I-1. PROJECT RESEARCHES

Project 9

Sophistication of radiation detectors aimed at application in accelerator BNCT

H. Tanaka

Institute for Integrated Radiation and Nuclear Science, Kyoto University

BACKGROUNDS AND PURPOSE: Insurance treatment using the accelerator BNCT system has been started at medical institutions, and the number of BNCT cases is expected to increase in the future. As a quality assurance and quality control for treatment, it is required to measure thermal neutron flux and gamma dose before irradiation, and the gold activation method and thermoluminescence dosimeters used in reactor BNCT have been followed. The method is complicated and thermoluminescence dosimeters will not be available in the future, and medical institutions are hoping for a simple and highly accurate measurement method.

In addition, there is a growing need for research and development of radiation detectors related to BNCT, such as epithermal and fast neutron flux, prompt gamma rays, and neutron energy spectrum. Therefore, the objective of this project is to upgrade radiation detectors for application in accelerator BNCT.

RESEARCH SUBJECTS:

R5P9-1: Measurements of Neutron Fluence and Gamma ray Distribution using Thermoluminescence Slabs(K. Shinsho *et al.*)

R5P9-2: Comparison of optical observation of boron dose distributions using different types of boron-added liquid scintillators(A. Nohtomi *et al.*)

R5P9-3: Development and Demonstration of a Bonner Sphere Spectrometer for Intense Neutron Measurements(A. Masuda *et al.)*

R5P9-4: Study on neutron monitor using Li glass scintillator and gamma-ray measurement system for BNCT(S. Yoshihashi *et al.*)

R5P9-5: Establishment of Characterization Estimation Method in BNCT Irradiation Field using Bonner Sphere and Ionization Chamber (VII)(Y. Sakurai *et al.*)

R5P9-6: Development of Real-time Boron-concentration Estimation Method using Gamma-ray Telescope System for BNCT (II)(Y. Sakurai *et. al,*)

R5P9-7: Experimental Investigation of A Real-time Epi-thermal Neutron Absolute Flux Intensity Monitor Using Scintillation Detectors (I. Murata *et al.*)

R5P9-8: Neutron Image Sensor for Boron Neutron Capture Therapy(V. T. Ha *et al.*)

R5P9-9: Improvement of the SOF detector system for energy-dependent discrimination and long-term stability(M. Ishikawa *et al.*)

R5P9-10: Fast Neutron Dosimetry Using Solid-State Nuclear Track Detector for BNCT(T. Takata *et al.*)

R5P9-11: Fiber-reading Radiation Monitoring System with an Optical Fiber and Red-emitting Scintillator at the ^{60}Co Radiation Facility and KUR(S. Kurosawa *et al.*)

R5P9-12: Improvement To Increase Accuracy of Absolute Fast Neutron Flux Intensity Monitor for BNCT(I. Murata *et al.)*

R5P9-13: Study on Hybrid Radiation Detector for BNCT(N. Matsubayashi *et al.*)

R5P9-14: Measurement of Thermal Neutron-Induced Soft Error Rates in Semiconductor Memories(H. Tanaka *et al.*)

Research subjects R5P9-1,10, and 12 are research and development on methods to measure thermal and fast neutrons and γ-rays. R5P9-2 and 6 propose methods to obtain boron distributions in real-time. R5P9-3,5, and 9 propose new methods for measuring neutron spectra. R5P9- 4, 7, 8, 11,13 have succeeded in obtaining real-time measurements of gamma rays, thermal and epithermal neutrons in the irradiation field of BNCT. All of them are expected to be applied to accelerator BNCT.

PR9-1

Measurements of Neutron Fluence and Gamma ray Distribution using Thermoluminescence Slabs

K. Shinsho, E. Sasaki, M.Kawane, H. Tanaka[1], T. Takata[1], S. Matsumoto, G. Wakabayashi[2], G. Okada[3], Y. Koba[4]

Graduate School of Human Health Science, Tokyo Metropolitan University
[1] Research Reactor Institute, Kyoto University
[2] Graduate school of Science and Engineering Research, Kindai University
[3]Co-creative Research Center of Industrial Science and Technology, Kanazawa Institute of Technology
[4]Center for Radiation Protection Knowledge, QST-NIRS

INTRODUCTION: Boron Neutron Capture Therapy (BNCT) is one of the radiation therapies using neutrons and ^{10}B drugs which are attracted to tumors. BNCT is expected to be next-generation cancer therapy which will improve the QOL of patient because it is able to irradiate a cancer cell at the molecular level selectively. However, dosimetry techniques in mixed neutron-gamma fields have not been established yet. Therefore, we focused on neutron and gamma ray measurements using two- dimensional thermoluminescence dosimeter (2D-TLD). We have reported that the thermoluminescence (TL) of a Cr-doped Al_2O_3 ceramic plate sandwiched between Cd plates can selectively measure only the thermal neutron fluence at the BNCT irradiation field without being affected by mixed γ-rays [1,2], and that the TL characteristics of a high thermal conductivity type BeO ceramic plate (Na undoped BeO ceramic plate) can be used to selectively measure the γ-ray fluence at the BNCT irradiation field without being affected by neutrons [2,3]. In this study, we will clarify the mechanism by which these techniques can selectively measure the objective radiation and establish a method to measure neutron fluence distribution selectively and accurately and γ dose distribution with high spatial resolution in a BNCT irradiation field.

EXPERIMENTS: A large-area TL distribution measurement system (Fig.1) was developed to measure γ-ray dose distribution in BNCT irradiation field. 114 mm square BeO ceramic plates were used.

RESULTS: Figure 2 shows the γ-ray dose distribution using the TL characteristics of 114 mm square BeO ceramics. The γ dose was obtained with a spatial resolution of 50 μm/pixel. However, optimization of correction methods for higher accuracy, such as two-dimensional sensitivity correction, flatness correction, and conversion to dose, has not been done. In particular, due to the low sensitivity, it is necessary to work on improving sensitivity and accuracy, including consideration of γ dose measurement using pre-irradiation and OSL characteristics.

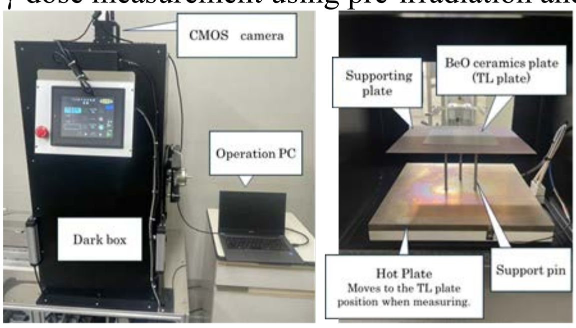

Fig.1. A large-area TL distribution measurement system

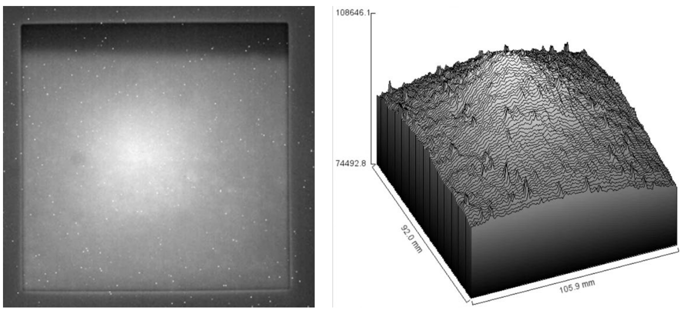

Fig.2. TL distribution (γ dose distribution) with 114 mm square BeO ceramic plates without correction

REFERENCES:

[1] R. Oh, K. Shinsho *et al.*, Sens. and Mater., **33(6)** (2021) 2129-213.
[2] K. Shinsho *et al.*, Jpn. J. Appl. Phys., **62** (2023) 010502.
[3] M.Tanaka, K. Shinsho *et al.*, J. Mater. Sci.: Mate. Elec., **33** (2022) 20271–20279.

