I-1. PROJECT RESEARCHES

Project 3

Advancement of radiation detectors aimed at application in accelerator BNCT

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BACKGROUNDS AND PURPOSE: With the initiation of insurance-covered treatments using accelerator-based BNCT systems at medical institutions, the number of BNCT cases is expected to increase significantly. As part of the quality assurance (QA) and quality control (QC) processes for clinical treatments, it is necessary to measure the thermal neutron flux and gamma-ray dose prior to irradiation. Currently, conventional methods developed for reactor-based BNCT, such as the gold foil activation technique and thermoluminescent dosimeters (TLDs), are still in use. However, these methods are complex, and the continued availability of TLDs is uncertain. Consequently, there is a strong demand from medical institutions for simplified, yet highly accurate, measurement techniques.

Furthermore, there is an increasing need for the development of advanced radiation detectors applicable to BNCT, including those capable of measuring epithermal and fast neutron fluxes, prompt gamma emissions, and neutron energy spectra. In response to these demands, this project aims to enhance radiation detector technologies for practical application in accelerator-based BNCT systems.

RESEARCH SUBJECTS:
R7P3-1: Study on the Measurement of Neutron Fluence and Gamma-ray Distributions Using a Combination of Thermoluminescent Plate and Converter (K. Shinsho et al.)
R7P3-2: Improvement To Increase Accuracy of Absolute Fast Neutron Flux Intensity Monitor for BNCT (I. Murata et al.)
R7P3-4: Study of Optically Stimulated Luminescent Dosimeter in BNCT Irradiation Field (N. Matsubayashi et al.)
R7P3-5: Development of Scintillator for Thermal Neutron Detector in BNCT (N. Matsubayashi et al.)
R7P3-6: Development and optimization of a Bonner sphere spectrometer for intense neutrons in BNCT (A. Masuda et al.)
R7P3-8: Establishment of Characterization Estimation Method in BNCT Irradiation Field using Bonner Sphere and Ionization Chamber (IX) (Y. Sakurai et al.)
R7P3-9: Development of Real-time Boron-concentration Estimation Method using Gamma-ray Telescope System for BNCT (IV) (Y. Sakurai et. al.)
R7P3-11: Basic research on methods for evaluating the radiation quality of neutron irradiation field (N. Hu et. al.)
R7P3-12: Development of a new SOF detector probe balancing radiation resistance and flexibility (M. Ishikawa et al.)
R7P3-13: Neutron energy spectrum evaluation based on 2D thermal neutron flux distribution measurement with SOF detector (M. Ishikawa et al.)
R7P3-14: Evaluation of response characteristics of semiconductor detectors in neutron irradiation field (N. Hu et al.)
R7P3-15: Characteristics of Etch Pit Shapes Induced by Recoil Protons on Solid-State Nuclear Track Detectors in Epithermal Neutron Irradiation Field for BNCT (T. Takata et al.)
R7P3-16: 4H-SiC Neutron Image Sensor for Boron Neutron Capture Therapy (V. T. Ha et al.)
R7P3-17: Study on the Optimal Size of a LiCAF Scintillator for a Neutron Ambient Dose Detector in BNCT (L. Zhao et al.)
R7P3-18: Measurement of Thermal Neutron-Induced Soft Error Rates in Semiconductor Memories (H. Tanaka et al.)
R7P3-19: Development of a Real-Time Monitoring System to Enhance Treatment Relia-bility in Boron Neutron Capture Therapy and Application to Nuclear Decommissioning (S. Kurosawa et al.)

Research subjects R7P3-1-5,7, 11,14,15,16 are research and development on methods to measure thermal and fast neutrons and γ-rays. R7P3-9, 19 propose methods to obtain boron distributions in real-time. R7P6, 8, 13 propose new methods for measuring neutron spectra. R7P3-12, and 17 have succeeded in obtaining real-time measurements of thermal neutrons in the irradiation field of BNCT. All of them are expected to be applied to accelerator BNCT.

PR3-1

Study on the Measurement of Neutron Fluence and Gamma-ray Distributions Using a Combination of Thermoluminescent Plate and Converter

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INTRODUCTION: Boron Neutron Capture Therapy (BNCT) is one of the radiation therapies that uses neutrons and ^{10}B drugs, which accumulate in tumors. BNCT is expected to be a next-generation cancer therapy that can improve patients' quality of life (QOL), as it enables selec-tive irradiation of cancer cells at the molecular level. However, dosimetry techniques in mixed neu-tron–gamma fields have not yet been established. Therefore, in this study, we focused on the meas-urement of neutrons and gamma rays using a two-dimensional thermoluminescence dosimeter (2D-TLD).We have previously reported that the thermoluminescence (TL) of a Cr-doped Al_2O_3 ce-ramic plate sandwiched between Cd plates can selectively measure the thermal neutron fluence in a 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) can selectively measure the γ-ray fluence without being affected by neutrons [2,3,4]. In this study, we investigated a new meth-od for selective fast neutron measurement using a novel TL plate combined with a converter based on the elastic scattering reaction between fast neutrons and hydrogen atoms.

EXPERIMENTS: A 3 mm thick high density polyethylene (HDPE) converter was placed. A high-density polyethylene (HDPE) plate with a thickness of 3 mm was used as a neutron converter to generate recoil protons via elastic scattering between fast neutrons and hydrogen atoms. BeO ceramic plates (Na-undoped) were placed on both the front and rear surfaces of the HDPE to detect the spatial distribution of deposited dose induced by recoil protons. Neutron transport and energy deposition were evaluated using a Monte Carlo simulation code. The absorbed dose in the front and rear BeO plates was calculated as a function of neutron energy. For comparison, the same configuration without the HDPE converter was also simulated to confirm the contribution of recoil protons.

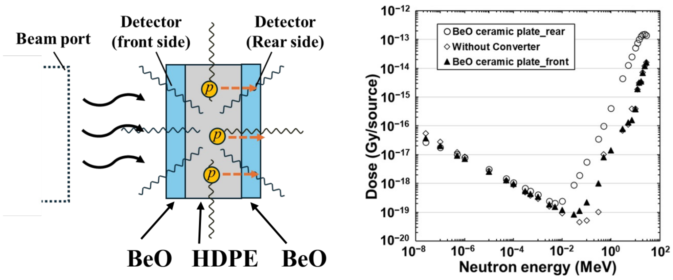

Fig. Schematic configuration of the proposed detector and calculated neutron energy response.

