DOI: 10.15669/pnst.4.327

Progress in Nuclear Science and Technology
Volume 4 (2014) pp. 327-331

ARTICLE

Shielding benchmark experiment using hundreds of MeV quasi-monoenergetic neutron source by a large organic scintillator

Masayuki Hagiwara[a*], Hiroshi Iwase[a], Yosuke Iwamoto[b], Daiki Satoh[b], Tetsuro Matsumoto[c], Akihiko Masuda[c], Hiroshi Yashima[d], Yoshihiro Nakane[b], Hiroshi Nakashima[b], Yukio Sakamoto[b], Atsushi Tamii[e], Kichiji Hatanaka[e] and Takashi Nakamura[f]

[a]High Energy Accelerator Research Organization, 1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305-0801, Japan; [b]Japan Atomic Energy Agency, 2-4 Shirakata, Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195, Japan; [c]National Institute of Advanced Industrial Science and Technology, 1-1-1 Higashi, Tsukuba-shi, Ibaraki-ken, 305-8561, Japan; [d]Research Reactor Institute, Kyoto University, 2-1010 Asashiro-nishi,Kumatori-cho, Sennan-gun, Osaka-hu, 590-0494, Japan; [e]Research Center for Nuclear Physics,10-1 Mihogaoka, Ibaraki-shi, Osaka-hu. 567-0047, Japan; [f]Shimizu Corporation,4-17, Etchujima 3-Chome, Koto-ku, Tokyo-to, 135-8530, Japan

A shielding benchmark experiment has been performed using a quasi-monoenergetic ^{7}Li(p,n) neutron source with 246 and 389 MeV protons at the Research Center for Nuclear Physics (RCNP) of Osaka University, in order to investigate the accuracy of nuclear data libraries and calculation codes for hundreds of MeV neutrons. Time-of-flight and energy spectra behind bulk shields of 10- to 100-cm-thick iron, 25- to 300-cm-thick concrete and their composite are measured using a NE213 organic liquid scintillator with a diameter and thickness of 25.4 cm each. A time-of-flight and an unfolding method are applied to obtain the energy spectra transmitted through the shields for the peak energy region and continuous energy region, respectively. The simulations with the PHITS code coupled with the JENDL-HE nuclear data library are performed for comparison with the measured data. The measured attenuation lengths of peak neutrons with energies of 244 and 387 MeV are in good agreement with the calculation result by the PHITS code within 6 %.

Keywords: quasi-monoenergetic neutron; hundreds of MeV; neutron energy spectrum; time-of-flight; unfolding

1. Introduction

In recent years, accelerators have been used for various purposes of not only research fields on fundamental sciences such as nuclear physics, material and life science but also industrial and medical applications. The developments of recent accelerator technologies are rapidly increasing the maximum energies and intensities that can be supplied. In high-energy accelerator facilities, the shielding of high-energy neutrons is of prime importance for keeping the radiation level of the working area and surrounding environment below the dose limits determined by law and the facilities. Adequate shielding designs are necessary for safety of radiation workers as well as saving of the building costs.

The shielding benchmark experiment using the p-^{7}Li quasi-monoenergetic neutron sources have been performed for 40 and 65 MeV in Takasaki Ion Accelerators for Advanced Radiation Application (TIARA), Japan Atomic Research Agency [1] and for 137 MeV in the Research Center for Nuclear Physics (RCNP), Osaka University, Japan [2, 3], because the data are very useful to investigate the attenuation length of monoenergetic neutrons and the accuracy of nuclear data libraries and nuclear reaction models implemented in the simulation codes used for the shielding designs of accelerator facilities. We have developed the irradiation field of p-^{7}Li quasi-monoenergetic neutron sources with the peak energies of hundreds of MeV in RCNP [2, 4]. In the previous study [2], we measured the neuron spectra in time and energy behind iron and concrete shields with several thicknesses from 10- to 200-cm using a p-^{7}Li quasi-monoenergetic neutron source with the peak energy of 137 MeV, using a NE213 scintillator of 12.7-cm in diameter and 12.7-cm in thickness. The measured spectra behind the shields and attenuation lengths of the peak neutrons showed excellent agreement with simulations by the PHITS code [5] coupled with JENDL-HE data library [6] and the MCNPX code with LA-150 data library [7]).

