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ARTICLE

Mobile radiation measurement system by multiple small gamma-ray detectors for radioisotope detection and identification supporting responders in the field of nuclear detection and nuclear security

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Rapid and precise detection or identification of radioisotopes is one of the challenging issues in the field of nuclear detection and nuclear security. Although many handheld instruments capable of automated radioisotope detection and identification using small gamma-ray detectors have been recently employed in the field of nuclear security, the performance of such instruments is suffered from the limitation on the cost of their detectors in many cases due to limited efficiency or limited energy resolution of the small size detectors. This paper proposes a mobile radiation measurement system using multiple gamma-ray detectors for radioisotope detection and identification. The proposed system consists of two small gamma-ray detectors, one with high resolution and low efficiency (HRLE) properties and the other with low resolution and high efficiency (LRHE) properties. The output spectrum of the system is obtained by combining the information on the energy distribution of the measured gamma-ray by the HRLE detector and the gross counts measured by the LRHE detector. The performance for radioisotope detection and identification in the artificially combined spectrum can be improved than individual spectra. The performance of the proposed mobile system for radioisotope identification has been tested for artificial radioisotopes by CdZnTe as the HRLE detector and CsI(Tl) as the LRHE detector. By analyzing the combined spectrum to be output by the proposed system, significant improvements in the radioisotope identification compared to the spectra measured by individual detectors. The spectrum combining process proposed in the present system can be easily applied. It can contribute as one of the solutions for the limited performance of handheld instruments using low-cost detectors.

Keywords: nuclear security; radioisotope detection and identification; handheld gamma-ray detector

1. Introduction

Nuclear security issues such as illicit trafficking of nuclear and other radioactive materials or nuclear terrorism have been global issues threatening the national security of all States. There has been no successful terrorist attack using nuclear or other radioactive materials. However, it has been reported that many incidents involving nuclear or other radioactive materials out of regulatory control (MORC) have been found all over the world (IAEA (2020))[1]. Many states have made efforts to develop their national capability to detect illicit trafficking or unauthorized acts involving MORC and the quick response to mitigate the incidents to deal with these nuclear security issues.

Rapid and precise identification of radioisotopes or nuclear materials in the scene of nuclear detection and nuclear security incidents is one of the challenging issues for the prompt response to the detection alarm or the incidents involving MORC (IAEA (2013))[2]. For instance, the capability to rapidly identify artificial radioisotopes, nuclear materials, or naturally occurring radioactive material (NORM) can support secondary inspection in case of anomaly radiation detection. It can also reduce radiation exposure on the first responders who identify hazardous substances in the crime scene involving MORC. For these reasons, many handheld instruments capable of automated radioisotope identification using small gamma-ray detectors have been recently employed in a nuclear security application. However, the radioisotope identification performance of such handheld instruments is severely limited in the cost of their detectors due to limited sensitivity with small-size detectors or limited energy resolution.

This paper proposes a mobile radiation measurement system using multiple gamma-ray detectors for radioisotope detection and identification. The proposed system consists of two small gamma-ray detectors, one with high resolution and low efficiency (HRLE) properties and the other with low resolution and high efficiency (LRHE) properties. The output spectrum of the system is obtained by combining the information on the energy distribution of the measured gamma-ray by the HRLE detector and the gross counts measured by the LRHE detector. The artificially combined

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spectrum can be directly used for spectrum analysis, and the performance for radioisotope detection and identification can be improved over the individual spectrum. The performance of the proposed system for radioisotope detection and identification has been tested for measured gamma-ray spectra of artificial radioisotopes by CdZnTe as the HRLE detector and CsI(Tl) as the LRHE detector. Significant improvements are confirmed compared to the spectra measured by individual detectors by analyzing the combined spectrum with the general spectrum analysis process for peak detection and radioisotope identifications. It was also confirmed that the combined spectrum could improve the lower detection limits of nuclear materials. The proposed method for combining spectra is a straightforward process, and it can be easily applied to various combinations of detectors. Therefore, this method could be one solution that contributes to the performance of handheld devices using inexpensive detectors.

