DESIGN AND IMPLEMENTATION OF MATRYOSHKA-TYPE NEUTRON SPECTROMETER

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Abstract: Aiming at the portability and mobility, the design and implementation of a portable neutron spectrometer, namely Matryoshka-type neutron spectrometer (MNS), was completed consulting the idea of a Bonner sphere spectrometer (BSS). The MNS used a spherical He-3 proportional counter as a thermal neutron detector. A series of cylindrical acrylic cups with diameters from 4 cm to 40 cm were made as containers of water moderator. The Monte Carlo method was adopted to obtain the energy response matrix of the MNS. During the measurement, each acrylic cup contained water as a moderator, and the He-3 proportional counter was placed at the geometric center to perform neutron counting. With the energy response matrix obtained above, the neutron spectrum was solved through a classical inversion algorithm. After the measurement, water was drained and the acrylic cups were placed one by one like a Matryoshka doll. The design of MNS has reduced the mass and volume of BSS, and was easy to carry around. Comparison test of acquiring background and Am-Be source neutron spectra between MNS and BSS proved the effectiveness of the MNS.

Key words: neutron detection, neutron spectrum, neutron spectrometer, full energy range

1. Introduction

As its wide energy response range, simple operation and ingenious calculation, multisphere neutron spectrometer is widely used to determine neutron spectrum for the purpose of neutron ambient dose equivalent measurement. For multisphere neutron spectrometer was invented by Bramblett R.L., Ewing R.I. and Bonner T.W. in 1960, it is also called Bonner sphere spectrometer (BSS) [1], which was composed of a series of polyethylene moderator balls and a thermal neutron detector in center. Since then, more mature products of BSS have been gradually coming out, including the NEMUS BSS jointly designed by the British Centronic Company and PTB, the LUDLUM 42-5 BSS, the ROSPEC BSS, etc. In China, MNSIL 100 BSS [2] was jointly developed by Tsinghua University and Tongfang Weishi; many other research institutes have developed a variety of prototypes for their own special needs [3, 4].

Although operation process is simple, the polyethylene moderator balls of BSS are inconvenient to be moved from one radiation field to another because their weight and volume. In this article, moderators were designed as a series of cylindrical acrylic cups filled with water, which could be drained out while acrylic cups could be placed into another one by one like a Matryoshka doll. In this way, the weight and volume of the whole neutron spectrometer are reduced sharply. The neutron spectrometer becomes portable and lightweight to carry around.

2. Instruments and Algorithm

2.1 Instruments

Matryoshka-type neutron spectrometer (MNS) is mainly composed of a spherical He-3 proportional counter as thermal neutron detector, a series of cylindrical acrylic cups which could be filled with water as moderators when measuring. The voltage pulse signal from spherical He-3 proportional counter is sent to the computer through the charge sensitive preamplifier, serial multichannel analyzer, 485 to USB convertor module, as shown in Fig. 1.

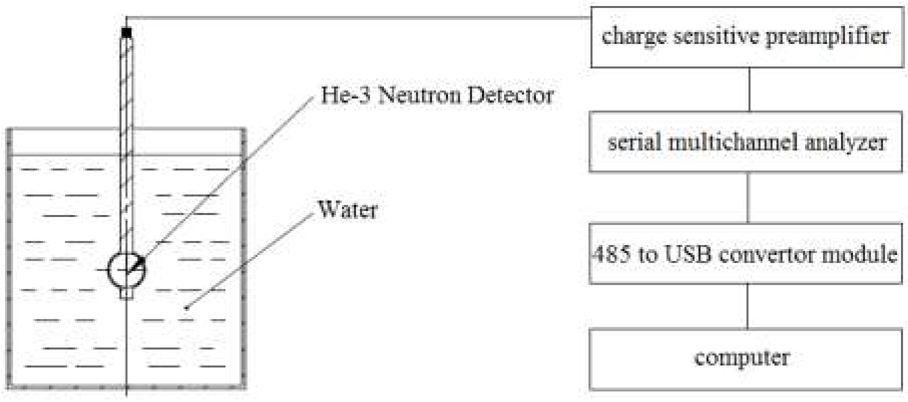

Fig. 1 Block diagram of MNS

The acrylic cups were designed as cylinders, whose diameter is the same with height each one, with values of 4 cm, 6 cm, 8 cm, 10 cm, 12 cm, 14 cm, 16 cm, 18 cm, 20 cm, 22 cm, 24 cm, 26 cm, 28 cm, 30 cm,32 cm, 35 cm and 40 cm, as shown in Fig. 2.