In this study, we have extended the benchmark experiment to higher energies with the p-^{7}Li quasi-monoenergetic neutron sources with the peak energies of 244 and 387 MeV. The spectra transmitted through the iron, concrete and their composite shield with thickness from 10- to 300-cm were measured with

*Corresponding author. Email: masayuki.hagiwara@kek.jp

a TOF and an unfolding method. The measured data are compared with calculation results by the PHITS code coupled with the JENDL-HE data library in the TOF and energy spectra and the attenuation length of peak neutrons.

2. Experiment and analysis

2.1. Experimental facility and setup

The experiment was performed at the neutron time-of-flight beam course in RCNP. **Figure 1** illustrates the experimental setup used in this study. Proton beams of 246 and 389 MeV extracted from the ring cyclotron were transported to the experimental room and hit a 1.0-cm-thick ^{nat}Li target installed in a vacuum chamber. The energy loss of protons in the target was 0.87 and 0.67 MeV for 246 and 389 MeV, respectively. Protons passing through the target were bended towards the beam dump by the swinger magnet to measure the proton beam intensity with a Faraday cup. The intensity of proton beam was also monitored with a plastic scintillator by counting protons scattered from a thin (100 μm) plastic film set in front of the Li target, if the beam intensity was lower than 50 nA. Neutrons produced at 0-degree from the target were extracted into the TOF tunnel through a 150-cm-thick iron collimator with 10 × 12 cm aperture embedded in a 150-cm-thick concrete wall located 4.5 m away from the target, while charged particles were rejected by a vertical bending magnet located in the collimator. The neutron beam size was 30 × 36 cm at 18 m from the target, which was determined by the 10 × 12 cm aperture. The yield and energy of the peak neutrons are $(1.11 \pm 0.17) \times 10^{10}$ $sr^{-1}\cdot\mu C^{-1}$ and 244 MeV, respectively, for the 246 MeV proton incidences and are $(0.96 \pm 0.15) \times 10^{10}$ $sr^{-1}\cdot\mu C^{-1}$ and 387 MeV, respectively, for the 389 MeV proton incidences. The ratios of the peak neutron yield to the yield in continuous region are 0.5 and 0.4 for 246 and 389 MeV, respectively. The details of the p-^{7}Li quasi-monoenergetic source neutrons were described in Ref. 4.

We used 118 × 118 × 10 cm-thick iron blocks and 120 × 120 × 25 cm-thick concrete blocks as shielding materials. In the shielding experiments, these blocks were assembled with thickness from 10 to 100 cm for the iron shield, from 25 to 300 cm for the concrete shield and for the composite shield, 70 cm-thick iron before 200 cm-thick concrete were used. The shielding assemblies were placed ~18 m away from the target. The density of the iron and concrete used in this experiment was 7.87 and 2.33 $g\cdot cm^{-3}$, respectively, and the atomic compositions of the concrete are listed in Ref. 3.

2.2. Measurement of neutron spectra behind shields

We used a large NE213 scintillator of 25.4 cm in diameter and 25.4 cm in thickness for the neutron detector [8], because the NE213 can stop recoil proton up to 180 MeV and therefore has good energy resolution for high energy neutrons. The NE213 was placed on the neutron beam axis in contact with the back surface of the shields. The distance between the target and the NE213 were changed from 18 m to 21 m with increasing the thickness of the shields. The proton beam was used of intensity between 1 nA to 1 μA. The data taking system was the same as that used in the previous measurements [2, 4].

