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VALIDATION OF THE IN-HOUSE DEVELOPED BONNER MULTI-CYLINDER NEUTRON SPECTROMETER IN STANDARD NEUTRON FIELDS

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This project aimed to demonstrate the characteristics and the performance of a newly developed multi-cylindrical moderator neutron spectrometer, which consists of a cylindrical ^{3}He proportional counter and cylindrical moderator shells of different sizes. The new spectrometer has a similar working principle as the Bonner sphere spectrometry system. The different thickness of the moderator surrounding the thermal neutron counter results in the different response characteristic of each spectrometer configuration, which can be used for unfolding neutron spectra in radiation fields of interest. The response matrix of the spectrometer was calculated by Monte Carlo simulation from thermal energy up to 14.8 MeV and validated with measurements in 0.144 MeV, 1.2 MeV, 14.8 MeV, ^{241}AmBe and ^{252}Cf neutron standard fields at the Facility of Radiation Standards, Japan Atomic Energy Agency (JAEA). The performance of the neutron spectrometer in terms of spectrum unfolding was verified in the ^{241}AmBe neutron standard field, showing a reliable neutron spectrum and fluence rate in the energy range of up to 10 MeV.

Key words: neutron spectrometry, response: instruments, Monte Carlo, neutron standards

1. Objectives

A multi-cylindrical moderator neutron spectrometer has been developed at Thailand Institute of Nuclear Technology (TINT) for determining dosimetric quantities of the neutron irradiation field produced by ^{241}AmBe and workplace neutron fields of interest. The response matrix of the spectrometer has been calculated with Monte Carlo simulation for neutron energies from 1×10^{-8} to 14.8 MeV. The objectives of this project were to demonstrate the response characteristics of the spectrometer in neutron standard fields for validation of the model calculation and to test the performance of the spectrometer in terms of spectrum unfolding in a neutron standard field.

2. Methods

2.1 Design principle

The spectrometer consists of a cylindrical ^{3}He proportional counter model LND 251 (LND, Inc.), seven moderator shells of different sizes and a moderator base. Figure 1 shows the design and arrangement of the spectrometer. The moderator is made of high-density polyethylene. The smallest moderator shell has the housing space for the thermal neutron counter at its center and each shell was designed to fit into the next larger shell. By covering the smallest shell with the next larger shells consecutively, the moderator thickness surrounding the counter is increased, resulting in different degrees of neutron moderation and, therefore, different energy response characteristics, depending on the thickness of the moderator.

In total, eight measurement conditions can be obtained, including the bare counter configuration and the moderated counter with seven moderator thicknesses. The bare counter placed at the center of the moderator base is denoted by

ID0 and the moderated counter configurations with the increased thicknesses are denoted by ID1 to ID7, respectively. When inserting all moderator shells together, the spectrometer has the diameter and height of 20 cm and the weight of 5.5 kg.

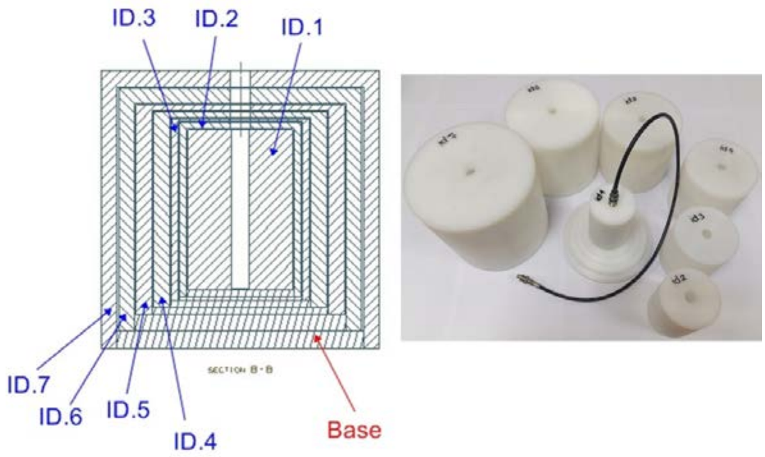

Figure 1. Design and arrangement of the neutron spectrometer, which consists of the thermal neutron counter, seven moderator shells and the moderator base.

2.2 Calculation of the response matrix

The response matrix of each spectrometer configuration has been calculated with PHITS (Particle and Heavy Ions Transport code System) Monte Carlo code version 2.76[(1)] for 49 neutron energies from 1×10^{-8} to 14.8 MeV. In addition to monoenergetic neutrons, the response to ^{241}AmBe and ^{252}Cf neutron standard fields[(2)] was also simulated for model validation.

