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Experimental study on the performance of an epithermal neutron flux monitor for BNCT

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HIGHLIGHTS

- An epithermal neutron flux monitor was developed for BNCT.
- The performance of this monitor was experimentally studied.
- The performance of this monitor was very satisfactory.

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ABSTRACT

The performance of an epithermal neutron ($0.5\ \text{eV} < E_n < 10\ \text{keV}$) flux monitor designed for boron neutron capture therapy (BNCT) was experimentally studied by using a prototype monitor in an appropriate neutron field at the intense deuterium-tritium neutron source facility OKTAVIAN of Osaka University, Japan. It was convinced from the experimental results that the developed monitor worked well and the epithermal neutron fluxes in BNCT neutron sources can be measured within 5% by the monitor.

1. Introduction

Boron neutron capture therapy (BNCT) is known as a very promising cancer therapy technology, which kills tumor cells while reducing exposure dose to normal tissues, simultaneously (Locher, 1936). Epithermal neutron ($0.5\ \text{eV} < E_n < 10\ \text{keV}$) flux is one of the basic characteristics for modern BNCT neutron sources. Therefore, in order to precisely measure the absolute integral fluxes of epithermal neutrons especially for practical BNCT neutron sources, a simple spherical monitor was designed by Monte Carlo simulations in the previous work (Guan et al., 2015a).

The principle of this monitor was based on the activation method using ^{71}Ga(n,γ)^{72}Ga reaction since the fluctuation of the monitor sensitivities (in the form of ^{72}Ga production yields, cm^{-3} per neutron) in the epithermal neutron energy range can be considered negligible compared to those of other considered reactions, i.e., ^{197}Au(n,γ)^{198}Au, ^{151}Eu(n,γ)^{152m}Eu, ^{127}I(n,γ)^{128}I, ^{115}In(n,γ)^{116m}In, ^{55}Mn(n,γ)^{56}Mn, ^{37}Cl(n,γ)^{38}Cl and ^{23}Na(n,γ)^{24}Na reactions. Gallium nitride (GaN) wafer was selected as the activation material instead of Ga metal due to its availability, high melting point and very few activated products resulted from its nitrogen (N) content. In the monitor, GaN wafer was positioned in the geometrical center of an optimized polyethylene sphere (neutron moderator) covered with cadmium (Cd) layer as thermal neutron absorber outside to give uniform monitor sensitivities in the epithermal neutron energy range. Experimentally, from the measurement of the main γ-rays emitted via the decay of ^{72}Ga with a high-purity germanium (HPGe) detector, the absolute integral fluxes of epithermal neutrons in BNCT neutron sources can be extracted finally.

In this work, in order to confirm the performance of the designed epithermal neutron flux monitor experimentally, a prototype monitor was developed and a test measurement with the monitor was carried out in an appropriate neutron field produced at the intense deuterium-tritium (D-T) neutron source facility

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OKTAVIAN of Osaka University, Japan (Sumita et al., 1990).

2. Materials and methods

2.1. Prototype monitor

According to the schematic view of the designed epithermal neutron flux monitor in the work reported by Guan et al. (2015a), a prototype monitor was developed, as shown in Fig. 1. The monitor has a spherical body. The activation material, i.e., GaN wafer with dimensions of 10.5 mm × 10 mm and 0.1 mm in thickness provided by Nanowin, China, was positioned in the geometric center of an optimized polyethylene sphere (71.1 mm in diameter) as neutron moderator covered with a 0.05 mm thick Cd foil as thermal neutron absorber outside. The polyethylene sphere and Cd foil were supplied by Japanese companies.

2.2. Experimental design

In this work, the experimental test of the epithermal neutron flux monitor was carried out at the intense D-T neutron source facility OKTAVIAN of Osaka University, Japan, the details of which were reported by Sumita et al. (1990). In OKTAVIAN facility, the deuteron (D^+) beam with energy of 300 keV and current of over 10 mA is accelerated by a Cockcroft-Walton circuit, and then the accelerated D^+ beam bombards a rotating titanium-tritium (Ti-T) target and induces deuteron-triton reaction to produce $\sim 10^{12}$ n/sec at maximum.

In order to obtain an appropriate neutron field for the experimental test of the epithermal neutron flux monitor, 14 MeV neutrons produced at the OKTAVIAN facility should be properly moderated. In this work, lead was used as a fast neutron moderator and graphite was selected as a neutron reflector, and a 0.5 mm thick Cd sheet was used to remove thermal neutrons in the neutron field. A general purpose Monte Carlo transport code, MCNP5 (X-5 Monte Carlo Team, 2003), was employed to carry out the experimental design calculations. The calculation model is shown in Fig. 2.