In order to deduce the energy spectra of neutrons transmitted through the shields, we applied a time-of-flight (TOF) method and an unfolding method based on the FORIST code [2] for the peak energy region and the continuous energy region, respectively, because it was difficult to obtain the energy spectra by the unfolding method alone due to oscillation caused by the sharp monoenergetic peak of the p-^{7}Li neutron source and the poor accuracy of responses for high-energy neutrons above 180 MeV which is the upper energy that recoil protons can be stopped in the detector and deposit their full energy. Thus, we separately analyzed the energy spectra for the peak energy region and the continuous energy region using the TOF and unfolding method, respectively. The TOF method was applied above the boundary of the times corresponding to 231 and 361 MeV in the TOF spectra for the incident proton energies of 246 MeV and 389 MeV, respectively. In order to deduce the energy spectra including the scattered neutrons for the TOF peak region, we used the relation between the TOF and the energy spectra calculated by the PHITS code. The energy spectra for the TOF peak region were normalized with the measured fluence of the TOF peak region considering the detector efficiency on the calculated energy spectra. The energy spectra for the continuous energy region were deduced by the FORIST unfolding code coupled with the response matrix which was prepared by the calculation with the SCINFUL-QMD code [9] based on the measured response data [8]. The energy spectra separately analyzed for the two TOF regions (peak and continuous region) were combined by summing them in each energy bin. The details of this technique are described in the Ref. 2. The energy calibration of the light output was performed using the Compton edge of 4.43 MeV γ rays from ^{241}Am-Be source and the recoiled proton edges. The proton energy was converted to electron energy of the equivalent light output (MeVee) by using the calibration value from Ref. 9.

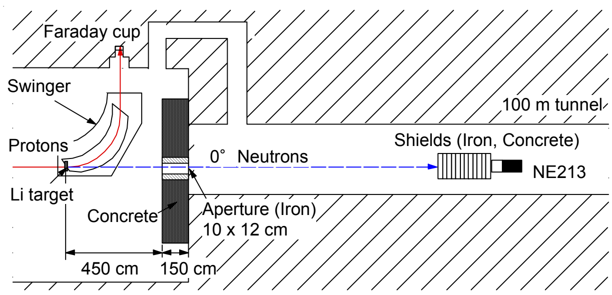

Figure 1. Illustration of the experimental setup used in this study.

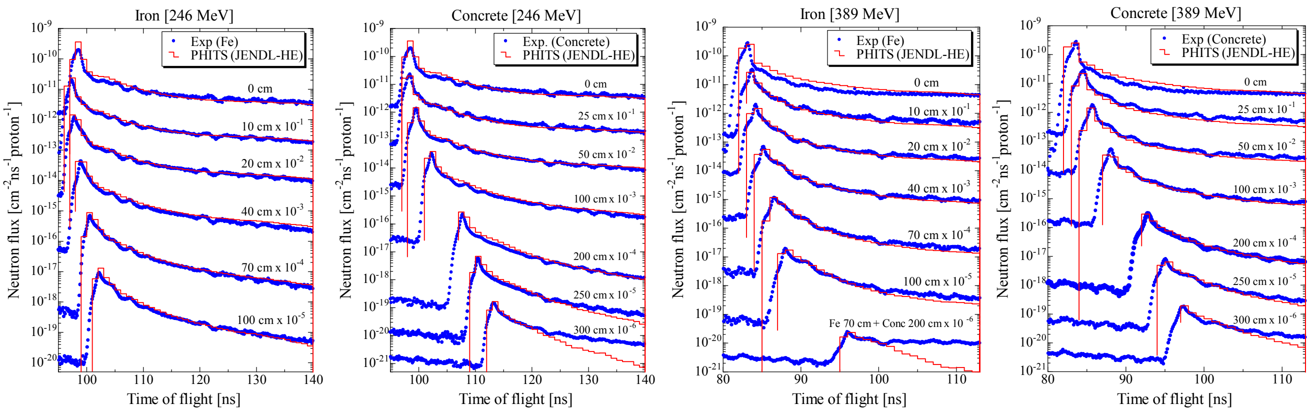

Figure 2. Comparison of the neutron TOF spectra transmitted through the iron, concrete and their composite shield with various thicknesses for the 246 and 389 MeV p-^{nat}Li quasi-monoenergetic neutrons between experiment (indicated by symbols) and a simple calculation by the PHITS code (indicated by lines).

