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Experimental validation of a Tokamak neutron spectrometer based on Bonner spheres*

CAO Jing(曹靖)[1,2;1)] JIANG Chun-Yu(蒋春雨)[1,2] CAO Hong-Rui(曹宏睿)[1,2] YIN Ze-Jie(阴泽杰)[1,2;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

Abstract: In order to realize real-time fusion neutron spectrum diagnosis for the HL_2A Tokamak, a Bonner Sphere Spectrometer (BSS) array has been developed, consisting of eight polyethylene spheres (PS) with embedded ^{3}He proportional counters. To validate its spectrometric capability, spectrum measurement of an ^{241}Am-Be neutron source was carried out and is described. The Monte Carlo code Geant4 was used to calculate the response functions, taking this interference into consideration. Finally, the neutron spectrum was unfolded in the energy range from 10^{-9} MeV to 20 MeV. The unfolded spectrum has remarkable consistency with the ISO 8529-1 standard ^{241}Am-Be neutron spectrum which is a preliminary demonstration that this BSS is reliable and practical.

Key words: neutron spectrometer, ^{241}Am-Be source, Geant4, Tokamak, Bonner sphere, HL_2A, multi-sphere

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1 Introduction

The HL_2A Tokamak at the Southwestern Institute of Physics is the first large controlled fusion experimental device with an operating divertor in China [1]. Neutron diagnosis is typically important for these fusion reactors because the emitted neutron flux and spectrum are directly related to the fusion reaction, but neutron spectra are quite difficult to acquire because they often span several orders of energy magnitude [2]. The typical fusion neutron energy is 2.45 MeV for the D-D fusion reaction or 14.07 MeV for the D-T fusion reaction, but due to elastic scattering or inelastic scattering with the tokamak shell and the surrounding material, the emitted neutrons will be moderated and the energy range extended to the thermal domain. Acquiring the neutron spectral information is of great significance in fusion power studies, fusion power density research, neutron activation analysis, neutron absorbed dose and dose equivalent physical analysis, environmental monitoring and so on.

Among many types of neutron spectrometers, the Bonner Sphere Spectrometer (BSS) [3] is the only one covering the wide energy range from meV to GeV. Since it was first proposed by Bramblett et al. [4] in 1960, the BSS has aroused the interest of more and more laboratories and scientists [5–8]. It has an isotropic response and is quite easy to operate, with a relatively high sensitivity to neutrons. Bad energy resolution is the major weakness, but for some applications such as neutron dosimetry this is less important.

BSS consists of spheres made of neutron moderation material and equipped with thermal neutron detectors, such as ^{3}He, BF_3 Proportional Counter or ^{6}LiI(Eu) scintillation detector in the active version, or gold foils and thermoluminiscent dosimeters pairs (TLD) in the passive version. The moderation material is usually polyethylene. By changing the spheres diameter the thermal neutron detection efficiency varies, with a series of spheres of different sizes, the thermal detectors can detect neutrons from different energy ranges with varying sensitivity, the measured count rates are then used to obtain the neutron spectrum through an unfolding procedure.

The mathematical principle is described by the Fredholm integral equation below, supposing there are m Bonner spheres:

$$C_i=\int R_i(E)\Phi(E)\mathrm{d}E,\ i=1,\ 2,\ 3,\cdots\cdots,m, \tag{1}$$

$\Phi(E)$ represents the incident neutron spectrum, $R_i(E)$ is the neutron response function for the i^{th} Bonner sphere, and C_i is the neutron count reading corresponding to the

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1) E-mail: jcao@mail.ustc.edu.cn

2) E-mail: zjyin@ustc.edu.cn

i^{th} Bonner sphere. After discretization, this becomes:

$$C_i=\sum_{j=1}^{n}R_{ij}\Phi_j,\ i=1,\ 2,\ 3,\cdots\cdots,m, \tag{2}$$

where j is the index over the discrete energy points; Φ_j stands for the neutron flux from E_j to E_{j+1}; R is an $m\times n$ matrix called the response matrix, which is known in advance, and in this work calculated by Geant4; and the neutron counts C_i are acquired through measurements. The spectrum unfolding is in fact the task of working out the neutron spectrum Φ_j in Eq. (2), solving a series of linear equations. The number of Bonner spheres is quite limited, however, far less than the number of discrete points ($m<n$), making it an underdetermined problem which can only be solved by some mathematical unfolding algorithms.

