I-1. PROJECT RESEARCHES

Project 8

PR8

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:
R6P8-1: Study on the Measurement of Neutron Fluence and Gamma-ray Distributions Using a Combination of Thermoluminescent Plate and Converter (K. Shinsho *et al.*)
R6P8-2: Comparison of optical observation of boron dose by using of boron-added liquid scintilla-tors: a property of Insta-Fluor Plus (A. Nohtomi *et al.*)
R6P8-3: Development and demonstration of a Bonner sphere spectrometer and investigation on neutron dose measurement with a modified neutron servey meter (A. Masuda *et al.*)
R6P8-4: Radiation quality evaluation method for neutron irradiation field (N. Hu *et al.*)
R6P8-5: Evaluation of response characteristics of semiconductor detectors in neutron irradiation field (N. Hu *et al.*)
R6P8-6: Development of Scintillator for Thermal Neutron Detector in BNCT (N. Matsubayashi *et al.*)
R6P8-7: Study of Optically Stimulated Luminescent Dosimeter in BNCT Irradiation Field (N. Matsubayashi *et al.)*
R6P8-8: Establishment of Characterization Estimation Method in BNCT Irradiation Field using Bonner Sphere and Ionization Chamber (VIII) (Y. Sakurai *et al.*)
R6P8-9: Development of Real-time Boron-concentration Estimation Method using Gamma-ray Telescope System for BNCT (III) (Y. Sakurai *et. al,*)
R6P8-11: 4H-SiC Neutron Image Sensor for Boron Neutron Capture Therapy（V. T. Ha *et. al,*)
R6P8-12: Improvement of the SOF detector system for energy-dependent discrimination and long-term stability (M. Ishikawa *et al.)*
R6P8-13: Etch Pit Analysis of Solid-State Nuclear Track Detectors Using a 3D Confocal Laser Mi-croscope for Fast Neutron Dosimetry in BNCT (T. Takata *et al.*)
R6P8-14: Development of a Real Time Dose Rate Monitor for BNCT Using Novel Scintillation Materials (S. Kurosawa *et al.*)
R6P8-15: Measurement of Current-to-Flux Ratio in Neutron Fields for BNCT (I. Murata *et al.*)
R6P8-16: Performance Evaluation of a Real-Time Thermal Neutron Detector for BNCT (H. Tanaka *et al.*)
R6P8-17: Characterization of a Thermal Neutron Detector for Measuring the Shielding Performance of Thermal Neutron Shielding Materials (H. Tanaka *et al.*)

Research subjects R5P9-1,4-7, 11,13,15, and 17 are research and development on methods to measure thermal and fast neutrons and γ-rays. R5P9-2 and 9 propose methods to obtain boron distributions in realtime. R5P9-3,8, and 12 propose new methods for measuring neutron spectra. R5P9-14, and 16 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.

PR8-1

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 ^10B 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 selective irradiation of cancer cells at the molecular level. However, dosimetry techniques in mixed neutron–gamma fields have not yet been established. Therefore, in this study, we focused on the measurement 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 ceramic 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].

In this study, we investigated a new method for selective fast neutron measurement using a novel thermoluminescent plate combined with a converter based on the elastic scattering reaction between fast neutrons and hydrogen atoms.

EXPERIMENTS: A 3 mm thick polyethylene converter was placed in front of a BeO ceramic plate (11 mm square) and affixed using heat-shrink film. Irradiation was conducted using both the epi-thermal mode and the mixed mode. Three BeO ceramic plates with the converter and three without it were each irradiated for one hour. In the mixed mode, a 3 mm thick LiF plate was used to eliminate thermal neutrons, which would otherwise act as noise.

RESULTS: A comparison of the TL responses of BeO ceramic plates with and without the converter is shown in Table 1. In the epi-thermal mode, except for sample No.10, the plates with the converter exhibited approximately 13% higher TL responses, indicating an increase attributable to fast neutrons. Only sample No.10 showed a lower TL response, which is likely due to insufficient contact between the converter and the ceramic plate.

In contrast, in the mixed mode, no significant difference in TL response was observed between plates with and without the converter. This may be due to the relatively smaller contribution of fast neutrons to the TL response, as a large proportion of γ-rays is present in the mixed mode, and possibly due to insufficient shielding of thermal neutrons. Further evaluation will be conducted by comparing these results with Monte Carlo simulation data to assess the utility of the method.

Table 1. TL responses of BeO ceramic plates with and without converter

Epi-thermal mode				
converter	No.	TL intensity	Ave.	S.D.
Without	BeO07	6699597	6637626	58620
	BeO08	6630220		
	BeO09	6583061		
With	BeO10	6265652	7196678	811354
	BeO11	7571694		
	BeO12	7752687		
converter	No.	TL intensity	Ave.	S.D.
Without	BeO13	9328973	9775622	425445
	BeO14	9821797		
	BeO15	10176097		
With	BeO16	9441903	9345213	86850
	BeO17	9273821		
	BeO18	9319916		

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 *et al.,* J. Mater. Sci.: Mate. Elec., **33** (2022) 20271–20279.

PR8-2

Comparison of optical observation of boron dose by using of boron-added liquid scintillators: a property of Insta-Fluor Plus

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INTRODUCTION: For boron-neutron capture therapy (BNCT), the information of boron dose plays a significant role. In our previous paper [1], a boron-added liquid scintillator has been proved to be very useful for the direct evaluation of boron dose by observing the luminescence with a CCD camera during the neutron irradiation. In that paper, as an attempt, we dissolved trimethyl borate in a commercially-available liquid scintillator, Insta-Gel Plus. Hence, at the last machine time, we tested other two types of liquid scintillators and the results inferred a possibility of high light-output yield when using Insta-Fluor Plus from the view point of its chemical composition. In the present work, in addition to other three types of commercially-available liquid scintillators, Insta-Fluor Plus was examined as boron-added liquid scintillator for comparison.