2. Spectrum Combining Process

It is estimated that detector sensitivity is a function of efficiency and resolution (Russ et al. (2011))[3]:

$$Sensitivity \propto \sqrt{\frac{Efficiency}{Resolution}} \tag{1}$$

The simplest way to increase the system sensitivity is to use multiple detectors with the same properties and sum the counts. This classical approach practically means to improve efficiency by increasing detector volume. Another approach combines the spectra of two detectors with different response functions by multiplying the spectra by the channel after the rebinning process into common energy bins (Russ et al. (2011))[3]. These approaches require energy calibrations to match the channels of different detectors to obtain an accurate spectrum. If assuming the use in the field of nuclear security, it would not be practical to use these approaches requiring accurate energy calibration since the possibility that the calibration of the detectors may frequently change by the operating environment must be addressed.

The spectrum-combining approach of the proposed radiation measurement system in this paper is similar to the latter of the above. However, it can be made by a more straightforward process combining individually measured spectra by two gamma-ray detectors with different efficiency and energy resolution. Assuming the case of a mono-energy gamma-ray measurement by a detector, the distribution of the counts at each energy bin (i.e., counting spectrum) could be determined by the product of the total counts and response function for the gamma-ray energy. This can be said that the total counts are allocated to the energy bin according to the response function. Meanwhile, the total counts would be proportional to the product of the source intensity and the detector efficiency. Suppose the total counts measured by the detector with better efficiency can be allocated to each energy bin according to the response function of the detector with higher resolution. In that case, it could be possible to take advantage of each of the two detectors to realize a system with high sensitivity. The output spectrum of the proposed system is created by combining the distribution of counting at each energy bin measured by the HRLE detector and the gross counts measured by the LRHE detector (Eq. 2).

$$N_{Ch}^{hybrid} = N_g^{LRHE} \times P_{Ch}^{HRLE} \tag{2}$$

The count distribution observed in the measured spectrum by the HRLE detector reflects the energy distribution of the gamma-ray source and the response function. In the present approach, the gross counts in a specific region of interest (ROI) measured by the LRHE detector (N_g^{LRHE}) are allocated based on the relative counts at each channel of the same ROI with the HRLE detector (P_{Ch}^{HRLE}). The artificial spectrum is created as measured with a hypothetical detector with high efficiency and high resolution (N_{Ch}^{hybrid}). The output spectrum can be analyzed using a standard algorithm for peak detection and radioisotope identification. One important advantage of the present approach is that it does not require precise energy calibrations to match the channels of the different detectors; it is sufficient to calibrate the two detectors with no significant difference in ROI. Slight differences in the calibrations between different detectors will cause errors in the gross counts of a combined spectrum, but will not significantly affect the spectral shape or peak-to-noise ratio, which are more important for peak detections and subsequent radioisotope identification processes.

Figure 1 shows example spectra for ^{134}Cs and ^{137}Cs sources using CdZnTe as HRLE detector and CsI(Tl) as LRHE detector. Compared to the CsI(Tl) spectrum, the energy resolution is improved in the combined spectrum.

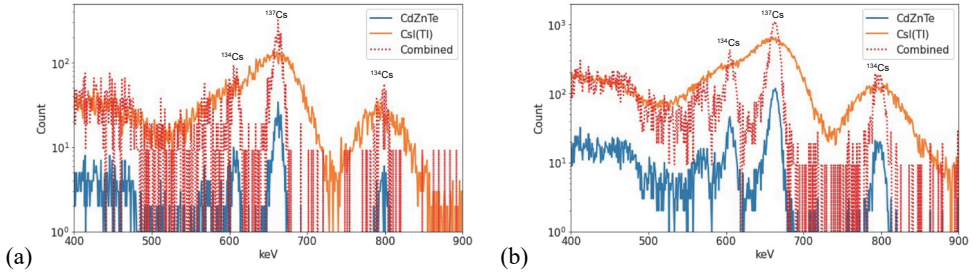

Figure 1. Comparison of the combined spectrum and individual spectra for ^{134}Cs and ^{137}Cs sources; (a) 60 sec, (b) 300 sec.

