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# A Monte Carlo study of an energy-weighted algorithm for radionuclide analysis with a plastic scintillation detector

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## HIGHLIGHTS

- Radiation portal monitor using plastic scintillator was modeled and the energy spectra of six radionuclides were assessed.
- Energy-weighted algorithm which enables radionuclide analysis with plastic scintillator was suggested and evaluated.
- The cases of moving and shielding effect were evaluated and simultaneous radionuclide identification was carried out.
- Analysis of the simulated spectra with suggested method shows clear results to enable the radionuclide identification.

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## ABSTRACT

Nuisance and false alarms due to naturally occurring radioactive material (NORM) are major problems facing radiation portal monitors (RPMs) for the screening of illicit radioactive materials in airports and ports. Based on energy-weighted counts, we suggest an algorithm that distinguishes radioactive nuclides with a plastic scintillation detector that has poor energy resolution. Our simulation study, using a Monte Carlo method, demonstrated that man-made radionuclides can be separated from NORM by using a conventional RPM.

## 1. Introduction

Recently, the threats of nuclear terrorism have increased and a nuclear security summit has been held since 2010 to promote international security (Diehl and Humphrey, 2010). To prevent nuclear terrorism, screening for illicit radioactive materials at international border crossings and airports/ports is fundamental. Various types of radiation portal monitors (RPMs), using the gross-count algorithm, and mobile radiation detectors are currently in use. Low-cost plastic scintillators are preferred in RPMs for screening cargos that are large in size (Burr et al., 2006). However, due to their poor energy resolution, plastic scintillators are limited in their ability to accurately predict the radionuclide type, which can be determined from the characteristic energy of the emitted gammas from individual radionuclides. Therefore, innocent false alarms have frequently been caused by naturally occurring radioactive material (NORM) in fertilizer, road salt, ore, rock, etc. Man-made radioisotopes used for medical purposes, including technetium, iodine, and thallium, are also sources that increase the occurrence of false alarms. These types of innocent alarms require extensive investigation in order to identify the radioisotope and verify that the alarm was caused by a non-threatening material. This investigation usually requires a lengthy holdup of the vehicles and affects logistics and traffic flow.

Methods used to distinguish various radionuclides have been studied by several groups. Mathematical model algorithms have been suggested, with principal components analysis (PCA) or artificial neural networks (Runkle et al., 2006; Kangas et al., 2008; Lo Presti et al., 2006); however, these algorithms have suffered from noise in the detection system and from variations in the measurement conditions. An inorganic scintillator using NaI(Tl) (Yaar and Peysakhov, 2013) was employed in RPMs to accurately measure the energy spectra of the gammas emitted from

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radionuclides, but the limited size of the inorganic scintillator can lead to an insufficient gamma count when used to analyze a large vehicle. Additionally, increasing the number of inorganic scintillators is likely to significantly increase the cost burden. Conventionally, the preferred method in a RPM system is to employ plastic scintillators; however, as mentioned above, the poor energy resolution of plastic scintillators is problematic. The energy window algorithm (Ely et al., 2006; Kwak et al., 2010) has been used in RPMs with plastic scintillators to assess the relatively high activity portions in measured energy spectra and can be used to predict the potential groups of illicit radioactive materials or NORM. However, it is still difficult to discriminate between isotopes with similar energies and Compton continuums, even if they are in different groups. There are other approaches with Gamma Detector Response and Analysis Software (GADRAS) which uses template-matching method (Mitchell and Mattingly, 2008) and with deconvolution algorithm (Burt and Ramsden, 2008). The purpose of this study is to demonstrate the principle behind accurately determining the radionuclide type based on the Compton edge with energy-weighted counts of the plastic scintillation detectors in a RPM system. The Monte Carlo method using the Geant4 toolkit was employed to demonstrate this principle.

## 2. Materials and methods

### 2.1. Source selection and Monte Carlo modeling

To assess the energy spectra with a plastic scintillator, the Geant4 toolkit, which enables the transport of optical photons, was employed in our current Monte Carlo study (Rakes, 2008). Six isotopes, namely $^{192}$Ir, $^{214}$Pb, $^{212}$Bi, $^{137}$Cs, $^{60}$Co, and $^{40}$K, were selected as sources. The $^{214}$Pb, $^{212}$Bi, and $^{40}$K are representative sources of nuisance alarms caused by NORM in RPMs, and $^{192}$Ir, $^{137}$Cs, and $^{60}$Co, which could be used in dirty bombs, are used as the target radionuclides for screening (Tintinalli et al., 2004). The sources were assumed to be a point within a steel container box (1 m$^3$), and the gammas of the representative energies were isotropically emitted. The photons, delivered to the RPM located 2 m from the point source, interact with the polyvinyl toluene (PVT) of the plastic scintillator ($500 \times 1000 \times 50$ mm$^3$) and generate optical photons with wavelengths between 400 and 500 nm, as illustrated in Fig. 1. Finally, the optical photons were directly and indirectly (through reflection) collected in a photomultiplier tube (PMT).