EXPERIMENTS: We dissolved trimethyl borate in four types of commercially-available liquid scintillator (Insta-Fluor Plus, 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. On the other hand, Insta-Fluor Plus is made of mainly sole pseudocumene. 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 mainly sole diisopropyl naphthalene isomers. 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 450 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 were clearly observed for all types of boron-added liquid scintillators for 450 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. Contrary to our inference, the luminescence of Ultima Gold F was the brightest among the four and approximately 1.6 times higher than that of Insta-Gel Plus. And, unexpectedly, the luminescence of Insta-Fluor Plus was approximately equivalent to that of Ultima Gold XR and was approximately 80 % of that of Insta-Gel Plus.

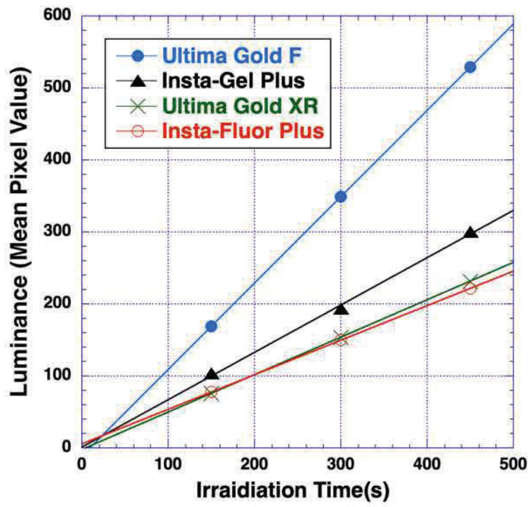

Fig. 1. Luminance value for different types of boron-added liquid scintillators as a function of neutron irradiation time.

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 and investigation on neutron dose measurement with a modified netron servey meter

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INTRODUCTION: Neutron spectral fluence measurement techniques are required in boron neutron capture therapy (BNCT). A BSS for intense neutron beams is developed and tested 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). A simple technique for measuring neutron dose in BNCT facilities is also needed. In this study, we fabricated a commercially available gas-based neutron survey meter customized for high-intensity neutrons and demonstrated it at the 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]. Output signals from PMT were processed using a preamplifier (ORTEC 113) and a signal processing and acquisition system (Amptek PX5). Previous studies had suggested the effectiveness of measurements using spheres with thinner moderators, so in this study, spheres with diameters of 1.5", 2", and 2.5" were added. In the demonstration of the survey meter, the direct signal from the detector was amplified by a linear amplifier, and the pulse height distribution was acquired by an ADC (Amptek MCA8000D).

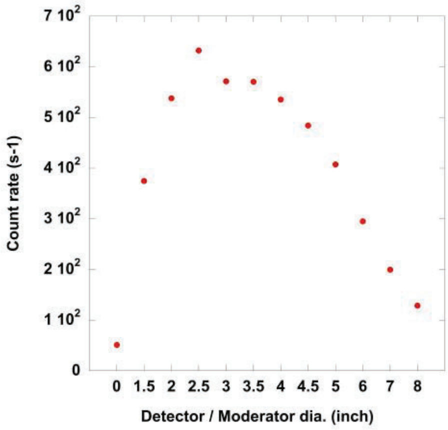

Fig. 1. Results of Bonner sphere measurements.

RESULTS: The measurement results using a Bonner sphere detector are shown in Figure 1. The count rate was confirmed to be dependent on the sphere diameter, and a reasonable decrease in the count rate was observed with a small diameter detector that is sensitive to the low energy region. The results for the neutron survey meter are shown in Figure 2. A pulse height spectrum was obtained that appears to be a superposition of the 14N(n,p)14C reaction caused by low-energy neutrons and the H(n,n)p reaction caused by fast neutrons.

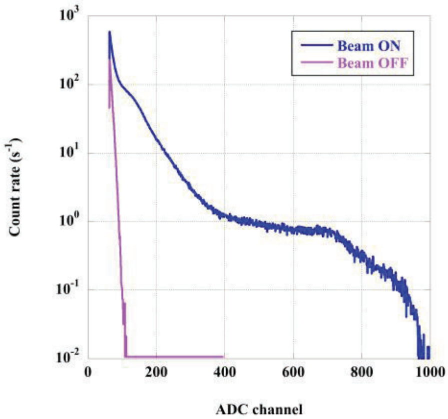

Fig. 2. Results of neutron survey meter measurements.

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PR8-4

Radiation quality evaluation method for neutron irradiation field

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INTRODUCTION: In a typical BNCT irradiation field, a mixture of radiation types is present, and measurements are by no means simple. A proportional gas counter is commonly used to measure the radiation beam quality of a mixed irradiation field, such as a neutron/gamma radiation field. To measure the biological effect of a neutron beam, a tissue equivalent proportional counter (TEPC) was used, and the gas density was reduced to mimic a micrometer sized cell volume.
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EXPERIMENTS: Experiment was performed using the epithermal irradiation mode of KUR at 1 MW. The TEPC was placed free-in-air in the center of the irradiation field with 1 hour measurement time. The raw data was converted to lineal energy spectrum (y distribution) and compared with simulation results calculated using Monte Carlo simulation (Particle and Heavy Ion Transport code System: PHITS).
****

RESULTS: Figure 1 shows the experimental set up and the results. The proton edge at approximately 100 keV/μm was clearly visible and closely matched the PHITS Monte Carlo simulation results. Deviation in the high lineal energy region (> 200 keV/μm) was observed. Possible reason could be due to the overestimation of the PHITS calculation in the high lineal energy region, which has been reported previously [1].
Repeating the experiment with a higher reactor power (5MW) or longer exposure time may improve the statistical uncertainty.
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REFERENCES:
[1] T. Sato *et al.,* Phys. Med. Biol., **68** (2023).

