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ORIGINAL PAPER - PARTICLES AND NUCLEI

Neutron irradiation facilities, neutron measurement system, and mono-energetic neutron fields at KRISS

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Abstract

The Korea Research Institute of Standards and Science (KRISS) has developed and maintained neutron calibration facilities and neutron measurement systems, providing national standards on neutron dose equivalent, neutron fluence, and neutron emission rate for Korea. Neutron calibration facilities at KRISS include neutron irradiation facilities and neutron sources, such as radioactive isotope neutron sources, thermal neutrons, and mono-energetic neutrons. Neutron measurement systems at KRISS include the Bonner sphere spectrometer and a manganese-sulfate bath measurement system. The neutron standard facilities and measurement systems at KRISS have supported the researchers. Here, we introduce the ongoing research and development of neutron measurement systems, such as the mono-energetic neutron field generation system, which is currently under development and will be operational within a few months.

Keywords Neutron radiation facility · Neutron measurement · Mono-energetic neutrons · Neutron spectrum measurements

1 Introduction

As a national metrology institute, the Korea Research Institute of Standards and Science (KRISS) has established and maintained neutron measurement standards. The neutron laboratory at KRISS provides the standard neutron irradiation services with neutron isotope sources for conducting calibration and performance tests of neutron detectors and shielding materials. Additionally, the laboratory has developed a neutron spectrometer system to measure the neutron energy spectrum. Currently, a neutron irradiation system with a 14.8 MeV mono-energetic neutron field is under development, and we have studied a measurement system of mono-energetic neutrons. Here, we introduce the neutron irradiation facilities, neutron measurement systems, and ongoing research works at KRISS.

Free neutrons, which are not bounded within the nucleus, are classified according to their kinetic energy. Here, we focus on three types of neutrons: thermal, epithermal, and fast neutrons. Thermal neutrons are free neutrons with a kinetic energy of approximately 0.025 eV. They are in equilibrium with the thermal energy of the surroundings of the moderator. At a reference temperature of 20 °C, the energy spectrum of thermal neutrons can be described by a Maxwell–Boltzmann distribution, with the most probable energy and most probable velocity being approximately 0.025 eV and 2200 ms$^-$1, respectively. Epithermal neutrons have a kinetic energy greater than thermal neutrons and lower than fast neutrons. Fast neutrons have a kinetic energy greater than 0.5 MeV and up to 20 MeV. Fast neutrons are produced by spontaneous fission and (α, n) reactions. In addition to these three types, different or more fine categories of neutron energies can be considered depending on research interests. For instance, neutrons with kinetic energies lower than 0.025 eV are called cold neutrons, and those with kinetic energies greater than 20 MeV are called ultra-fast neutrons, high-energy neutrons, or relativistic neutrons.

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2 Neutron emission and fluence

The neutron emission rate, fluence, and fluence rate are defined in ISO8529-1[1] and ISO8529-2[2]. When a source emits neutrons in all directions, the emission rate of the neutron source, B, is defined by a differential quotient of N to time:

$$B = dN/dt, \tag{1}$$

where N is the number of neutrons emitted from the source in all directions. The unit of the neutron emission rate is s^{-1}. The angular distribution of the neutron emission rate, B_Ω, is defined by a differential quotient of B to the solid angle:

$$B_\Omega = dB/d\Omega, \tag{2}$$

where Ω is a specific spatial direction. The unit of the angular distribution of the neutron emission rate is $s^{-1}sr^{-1}$. The spectral neutron emission rate, B_E, is defined by a differential quotient of B to energy:

$$B_E = dB/dE, \tag{3}$$

where E is the neutron energy. The unit of the neutron emission rate is $s^{-1}J^{-1}$, and another frequently used unit is $s^{-1}MeV^{-1}$. The neutron source emission rate, B, is derived from B_E as follows:

$$B = \int_0^\infty B_E\, dE = \int_0^\infty dB/dE\, dE. \tag{4}$$

The unit of the neutron source emission rate is s^{-1}.

When neutrons pass through an area a, the fluence Φ is defined by a quotient of dN by da:

$$\Phi = dN/da, \tag{5}$$

where dN is the number of neutrons incident on a sphere of cross-sectional area da. The unit of the fluence is cm^{-2}.

The neutron fluence rate produced by a source is determined from its neutron emission rate B and the distance between the source center and the point of test. The neutron fluence rate, at a distance l from the center of the source, in a direction for θ=90° is

$$\varphi_{(l,90^\circ)} = \frac{dB}{d\Omega} \times \frac{1}{l^2}. \tag{6}$$

The unit of the fluence rate is $cm^{-2}s^{-1}sr^{-1}$. The neutron fluence rate produced in all directions is

$$\varphi_{(l)} = \int_\Omega \frac{dB}{d\Omega} d\Omega \times \frac{1}{l^2}. \tag{7}$$

The unit of the fluence rate in all directions is $cm^{-2}s^{-1}$.