In this paper an experimental validation of a BSS which is specially designed for fusion neutron spectrum diagnosis is introduced in detail, namely the measurement with a standard ^{241}Am-Be neutron source. Due to the requirement of monitoring the evolution of the fusion neutron spectrum, the capability of real-time measurements is achieved in this BSS system. Therefore, in this validation experiment all the neutron readings were acquired synchronously and in real time. This synchronous measurement has brought in many sources of interference, such as scattering neutrons from other Bonner spheres and the environment. Geant4 has been used to calculate the response functions with consideration of these interference factors. In addition, the fusion spectrum is evolving throughout the Tokamak reaction period, the Tokamak shell and the surrounding material also have a moderation impact on the neutron spectrum, and a common guess spectrum can hardly be used for spectrum unfolding. To match this requirement, limited a priori information about the energy distribution of the neutron source was used. The spectrum was unfolded at the wide energy range from 10^{-9} MeV to 20 MeV, covering the whole energy region where the BSS is sensitive. The final unfolded spectrum has a remarkable consistency with the standard ^{241}Am-Be spectrum.

2 Experiment

The BSS used consists of eight PTB Polyethylene Spheres (PS) [9] with ^{3}He-filled spherical proportional counters embedded in the center (type SP9, Centronic Ltd., UK). The counters act as central thermal neutron detectors, and the diameters of the PSs are 4, 5, 6, 7, 8, 9, 10 and 12 inches with a density of 0.946 g/cm^3. The SP9 ^{3}He proportional counter has a diameter of 33 mm for its spherical part, which contains 2 atmospheres ^{3}He gas; its total length is 134 mm, and the operating voltage is 800–900 V with a neutron sensitivity of 8 cps for 3.2 mrem/hr.

The BSS was applied to measure the neutron spectrum of a standard Chinese-made ^{241}Am-Be neutron source [10] belonging to the Department of Modern Physics, University of Science and Technology of China. The neutron source was manufactured in 1978 with an activity of 2.00×10^8 Bq, and the energy of the emitted neutrons ranges from 10^{-7} MeV to 11 MeV according to the ISO 8529-1 standard ^{241}Am-Be neutron spectrum [11]. This is quite similar to the energy of fusion neutrons around tokamak facilities, which ranges from thermal to 15 MeV, so it was chosen to replace the real tokamak neutron radiation environment as a preliminary validation test of the spectrometric capability of this BSS.

In Tokamak neutron spectrum diagnosis, the real-time feature is indispensable, since the neutron spectrum is evolving during the short reaction period. To fulfill this requirement all the readings of the eight PSs should be acquired synchronously and in real time, therefore in this validation measurement the PSs were placed around the neutron source with geometric symmetry, as illustrated in Fig. 1. The neutron source was arranged to be set on a central columnar platform, and all the eight PSs were placed 40 cm away from the center. When the measurement was started, the neutron source was placed in the center by a lifting device, which was controlled from the next-door monitoring room to avoid radiation injury from this neutron source. All the PSs shared the same distance and the same height to the central neutron source. This spatial symmetry generally allowed all the PSs to be exposed to the same neutron radiation and ensured the consistency of measurements. During measurement a high operating voltage of 900 V was added to each ^{3}He proportional counter in its PS through

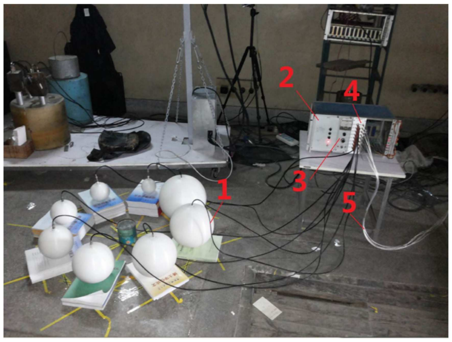

Fig. 1. (color online) The measurement environment of the ^{241}Am-Be neutron source. Part 1 is the high voltage and signal cable of the ^{3}He proportional counter in PS; Part 2 is a NIM chassis; Part 3 is the high voltage power supply module; Part 4 is the 8-channel pre-amplifier module in the NIM chassis; Part 5 is the output signal wires of the pre-amplifier which are pulled to the next-door monitoring room and connected to the main electronics system.