The simulation took into account physical characteristics of the neutron counter, the moderator shells, the moderator base and air between the shells. The counter has the gas pressure of 4 atm (corresponding to the ^{3}He atom density of 9.71×10^{19} cm^{-3}), the active length of 6.35 cm and the active volume of 5.15 cm^{3}. The detailed dimension of the counter was obtained from the datasheet provided by the manufacturer.

Plane parallel neutron beams with the cross-sectional area fully covering the largest spectrometer configuration were simulated as source neutrons. The response was calculated from the yield of protons or tritons (^{3}H) produced by ^{3}He(n, p)^{3}H reactions, divided by the incident neutron fluence. For all simulations, the standard deviations of the yields were less than 5%.

2.3 Measurement of energy response in neutron standard fields

The response of the neutron spectrometer was measured in the accelerator-produced 0.144, 1.2 and 14.8 MeV monoenergetic neutron standard fields[(3)] and in the ^{241}AmBe and ^{252}Cf neutron standard fields[(4)] at the low-scatter irradiation rooms of FRS. Except for the 1.2 MeV neutron field, reference neutron fluence rates at measurement positions were traceable to the primary standards. The measured response in the unit cm^{2} corresponds to the ratio of the measured count rate to the reference fluence rate.

The influence of scattered neutrons due to room and air scattering was properly eliminated from the measured response using the shadow cone technique[(5)]. In this method, the scattered neutron component was measured by positioning the spectrometer in the shadow of a cone-shape neutron absorber (a shadow cone), as shown in Figure 2. The difference between the response without and with the shadow cone corresponds to the response to the direct neutron component from the source. For the measurements in the monoenergetic neutron fields, a scattering correction due to the presence of the calibration table was also taken into account in the determination of the reference neutron fluence rates.

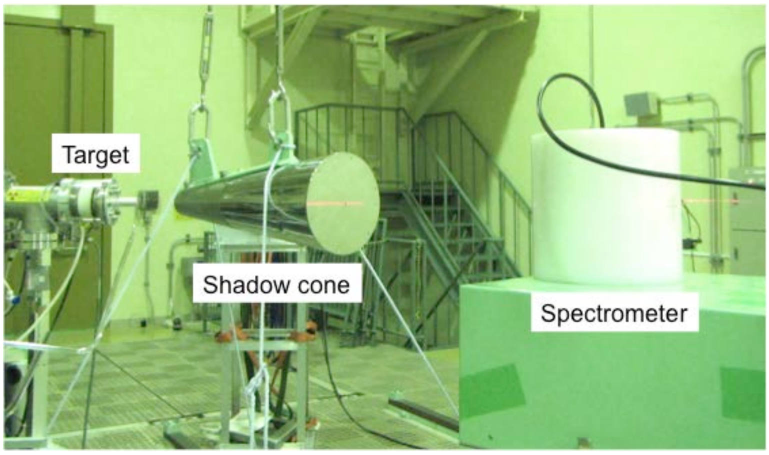

Figure 2. Measurement of the scattered neutron component using the shadow cone technique at the FRS monoenergetic neutron irradiation room. From left to right: the target for neutron production, the shadow cone and the spectrometer. The source-to-detector distance was 120 cm.

In this study, high voltage applied to the neutron counter was 1000 V. Signals from the counter were run through a preamplifier and an amplifier and, finally, analyzed by a multichannel analyzer (MCA). Figure 3 shows an example of the pulse height spectrum analyzed by the MCA. The channel number of the MCA is associated with energy deposited in the counter. The full energy peak is expected at 764 keV, corresponding to kinetic energy of both reaction products. Discrimination of neutron signals from photon signals and noises was set at 1/5 of the full energy deposition (152.8 keV). The integrated spectrum from this deposited energy upwards corresponded to the measured neutron count. The counting time for each measurement was varied to achieve statistical uncertainty of less than 1% in most cases and less than 3% in a few cases where neutron count rates were very low.

