Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Characterization of 30 MeV Proton Cyclotron-Based Neutron Source by Utilizing Bonner Sphere Spectrometer

Gyuhaeng Jo[a], Soobin Lim[a], Bong-Ki Jung[b], Kyoung-Jae Chung[a*]
[a]*Nuclear Engineering, Seoul National University, 1, Gwanak-ro, Gwanak-gu, Seoul, Republic of Korea*
[b]*KAERI, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, Republic of Korea*
[*]*Corresponding author: jkjlsh1@snu.ac.kr*

***Keywords:** neutron source, Monte Carlo simulation, Bonner sphere spectrometer, spectrum unfolding

1. Introduction

Recently, a neutron source was developed at Advanced Radiation Technology Institutes (ARTI), Jeongeup. Neutrons are generated via a target-moderator-reflector-shield (TMRS). It is installed at the RFT-30 30 MeV proton cyclotron at ARTI [1]. The neutrons from the TMRS are detected by a Bonner sphere spectrometer (BSS) which is a set of thermal neutron detectors including HDPE (High density polyethylene) with different sizes [2]. Then, the neutron energy spectrum can be obtained through neutron spectrum unfolding by exploiting neutron counts from the BSS.

In this paper, neutron detection results at the TMRS room and corresponding neutron unfolding results are discussed with Monte Carlo simulation results obtained by MCNP6.2 [3].

2. Monte Carlo Simulation

Fig. 1 depicts the structure of the TMRS system installed at RFT-30. A beryllium target at the center of TMRS generates neutrons through collisions with 30 MeV protons. The neutrons lose their energies while penetrating an HDPE moderator and the HDPE around the target acts as a reflector to mitigate neutron loss. Additional lead and HDPE covering the reflector are equipped as shields for removing gamma rays and neutrons deviating from the neutron beam line.

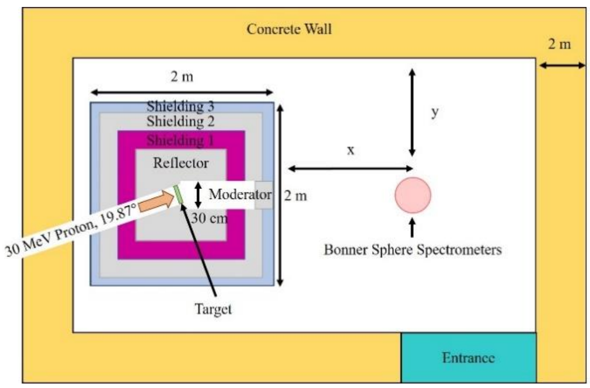


Fig. 1. TMRS structure designed for RFT-30

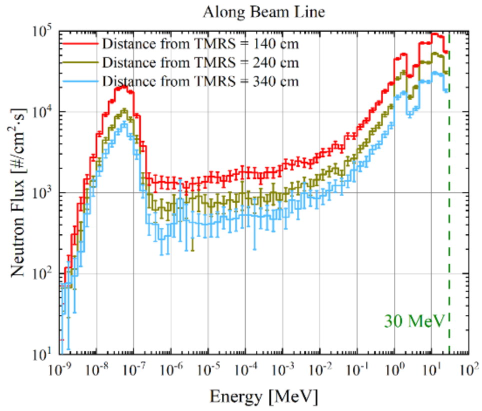


Fig 2. Neutron energy spectrum when 1.2 μA proton beam is incident on the target

Fig. 2 illustrates a wide neutron energy range by the TMRS which is universal to an accelerator-based neutron source. The spectrum roughly consists of three regions: fast neutrons which experienced negligible moderation, fully thermalized neutrons, and neutrons with moderate collisions.

Bonner sphere spectrometer with diverse HDPE sphere has the ability to measure the neutrons ranging from meV to MeV. Fig. 3 demonstrates that the sphere sizes that correspond to neutron scattering frequencies with hydrogen nuclei vary the response functions.

