Shielding experiments of concrete and iron for the 244 MeV and 387 MeV quasi-monoenergetic neutrons using a Bonner sphere spectrometer (at RCNP, Osaka Univ.)

Tetsuro Matsumoto1,9, Akihiko Masuda1, Jun Nishiyama1,2, Hiroshi Iwase3,4, Yosuke Iwamoto5, Daiki Satoh5, Masayuki Hagiwara3,4, Hiroshi Yashima6, Tatsushi Shima7, Takashi Nakamura8,8, Hideki Harano5, Atsushi Tami7, Kichiji Hatanaka7

1National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan
2Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo, 152-8500 Japan
3High Energy Accelerator Research Organization (KEK), 1-1Oho, Tsukuba, Ibaraki 305-0801, Japan
4Department of Accelerator Science, Graduate University for Advanced Studies (SOKENDAI), 1-1Oho, Tsukuba, Ibaraki 305-0801, Japan
5Japan Atomic Energy Agency (JAEA), 2-4 Shirakata, Tokai, Naka, Ibaraki 319-1195, Japan
6Research Reactor Institute, Kyoto University, 2-1010 Asahi, Kita-in, Kumatori, Sennan, Osaka 590-0494, Japan
7Research Center for Nuclear Physics (RCNP), Osaka University, 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan
8Shimizu Corporation, Etchujima 3-4-17, Koto-ku, Tokyo 135-8530, Japan
9Cyclotron and Radioisotope Center, Tohoku University, 6-3 Aramaki, Aoba, Sendai 980-8578, Japan

Abstract. Neutron energy spectra behind concrete and iron shields were measured for quasi-monoenergetic neutrons above 200 MeV using a Bonner sphere spectrometer (BSS). Quasi-monoenergetic neutrons were produced by the 7Li(p,xn) reaction with 246-MeV and 389-MeV protons. Shielding materials are concrete blocks with thicknesses from 25 cm to 300 cm and iron blocks with thicknesses from 10 cm to 100 cm. The response function of BSS was also measured at neutron energies from 100 MeV to 387 MeV. In data analysis, the measured response function was used and the pinball scattering effect between the BSS and the shielding material was considered. The neutron energy spectra behind the concrete and iron shields were obtained by the unfolding method using the MAXED code. Ambient dose equivalents were obtained as a function of a shield thickness successfully.

1 Introduction

Recently, high-energy and intense beam accelerators, such as the Japan Proton Accelerator Research Complex (J-PARC) are used for various studies and industries. In these facilities, secondary neutrons with energies above 100 MeV are produced around accelerators and beam lines by nucleon-nucleus and nucleus-nucleus reactions. For accurate shielding design of high energy accelerators, experiment data are indispensable to construction of these facilities from the point of view of radiation protection. High-energy neutron penetration data for main shielding materials (concrete and iron) are very important. However, the shielding experimental data for high energy neutrons above 100 MeV are still insufficient both in quality and in quantity as compared with those below 100 MeV [1-3].

In this study, we measured the neutron energy spectra behind concrete and iron shields using a Bonner sphere spectrometer (BSS) for quasi-monoenergetic neutrons produced by the 7Li(p,xn) reaction with 246-MeV and 389-MeV protons at the Research Center for Nuclear Physics (RCNP) of the Osaka University. Moreover, the response function of the BSS was also measured for energy range from 100 MeV to 400 MeV at RCNP. The measured response function of BSS was used in data analysis of the shielding experiments.

2 Experiments

2.1 Shielding experiments

Figure 1 shows a schematic view of a typical experimental arrangement. Shielding experiments were performed at the time-of-flight (TOF) beam course of RCNP. Quasi-monoenergetic neutrons with peak energies of 243.5 MeV and 386.6 MeV were produced by the 7Li(p,xn) reaction by bombarding a 1-cm thick Li

Figure 1. Schematic view of typical experimental arrangement at RCNP.
target with 246-MeV and 389-MeV protons from the AVF cyclotron and the ring cyclotron of RCNP. A the neutron beam emitted in the forward direction was extracted into the TOF room through an iron collimator of 12-cm wide and 10-cm high aperture embedded inside a concrete wall with a thickness of 15 cm. The proton beam penetrated through the target was guided to a beam dump using a beam swinger magnet. Neutron source spectra in the TOF room were measured with liquid scintillators by means of the TOF method [4, 5].

Shielding materials are concrete blocks (2.33 g/cm³) with thicknesses from 25 cm to 300 cm and iron blocks (7.87 g/cm³) with thicknesses from 10 cm to 100 cm. The components of concrete are given in Table 1. The distance between the Li target and upstream surface of the shielding materials was 17.7 m. The BSS was contact with the backward surface of shielding material.

Neutron energy spectra behind the shields were measured with the BSS [6]. The BSS consists of a 3He spherical proportional counter (CENTRONIC LTD, SP9, gas pressure: 21.3 kPa) and polyethylene (PE, 0.95 g/cm³) moderators with diameters from 7.62 cm to 24.1 cm. In addition, measurements were performed using inserting metal shells made of lead (457p: 10.2-cm-diameter PE sphere + 1.27-cm-thick Pb shell + 2.54-cm thick PE shell) and copper (457c: 10.2-cm-diameter PE sphere + 1.27-cm-thick Cu shell + 2.54-cm thick PE shell) [7].

2.2 Response measurements of BSS

The responses of BSS were measured at neutron energies from 100 MeV to 387 MeV in neutron fields of RCNP. The responses for mono-energetic neutrons were evaluated by the two-angle differential measurement method, which was described in detail elsewhere [6]. The responses at neutron energies of 144 keV, 565 keV, 5.0 MeV and 14.8 MeV were also calibrated in the mono-energetic neutron standard fields [10] of the National Institute of Advanced Industrial Science and Technology.