Comparison of optical observation of boron dose distributions using different types of boron-added liquid scintillators

A. Nohtomi, H. Maeda, T. Yamane, Y. Kojima, G. Wakabayashi[1], Y. Sakurai[2], H. Tanaka[2] and T. Takata[2]

Graduate School of Medicine, Kyushu University
[1]Atomic Energy Research Institute, Kindai University
[2]Institute for Integrated Radiation and Nuclear Science, Kyoto University

INTRODUCTION: For boron-neutron capture therapy (BNCT), the information of boron dose distribution plays a significant role. In our previous work [1], a boron-added liquid scintillator has been proved to be very useful for the direct evaluation of boron dose distribution by observing the luminescence with a CCD camera during the neutron irradiation. In that work, as an attempt, we dissolved trimethyl borate in a commercially-available liquid scintillator, Insta-Gel Plus, approximately 1 wt%. However, other types of liquid scintillators have not been examined yet. In the present work, in addition to the Insta-Gel Plus, another two types of commercially-available liquid scintillators were examined as boron-added liquid scintillator for comparison.

EXPERIMENTS: We dissolved trimethyl borate in three types of commercially-available liquid scintillator (Insta-Gel Plus, Ultima Gold XR and Ultima Gold F: Perkin Elmer) approximately 1 wt% in natural boron concentration. The main component of Insta-Gel Plus is pseudocumene with a certain amount of addition of alkylphenol polyglycol ether as emulsifier. The main component of Ultima Gold XR is diisopropyl naphthalene isomers with a certain amount of addition of alkylphenol polyglycol ether as emulsifier. On the other hand, Ultima Gold F is made of almost diisopropyl naphthalene isomers solely. The boron-added liquid scintillator was filled in a quartz bottle phantom and was irradiated by thermal neutrons (~10^5 n/cm^2/s) during 150, 300 and 600 seconds at E-3 irradiation port [2]. Luminescence of each boron-added liquid scintillator was observed by a cooled CMOS camera (Bitran, CS-67M) during the irradiation in a black box.

RESULTS: The luminescence distributions were clearly observed for all types of boron-added liquid scintillators for 600 seconds irradiation. The luminance was proportional to the irradiation time as indicated in Fig. 1 for all types of boron-added liquid scintillators. However, the luminance was different for each type of liquid scintillator. The luminescence of Ultima Gold F was the brightest among the three and approximately 1.6 times higher than that of Insta-Gel Plus. The luminescence of Ultima Gold XR was approximately 82 % of that of Insta-Gel Plus.

From the facts mentioned above, it has been revealed that the image quality of boron dose distribution will be able to be improved by the optimization of choice of liquid scintillator without emulsifier.

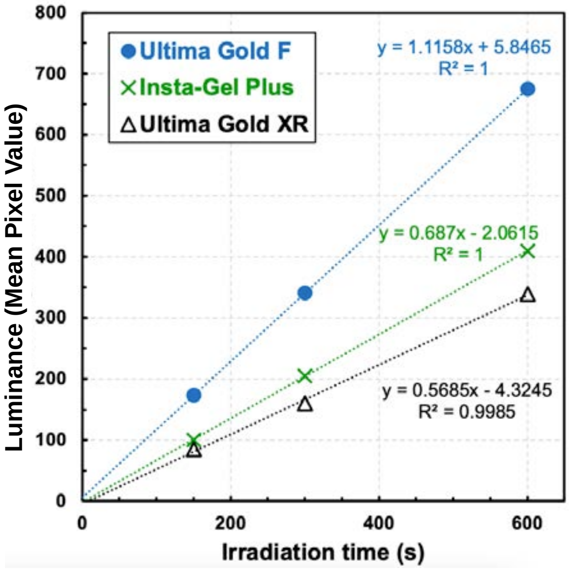

Fig. 1. Luminance value for different types of boron-added liquid scintillators as a function of neutron irradiation time.

REFERENCES:

[1] A. Nohtomi *et al.*, Radiol. Phys. Technol., **15** (2022) 37-44.
[2] T. Kobayashi and, K. Kanda. Nucl. Instrum. Meth., **204** (1983) 525-531.

Development and Demonstration of a Bonner Sphere Spectrometer for Intense Neutron Measurements

A. Masuda, T. Matsumoto, S. Manabe, K. Watanabe[1], A. Ishikawa[2], H. Tanaka[3], Y. Sakurai[3], H. Harano, T. Takata[3], A. Uritani[4] and H. Kumada[5]

National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology
[1]Graduate School of Engineering, Kyushu University
[2]Nuclear Science Research Institute, Japan Atomic Energy Agency
[3]Institute for Integrated Radiation and Nuclear Science, Kyoto University
[4]Graduate School of Engineering, Nagoya University
[5]Proton Medical Research Center, University of Tsukuba

INTRODUCTION: Neutron spectral fluence measurement techniques are required in boron neutron capture therapy (BNCT). Bonner sphere spectrometer (BSS) is one of the best known and proven solutions [1]. A BSS for intense neutron beams is developed in this study. A small lithium-glass scintillator is adopted to the Bonner sphere detectors to accommodate the neutron intensity of 10^9 cm^{-2} s^{-1}. Demonstration measurements of the assembled BSS were performed at the Kyoto University Research Reactor (KUR).

EXPERIMENTS: The Bonner sphere detectors with the small lithium-glass scintillator coupled with an optical fiber [2] and a photomultiplier (PMT, Hamamatsu R9880U-21) were set and irradiated by the standard mixed neutrons in rotation at the measurement position of the heavy water irradiation facility of the KUR [3]. Diameter of HDPE moderators for BSS were 3”, 3.5”, 4”, 4.5”, 5”, 6”, 7” and 8”. Output signals from PMT were processed using a preamplifier (ORTEC 113) and a signal processing and acquisition system (Amptek PX5).

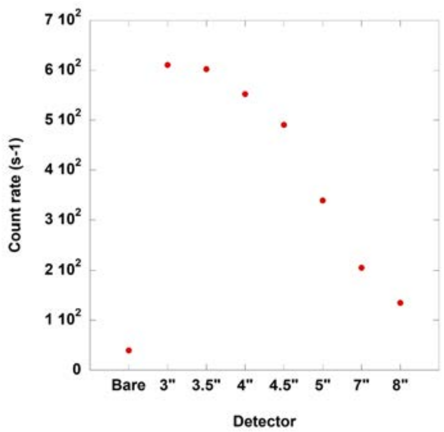

Fig. 1. Results of Bonner sphere measurements.