This makes it much easier to separate overlapping peaks, such as the ^{134}Cs and ^{137}Cs peaks observed around 600 keV, which are difficult to detect with lower resolution detectors. Furthermore, it can be observed that the absolute value of the counts is amplified in the combined spectrum, compared to the CdZnTe detector. This may allow small peaks that do not have statistically sufficient counts in a spectrum with short measurement times to be determined as effective peaks, such as the ^{134}Cs peak at around 800 keV in Figure 1 (a). It should be noted that the count distribution (or spectral shape) and signal-to-noise ratio of the combined spectrum becomes the same as those of the CdZnTe detector. Consequently, the combined spectrum has little benefit when sufficient peak counts can be obtained (i.e., in the case of longer measurement time). However, the amplification effect of the combined spectrum could be very effective in detecting small peaks in a spectrum with insufficient counts, as it is crucial in nuclear security applications to detect abnormal radiation and identify the source radioisotopes in a short measurement time. A similar effect can be obtained by simply amplifying the CdZnTe spectrum, but if the amplification factor becomes too large, there is a greater possibility of false detections of noise as the peaks. In the proposed method, the HRLE spectrum is amplified with a very simple process based on the gross counts measured by the LRHE detector. This allows to skip the determination of the practical amplification factor, which would be an advantage in nuclear security applications where a timely response is significant. In addition, by using the appropriate combination of the detectors, it may be possible to amplify the HRLE spectrum with optimal conditions.

3. Performance Evaluation

3.1. Methodology

The benefits of the combined spectrum for the detection and identification of artificial radioisotopes and nuclear materials were quantitatively evaluated using the measurement data of sources and nuclear material samples. Two handheld instruments with gamma-ray detectors have been used to demonstrate the proposed spectrum-combining approach. The Kromek GR-1A+ installing a CdZnTe detector was used as an HRLE detector (<2.0% FWHM at 662 keV), and the Kromek SIGMA-50 installing a CsI(Tl) detector (<7.2% FWHM at 662 keV) was used as an LRHE detector. The spectrum combining process shown in Eq. (2) was performed on the spectra acquired by the two detectors at ROIs of 50 – 1500 keV for the tests of artificial radioisotopes or 200 – 500 keV for the test of nuclear material detection. The individual spectra at the same ROIs were also used for the comparisons.

The detection probability of ^{137}Cs was evaluated with the measurement data of a ^{137}Cs source alone and with a ^{134}Cs source. The net dose rate of each source was set as 0.44 μSv/h ± 2σ (≒ 50 μR/h ± 2σ) specified by ANSI (IEEE (2007))[4], and 25 measurements were performed at 5, 10, 30, and 60 seconds with live time settings (**Figure 2**). The benefits of the combined spectrum can be evaluated by comparing the detection probability of ^{137}Cs in the combined and the individual spectrum under the same measurement conditions.

The performance for the identification of several artificial radioisotopes (^{60}Co, ^{133}Ba, ^{134}Cs, ^{137}Cs, and ^{152}Eu) was evaluated with the measurement data of check sources. The net dose rate of each source was set as 0.44 μSv/h ± 2σ (≒50 μR/h ± 2σ) specified by ANSI (IEEE (2007))[4], and ten measurements were performed at 60 and 300 seconds with live time settings for single source and combination of two of each source (25 measurements at 60 seconds for the cases of single ^{137}Cs and the ^{134}Cs with ^{137}Cs). The performance of the radioisotope identification was evaluated by using *precision*, *recall*, and *F-score*, shown below. The benefits of the combined spectrum can be evaluated by comparing the values of the performance indicators shown below. The false alarm rate was also evaluated for the ten measurement data of background at the same live time settings.