3 Neutron irradiation facility

3.1 Neutron isotope irradiation facility

The isotope neutron sources, ^{252}Cf and ^{241}AmBe, are used for neutron measurement research, neutron irradiation services, and detector calibrations. The emission rate of the isotope neutron sources is measured by a manganese sulfate bath system, explained in Sect. 4.1. Figure 1 shows the current emission rate of isotope neutron sources at KRISS. The emission rate is approximately $10^3 - 10^8$ n/s, which is calculated from the initial emission rate from the company and its retained period at KRISS. The neutron irradiation facility using radioactive sources was initially developed at the Korea Standards Research Institute in 1989[3]. The neutron irradiation facility has been upgraded with new ^{252}Cf neutron sources regularly [4] because the half-life of ^{252}Cf is 2.64 years. The dimensions of the neutron irradiation room are 8.0(L) × 6.6(W) × 6.4(H) m^3, and the irradiation room is sufficiently enough for the effect of scattered neutrons to be less than 40 % of the total fluence at a calibration point, as required by ISO8529-2 [2].

The ^{252}Cf source produces neutrons by the spontaneous fission process, and the ^{241}AmBe source produces neutrons by (α, n) reactions. The ^{252}Cf isotope source produces a continuous energy spectrum up to 11 MeV with the most probable energy of ~1 MeV and average energy of ~2 MeV. In comparison, the ^{241}AmBe source produces a continuous energy spectrum up to 11 MeV with multiple peaks[1] and average energy of 4.2 MeV. A D_2O-moderated ^{252}Cf source has been developed to produce sub-MeV neutrons. A ^{252}Cf source is located at the center of the sphere, filled with D_2O liquid. Figure 2 shows the neutron energy spectra of ^{252}Cf and D_2O-moderated ^{252}Cf from the ISO8529[1].

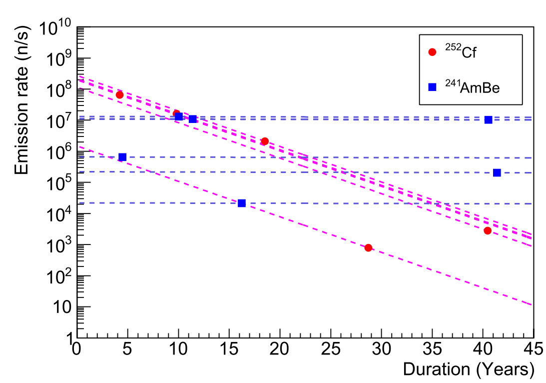

Fig. 1 Current emission rate of ^{252}Cf (circles) and ^{241}AmBe (squares) sources as of Aug. 5, 2022. Dashed lines represent their expected rate, following half-lives of ^{252}Cf and ^{241}AmBe decays. The emission rate is calculated by their initial emission rate and retained period

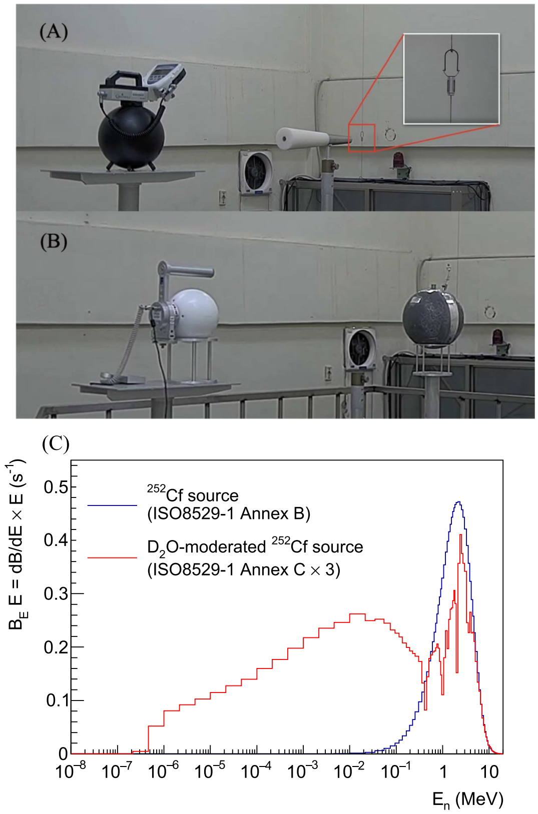

Fig. 2 Irradiation of a ^{252}Cf source with a shadow cone (A) and a D_2O-moderated ^{252}Cf source (B) at the irradiation laboratory. The ^{252}Cf source is placed at the center of the irradiation room with a wire (A). The gray sphere is a D_2O-moderated ^{252}Cf source (B). The neutron energy distribution of a ^{252}Cf source and a D_2O-moderated ^{252}Cf source (C) from ISO8529-1 Annex B and C [1]

KRISS provides neutron irradiation and survey meter calibration services with these neutron sources. KRISS has also supported neutron detector calibration tests for a space mission from Korea Astronomy and Space Science Institute [5]. A LiF crystal from the Institute for Basic Science (IBS) was irradiated [6]. Several tens of neutron survey meters have been calibrated yearly.