2.4 Spectrum unfolding

Neutron spectrum is obtained by solving the system of linear equations,

$$M_i = \sum_k R_{i,k} \Phi_k \tag{1}$$

where M_i is the count rate measured by the spectrometer configuration *i*, $R_{i,k}$ is the response of *i* to neutrons of energy E_k and Φ_k is the neutron fluence rate in the energy range represented by E_k. The spectrum unfolding code was developed with MATLAB (MathWorks, Inc.) to find a neutron spectrum $\{\Phi_k\}$ that results in a minimum of the sum of squared residuals

$$F(\{\Phi_k\}) = \sum_i \left(M_i - \sum_k R_{i,k} \Phi_k \right)^2 \tag{2}$$

Due to the underdetermined nature of equation (2), more than one solution is possible and a proper guessed spectrum is required for equation solving. In this study, the performance of the neutron spectrometer in terms of spectrum unfolding was tested in the ^{241}AmBe neutron standard field.

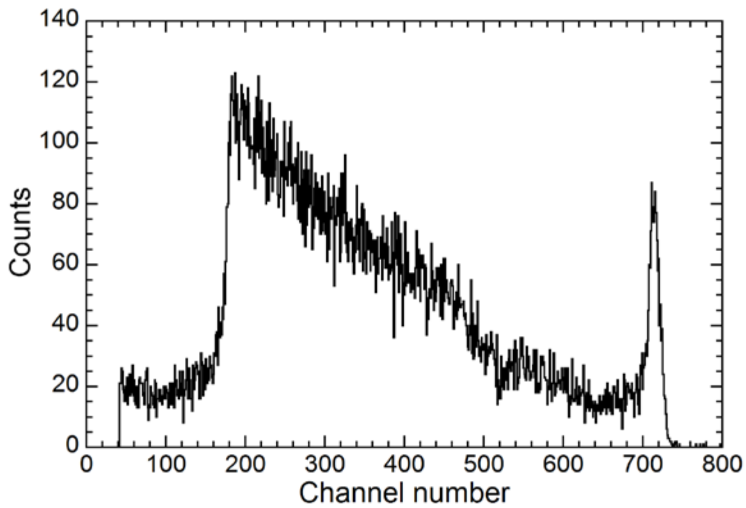

Figure 3. Pulse height spectrum measured by ID7 in the 1.2 MeV neutron field (without the shadow cone). The full energy peak is approximately at the channel number 710.

3. Results and Discussion

Figure 4 shows the calculated response matrix for neutron energies from 1×10^{-8} to 14.8 MeV. Comparisons with the measurements in the neutron standard fields are presented in Figure 5 as the ratios of the calculated response to the measured response. Except for the 14.8 MeV neutron field, the calculated response agreed within ±10% with the measured response for all moderated configurations (ID1-ID7), confirming the reliability of the model calculation. Larger discrepancies (22-38%) were observed for the bare counter configuration (ID0) in these neutron fields. ID0 represents the bare counter positioned at the center of the moderator base. Therefore, the response of ID0 was due to source neutrons and neutrons that were scattered by the moderator base. Although both neutron contributions have been taken into account in the simulation, the response to scattered neutron is dominant in this energy range and may affect the accuracy of the calculated response.

In the case of the 14.8 MeV neutron field, the calculation underestimated the measurement for all spectrometer configurations. Further investigation is needed for this neutron energy and the calculated response matrix is to be used for neutron energies of up to 10 MeV.

The calculated response matrix was used for unfolding the spectrum of the ^{241}AmBe neutron standard field. Figure 6 shows the unfolded neutron fluence rates per unit lethargy compared with the ISO standard spectrum(2). Both spectra were in good agreement with 7% average discrepancy in all energy groups up to 10 MeV. It is to note that, since the response matrix was considered up to 10 MeV, the unfolded spectrum at energies higher than 10 MeV was necessarily zero. Since the contribution of neutrons with energies above 10 MeV to the ^{241}AmBe neutron spectrum is only 1.3%(2), the missing component did not have large effect on the total neutron fluence rate. In this study, the reference neutron fluence rate at the measurement position was 13.5±0.3 $cm^{-2}s^{-1}$, while the evaluated fluence rate from the unfolded spectrum was 13.7 $cm^{-2}s^{-1}$.

Another consistency check was performed by comparing the measured count rates with the evaluated count rates, which were calculated from the unfolded spectrum using equation (1). As shown in Table 1, both sets of data agreed well with each other in most cases. The discrepancies were less than 1% for all moderated configurations, while for ID0 the evaluated count rate overestimated the measured value by 21%.

In conclusion, the application of the neutron spectrometer together with the calculated response matrix and the in-house developed unfolding code has shown to be reliable for characterization of a neutron field in the energy range of up to 10 MeV.