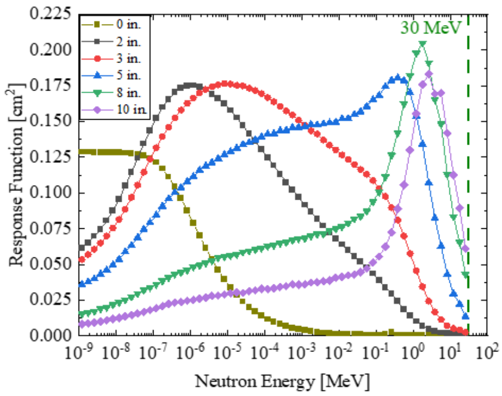


Fig. 3. Response functions of BSS depending on the sphere sizes

3. TMRS Experiment

3.1. BSS setup for TMRS experiment

The Bonner sphere spectrometer is installed in the TMRS room of Fig. 1 and located 290 cm away from the TMRS. 10 μA protons with 30 MeV are incident on the target for 120 s. Five detectors are utilized whose sphere diameters are 2, 3, 5, 8 and 10 in. $\phi\, 4 \times 4$ mm ^{6}Li-containing glass scintillator called GS20 is chosen due to fast decay time (~18 ns) and capability of neutron-gamma discrimination [4]. Generated pulses during the measurement experiment are recorded by a 250 MHz digitizer, DT5725 from CAEN.

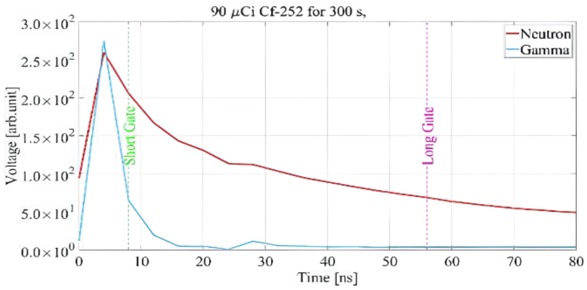
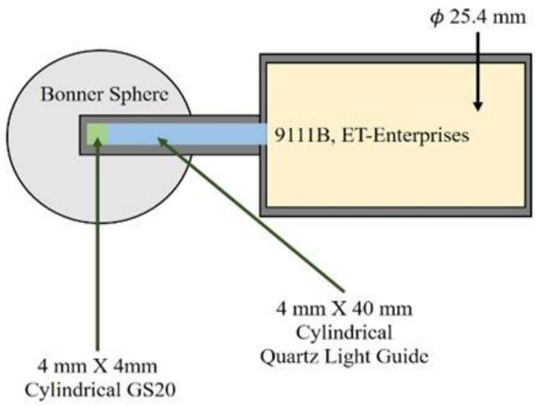


Fig. 4. Averaged neutron and gamma pulse from GS20

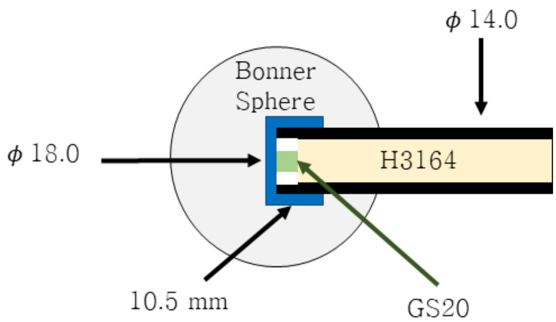
Fig. 4 is a plot for the pulse shape difference generated by GS20. The pulse shape discrimination (PSD) method is applied to discriminate all the pulses. For this method, Q_{total} and Q_{tail} are defined which correspond to the V-t integral from pulse rise to signal tail and signal head to signal tail, respectively. The signal head and tail are called short gate and long gate and the PSD is defined below [5]:

$$(\text{PSD Ratio}) = \frac{Q_{tail}}{Q_{total}} \qquad (1)$$

Simplified BSS designs appear in Fig 5. The detectors with 2 in. and 3 in. HDPE spheres use 9111B series photomultiplier tubes (PMTs) manufactured by ET-enterprises while the others utilize H3164 PMTs by Hamamtsu. Due to the larger diameter of the 9111B series, scintillation photons by 2 in. and 3 in. detectors are transported through $\phi\, 4 \times 40$ mm quartz light guide. All components of the detectors are shielded by aluminum casing except for the spheres.



