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Computational investigation of suitable polymer gel composition for the QA of the beam components of a BNCT irradiation field

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HIGHLIGHTS

- A gel detector in the QA of the BNCT beam components' fluence was investigated.
- Simulation using the PHITS code was performed for the Kyoto University Reactor.
- 6Li concentrations of 0, 10 and 100 ppm were found to be potentially usable.

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ABSTRACT

This study investigated the optimum composition of the MAGAT polymer gel which is to be used in the quality assurance measurement of the thermal neutron, fast neutron and gamma ray components in the irradiation field used for boron neutron capture therapy at the Kyoto University Reactor. Simulations using the PHITS code showed that when combined with the gel, ^{6}Li concentrations of 0, 10 and 100 ppm were found to be potentially usable.

1. Introduction

In Boron Neutron Capture Therapy (BNCT), an important factor which influences the result of treatment is the internal dose originating within the patient from gamma rays and neutrons generated by the ^{10}B(n,α)^{7}Li and ^{1}H(n,n)^{1}H reactions (International Atomic Energy Agency, 2001). One of the possible ways for the quality assurance and quality control (QA/QC) of this dose is to monitor the spatial fluence distributions of the irradiation field components, i.e., gamma rays, fast neutrons, and thermal neutrons. A QA regime that is easy to implement as a routine verification method is desirable.

A gel detector is able to measure three-dimensional dose distribution. Its use in cancer therapy with photons and heavy ions has been reported (Baldock et al., 2010; Deene and Vandecasteele, 2013; Vandecasteele and Deene, 2013a, 2013b, 2013c; Hurley et al., 2005; Doran, 2009). The validity of gel dosimetry in BNCT has also been demonstrated using the Fricke gel (Gambarini et al., 2009) and the polymer gel (Khajeali et al., 2015a, 2015b). This study investigated the use of a gel detector in the QA of the relative distribution of a BNCT beam components' fluence. The investigation of the ideal composition of the gel detector that will allow the measurement of these three components is reported here.

2. Materials and methods

The gel composition needed to separate thermal neutrons, fast neutrons, and gamma rays was investigated by means of simulation calculations. To measure the beam components separately, the sensitivity of the gel detector to the fast neutron component is increased via recoil protons produced in the gel while the sensitivity of the detector to the thermal neutron component is increased via the secondary particles from the ^{6}Li(n,α)^{3}H reaction. The enhancement of the measured signal from ^{10}B(n,α)^{7}Li reaction is not attempted in the present study in order to reduce the secondary photons from ^{10}B(n,αγ)^{7}Li reaction, which have longer ranges than the other secondary particles and potentially interfere in the separation of the components at distant points.

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On the other hand, the gamma ray component of the beam deposits its energy mainly via secondary electrons.

In practical use, three gel detectors with different compositions will be prepared and irradiated separately. The energy (i.e., dose) deposited in the gel detector will be read-out using the equipment such as magnetic resonance imaging (MRI). The intensities of the measured signals are related to the fluence by the equation:

$$\begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \Phi_3 \end{pmatrix}, \tag{1}$$

where S_i denotes the intensity of the signal from the gel detector i, Φ_j denotes the fluence of the beam component j, and a_{ij} denotes the sensitivity of the ith gel to the jth component. The sensitivity is the signal intensity per unit amount of the beam fluence. The sensitivity should be determined, in advance, from the beam component fluence and the gel signal intensity by actual measurement, simulation or a combination of both.

In order to measure a beam component separately, a gel with high sensitivity to that beam component is needed. However, if the signal intensity $a_{ij}\Phi_j$ corresponding to the beam component j is low compared with the total signal intensity of all the beam components, $S_i = \sum_j a_{ij}\Phi_j$, the beam component of interest would not be measured precisely due to experimental error of the other components with high signal intensity. This indicates that it is not the sensitivity but the contribution to the signal intensity $a_{ij}\Phi_j/S_i$ that determines whether or not the component can be separately measured successfully (Tanaka et al., 2016). In experiments, the gel is usually irradiated and the signal intensity is measured in a condition where the signal intensity is proportional to the energy deposition on the gel. The dependence of the signal intensity on the experimental conditions such as dose rate, temperature, time between the irradiation and measurement, and radiation type which determines the LET should be corrected. In this study, the energy deposition on the gel detector was calculated and considered as a representative of the signal intensity. The energy deposited by electrons was regarded as a representative of the signal intensity of the gamma ray component, the energy deposited by the protons as the signal intensity of the fast neutron component, and the energy deposited by the alpha particles and tritons as the signal intensity of the thermal neutron component. The contribution of a beam component to the total of the energy deposition from all of the beam components was calculated to investigate whether or not the beam component could be measured separately.