$$p = \frac{TP}{TP + FP} \tag{3}$$

$$r = \frac{TP}{TP + FN} \tag{4}$$

$$F = 100 * \frac{2 * p * r}{p + r} \tag{5}$$

TP : true positives, FP : false positives, FN : false negatives, p : *precision*, r : *recall*, F : *F-score*

A Python script according to the standard analytical approach for peak detection (Nuclear Regulation Authority (2020))[5] with a simple procedure for radioisotope identification using a search library was developed and used for the performance evaluations. Peak detections were performed with a threshold set at -3.0 times the error of the second derivative value derived by using a Gaussian-type filter. The net counts and the standard deviation of the detected peaks were calculated by the

Figure 2. Experimental set-up for performance evaluation of ^{137}Cs detections and radioisotope identifications. Measurements were made for single or paired sources placed at the same dose rate (0.44μSv/h±2σ) from individual sources.

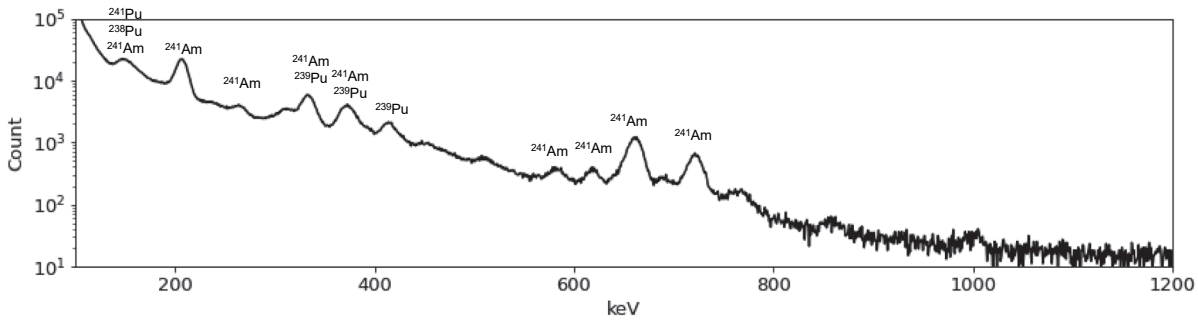

Figure 3. Example of a gamma-ray spectrum of MOX fuel bundle (19 rods).

Covel method, and peaks with a net count greater than three times the standard deviation were set as effective peaks. Radioisotopes were searched with gamma-ray energies in the range of ±0.1 × FWHM or ±1.0 × FWHM from the center for each effective peak. The search library contains the data sets of gamma-ray energy and emission rate (Burrows (1990))[6] for the five selected radioisotopes. The one with the highest emission rate among the searched radioisotopes is automatically determined as the corresponding radioisotope of each effective peak. In order to prevent false positives, radioisotopes with multiple peaks were determined based on the number of the corresponding peaks determined in single spectrum data (≧2 peaks for ^{60}Co, ^{133}Ba, and ^{134}Cs; ≧3 peaks for ^{152}Eu).

The lower detection limit of ^{239}Pu was evaluated to discuss the benefits of combined spectrum for nuclear material detection with measurement data of mixed oxide (MOX) fuel bundles in the SCK CEN exercise for disarmament technologies (IPNDV Technology Track (2021))[7]. The detectors were set at a 40cm distance from the center of the MOX fuel bundles with 12.6%wt plutonium content and 61%wt ^{239}Pu amount. The number of MOX fuel rods was 1, 19, or 61, with a ^{239}Pu mass range from 0.1 to 2.6 kg. **Figure 3** shows an example of a gamma-ray spectrum of the MOX bundle acquired with the CdZnTe detector. In order to accurately evaluate the performance for the detection of plutonium with a large amount of ^{241}Am accumulation, the detection limit in ^{239}Pu mass was evaluated for a gamma-ray peak at 413.7 keV based on the gross (*S*) and background (*B*) peak counting rates calculated by the *Covel* method. The Cooper criteria with three times the standard deviation was used to determine the detection limit (Nuclear Regulation Authority (2020))[5].

