Neutron Spectrum Unfolding Using Response Matrix and 1D-CNN for CLYC-7 Neutron Spectrometer

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1. Introduction

For space missions, it is necessary to analyze space neutron spectrum to protect human from space neutrons and evaluate the biological effects of space neutrons. When fast neutrons interact with human tissue, they can produce high LET charged particles [1]. Therefore, fast neutrons in space can give higher biological effects to human than neutrons in other energy regions. Then it is more important to analyze space fast neutron spectrum and understand the biological effects.

There have been several researches to evaluate the biological effects of space protons and heavy charged particles. Health risks of protons and heavy ions from galactic cosmic radiation (GCR) and solar particle event (SPE) beyond low-Earth-orbit (LEO) have been evaluated [2]. Also, several researches to detect thermal and epithermal neutrons using CLYC-6, which has high Li-6 concentration suitable for detecting thermal neutrons to map hydrogen distributions on lunar surface [3]. However, there are only few researches to map space fast neutrons and evaluate the biological effects of fast neutrons.

CLYC is an elpasolite class inorganic scintillation detector which consists of Cs_2LiYCl_6 crystal and activated with Ce^{3+}. CLYC scintillation detector has an ability to discriminate neutron signals from gamma signals using pulse shape discrimination (PSD). Different waveforms between neutron signals and gamma signals due to different scintillation mechanisms of neutrons and gammas make pulse shape discrimination possible [4]. This property makes CLYC scintillation detector suits for space radiation environment which has mixed neutron/gamma radiation field.

Along with high light yield and good energy resolution, CLYC scintillation detector has sufficiently high radiation hardness for space missions. Radiation hardness test showed unchanged pulse shapes of CLYC scintillation detectors to 13.8 kRad radiation dose from 800 MeV protons [5].

In this study, CLYC-7 neutron spectrometer, which has high ^{7}Li concentration to suppress thermal neutron reaction was used to obtain fast neutron spectrum in energy range 1-10 MeV.

For poly-energetic neutron distribution, two main fast neutron reactions: (n,p) and (n,a) have different Q-values according to different excited states and make broad pulse height spectrum to CLYC-7 neutron spectrometer [6]. Therefore, spectrum unfolding is needed obtain the original neutron energy distribution spectrum.

To obtain fast neutron energy spectrum in neutron energy range 1-10 MeV, neutron spectrum unfolding algorithms using response matrix and 1D-CNN (convolutional neural network) were developed. Response matrix and 1D-CNN training dataset were generated by using Monte Carlo simulation using MCNP6.2. To verify these unfolding algorithms, pulse height spectrum of Am-Be neutron source was detected using CLYC-7 neutron spectrometer.

2. Materials and Methods

2.1 CLYC-7 Neutron Spectrometer

CLYC scintillation detector has four scintillation mechanisms: direct electron-hole capture by Ce^{3+}, core-to-valence luminescence (CVL), Binary V_k and electron diffusion, and emission by self-trapped excitons (STE) [4]. Direct electron-hole capture by Ce^{3+} and core-to-valence luminescence (CVL) are fast and ultrafast scintillation mechanisms which took 10s of nanoseconds and a few nanoseconds [4]. Binary V_k and electron diffusion and emission by self-trapped excitons (STE) are intermediate and slow scintillation mechanisms which took 100s of nanoseconds and microseconds. In case of neutron interactions, only slow scintillation mechanisms: only binary V_k and electron diffusion and emission by self-trapped excitons (STE) are exist [4]. Therefore, neutron signals have slow decay time compared to gamma signals which can occur fast scintillation mechanisms such as direct electron-hole capture by Ce^{3+} and core-to-valence luminescence (CVL). Different decay times of neutron signals and gamma signals comes from these four scintillation mechanisms make CLYC scintillation detector to separate neutron spectrum and gamma spectrum [4].

In this study, CLYC-7 neutron spectrometer, which has 99.9% concentration of ^{7}Li in CLYC scintillation detector to suppress thermal neutron reaction from ^{6}Li was used to obtain fast neutron spectrum in energy range 1-10 MeV. There are two main fast neutron reactions of CLYC-7 neutron spectrometer: $^{35}Cl(n,p)^{35}S$ and $^{35}Cl(n,a)^{35}P$. By this two main reactions of fast neutron, CLYC-7 neutron spectrometer has capability to detect fast neutron spectrum.