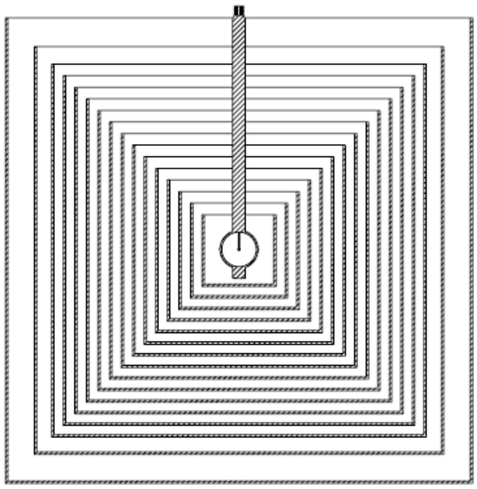

Fig. 2 Acrylic cups of Matryoshka-type neutron spectrometer

2.2 Algorithm

Before entering the thermal neutron detector, the neutrons might escape caused of elastic scattering with carbon nucleus, oxygen nucleus and hydrogen nucleus in the moderator, or react and be captured. The neutron could only be detected after moderated by the acrylic cups filled with water and enters into the spherical He-3 proportional counter.

The full energy range of neutron under analyzed covers from 10^{-9} to 10 MeV, and it is divided into n energy groups with the width ΔE_j. For each moderator, that is an acrylic cup full of water, the neutron count rate N_i measured by the He-3 proportional counter is:

$$N_i = \sum_{j=1}^{n} R_i(E_j)\varphi(E_j)\Delta E_j = \sum_{j=1}^{n} R_{ij}\varphi_j \qquad j = 1, 2, \cdots \tag{1}$$

where $\varphi_j = \varphi(E_j)\Delta E_j$ is the total neutron fluence in the jth energy group of width ΔE_j, and R_{ij} is the fluence response of the ith moderator to neutrons in the jth energy group. For a MNS composed of m moderators, formula (1) can be rewrite as a matrix form:

$$N = R \cdot \varphi_E \tag{2}$$

where N is an m-dimensional column vector representing the count rate of each moderator; R is a neutron fluence response matrix with m rows and n columns, and each row represents a neutron fluence response function of a size of moderator to each neutron energy group; φ_E is an n-dimensional column vector, which represents the group fluence rate of each neutron energy group, that is, the neutron energy spectrum over the full energy range.

Neutron fluence response matrix R could be calculated by Monte-Carlo method and calibrated in reference neutron radiations field, as shown in Fig. 3. After measuring the count rate N_i of each moderator, combined with the energy response matrix R, inversing the matrix (2) and we can obtain the neutron energy spectrum φ_E.