3.2. Results and Discussions

Figure 4 and **Figure 5** show the results of the detection probability evaluation. Higher detection probabilities can be confirmed for the combined spectrum at all the different measurement times and radioisotope search conditions.

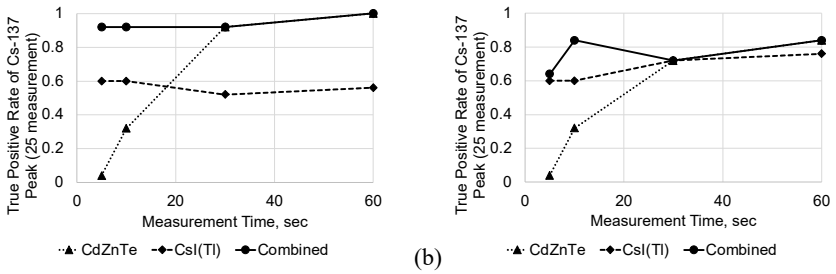

Figure 4. ^{137}Cs detection probability for single ^{137}Cs source; (a) ±1×FWHM, (b) ±0.1×FWHM.

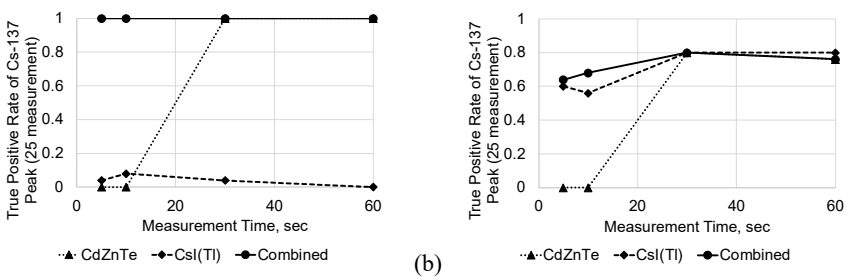

Figure 5. ^{137}Cs detection probability for ^{134}Cs and ^{137}Cs source; (a) ±1×FWHM, (b) ±0.1×FWHM.

The lower efficiency of the CdZnTe detector as the HRLE detector causes longer measurement time for ^{137}Cs detection, which can be significantly reduced by the combined spectrum. The CsI(Tl) detector as LRHE detector shows lower probability consistently with the measurement time in the case of the measurement of the pair sources with the broader radioisotope searching range (Figure 4 (a), Figure 5 (a)). This is obviously due to the lower resolution (or higher FWHM) of the LRHE detector and makes it difficult to separate the ^{137}Cs peak from ^{134}Cs peaks. The combined spectrum can benefit energy resolution in terms of the LRHE detector. As mentioned earlier, the spectrum-combining process can be regarded as an amplification of the spectrum acquired with the HRLE detector. It can be confirmed from the results of ^{137}Cs detection that the detection probability in the combined spectrum is almost the same as for the individual HRLE spectrum at longer measurement times. Compared to HRLE detectors, the spectrum combining approach has significant benefits for short measurement times, so it should be a more practical approach in nuclear security applications where a timely response is significant.

Table 1 and **Table 2** show the results of the performance evaluation for radioisotope identification. The benefits of the combined spectrum can be mainly observed in the results of *recall* for the different ranges at the radioisotope search process. This is likely due to the mutual benefit of signal amplification for the HRLE detector and improvement of resolution for the LRHE detector, resulting in a significant increase in true positives (TP) or a decrease in false negatives (FN) for radioisotope identification. The opportunity for radioisotope detection by the CdZnTe detector increases with longer measurement time, but the CsI(Tl) detector is suffered from its low energy resolution. The combined spectrum and the CsI(Tl) detector showed a small and similar change in the performance index values to the measurement time. This is because 60 seconds of measurement time is sufficient to obtain the gamma-ray counts required for radioisotope identification. Therefore, the benefit from spectrum combining to *recall* could be more pronounced with shorter measurement times.