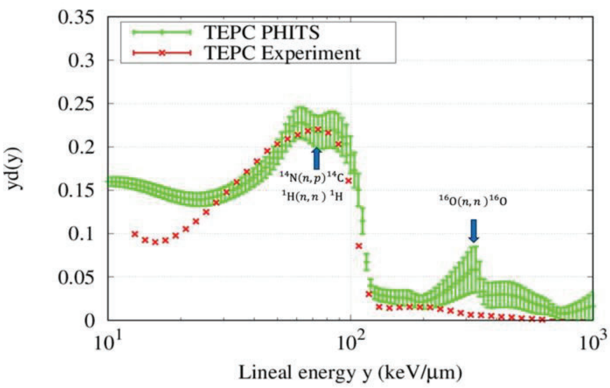

Fig. 1. Left) Experimental set up. Right) Experimentally measured lineal energy distribution (ydy) of KUR epithermal mode.

PR8-5

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 deposition 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. A commonly used detector to measure the microdosimetric distribution is a gas filled proportional counter [1]. Initial experiments were performed using this detector as a base for comparison with the silicon microdosimeter.
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EXPERIMENTS: The microdosimetric spectrum of the heavy water irradiation facility (epithermal irradiation mode) of the Kyoto University Research Reactor was measured using a proportional gas counter. Both a tissue equivalent walled (tissue equivalent proportional counter: TEPC) and graphite walled counter (carbon walled proportional counter: CWPC). Measurements were performed free-in-air at the center of the irradiation field. One-hour measurements were performed with the reactor power at 1 MW.
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RESULTS: Figure 1 represents the frequency distribution curve of the KUR epithermal mode measured with both types of proportional counters. Proton events (20 – 100 keV/μm) were observed with the TEPC (nitrogen and hydrogen component of the wall) but not with the CWPC (no hydrogen component). By subtracting these two results, gamma ray events can be separated from neutron events. These results will be compared with the silicon microdosimeter results.
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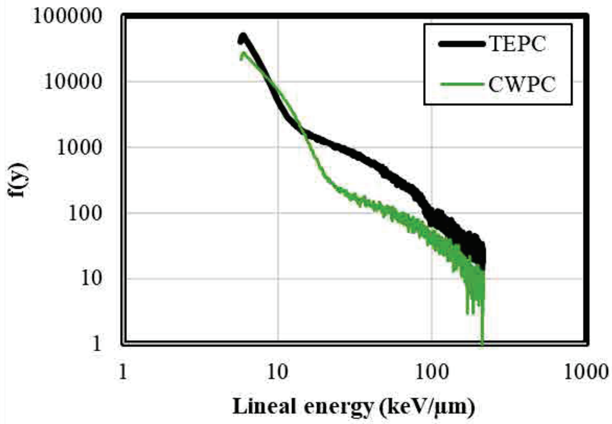
REFERENCES:

[1] H. Rossi, Radiation Research Supplement, **2** (1960) 290-299.



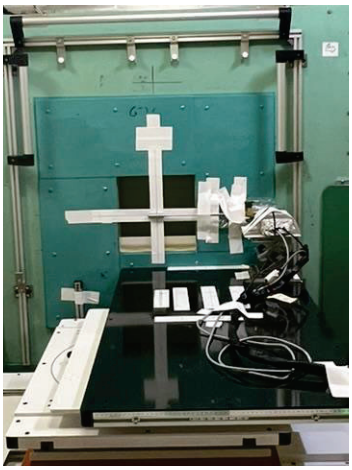


Fig. 1. Left) The frequency distribution curve of the KUR epithermal mode measured with the TEPC (black line) and CWPC (green line). Right) Image of the experimental set up.

PR8-6

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 developed a new scintillator with fast response and high detection efficiency.
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EXPERIMENTS: As the thermal neutron detector for BNCT, a scintillator with 0.3~0.6 mm is mounted on the tip of the fiber to reduce gamma-ray sensitivity. In this study, we selected LiBr/CeBr_3 and Ce:LiBr/LaBr_3 eutectics, which have fast response and high light yield [2][3]. Since the selected scintillators were hygroscopic, they were packaged using quartz glass and cement to prevent exposure to the outside air. The irradiation tests of each detector were performed at Kyoto University Research Reactor-Heavy Water Neutron Irradiation Facility (KUR-HWNIF) [4]. A Cd shutter was installed to change the thermal neutron flux with each aperture. The irradiation tests were carried out by changing the aperture to 0, 100, 200, 300, 400, 500, and 600 mm. The scintillation lights though the fiber were measured by a photomultiplier tube (PMT). The signal from the PMT was processed by a multi-channel analyzer (MCA). The pulse height distributions were measured by the MCA and the neutron count rates were evaluated by summarizing high channel area to remove the gamma-ray events.
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RESULTS: In the irradiation tests at KUR-HWNIF, neutron peaks were not formed in the pulse height distribution. However, neutron events were identified in higher channel area than gamma-ray events, and the count rate varied with Cd shutter aperture. As shown in Fig. 1, the neutron count rates obtained by the detectors and thermal neutron flux showed good linearity. It is confirmed that the detectors developed in this study can be used as neutron monitor for BNCT. In the future, we will carry out the irradiation tests repeatedly to evaluate the long-term stability of the detector.
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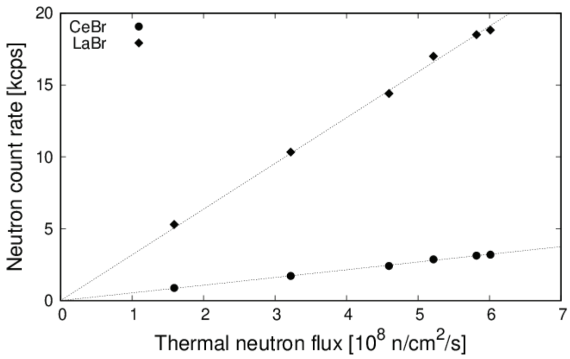

