BNCT dosimetry with thermoluminescent dosimeter

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Abstract: A pair of thermoluminescent dosimeters made of lithium fluoride compounds could measure a thermal neutron flux. The calibration factor (3.8 × 10^4 $cm^{-2}nC^{-1}$) evaluated in the previous study was verified for the measurement of the thermal neutron flux in a research reactor. The conventional thermal neutron flux measurement uses gold foil or gold wire, and the measured thermal neutron flux is used to evaluate the boron dose, a dose contributing to the treatment in the boron neutron capture therapy. The use of a cadmium filter is essential because the neutron cross-section of gold has a relatively low energy range showing a 1/v behavior. However, thermoluminescent dosimeters made of lithium fluoride compounds have a much wider energy range in which the cross-section of lithium is 1/v, and the tendency is similar to that of boron so that the dose of boron is able to be evaluated more accurately than gold. To verify the measured calibration factor, a research/educational reactor of Kyunghee University was used. When the thermal neutrons of the nuclear reactor were measured using gold, it was measured as 2.17 × 10^4 $cm^{-2}W^{-1}s^{-1}$, and the thermoluminescent dosimeter measured as an average 2.29 × 10^4 $cm^{-2}W^{-1}s^{-1}$ using a cadmium filter. The thermal neutron flux was accurately measured. In conclusion, through this study, a more accurate method of evaluating boron dose using a thermal fluorescence dosimeter was proposed.

1. Introduction

The Boron Neutron Capture Therapy (BNCT) is binary radiation treatment modality. It delivers radiation damage to the tumor cell selectively using ^{10}B compound and neutron beam. The ^{10}B nuclei which have high thermal neutron capture cross-section, release α particle and ^{7}Li ion in $^{10}B(n, \alpha)^{7}Li$ reaction. These products have high linear energy transfer characteristics and their ranges are around single cell diameter (~10 μm) in the tissue. The BNCT can selectively treat the tumor cell with the targeted boron drug delivery [1, 2]. Therefore, measuring thermal neutron flux should be done in air or in phantom configuration is important to optimize therapeutic effect at the treatment planning procedure.

The measurement of thermal neutron flux in the neutron and gamma mixed radiation fields is commonly done with gold foil activation method. However, this method requires additional instruments such as a High Purity Germanium (HPGe) detectors, liquid nitrogen cooling system and lead shielding blocks. In this study, we validated the calibration factor of thermoluminescent dosimeters (TLD) To separate the neutron and gamma induced signals of TLDs in the mixed radiation fields, we used pairs of TLD-600 and TLD-700 and cadmium sheets. The cadmium sheets were used to estimate the thermal neutron induced signals from total neutron induced signals.

The primary object of this study is to develop the method to estimate the thermal neutron flux with TLDs. The TLDs were irradiated at the research/educational reactor and the measured thermal neutron flux was compared with the gold activation analysis.

2. Materials and Methods

2.1 TLD reading

The 21 TLD-600 and 21 TLD-700 (Harshaw, USA) chips were prepared for this study. Its diameter was 4.5 mm and the thickness was 0.6 mm. The TLDs used in this study are lithium fluoride based materials (LiF:Mg,Ti). TLD-600 was enriched by ^{6}Li (95.6%) whereas TLD-700 was enriched by ^{7}Li(99.99%) [3]. Due to the difference in neutron cross-section of ^{6}Li and ^{7}Li, TLD-600 is sensitive to neutrons and TLD-700 is insensitive to neutrons [4]. The TLDs were annealed with an electric furnace at 400℃ for 1 hour followed by 100℃ for 2 hours to eliminate the residual signals before the irradiation.

The readout of TLDs was done by using Harshaw TLD reader (Model 3500). The TLDs were linearly heated from 50 ℃ to 300 ℃ at 10 ℃/sec. The acquisition time was 33.3 seconds.

The TL signal was converted in the unit of electric charges by integrating the glow curves from channels 72 to 200. The thermal neutron induced TL signal was separated by using the combination of TLD-600, TLD-700 and cadmium sheets with their different interaction probabilities of neutrons and gamma rays.

2.2 TLD validation

To evaluate whether the calculated TLD calibration factor is valid, a research/educational reactor at Kyunghee University, known as a thermal neutron source, was used. The thermal neutron flux measured through the applying calibration factors of TLDs was compared with the thermal neutron flux using the conventional gold wire activation method. At this time, the thermal neutron flux is the Westcott fluence.

In this study, measurements were made using a Cd sheet that absorbs thermal neutrons with high probability. Therefore, if Cd sheet is placed in the existing beam port in AGN-201K, it absorbs too many thermal neutrons and lowers the criticality. Due to the insufficient margin of the criticality of the educational/research reactor, the neutron irradiation was conducted at the top of the vessel far from the core.

3. Results and discussion

3.1 TLD validation

The gold wire activation methods conducted in this study are summarized in Table. 1. The thermal neutron flux measured by the gold wire activation method is 2.00 × 10^5 $cm^{-2}s^{-1}W^{-1}$. The self-shielding correction factor of 0.2 mm diameter gold wire was 0.928 by MCNP6 simulations. The corrected value was 2.17 × 10^5 $cm^{-2}s^{-1}W^{-1}$ and it used as the standard for thermal neutron flux measurement.

Irradiation	**Bare**	**Cd covered**
Gold mass [mg]	183.1	185.6
Cooling time [sec]	9289	1523
Measuring time [sec]	7212	7211
Count	15916	677
A_{sat} per nuclide	2.06 × 10^{-17}	8.56 × 10^{-19}
Neutron flux (Westcott) [$cm^{-2}s^{-1}W^{-1}$]	2.08 × 10^5	8.56 × 10^3
Thermal neutron flux (Westcott) [$cm^{-2}s^{-1}W^{-1}$]	2.00 × 10^5	

Table 1. Summary of gold wire activation method in this study.

Table. 2 shows the thermal neutron flux at the irradiation site of the reactor by multiplying the TLD reading value obtained in the TLD validation setup by the calibration factor. In 4 measurements, when the thermal neutron flux was normalized to the reactor power and irradiation time, the average value was 2.285 × 10^5 $cm^{-2}W^{-1}s^{-1}$. The thermal neutron flux measured by TLD showed an average difference of 5%.

Irradiation	**#1 (2W, 0.5 h)**	**#2 (2W, 0.5 h)**	**#3 (4W, 0.5h)**	**#4 (4W, 0.5h)**
Thermal neutron induced signal (nC)	6720.67	6396.22	13873.72	13573.92
Calibration factor [cm^{-2} nC^{-1}]	**3.8 × 10^4**			
Thermal neutron flux (Wescott) [$cm^{-2}s^{-1}W^{-1}$]	2.29 × 10^5	2.18 × 10^5	2.36 × 10^5	2.31 × 10^5
	Gold wire: 2.17 × 10^5			
Relative difference [Flux TLD / Gold]	**1.05**	**1.004**	**1.08**	**1.06**

Table 2. The results of validation of TLDs at the reactor.

4. Conclusions

In this study, TLD-600, TLD-700 and cadmium sheets were used to validate the calibration factor. The established method enables to estimate thermal neutron flux without complex instruments used in the conventional method. The thermal neutron flux measured by TLD showed an average difference of 5% with gold activation analysis.

For the further study, the uncertainty analysis about the other features such as the errors of reader system (including a high voltage supplier, photomuliplier tube and heating system) and experimental setup errors.

5. Acknowledgements

The authors thank to Prof. Myung-Hyun Kim (KHU) for the assistance during the neutron irradiation with the reactor for this study.

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