EXPERIMENTAL VERIFICATION OF NEUTRON FLUX CALCULATION FOR COMPACT ACCELERATOR-BASED MULTI-PORT BNCT SYSTEM

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Abstract

This work aims to verify the neutron transportation calculations performed in PHITS code for the development of a compact accelerator-based multi-port Boron Neutron Captured Therapy (BNCT) system. Two test experiments were performed in RCNP using a 53 MeV proton beam from an AVF cyclotron onto a tungsten (W) target, with and without a test moderator assembly. An NE213 liquid scintillator and a ^{6}Li plastic scintillator were used for the detection of neutrons for the former and later experiments respectively. As for the one without any moderator, the measured integrated angular neutron yield agreed with the calculations within 20 to 23%. The difference appeared mainly in the higher energy region. On the other hand, the preliminary neutron spectrum with a test moderator assembly shows significant moderating effect. Further effort is required to determine the detector efficiency for reliable verification of calculations. In this paper, the current status of the experimental results and comparison to the calculations will be discussed.

INTRODUCTION

Boron Neutron Captured Therapy (BNCT) is a binary therapy for cancers. Since this decade, many accelerator-based BNCT (AB-BNCT) were built around the world and some of them are currently performing clinical trials [1, 2]. Most of the clinical trials had shown positive result with an effective rate of more than 90% [3, 4]. These show that BNCT is a potential curative therapy in the coming future, especially for those radio-resistant cancers which have poor results of conventional therapy. Owing to this effectiveness, we have proposed a compact AB-BNCT to deliver multiple neutron beams with high intensity epithermal neutron flux of about 2×10^9 cm^{-2} s^{-1} in [5] to support the increasing demand of BNCT. The proposed AB-BNCT implements a 50 MeV proton beam onto a W target to produce spallation neutrons. The fast neutrons are then moderated by Fe, AlF_3 and Teflon, and further shielded by Bi, Pb, Borated-polyethlene and others. The details of the design will not be discussed here as its feasibility was confirmed in the previous study. Despite of its proven feasibility by simulations, in order to realize the proposed system, it is vital to validate all the neutron calculations performed by PHITS with real experiments. Thus, in order to fulfill this goal, two test experiments were performed at RCNP cyclotron facility.

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MATERIAL AND METHOD

Target

The first experiment was performed using a 53 MeV proton beam from the AVF cyclotron onto a 20 × 20 mm^2 wide W target with a thickness of 0.2 mm to confirm the spallation neutron yield. Fast neutrons were detected by TOF method. They were allowed to pass through a flight length of 10 m in the TOF tunnel of N0 course in RCNP. Neutrons were detected by an NE213 liquid scintillator at 0°, 15°, 30°, 45°, 60° and 75°. The measured angle was varied by changing the W target position along a central trajectory in the magnetic field of a bending magnet. Data was taken using the conventional NIM electronics and CAMAC module. The layout of the experiment is shown in Fig. 1 and the electronic circuit for the main data detection is shown in Fig. 2.

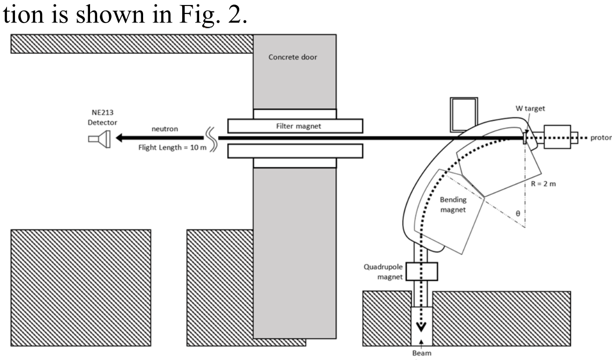

Figure 1: The schematic view of neutron TOF measurement from a bare W target at N0 course of RCNP (not to scale).