RESULTS: The results of the measurements are shown in Fig. 1. A reasonable dependence of the count rate on the detector is observed. Response functions of the developed BSS are shown in Fig. 2, that were calculated by Monte Carlo simulations using MCNP 6.2. The statistical fluctuations will be resolved by improving statistics. The neutron spectral fluence will be derived from the measurement results and improved response functions.

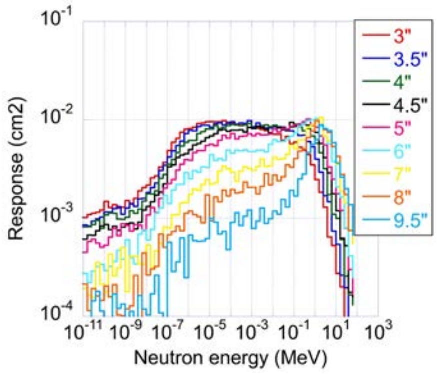

Fig. 2. Calculated response functions of Bonner spheres.

REFERENCES:

[1] A. Masuda *et al.,* Appl. Radiat. Isot., **127** (2017) 47-51.
[2] A. Ishikawa *et al.,* Sensors and Materials, **32** (2020) 1489-1495.
[3] Y. Sakurai and T. Kobayashi, Nucl. Instrum. Meth-ods Phys. Res. A, **453** (2000) 569-596.

This study is supported by Grant-in-Aid for Scientific Research, Japan Society for the Promotion of Science (JSPS KAKENHI Grant Number JP22K12667).

Study on neutron monitor using Li glass scintillator and gamma-ray measurement system for BNCT

S. Yoshihashi, K.Watanabe[1], A. Uritani, A. Yamazaki, I. Suzuki, T. Fukutomi, K. Tsuchimoto, Y. Oshima[1], S. Hasegawa[1], Y. Sakurai[2] and H. Tanaka[2]

Graduate School of Science, Kyoto University
[1]Graduate School of Engineering, Kyushu University
[2]Institute for Integrated Radiation and Nuclear Science, Kyoto University

INTRODUCTION: Boron neutron capture therapy (BNCT) is one of the radiotherapies. This is a combined modality of radiotherapy and chemotherapy for cancer treatment. Recently, an accelerator-driven neutron source has actively been developed instead of nuclear reactors, owing to its simplicity of management. It is important to characterize an irradiation field of BNCT facility.
In this study, we are developing a novel neutron detector using an optical fiber. So far, in order to realize the optical fiber type neutron detector showing a neutron peak in the pulse height spectrum, bright neutron scintillators, such as Eu:$LiCaAlF_6$ or LiF/Eu:CaF_2 eutectics, have been used [1]. Recently, we attempted to replace them with the faster Li glass scintillator [2]. For both cases, we have never controlled a shape of scintillators because the scintillator size has been too small. Since they had random shapes, the Monte-Carlo simulation-based study was difficult to be conducted. To evaluate the accurate detector response, the scintillator shape is required to be controlled. We proposed that a transparent composite Li glass scintillator, in which fine Li glass scintillator powder and resin are mixed. This type of scintillator is expected to be easily shaped because it is a resin-based material. In this study, we fabricate the optical fiber type neutron detector using the transparent composite Li glass scintillator and evaluate its response to thermal neutron irradiation.

EXPERIMENTS: We fabricated the optical fiber type neutron detectors using the transparent composite Li glass scintillator. First, fine powder of the Li glass and UV curable resin were mixed. The mixed resin was attached on a tip of an optical fiber using PC controlled fabrication system to control the attached resin amount. The resin was spontaneously shaped to a hemispherical shape by surface tension. And then, the mixed resin was irradiated with UV light to solidify it. The two fabricated detectors were irradiated with thermal neutron.

RESULTS: Figure 1 shows the signal pulse height spectra obtained from the two fabricated optical-fiber-based neutron detectors when they were irradiated with thermal neutron. The fabricated optical fiber type neutron detector shows a clear neutron peak in the signal pulse height spectrum. In addition, both detectors show almost the same response. By using the PC controlled fabrication system, we can control the attached amount of the mixed compound resin on a tip of an optical fiber.

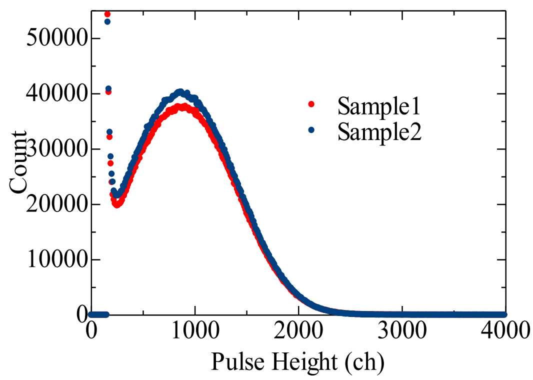

Fig. 1. Pulse height spectra obtained from the two fabricated optical-fiber-based neutron detectors. They were fabricated using the PC controlled fabrication system.

REFERENCES:

[1] K. Watanabe *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. A., **802** (2015) 1-4.
[2] A.1 Ishikawa *et al.*, Sensors and Materials, **32** (2020) 1489-1495.

Establishment of Characterization Estimation Method in BNCT Irradiation Field using Bonner Sphere and Ionization Chamber (VII)

Y. Sakurai, J. Prateepkaew[1], R. Narita[1], T. Takata and H. Tanaka

Institute for Integrated Radiation and Nuclear Science, Kyoto University
[1]Graduate School of Engineering, Kyoto University

INTRODUCTION: Development in accelerator-based irradiation systems for BNCT is underway. BNCT using newly developed accelerator systems is being implemented at multiple facilities around the world. Considering this situation, it is important that the estimations for dose quantity and quality are performed consistently among several irradiation fields, and that the equivalency of BNCT is guaranteed, within and across BNCT systems. Then, we are establishing QA/QC system for BNCT. As part of the QA/QC system, we are developing estimation method for neutron energy spectrum using Bonner-sphere technique [1]. In our spectrometer, liquid such as pure water and/or boric acid solution is used as the moderator. A multi-layer case with multiple moderator layers is prepared. The moderator and its thickness are changeable without entering the irradiation room, by the remote supply and drainage of liquid moderator in the several layers. For the detector, activation foils are remotely changed, or online measurement is performed using SOF detector, etc. As a new type of spectrometer, we are developing the Cylindrical Hemisphere Accurate Remote Multilayer Spectrometer (CHARMS) [2]. In 2023, experiments using Simple Multilayer Spectrometer (SMS) were performed at Heavy Water Neutron Irradiation Facility of Kyoto University Reactor (KUR-HWNIF) in order to confirm the effectiveness of CHARMS [3].

MATERIALS AND METHODS: The shape of the SMS is a square, which is easy to prepare. It consists of three-layer acrylic square containers, with external dimensions of each container: 5 cm × 5 cm × 15 cm, 10 cm × 10 cm × 15 cm, and 15 cm × 15 cm × 15 cm. Pure water and boric acid water (^{10}B 0.14%wt) are used as the liquid moderators. The empty layers are also used. Activated foil is chosen as the neutron detector. In this study, bare and cadmium-covered gold foils were used. The response function for SMS and initial guess spectrum were calculated using PHITS 3.33. The MAXED and GRAVEL unfolding codes were used in the spectrum unfolding procedure. Figure 1 shows the experimental setup for SMS measurements at KUR-HWNIF. In this study, the standard epi-thermal neutron irradiation mode was selected.