In the simulations, D-T neutron source was assumed as a mono-energetic point source. The distance between the D-T neutron source and the front surface of lead was 50 mm. Track length neutron tally was employed to estimate the average neutron flux in the neutron field and JENDL-4.0 (Shibata et al., 2011) was selected as the cross section library. The number of source histories was 6.0×10^8.

Using the MCNP5 calculation model for the experimental design shown in Fig. 2, the Monte Carlo simulations were performed to obtain the neutron spectra of the neutron fields by varying the thicknesses of lead and graphite, i.e., y_1 and y_2, simultaneously. In the simulations, the sizes of lead and graphite in x- and z-axis were kept to be 400 mm considering that they have little influence on the final simulation results.

Under the present experimental conditions, it was found from the simulations that the neutron field for 400 mm thick lead and graphite, whose neutron spectrum is shown in Fig. 3, was appropriate for the experimental test of the epithermal neutron flux monitor: (1) the fast neutrons above 1 MeV were effectively reduced and the ratio of the absolute integral flux of epithermal neutrons, Φ_{epi}, to that of neutrons between 10 keV and 1 MeV, i.e., $\Phi_{10keV<E_n<1MeV}$, was large, that is, $\Phi_{epi}/\Phi_{10keV<E_n<1MeV}=2.32$ (the values of $\Phi_{epi}/\Phi_{10keV<E_n<1MeV}$were smaller for both the smaller and larger graphite thicknesses), (2) the component of epithermal neutrons in the neutron field was high, i.e., $\Phi_{epi}=3.39 \times 10^{-6}\ cm^{-2}$ per neutron, and (3) the thermal neutrons were almost completely removed.

2.3. Experimental system

According to the experimental design results mentioned in Section 2.2, the experimental system was set up, as shown in Fig. 4.

A niobium (Nb) foil of 99.9% purity with dimensions of 20 mm × 20 mm and 0.1 mm in thickness, positioned at 0° angle relative to the D^+ beam direction and on the front surface of lead, was employed to measure the intensity of the D-T neutron source. The distance between the Nb foil and the Ti-T target was 50 mm. The neutron field, which was surrounded by six 0.5 mm thick Cd sheets, was a cubic space with inside dimensions of about 100 mm × 100 mm × 100 mm. The prototype monitor was positioned in the center of the neutron field during the irradiation.

2.4. Measurement of the induced activities

After the irradiation, the induced activities in the GaN wafer and Nb foil were measured with two conventional coaxial HPGe detectors with sample-to-detector distances of 37 and 47 mm, respectively. The absolute efficiencies of these two HPGe detectors were calibrated by using standard γ-ray sources including ^{152}Eu, ^{60}Co and ^{137}Cs, all of them with 25 mm diameter. The results are shown in Figs. 5(a) and (b), respectively. The energy resolutions of these two HPGe detectors were 2.52 and 1.62 keV at 1332.5 keV with uncertainties of 0.81% and 1.42%, respectively. More than 10,000 counts in the main activity peaks were collected by the HPGe detectors to keep the uncertainty of the counting less than 1%.

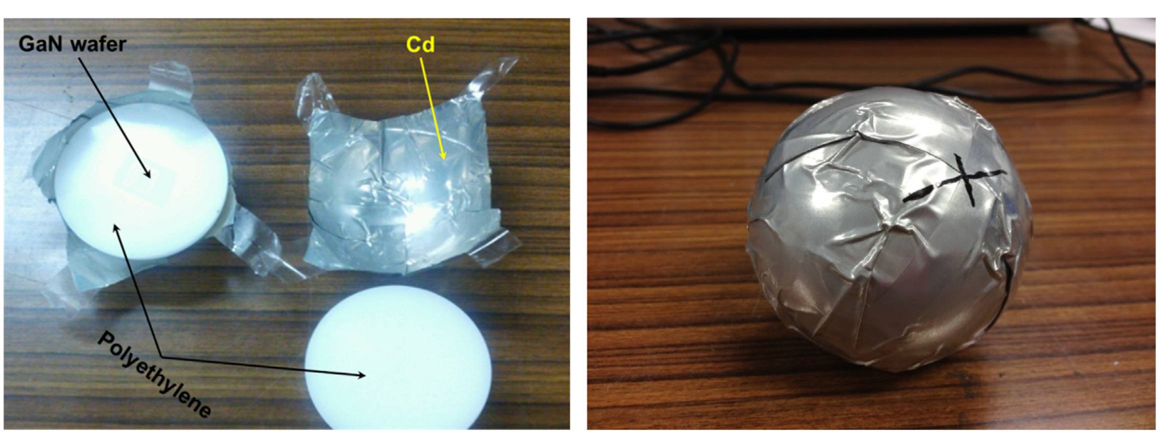

Fig. 1. Prototype monitor.