Fig. 1. Relationship of the thermal neutron flux

REFERENCES:

[1] H. Tanaka *et al.,* Rev. Sci. Instrum., **88 (5)** (2017) 056101.
[2] R. Yajima *et al.,* Jpn. J. Appl. Phys., **61** (2022) SC1028.
[3] Y. Takizawa *et al.,* Nucl. Instrum. Methods. Phys. Res A., **1028** (2022) 166384.
[4] Y. Sakurai *et al.,* Nucl. Inst. Methods. Phys. Res., **453(3)** (2000) 569-596.

PR8-7

Study of Optically Stimulated Luminescent Dosimeter in BNCT Irradiaiton 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. To use the OSLD in the BNCT irradiation field, the sensitivity to thermal neutron needs to be evaluated [3]. In this study, before the irradiation tests of the OSLD, the characteristics of the irradiation field were evaluated.

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EXPERIMENTS: The irradiation tests of the BNCT irradiation field were performed at Heavy Water Neutron Irradiation Facility (HWNIF) at Kyoto University Research Reactor (KUR) [4]. A cadmium shutter, which shields only thermal neutrons, was installed to control the thermal neutron flux with each openness. To investigate the thermal neutron flux per the cadmium shutter openness, the irradiation tests were carried out by changing the openness to 0, 100, 200, 300, and 600 mm. A gold foil was placed in the center of the irradiation field, and the radioactivity of the gold foil was measured by high-purity germanium detector. Thermal neutron flux was measured using the reaction rate of the gold foil, the detection efficiency of the germanium detector, the gamma-ray emission rate of the gold, the irradiation time, and the measurement time.

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RESULTS: Fig.1 shows thermal neutron flux by changing the cadmium shutter openness. The thermal neutron flux of KUR-HWNIF was found to be from 1.4×10^7 to 1.2×10^9 cm^{-2} s^{-1} depending on the openness. It was found that the range of thermal neutron flux was over an order of magnitude at KUR-HWNIF. Since the cadmium had a large cross section in the thermal neutron energy region, the high energy neutron was not changed depending on the cadmium shutter openness. The OSLD was manly sensitive to thermal neutron, and the KUR-HWNIF is a suitable irradiation field for evaluating the thermal neutron sensitivity of the dosimeter.

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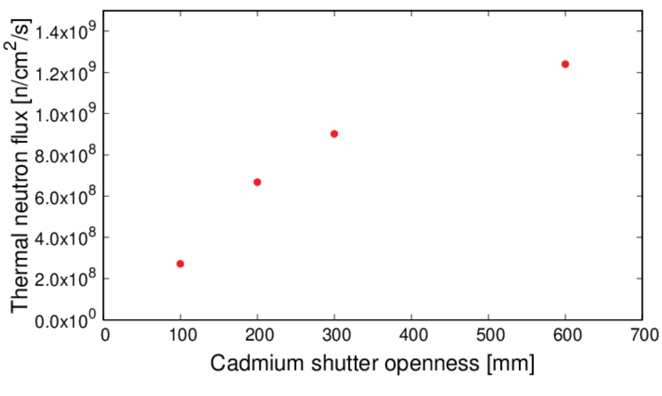

Fig. 1. Relationship of the thermal neutron flux and the cadmium shutter openness.

REFERENCES:

[1] K. Yamamoto *et al.,* Res. Dev. NCT, **46** (2002) 499-503.
[2] N. Matsubayashi *et al.,* Radi. Meas., **161** (2023) 106900.
[3] Y. Sakurai *et al.,* Nucl. Inst. Methods. Phys. Res., **453(3)** (2000) 569-596.

PR8-8

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

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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) [2,3]. In 2024, a prototype of CHARMS was manufactured and a validation experiment was performed to verify its effectiveness.

MATERIALS AND METHODS: A LiCaAlF6 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].

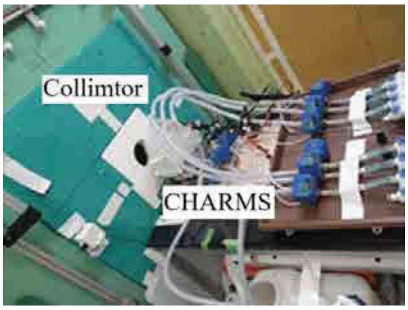

Fig. 1. Experimental setup for CHARMS measurements at KUR-HWNIF.

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.