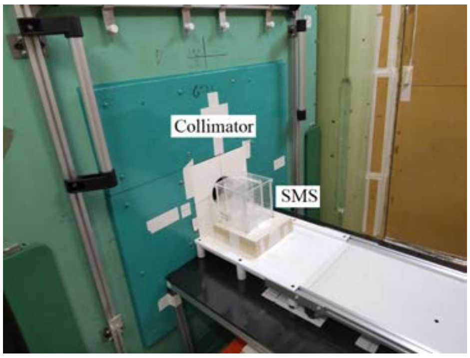

Fig. 1. Experimental setup for SMS measurements at KUR-HWNIF.

RESULTS: The effectiveness of the multi-layer neutron spectrometer with liquid moderators was experimentally confirmed using SMS. The neutron energy spectrum in the epi-thermal neutron irradiation mode of KUR-HWNIF was evaluated with an uncertainty of less than 15% by SMS. It is expected that the use of CHARMS will further reduce the uncertainty in the evaluation of the neutron energy spectrum.

REFERENCES:

[1] S. Shiraishi, *et al.*, Appl. Radiat. Isot. **163** (2020) 109213.
[2] J. Prateepkaew, *et al.*, Nucl. Instr. Meth. A., **1059** (2024) 168948.
[3] Y. Sakurai and T. Kobayashi, Nucl. Instr. Meth., **453** (2000) 569-596.

Development of Real-time Boron-concentration Estimation Method using Gamma-ray Telescope System for BNCT (II)

Y. Sakurai, J. Prateepkaew[1], T. Takata, H. Tanaka and M. Suzuki

Institute for Integrated Radiation and Nuclear Science, Kyoto University
[1]Graduate School of Engineering, Kyoto University

INTRODUCTION: It is important to decide the boron concentrations for tumor and normal parts in the dose estimation for BNCT. The on-line and real-time estimation method for the spatial distribution of boron concentration is expected for the advancement. The information about the boron concentration distribution can be obtained using the prompt gamma-ray analysis (PGA) for the prompt gamma rays from boron-10 (B-10). The improved gamma-ray telescope system is settled at Heavy Water Neutron Irradiation Facility of Kyoto University Reactor (KUR-HWNIF) [1-3]. This system consists of an HPGe semiconductor detector and a collimation system including two lead collimators. The gamma rays through these collimators can be detected, and the telescope view-filed can be changed by moving the two collimators independently. The experimental verification for the ability to distinguish between tumor and normal parts was continued in 2023 as well.

MATERIALS AND METHODS: Figure 1 shows the improved gamma-ray telescope system. A rectangular liquid phantom of 20 cm in width 20 cm in length and 40 cm in depth was used in the experiment. An acrylic hollow sphere with an outer diameter of 5 cm filled with boric acid with a B-10 concentration of 200 ppm was placed as the tumor part inside of the phantom. The phantom liquid was pure water or boric acid water with a B-10 concentration of 25 ppm. The epi-thermal neutron irradiation was performed in an irradiation field with a diameter of 12 cm. The initial position of the center of the tumor sphere was set on the beam axis at the center of the telescope view-field, and was moved to the right from 0 to 6 cm from the viewpoint on the beam aperture side. The positions of the two telescope collimators were fixed at the lowest position. At these positions, the effective telescope field on the beam axis is no more than 3 cm wide to the right in viewing from the beam aperture side. The prompt gamma rays from the neutron reaction with B-10 and hydrogen (H-1) from the tumor sphere and its surroundings during the neutron irradiation were measured.

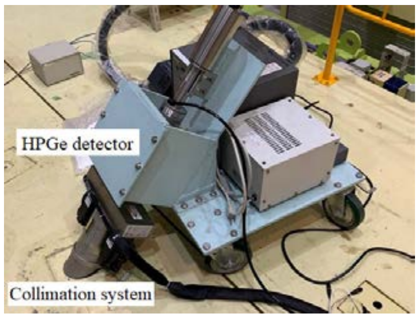

Fig. 1. Gamma-ray telescope system.

RESULTS: It was confirmed that the closer the tumor sphere center is to the beam axis, that is, the closer to the center of the effective telescope view-field, the larger the B/H count ratio becomes. It was also confirmed that the B/H count ratio was higher in the boric acid water phantom than in the pure water phantom. This is because the B-10 gamma rays from the boric acid water with a B-10 concentration of 25 ppm within the telescope view-field further contribute to the B-10 gamma ray count. If the B-10 concentration ratio between the tumor and normal parts is almost the same as this experiment, it is expected to be possible to distinguish between tumor and normal parts by comparing the counting ratio for the tumor positions inside and outside of the telescope view-field.

REFERENCES:
[1] Y. Sakurai, *et al.*, Appl. Radiat. Isot., **61** (2004) 829-833.
[2] Y. Sakurai, *et al.*, Appl. Radiat. Isot., **165** (2020) 109256.
[3] Y. Sakurai and T. Kobayashi, Nucl. Instr. Meth. A., **453** (2000) 569-596.

Experimental Investigation of A Real-time Epi-thermal Neutron Absolute Flux Intensity Monitor Using Scintillation Detectors

I. Murata[1], J. Qiu[1], Y. Ge[1, 2], N. Voulgaris[1], K. Sagara[1], D. Hatano[1], S. Tamaki[1], S. Kusaka[1] and T. Takata[3]

[1]*Graduate School of Engineering, Osaka University*
[2]*Sino-French Institute of Nuclear Engineering and Technology, Sun Yat-sen University, China*
[3]*Institute for Integrated Radiation and Nuclear Science, Kyoto University*

INTRODUCTION: In boron Neutron Capture Therapy (BNCT), epi-thermal neutrons (0.5 eV to 10 keV) are irradiated and converted into thermal neutrons that have a larger neutron capture reaction cross-section before reaching the tumor by slowing down process in a human body. Therefore, it is significantly required to develop a real-time monitor for measuring epi-thermal neutron flux intensity on the body surface of a patient during the irradiation to evaluate the therapeutic effect of BNCT. We have proposed a measurement system that has a constant response to incident epi-thermal neutrons using multiple detectors covered by neutron absorbers such as boron with various thicknesses. LiCAF glass scintillator [1] based on ^{6}Li(n, α)^{3}H reaction, and EJ-254 plastic scintillator [2] based on ^{10}B(n, α)^{7}Li reaction, were considered as potential detection elements. T-Yield tally of PHITS code is used to calculate the reaction rate and evaluate the detection response.

EXPERIMENTS: In this study, we conducted an irradiation experiment using the standard epi-thermal irradiation mode (1 MW) of Heavy Water Neutron Irradiation Facility in Kyoto University Research Reactor (KUR) [3] to verify the performance of our fabricated monitor. We constructed a prototype detector with a scintillator crystal glued to the tip of an optical fiber. And some cylindrical neutron absorbers were fabricated by using a powder molding press. The measurement circuit contains photomultiplier tube, pre-amplifier, linear amplifier, and multi-channel analyzer. Furthermore, we placed gold foils near the scintillator during irradiation, and measured the radioactivity of the activated foils to estimate the neutron flux intensity.