2.2 Monte Carlo Simulation

To model CLYC-7 neutron spectrometer for making response matrix and training dataset of neutron spectrum unfolding algorithms, Monte Carlo simulations were conducted using MCNP (Monte Carlo N-Particle Transport Code) version 6.2 to model CLYC-7 neutron spectrometer developed by the Korea Astronomy and Space Science Institute (KASI). CLYC-7 crystal which diameter and height of 1.5" was made up of Cs_2LiYCl_6 which has 99.9% enrichment of ^7Li. 1.25 mm thickness crystal casing, 3 mm thickness crystal shield, and 1.5 mm thickness chamber shell were made up of Al7075-T6 alloy.

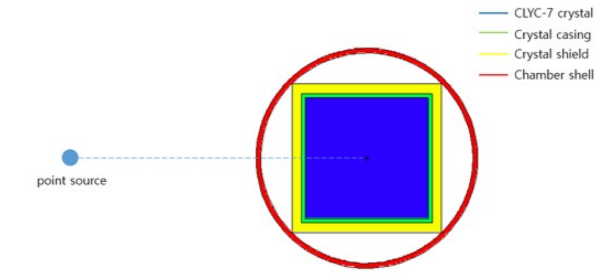

Fig. 1. MCNP6.2 simulation geometry of CLYC-7 neutron spectrometer

For neutron transport in this Monte Carlo simulations, ENDF/B-VII (Evaluated Nuclear Data File) library was used and neutron source was assumed to be isotropic point source. Protons and alpha particles were scored to CLYC-7 crystal to detect neutron energies. To consider reduced scintillation efficiency of particles in SiPM due to quenching effect, scintillation quenching factor of 0.72 was applied in this Monte Carlo simulations.

2.3 Neutron Spectrum Unfolding Algorithm Using Response Matrix

Response matrix (R) was obtained by band-wise neutron beam simulation to solve inverse matrix problem to obtain original neutron energy distribution spectrum (Φ) from CLYC-7 neutron spectrometer pulse height spectrum (N). 30 x 30 response matrix with 0.3 MeV bin was generated by 0.3 MeV band-wise beam simulation (0.9-1.2 MeV, 1.2-1.5 MeV, … , 9.6-9.9 MeV).

$$N = R\Phi \ , \ \Phi = R^{-1}N \tag{1}$$

$$\begin{pmatrix} N_1 \\ N_2 \\ \cdots \\ N_n \end{pmatrix} = \begin{pmatrix} R_{1,1} & R_{2,1} & \cdots & R_{n,1} \\ R_{1,2} & R_{2,2} & \cdots & R_{n,2} \\ \vdots & & \ddots & \vdots \\ R_{1,n} & R_{2,n} & \cdots & R_{n,n} \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \cdots \\ \Phi_n \end{pmatrix} \tag{2}$$

To obtain only nonnegative physical solution, least square method was applied with $\Phi \geq 0$ condition. Smoothing spline fitting was applied to prevent noisy data.

2.4 Neutron Spectrum Unfolding Algorithm Using 1D-CNN

To obtain original neutron energy distribution spectrum from CLYC-7 scintillation detector pulse height spectrum, 1D-CNN (convolutional neural network), one of the deep learning neural network was applied for the development of neutron spectrum unfolding algorithm. For making random neutron energy distribution, 5 Gaussian distributions with different amplitudes (A), means (μ), and standard deviations (σ) were generated and summed. Each summed random distributions was made up of 30 energy bins (0.9-1.2 MeV, 1.2-1.5 MeV, ... , 9.6-9.9 MeV).

$$f = \frac{A_1}{\sqrt{2\pi}\sigma_1} e^{-\frac{(x-\mu_1)^2}{2\sigma_1^2}} + \frac{A_2}{\sqrt{2\pi}\sigma_2} e^{-\frac{(x-\mu_2)^2}{2\sigma_2^2}} + \frac{A_3}{\sqrt{2\pi}\sigma_3} e^{-\frac{(x-\mu_3)^2}{2\sigma_3^2}} + \frac{A_4}{\sqrt{2\pi}\sigma_4} e^{-\frac{(x-\mu_4)^2}{2\sigma_4^2}} + \frac{A_5}{\sqrt{2\pi}\sigma_5} e^{-\frac{(x-\mu_5)^2}{2\sigma_5^2}} \tag{3}$$

These generated random distributions were used as neutron source energy distribution in MCNP6.2, then pulse height spectra of CLYC-7 scintillation detector were obtained by Monte Carlo simulations. 900 random neutron energy distributions were generated by summation of 5 Gaussian distributions and simulated in MCNP to get pulse height spectrum. Then, 900 input (CLYC-7 pulse height spectrum) - Target (random neutron energy distribution) pairs were trained to generate 1D CNN model.