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] J. Prateepkaew *et al.,* Appl. Radiat. Isot., **219** (2025) 111717.
[4] Y. Sakurai and T. Kobayashi, Nucl. Instr. Meth. A, **453** (2000) 569-596.

PR8-9

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

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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 2024 as well.

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. The simulation calculation was performed using Particle and Heavy Ion Transport code System (PHITS) version 3.25 [4]. To simplify the simulation process, the irradiation room and the telescope system were separately used as the simulation geometry.

RESULTS: The count rates for 478-keV prompt gamma rays with the different irradiation conditions were obtained from the experimental results. In the case of the 70-ppm tumor sphere, the experimental count rate was 29.6 cps (s^{-1}). 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. The more precise estimation will be performed for the B-10 concentration, size and position of the tumor sphere, and for the position of two telescope collimators. Moreover, the effective range for the discrimination between tumor and normal parts will be clarified.

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.
[4] T. Sato *et al.,* J. Nucl. Sci. Technol., **61** (2024) 127-135.

PR8-10

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, for making this therapy more accurate one, it is better to measure the neutron beam's position and profile in real time. On the other hand, silicon carbide (SiC) semiconductors integrated circuits have been developed as radiation hardened electronics [1], and the SiC CMOS image sensors also have been demonstrated [2]. We are suggesting a neutron CMOS image sensor by combining the SiC CMOS image sensor and neutron conversion layer for the neutron real time imaging [2]. In this year, we continue to design and fabricate the neutron CMOS image sensors and simulate the device operations by using circuits simulator.

EXPERIMENTS: The structure of our neutron sensor is based on a three- and four-transistor type CMOS 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.

RESULTS: Figure 1 shows the device layout of neutron image sensors. Now this chip is under fabrication. On the other hand, circuit-level simulation was also carried out. In this simulation with the realistic device parameters, real time output signals were observed.

REFERENCES:
[1] Masayuki Tsutsumi *et al.,* IEEE Electron Device Lett., **44(1)** (2023)100 - 103.
[2] Tatsuya Meguro *et al.,* Appl. Phys. Ex-press, **17** (2024) 081005-1 - 081005-5.
[3] M. Taniguchi *et al.,* "Neutron Image Sensor for Boron Neutron Capture Therapy", The International Symposium on Biomedical Engineering 2022 (2022) 66.

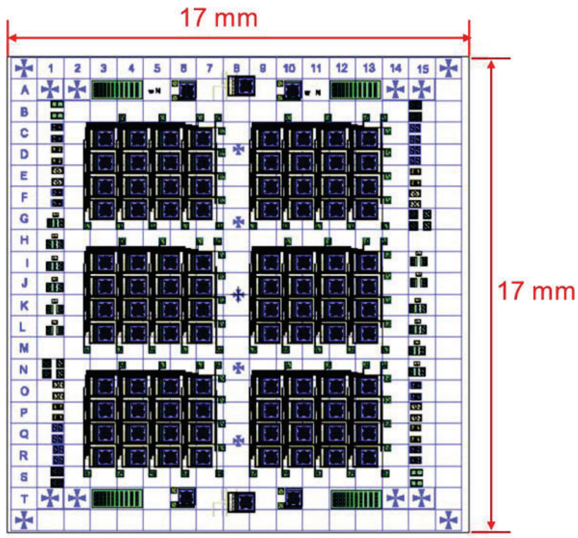

Fig. 1. Chip layout of the neutron CMOS

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

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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 tried to estimate the neutron energy spectrum at KUR HWNIF (Heavy Water Neutron Irradiation Facility) using 2-dimensional thermal neutron flux distribution.

EXPERIMENTS: For energy spectrum estimation, the MLEM (Maximum Likelihood Expectation Maximization)-based energy spectrum estimation was tested using Monte Carlo simulation (PHITS ver 3.32) data assuming 2D thermal neutron flux distribution using SOF detectors prior to actual experiment. As shown in Fig. 2 (a), the estimated energy spectrum showed a good agreement with energy spectrum used for neutron source.

In measuring 2D thermal neutron flux distribution, the assigned machine time of 3 hours is insufficient for accomplish data acquisition. So, we expected efficient data acquisition by using high-sensitivity SOF probe. 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 10 sec. However, as shown in Fig. 2(b), the estimated neutron energy spectrum using the measured data shows a rather large deviation in the fast energy region. This is because photon signals were saturated due to high thermal neutron flux with 5MV operation, so measurement data was not adequate for analysis.

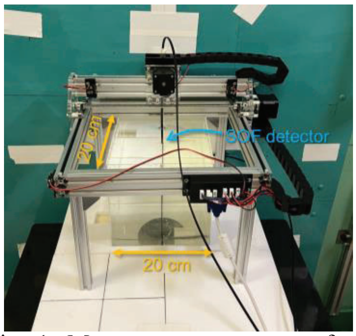

Fig. 1. Measurement geometry for neutron energy spectrum estimation using MLEM unfolding method.

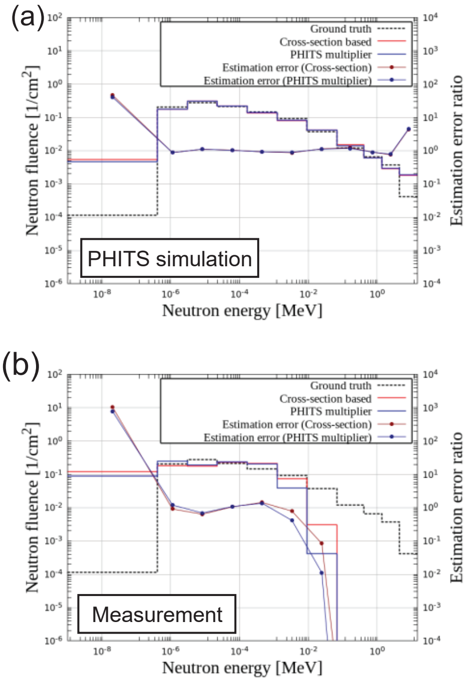

Fig. 2. Estimated neutron energy spectrum bv SOF detector.