RESULTS: The pulse height spectrums of two scintillators were obtained successfully from the experiment, as shown in Fig. 1. In the actual irradiation field, the contribution of scattered neutrons from various directions to the scintillator is too large to be ignored, so we analyzed the components of front incident and scattered neutrons using the neutron flux intensity measured by gold foils, and evaluated the performance of the monitor. In summary, we demonstrated the feasibility of a real-time epi-thermal neutron absolute flux intensity monitor with a constant response to epi-thermal neutrons from a measurement experiment in the BNCT neutron irradiation field.

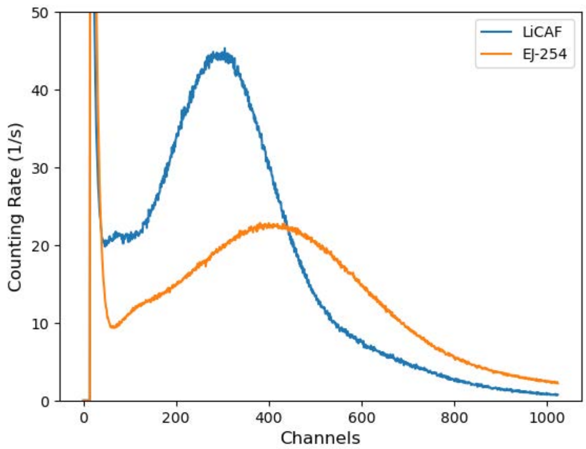

Fig.1 The measured pulse height spectrum

REFERENCES:

[1] T. Yanagida *et al.*, Appl. Phys. Express, **4(10)** (2011) 106401.
[2] G. Gabella *et al.*, IEEE Trans. Nucl. Sci., **68(1)** (2021) 46–53.
[3] H. Tanaka *et al.*, Nucl. Instrum. Methods Phys. Res. B, **267(11)** (2009) 1970–1977.

Neutron Image Sensor for Boron Neutron Capture Therapy

V. T. Ha[1], T. Meguro[1], H. Tanaka[2], and S.-I. Kuroki[1]

1Research Institute for Semiconductor Engineering, Hiroshima University
2 Institute for Integrated Radiation and Nuclear Science,
Kyoto University Graduate School of Science, Kyoto University

INTRODUCTION: Boron neutron capture therapy (BNCT) has been attracting attention as an advanced treatment method on cancer because this therapy has a great advantage on a minimally invasive and selective treatment. In the BNCT, for making this therapy more accurate one, it is better to measure the position of neutron beam profile. On the other hand, silicon carbide (SiC) semiconductor has a strong radiation hardness [1], and then is expected as radiation hardened devices. The purpose of this study is to develop a neutron image sensor with SiC devices [2].

EXPERIMENTS: The structure of our neutron sensor is based on a three- and four-transistor type image sensor pixel. The neutron sensor is based on an image sensor pixel using SiC, which has been developed in our laboratory, focusing on stable operation under neutron irradiation for a long time. The neutron sensors are equipped with boron-10 layer as a neutron conversion layer. In this layer, the injected neutrons have a reaction with boron-10, and then, alpha and lithium particles are emitted. The alpha particles penetrate the device, and generate electron-hole pairs, electrons are collected at gate electrode of SF(source-follower) transistor, and then the induced charge is detected as the output voltage from the sensor. For the highly sensitive neutron sensor, we designed the structure of the device, and design the device layout for next fabrication.

RESULTS: Figure 1 shows the result of our device designing and shows the chip layout of the device. We designed 4-transistor pixel devices in addition to former 3-transistor type. With this new device layout data, we'll fabricate new neutron 2D image sensors.

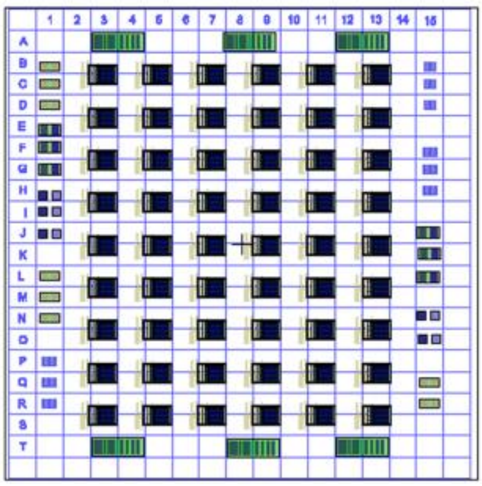

Fig. 1. Chip layout of the neutron sensors. This is a test chip with active pixel sensors.

REFERENCES:

[1] M. Tsutsumi *et al.,* IEEE Electron Device Lett., **44(1)** (2023) 100.

[2] M. Taniguchi, *et al.,* The Interna-tional Symposium on Biomedical Engineering 2022, (2022) 66 .

PR9-9

Improvement of the SOF detector system for energy-dependent discrimination and long-term stability

M. Ishikawa[1,2], Y. Ikeda[2], K. Takamiya[3] and Y. Sakurai[3]

[1]*Faculty of Health Sciences, Hokkaido University*
[2]*Graduate School of Biomedical Science and Engineering, Hokkaido University*
[3]*Institute for Integrated Radiation and Nuclear Science, Kyoto University*

INTRODUCTION: We have been conducting research on SOF detectors as thermal neutron flux monitors in BNCT for many years. [1,2] However, degradation of the SOF detector due to long-term irradiation has been reported.[3] As anti-degradation methods, we have replaced plastic optical fibers, which cause degradation, with quartz fibers, and developed degradation monitors using blue laser source. In addition, since epithermal neutron irradiation has become mainstream in recent years, it is desirable to be able to measure the epithermal neutron flux. In this study, we conducted to estimate the neutron energy spectrum at KUR HWNIF (Heavy Water Neutron Irradiation Facility).

EXPERIMENTS: In the degradation acceleration experiment using the slant-hole irradiation facility, it was found in last year's experiment that effective degradation monitoring could not be performed because fluorescence was generated in areas other than the scintillator as a problem with the degradation monitoring mechanism using a UV light source. Therefore, this year we attempted to monitor degradation using blue laser light source. However, the expected results could not be obtained because the degradation mechanism did not function effectively due to the failure of the blue laser source or the failure of the probe itself.

For flux estimation in each energy region using SOF detectors, energy spectrum estimation using the MLEM (Maximum Likelihood Expectation Maximization) method from 1D thermal neutron flux profile data using SOF detectors was performed in experiments up to last year, but sufficient estimation results could not be obtained. Therefore, this year we attempted to estimate the energy spectrum using the MLEM method by extending the previous 1D scanning to 2D scanning data. Figure 1 shows the 2D scanning measurement experiment at KUR-HWNIF, where the SOF detector probe was located at a pitch of 1 cm in the lateral direction and 5 mm in the depth direction inside a 20 x 20 x 20 cm^3 PMMA phantom, and measurements were performed at each point for 20 sec. The PHITS simulation showed a relatively good estimation of the energy spectra of the 11 groups, as shown in Fig. 2 (a). However, as shown in Fig. 2(b), the estimation using the measured data shows a rather large deviation in the fast energy region.