3.2 Thermal neutron field

A thermal neutron field system was constructed with a high-purity graphite pile and a ^{241}AmBe neutron source at KRISS in 2015 [7], as shown in Fig. 3. The dimensions of the graphite pile are 1.4 (L) × 1.2 (W) × 1.2 (H) m^3, and the emission rate of the ^{241}AmBe source is 1.2×10^7 s^{-1}[8]. A sample or detector, suitable for an entering area of 10 × 10 cm^2, can be placed at the reference position, i.e., the center of the cavity hole, which is 70 cm away from the source inside the graphite pile. At the reference position, the thermal neutron fluence rate is (2371 ± 36) $cm^{-2}s^{-1}$. When the area of the sample or detector is larger than the entering

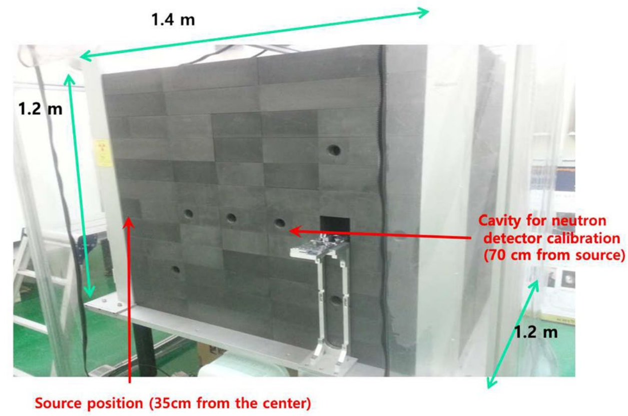

Fig. 3 Thermal neutron irradiation field system. The system is composed of a ^{241}AmBe neutron source surrounded by a graphite pile

area, it can be irradiated by parallel thermal neutrons at a rate of ~39 $cm^{-2}s^{-1}$ outside the graphite pile. The thermal neutron field system is generally used to calibrate a detector or to measure the shielding efficiency of shielding materials. For instance, a neutron shielding pad was developed using silicone rubber and boric acid powder at the Center for Underground Physics, IBS. Its shielding efficiency for thermal neutrons was over 99 %[9].

4 Neutron measurement system

4.1 Manganese sulfate bath system

The manganese-sulfate bath system (Mn-bath), developed in 1988 to measure the emission rate of a neutron source [10], is one of the primary neutron measurement systems used to establish the neutron measurement standards at KRISS. The system is regularly maintained and upgraded. For example, this year, the main bath filters in a circulation system and agitators were replaced. The system measures the neutron emission rate of the neutron source in a wide range of emission rates of 2×10^5 - 2×10^8 s^{-1} with an uncertainty of < 1 % (k = 1) [8]. The Mn-bath system consists of a spherical bath with an inner diameter of 125 cm, a circulation system, and two NaI(Tl) detectors inside a lead shielding box, as shown in Fig. 4. The spherical bath of the Mn-bath system is filled with 1000 L of $^{55}MnSO_4$ solution. The neutron emission rate is proportional to the production rate of ^{56}Mn nuclei by neutron-capture reactions. When a neutron source is positioned at the center of the Mn-bath sphere, neutrons captured by manganese nuclei produce radioactive ^{56}Mn nuclei, which decay to ^{56}Fe with a half-life of 2.578 hrs. The reactions are as follows:

Fig. 4 A Manganese-sulfate bath system with 1000 L of $^{55}MnSO_4$ solution (A) and two NaI(Tl) detectors within a lead shielding box with a data acquisition system (B)

$$
\begin{aligned}
&{}^{55}\mathrm{Mn} + n \rightarrow {}^{56}\mathrm{Mn} \\
&\quad {}^{56}\mathrm{Mn} \rightarrow {}^{56}\mathrm{Fe}^{*} + e^{-}.
\end{aligned}
\tag{8}
$$

The $^{55}MnSO_4$ solution in the Mn-bath circulates through a Marinelli beaker type detector bath (~10 L) with two NaI(Tl) detectors. NaI(Tl) detectors measure the gammas rays from the decay of ^{56}Mn. Correction factors can be estimated using Monte Carlo N-Particle (MCNP) simulations. After applying the efficiency and corrections of the system, the Mn-bath system determines the emission rate of the neutron source with an uncertainty of $< 1\ \%(k = 1)$ (see details in reference [8]). Neutron emission rate measurement services are provided using the Mn-bath system. An official certificate of the neutron emission rate is provided for calibration or disposal purposes of neutron sources.

