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Prompt gamma and neutron detection in BNCT utilizing a CdTe detector

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HIGHLIGHTS

- We tested a modern CdTe spectrometer for simultaneous gamma and neutron detection.
- Prompt gamma (PG) signals from both sources were able to be distinguished.
- PG from 10B(n,a) and 113Cd(n,g) were also seen in a phantom used for BNCT.
- The results open the possibility to determine 10B dose in real time for BNCT.

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ABSTRACT

In this work, a novel sensor technology based on CdTe detectors was tested for prompt gamma and neutron detection using boronated targets in (epi)thermal neutron beam at FiR1 research reactor in Espoo, Finland. Dedicated neutron filter structures were omitted to enable simultaneous measurement of both gamma and neutron radiation at low reactor power (2.5 kW). Spectra were collected and analyzed in four different setups in order to study the feasibility of the detector to measure 478 keV prompt gamma photons released from the neutron capture reaction of boron-10. The detector proved to have the required sensitivity to detect and separate the signals from both boron neutron and cadmium neutron capture reactions, which makes it a promising candidate for monitoring the spatial and temporal development of in vivo boron distribution in boron neutron capture therapy.

1. Introduction

Boron neutron capture therapy (BNCT) (Menéndez et al., 2009; Kankaanranta et al., 2007, 2011; Barth et al., 2012) is based on high-LET radiation released from the neutron capture reaction $^{10}B(n,\alpha)^{7}Li^{*}$, in which a prompt gamma (PG) photon of 478 keV is emitted with a probability of 94%. These photons leave the patients body with small attenuation (Minsky et al., 2009). Previously, the estimation of the ^{10}B concentration in the tumor and healthy tissues during the treatment has been based on average tumor concentrations for several patients analyzed from tissues at a certain time after the boron administration. A procedure that includes an uncertainty for the individual patient and time of measurement. A more accurate determination of the boron concentration could be achieved by detecting the 478 keV PGs during patient treatment (Minsky et al., 2009; Munck af Rosenschöld et al., 2001; Verbakel et al., 2003; Verbakel and Stecher-Rasmussen, 1997; Kobayashi et al., 2000). However, the technical realization of a capable detector system requires further development to identify the 478 keV PG from the photon spectrum, emitted from patient during neutron irradiation (Kobayashi et al., 2000).

In 2003 a study on 478 keV PG detection using a CdTe/CdZnTe detector was carried out in Finland, with the result that about 3% energy resolution and appropriate neutron shielding and collimation techniques are needed (Morozov et al., 2006). Since then further work has been done by Murata et al. from the University of

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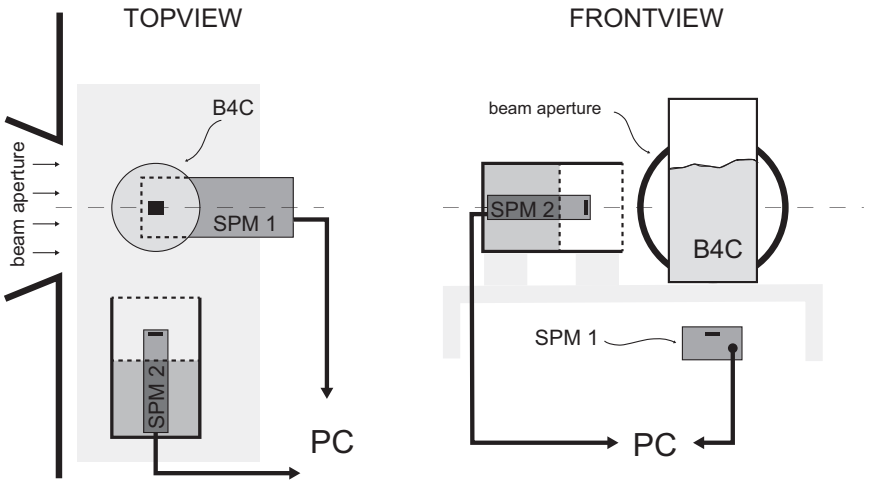

Fig. 1. Schematic drawing of the B4C setup.

Osaka, pointing out an improvement in energy resolution (Murata et al., 2014). In the present work, we evaluate the performance of the latest CdTe detector technology capable of high resolution spectrometry. Additionally, we evaluate the ability of the same device to detect and distinguish neutron and γ signals, by comparing the PG photons from both cadmium and boron neutron capture reactions. Previously, the strong background caused by the cadmium neutron capture reaction, ^{113}Cd(n,γ)^{114}Cd, has been considered a drawback, since the 559 keV PG peak from that reaction occurs close to the 478 keV peak of the ^{10}B neutron capture reaction. We ultimately aim to calculate a tomographic image of the ^{10}B concentration of the tumor and surrounding healthy tissue, similar to the approach published by Minsky et al. (2011). However, doing so by involving signals from both boron neutron and cadmium neutron reactions.