RESULTS: As shown in Fig. X, the absorbed dose in the BeO plates exhibits a clear dependence on neutron energy. When the HDPE converter is introduced, a significant difference in absorbed dose between the front and rear BeO plates is observed, particularly in the fast neutron energy region (>0.1 MeV). This difference originates from recoil protons generated in the HDPE, which preferentially deposit energy toward the forward direction. In contrast, when the converter is not used, the absorbed dose in the front and rear BeO plates shows almost identical values over the entire energy range, indicating that the observed asymmetry is attributed to recoil protons. These results demonstrate that the proposed configuration enables selective detection of fast neutrons based on the difference in absorbed dose between the front and rear detectors.

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PR3-2

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

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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 overestimated by about 226 % compared to the calculated value [2], which is attributed in part to the non-constant sensitivity of the monitor. Therefore, this work aims to modify the shielding structure to achieve constant sensitivity for more accurate measurements.

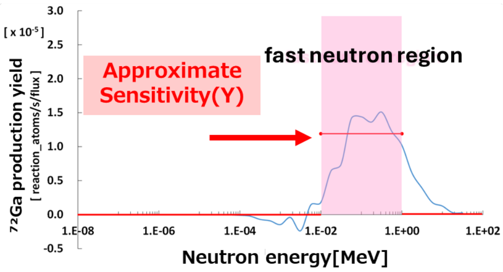

Fig. 1 Sensitivity of the fast neutron monitor in previous research.

EXPERIMENTS: The monitor consists of a 6.2 cm cubic polyethylene (PE) moderator with a 1.0 cm thick ^{10}B shield on the irradiation surface and a Cd-covered GaN foil at the center. To achieve constant sensitivity to fast neutrons, we propose a design that places multiple types of absorbers in front of the ^{10}B wall. In this study, preliminary experiments were conducted at KUR to verify the simulation accuracy and the linearity of combined absorbers. Four configurations were tested: (1) no absorber, (2) Fe, (3) Nb, and (4) a combination of Fe and Nb (half-area each). Irradiations were performed for 15 min in 5 MW mode for configurations (1), (2) and (3), and 90 min in 1 MW mode for configuration (4) operation, respectively.

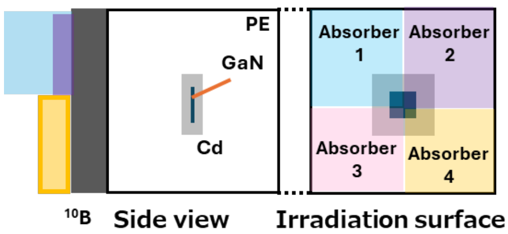

Fig. 2 Design of the montor for sensitivity optimization featuring multi-type absorbers

RESULTS: Irradiations were successfully performed for all the four configurations, and activation of the GaN foils was observed. Currently, the experimental data are being processed to deduce the absolute fast neutron flux intensity. Specifically, we are calculating correction factors to normalize the experimental values for comparison with the MCNP5 simulation results. A preliminary analysis indicates that the relative change in flux intensity for each absorber (Fe and Nb) follows the predicted result. The linearity of the combined absorbers (Fe+Nb) is also being evaluated by comparing the superimposed result of individual absorber results with the actual measurements.

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PR3-3

Study of Optically Stimulated Luminescent Dosimeter in BNCT Irradiation Field

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INTRODUCTION: The BNCT irradiation field consists of neutrons with a wide energy range and undesired gamma-rays, which are mainly caused by nuclear reactions with surrounding structures. For quality control/quality assurance (QA/QC), the undesired gamma-ray dose in a phantom must be measured [1]. To evaluate gamma-ray dose in the BNCT irradiation field, a thermoluminescent dosimeter (TLD) composed of beryllium oxide power enclosed in a quartz glass capsule, which is less sensitive to thermal neutrons, has been used. However, as the TLD was out of production, a new gamma-ray dosimeter is required for QA/QC of BNCT [2]. In this study, we selected optically stimulated luminescent dosimeter (OSLD), which is made of Al_2O_3:C. The OSLD has been used in other radiation therapies, has almost no fading effect and can be measured repeatedly. However, it is difficult to completely eliminate the thermal neutron sensitivity of OSLD. In this study, we investigated whether it is possible to measure the thermal neutron flux via the activation method using OSLD (^{27}Al (n, γ)^{28}Al).

EXPERIMENTS: The irradiation tests of the BNCT irradiation field were performed at Heavy Water Neutron Irradiation Facility (HWNIF) at Kyoto University Research Reactor (KUR) [3]. A cadmium shutter, which shields only thermal neutrons, was installed to control the thermal neutron flux with each openness. To investigate the activation of the OSLD, radioactivity was measured immediately after the irradiation test using a high-purity Ge detector. Neutron reaction rate of the OSLD was evaluated by the count rates, the detection efficiency of the Ge detector, and the average cross section. We compared it with thermal neutron flux measured by the gold activation method. The irradiation tests were carried out by changing the openness to 0, 100, 200, 300, and 600 mm.

RESULTS: Fig. 1 shows the ratio of the reaction rate to the thermal neutron flux. The results of the linear fitting shown in Fig. 2 indicate $R^2 = 0.98$, confirming that the relationship is approximately linear. In conclusion, the OSLD was capable of measuring thermal neutron response via the activation method, and it was suggested that it could self-correct its sensitivity.

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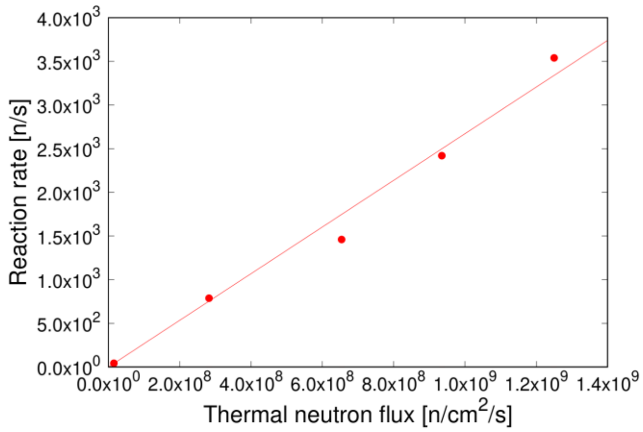

Fig. 1. Relationship between thermal neutron flux and ^{27}Al neutron reaction rate.