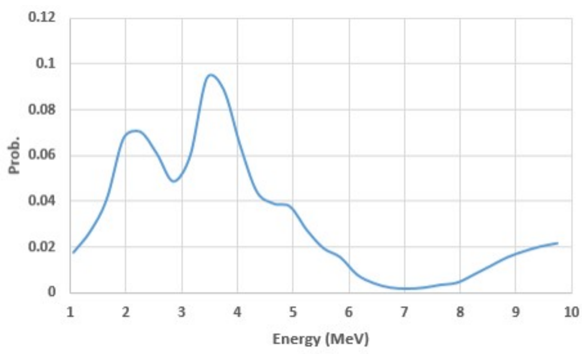

Fig. 2. 5 Gaussian peak random neutron energy distribution

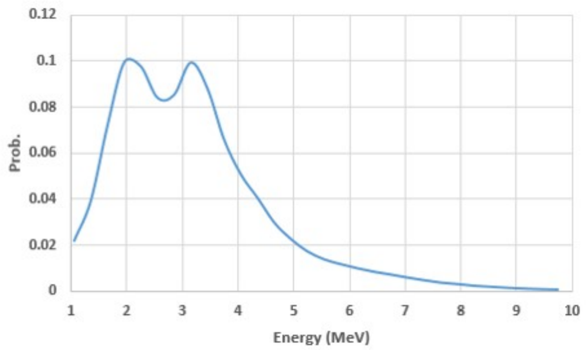

Fig. 3. CLYC-7 pulse height spectrum from random neutron energy distribution

2.5 Am-Be Neutron Source Unfolding

Am-Be neutron source was detected by CLYC-7 scintillation detector and neutron pulse height spectrum was obtained to evaluate neutron spectrum unfolding algorithms. Am-Be neutron source in Korea Research Institute of Standards and Science (KRISS) was detected using CLYC-7 scintillation detector. Then, neutron pulse height spectrum was separated from gamma pulse height spectrum using pulse shape discrimination (PSD) by charge comparison method using 2 gates. Noise below 1 MeV was eliminated and neutron spectrum in 1-10 MeV range was used for spectrum unfolding.

Am-Be fast neutron pulse height spectrum obtained by pulse shape discrimination of neutron energy range 1-10 MeV was tested by neutron spectrum unfolding algorithms to predict the original neutron energy distribution of Am-Be neutron source from "A.D. Vijaya and A. Kumar,, The neutron spectrum of the Am-Be neutron sources" obtained by GetData Graph Digitizer [7].

Am-Be neutron pulse height spectrum obtained by Monte Carlo simulation was also tested by neutron spectrum unfolding algorithms and compared with original neutron energy distribution obtained by GetData Graph Digitizer.

3. Results

3.1 Am-Be Neutron Spectrum Unfolding Using Response Matrix

Am-Be neutron spectrum unfolding results using response matrix of Am-Be neutron pulse height spectrum obtained by Monte Carlo simulation and by detection of CLYC-7 neutron spectrometer were compared with original Am-Be energy distribution spectrum. Unfolding result using neutron pulse height spectrum by Monte Carlo simulation showed good agreement with original Am-Be spectrum. However, Unfolding result using CLYC-7 detected pulse height spectrum showed large differences in 6-9 MeV energy range.

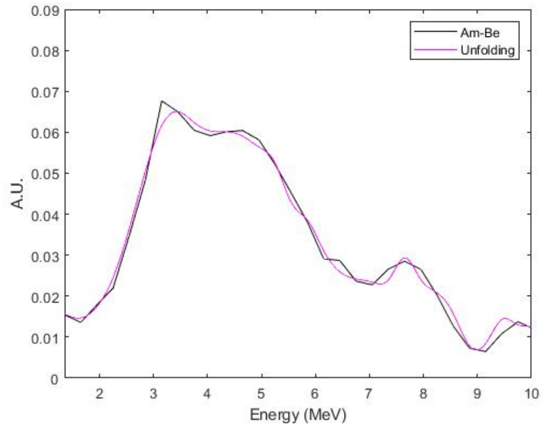

Fig. 4. Am-Be neutron spectrum unfolding result using response matrix (Monte Carlo simulation)

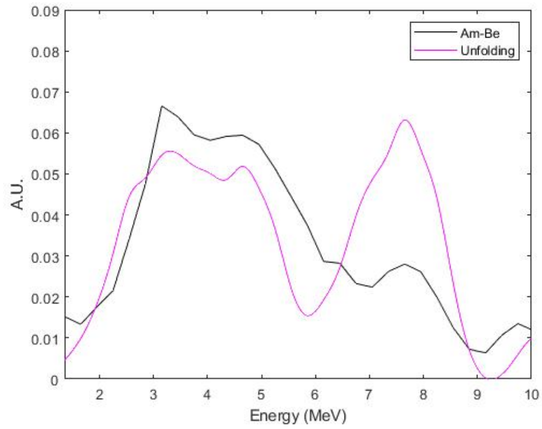

Fig. 5. Am-Be neutron spectrum unfolding result using response matrix (CLYC-7 detection)

