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Verification of a fusion neutron diagnostic Bonner sphere spectrometer on measurement of a ^{241}Am–Be neutron source

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Abstract A Bonner sphere spectrometer (BSS) was developed for neutron diagnostic on HL_2A Tokamak. It contains eight polyethylene spheres embedded with SP9 ^{3}He proportional counter. Before setting up on the Tokamak experimental hall, a verification experiment was arranged on a ^{241}Am–Be neutron source to test its spectrometry capability. The neutron response functions were calculated by Monte Carlo code Geant4 to simulate the real measurement environments. By least square method, the neutron spectrum was finally unfolded on log domain from 0.1 eV to 11 MeV. It has a remarkable consistency to the ISO 8529-1 standard ^{241}Am–Be neutron spectrum. This shows that the BSS is effective and reliable for neutron spectrum determination.

Keywords Bonner sphere spectrometer · Tokamak · HL_2A · Geant4 · ^{241}Am–Be

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1 Introduction

Neutron spectrum determination is a difficult task, because of its uncharged nature, and the distinctive energy spans of orders of energy magnitude, even from meV to GeV [1]. Neutrons emitted in a Tokamak fusion reactor are either 2.45 MeV from D–D reaction or 14.06 MeV from D–T reaction, but due to moderation impact of the Tokamak shell and surrounding materials, the neutrons can be distributed into the thermal domain. The simulation results in EAST Tokamak [2] showed that the neutron energy spectrum in its experimental hall covers the energy range from 0.001 eV to 10 MeV [3]. Acquiring the neutron spectrum is of significant importance for its capacity to access some key plasma parameters, such as fusion power, ion temperature, fast ion energy and spatial distribution of these parameters in Tokamak plasma reaction zone.

Bonner sphere spectrometer (BSS) [1], known as multi-sphere spectrometer, is at present the only type of neutron spectrometer covering the wide energy range from meV to GeV. Proposed in 1960 by Bramblett et al. [4], it has been established and used in laboratories [5–8], due to its advantages of wide energy coverage, isotropic response and operation convenience, despite its drawback of poor energy resolution. It usually consists of PE spheres (PS) equipped with thermal neutron detector, such as ^{3}He, BF_3 proportional counter or ^{6}LiI(Eu) scintillation detector in the active version, or gold foils and thermoluminescent dosimeters pairs (TLD) in the passive version. The use of water was suggested to replace PE as moderator [9]. In the spheres of different diameters, the thermal neutron detection efficiency varies, hence the wide energy range of BBS. The measured count rates are used to obtain the neutron spectrum through an unfolding procedure [1].

A BSS was developed, with eight PE spheres and an SP9 ^{3}He proportional counter, to accomplish the neutron diagnostics on HL_2A Tokamak of Southwestern Institute of Physics, the first large controlled experimental device with an operating diverter in China [10]. Before its establishment on the Tokamak experimental hall, the BSS was applied to measure a ^{241}Am–Be neutron source to verify its spectrometry capability as an experimental validation.

2 Mathematical principle

The method of BSS can be described as the Fredholm integral equation:

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

where N_i is the reading of the ith PS, i.e., neutron count of the ^{3}He proportional counter inside the PS; m is the number of PSs in the BSS; $\Phi(E)$ is the neutron spectral fluence; and $R_i(E)$ is the neutron response functions of the ith PS. Each PS has a unique response function depending on the size and type of moderation shell, since inner detector is usually thermal sensitive. Equation (1) should be discretized for unfolding procedure, and it was turned to:

$$N_i = \sum_{j=1}^{n} R_{ij} \Phi_j, \quad i = 1, 2, 3, \ldots, m, \tag{2}$$

where the whole energy region is divided into n parts by discrete energy points E_0 to E_n, Φ_j is the neutron flux from E_{j-1} to E_j and $\boldsymbol{R}_{ij}$ is a $m \times n$ matrix called the response matrix, which can be calculated by with Geant4 [11] or MCNP [12] and validated by mono-energy neutron source. The aim of spectrum unfolding is to solve the neutron flux Φ_j, which is made up of a series of linear equations. Due to the limitation of reality, the number of PSs is about ten, but discrete energy points are far more than that, i.e., $m < n$, in Eq. (2). This problem can be solved using some mathematic algorithms [13–15].