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.

PR8-12

Etch Pit Analysis of Solid-State Nuclear Track Detectors Using a 3D Confocal Laser Microscope for Fast Neutron Dosimetry in BNCT

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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, causing an uncertainty of the derived fast neutron dose. Also, perturbation of the radiation field caused by the gas cavity must be taken into account.

In this study, utilization of solid-state nuclear track detector (SSNTD), which is not sensitive to gamma-rays and has less field perturbation than ionization chambers, has been investigated as an alternative method. It is known that a pit shape formed on the SSNTD by chemical etching depends on LET of incident particles [1]. In the application to BNCT, small and shallow pits formed by low-energy recoil protons need to be analyzed. We report the applicability of a 3D-measuring confocal laser microscope for the pit-shape measurements.

MATERIALS AND METHODS: Commercially available SSNTDs (Baryotrack, Nagase Landauer, Ltd.) were irradiated with two types of charged particles induced by low energy neutron beam from the E-3 guide tube at KUR [2]. One is an alpha particle from $^{10}B(n,\alpha)^{7}Li$ reaction occurred in the boric acid solution. Another is a proton from $^{14}N(n,p)^{14}C$ reaction occurred in the atmospheric air [3]. The irradiated detectors were etched with 6M NaOH solution for 2 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. 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: The formation of pits was observed on the SSNTDs with a variety of its size. An example of the measured surface profile is shown in Fig. 1. The elliptical shape of the pit aperture and the conical shape along the direction of the particle track can be clearly observed, confirming that the 3D shape measurement has more advanced feature than the usual 2D pit measurement with an optical microscope. We will develop a tool to quickly analyze the shapes of many pits and investigate the measurement of the energy and angular distribution of incident radiation.

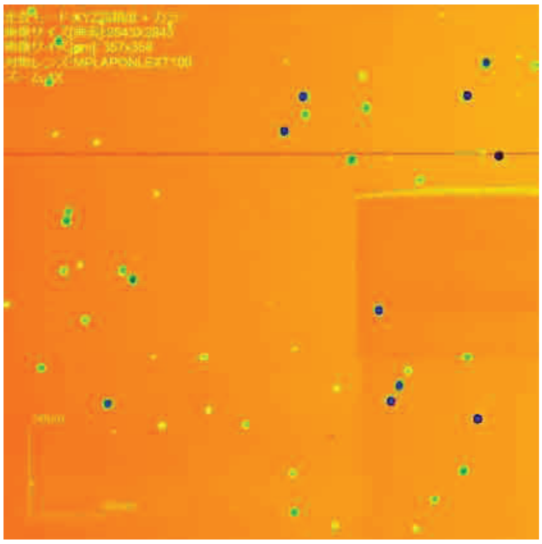

Fig. 1 Surface profiles with conical-shaped etch pits formed on SSNTD.

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. Takata *et al.,* KURNS Progress Report 2023, R5P9-10 (2023) 86.

PR8-13

Development of a Real-Time Dose Rate Monitor for BNCT Using Novel Scintillation Materials

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INTRODUCTION: Boron neutron capture therapy (BNCT) is radiation therapy based on the nuclear reaction of boron (^{10}B) and thermal neutrons. To estimate the treatment effect in real-time, the use of prompt gamma rays (478 keV) emitted by the ^{10}B(n,α)^{7}Li reaction has been proposed using a collimator [1]. Although the proposed detector uses a collimator, the collimator led to a decrease in detection efficiency due to the collimator space and an increase in gamma-ray background by scattering. From the above results, we have developed a new detector consisting of a scintillator, optical fiber and photomultiplier tube without such a collimator.
The scintillators are required to have high output, good non-proportionality (NPR), and low hygroscopicity. In this study, we focused on Tl-doped $Cs_3Cu_2I_5$ (Tl:CCI) scintillator [2] because of a high light output of more than 98,200 photons/MeV and low hygroscopicity.

EXPERIMENTS: Tl:CCI crystals were grown by the vertical Bridgman-Stockburger method, and the crystal phase was verified by powder X-ray diffraction. To evaluate the light output and NPR, the pulse height spectra excited by several line gamma rays from ^{137}Cs source and other sources were measured with a photomultiplier tube (R7600U-200, Hamamatsu K.K.), shaping amplifier (572A, ORTEC) and multichannel analyzer (Pocket MCA8000D, AMPTEK).
Using Tl:CCI and optical fiber, we measured 478-keV gamma rays originating from samples containing ^{10}B at The Heavy-Water Thermal Neutron Facility at Kyoto University Research Reactor. The scintillation photons were measured with a photomultiplier tube and pico-ammeter. Here, the target samples had different concentrations of ^{10}B, and the samples were irradiated with neutrons with a flux of around 10^9 cps.

