional response-energy curves of the eight spheres calculated by Geant4 are shown in Fig. 3. The abscissa represents energy (MeV) and the ordinate represents response (cm^2).

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

The three-dimensional response-energy curves of the eight spheres are shown in Fig. 4. A sliding bar can control the source height precisely. The center of the neutron source and the polyethylene sphere were located in the same horizontal plane, with a distance of 24 cm between the neutron source and the sphere.

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

From Figs. 3 and 4, we can conclude that each sphere has a unique neutron response function. The peak of the response function appears in the low-energy region for smaller-diameter spheres (e.g., 4-inch). As the sphere diameter increases, the peak of the response function moves to the high-energy region. The response function of small-size spheres is 4 to 15 times that of large-size spheres in the low-energy region, while the response function of large-size spheres is 3 to 12 times that of small-size spheres in the high-energy region.

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4. Experimental Calibration

The experimental calibration [10] employed a ^{241}Am-Be neutron source produced in 1978 with product number 0078AB473395. The radioactivity of the ^{241}Am-Be neutron source was 2.0$×10^{8}$ [11-13]. The experimental environment diagram is shown in Figs. 5 and 6. The experimental devices were placed on a mobile table. The polyethylene sphere (3) was placed on a small table (7) next to the neutron source (1).

The distance between the neutron source and the sliding bar (5) was 1 meter when the neutron source was located at the bottom of the shielding barrel (2). The center of the neutron source and the polyethylene sphere were located in the same horizontal plane, and the distance between the neutron source and the sphere was 24 cm.

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

From Eq.(1), if the energy spectrum E is fixed, the count N and the detection efficiency are proportional to the response R (E). We can verify the simulated response function by comparing the simulated detection efficiency with experimental 4π solid angle counts.

The normalized data for detection efficiency from simulation and experimental 4π solid angle counts are shown in Table 1. The statistical error is $1/\sqrt{N}$, where N is the 4π solid angle count.

**** Compare normalized data

The normalized curves for simulation and experiment are 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 is entirely consistent in Table 1 and Fig. 5. The relative errors for 4, 5, 6, 7, and 8-inch spheres are relatively small, while those for 9, 10, and 12-inch spheres are relatively large. The neutron energy range in the simulation was from 0.001 eV to 12 MeV, while the energy of the ^{241}Am-Be neutron source was 5 MeV.

The peak of the response function for large-size spheres lies in the high-energy region, meaning most low-energy and medium-energy neutrons are moderated and captured after entering the sphere. Therefore, the experimental count for large-size spheres is smaller than the simulation data, resulting in larger relative error. This proves the correctness of the response function obtained by simulation. Combining the response function with multi-sphere spectrometer readings from the eight SP9 ^{3}He detectors enables solution of the neutron spectrum.

5. Conclusion

The response function of the multi-sphere spectrometer was simulated and calculated using Geant4. The multi-sphere system was calibrated using a ^{241}Am-Be neutron source. The absolute values of relative error for spheres from 4 to 8 inches were less than 12.5%. The good agreement between measured and simulated response functions confirms the validity of the Monte Carlo model adopted for the multi-sphere simulation. The response function of the multi-sphere system is key to precisely solving the real-time neutron spectrum. We can obtain the response function of each sphere through Monte Carlo simulation and experimental calibration, which lays the foundation for solving the online real-time neutron spectrum of ITER fusion experiments. Future research will include similar experiments with monoenergetic beams to improve the response function of the multi-sphere system, specifically for high-energy monoenergetic neutron beams greater than 5 MeV. Future work will focus on using the multi-sphere spectrometer to measure neutron spectra.

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Note: Figure translations are in progress. See original paper for figures.