Development of Scintillator for Thermal Neutron Detector in BNCT

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INTRODUCTION: In recent years, accelerator-based BNCTs have been developed worldwide, and clinical cases are increased. The activation method has been used for measurement of thermal neutron flux but cannot measure in real-time. The development of thermal neutron detectors as neutron monitors is needed. The neutron monitor using Eu:$LiCaAlF_6$ (LiCAF) scintillator with quartz fiber was developed [1]. It is necessary for the use of the scintillator as neutron monitor to determine the relationship between the count rates obtained by the detector and thermal neutron flux. Considering the increase in the clinical cases, we must calibrate the detector in primary national standard field. However, the neutron intensity of the standard field is much lower than that of the BNCT irradiation field. In this study, we applied pulse shape discrimination (PSD) to the neutron detection in BNCT irradiation field (Fig. 1). The neutron monitor uses a light guide to prevent the effects of the photodetector, but the waveform becomes less sharp, making it difficult to use the PSD. In this study, we investigated the length of the light guide that is unaffected by a photomultiplier tube (PMT).

EXPERIMENTS: The irradiation tests of each detector were performed at Kyoto University Research Reactor-Heavy Water Neutron Irradiation Facility (KUR-HWNIF) [2]. The Ce doped LiCAF scintillator, which has a short decay time, was directly attached to the PMT. Considering the use in BNCT, a 30 cm square polyethylene block was placed at the collimator, and measurements were taken with detectors positioned 0, 5, and 10 cm above the block surface (15, 20, and 25 cm from the beam center). We measured the pulse height distribution by multichannel analyzer to evaluate the effect of the PMT.

RESULTS: As shown in Fig. 2, at distances of 20 and 25 cm from the beam center, the neutron events can be distinguished in the high channel region. The count rates summarized from 1000 to 2000 ch were 59.6, 1123, and 963 cps at 15, 20, and 25 cm, respectively. Based on these results, it was confirmed that the light guide of at least 20 length is necessary to prevent the effect of the PMT.

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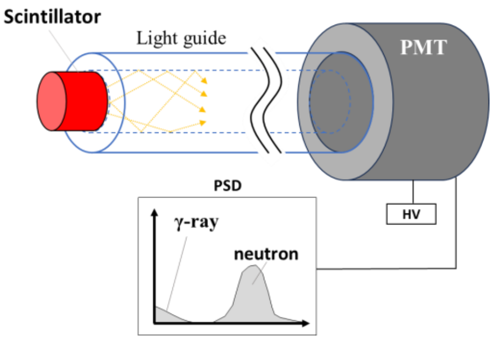

Fig. 1. Schematic layout of neutron detector

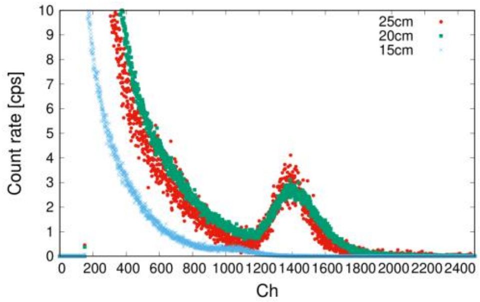

Fig. 2. Pulse height distribution at distances of 15, 20, and 25 cm from the beam center.

PR3-5

Development and optimization of a Bonner sphere spectrometer for intense neutrons in BNCT

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INTRODUCTION: Neutron spectral fluence measurement is required in boron neutron capture therapy (BNCT). A Bonner sphere spectrometer (BSS) has been developed that incorporates a small lithium-glass scintillator to enable the measurement of intense neutrons up to 10^9 cm^{-2} s^{-1} in this study. The BSS was modified to include variations in moderator thickness that are optimal for measurements focusing on epithermal neutrons, and demonstration measurements of BNCT epithermal neutrons were conducted in the Kyoto University Research Reactor (KUR).

EXPERIMENTS: The Bonner sphere detectors with the small lithium-glass scintillator coupled with an optical fiber and a photomultiplier (PMT, Hamamatsu R9880U-21) were set in the heavy water irradiation facility of the KUR [1]. Output signals from the PMT were processed using a preamplifier (ORTEC 113) and a signal processing and acquisition system (Amptek PX5). Measurements were performed sequentially with varying sizes of moderators,

RESULTS: Fig. 1 shows the dependence of the measured count rates of the Bonner sphere detector on the sphere diameter and compares it with the count rates predicted by Monte Carlo simulations. The two measurement series were performed completely independently in different years. The experimental results and calculated values were normalized by the result of the 3” detector of the 2nd measurement. The trends of the measurement results generally agreed with the simulation, but the count rates for detectors smaller than 2.5" were higher than the calculated results. This is likely due to the significant influence of the low-energy scattered neutrons in the irradiation room on the smaller detectors, and inaccuracies in the modeling of the detector structure in the simulations. They will be investigated mainly through further simulations, and correction factors should be introduced if necessary.

The BSS response matrix will be precisely determined through measurements at the reference neutron fields of the National Institute of Advanced Industrial Science and Technology (AIST) and Monte Carlo simulations. Using these results, the measurement results of the KUR experiment will be unfolded, and the neutron spectral fluence will be derived.

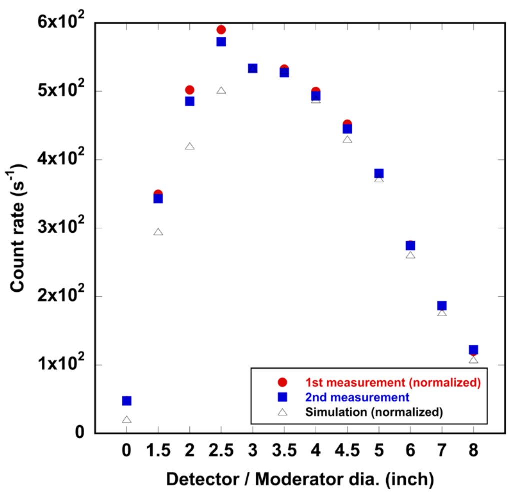

Fig. 1. Results of the Bonner sphere measurements.

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

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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]. The experimental verification for the effectiveness of a prototype of CHARMS was continued in 2025 as well [3].