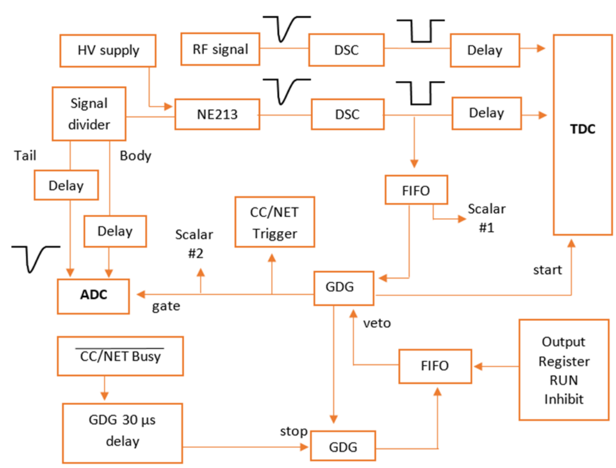

Figure 2: The electric block diagram using NIM and CAMAC module for the detection of fast neutrons by NE213.

The data taken are then analysed by pulse shape discrimination (PSD) as neutron pulses tend to have a larger tail of an output signal charge Q (tail-Q) owing to its slower fluorescent effects. Taking the ratio of tail-Q to total-Q, we identify data with larger ratio to be neutrons, whereas the smaller one as gamma-rays.

Moderator Assembly

In order to confirm the moderating effects calculated by PHITS code, another experiment was performed with a test moderator assembly using ES course in RCNP. Owing to space limitation in experimental hall, the configuration of the test moderator assembly used is different from the one proposed in [5]. During this experiment, neutrons at 90° were moderated and detected by using TOF method with a flight length of 1 m away from the target. A combination of 10 cm thick blocks of Fe, AlF_3, Teflon and 1.5 cm thick plates of LiF were used together as the test moderator assembly. Concrete collimator as well as Pb and borated paraffin were used to reduce the background (BG) neutrons and gamma-rays. An EJ270 ^{6}Li plastic scintillator was used as the neutron detector. Data was again taken with the conventional NIM electronics and CAMAC with electronic circuit similar to the one shown in Fig.1.

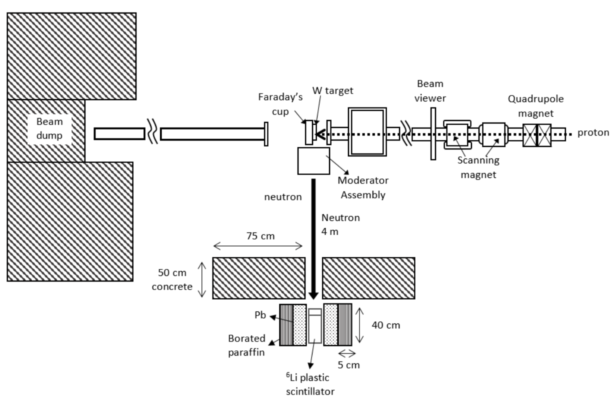

Figure 3: The schematic view of experiment setup at ES course of RCNP (not to scale).

Similar PSD method as that of NE213 is applied for EJ270 plastic scintillator. However, besides fast neutrons and gamma, capture reaction by ^{6}Li leads to the production of alpha and triton particles. These two are heavy ions with high stopping power and thus they result in a higher probability of delayed fluorescence. Thus, this causes a bigger ratio of total-Q to tail-Q as compared to fast neutrons as well as gamma components.

RESULTS AND DISCUSSIONS

Target

All the calculations were performed by using PHITS code ver. 2.87 developed by JAEA, RIST and KEK [6]. INCL model is implemented and JENDL-4.0 cross section library is used for neutrons of energy < 20 MeV [7, 8]. Fig 4 shows the comparison between experimental results and PHITS simulation.

The detector efficiency of NE213 detector is obtained by integrating the response functions calculated in SCINFUL-QMD. A small amount of fluorescent light attenuation of 0.01/cm is assumed in the calculation. The bias (threshold) level of the electronic output was estimated to be (0.57±0.06) MeV by calibrating the pulse height spectrum (PHS) channel using known gamma-ray sources. The data is then divided by the detector efficiency.

