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MCNP analysis of a multilayer phoswich detector for β-particle dosimetry and spectroscopy

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Abstract

To measure and study energy deposition of β-particles at different depths, a triple-layer phoswich detector has been designed. The phoswich detector consists of BC-400/CaF2:Eu/BC-444 with decay time constants of 2.4, 940 and 264 ns, respectively, all with thicknesses corresponding to that necessary to completely stop 0.1 MeV electrons in the first layer, 1.0 MeV electrons in the second layer and 2.5 MeV electrons in the third layer. Monte Carlo N-Particle (MCNP) version 4B was used to simulate energy deposition in each layer from monoenergetic β-particles. The simulations and measurements revealed that the traditional rise time measurement technique is not able to provide appropriate and accurate pulse shape discrimination for this type of detector.

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1. Introduction

The combination of two dissimilar scintillators optically coupled to a single photomultiplier tube is often called a phoswich (or phosphor sandwich) detector. The scintillators are chosen to have different decay times so that the shape of the output pulse from the photomultiplier tube is dependent on the relative contribution of scintillation light from the two scintillators [1]. Pulse shape analysis (PSA) distinguishes the signals from the scintillators, thus identifying in which scintillator the event occurred. Phoswich detectors for simultaneous counting of α-, β- and γ-rays have been successfully developed by coupling two or three scintillators with different decay times [2,3]. The rise time measurement is the most popular technique to discriminate among pulses from a phoswich detector. This technique is based upon the integration of the light pulse (e.g. of the anode pulse of the PMT), followed by the determination of the time at which this integral reaches a certain fraction of its maximum (e.g. time interval between 0.1 and 0.9 of the maximum).

Generally, phoswich detectors are designed either for simultaneous detection of different radiation types [2,3] or minimizing the recording of background radiation in a radiation field of interest [4,5]. In both applications, each scintillation layer is chosen to be sensitive to a particular radiation type. Independent measurements of the energy deposited in each scintillator can then be obtained without the need for a second PM tube.

The dose equivalent in tissue at depths of 0.007, 0.3 and 1.0 cm (shallow, lens and deep dose equivalent) are widely used as an indication of the hazard from β-radiation [6].

A multilayer phoswich design, with sufficiently different decay times for each scintillation layer, can provide a mechanism by which β-absorption events in each layer can be discriminated. Therefore shallow, lens and deep equivalent doses due to β-particles can be measured simultaneously with an acceptable accuracy if the scintillation layers are designed to be very thin at the appropriate depths.

As a first attempt to utilize the above concept, a preliminary design for a triple-layer specialized phoswich

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detector was developed and constructed to collect three energy spectra corresponding to the energy deposition by lightly, moderately and highly penetrating β-particles [7]. The detector contains three thin-layer scintillators (BC-400, CaF2:Eu and BC-444) with decay time constants of 2.4, 940 and 264 ns, respectively. The thickness of each scintillator corresponds to that necessary to completely stop 0.1, 1.0 and 2.5 MeV electrons in the first, second and third layer, respectively [8]. Fig. 1 shows a simplified schematic of the detector. To protect the detector against incoming light and to eliminate light-induced background, a very thin piece of aluminized Mylar (0.75 mg/cm^2) is placed as the front window. Table 1 shows the physical constants of the scintillators used.

The goal of this work was to study and evaluate the ability of the rise time technique as a pulse shape discrimination method for separating events that take place in each layer of this type of detector. The evaluation was performed using both the rise time measurements and MCNP simulations. MCNP analysis was also used to estimate energy spectra and intrinsic efficiency for each layer from different monoenergetic electrons.

2. Materials and methods

Generally, a typical rise-time measurement employs a set of traditional pulse shape discrimination modules including a delay-line clipped amplifier, a pulse shape analyzer (PSA), a time-to-amplitude converter (TAC), and a multi-channel analyzer (MCA). The fundamental concept in using these modules is that the amplifier used (delay-line-clipped) is one in which the signal pulse is shaped, without altering pulse amplitude, such that its decay time is identical to its input rise time. The input rise time also corresponds to the decay time of the original signal (i.e., the light output from the scintillator). Therefore, the rise time measurement can be performed by measuring the amplifier's output pulse width, usually the time interval between 10% and 90% of the pulse amplitude.