MATERIALS AND METHODS: A $LiCaAlF_6$ scintillation neutron detector is positioned at the center of CHARMS, and it is surrounded by three layers of liquid moderators. With a remote operation of liquid moderator supply and drainage system from outside the irradiation room, we can realize a fully remote-operating neutron spectrometer. The performance of CHARMS in measuring the neutron energy spectrum was evaluated at Heavy Water Neutron Irradiation Facility of Kyoto University Reactor (KUR-HWNIF) [4].

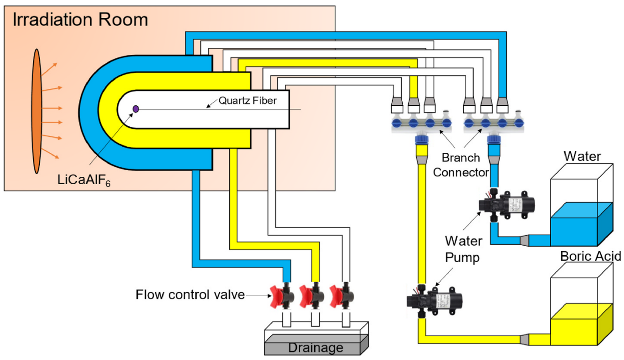

Fig. 1. Outline of a prototype CHARMS.

RESULTS: The neutron energy spectrum of the BNCT irradiation at KUR-HWNIF was measured using CHARMS without the need to enter the irradiation room. The evaluated neutron energy spectrum closely matched the results of simulation calculations. The entire measurement process took approximately one hour by using CHAMRS. It was confirmed that CHARMS can provide a reliable neutron energy spectrum with a short measurement time compared to conventional methods. It is considered that CHARMS is a promising neutron spectrometer for use in BNCT irradiation field in the future.

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PR3-7

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

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INTRODUCTION: It is important to decide the boron concentrations for tumor and normal parts in the dose estimation for BNCT. To improve the dose estimation in BNCT, a method for estimating the spatial distribution of boron concentration online in real time is expected. 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 2025 as well [4].

MATERIALS AND METHODS: The phantom experiment was performed using the epi-thermal neutron irradiation mode at KUR-HWNIF. The phantom size was 20 cm × 20 cm × 20 cm. Within the phantom, a 5-cm diameter acrylic hollow sphere was placed as the tumor. Both the phantom and tumor sphere were filled with different concentrations of boric acid water. For example, the tumor spheres with the B-10 concentration of 70, 100 and 200 ppm were put into a phantom with B-10 concentration of 20 ppm. The irradiation field was set to 12 cm in diameter. The tumor sphere was fixed at the center of the telescope view-field. The 1st and 2nd telescope collimators were set at the bottom of the telescope.

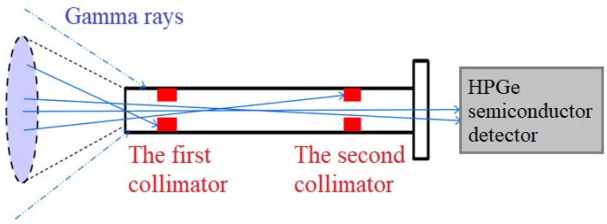

Fig. 1. Outline of the collimation system.

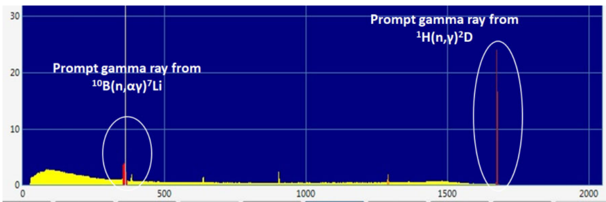

Fig. 2. An example of the gamma-ray energy spectrum by the telescope system.

RESULTS: The count rates for 478-keV prompt gamma rays with the different irradiation conditions were obtained from the experimental results. The experimental count rates were almost 30 cps (s^{-1}) for the 70-ppm tumor sphere, 33 cps (s^{-1}) for the 100-ppm tumor sphere, and 46 cps (s^{-1}) for the 200-ppm tumor sphere. Therefore, because the time required to reach 1000 counts was just over 30 seconds, the time course of B-10 concentration can be estimated almost in real-time. From the results of the experimental verification, the effectiveness and usefulness of the improved gamma-ray telescope system were confirmed.

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Basic research on methods for evaluating the radiation quality of neutron irradiation field

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INTRODUCTION: In a typical BNCT irradiation field, multiple types of radiation are present, making accurate measurement challenging. A proportional gas counter is commonly used to assess the radiation quality in mixed fields, such as neutron–gamma environments. To evaluate the biolog-ical effects of a neutron beam, a tissue-equivalent proportional counter (TEPC) is employed. In this method, the gas density is reduced to simulate a micrometer-scale tissue volume.

EXPERIMENTS: The experiment was conducted using the epithermal neutron irradiation mode at KUR operating at 1 MW. The TEPC was positioned free-in-air at the center of the irradiation field, and data were collected over a period of one hour. The acquired raw data were converted into a lin-eal energy spectrum (y-distribution) and compared with results obtained from Monte Carlo simula-tions using the Particle and Heavy Ion Transport code System (PHITS).
Following validation of the PHITS lineal energy distribution, Monte Carlo simulation was per-formed for different neutron sources (KUR thermal mode, cyclotron-based epithermal neutron source (CBENS), and CICS-1 accelerator system) and the relative biological effectiveness (RBE) was calculated.

RESULTS: As shown in Fig. 1, the RBE values for the different neutron sources vary, which is consistent with previously published report [2]. This result indicates the PHITS Monte Carlo simu-lation may be used to estimate biological effectiveness of neutron sources.

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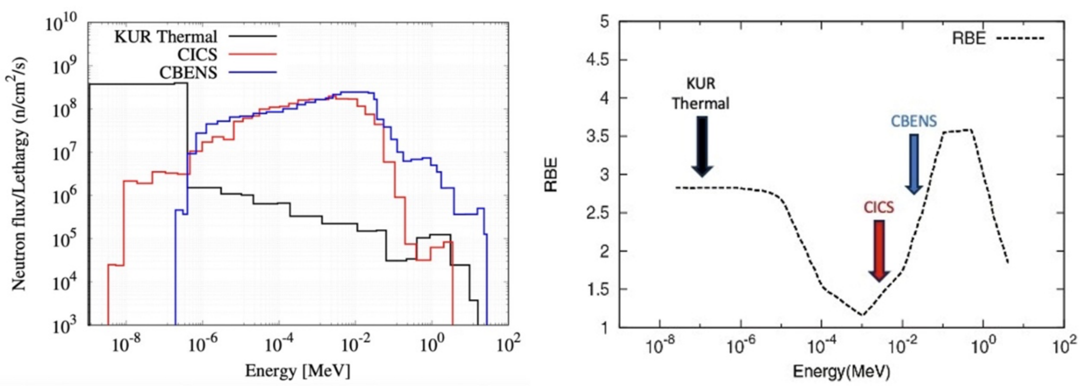

Fig. 1. Left) Neutron energy spectra per lethargy of KUR Thermal (black), CICS (red), and CBENS (blue). Right) RBE versus Neutron Energy with KUR, CBENS, and CICS spectra. The arrows indicate the peak neu-tron flux for each neutron spectra.