(a) 9111B Series



(b) H3164

Fig. 5. BSS structure for each PMT

3.2. TMRS experiments and unfolding results

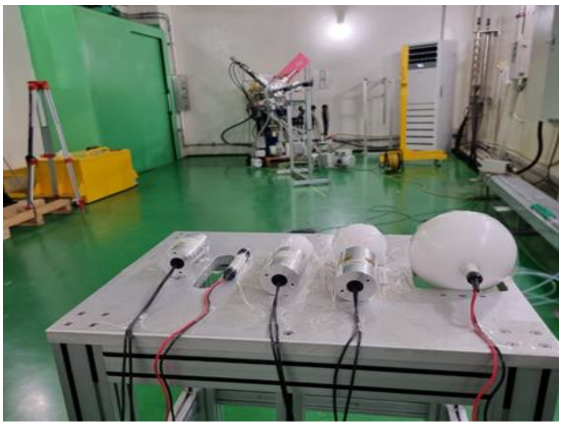
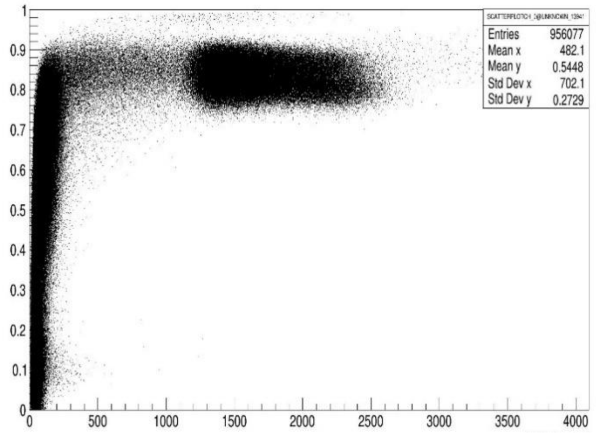
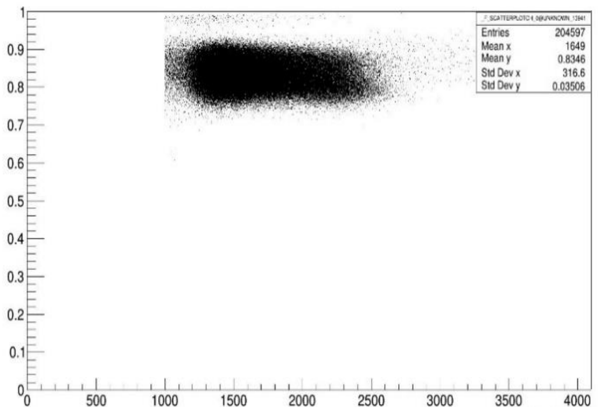


Fig. 6. Bonner sphere spectrometer for TMRS experiment

Fig. 6 is a picture of the Bonner sphere spectrometer used in the TMRS experiments. Then, Fig. 7 illustrates the detected results at 10 in. BSS at Fig. 6 when the 10 μA protons are impinging on the target for 120 s. The abscissa of Fig. 7 represents Q_{total} and the ordinate means PSD ratio. The neutron counts appear at the upper region in the PSD plot due to the heavier tails of their pulses.



(a) Total counts



(b) Neutron counts only

Fig. 7. TMRS experiment results at the 10 in. BSS

Table I: TMRS experiment results at each detector

Sphere size [in.]	Neutron counts	
	Experiment	MCNP6.2
2	2.103×10^5	6.141×10^4
3	7.215×10^4	2.351×10^4
5	3.690×10^5	3.478×10^5
8	2.103×10^5	4.548×10^5
10	2.046×10^5	4.805×10^5