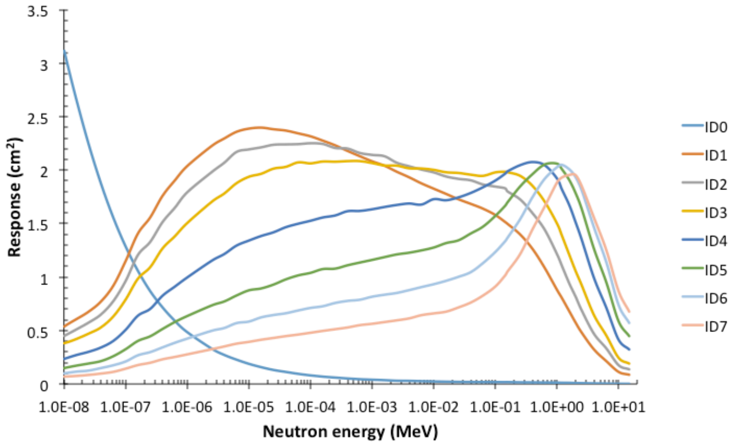

Figure 4. The calculated response matrix for each spectrometer configuration.

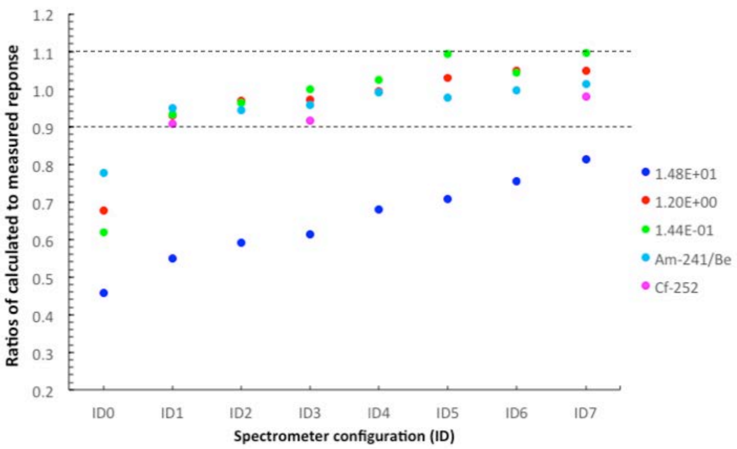

Figure 5. Ratios of calculated to measured response. The dashed lines designate differences of ±10%.

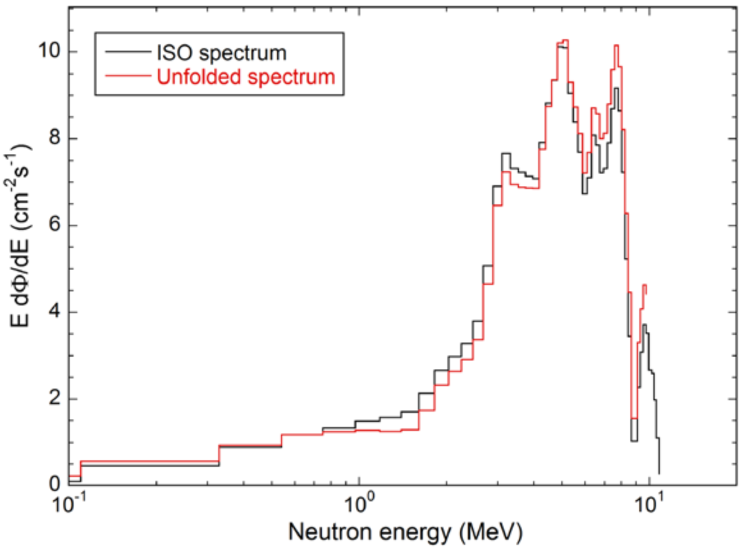

Figure 6. The unfolded spectrum of the ^{241}AmBe neutron field compared with the ISO standard spectrum(2). The reference neutron fluence rate was 13.5±0.3 cm^{-2}s^{-1}.

Table 1. Comparison of measured and evaluated count rates for the ^{241}AmBe neutron field with the reference neutron fluence rate of 13.5±0.3 cm^{-2}s^{-1}.

Spectrometer configuration	Measured count rate (s^{-1})	Evaluated count rate (s^{-1})
ID0	0.14	0.17
ID1	6.60	6.66
ID2	9.19	9.06
ID3	11.41	11.38
ID4	15.24	15.42
ID5	18.03	17.96
ID6	19.55	19.49
ID7	19.76	19.79

4. References

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