PR3-9

Development of a new SOF detector probe balancing radiation resistance and flexibility

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INTRODUCTION: Our laboratory has developed a Scintillator with Optical Fiber (SOF) detector, which features a plastic scintillator attached to the tip of an optical fiber, for the purpose of real-time thermal neutron fluence measurement during Boron Neutron Capture Therapy (BNCT) irradiation. Previous collaborative experiments confirmed the SOF detector's long-term stability and wide dynamic range, maintaining linearity from 10^4 to 10^{10} n/cm²/s, but also revealed that the primary cause of signal degradation was the deterioration of the plastic optical fiber. While quartz optical fibers showed almost no signal degradation in subsequent trials, their bending performance was significantly poor, leading to concerns regarding probe breakage during practical use. Consequently, this research aims to develop a new probe that incorporates both the flexibility of plastic optical fibers and the radiation resistance of quartz optical fibers.

EXPERIMENTS: In the 2025 fiscal year, degradation characteristic tests were performed using a high-intensity thermal neutron irradiation field at the Slant irradiation hole of the Kyoto University Research Reactor (KUR). The SOF detector methodology estimates pure thermal neutron flux by calculating the difference between signals from a probe containing a ^{6}LiF neutron sensitizer mixed into the plastic scintillator and one without the sensitizer. For these experiments, Saint-Gobain BC620 was utilized as the reflector, and four distinct quartz fiber probe configurations were fabricated to evaluate the radiation hardness of individual components, including variations with and without the neutron sensitizer and the reflector coating. Irradiation was conducted at a reactor power of 5 MW for approximately five hours, with the measurement position set 181 cm from the lower end of the Slant hole to minimize counting losses. The results indicated a signal decrease of approximately 2% only in the probe containing ^{6}LiF without a reflector coating, whereas the standard SOF probe configuration—including both ^{6}LiF and a reflector—showed no significant signal degradation. In contrast, plastic fiber probes measured simultaneously experienced extremely high signal volumes and significant counting losses, which prevented the collection of effective data. The stability observed in the standard quartz probe configuration confirms its potential for high-dose clinical applications where plastic fibers typically fail. However, the estimated thermal neutron flux from the measurement position at 181 cm exceeded 1×10^{10} n/cm^2/s, which is remarkably higher than the previously reported flux of 2×10^8 n/cm^2/s at a position closer to the source (70 cm from the bottom). This discrepancy strongly suggests that the detector output at this location is likely dominated by non-neutron signals, potentially including high-energy gamma rays or Cerenkov radiation generated within the optical fiber itself. Future development will focus on isolating these background components to ensure that the increased radiation resistance of the fiber translates into more accurate neutron dosimetry in high-intensity irradiation environments.

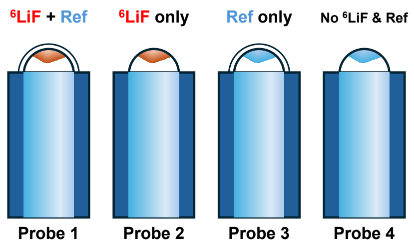

Fig.1 SOF detector probes categorized by individual components.

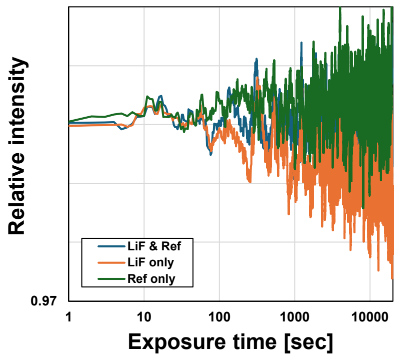

Fig.2 Accelerated degradation test of SOF detector components.

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Neutron energy spectrum evaluation based on 2D thermal neutron flux distribution measurement with SOF detector

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INTRODUCTION: We have been developing a SOF (Scintillator with Optical Fiber Detector) detector—a plastic scintillator attached to the tip of an optical fiber—for real-time thermal neutron fluence monitoring during boron neutron capture therapy (BNCT) irradiation. Previous experiments at KUR have confirmed the wide dynamic range of the SOF detector (linearity from 10^4 to 10^{10} n/cm²/s)[1]. In accelerator-based BNCT, neutrons are generated through nuclear reactions at the target; however, long-term operation may cause target degradation and potentially alter the generated neutron energy spectrum. Changes in beam diameter or irradiation position may also affect the spectrum. Therefore, as a quality assurance measure for the accelerator BNCT irradiation field, this study investigates a method for estimating the neutron energy spectrum at the beam port surface from two-dimensional (2D) neutron flux distribution data measured with the SOF detector in a water phantom.

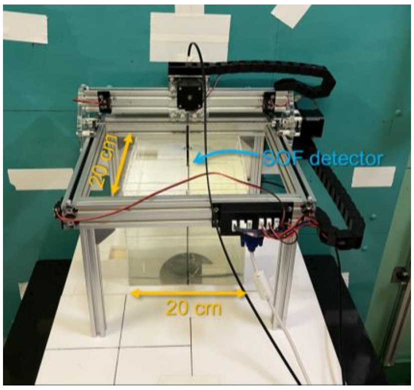

Fig.1 Geometry for 2D neutron flux distribution using scanning device.