In this work, least square method (LSM) [15] was utilized for unfolding procedure. Its main idea is to find the result which is best approaching the measured data; in other words, the squared residual error of Eq. (2)

$$\boldsymbol{S} = ||\boldsymbol{N} - \boldsymbol{R\Phi}||^2 \tag{3}$$

should be minimized. Therefore, Eq. (2) should be changed to its regularized version:

$$\boldsymbol{R}^{\mathrm{T}}\boldsymbol{N} = \boldsymbol{R}^{\mathrm{T}}\boldsymbol{R\Phi}, \tag{4}$$

where $\boldsymbol{R}^{\mathrm{T}}$ is the transposed matrix of response matrix $\boldsymbol{R}$. Assuming $\boldsymbol{X} = \boldsymbol{R}^{\mathrm{T}}N$ and $\boldsymbol{A}$ combines $\boldsymbol{R}^{\mathrm{T}}$ and $\boldsymbol{R}$:

$$\boldsymbol{X} = \boldsymbol{A\Phi}. \tag{5}$$

Iteration method can be used to solve Eq. (5) for its good tolerance for data error, and the flux spectrum $\boldsymbol{\Phi}$ can finally be estimated.

3 Measurements

The BSS we developed consists of eight PTB PSs [16] and SP9 ^{3}He proportional counters from Centronic Ltd., UK (Fig. 1). The PSs are of 4, 5, 6, 7, 8, 9, 10 and 12 inches in diameter, with density of 0.946 g/cm^{3}. The ^{3}He counter contains 2 atmospheres ^{3}He gas in its spherical structure of Φ 33 mm, in a total length of 134 mm. Its high power supply is 800–900 V, and it has a neutron sensitivity of 8 cps in a neutron radiation field of 3.2 mrem/h.

A ^{241}Am–Be neutron source was used to test the spectrometric capability of the BSS as a preliminary validation. It is the most widely used isotopic neutron source in laboratories, with a half lifetime of 433 years, and an energy distribution covering the interest of many applications [17]. According to ISO 8529-1 standard [18], the ^{241}Am–Be neutron spectrum extend from 0.1 eV to 11 MeV, being quite similar to the neutron spectrum in Tokamak experimental hall (from thermal domain to 15 MeV) and suitable for this validation. The ^{241}Am–Be neutron source, belongs to Modern Physics Department, USTC, was manufactured in 1978 with activity of 2×10^{8} Bq. It is a typical China-made compressed-mixture neutron source [19].

The measurement assembly is illustrated in Fig. 2. The neutron source was placed in a paraffin bucket as bioshielding. It can be lifted by a remote-control device to irradiate the PS sitting on the table. The source–target distance is 24 cm. The coaxial cable transports neutron signals from the ^{3}He proportional counter inside the PS to a preamplifier and then the main electronic system for data acquisition, and the 900 V bias is provided to the proportional counter through the cable. The insert in Fig. 2 is a photograph taken by the monitor camera in the control room next to the measurement room.

In the measurement, the PE spheres were seated one by one on the table at the same location to measure the

Fig. 1 Eight PTB polyethylene spheres and SP9 ^{3}He proportional counter

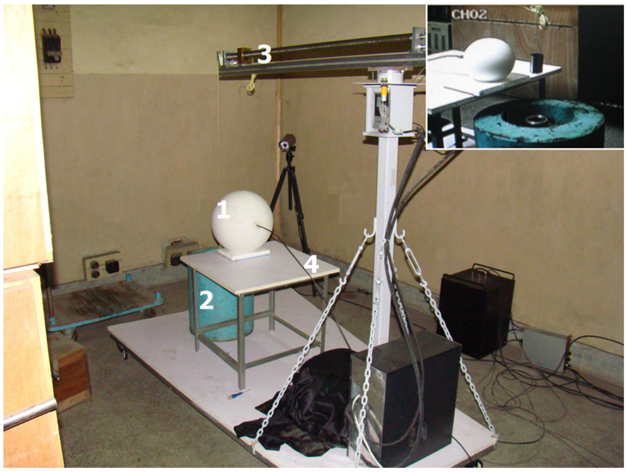

Fig. 2 Measurement assembly. *1* PE sphere, *2* ^{241}Am–Be neutron source, *3* source-lifting mechanism and *4* coaxial cable

neutron source, with the same source height and source–target distance to ensure consistency of the measurements. The neutron count rate was found to be quite low. To improve the statistics, each measurement was lasted for 2 min and repeated for 12 times to estimate its level of uncertainty. Before their neutron source measurement, every PS was counted for 10 min to acquire the background counting. The neutron count rates of the PSs are given in Table 1, together with their uncertainties and backgrounds. The backgrounds were subtracted from the total count rates to obtain the net count rates for spectrum unfolding.

4 Response functions

The neutron response functions of this BSS were calculated by Geant4 [20], a popular M-C code for simulating particle passages through matter, written by CERN in C++ programming language. Due to its open-source feature, powerful processing capacity, continuous updating and full cross-section coverage, Geant4 [20] is widely used for applications in particle physics, nuclear physics, accelerator, space engineering and medical physics.