3. Results and discussion

3.1. TOF spectra

The measured TOF spectra of neutrons transmitted through the iron, concrete and their composite shield with various thicknesses are shown together with the results of the PHITS calculation in **Figure 2**. The TOF spectra with the light outputs higher than 8.66 MeVee (twice of that of the γ ray from a ^{241}Am-Be source) were obtained in the time range from 80 ns to 140 ns which corresponds to the neutron energies above several tens of MeV. In the PHITS calculation, the measured p-^{7}Li quasi-monoenegetic neutron spectrum at 0-degree and JENDL-HE data library was used as the source term and cross section data for the transport and nuclear reactions of neutrons and protons in the shields, respectively. The emission angles of the source neutrons were determined to be within 3.88 × 10^{-4} sr, which is the angle determined by the 12 × 10 cm aperture. The neutrons with energies higher than 20 MeV were scored with a track length technique in the tally cell placed at the same location and with the same size as the detector used in the experiment. The detection efficiency of the PHITS calculation was assumed to be as 10 % for any neutron energies higher than 20 MeV considering the efficiency curve of NE213 for the light output threshold of 8.66 MeVee. The calculations generally show good agreement with the measured data. The measured TOF spectra, however, show higher values than the calculated spectra in the time above 120 ns in the 246 MeV experiment and 100 ns in the 389 MeV experiment for thick shields (250-cm- to 300-cm-thick concrete and composite). It might be due to neutrons penetrating the collimator wall outside the 12 × 10 cm aperture and/or streaming into the side gap between the shielding materials and the tunnel wall. These effects are not included in this calculation.

3.2. Energy spectra

Figure 3 shows the measured energy spectra of neutrons transmitted through the iron, concrete and their composite shields with energies above 30 MeV, in comparison with the calculation results using the PHITS code coupled with the JENDL-HE data library. For 246 MeV, the experimental spectra are generally in good

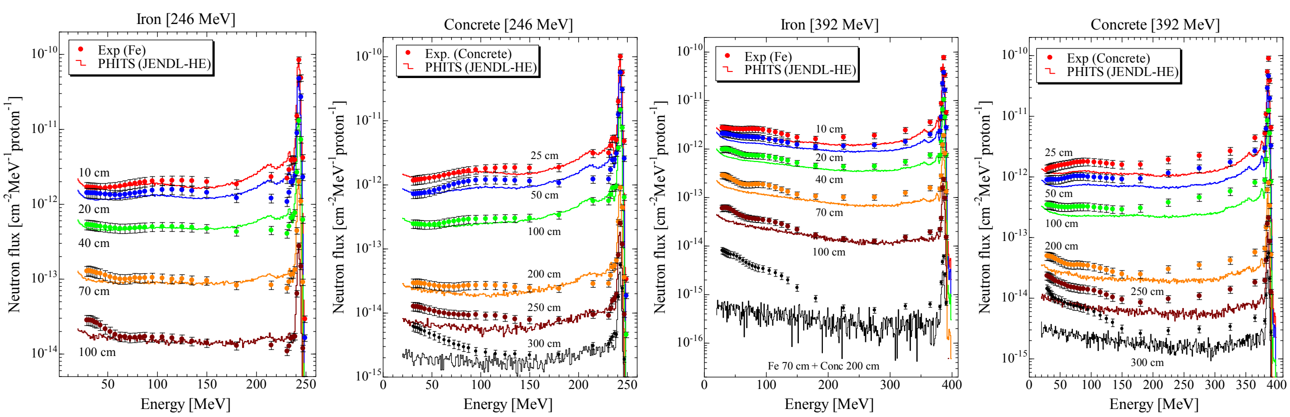

Figure 3. Comparison of the neutron energy spectra transmitted through the iron, concrete and their composite shield with various thicknesses for the 246 and 389 MeV p-^{nat}Li quasi-monoenergetic neutrons between experiment (indicated by symbols) and a simple calculation by the PHITS code (indicated by lines).