**Table 1**
Representative gamma decay energies and the energy of Compton edge of each isotope.

| Radionuclide | Gamma energy of relatively high yield (MeV) | Energy of Compton edge (MeV) |
|---|---|---|
| $^{192}$Ir | 0.316 | 0.175 |
| $^{214}$Pb | 0.352 | 0.204 |
| | 0.609[a] | 0.429[a] |
| | 1.120[a] | 0.912[a] |
| $^{212}$Bi | 0.583[b] | 0.406[b] |
| | 2.614[b] | 2.391[b] |
| $^{137}$Cs | 0.662 | 0.478 |
| $^{60}$Co | 1.173 | 0.963 |
| | 1.332 | 1.118 |
| $^{40}$K | 1.505 | 1.287 |

[a] Representative gamma decay energies of $^{214}$Bi, which are daughter isotopes of $^{214}$Pb.

[b] Representative gamma decay energies of $^{208}$Tl, which are daughter isotopes of $^{212}$Bi.

The PVT was wrapped with reflective Teflon tape with a refractive index of 1.5 and a thickness of 1.2 mm (Smith et al., 2004). This was simulated based on the properties of the BC-408 model (Saint-Gobain:BC-408), which has a scintillation efficiency of 10,000 photons/MeV, density of 1.023 g/cm$^3$, and refractive index of 1.58. The PMT on the top center of the PVT was assumed to be 50 mm in diameter and 100 mm tall. To evaluate the effects of the cargo thickness, the thickness of the steel box was varied from 0 to 2 cm.

### 2.2. Radionuclide analysis with energy-weighted counts

With a low-energy resolution, the energy spectra measured with a PVT scintillator generally show a gradually decreasing Compton edge without any photopeak (Siciliano et al., 2008). This photopeak is generally used to predict the initial gamma energy and the original radionuclide. We suggest a novel method for determining the radionuclide using the Compton edge that appears at the estimated specific location from the photopeak. To change the gradual distribution of the Compton edge into a conspicuous curve, the energy-weighted algorithm was employed. First, energy calibration was performed by comparing the

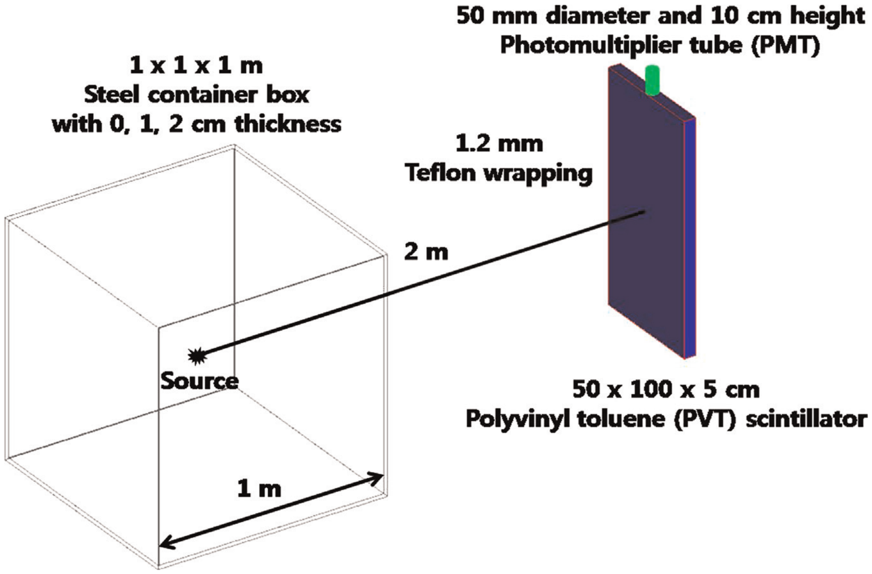

**Fig. 1.** Schematic illustration of source, container box, and PVT scintillator with PMT.