The variation in the amount of ^{6}Li produces a variation in the specific a_{ij} coefficient in Eq. (1). In this study, the combination of the gel with varying compositions, for the purpose of separating the beam components, is investigated from three viewpoints; (a) the energy deposition contribution from the beam component of interest is exclusively high, (b) the spatial distribution of the fluence of the beam component in the gel detector is close to that in water as a representative of the human body, and (c) the fluence distributions are similar between the gels with varied compositions. The details of these viewpoints are described together with the results in the next section for better clarity.

The simulations in this study were performed using the Monte Carlo code PHITS ver. 2.82 (Sato et al., 2013). The irradiation field modeled in the simulations was that which is produced by the standard epithermal neutron irradiation mode, at a power of 5 MW, of the Heavy Water Neutron Irradiation Facility at the Kyoto University Research Reactor Institute (KUR-HWNIF) (Sakurai and Kobayashi, 2000). The energy spectra used in the calculation is shown in Fig. 1. The irradiation geometry consisted of a 10 × 10 cm^2 beam incident on one of the circular faces of a cylindrical polymer gel detector with a diameter of 200 mm and thickness of 200 mm, as shown in Fig. 2. The gel was divided into the regions with the thicknesses of 5 mm in order to investigate the depth profile. The polymer gel detector considered in this work was the "Methacrylic Acid, Gelatin And THPC (MAGAT)". MAGAT is a normoxic gel which uses Tetrakis (Hydroxymethyl) Phosphonium Chloride (THPC) to remove oxygen which prevents methacrylic acid ($CH_2=C(CH_3)COOH$) from polymerization (Hurley et al., 2005). Its weight composition was set to be H:10.5%, C:9.5%, N:1.4%, O:77.7%, P :0.4%, Cl:0.5%. In this study, Li was assumed to be doped into the gel in the chemical form of LiF, which is commonly used as a thermal neutron filter. The atomic composition of Li was set at 95% of ^{6}Li. The concentration of ^{6}Li in the gel was varied from 0% to 1% in order to change the effect of low energy neutrons. The ^{6}Li concentration was then specified by the weight composition in the gel detector. Considering the solubility of LiF in water, the achievable ^{6}Li concentration in the gel was expected to be in the order of 100 ppm, at the most. In order to investigate whether higher concentrations should be achieved using other chemical forms, ^{6}Li concentration was set to more than 100 ppm in this study.

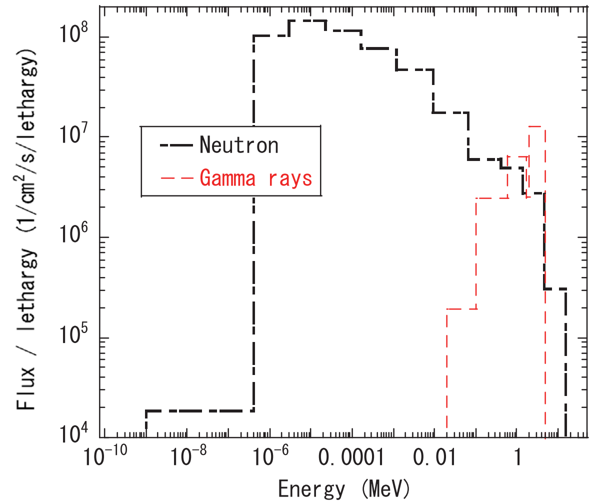

Fig. 1. Energy spectra used as input in the simulations.

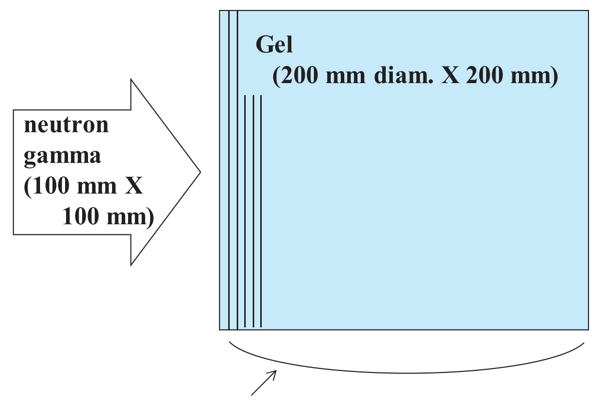

Fig. 2. Simulated irradiation geometry.

3. Results and discussion

3.1. Contribution of beam component to energy deposition

The energy deposition as a function of depth is shown in Fig. 3. As the ^{6}Li concentration increases, the energy deposition by alpha particles and tritons increases due to the increase in the yield of the $^6Li(n,\alpha)^3H$ reaction. Results for ^{6}Li concentrations of 100 ppm and above are no longer shown in Fig. 3 but had similar relative shapes as those for a 1 ppm concentration. In contrast, the energy deposition by electrons