RESULTS: The scintillation photons were converted to current with a pico-ammeter, and Figure 1 shows current values as a function of ^{10}B concentration. These results indicated our system has concentration sensitivity. Here, the typical ^{10}B concentration in the actual application is the order of 10 ppm (10-50 ppm). Since the detection lower limit of our system was found to be 100 ppm, the sensitivity of this system should be improved by an order of magnitude. Thus, now we have developed scintillation materials, their size and the detection sensitivity of the photo sensor, and this detection lower limit is found to be a few ppm. As a next step, we also measured and found the position sensitivity.

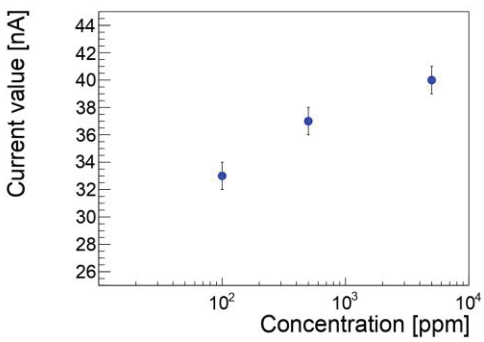

Fig. 1. Current value from scintillation signal as a function of concentration of ^{10}B in the target sample.

REFERENCES:
[1] K. Okazaki *et al.,* NUCL INSTRUM METH A, **1055** (2023) 168546.
[2] L. Stand *et al.,* Instrum. Methods Phys. Res. A, **991** (2021)164963.
[3] T. Jun *et al.,* Adv. Mater., **30** (2018) 1804547.

Measurement of Current-to-Flux Ratio in Neutron Fields for BNCT

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INTRODUCTION: BNCT is a promising cancer therapy which kills only tumor cells selectively. The neutron field 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 is overestimated by about 196 % compared to the calculated value. We discussed one possible reason for this error was the unknown current-to-flux (C/F) ratio of the neutron source in KUR, Kyoto University Reactor. Therefore, the objective of this work is to measure the C/F ratio of the neutron source for BNCT in KUR.

EXPERIMENTS: We have developed a device to measure the C/F ratio. The device consists of an acrylic container with two tubes passing through it. The two tubes are set so that one is perpendicular to the surface of the neutron source and the angle between the two tubes is 30 deg. As shown in Fig. 1. The acrylic container is filled with B_4C powder and water to shield neutrons. As an activation foil, two Au foils covered with a Cd sheet are placed at an equal distance from the neutron source. Because the angular distribution of the neutron beam is determined by the C/F ratio, the C/F ratio can be estimated from the ratio of the radioactivity of the Au foils. Using the device in Fig. 1, we conducted an experiment to measure the C/F ratio at KUR. Irradiation was carried out for 8 min in 5 MW operation.

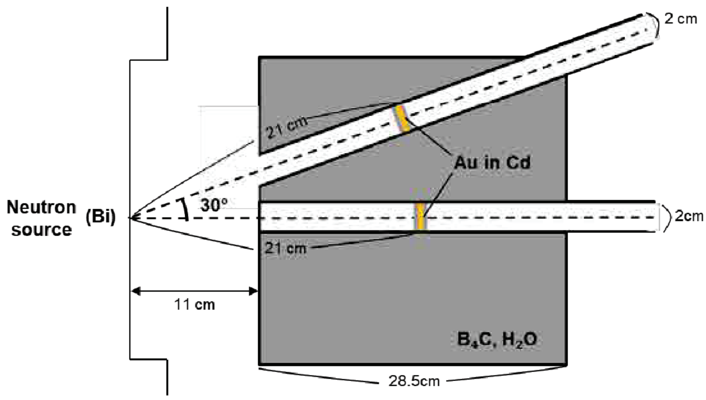

Fig.1 Device for measurement of C/F ratio.

RESULTS: The results of the experiment are shown in Table 1. The C/F ratio was deduced to be 0.543±0.042 from the ratio of the ^{198}Au activities. However, the calculated value of the C/F ratio obtained by the simulation was 0.501±0.002, which was slightly different from the experimental results. Since the device is not completely shielded from neutrons, the discrepancy could be due to neutrons entering the device from the side surface of the tube. Therefore, in the future, we will remove the contribution of neutrons coming from the side surface of the tube and measure a more accurate C/F ratio.

Table.1 C/F Ratio.

	0°	**30°**
Au Radioactivity [Bq]	544±6	526±6
Nomalized Au Radioactivity [Bq]	544±6	514±5
C/F Ratio	0.543±0.042	

REFERENCES:

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

PR8-15

Performance Evaluation of a Real-Time Thermal Neutron Detector for BNCT

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INTRODUCTION: In quality assurance and quality control (QAQC) for boron neutron capture therapy, it is necessary to measure the thermal neutron flux in a water phantom. Until now, the thermal neutron flux has been measured using the gold activation method. Since the start of accelerator BNCT in medical institutions, the number of measurements required for QAQC has increased. Therefore, a method that can measure more quickly than the gold activation method is desired.

We have developed a thermal neutron real-time neutron detector using a combination of LiCAF scintillators and optical fibers [1], and are considering the use of scintillators with fast scintillation light decay. In this study, we report the results of adapting a lithium glass scintillator with a fast decay time to a heavy water neutron irradiation facility.

EXPERIMENTS: A lithium glass scintillator was installed at the tip of an optical fiber, and the scintillation light was guided through the optical fiber to a photomultiplier tube. The signal was amplified in the photomultiplier tube, and the pulse height distribution was acquired using a multichannel analyzer.

The scintillator was placed at a depth of 2 cm in a water phantom, and an epithermal neutron beam with a collimator diameter of 12 cm was irradiated.