Unlike the results in *the recall*, the combined spectrum shows lower *precision* values. **Table 3** shows the number of false positives for the background measurement. The lower *precision* in the combined spectrum is due to the increase in false positives (FP). The spectrum combining process amplifies the HRLE detector signals, which means that the noise of the signals and background counts

Table 1. Results of radioisotope identification tests (±1×FWHM).

Spectrum	Measurement time, sec.	*precision*	*recall*	*F-score*
Combined	60	0.584	0.993	73.526
CsI(Tl)	60	0.855	0.600	70.518
CdTeZn	60	0.976	0.559	71.121
Combined	300	0.572	0.996	72.701
CsI(Tl)	300	0.775	0.536	63.357
CdTeZn	300	0.897	0.732	80.617

Table 2. Results of radioisotope identification tests (±0.1×FWHM).

Spectrum	Measurement time, sec.	*precision*	*recall*	*F-score*
Combined	60	0.832	0.773	80.141
CsI(Tl)	60	0.970	0.441	60.606
CdTeZn	60	1.000	0.431	60.190
Combined	300	0.849	0.856	85.259
CsI(Tl)	300	0.991	0.464	63.215
CdTeZn	300	0.982	0.660	78.947

Table 3. False positives for background measurement.

Measurement time, sec	Radioisotope search range, ×FWHM	Combined	CsI(Tl)	CdZnTe
60	1	16	9	0
300	1	22	2	0
60	0.1	5	0	0
300	0.1	8	0	0

Table 4. Examples of radioisotopes in false positive cases.

Case	Trials	Radioisotope search range, ×FWHM	False positives				
			^{60}Co	^{133}Ba	^{134}Cs	^{137}Cs	^{152}Eu
^{60}Co	10	1	-	7	3	2	8
^{137}Cs	25	1	0	11	5	-	6
Background	10	1	0	7	2	2	5
^{60}Co	10	0.1	-	2	0	1	1
^{137}Cs	25	0.1	0	3	1	-	0
Background	10	0.1	0	3	1	1	0

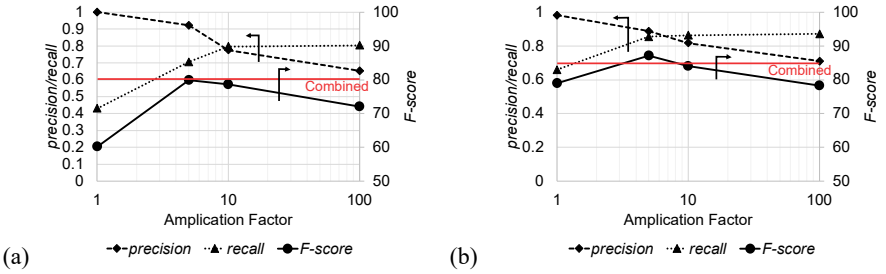

Figure 6. Radioisotope identification performance in simple amplifications of the HRLE spectrum (±0.1×FWHM); (a) 60 sec, (b) 300sec. *F-scores* in the combined spectrum are shown in red lines for comparisons.

Table 5. The lower detection limit in ^{239}Pu mass.

