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Feasibility of in situ beta ray measurements in underwater environment

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ABSTRACT

We describe an attempt at the development of an in situ detector for beta ray measurements in underwater environment. The prototype of the in situ detector is based on a CaF2: Eu scintillator using crystal light guide and Si photomultiplier. Tests were conducted using various reference sources for evaluating the linearity and stability of the detector in underwater environment. The system is simple and stable for long-term monitoring, and consumes low power. We show here an effective detection distance of 7 mm and a 2.273 MeV end-point energy spectrum of ^{90}Sr/^{90}Y when using the system underwater. The results demonstrate the feasibility of in situ beta ray measurements in underwater environment and can be applied for designing an in situ detector for radioactivity measurement in underwater environment. The in situ detector can also have other applications such as installation on the marine monitoring platform and quantitative analysis of radionuclides.

1. Introduction

The recent development of radiation-related industries has resulted in increased attention on the environmental pollution caused by radioactive waste and radioactive materials with increase in operation of nuclear facilities and use of radioisotopes in industrial and medical fields. Especially, the marine contamination caused by the explosions of the Fukushima Daiichi Nuclear Power Plant in March 2011 is significant. The issues with continuous monitoring, pollution warning and emergency response of radioactivity in the marine environment has attracted global attention. In most countries, radioactivity monitoring in underwater environment has been performed using the traditional method of in situ sampling and subsequent analysis in the laboratory. However, it almost takes two or three days to obtain quantitative results through the complicated handling procedures. Therefore, it is not feasible to timely and effectively monitor radiation in the underwater environment and even provide early warnings (Zhang et al., 2015). Thus, it is necessary to develop a technology capable of monitoring and analyzing radiation in real time in case of radioactive contamination in water. However, most commercially available underwater radiation detection devices, where a thallium doped sodium iodide (NaI: Tl) scintillator and a photomultiplier tube are used, can detect only gamma radionuclide. Quantitative analysis of the ^{90}Sr beta-nuclide, a major product of nuclear fission in the event of a nuclear accident, is not possible by this technique (Rao et al., 2000). Therefore, for quantitative beta ray monitoring in water, it is necessary to develop an in situ beta ray detector, which is more effective in detecting beta rays than the conventional NaI: Tl detector. This paper describes the initial proof-of-concept experiments performed to test the validity of our approach toward designing a prototype in situ beta ray detector for underwater operation. In this work, a developed system named K-BETA, is presented. It is intended to embed the developed system on a river buoy, in the near future.

2. Materials and methods

2.1. Prototype concept

The prototype unit, shown in Fig. 1, measures about 79.8 mm in length, 79.8 mm in width and 120 mm in height, and was designed with an emphasis on compactness and waterproofing. The radioactivity sensor of the prototype consists of a CaF2:Eu crystal using crystal light guide, a Si photomultiplier (SiPM) and an electronic card. A separate external power supply (5 V), together with an

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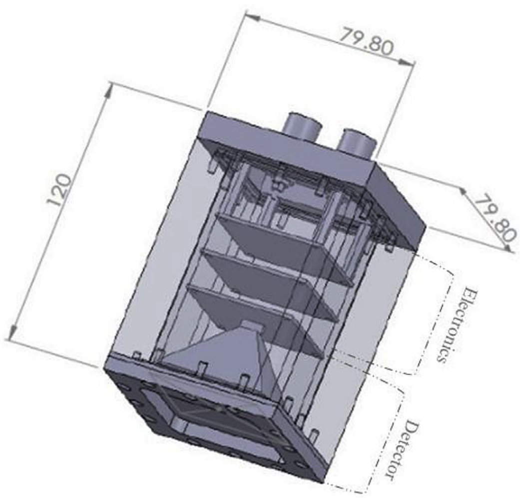

Fig. 1. Conceptual design of the in situ beta ray detector.

electronic card for sensor operation, data acquisition and storage is used. A watertight enclosure for the sensor and electronics is also developed. The power consumption of the whole system is relatively low (~32.4 mW).

The feasibility of the prototype was evaluated by testing the beta ray detection components. In the following subsections, details of the design, fabrication and performance of the K-BETA assembly are presented.

2.2. System description

The K-BETA assembly uses an S13360–6050CS (photosensitive area: 6 × 6 mm^2) Hamamatsu multi-pixel photon counter (MPPC) as SiPM to minimize of the overall system dimensions and power consumption (see Table 1).