4.2 Bonner sphere spectrometer

Another neutron measurement system to establish neutron measurement standards at KRISS is the Bonner sphere spectrometer, which consists of 2-atm ^{3}He-proportional counters (SP9 proportional counters from Centronic Ltd.) and moderators, called Bonner spheres. The ^{3}He proportional counter detects neutrons by measuring the products of the following reaction:

$$
{}^{3}\mathrm{He} + n \rightarrow {}^{1}\mathrm{H} + {}^{3}\mathrm{H} \ \ (Q = 0.764\ \mathrm{MeV}). \tag{9}
$$

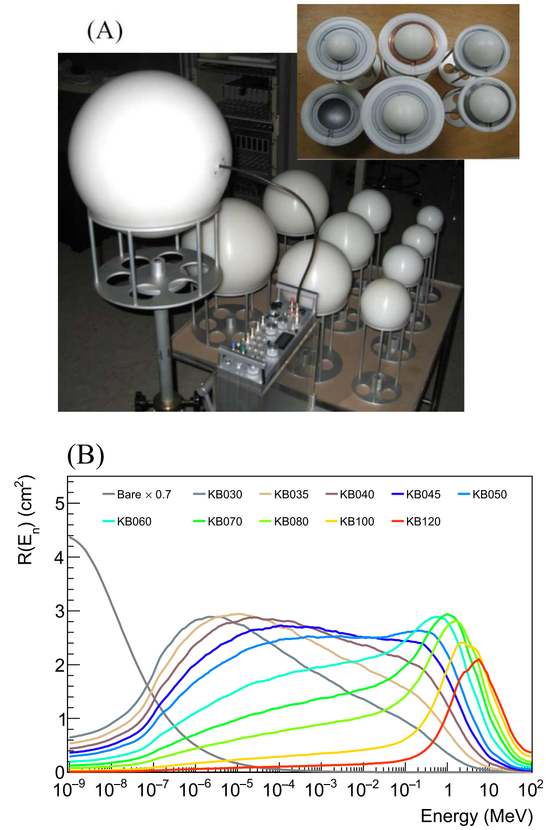

Fig. 5 Ten HDPE Bonner spheres (A) and Bonner spheres with a metal layer (right top in A). Response function (B) of eleven SP9 thermal neutron detectors without a moderator and with ten moderators with a diameter from 76.2 to 304.8 mm

The Bonner sphere set is composed of 10 high-density polyethylene (HDPE) spheres with diameters of 76.2, 88.9, 101.6, 114.3, 127, 152.4, 177.8, 228.6, 254, and 304.8 mm, as shown in Fig. 5(A), designed by Physikalisch-Technische Bundesanstalt (PTB) [11]. For each size of the moderator with an SP9 thermal neutron detector, response functions can be calculated using MCNP simulations and calibrated with a ^{252}Cf neutron source. The results indicate that the neutron energy ranges from the thermal neutron energy region to over 20 MeV are covered by the Bonner spheres and SP9 thermal neutron detectors, as shown in Fig. 5(B). HDPE moderators, including a metal layer such as copper, lead, and iron, have been developed to cover the high-energy neutron response for energies greater than 20 MeV. All the Bonner spheres are not used for neutron spectrum measurements. The numbers of Bonner spheres and SP9 thermal neutron detectors are determined based on the measurement conditions and the environment.

After measuring the neutron rate with a set of Bonner spheres and SP9 thermal neutron detectors, the neutron differential flux ($cm^{-2}s^{-1}$) is estimated by an unfolding procedure using the MAXED code, which is based on the maximum entropy principle [12]. The unfolding method should be applied carefully because the shape of the input spectrum can lead to biased results in a few cases.

The Bonner sphere spectrometer has been used to measure fluence rate or energy spectra for various neutron sources and environments, such as isotope neutron sources in the irradiation room [4], an accelerator-based boron neutron-capture therapy beam, a radiation therapy room for secondary neutrons produced from proton or electron beams, and a nuclear power plant area [13]. In addition, the neutron energy spectrum was measured at two sites of Yangyang underground laboratory in 2009 [14] and 2019 [15]. Additionally, the cosmic neutron spectrum on the ground has been measured [16]. We officially provide neutron spectra or fluence measurement services using the Bonner sphere spectrometer.

5 Development of mono-energetic neutron fields

Neutron fields with only one neutron group, produced from nuclear reaction, are referred to as mono-energetic [17]. The neutron energy in a reaction depends on the measurement angle in the two-body reaction and the projectile particle energy. The mono-energetic neutron reference fields between 1 keV to 20 MeV are listed with their reactions in ISO8529-1 [1]. At KRISS, we are developing the 14.8 MeV and 2.5 MeV mono-energetic neutron fields to establish mono-neutron measurement standards.