the black cables, and then the neutron source was lifted to the central platform. The output pulse signal of the ^{3}He proportional counters is quite weak, with an average electric charge of 7×10^{-14} C, therefore an 8-channel pre-amplifier was used to amplify the signals, which were sent to the electronics system in the monitoring room. The electronics system sets suitable pulse amplitude thresholds to discard the noise signals, while the real neutron signals are acquired and processed in real time. Readings of the eight PSs are gathered in a preset sub-time as low as 20 ms, and then uploaded to the host computer for the spectrum unfolding procedure. The measurement lasted for 50 seconds, and based on all the real-time neutron count data acquired from this experiment, the neutron count rate corresponding to each PS was calculated. Then the measurement was repeated 12 times and the uncertainties found. All the data is shown in Table 1.

Table 1. Neutron count rates and their uncertainties for the eight PSs.

PS diameter/in	counts rate/cps	max uncertainty	average uncertainty
4	10.68	6.32%	2.57%
5	21.54	4.98%	2.60%
6	23.22	6.56%	2.51%
7	34.34	5.54%	2.02%
8	35.36	4.11%	1.65%
9	47.34	3.09%	1.28%
10	39.18	3.12%	1.12%
12	13.24	7.61%	2.32%

3 Response functions

The neutron response functions of the BSS were calculated through the particle transport Monte Carlo simulation toolkit Geant4. In this work Geant4 version 10.00.p01 was used, with the neutron cross section data in the library G4NDL4.4 mainly based on ENDF/B-Ⅶ cross-section evaluation and $S(\alpha,\ \beta)$ tables for thermal neutrons. Neutron High Precision models were used to deal with neutrons below 20 MeV; for neutrons under 4 eV (thermal neutrons), individual thermal motions become important, and the Neutron HP Thermal Scatter model based on the free gas approximation is taken to deal with their elastic scattering action.

The normally calculated BSS neutron response functions [12] needed to be corrected sufficiently during this experiment. First, the eight PSs were quite close to the neutron source, with a distance of only 40 cm, so the neutron radiation could not be treated as parallel; second, the existence of scattering neutrons from other PSs and the floor could not be ignored. Precise mathematical correction to the response functions seems impossible, therefore, instead of correction, new response functions were calculated based totally on the real measurement environment. Fig. 2 shows the simulation environment. The green lines represent the trajectories of the isotropically emitted neutrons from the center. Fig. 3 shows the simplified polyethylene sphere structure in the simulation.

The neutrons will be detected by the ^{3}He proportional counter by the ^{3}He(n, p)T reaction, so in Geant4 simulation a neutron count is acquired or not and is judged by the energy deposition of reaction products of protons and tritons. 48 discrete energies were picked from 10^{-9} MeV to 20 MeV at logarithmically equidistant intervals, except for the area between 1 MeV and 10 MeV. Four energy points were selected for each order of energy magnitude, but 10 energy points were chosen

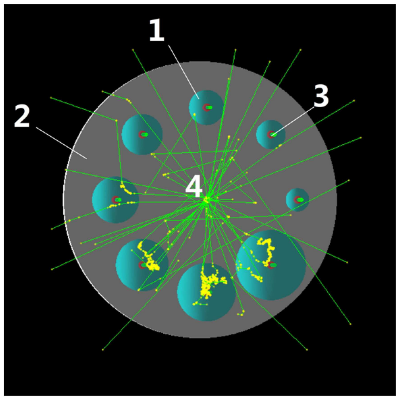

Fig. 2. (color online) Simulation geometric structure of the experiment environment in Geant4. Part 1 is the polyethylene sphere, with density 0.946 g/cm^3; Part 2 is the floor, simplified to be made of cement; Part 3 is the ^{3}He Proportional Counter; Part 4 is the neutron source.