RESULTS: Figure 1 shows the results of the pulse height distribution. The peak around 100 channels is formed by the total energy absorption of the Li(n,α)T reaction. Since gamma rays are events with energies of approximately 50 channels or less, events with energies of 70 channels or more were considered to be neutron-induced events. Figure 2 shows the time trend of the thermal neutron flux. A constant thermal neutron flux distribution was confirmed.

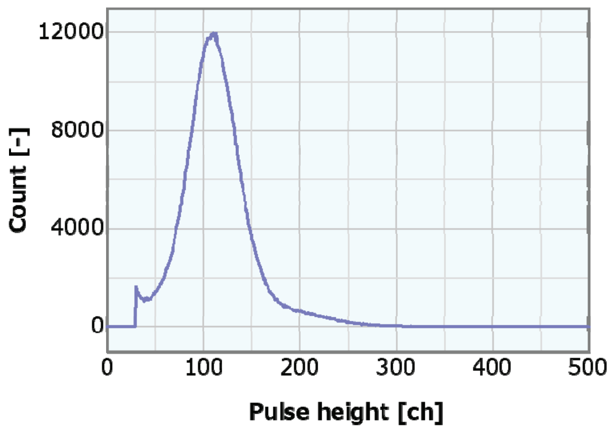

Fig. 1. Pulse height distribution of lithium glass scintillator.

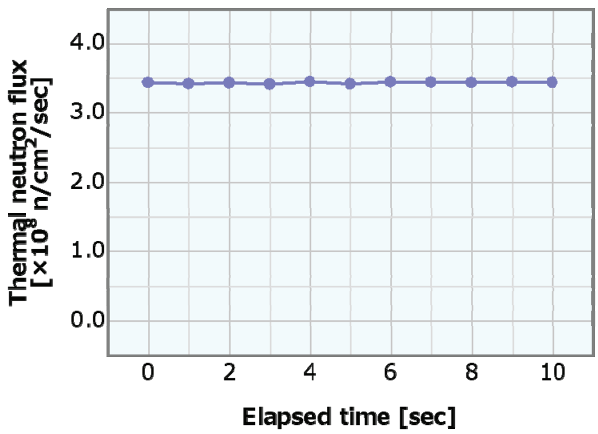

Fig. 2. Time trend of thermal neutron flux.

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

PR8-16

Characterization of a Thermal Neutron Detector for Measuring the Shielding Performance of Thermal Neutron Shielding Materials

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INTRODUCTION: Since the start of insurance-covered treatment with accelerator-based BNCT (Boron Neutron Capture Therapy) systems, a significant increase in the number of clinical cases is anticipated. In BNCT irradiation fields, there is a possibility that semiconductor-based electronic devices—such as neutron monitors, patient monitoring cameras, and implanted pacemakers—will be exposed to irradiation. If a semiconductor device contains nuclides with large thermal neutron cross sections, the irradiation of thermal neutrons may induce the generation of charged particles within the semiconductor material. These charged particles create electron-hole pairs along their tracks, and the resulting charge can lead to noise currents within the semiconductor device. Such noise currents may cause malfunctions of the semiconductor devices. To prevent radiation damage induced by thermal neutrons, we are developing materials capable of efficiently shielding thermal neutrons.

To evaluate the performance of these thermal neutron shielding materials, a thermal neutron beam is required. By placing a thermal neutron detector behind the shielding material and measuring the resulting count rate, the attenuation performance of the shielding material can be assessed. In the current fiscal year, we have characterized the thermal neutron detector intended for this evaluation.

EXPERIMENTS: The thermal neutron beam extracted from the E3 guide tube facility was used in this study. The thermal neutron detector needed to fulfill two requirements: it had to measure thermal neutrons transmitted through the shielding material, and it had to have a sensitive volume smaller than the size of the thermal neutron beam in order to minimize the effects of scattered neutrons.

In this study, we employed a thermal neutron detector consisting of a 0.3 mm square LiCAF scintillator coupled to an optical fiber with a core diameter of 0.6 mm. The optical fiber was connected to a photomultiplier tube, and the resulting signals were processed using a multichannel analyzer.

RESULTS: The obtained pulse height distribution is shown in the figure 1. To minimize the contribution from gamma rays, the integration was performed over the higher pulse heights from the peak center. The thermal neutron flux measured using the gold foil activation method was 2×10^{6} (n/cm^{2}/s), and the corresponding count rate was 17 cps, resulting in a thermal neutron sensitivity of 9×10^{-6} (cps/(n/cm^{2}/s)). Measurement of the shielding performance of a typical shielding material yielded a transmission rate of 0.01, indicating that evaluation with a statistical error of 2% can be achieved within 1.5 hours.

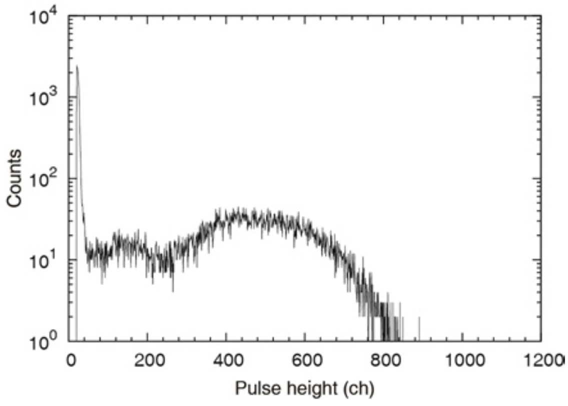

Fig. 1. Pulse height distribution of small LICAF scintillator.