From Fig. 4, experimental results agree with the PHITS calculations at energy < 30 MeV for 0° and 15°. At energy beyond 30 MeV, PHITS calculations estimated a higher production of high energy neutrons. This disagreement could be due to the failure of INCL model adopted in PHITS in predicting the quasi-elastic reactions, especially at the forward direction. On the other hand, at 30°, PHITS agrees with the experimental results only at E<20 MeV. The neutron yield is overestimated for energy range of 20-40 MeV and underestimated beyond 40 MeV. At 45°, PHITS overestimated neutron yield for energy range of 10-30 MeV and underestimated the yield beyond 30 MeV. At angles larger than 45°, TOF spectrum could not show a clear time structure after off-line BG subtraction. This might be due to geometry misalignments, as well as mismatched of proton orbit incurred within the Fe magnet. Thus, from this experiment, we do not obtain any useful data beyond 45°. The neutron energy spectra at larger angle shall remain as a part of the future works.

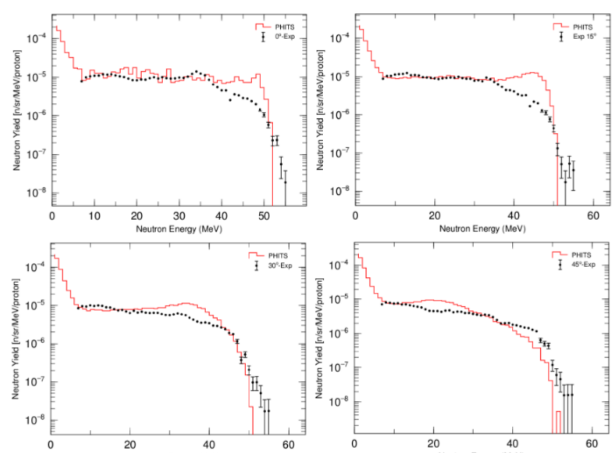

Figure 4: Double differential yield of neutron emitted at 0°, 15°, 30° and 45° from W target for 53 MeV proton obtained by the experiment (black line) and PHITS simulation (red line).

Figure 5 shows the comparison of integrated neutron yield at different laboratory angles for PHITS calculations and experimental results. Although experimental data seems to have a consistently lower yield as compared to PHITS calculations, after taking into account the estimated error, we can conclude that the integrated neutron yield at these four angles actually agree with the PHITS calculations within 20 to 23 %.

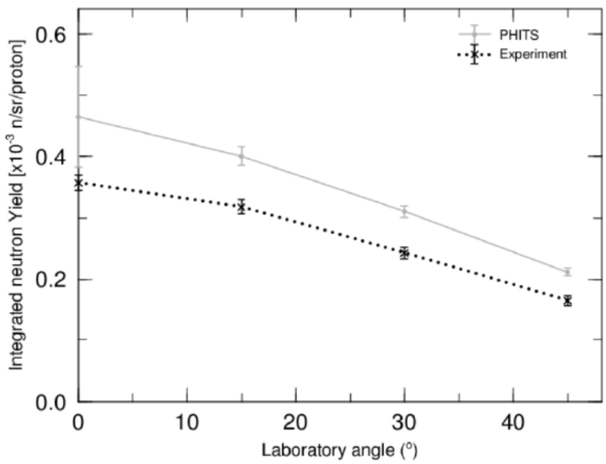

Figure 5: A summary of the integrated neutron yield as a function of laboratory angle for experimental data and PHITS calculations.