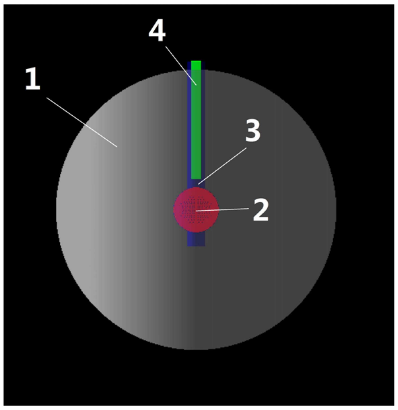

Fig. 3. (color online) Simulation structure of Bonner sphere (8 inch) in Geant4. Part 1 is the polyethylene material; Part 2 is the ^{3}He gas with pressure of 2 atmospheres; Part 3 represents the stainless steel shell of the ^{3}He proportional counter, its material assumed to be pure iron; Part 4 is the air cavity.

between 1 MeV and 10 MeV to show the fine structure of the ^{241}Am-Be spectrum there. In the Geant4 simulation 10^8 neutrons were simulated for each energy point, the acquired neutron counts were gathered for each PS, and thus the whole neutron response functions were calculated as shown in Fig. 4. It can be seen that the peak gradually moves to higher energy ranges as the sphere size increases. While the larger PSs are sensitive to neutrons of higher energy, from the 7-inch sphere upwards the neutron response function decreases, on the whole. Precisely calculated response functions are extremely important for the spectrum unfolding procedure.

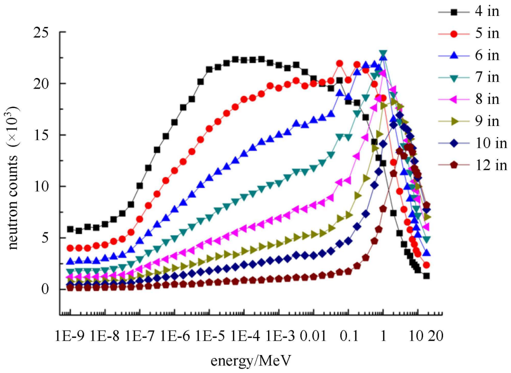

Fig. 4. (color online) BSS neutron response functions in this measurement environment.

4 Result

Based on Eq. (2), the neutron spectrum was unfolded with the neutron counts acquired from the experiments (Table 1) and the calculated neutron response functions (Fig. 4), and then the unfolded flux spectrum was converted to an intensity spectrum and compared with the ISO 8529-1 standard intensity spectrum [10] in Fig. 5. It can be seen that the unfolded intensity spectrum has a remarkable consistency with the standard ^{241}Am-Be neutron spectrum.

5 Conclusion and discussion

To validate the tokamak neutron real-time diagnostic BSS, preliminary measurement experiments were carried out on an ^{241}Am-Be neutron source. To ensure its real-time feature, all the polyethylene spheres were placed around the source, and neutron count readings needed for spectrum unfolding were acquired synchronously and in real time. The influence of scattering neutrons was considered in the neutron response function calculation. Limited a priori information about the energy distribution of the ^{241}Am-Be neutron source was used, and the spectrum was unfolded for the whole 10^{-9} MeV to 20 MeV energy range. The unfolded spectrum has a remarkable consistency with the standard spectrum, which demonstrates that the Bonner Sphere Spectrometer is applicable and reliable.

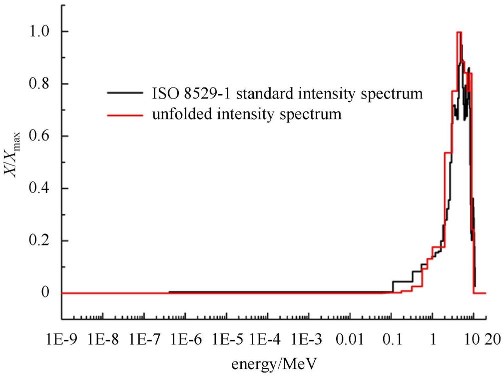

Fig. 5. (color online) The unfolded intensity spectrum in comparison to the ISO 8529-1 standard intensity spectrum.

Due to the limitations of time and computing capability, only 10^8 neutrons were simulated for each energy point in the response function calculation. A little statistical fluctuation can be observed in the response functions shown in Fig. 4. In future work we hope to improve this and reduce the uncertainty of the response functions. In this work the neutron spectrometer has been tested on a ^{241}Am-Be neutron source, but this is not enough for full testing. Some mono-energetic neutron sources should be applied to complete the calibration; however, this would be quite expensive and time-consuming.

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