Neutrons with energies of 14.8 and 2.5 MeV are produced by the T(d, n)^{4}He reaction (DT) and D(d, n)^{3}He reaction (DD) from a deuterium beam bombarded on a tritiated titanium (TiT) target and a deuterated titanium (TiD) target, respectively. The reactions and Q-value are as follows:

$$\begin{aligned} &^3\mathrm{H} + {}^2\mathrm{H} \rightarrow n + {}^4\mathrm{He} \;\; (Q = 17.589\ \mathrm{MeV}) \\ &^2\mathrm{H} + {}^2\mathrm{H} \rightarrow n + {}^3\mathrm{He} \;\; (Q = 3.269\ \mathrm{MeV}) \end{aligned} \tag{10}$$

Both DT and DD reactions are exothermic reactions with appreciable cross sections for deuterons with an incident energy of approximately hundreds of keV. Neutron and α-particle energies depend on the measurement angle, which can be calculated by two-body kinematic relations, as shown in Fig. 6. The energy ranges of neutrons and α particles are related to the Q-value and energy of incident deuteron particles. For example, neutrons with an energy of 14.8 MeV are available at 0 ° for incident deuterons with a minimum energy of 110 keV. The α-particle energy of the DT reaction is between 2.88 and 4.30 MeV for 110 keV deuteron beams, as shown in Fig. 6. In the DD reaction, the ^{3}He energy is between 416 keV and 1.42 MeV for 200 keV deuteron beams.

A Cockcroft–Walton accelerator with a maximum high-voltage of 400 kV is currently being installed at KRISS. We have developed a target chamber for a target and an associated α particle (AP) detector system. The AP can be used to measure the neutron fluence absolutely. Target specifications have been determined by simulation results, and the AP detector system has been designed using simulation results and two-body kinematics calculations. The neutron yield and energy distribution were estimated at different thicknesses and incident deuteron energies using the TARGET simulation code, which was developed by PTB. Using the simulation results, the thicknesses of the TiT and TiD targets were determined to be 250 μg/cm^2 by optimization between the allowed neutron yield, $< 5 \times 10^8$,

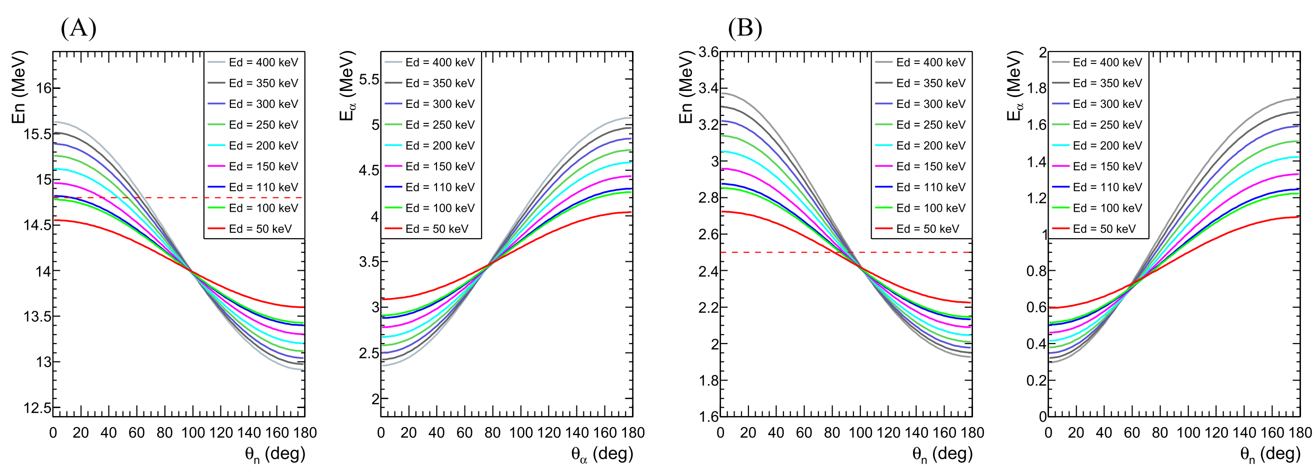

Fig. 6 Neutron and α-particle energies from DT (A) and DD (B) reactions over measurement angles. For incident deuteron energy of 50 keV - 400 keV, energies of the reaction products were calculated by two-body kinematics. Dashed lines represent the energy for 14.8 MeV and 2.5 MeV

and neutron energy resolution (for more details, see reference [18]).

The absolute neutron fluence has been obtained by measuring the α-particle rate. For the DT reactions, the α-particle measurement angle of DT reactions was determined to be 89 ° from the incident deuteron direction based on the minimum total folding angle [17], which was the sum of two reaction product angles from the incident deuteron direction. Additionally, another α-particle measurement angle was determined to be 135 ° [19]. The second α-particle measurement is used to determine the energy of incident deuterons using the two-body kinematic relations.