CaF_2: Eu (OKEN Co., Tokyo, JP), which is an inorganic scintillator, was used for beta-ray detection. The scintillator must have the following characteristics for efficient beta-ray detection: short decay time, high light yield efficiency, and low atomic number and density. The probability of backscattering of beta rays increases as the atomic number increases and the absorption probability of the full energy peak for the incident charged particles decreases accordingly. Hence, the CaF_2: Eu scintillator material with a relatively lower atomic number was used. The scintillator characteristics are shown in Table 2 (Saint-Gobain Crystals, 2016).

The size of the CaF_2: Eu crystal was determined as 50.8 × 50.8 × 1 mm^3, by considering the beta ray detection area, based on the 2″ × 2″ NaI: Tl detector, which is a commercial gamma ray detection module (Abdollahnejad et al., 2016). Because the ranges of the major gamma radionuclides and natural radioactivity generated during nuclear fission are greater than that of beta rays,

Table 1
Specifications of the SiPM used in this study.

Parameter	Value
Photosensitive area	6 × 6 mm^2
Number of pixels	14,400
Spectral response range	270–900 nm
Peak PDE (at 450 nm)	40%
Bias voltage	Vbr + 3 V
Breakdown voltage	53 ± 5 V
Gain	1.7 × 10^6
Operating temperature	−20 ~ 40 °C

Table 2
Physical and scintillation properties of CaF2:Eu and other scintillators.

Scintillator	NaI:Tl	CaF2:Eu	YAG:Ce	YAP:Ce
Density (g/cm^3)	3.67	3.18	4.57	5.4
Effective atomic number	50	16	32	36
Peak emission (nm)	415	435	550	370
Decay time (ns)	230	940	70	25
Light yield (photons/MeV)	38,000	23,000	8000	18,000
Hygroscopic	Yes	No	No	No

the CaF_2: Eu crystal was thinly fabricated to lower the generation probability of secondary electrons by the radiation interaction between gamma rays and the CaF_2: Eu crystal. The beta particle range of the maximum energy for $^{90}Sr/^{90}Y$, which was used as a beta radiation source in the experiment, was calculated as 3.443 mm in the CaF_2: Eu crystal, as shown below.

The maximum range, Rmax, (material independent) of a beta particle can be computed from an empirical formula given by Katz and Penfold (1952):

$$R_{\max}\left[g/cm^2\right] = 0.412E_\beta^{1.265-0.0954\,\ln(E_\beta)} \quad 0.01 \le E_\beta \le 2.5MeV \tag{1}$$

^{90}Y emits beta particles with a maximum energy, E_β, of 2.273 MeV, and hence the maximum range of those particles is:

$$R_{\max} = (0.412)(2.273)^{1.265-0.0954\,\ln(2.273)} = 1.0916g/cm^2$$

CaF2:Eu has a density, ρ, of 3.18 g/cm^3, and thus the beta particle range, S, is:

$$S = \frac{R_{\max}}{\rho} = \frac{1.0916g/cm^2}{3.18g/cm^3} = 3.443mm$$

The ability to stop beta particles depends primarily on the number of electrons in the absorber (i.e., the areal density, which is the number of electrons per cm^2). Furthermore, the thickness of CaF_2:Eu crystals must be determined considering the self-absorption phenomenon, in which photons generated from the scintillator are absorbed into the CaF_2: Eu crystals due to the optical properties of the crystals. As the crystals become thicker, the number of transmitted photons gradually decreases, resulting in light attenuation.

Finally, the thickness of the CaF_2: Eu crystal was determined as 1 mm by considering the maximum energy of beta rays, radiation interaction, and physical properties of the scintillator. As a reflector of the CaF_2: Eu crystal, a Teflon reflector was used, having a reflectance of 90% or more for the CaF_2: Eu emission wavelength. Fig. 2 shows the beta ray detection unit of K-BETA.

The detection unit was fabricated by using a light guide by considering the area of 50.8 × 50.8 × 1 mm^3 of the CaF_2: Eu crystal and the photo-sensitive area of 6 × 6 mm^2 for the SiPM. The light guide used was BK-7 optical glass (Sipat Co., Chongqing, CN) whose structure is tapered, and the incident area to be bonded with CaF_2: Eu was 50.8 × 50.8 mm^2. The exit area to be bonded with the window of SiPM was 6 × 6 mm^2, which was 20 mm thick. Considering the light reflection effect, where most of the photons are reflected from the incidence plane of the light guide to the incident surface as the thickness of the light guide decreases in the tapered structure, as well as light attenuation, where the number of photons gradually decreases as the thickness increases, the thickness of the light guide was determined as 20 mm by using LightTools Software Tool, which can track and design the light guide based on the optical characteristics