Moderator Assembly

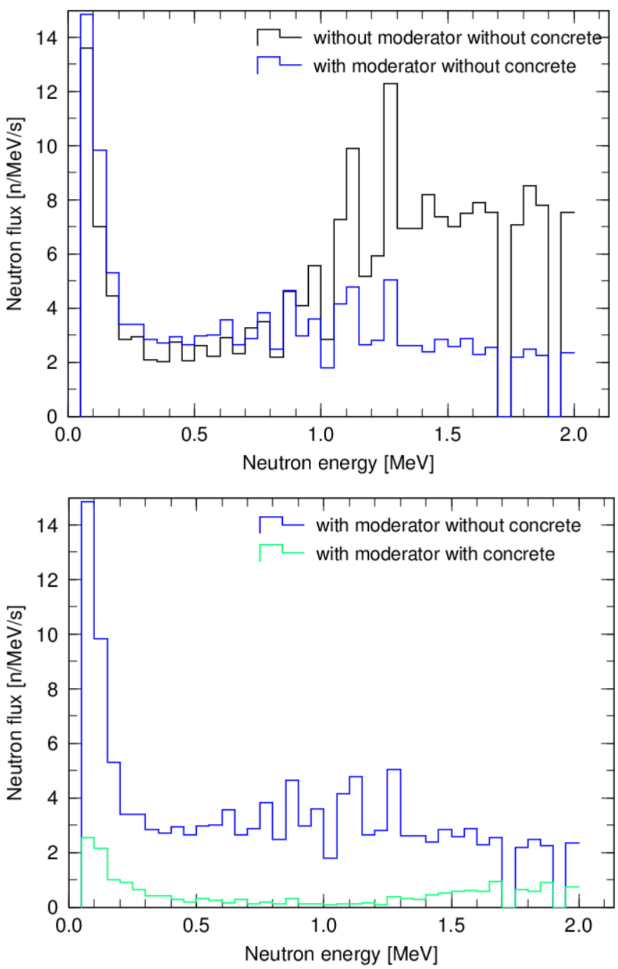

Figure 6: Preliminary experimental results before dividing by the detector efficiency to compare: *Top* (a) moderating effects (b) Collimator and shielding effect

The comparison of neutron spectrum with and without a test moderator assembly before dividing by the detector efficiency is shown in Fig. 6. As we can see, with the addition of the test moderator assembly, fast neutrons with energy more than 1 MeV are attenuated significantly and a higher production of slower neutrons with energy less than 200 keV is recorded. This confirms the moderating effect by the test moderator assembly. On top of this, with the addition of concrete collimator as well as gamma and thermal neutron shielding, the overall neutron flux reduces. This might indicate a successful shielding from background scattering.

The moderated neutron flux is then divided by the neutron flux without any moderation. The experimental ratio is then compared with the PHITS calculation as shown in Fig. 7. The one without any shield and collimator shows significant discrepancy especially at high energy region. The one with a shield and collimator requires more statistics for better comparison. This will remain as the next effort of this work.

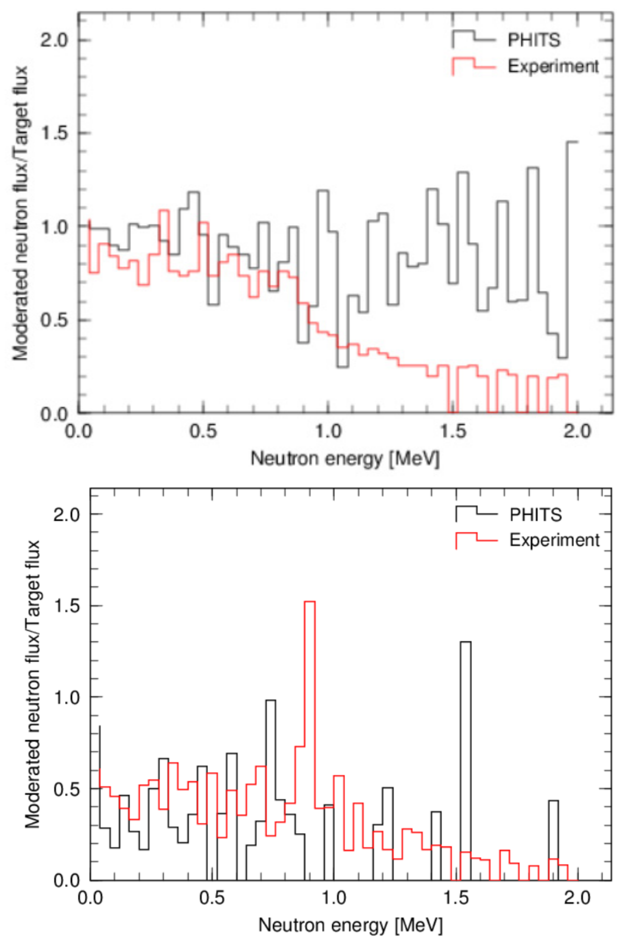

Figure 7: Preliminary comparisons between PHITS and experimental ratio of target-to-moderated flux: *Top* (a) without collimator and shield (b) with collimator and shield