Pins	Trials	Measurement time, min.	Lower detection limit, g(^{239}Pu)		
			Combined	CdZnTe	CsI(Tl)
1	42	60	16.40	22.55	N/A
19	798	20	31.41	158.58	N/A
61	2562	20	41.43	231.29	N/A

are also enhanced over the individual HRLE detector. They could subsequently be determined as effective peaks and misidentifications as radioisotopes. **Table 4** shows examples of false positives that occurred in the combined spectrum. Many false positives were found for ^{133}Ba or ^{152}Eu, which have a larger number of gamma-ray peaks but are not significantly biased to either of them. In addition, no false positives were observed for ^{60}Co. These facts suggest that the false positives in the combined spectrum are likely due to statistical noise rather than background counts. The increase in false positives due to amplification of the HRLE spectrum indicates that optimizing the amplification factor of the spectrum is important for performance in radioisotope identifications. Simply amplifying the HRLE spectrum can increase true positives, but it also increases false positives, which may result in a decrease in performance (**Figure 6**). It was demonstrated that the proposed method can provide a practical level of amplifications, by amplifying the HRLE spectrum based on the gross counts measured by the LRHE detector. This could be an advantage in nuclear security applications where various types of detectors are expected to be used and rapid response is required. Although this paper discusses a limited number of detector combinations and needs further study, a more optimal amplification factor for the HRLE spectrum could be obtained by selecting the appropriate combination of detectors.

Table 5 shows the results of the ^{239}Pu detection limit evaluation. Similar to the tests of artificial radioisotope detection, the performance of the combined spectrum for ^{239}Pu detection was confirmed to be significantly better than that of individual detectors, and its benefits are more pronounced in the shorter measurement time. In comparison with the individual spectrum acquired with the CdZnTe detector, the spectrum combining process observed a reduction of the detection limit by about 80%. The evaluated detection limits varied with the number of MOX fuel pins, likely due to the self-shielding of the pin in hexagonal arrangements and the difference in measurement time. Since no effective peaks could not be detected due to the lower resolution, the detection limit could not be evaluated for the individual spectra acquired with the CsI(Tl) detector.

A series of tests for the detection and identification of artificial radioisotopes and nuclear materials showed that the performance could be significantly improved in

radioisotope detections by the spectrum combining process. At the same time, it suffers from the increase of false positives by the amplified statistical noise by the spectrum combining. This paper used an algorithm according to a standard peak detection approach and a very simple radioisotope search procedure to discuss the benefits of the spectrum-combining process. The procedure for the determination of radioisotopes could reduce false positives. The results in Table 3 showed that false positives in the combined spectrum were significantly reduced in the smaller range of radioactive searching (i.e., ±0.1 × FWHM). As can be seen in the values of *precision* (Table 1), the limitation of the radioisotope search range is a practical approach for the reduction of false positives in the combined spectrum as well as in the individual ones (it also reduces the *recall* since the *precision* and *recall* are in the relationship of trade-off). The performance of radioisotope identification represented by *the F-score* could be improved by using an advanced radioisotope determination algorithm. Importantly, the spectrum combining process proposed in this paper enables the determination of effective peaks by the standard peak analysis approach much more quickly, which is especially effective for shorter measurement times.

4. Conclusion

Rapid and precise detection or identification of radioisotopes is one of the challenging issues in the field of nuclear detection and nuclear security. In this paper, a mobile radiation measurement system using multiple gamma-ray detectors for radioisotope detection and identification has been proposed and tested. The proposed system consists of two small gamma-ray detectors with different properties in energy resolution and efficiency, and the output spectrum of the system is obtained by combining the individual spectra. It was demonstrated that the spectrum-combining process of the proposed system significantly enhances the capability of detecting radioisotopes and nuclear materials represented by plutonium. The benefit of the combined spectrum is more significant in shorter measurements time. Therefore, it should be more effective in nuclear security applications where a timely response to anomalous radiation and the MORC is significant. It was also found that the amplified statistical noise in the combined spectrum increases false positives in radioisotope identification. The performance of the proposed system could be improved by using an advanced algorithm for radioisotope identification. A limited combination of detectors has been discussed in this paper, but additional study with various detector combinations is required to optimize the system in terms of performance and cost. It is also necessary to discuss the application of commercial software for spectrum analysis and to evaluate their performance on measured data a wide variety of sources or nuclear materials.

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