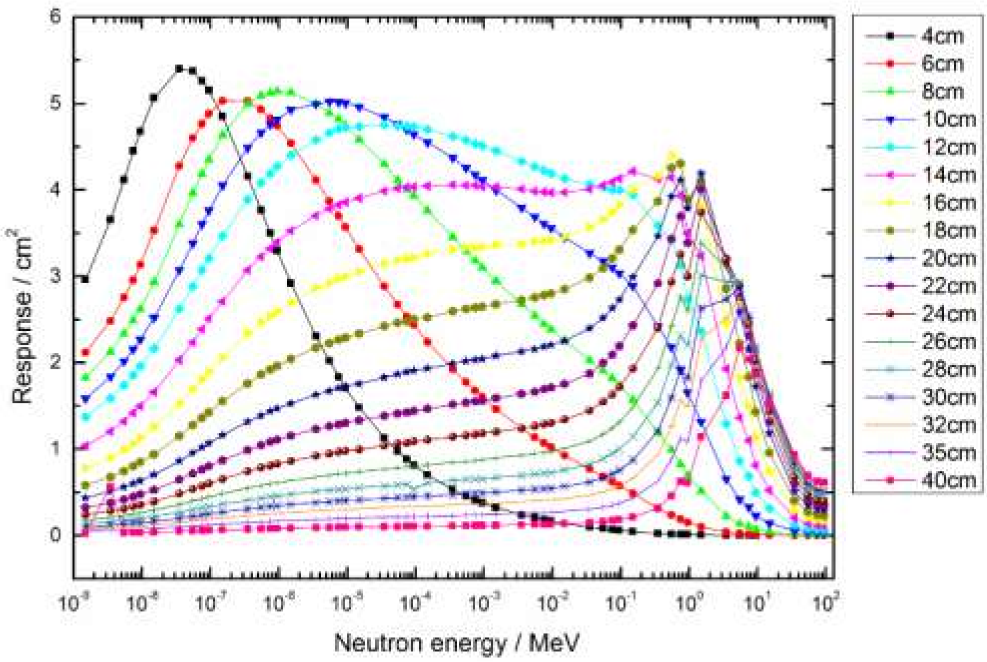

Fig. 3 Curve of neutron fluence response

Since the number m of moderators is less than the number n of neutron energy groups, this is a typical problem of "few-channel" unfolding, which can be solved by iterative method, maximum entropy method, nonlinear least squares method, genetic algorithm, neural network algorithm, etc. In this paper, the GRAVEL iterative algorithm is used to solve the "few-channel" unfolding problem [5].

The advantage is that the initialization conditions of the neutron spectrum are not too strict. As long as the shapes are roughly similar, the iterative formula will adjust the neutron spectrum with reference to the measured values and the response matrix, and finally get a better result. If there is no prior information of the preset spectrum, it can be replaced by a uniform distribution.

3 Measurements and Analysis

3.1 Measurements

The MNS was used to acquire the neutron spectrum of Am-Be neutron source radiation field. The laboratory is 12 m (long) × 6 m (wide) × 4 m (high). It is a reinforced concrete structure with indoor space. The Am-Be neutron source was 1.2 m high away from the ground and was located at the center of the ground plane. The geometric center of the thermal neutron detector was 0.5 m away from the Am-Be neutron source. Before Am-Be neutron source radiation field spectrum measurement, background neutron spectrum measurement of this lab was under consideration. The measurement results are shown in Table 1.

Table 1 Neutron counting rate for three kinds of radiation fields

Diameter /cm	Background /cps	Am-Be neutron source /cps
6	0.00465	2.42
8	0.00549	5.25
10	0.00553	8.48
12	0.00641	12.76
14	0.00576	16.12
16	0.00630	16.30
18	0.00613	17.43
20	0.00523	16.68
22	0.00595	19.27
24	0.00539	16.13
26	0.00520	18.69

3.2 Analysis

Neutron energy analysis interval was limited between 1×10^{-9} and 10 MeV. With the Algorithm introduced above, the inversed neutron spectra of radiation field are shown in Fig. 4 and Fig. 5.

Fig. 4 illustrates the background neutron spectrum of the lab. The dotted line was the result obtained by MNS this paper designed, compared with solid line, which was the result obtained by BSS. There exist two peaks in the spectrum:

i. Evaporation neutron zone [6]. The neutron energy in this region is between 0.1 MeV and 10 MeV, the main source is the resonance nuclear reaction between neutrons and atmosphere or with buildings. The energy of the neutron generated by the de-excitation is 0.1 ~10 MeV.
ii. Thermal neutron zone. The neutron energy of this region is less than 0.4 eV, and the most probable distribution is between 10^{-8}~10^{-7} MeV, which is basically consistent with the Maxwell distribution [6]. The neutron is derived from the collision of neutrons in the air with the walls of the laboratory, the ground and other materials, and finally reaches the thermal equilibrium state, finally forming a thermal neutron peak on the background neutron energy spectrum.