agreement with the calculated results. In the low energy region below 150 MeV, however, the measured spectra are larger than the calculation results which show rather flat spectra comparing to the measured data. This difference might come from the difference of the source term and geometry between experiment and calculation as mentioned above. For 389 MeV, the measured data are generally several tens % higher than the calculation results in addition to the difference observed in the low energy region below 150 MeV. This difference might come from counting the charged hadrons (p, $\pi^{\pm}$) produced in the shields. This effect will be checked in the future study and will be corrected.

Figure 4 shows the peak flux attenuation profiles in the iron and concrete shields, and the fitting results with single exponential curves are also given. The measured attenuation length of 244 MeV mono-energetic neutrons is 128.3 g·cm^{-2} for iron, 91.6 g·cm^{-2} for concrete and the calculated attenuation length by the PHITS code is 125.6 g·cm^{-2} for iron, 88.9 g·cm^{-2} for concrete. The measured attenuation length of 387 MeV mono-energetic neutrons is 133.2 g·cm^{-2} for iron, 95.4 g·cm^{-2} for concrete and the calculated attenuation length by the PHITS code is 129.5 g·cm^{-2} for iron, 90.0 g·cm^{-2} for concrete. These attenuation lengths give good agreement between experiment and calculation within 6 %.

4. Conclusion

Neutrons transmitted through 10- to 100-cm-thick iron, 25- to 300-cm-thick concrete and their composite shield (70-cm-iron before 200-cm-concrete) were measured in the TOF and energy spectra with a 25.4 diameter × 25.4 thick NE213 scintillator using the 244 and 387 MeV p-^{7}Li quasi-mono-energetic neutron sources at RCNP. The comparison between the measured and calculated results by the PHITS code coupled with the JENDL-HE data library shows generally good agreement for the 244 MeV neutron source. Quantitative difference between measured and calculated spectra are also observed for thick shields and for the 387 MeV neutron source, due primarily to the simplified source term and geometry used in the calculation and counting of the charged hadrons (p, $\pi^{\pm}$) produced in the shields, respectively. This effect will be corrected in the future study. The attenuation lengths estimated from the well-fitted curves with single exponential form give good agreement between experiment and calculation for both neutron sources within 6 %.

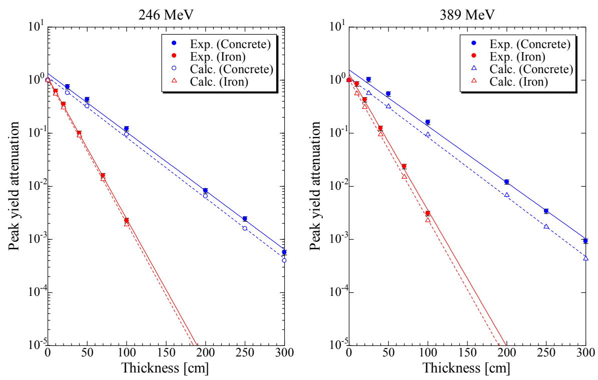

Figure 4. Comparison of the measured and the calculated peak flux attenuation of 244 and 387 MeV neutrons transmitted through the iron and concrete shields as a function of the thickness. The plotted data are given by dividing the peak flux of the source neutron and the data are fitted by a single exponential curve.