EXPERIMENTS: Two-dimensional thermal neutron flux measurements in a water phantom were performed using the SOF detector in epithermal neutron mode (CO–0000-F) (Fig. 1). A 20 cm × 20 cm × 20 cm acrylic water phantom (PMMA wall thickness: 3 mm) was used. Measurements were carried out at 1 cm intervals up to a depth of 12 cm along the beam axis and within ±7 cm in the lateral direction. The reactor output was 1 MW, and the measurement time was 10 seconds per point, resulting in a total measurement time of approximately 50 minutes. Dedicated software for 2D scanning measurements was used, and the data were monitored in real time during irradiation. The measured 2D distribution was compared with Monte Carlo simulations performed using PHITS. The neutron energy spectrum of the beam was taken from that reported by Prateepkaew[2]. Figure 2 shows that the 2D measurements obtained with the SOF detector are in relatively good agreement with the PHITS calculations. ML-EM[3]-based neutron energy spectrum estimation was also performed using the measurement data, however, the estimated spectrum did not agree well with the reported spectrum[4] especially at thermal-neutron energy region (Fig.3).

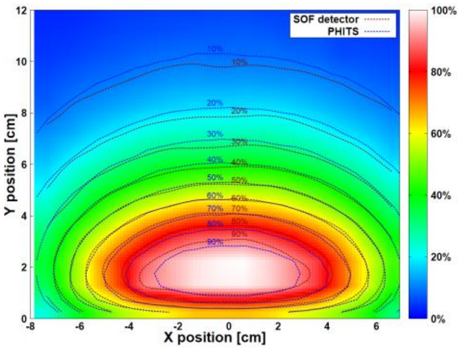

Fig.2 Comparison of measured and calculated relative distributions in the epithermal irradiation mode (CO–0000-F).

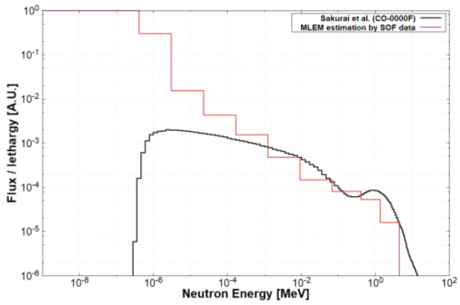

Fig.3 ML-EM-based neutron energy spectrum estimation using measurement data.

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PR3-11

Evaluation of response characteristics of semiconductor detectors in neutron irradiation field

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INTRODUCTION: The Centre for Medical Radiation Physics, University of Wollongong, Australia, has developed a silicon microdosimeter to measure directly the microdosimetric spectrum. The detector has an array of micro-sized sensitive volumes, which can measure the energy deposi-tion at the cellular-level. The use of this detector in a mixed neutron/gamma ray radiation field is of high interest, particularly for evaluating the dose deposited to a volume mimicking a single cell.

EXPERIMENTS: The measurements were performed using the heavy water irradiation facility (epithermal irradiation mode) of the Kyoto University Research Reactor under 1MW. The silicon microdosimeter fitted with an enriched boron-10 converter was placed inside a water phantom placed on the couch top (Fig 1.).

RESULTS: As shown in Fig. 2, the energy deposition distribution and the dose lineal energy dis-tribution (yd(y)) was obtained and the results closely matched Monte Carlo simulation results. The results indicate the silicon microdosimeter are able to detect single-event alpha particles from the boron neutron capture reaction.

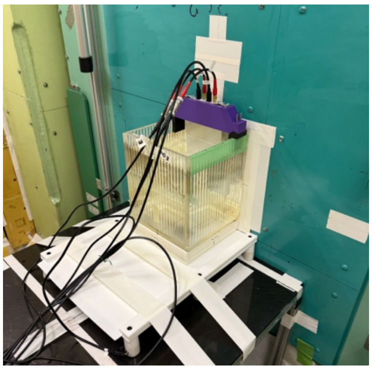

Fig. 1. Image of the experimental set up using the heavy water irradi-ation facility.

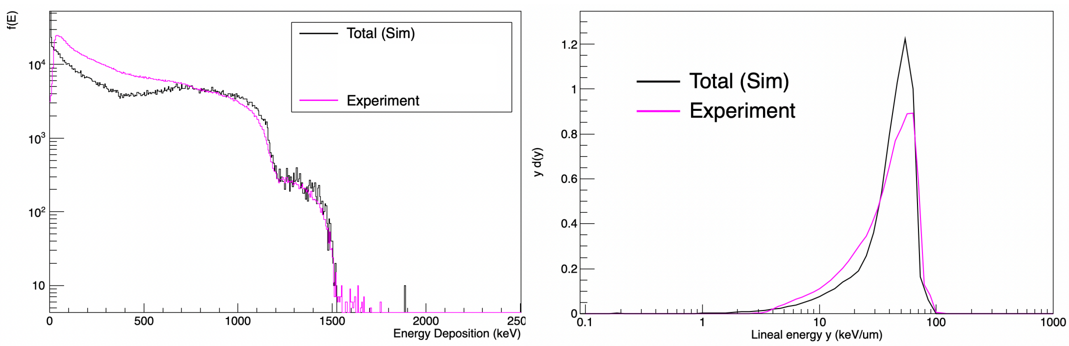

Fig. 2. Left) Energy deposition distribution, Right) dose lineal energy distribution (yd(y)), obtained using the silicon microdosimeter with the boron-10 converter.

PR3-12

Characteristics of Etch Pit Shapes Induced by Recoil Protons on Solid-State Nuclear Track Detectors in Epithermal Neutron Irradiation Field for BNCT

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INTRODUCTION: In the dosimetry of boron neutron capture therapy (BNCT), it is essential to separately measure doses from thermal neutrons, fast neutrons, and gamma rays. Within this mixed field of neutrons and gamma rays, the paired ionization chamber method is typically used for fast neutron dosimetry. This method inherently requires the compensation of gamma-ray doses, which introduces uncertainty in the calculated fast neutron dose. Additionally, the radiation field can be disturbed by the gas cavity, which must be considered. This study explores the use of a solid-state nuclear track detector (SSNTD) as an alternative method, as it is not sensitive to gamma rays and causes less field disturbance than ionization chambers. It is established that the shape of pits formed on the SSNTD through chemical etching is influenced by the LET of incoming particles [1]. We report an analysis of the pit shapes created by recoil protons in the epithermal neutron irradiation field for BNCT.