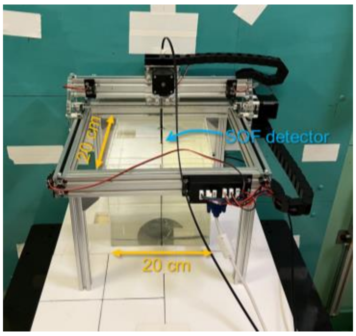

Fig. 1. Measurement geometry for neutron energy spectrum estimation using MLEM unfolding method.

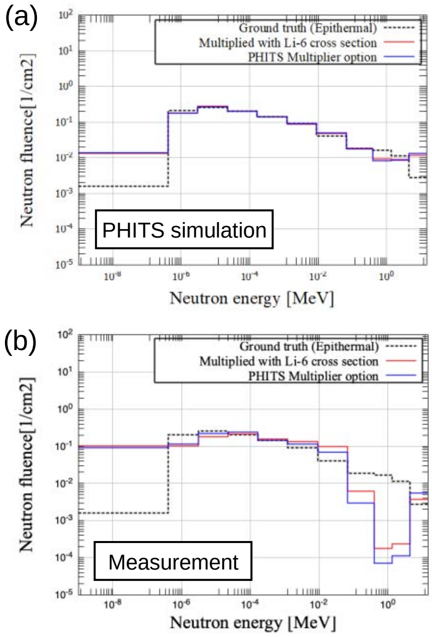

Fig. 2. Estimated neutron energy spectrum by SOF detector.

REFERENCES:
[1] M. Ishikawa *et al.*, Appl. Radiat. Isot., **61** (2004) 775-779.
[2] M. Ishikawa *et al.*, Nucl. Instr. Meth., A, **551** (2005) 448-457.
[3] M. Komeda *et al.*, Appl. Radiat. Isot., **67** (2009) 254-257.

Fast Neutron Dosimetry Using Solid-State Nuclear Track Detector for BNCT

T. Takata, Y. Sakurai, H. Tanaka and M. Suzuki

Institute for Integrated Radiation and Nuclear Science, Kyoto University

INTRODUCTION: In dosimetry of boron neutron capture therapy (BNCT), separate measurements of doses from thermal neutrons, fast neutrons, and gamma rays are required. In such a mixed neutron and gamma-ray field, a paired ionization chamber method is a standard for fast neutron dosimetry. In principle, the method requires compensation of gamma-ray dose, where the conversion factor used to derive the doses from the detector output causes an uncertainty of the fast neutron dose. Also, perturbation of the radiation field caused by the detectors must be taken into account.

In this study, a fast neutron dosimetry method using a solid-state nuclear track detector (SSNTD), which is not sensitive to gamma-rays and has less field perturbation than ionization chambers, is investigated as an alternative method. The detection characteristics for low-energy recoil protons, which account for most of the fast neutron dose impartation, are important to evaluate its applicability to BNCT irradiation field. A method for characteristic measurement of low-energy protons generated from $^{14}N(n, p)^{14}C$ reaction in the atmospheric air is introduced in this report.

MATERIALS AND METHODS: Consider the situation where the SSNTD is placed in a uniform field of thermal neutron formed in the atmospheric air. Protons are produced by the reaction with an initial kinetic energy of 584 keV, slowed down by collisions with molecules in the atmosphere, and then incident on the SSNTD with a reduced energy corresponding to the distance from the position where the reaction occurred. It is known that a diameter of a pit formed in the SSNTD by chemical etching depends on LET of incident particles [1]. Based on an energy spectrum of the incident protons, relationship between LET and pit diameter can be experimentally evaluated for low-energy protons. To confirm the usefulness of this technique, we performed an experiment using a low-energy neutron beam from the E-3 neutron guide tube at KUR [2]. A commercially available SSNTD (Baryotrack, Nagase Landauer, Ltd.) was located downstream of the beam collimated to 5 mm in diameter. After irradiation for 1 hour at 1 MW operation, etching with 6M NaOH solution was performed for 2 hours at 70°C, and the pits formed were observed with an optical microscope. In addition, the energy spectrum of protons produced in the atmosphere and incident on the SSNTD was estimated by simulation calculation using PHITS [3].

RESULTS: The formation of pits was observed on the SSNTD with a variety of its size, where a maximum diameter is a few micrometers. The characteristic analysis of these pits is now in progress. The calculated energy spectrum of the incident protons is shown in Fig. 1. Based on these initial results, methods for the irradiation experiments and their analysis are being investigated to establish a more appropriate evaluation method.

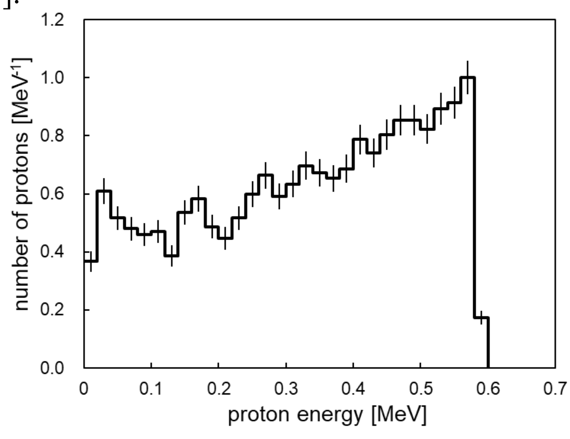

Fig. 1. Calculated energy spectrum of incident protons on SSNTD.

REFERENCES:

[1] M. Caresana *et al.,* Nucl. Instrum. Methods Phys. Res. Sect. A, **638** (2012) 8-15.
[2] T. Kobayashi and K. Kanda, Nucl. Instrum. Methods, **204** (1983) 525-531.
[3] T. Sato *et al.,* J. Nucl. Sci. Technol., **55** (2018) 684-690.

Fiber-reading Radiation Monitoring System with an Optical Fiber and Red-emitting Scintillator at the ^{60}Co Radiation Facility and KUR

S. Kurosawa[1,2,3], D. Matsukura[2,4], C. Fujiwara[2,4], A. Yamaji[1,2], T. Takata[5], H. Tanaka[5]

[1]*New Industry Creation Hatchery Center, Tohoku University*
[2] *Institute for Materials Research Tohoku University*
[3] *Institute of Laser Engineering, Osaka University*
[4] *Department of Materials Science, Graduate School of Engineering, Tohoku University*
[5] *Institute for Integrated Radiation and Nuclear Science, Kyoto University*

INTRODUCTION: Decommissioning reactors at nuclear power plant safety is an important is-sue, and a real-time dose-rate monitor in extremely high radiation dose conditions is required. We have proposed a dose-rate monitor system consisting of a scintillator, optical fiber and Charge Cou-pled Device (CCD) spectrometer, and scintillation photons through the fiber are read under the lower dose condition with the CCD. As we mentioned in the previous reports [1-2], the scintillator is required to have a long-emission wave-length (550 – 1,000 nm) and (ii) high light output (over 40,000 photons/ thermal neutron). Cs_2HfI_6 (CHI) has a high light output (over 60,000 pho-tons/MeV) and red and infrared emission (600 – 800 nm) [1][3].