References

[1] H. Nakashima, N. Nakao, Sh. Tanaka, T. Nakamura, K. Shin, Su. Tanaka, S. Meigo, Y. Nakane, H. Takada, Y. Sakamoto and M. Baba, Transmission through shields of quasi-monoenergetic neutrons generated by 43- and 68-MeV protons: part II - iron shielding experiment and analysis for investigating calculation methods and cross-section data, *Nucl. Sci. Eng.* 124 (1996), pp. 243-257.

[2] M. Hagiwara, H. Iwase, Y. Kirihara, H. Yashima, Y. Iwamoto, D. Satoh, Y. Nakane, H. Nakashima, T. Nakamura, A. Tamii and K. Hatanaka, Benchmark experiment of neutron penetration through iron and concrete shields for hundreds-of-MeV quasi-monoenergetic neutrons - II: Measurements of neutron spectrum by an organic liquid scintillator, *Nucl. Tech.* 168 (2009), pp. 304-309.

[3] H. Yashima, H. Iwase, M. Hagiwara, Y. Kirihara, S. Taniguchi, H. Yamakawa, K. Oishi, Y. Iwamoto, D. Satoh, Y. Nakane, H. Nakashima, T. Itoga, N. Nakao, T. Nakamura, A. Tamii and K. Hatanaka, Benchmark experiment of neutron penetration through iron and concrete shields for hundreds-of-MeV quasi-monoenergetic neutrons - 1: Measurements of neutron spectrum by a multimoderator spectrometer, *Nucl. Tech.* 168 (2009), pp. 298-303.

[4] Y. Iwamoto, M. Hagiwara, D. Satoh et al., Quasi-monoenergetic neutron energy spectra for 246 and 389 MeV ^{7}Li(p,n) reactions at angles from 0° to 30°, *Nucl. Instr. and Meth. A* 629 (2011), pp. 43-49.

[5] K. Niita, N. Matsuda, Y. Iwamoto, H. Iwase, T. Sato, H. Nakashima, Y. Sakamoto and L. Sihver, *PHITS: Particle and Heavy Ion Transport Code System, Version 2.23*, JAEA-Data/Code, 2010-022, Japan Atomic Energy Agency, (2010).

[6] Y. Watanabe, T. Fukahori, K. Kosako, N. Shigyo, T. Murata, N. Yamano, T. Hino, K. Maki, H. Nakashima, N .Odano and S. Chiba, Nuclear data evaluation for JENDL high-energy file, *Proceedings of International Conference on Nuclear Data for Science and Technology*, Sep. 26–Oct. 1, 2004, Santa Fe, USA, (2005) *AIP*

Conference Proceedings 769, pp. 326-331.
[7] M. B. Chadwick, P. G. Young, S. Chiba, S. C. Frankle, G. M. Hale, H. G. Hughes, A. J. Koning, R. C. Little, R. E. MacFarlane, R. E. Prael and L. S. Waters, Cross-section evaluations to 150 MeV for accelerator-driven systems and implementation in MCNPX, *Nucl. Sci. Eng.* 131 (1999), pp. 293-328.
[8] S. Taniguchi, N. Nakao, T. Nakamura, H. Yashima, Y. Iwamoto, D. Satoh, Y. Nakane, H. Nakashima, T. Itoga, A. Tamii and K. Hatanaka, Development of a quasi-monoenergetic neutron field using the ^{7}Li(p,n)^{7}Be reaction in the energy range from 250 to 390 MeV at RCNP, *Rad. Prot. Dosim.* 126, 1-4 (2007), pp. 23-27.
[9] D. Satoh, T. Sato, N. Shigyo and K. Ishinbashi, *SCINFUL-QMD: Monte Carlo based Computer Code to Calculate Response Function and Detection Efficiency of a Liquid Organic Scintillator for Neutron Energies up to 3 GeV*, JAEA-Data/Code, 2006-023, Japan Atomic Energy Agency, (2006).