The rise time distribution shown in Fig. 2 was obtained using the triple layer phoswich detector and a digital oscilloscope from ^{90}Sr/^{90}Y, a pure β-emitter. β-particles emitted from a thin ^{90}Sr/^{90}Y source have a maximum energy of 2.281 MeV, enough energy to pass through all three layers of the phoswich. The first, second and third peaks appearing in Fig. 2 represent the interaction of β-particles with the first, third and second layers, respectively (see principle decay constants of scintillators in Table 1). Because all three scintillators used in this type of detector are almost equally sensitive to β-particles, each β-particle with energy greater than 100 keV can release energy in more than one layer of the detector. Releasing energy in more than one layer generates a voltage pulse with two or three decay components corresponding to the β-interactions within each layer.

To develop a better interpretation of the rise time distribution shown in Fig. 2, voltage pulses from two

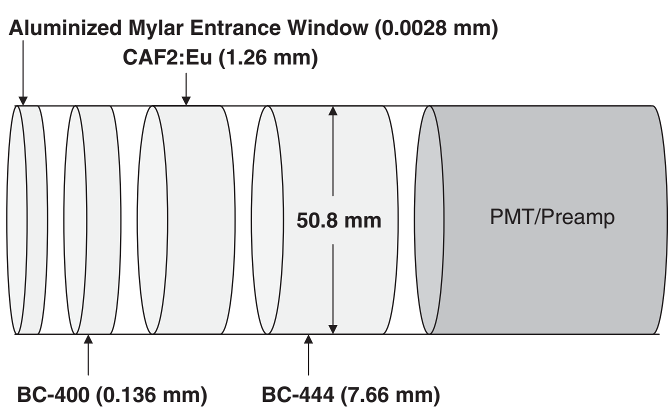

Fig. 1. Schematic arrangement of the phoswich detector. Layers are separated for clarity, but the real design has no spaces.

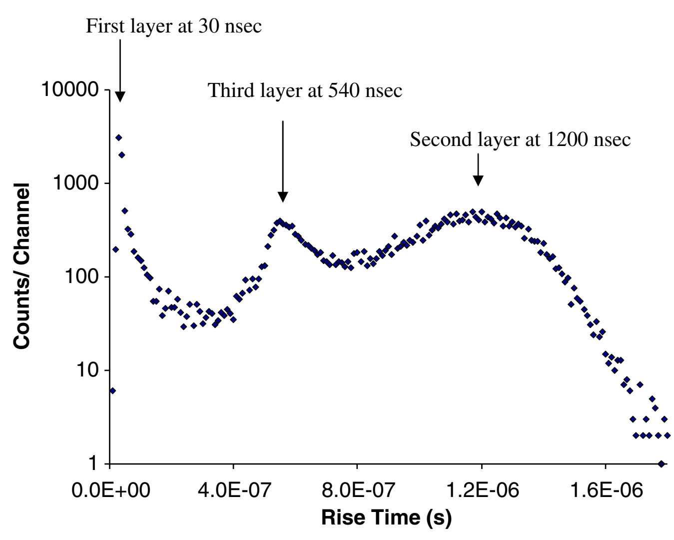

Fig. 2. Rise time distribution of β-particles from ^{90}Sr/^{90}Y, with maximum β-energy of 2.281 MeV.

Table 1
Physical properties of scintillators used in triple layer phoswich detector

Scintillator	Density (g/cm^3)	Wavelength of max emission (nm)	Light output % of NaI:Tl	Index of refraction	Principle decay constant (ns)
BC-400	1.032	423	28	1.58	2.4
CaF_2:Eu	3.19	435	50	1.47	900
BC-444	1.032	428	18	1.58	285