3.2 Am-Be Neutron Spectrum Unfolding Using 1D-CNN

Am-Be neutron spectrum unfolding result using 1D-CNN of Am-Be neutron pulse height spectrum obtained by Monte Carlo simulation and by detection of CLYC-7 neutron spectrometer were compared with original Am-Be energy distribution spectrum. Unfolding result using neutron pulse height spectrum by Monte Carlo simulation showed good agreement with original Am-Be spectrum. Unfolding result using neutron pulse height spectrum by detection of CLYC-7 showed better result than using response matrix and showed good agreement with the location of each peaks. Some discrepancies were shown in amplitudes of peaks over neutron energy of 5 MeV.

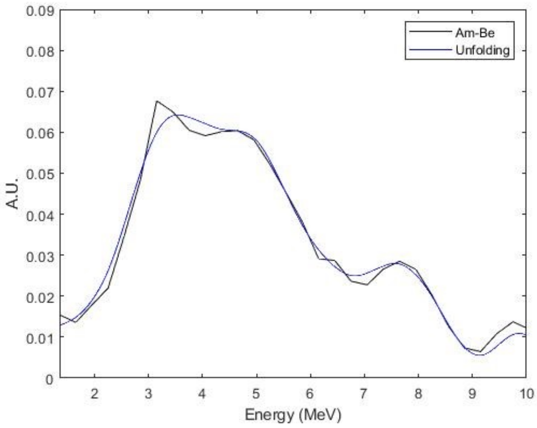

Fig. 6. Am-Be neutron spectrum unfolding result using 1D-CNN (Monte Carlo simulation)

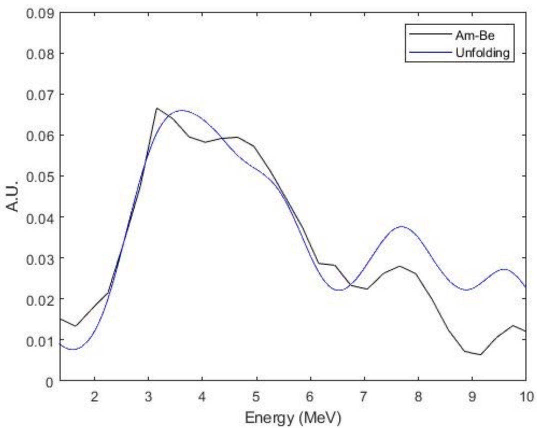

Fig. 7. Am-Be neutron spectrum unfolding result using 1D-CNN (CLYC-7 detection)

4. Discussion

Neutron spectrum unfolding result using response matrix and 1D-CNN for CLYC-7 pulse height spectrum from Monte Carlo simulation showed good agreement with original Am-Be neutron energy distribution spectrum. Unfolding result using response matrix and 1D-CNN for pulse height spectrum from CLYC-7 neutron spectrometer detection showed some differences over 5 MeV neutron energy region. It can be said that some discrepancies between unfolding result from CLYC-7 detected Am-Be pulse height spectrum and original energy distribution came from differences between Monte Carlo simulation and real experiments in high neutron energies above 5 MeV. Unfolding result using 1D-CNN for neutron pulse height spectrum by detection of CLYC-7 showed better result than using response matrix. Large differences of response functions which compose response matrix above 5 MeV between simulation and experiment makes large differences in spectrum unfolding result over neutron energies of 5 MeV. On the other hand, similar tendency of Am-Be pulse height spectrum between simulation and experiment showed better result for 1D-CNN than response matrix.

5. Conclusion

Fast neutron energy spectrum in energy range 1-10 MeV of Am-Be neutron source was obtained by spectrum unfolding. Neutron spectrum unfolding algorithms using response matrix and 1D-CNN model were developed by solving inverse matrix problem and training random neutron energy distribution - neutron pulse height spectrum pairs. Suitability of developed neutron spectrum unfolding algorithms were confirmed by good unfolding result of Am-Be pulse height spectrum obtained by Monte Carlo simulation. Both algorithms showed some discrepancies with original Am-Be spectrum over 5 MeV due to differences between simulation and experiment. Other fast neutron sources will also be tested to validate this neutron spectrum unfolding algorithm with final goal for mapping fast neutrons in space.

6. Acknowledgements

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