The silicon surface barrier (SSB) detector has been installed at the end of the two arms of the chamber for α-particle measurements. It is used as a primary α-particle detector for measurements. The expected α-particle energy from the DT reaction is 3.63 MeV for 110 keV deuterons, and the ^{3}He nuclei energy from the DD reaction is 0.97 MeV for 200 keV deuterons. The thickness of the α-particle detector was determined to have a full deposition of 3.6 MeV α particles. A PIN diode detector can be an alternative α-particle detector in the AP system.

The responses of the SSB and PIN diode detectors were tested with a 3.2 MeV α source (^{148}Gd), and their performance was validated. The measured energy resolution of the 3.2 MeV α-particle peak was less than 1 % for SSB and PIN diode detectors. When deuterons were bombarded into the deuteron targets, the cross sections of D(d, n)^{3}He and D(d, p)T reactions were 0.037 and 0.033 barn, at 200 keV, respectively, which were nearly similar, implying that the D(d, p)T reaction products, p and T, could be background signals for the ^{3}He measurement of the D(d, n)^{3}He reaction. For example, for 200 keV incident deuterons, ^{3}He nuclei with an energy of 0.97 MeV were generated from the D(d, n)^{3}He reaction and tritium nuclei with an energy of 1.03 MeV were generated from D(d, p)T reaction. The energy resolution of the SSB and PIN diode detectors was sufficient to distinguish the two peaks with energies of 1.03 and 0.97 MeV. The energy resolution of SSB and PIN diode detectors was less than 10 keV for 3.2 MeV α particles. The energy resolution for 1 MeV α particle was expected to be ~1 %, which would be validated.

A 400 kV electrostatic ion-source accelerator from High-Voltage Engineering Europa BV is currently under installation. After the accelerator installation is completed, the mono-energetic neutron field generation system will be tested and optimized. The mono-energetic neutrons of 14.8 and 2.5 MeV will be available in 2023. We will continue working on developing and improving fast neutron measurement techniques.

6 Recent research activities

6.1 Development of fast neutron detector

We studied the neutron response and characteristics of a scintillation neutron detector, Cs_2LiYCl_6:Ce (CLYC), to measure 2.5 MeV mono-energetic neutrons. A CLYC scintillator was reported as a neutron detector with a reliable separation of gamma and neutron signals with a pulse shape discrimination (PSD) parameter, a ratio of the tail to body area in a waveform. Additionally, the scintillator could measure fast neutrons [20, 21] since the neutron-capture cross section of ^{35}Cl increased significantly over 2 MeV, which was appropriate for the measurements of 2.5 MeV neutrons without thermal neutrons. The thermal neutron-capture cross sections of ^{6}Li was 940 b, while (n, p) and (n, α) cross section of ^{35}Cl were ~1.2 b. The neutron reactions in the CLYC are as follows:

$$\begin{aligned} &{}^{6}_{3}\mathrm{Li} + n \rightarrow {}^{3}\mathrm{H} + {}^{4}_{2}\mathrm{He} \ \ (Q = 4.782\ \mathrm{MeV}) \\ &{}^{35}_{17}\mathrm{Cl} + n \rightarrow {}^{1}\mathrm{H} + {}^{35}_{16}\mathrm{S} \ \ (Q = 0.614\ \mathrm{MeV}) \\ &{}^{35}_{17}\mathrm{Cl} + n \rightarrow {}^{4}_{2}\mathrm{He} + {}^{32}_{15}\mathrm{P} \ \ (Q = 0.943\ \mathrm{MeV}). \end{aligned} \tag{11}$$

A CLYC scintillator with depleted ^{6}Li and enriched ^{7}Li works for fast neutron measurements. The natural abundance of ^{6}Li and ^{7}Li is 7.59 % and 92.41 %, respectively. CLYC scintillators with enriched ^{6}Li (CLYC6) and ^{7}Li (CLYC7) are commercially available.

We measured the PSD parameters of neutron and gamma signals for each CLYC6 and CLYC7 from RMD Co. to select neutrons from gamma signals. Each CLYC scintillator with a photomultiplier (Hamamatsu R6231) was connected to a fast amplifier (Notice Co.) and a 250 mega-sampling/s digitizer (CAEN DT5725S). Two CLYC detectors were calibrated with gamma sources, such as ^{137}Cs, ^{22}Na, and ^{208}Tl. The energy resolution of gamma signals at 662 keV was ~4%.

The CLYC6 and CLYC7 detectors were exposed to 2.5 MeV neutrons using a DD generator (DD109) of the Adelphi Technology, Inc. Figure 7 shows a PSD parameter over electron equivalent energy for CLYC6 and CLYC7 detectors at 2.5 MeV neutrons. A thermal neutron peak was dominant in the CLYC6 detector, while a ^{35}Cl(n, p) reaction peak was dominant in the CLYC7 detector. The CLYC6 distribution shows ^{6}Li(n,α), an ^{35}Cl(n,p), and ^{35}Cl(n,α) reaction events. The CLYC7 distribution shows ^{35}Cl(n,α) reaction events and a thermal neutron peak.