EXPERIMENTS: Commercially available SSNTDs (Baryotrack, Nagase Landauer, Ltd.) were irradiated at Heavy Water Neutron Irradiation Facility in KUR [2]. As a recoil proton converter, a polyester film with a thickness of 200 μm was attached on the detector surface. The detector was placed in free air at the collimator outlet and irradiated for 30 minutes during 1 MW operation. Post-irradiation, the detectors were etched with 6M NaOH solution for 7 hours at 70°C. The surface profiles of the etched detectors were measured by using a 3D confocal laser microscope (LEXT4000, Evident Corporation) with 100× objective lens [3]. The measurement was performed with the support of the Kyoto University Nanotechnology Hub under “Advanced Research Infrastructure for Materials and Nanotechnology Project” sponsored by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

RESULTS: By analyzing the surface profile, parameters of the pit shapes were obtained. Figure 1 illustrates the distributions of the measured pit diameters and depths. Pits with a diameter of 2 μm and a depth of 0.4 μm were observed most frequently, with larger diameters and greater depths occurring less often. These features imply that the distribution of pit shapes reflects the incident proton energy spectrum. In future work, we will examine the feasibility of estimating the recoil proton spectrum by analyzing pit shape parameters.

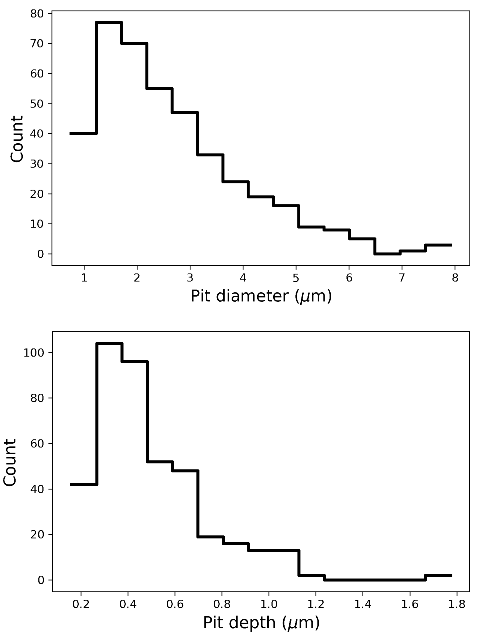

Fig. 1 Frequency distribution of the diameter and depth of etch pits.

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4H-SiC Neutron Image Sensor for Boron Neutron Capture Therapy

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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, to make this therapy more accurate one, it is better to measure the neutron beam's position and profile. On the other hand, silicon carbide (SiC) semiconductor image sensors have been developed as radiation hardened electronics [1,2], and we are suggesting a neutron CMOS image sensor by combining the SiC CMOS image sensor and neutron conversion layer for the real time imaging [3]. In this year, we fabricated the neutron CMOS image sensors and tested the device operations under neutron irradiation.

EXPERIMENTS: In this study, neutron sensors were designed based on 4H-SiC substrate with three transistor-active pixel sensors (3T-APS) structure which amplifies the signal in each pixel. A neutron conversion layer with ^{10}B was formed inside the aluminum layer on the top of the sensor by ion implantation. By changing the thickness of aluminum layer under the neutron converter with ^{10}B, it is possible to control the energy entering the detection area and thereby change the number of electron-hole pairs generated during the ionization process. On the other hand, a circuit simulation model of the neutron sensor was also developed.

RESULTS: The SiC neutron sensors for BNCT were designed and fabricated based on 3T-APS structure and investigated for their performance by using LT spice simulation. Simulation results show the neutron detection ability of SiC neutron sensors based on 3T-APS structure and a parasitic n-p-n structure in the detection area. These results laid the foundation for fabricating SiC neutron sensors for BNCT and testing thermal neutron irradiation.

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Study on the Optimal Size of a LiCAF Scintillator for a Neutron Ambient Dose Detector in BNCT

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INTRODUCTION: Accurate evaluation of neutron leakage dose is essential for radiation protection in Boron Neutron Capture Therapy (BNCT). A moderated spherical neutron detector was designed for the direct measurement of the newly proposed operational quantity, the neutron ambient dose, H*[1]. The detector assembly consists of two polyethylene layers, a gadolinium layer, and a tungsten layer, with a relatively large diameter of 27 cm. A thermal neutron detector Eu-doped $LiCaAlF_6$ (LiCAF) scintillator was placed at the center. Due to the thick moderator structure, a relatively large LiCAF scintillator was required to improve detection efficiency while maintaining gamma-ray event suppression[2]. In this research, the characteristics of gamma ray discrimination were confirmed.

EXPERIMENTS: Neutron–gamma discrimination performance was evaluated at the E3 thermal neutron beam port of the Kyoto University Research Reactor under irradiation conditions both with and without a cadmium cover. The cadmium cover was used to suppress thermal neutrons because cadmium has a very large cross section for thermal neutrons and produces gamma rays via the ^{113}Cd(n,γ) reaction, thereby enabling gamma-ray-only irradiation of the LiCAF scintillator.
Three relatively large LiCAF crystals were prepared: (i) a 2 mm cube, (ii) a 2 mm diameter × 1 mm thick disk, and (iii) a 2 mm diameter × 0.5 mm thick disk. Each crystal was coupled to a quartz glass light guide and connected to a photomultiplier tube (PMT) for irradiation measurements.

RESULTS: Among the samples, the 2 mm diameter × 0.5 mm thick disk (iii) exhibited the best gamma-ray suppression, with a gamma-ray contribution of 0.4% within ±3σ of the neutron peak, as shown in Fig. 1. This scintillator was therefore selected for the designed neutron ambient dose detector.
The detector was subsequently fabricated and tested in a BNCT irradiation field, demonstrating good performance in H* measurement with high detection efficiency.

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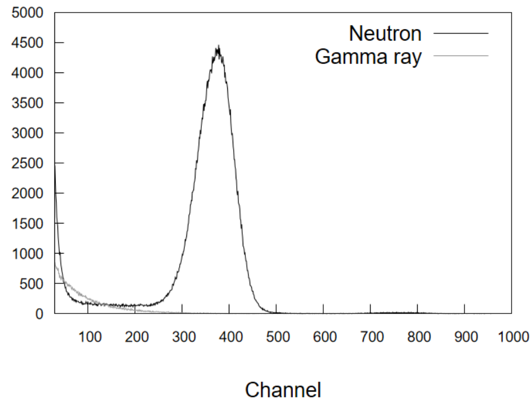

Fig. 1. Pulse height distribution of sample (iii): a 2 mm diameter × 0.5 mm thick disk.