The simulation geometry is based on the real measurement, as illustrated in Fig. 3a taking a 10-inch PS as an example. Figure 3b is the simulated neutron tracks. To increase the counting rate from a 2×10^8 Bq source, the source–target distance is only 24 cm, so the neutron irradiations are not in parallel. The PS is irradiated by neutrons emitting from a random position from the cylindrical surface of the source. The wooden table, which could scatter neutrons, is added to ensure accuracy of the PS readings. The neutron cross section in file G4NDL4.4 mainly derives from ENDF/B-VII cross-section evaluation. To be more specific, high-precision model handles with neutrons below 20 MeV. NeutronHPThermalScatter model deals with the elastic scattering of neutrons below 4 eV, based on free gas approximation, because for thermal neutrons, individual thermal motions become dominate.

If the incident neutrons react with the ^{3}He gas in the ^{3}He proportional counter as below:

Table 1 Measurement results of the eight PSs

PS diameter (in)	4	5	6	7	8	9	10	12
PS reading in 120 s	961	1553	2210	2364	2331	2479	2440	1941
Max uncertainty (%)	6.48	6.61	4.76	3.73	2.67	5.14	7.02	8.40
Average uncertainty (%)	3.71	2.26	1.71	1.44	0.90	1.84	3.36	2.67
Total count rate (cps)	8.01	12.94	18.42	19.70	19.43	20.66	20.33	16.18
Background counting rate (cps)	0.75	0.85	1.08	1.02	0.72	0.62	0.75	0.57
Net neutron count rate (cps)	7.26	12.09	17.34	18.68	18.71	20.04	19.58	15.61

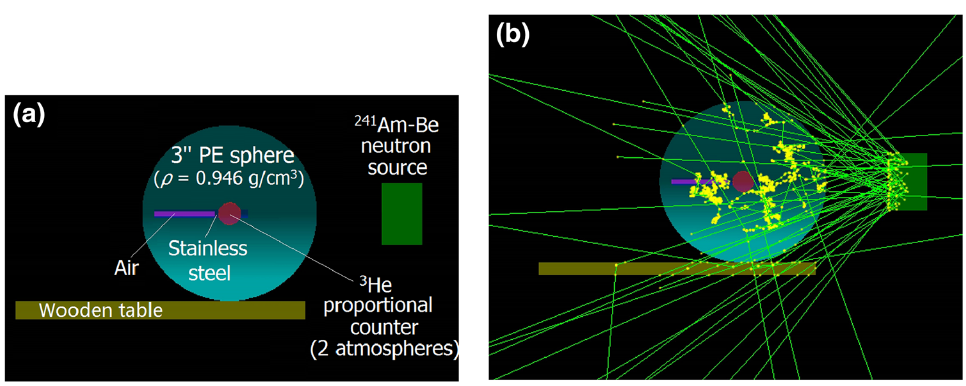

Fig. 3 Geant4 simulation geometry (**a**) and the simulated neutron tracks in 8″ PS from the surface of the ^{241}Am–Be source (**b**)

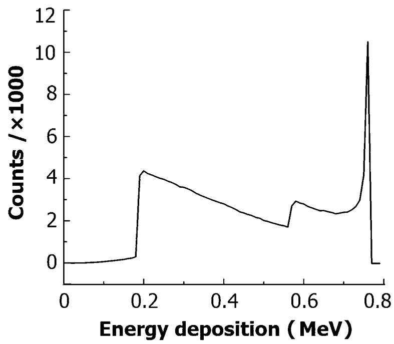

Fig. 4 Energy deposit spectrum of the ^{3}He proportional counter. *Peak 1* is a full collection of the energy deposition of 0.2 MeV triton; *peak 2* was contributed by the full collection of the energy deposition of 0.57 MeV protons; and *peak 3* is the whole energy peak with total collection of the energy deposition of 0.2 MeV triton and 0.57 MeV proton

$$ {}^{3}_{2}\mathrm{He} + n \rightarrow p(0.57\,\mathrm{MeV}) + {}^{3}_{1}\mathrm{H}(0.2\,\mathrm{MeV}). \quad (6) $$

The counter generates an electric pulse due to energy deposition and ionization of the 0.57 MeV proton and 0.2 MeV triton. However, when the reaction occurs at the edge of ^{3}He gas, the generated protons and tritons may enter the shell and will not cause much ionization in the proportional amplification area. These weak signals shall be ignored by the electronic acquisition system. In the Geant4 simulation, a neutron count event was judged by the amount of energy deposition. A total of 10^{8} neutrons at 1 MeV were simulated to irradiate the 8$''$ PS, and the energy deposit spectrum in ^{3}He gas area was gathered (Fig. 4), with the energy interval of 0.01 MeV. The energy threshold was set to be 0.2 MeV, and an event with energy deposition less than 0.2 MeV would be ignored.