For 2.5 MeV neutrons, the energy resolution of an (n,p) peak in CLYC7 was 4.3 % and a figure of merit value of the PSD parameter, defined by a ratio of difference of the two peaks' Gaussian mean to a sum of the two peaks' full-width-half-maximum, was 3.45. It was confirmed that CLYC7 could be used as a fast neutron detector for 2.5

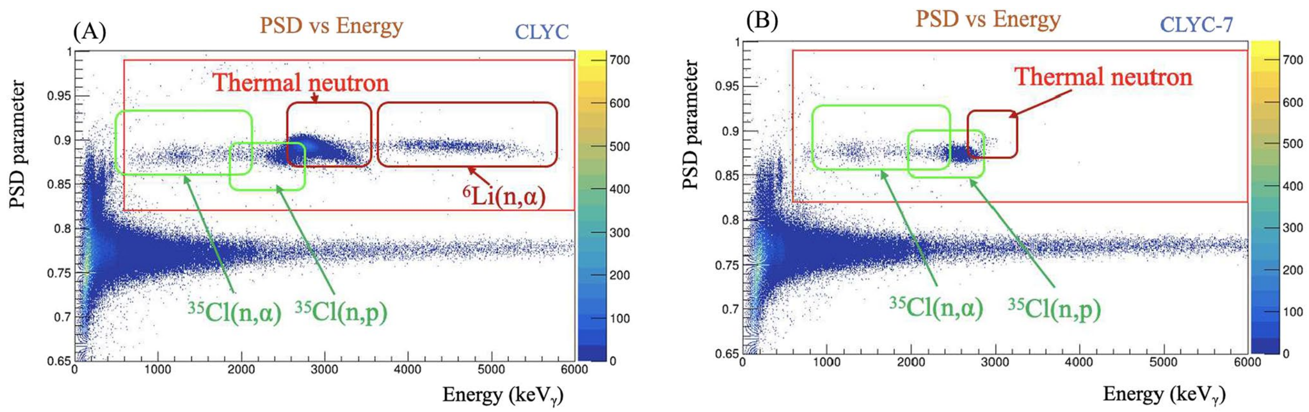

Fig. 7 PSD parameter with energy for CLYC6 (A) and CLYC7 (B) scintillators. Neutrons (inside red box) and gammas are well separated. The two distributions exhibit thermal neutron, ^{35}Cl(n,p) reaction, and ^{35}Cl(n,α) reaction events. The ^{6}Li(n,α) reaction events only appeared in the CLYC6 distribution

MeV neutron measurements. However, its neutron energy resolution should be improved for measurement standard studies. It was assumed that projectile deuteron beam energy of the DD generator was the same as that applied to the DD generator. In the CLYC7 scintillator, the quenching factors of protons and α particles were calculated by a ratio of the measured neutron energy to expected energy from simulation results. They were 0.9 and 0.5 for protons and α particles, respectively. More precise measurements are conducted to determine projectile beam energy and quenching factors. With a CLYC detector, we will measure neutrons using a time-of-flight system. In addition, we are researching other potential scintillation detectors.

6.2 Development of cosmic neutron spectrometer

We are developing a high-sensitivity neutron spectrometer for cosmic neutron spectrum measurements. The existing neutron spectrometers with Bonner spheres and SP9 thermal neutron detectors require a long measurement duration in a relatively low neutron fluence rate environment to have enough counts or distributions. For example, neutron spectrum measurement at the underground laboratory in 2019 was performed for 94 d[15]. The primary goal of this spectrometer is to measure the cosmic neutron spectrum. However, the spectrometer can measure neutron spectrum in any low-fluence environment.

A ^{3}He tube-type proportional counter (model 50He3/304/25SS from Centronic Co.) was selected for a thermal neutron detector. The thermal neutron sensitivity of the ^{3}He tube detector was approximately ten times greater than that of the SP9 thermal neutron detector, as shown in Table 1.

The high-sensitivity neutron spectrometer consists of eight moderators with a ^{3}He tube neutron detector and a bare ^{3}He tube neutron detector, as shown in Fig. 8. The diameters of the moderators were determined by MCNP simulations to cover a wide neutron energy range and were found to be 76.8, 88.9, 114.3, 127, 177.8, 228.6, 165.1, and 190.5 mm (Fig. 8). HDPE-based moderators with diameters of 165.1 and 190.5 mm include a copper layer with 12.7 and 25.4 mm thickness, respectively. The moderators with a copper layer show higher responses (over 20 MeV) than those using only HDPE.