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

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INTRODUCTION: Radiation-induced soft errors are one of the concerns threatening the reliability of semiconductor devices. Assessing the soft error risk is critically important especially in highly reliable applications, such as automotive and data center [1, 2]. In the terrestrial environment, thermal neutrons are one of the sources triggering the soft errors [3]. Susceptibility to the thermal neutrons depends on the amount and location of ^{10}B atoms introduced during manufacturing as a contaminant. However, such ^{10}B information is generally unavailable, making it difficult to predict the impact of thermal neutrons. In this context, irradiation testing is essential to assess the reliability risk due to thermal neutrons. This work investigates the thermal neutron-induced soft errors in static random-access memories (SRAMs) with two different process technologies. Soft error rates (SERs), which are the occurrence rates of soft errors, are measured by thermal neutron irradiation testing.

EXPERIMENTS: Thermal neutron irradiation was performed using Heavy Water Neutron Irradiation Facility (HWNIF) at KUR [4]. Irradiation modes used were "OO–0000F" and "CO–0000F." Fig. 1 shows the energy spectra of these modes together with the terrestrial one [5]. Test samples were two SRAM chips with different technologies, which were labeled as Tech. A and Tech. B. The SERs were statistically calculated according to the JEDEC standard [6]. Thermal neutron fluxes at the sample positions were measured by the gold activation method.

RESULTS: The thermal neutron susceptibility was examined by comparing the SERs under "OO–0000F" and "CO–0000F" irradiations. Fig. 2 shows the measured SERs for Tech. A and Tech. B. For both the technologies, the SER under "CO–0000F" was significantly lower than that of "OO–0000F." This clearly demonstrates that these SRAMs are susceptible to thermal neutrons. When focusing on the SER ratio between "OO–0000F" and "CO–0000F", the ratio is higher for Tech. A than for Tech. B. One of the possible reasons for this is that the ^{10}B atoms are more abundant for Tech. A. Further analysis will be required to understand this difference.

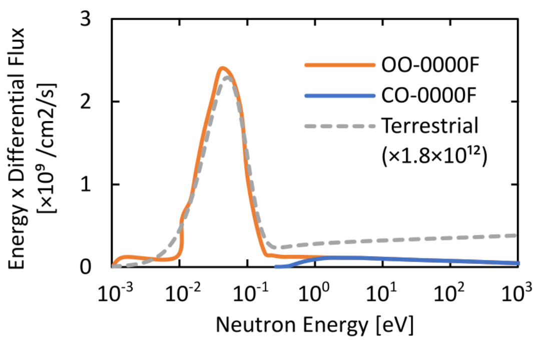

Fig. 1. Neutron energy spectra of KUR HWNIF [4] and terrestrial environment [5]

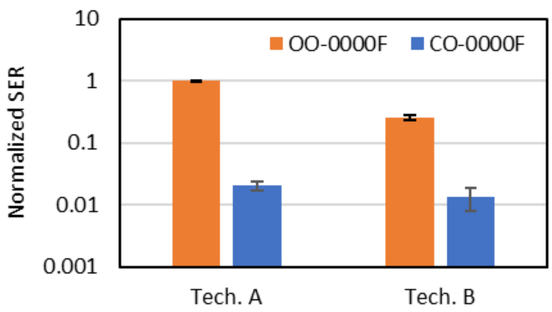

Fig. 2. Measured SERs for Tech. A and Tech. B SRAMs under two irradiation modes.

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Development of a Real-Time Monitoring System to Enhance Treatment Reliability in Boron Neutron Capture Therapy and Application to Nuclear Decommissioning

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INTRODUCTION: Real-time evaluation system of treatment effects in Boron Neutron Capture Therapy (BNCT) is important technique and required to improve treatment reliability. During BNCT, 478-keV gamma rays are emitted from the nuclear reaction between neutrons and ^{10}B, and various detectors have been proposed to image them. However, most methods have collimators [1–3], which act as scattering sources and reduce gamma-ray sensitivity. Although Compton cameras do not require collimators, their large size remains a drawback. In this study, we investigated the potential of an optical fiber-based dosimeter, previously tested with a ^{60}Co source and nuclear reactors at the Kyoto University Research Reactor Institute, and applied at the Fukushima Daiichi Nuclear Power Plant.

EXPERIMENTS: Four detector units were fabricated by coupling optical fibers with a newly developed scintillator based on the zero-dimensional perovskite-type halide crystal $Cs_3Cu_2I_5$. As shown in Fig.1, thermal neutrons were irradiated onto a boric acid sample using the E-3 neutron guide tube, and 478 keV prompt gamma rays were detected. The scintillator exhibits high light output and negligible hygroscopicity, providing advantages under conditions of low light collection efficiency, such as optical fiber readout systems. Image reconstruction was performed using a center-of-gravity algorithm. Considering the high count rates in practical environments, single-photon counting is difficult; therefore, we adopted a current-mode measurement without explicit energy discrimination. The influence of gamma rays other than 478 keV was also investigated.

RESULTS: Imaging of 478 keV gamma rays was successfully demonstrated using the optical fiber-based detector. The E-3 neutron guide tube, with a thermal neutron flux of approximately three orders of magnitude lower than actual treatment conditions, allowed single-photon counting. Imaging results with energy discrimination were compared to those using all spectral events (pseudo current mode), showing no significant difference. Consistent results were also obtained with an actual current-mode setup. Measurements using a Ge detector near the boric acid sample (Fig.1) showed 2.2-MeV and 511-keV gamma rays. However, 478-keV gamma-ray events were dominant. The 2.2-MeV gamma-event is negligible due to the small scintillator size (a few mm). Thermal neutron flux and background sources (e.g., oxygen-induced 511 keV gamma rays and activation) were silent in this experiment. Although evaluation under realistic conditions is required, in this time, we successfully demonstrated the imaging with current mode.

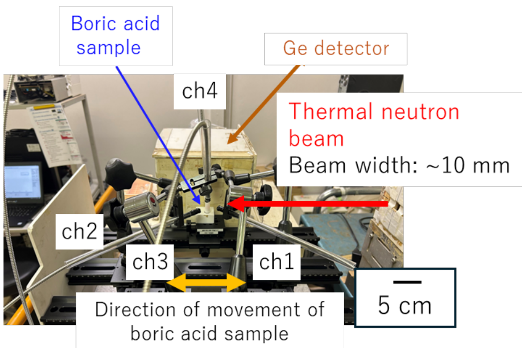

Fig.1. Schematic view of the setup for 478-keV gam-ma-ray detection with optical fiber-type detectors.

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