On the other hand, we need evaluate some noises to understand the sensitivity for such detectors, and such noises can be generated as Cherenkov photons or/and scintillation photons originating from some emission centers like defects or OH part in the optical fiber itself. Moreover, such back-ground noises are expected to have some dose and position information, so that we evaluated the noises in this time.

EXPERIMENTS: Evaluation of the noises was operated using a ^{60}Co gamma-ray source (ap-proximately 60 TBq) at Institute for Integrated Radiation and Nuclear Science, Kyoto University. The system consisted of CCD spectrometer (Preconfigured QE Pro Series Spectrometer, Ocean In-sight) and 20 m-long optical fiber (S.600/660, Fujikura) with a core-diameter of 600 μm and mini-mum bending radius of 132 nm. In this time, we did not set the scintillator, and the exposure time was 3 seconds for 1 measurement with the CCD.

RESULTS: We succeeded in obtained wavelength spectra for the background noises, and the noise was observed to be dominant under 500 nm. Moreover, some absorption bands originating from OH absorption was also observed in the emission bands. In this time, some points through the fiber were irradiated with gamma rays from the ^{60}Co source, and using this data, the distance from CCD spectrometer to radiation hot spots was found to be estimated. The details of this results and discussion were reported in ref [4]. Using this background noises and signal intensities, we evalu-ated the dose-rate dynamic range, and this result of the range was estimated to be 0.1 mGy/h to a few kGy/h, which is suitable range for the application in Fukushima Daiichi Nuclear power plant and other decommissioning reactors. Here, the details of the signal intensities and this dynamic range are planned to describe in a new regular paper.

REFERENCES:

[1] S. Kurosawa *et al.*, KURNS PROGRESS REPORT 2020 (2021) 79.
[2] S. Kurosawa *et al.*, KURNS PROGRESS REPORT 2021 (2022) 248.
[3]. S. Kodama *et al.*, Radiat. Meas., **124** (2019) 54-58.
[4] D. Matsukura *et al.*, Instrumentation, **19** (2024) C02053.

Improvement To Increase Accuracy of Absolute Fast Neutron Flux Intensity Monitor for BNCT

I. Murata, K. Sagara, R. Kawahata, S. Tamaki, S. Kusaka, H. Tanaka[1], Y. Sakurai[1], T. Takada[1]

Graduate School of Engineering, Osaka University
[1]Institute for Integrated Radiation and Nuclear Science, Kyoto University

INTRODUCTION: BNCT is a promising cancer therapy which kills only tumor cells selectively. The neutron field of neutron sources for BNCT includes not only thermal and epi-thermal neutrons but also fast neutrons that are harmful to the human body. Therefore, we have to measure the absolute integral flux intensity of fast neutrons (10 keV ~ 1 MeV) to evaluate their exposure dose. Now we are developing a monitor to precisely measure it and repeatedly improving the monitor [1]. In the previous research, the experimental value was found to overestimate by about 226 % compared to the calculated value [2]. We discussed this discrepancy was caused by scattered neutrons generated in the irradiation laboratory of the KUR, Kyoto University Reactor. Therefore, the objective of this work is to modify the monitor to shield scattered neutrons.

EXPERIMENTS: For the fast neutron monitor, two detectors are used. One of them has a cubic PE and a small piece of B_4C in the cubic PE and GaN foil covered with a Cd sheet at the center of the cubic PE (PE type). The other one consists of a cubic PE surrounded by a B_4C sheet and a GaN foil covered with a Cd sheet is placed at the center of the cubic PE (B_4C type). In addition to the above, we placed a $^{10}B_4C$ plate in front of the monitor, and B_4C cover to shield scattered neutrons. Fig.1. shows the overview of the modified monitor. In this study, the performance of the modified monitor was verified experimentally at KUR. Irradiations were carried out for 20 min in 5 MW operation for each detector.

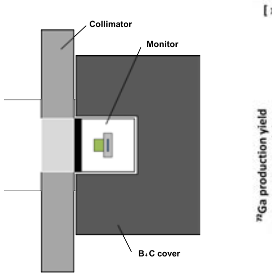

Fig. 1. Overview of the monitor surrounded with a $^{10}B_4C$ cover.

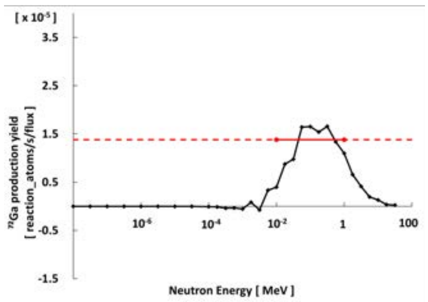

Fig. 2. Sensitivity of the fast neutron monitor.

RESULTS: After the irradiation at KUR, the absolute fast neutron flux was deduced from the ^{72}Ga activities and the sensitivity shown in Fig. 2. From Table 1, the experimental value is overestimated by about 196 % relative to the calculated value and improved by about 30 % compared with the previous research. However, the experimental result is still much larger than the calculated value. This could be due to the fact that sensitivity in high-energy region is not constant. When evaluating the experimental values, it was assumed that the sensitivity was constant. However, since the actual sensitivity is not constant, the discrepancy is considered to have occurred. Therefore, it is necessary to optimize the design of the monitor to make it as constant as possible in the future.

Table 1 Absolute fast neutron flux intensity obtained by the improved monitor.

	Experimental value (E)	Calculated value (C)	E/C
^{72}Ga activity^{*1} [Bq]	162.4±3.2	—	—
^{72}Ga activity^{*2} [Bq]	171.1±3.0	—	—
ϕ_{fast} [n/cm²/sec]	15.3x10^7	5.17x10^7	2.96

*1 For the PE type detector.
*2 For the B_4C type detector.

REFERENCES:

[1] K. Aoki, "Development of absolute epi-thermal and fast neutron flux intensity detector for BNCT", Thesis, University of Osaka, 2021.
[2] K. Sagara, "Improvement of absolute fast neutron flux intensity monitor for BNCT", Thesis, University of Osaka, 2023.

Study on Hybrid Radiation Detector for BNCT

N. Matsubayashi, T. Takata, S. Sakurai, H. Tanaka

Institute for Integrated Radiation and Nuclear Science, Kyoto University

INTRODUCTION: The BNCT system requires the measurement of gamma-ray dose and thermal neutron flux in water phantoms for quality control/quality assurance (QA/QC). Thermofluorescence dosimeters and gold activation methods have been used to measure gamma-ray doses and thermal neutron flux, respectively. Recently, medical institutions have started insured treatment using the accelerator BNCT system, and it is desired to establish a rapid and simple method for measuring gamma-ray doses and thermal neutron fluxes in QA/QC that can replace the conventional methods. Therefore, the purpose of this study is to develop a hybrid radiation detector that can discriminate and measure gamma-rays and thermal neutrons by combining an ionization chamber and a scintil-lator for thermal neutron measurement.