Table 1 SP9 and ^{3}He-tube thermal neutron detectors

Model	SP9	50He3/304/25SS
Detector shape	Sphere	Tube
Active diameter (cm)	3.2	2.44
Active length (cm)	3.1	50
Gas	^{3}He	^{3}He
Pressure (atm)	2	4
Thermal neutron sensitivity (cps/nv)	8	81

We will measure the cosmic neutrons at different sites with this spectrometer. Therefore, the spectrometer system was designed to be disassembled and portable. For example, a 60-cm-long HDPE moderator is divided into five pieces. Additionally, pieces of moderators with a copper layer were heavy to disassemble and assemble. We used a copper layer inside the moderator instead of a lead layer; however, moderators with a lead layer have higher responses than those with a copper layer.

The data acquisition system of the spectrometer was constructed with preamplifiers (CAEN A1422), an amplifier (CAEN N1068), two high-voltage power supplies (CAEN DT8033 and DT1470ET), and two digitizers

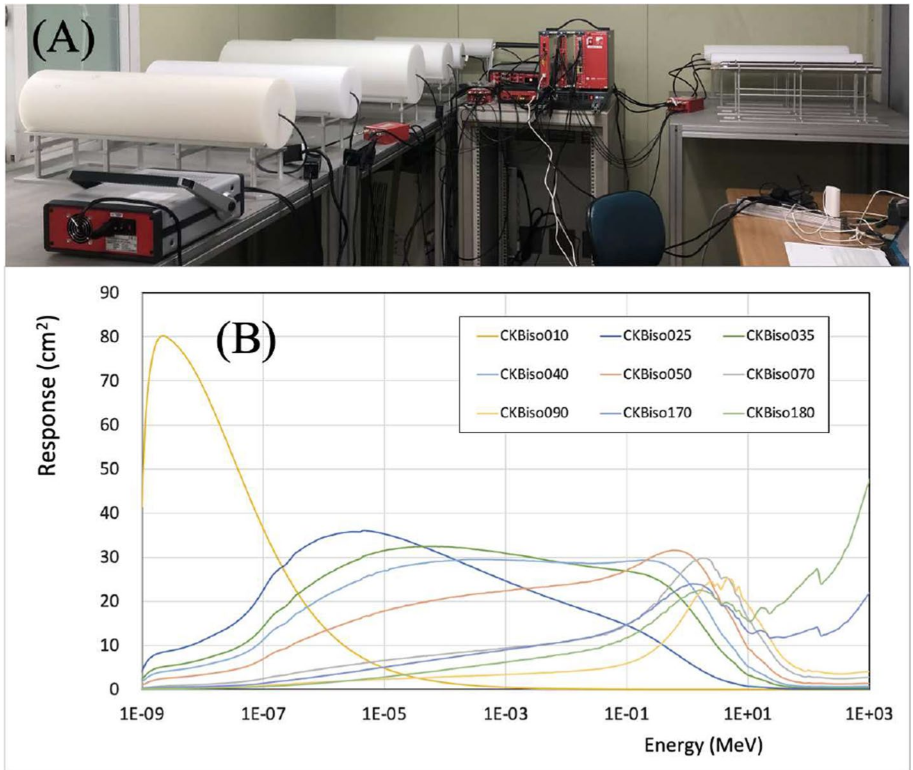

Fig. 8 Cosmic neutron spectrometer measurement setup on the ground (A) and response function of moderators with the ^{3}He-tube detectors from MCNP simulations (B)

(CAEN DT5725S and N6725S). A 1 μs shaping amplifier processed the signals from the proportional counters and afterward, the maximum signals were recorded by two 250 mega-sampling/s digitizers. A DAQ software, CoMPASS from the CAEN company, was used to independently record data of ten channels from two modules. We will study the separation of particles utilizing a rise time information later.

The internal background of the ^{3}He tube detector was measured at the Yangyang underground laboratory. A long-duration measurement revealed the existence of a background caused by internal α particles inside the detector materials [15, 22]. Ten ^{3}He tube detectors were installed inside a Cd shield to measure the internal background rate of the ^{3}He-tube detectors. The measurement was performed for a week, and the measured internal background rates of detectors were from 9.5×10^5 to 1.4×10^4 s^{-1}.

Currently, the spectrometer is operating on the ground to verify the long-term stability of the DAQ system. We are preparing a system for collecting environmental monitoring data, such as pressure, temperature, humidity. When the spectrometer and system are ready, we will start measuring the cosmic neutron spectrum at various sites in Korea.

7 Conclusions

As a national standard institution, the KRISS has established the neutron measurement standards. Researchers and industries can use its neutron standard measurement services, such as detector calibration, dose equivalent measurements, emission rate measurements, neutron fluence measurements, neutron spectrum measurements, and neutron source irradiation. These neutron standard facilities and measurement systems at KRISS have supported researchers in the physics community and radiation measurement industry. A mono-energetic neutron field with energies of 14.8 MeV and 2.5 MeV is currently under development. In the near future, mono-energetic neutron fields will be available in addition to the radioisotope neutron sources. Research and development related to mono-energy measurement techniques and neutron detectors are ongoing. In addition, a high-sensitivity neutron spectrometer is developed for performing cosmic neutron spectrum measurements.

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