CONCLUSION

The angular neutron spectrum at higher energy shows discrepancy, especially at a smaller angle. Despite of such discrepancy in neutron spectrum, the integrated angular neutron yield of W target at 53 MeV agrees with PHITS calculations within 20 to 23%. Hence, the INCL model adopted in PHITS is capable to predict the actual primary neutron yield.

On the other hand, experiment with a test moderator assembly shows a significant attenuation of fast neutrons. This proves the moderating effects of the test assembly. Further work after this is to determine better statistics by PHITS. On top of this, the detector efficiency of EJ270 plastic scintillator will be studied in future for effective comparison with PHITS calculations.

REFERENCES

[1] H. Tanaka, M. Suzuki, S. Masunagaa, Y. Kinashi, G. Kashino, Y. Liu, T. Mitsumoto, S. Yajima, H. Tsutsui, A. Maruhashi, K. Ono, "Characteristics comparison between a cyclotron-based neutron source and KUR-HWNIF for boron neutron capture therapy," Nuclear Instruments and Methods in Physics Research B, vol. 267 pp. 1970–1977, 2009.

[2] A. Masuda, Matsumoto, T., Takada, K., Onishi, T., Kotaki, K., Sugimoto, H., Kumada, H., Harano, H., & Sakae, T. , "Neutron spectral fluence measurements using a Bonner sphere spectrometer in the development of the iBNCT accelerator-based neutron source," Applied radiation and isotopes, vol. 127, pp. 47-51, 2017.

[3] M. Suzuki, O. Suzuki, Y. Sakurai, H. Tanaka, N. Kondo, Y. Kinashi, et al., "Reirradiation for locally recurrent lung cancer in the chest wall with boron neutron capture therapy (BNCT)," International Cancer Conference Journal, vol. 1, pp. 235-238, October 01 2012.

[4] Aihara T, Kamitani N, Kumada H, Ono K, Hiratsuka J, Harada T., "BNCT for advanced or recurrent head and neck cancer," Applied Radiation and Isotopes, vol. 88, pp. 12-15, 2014.

[5] H. W. Koay, H. Toki, R. Seki, H. Kanda, T. Yorita, "Feasibility study of compact accelerator-based neutron generator for multi-port BNCT system," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 899, pp. 65-72, 2018.

[6] T. Sato, N. Matsuda, S. Hashimoto, Y. Iwamoto, S. Noda, T. Ogawa, H. Iwase, H. Nakashima, T. Fukahori, K. Okumura, T. Kai, S. Chiba, T. Furuta and L. Sihver, "Particle and Heavy Ion Transport Code System PHITS, Version 2.87," J. Nucl. Sci. Technol. , vol. 50, pp. 913-923, 2013.

[7] K. Shibata, T. Nakagawa, N. Iwamoto, A. Ichihara, S. Kunieda, S. Chiba, K. Furutaka, N. Otuka, T. Ohsawa, T. Murata, H. Matsunobu, A. Zukeran, S. Kamada, and J. Katakura, "JENDL-4.0: A New Library for Nuclear Science and Engineering," in J. Nucl. Sci. Technol. vol. 48, ed, 2011, pp. 1-30.

[8] A. Boudard, Cugnon, J., David, J.C., Leray, S. and Mancusi, D., "New potentialities of the Liege intranuclear cascade model for reactions induced by nucleons and light charged particles. ," Physical Review C, vol. 87, p. 014606, 2013.