Neutron spectrum unfolding is a process of obtaining a neutron energy spectrum from a pulse height spectrum acquired through an experiment. In other words, the neutron spectrum unfolding is the process of obtaining the neutron flux at the j-th energy bin, ϕ_j, by employing the neutron counts at the i-th Bonner sphere, N_i, and the detector response matrix at i-th sphere for the j-th energy bin, R_{ij}. These three values correlate as below:

$$N_i = \sum_j R_{ij}\phi_j \qquad (2)$$

Since the number of energy bins is larger than that of Bonner spheres, it is essential to introduce an additional iterative method. Therefore, the iterative method employing the principles of GRAVEL unfolding code developed by Physikalisch-Technische Bundesanstalt (PTB) is exploited to acquire the neutron energy spectrum of the TMRS. GRAVEL code minimizes a chi-squared value and it is defined below when σ_i represents the standard deviation of N_i [2, 6]:

$$\chi^2 = \sum_i \frac{\left(N_i - \sum_j R_{ij}\phi_j\right)^2}{\sigma_i^2} \qquad (3)$$

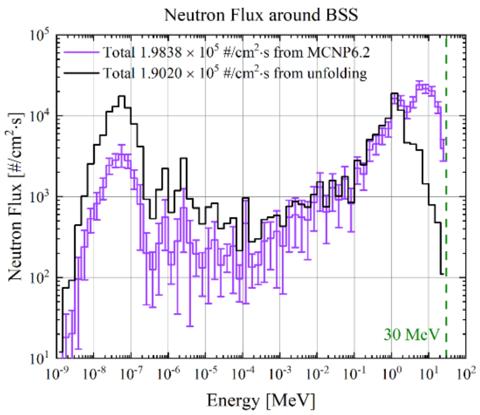


Fig. 8. Comparison between MCNP6.2 simulations and unfolding results

Though total neutron fluxes of the simulation and unfolding results show less than 5 % differences in Fig. 8, significant discrepancies between them appear in the fast and thermal neutron regions. The higher thermal neutron flux is induced by the detection of the neutrons scattered from the other spheres. While, the lower fast neutron flux results from the lack of the Bonner sphere whose response function has a peak over 10 MeV.

4. Conclusions

Neutron spectrum measurements using the BSS are carried out during the cyclotron-based neutron source development. This spectrometer is selected because of the wide energy spectrum resulting from the Monte Carlo simulation. Then, the GS20 scintillator of the BSS is chosen due to its distinct decay time difference between gamma and neutron signals which is suitable for the PSD method. From the TMRS experiment, it is verified that the total neutron fluxes are agreed within the 5 % difference between the simulation and the unfolding results. Therefore, this study confirms that the characterization of the neutron source is able to be accomplished successfully by utilizing the BSS and the unfolding technique. This BSS will be exploited henceforth as a prompt neutron monitoring system during the experiments. The accuracy of the unfolding results will be improved in the future if the number of Bonner spheres increases or a radiation shield among the spheres is equipped.

Acknowledgments

This work was supported by the National R&D Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (2020M2D1A1064206) and by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) (No. RS-2022-00154676 and No. RS-2023-00281276).

REFERENCES

[1] Y. B. Kong, M. G. Hur, E. J. Lee, J. H. Park, Y. D. Park, and S. D. Yang, Predictive ion source control using artificial neural network for RFT-30 cyclotron, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Vol.806, pp.55-60, 2016.

[2] G. F. Knoll, Radiation Detection and Measurement, John Wiley & Sons, New York, 2010.

[3] T. Goorley, M. James, T. Booth, F. Brown, J. Bull, L. Cox, ..., and T. Zukaitis, Initial MCNP6 release overview, Nuclear technology, Vol.180, pp.298-315, 2012.

[4] Y. Song, J. Conner, X. Zhang, and J. P. Hayward, Monte Carlo simulation of a very high resolution thermal neutron detector composed of glass scintillator microfibers, Applied Radiation and Isotopes, Vol.108, pp.100-107, 2016.

[5] G. H. Jo, S. B. Lim, B. K. Jung and K. J. Chung, Development of Bonner Sphere Spectrometer for Neutron Source with 30 MeV Proton Cyclotron, Proceedings of 2023 KNS Spring Conference, Republic of Korea.

[6] M. Matzke, Unfolding of particle spectra, International Conference Neutrons in Research and Industry, SPIE, Vol.2867, pp.598-607, 1997.