The response function of BSS was also simulated with the MCNPX code [8]. The JENDL-HE[9] file was used in the simulation.

3 Data Analysis and Results

The measured and the calculated response results of BSS are in good agreement within measurement uncertainties above 100 MeV for the BSS with the polyethylene moderator. However, there is the difference between the measured and calculated results for the BSS with the Pb or Cu shell. The measured responses were reflected in data analysis of shielding experiments. The BSS was contacted with the surface of shielding block, actual response functions were affected by the neutron multi-scattering effect between the moderator of BSS and the shielding block, called ping-pong effect. The response function with the ping pong effect was also evaluated with the MCNPX code. The response function including the ping-pong effect was used in the data analysis to obtain more precise results.

Neutron energy spectra behind the shields were obtained by unfolding method using the MAXED code [11]. From the neutron energy spectra with the BSS, the ambient dose equivalent was obtained using conversion coefficients based on the International Commission on Radiological Protection recommendations in 1990 [12, 13]. Figure 2 shows results of neutron ambient dose equivalent per proton beam charge for the 244 MeV experiment of the concrete shielding. Figure 2 shows the results obtained using the response function of BSS with and without the ping pong effect.

In the shielding experiments, other measurements with a 25.4-cm-diameter and 25.4-cm-thick NE213 scintillator were also performed. The final results of neutron ambient dose equivalents and the attenuation length will be obtained after comparing with the experimental data obtained by the NE213 scintillator in fast energy region and calculated results in all energy region.

![Figure 2](image-url) Ambient dose equivalents as a function of the concrete shield. The results were obtained using the response function with and without the ping pong effect.

References

1. T. Ishikawa, Y. Miyama and T. Nakamura, Neutron penetration through iron and concrete shields with the use of 22.0- and 32.5-MeV quasi-monoenergetic sources, Nucl. Sci. Eng. 116, 278 (1994).
2. N. Nakao, H. Nakashima, T. Nakamura, S. Tanaka, S. Tanak, K. Shin, M. Baba, Y. Sakamoto and Y. Nakane, Transmission through shields of quasi-monoenergetic neutrons generated by 43- and 68-MeV protons – I: Concrete shielding experiment and calculation for practical application, Nucl. Sci. Eng. 124, 228 (1996).
3. H. Yashima, H. Iwase, M. Hagiwara, Y. Kirihiara, S. Taniguchi, H. Yamakawa, K. Oishl, 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 – I: Measurements of neutron spectrum by a multimoderator spectrometer, Nucl. Technol. 168, 298 (2009).
4. Y. Iwamoto, M. Hagiwara, D. Satoh, H. Iwase, H. Yashima, T. Itoga, T. Sato, Y. Nakane, H. Nakashima, Y. Sakamoto, T. Matsumoto, A. Masuda, J. Nishiyama, A. Tamii, K. Hatanaka, C. Theis, E. Feldbaumer, L. Jaegerhofer, C. Pioch, V. Mares and T. Nakamura, Quasi-monoenergetic neutron energy spectra for 246 and 389 MeV $^7$Li(p,n) reactions at angles from 0 to 30, Nucl. Instr. Methods A 629, 43 (2011).

5. Y. Iwamoto, M. Hagiwara, D. Satoh, S. Araki, H. Yashima, T. Sato, A. Masuda, T. Matsumoto, N. Nakao, T. Shima, T. Kin, Y. Watanabe, H. Iwase, T. Nakamura, Nuclear Instrument and Methods A 804, 50 (2015).

6. A. Masuda, T. Matsumoto, H. Harano, J. Nishiyama, Y. Iwamoto, M. Hagiwara, D. Satoh, H. Iwase, H. Yashima, T. Nakamura, T. Sato, T. Itoga, Y. Nakane, H. Nakashima, Y. Sakamoto, C. Theis, E. Feldbaumer, L. Jaegerhofer, C. Pioch, V. Mares, A. Tamii and K. Hatanaka, Response measurement of a Bonner sphere spectrometer for high-energy neutrons, IEEE trans. Nucl. Sci. 59 (1), 161 (2012).

7. B. Weigel and A. V. Alevra, NEMUS – the PTB Neutron Multisphere Spectrometer: Bonner sphere and more, Nucl. Inst. Meth. A 476, 36 (2002).

8. D. B. Pelowitz, MCNPX use’s manual Ver 2.5.0, Los Alamos National Laboratory, LA-CP-05-0369 (2005).

9. Y. Watanabe, K. Kosako, S. Kunieda, S. Chiba, R. Fujimoto, H. Harada, M. Kawai, F. Maekawa, T. Murata, H. Nakashima, K. Niita, N. Shigyo, S. Shimakawa and N. Yamano, Status of JENDL High Energy File, J. Korean Physical Society 59 (2), 1046 (2011).

10. H. Harano, T. Matsumoto, Y. Tanimura, Y. Shikaze, M. Baba and T. Nakamura, Monoenergetic and quasi-monoenergetic neutron reference fields in Japan, Radiat. Meas. 45, 1076 (2010).

11. M. Reginatto, P. Goldhagen and S. Neumann, Spectrum unfolding, sensitivity analysis and propagation of uncertainties with the maximum entropy deconvolution code MAXED, Nucl. Inst. Methods A 476, 242 (2002).

12. 1990 Recommendations of the International Commission on Radiological Protection, ICRP Publication 60, International Commission on Radiological Protection (1991).

13. T. Sato, A. Endo, M. Zankl, N. Petoussi-Henss, H. Yasuda and K. Niita, Fluence-to-dose conversion coefficients for aircrew dosimetry based on the new ICRP Recommendations, Prog. Nucl. Sci. Technol. 1, 134 (2011).