A system combining a Eu:$LiCaAlF_6$ (LiCAF) scintillator and a quartz fiber will be adapted for measuring thermal neutron flux. Since air is present in the sensitive volume of the ionization cham-ber, the charge from charged particles produced by the $^{14}N(n,p)^{14}C$ reaction will be mixed. The gamma-ray dose can be discriminated and measured by subtracting the charge due to the $^{14}N(n,p)^{14}C$ reaction from the thermal neutron flux. In this year, we tested the characteristics of the LiCAF scintillator.

EXPERIMENTS: A LiCAF scintillator with 0.6 mm long side mounted on the tip of quartz fiber to reduce gamma-ray sensitivity was used[1]. The scintillator light entered the fiber and reached a photomultiplier tube (PMT). The signal from the PMT was then processed by a multi-channel ana-lyzer (MCA). The pulse height distribution obtained by the MCA with the peak corresponding to neu-tron events was fitted via a gaussian distribution, and the counts were summarized from the mean to +2σ as neutron events[2]. To use the LiCAF scintillator as the thermal neutron monitor, it is necessary to determine the relationship between the counts and the thermal neutron flux. The counts obtained by the LiCAF scintillator were calibrated by an irradiation test using a water phantom at the Heavy Water Neutron irradiation facility (HWNIF) in Kyoto University. When the LiCAF scintillator was placed in the phantom at a depth of 10cm, the count rates were measured. The thermal neutron flux was evaluated via a gold activa-tion method using a gold wire placed in the same position as the LiCAF scintillator.

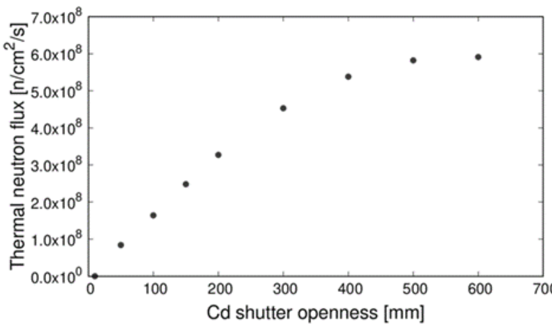

Fig. 1. Relationship of the thermal neutron flux and the Cd shutter openness.

The irradiation tests in free air were performed at the HWNIF. A Cd shutter of 1mm thickness was installed to change the thermal neutron flux with each openness. To investigate the thermal neutron flux per the openness, the irradiation tests were carried out by changing the Cd shutter openness to 0, 50, 100, 150, 200, 300, 400, 500, 600mm. The calibrated LiCAF scintillator was set at the center of a collimator, and the count rates were measured.

RESULTS: Fig. 2 shows the thermal neutron flux by changing the Cd shutter openness. The thermal neutron flux of HWNIF was found to be from 1.1×10^7 to 5.9×10^8 cm^{-2} s^{-1} depending on the Cd shutter openness. It was found that the range of thermal neutron flux was over an order of mag-nitude at HWNIF, and the intensity can be monitored in real-time by using the LiCAF scintillator.

REFERENCES:

[1] H. Tanaka *et al.,* Review of Scientific Instruments, **88(5)** (2017) 056101.

[2] N. Matsubayashi *et al.,* Radiation Measurements, **140** (2021) 106489.

Measurement of Thermal Neutron-Induced Soft Error Rates in Semiconductor Memories

H. Tanaka, [1]R. Nakamura, and [1]T. Kato

Institute for Integrated Radiation and Nuclear Science, Kyoto University
[1]Reliability and Engineering Department, Socionext Inc.

INTRODUCTION: Soft errors are radiation-induced errors in semiconductor devices. With aggressive scaling down of the devices, the soft error susceptibility is increasing. Therefore, to assess the reliability of electronic systems, it is necessary to investigate the characteristics of the soft errors. It has been reported that in recent semiconductor devices the thermal neutron-induced soft errors appear due to the contamination of ^{10}B atoms during manufacturing processes [1]. In previous ex-periments, the authors have demonstrated that the detailed characteristics of the thermal neu-tron-induced soft errors in static random access memories (SRAMs) [2]. This study investigates the thermal neutron-induced soft errors in SRAMs with different technologies and circuit designs. Soft error rates (SERs), which are the occurrence rates of soft errors, are measured by neutron irradiation testing at KUR.

EXPERIMENTS: Neutron irradiation tests were performed using Heavy Water Neutron Irradiation Facility (HWNIF) of KUR. The irradiation modes used were "OO–0000F" and "CO–0000F." The thermal neutron sensitivity was examined by comparing SERs between "OO–0000F" and "CO–0000F" irradiations.
The test samples were SRAM chips manufactured in two process technologies, which were labeled as Tech. A and Tech. B. For Tech. B, three designs of SRAMs (Type I, II, and III) were measured. During the irradiation, the SRAM chips were remotely operated, and the error events were recorded. The SERs were then statistically calculated according to the JEDEC standard. Thermal neutron fluxes at the locations of the samples were measured by the gold activation method.

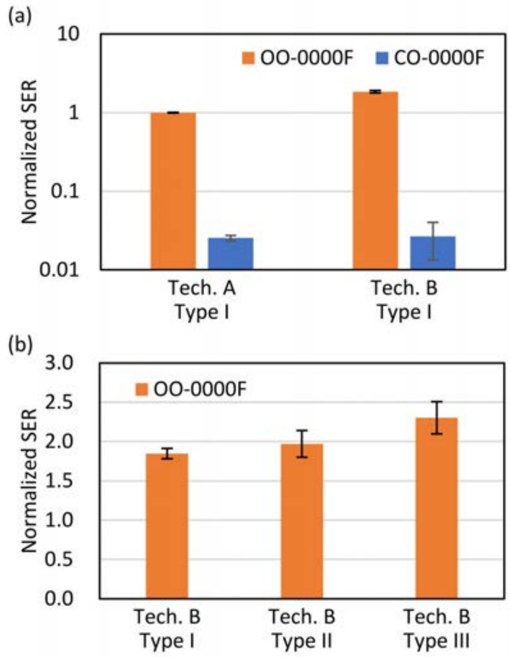

Fig. 1. Measured SERs: (a) Technology comparison and (b) SRAM design comparison.

RESULTS: Fig. 1 presents the measured SERs for Tech. A and Tech. B. Fig. 1(a) shows the comparison of "OO–0000F" and "CO–0000F." Fig. 1(b) shows the comparison of SRAM designs for Tech. B. For both technologies, the SER of "CO–0000F" was significantly lower than that of "OO–0000F," as seen in Fig. 1(a). This clearly demonstrates that thermal neutrons induce soft errors, indicating the containing of ^{10}B atoms. The results also showed that the thermal neutron sensitivity is higher for Tech. B than for Tech. A. For Tech. B, the different SRAM types showed different thermal neutron sensitivity. It is found from Fig. 1(b) that the SER of Type III is higher than that of Type I. This result suggests that the thermal neutron sensitivity is determined not only by manufacturing processes but also by SRAM designs.
In summary, we demonstrated that the thermal neutron sensitivity depends on both the manufacturing process and the SRAM design. This result indicates the importance of thermal neutron irradiation testing for assessing soft error reliability.

REFERENCES:

[1] Y. Fang *et al.,* IEEE Trans. Device Mater. Rel., **14** (2014) 583.
[2] T. Kato *et al.,* IEEE Trans. Nucl. Sci., **68** (2021) 1436.