2. Experiment

2.1. Detectors

Two CdTe based spectrometers were studied, the first (SPM1) is a recently manufactured and customized Amptek X-123 CdTe detector with a $3 \times 3 \times 1$ mm^3 crystal and state of the art readout electronics. The second spectrometer (SPM2) is a ten year old custom built device utilizing a single $6 \times 6 \times 1$ mm^3 CdTe crystal together with the readout electronics of the same age. Both devices were protected with a 6 mm lead housing that did not cover the detector crystals.

2.2. Experimental setup

The epithermal neutron beam of the FiR 1 reactor was used at a power of 250 kW for clinical BNCT (Joensuu et al., 2003). Our experiments, however, were performed at lower power levels (0.25, 1.25 and 2.5 kW) to avoid radiation damage to the detector electronics. In turn excessive device shielding in front of the detector crystals was omitted and a 6 mm layer of lead was used only to protect the electronics from the expected secondary radiation. The detectors were placed perpendicular to the 14 cm diameter circular neutron beam port at 11.5 cm (SPM1) and 18 cm (SPM2) distance from the beam center. The applied beam consists mainly of epithermal neutrons ($0.5\ \text{eV} < E < 10\ \text{keV}$) with about 7% thermal (<0.5 eV) and fast (>10 keV) neutrons. Thermalized neutrons from the phantom are mainly detected in this study (Auterinen et al., 2004).

The expected data quality strongly depends on the ability of the detector system to distinguish signals from the ^{10}B(n,α)^{7}Li* and the ^{113}Cd(n,γ)^{114}Cd reactions, as well as both signals from the background. The background is consisting of secondary photons emitted from neutron capture reactions in beam shaping assembly, surrounding structures and the phantom. The associated PG peak of the ^{10}B(n,α) reaction is 477.59 (53) keV (http://www-pub.iaea.org/MTCD/publications/PDF/Pub1263_web.pdf) and of the ^{113}Cd(n,γ) reaction 558.46 keV (http://www.nndc.bnl.gov/capgam/byn/page128.html).

The irradiation was performed in four setups: (1) Free beam. (2) A bottle (90 mm diameter) filled to 11.5 cm height with B4C powder (774 g Borcarbid MG 55,29, grain size 40–60 µm, Schuchardt, München) placed in front of the neutron beam. (3) A cylindrical PMMA phantom with a radius of 10 cm and a length of 24 cm placed in front of the neutron beam. (4) Two boronated plastic disks (diameter 30 mm and 19 mm length, 3-wt% ^{10}B) placed inside the PMMA phantom at the depth of 0–38 mm. In this work, each setup will be referred to either by number or by the names *Free Beam*, *B4C*, *PMMA* and *Neutrostop*, respectively. The experimental setups are shown in Fig. 1 for the setup 2 and Figs. 2 and 3 for the setups 3 and 4. The setups 1 and 2 are essentially identical, with the only difference of the added B4C bottle in the beam line of setup 2. In setups 3 and 4, no in-line arrangement of the SPM1 with the center of the disks (dashed line, Fig. 2) was possible, due to the size of the lead shielding. An irradiation time of 900 s was used for each measurement.

The Free Beam measurement was performed to detect the baseline spectrum, which includes the scattering from the surrounding structures that are present in all setups (excluding the PMMA phantom). The aim of the second setup was to record a clearly identifiable signal from the boron neutron capture reaction by placing a large amount of B4C directly in the neutron beam. The setups 3 and 4 simulated the treatment situation more closely. The setup 3 is a reference irradiation condition with no ^{10}B present within the phantom, while in the setup 4 boronated PMMA disks were placed in the phantom to simulate a patient's tumor.

The detectors were calibrated using the common isotopes (^{22}Na, ^{133}Ba, ^{137}Cs and ^{152}Eu). Background spectra were recorded before and after the measurements. The background spectra recorded after the experiments were also used to examine possible activation of the detector structures as well as a change in the background radiation in the treatment room. The data was recorded with the energy range of 1–800 keV, which also is the area of sensitivity of the detectors.

All spectra were reduced by the background spectrum before

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