To calculate the neutron response function of each PS, the total sensitive energy region from 10^{-9} to 100 MeV was divided into 50 energy bins, and 51 discrete energy points were selected at logarithmically equidistant intervals. Four points for an order of energy magnitude, except the 1–10 MeV regions, where 10 points were selected to show detailed structure of the response functions there. A total of 10^{8} mono-energy neutrons at each selected discrete energy were simulated to irradiate the PS, its neutron counts were gathered, the simulation was repeated for each PS, and all their neutron response functions were obtained (Fig. 5).

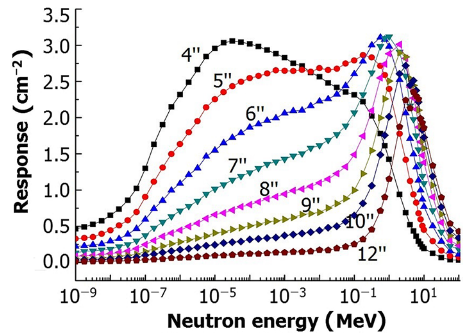

Fig. 5 Neutron response functions of the eight PSs

5 Results

Based on Eq. (2), the neutron spectrum of ^{241}Am–Be source was unfolded with the measured neutron count rates in Table 1, the neutron response functions (Fig. 5) and the LSM unfolding algorithm. The unfolded spectrum was compared to ISO 8529-1 standard ^{241}Am–Be spectrum. Figure 6a shows the neutron spectral fluence $\Phi(E)$ times neutron energy E as function of E in MeV. The unfolded neutron fluence spectrum $\Phi(E)$ was also compared to the ISO 8529-1 standard spectrum in linear domain in Fig. 6b. A large difference between the two spectra can be seen in 9–11 MeV in Fig. 6a, while in Fig. 6b the difference is

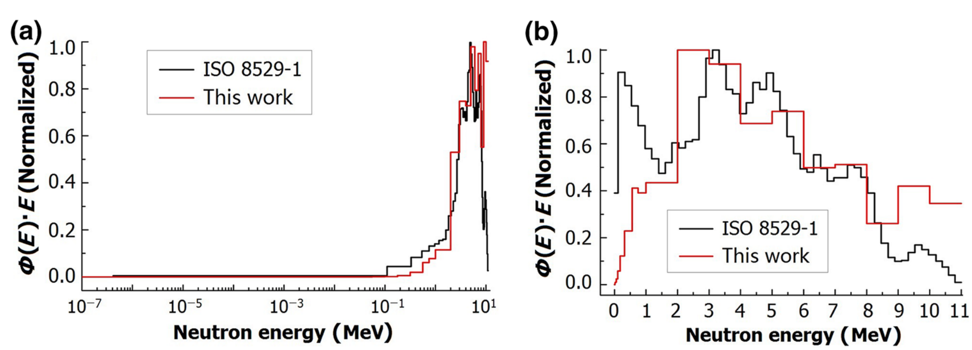

Fig. 6 Comparisons of the unfolded neutron spectra with ISO 8529-1 standard ^{241}Am–Be spectrum. **a** Logarithmic and **b** linear

much smaller, because the multiplying $\Phi(E)$ by E highlights the error of $\Phi(E)$ in high energy region (9–11 MeV). Generally, the unfolded spectrum has a remarkable consistency with the ISO 8529-1 standard spectrum. This proves that the BSS, and our measurement method, is reliable and practical.

6 Conclusion and discussion

In this work, a Tokamak fusion neutron diagnostic BSS was validated by measuring the spectrum of a ^{241}Am–Be neutron source. The measured neutron spectrum has a remarkable consistency with the ISO 8529-1 standard spectrum. The BSS was verified to be reliable and practical for future neutron diagnostic applications on HL_2A Tokamak. The Monte Carlo simulation code Geant4 shall be prospect for neutron diagnostic on Tokamak devices.

The spectrometric capability of this BSS can be improved. The neutron response functions shall be validated by mono-energy neutron sources, though it is quite expensive and time-consuming. The unfolded spectrum differs greatly from the ISO 8529-1 standard spectrum in 0–1 and 9–11 MeV regions. This may have the following reasons. With the BSS consisting of only eight Bonner spheres, the spectral information acquired is quite limited. The other reasons may include inaccuracies of the experimental data and the calculated neutron response functions. The BSS will be added with 3″, 3.5″, 4.5″, 15″ and 18″ Bonner spheres, so as to enhance its spectrometric capability. The spectrum of ^{241}Am–Be neutron source has an energy range of up to 11 MeV, so detection quality of the BSS for D–T period fusion neutrons of 14.06 MeV needs further validated, with the 15″ and 18″ Bonner spheres.

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