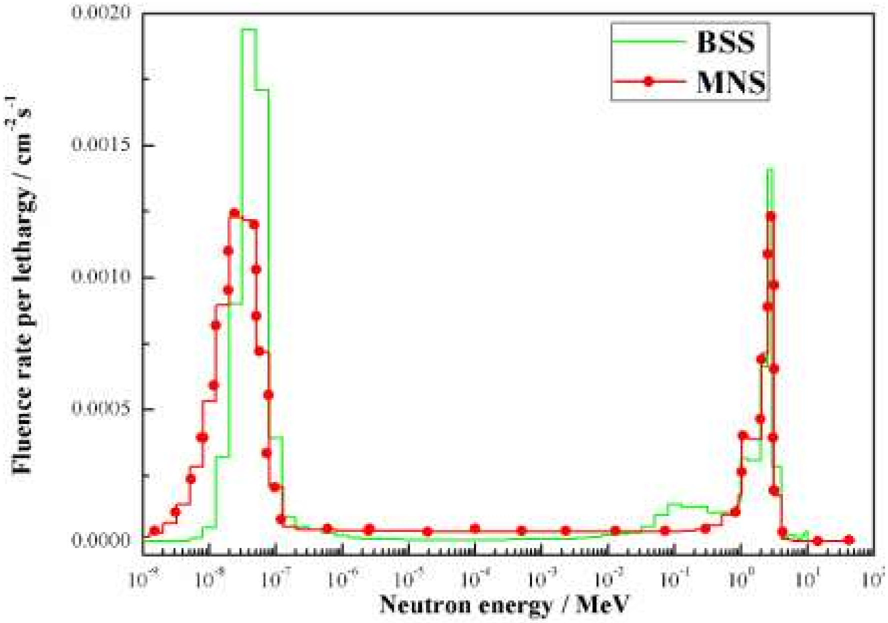

Fig. 4 Background neutron spectrum of laboratory

Fig. 5 illustrates the neutron spectrum of Am-Be neutron source radiation field. The dotted line was the result obtained by MNS this paper designed, compared with solid line, which was the result obtained by BSS. There exist three peaks in the spectrum:

i. Fast neutron zone. The neutron peak region of the Am-Be source is mainly between 1 MeV and 10 MeV, which is consistent with ISO 8529-1, in which the extreme values around 3.1 MeV, 4.4 MeV, 6.6 MeV, 7.7 MeV, 9.8 MeV [7], shown in Fig. 6.

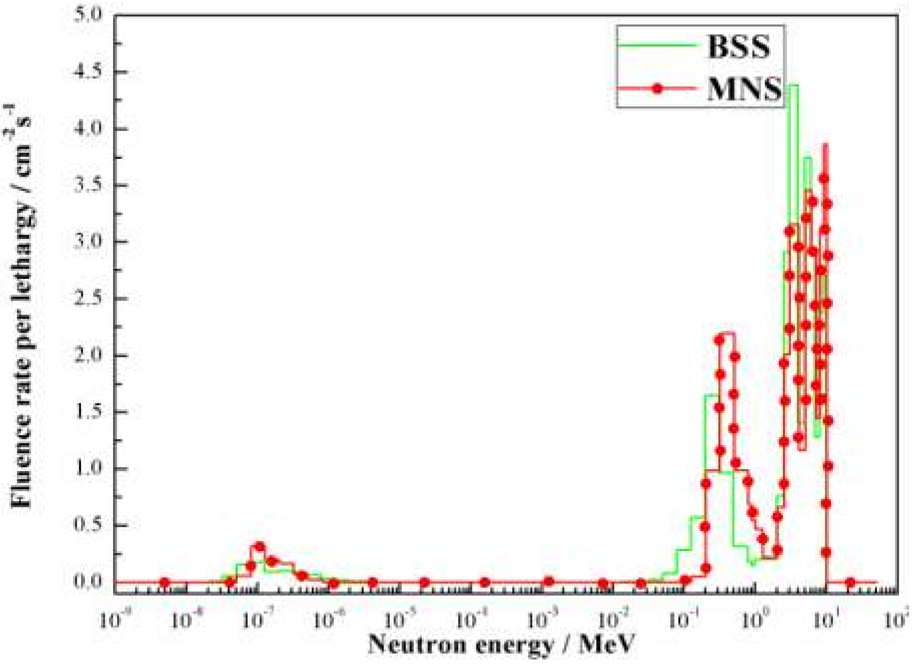

Fig. 5 Neutron spectrum of Am-Be neutron source radiation field

ii. Evaporation neutron zone. The neutron energy in this region is between 10^{-1} MeV and 1 MeV. Since the neutron collimator was not applied in this experiment, the 1 MeV ~ 10 MeV neutron emitted from Am-Be neutron source collided with the concrete wall around, lost a certain amount of energy, and then entered the detector. Its essence is the secondary neutron spectrum of the Am-Be neutron source [6].

iii. Thermal neutron zone. The peak position is around 1×10^{-7} MeV. The neutrons originally emitted by Am-Be neutron source, scattering neutrons, and environmental background neutrons collide with various materials such as the walls of the laboratory and the ground, and finally reach a thermal equilibrium state, forming the thermal neutron zone.

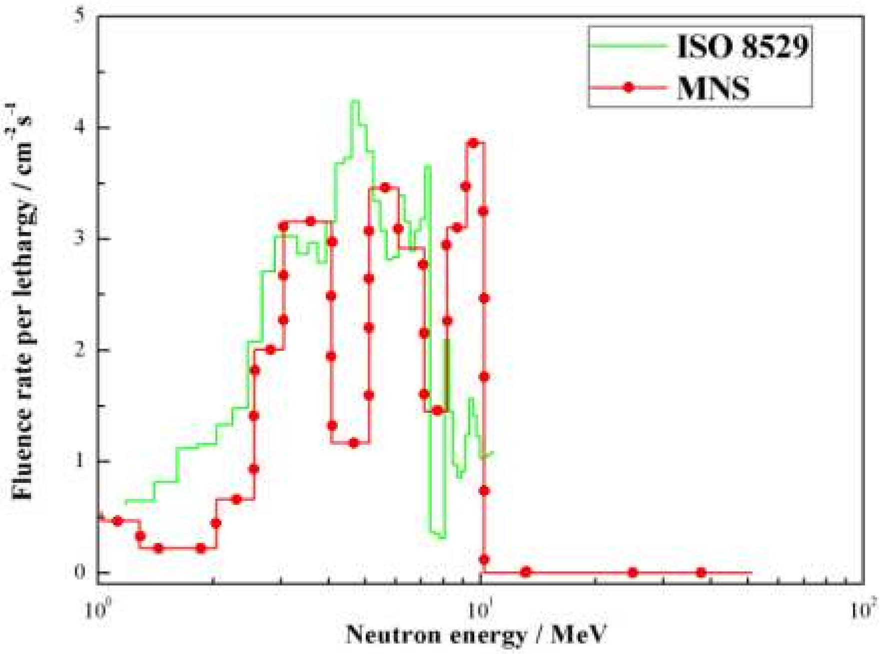

Fig. 6 Neutron spectrum of Am-Be neutron source between 1 MeV and 10 MeV

4 Comparison and Results

Furthermore, we divided the full energy range of neutron into different region, compared neutron fluence rate of each region between MNS and BSS, as shown in Table 2.

Table 2 Comparison of neutron fluence rate between MNS and BSS/ cm^{-2}·s^{-1}

Radiation fields	Fluence rate	Thermal neutron < 0.4 eV	Slow neutron 0.4 eV ~100 keV	Fast neutron 100 keV~10 MeV
Background	BSS	3.25×10^{-3}	2.44×10^{-4}	1.32×10^{-3}
	MNS	3.42×10^{-3}	2.63×10^{-4}	1.27×10^{-3}
Am-Be neutron source	BSS	2.66×10^{-1}	8.61×10^{-1}	6.61
	MNS	2.86×10^{-1}	0.82×10^{-1}	6.75

Generally speaking, from the result of Comparison, neutron energy distribution inversed by MNS is consistent with BSS as shown in Fig. 4 and Fig. 5, which illuminates the correctness of MNS design.

Compare two sets of moderator between MNS and BSS, 13 hollow acrylic cups V.S. 13

polyethylene balls, diameters from 3 inch to 15 inch:

i. To the volume. During the carrying process after measurement, because the smaller acrylic cup could be placed into a bigger cup one by one like a Matryoshka doll, the space MNS occupied is only decided by the biggest cup, which is 43.4 L, 35% of all the 13 polyethylene balls of BSS.
ii. To the weight. During the carrying process after measurement, water could be drained out, the weight of 13 hollow acrylic cups is 5.75 Kg, only 5% of 13 polyethylene balls of BSS.

Under the precondition of acquiring neutron spectrum successfully, the Matryoshka-type neutron spectrometer makes the weight and volume of the whole neutron spectrometer reduced sharply, and becomes portable and lightweight to carry around.

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