Gamma-ray Source Detection with Coded-aperture Gamma Imager in a Complex Gamma-ray/Neutron Environment for Nuclear Security

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1. Introduction

Radioactive material is widely used in energy, medicine, and industry [1]. But if it gets into the wrong hands it can cause serious harm. Illicit trafficking or smuggling of nuclear or other radioactive materials including special nuclear material (SNM, plutonium, and certain types of uranium) is an existing problem all over the world. A compact radiation imaging system capable of detecting, localizing, and characterizing SNM would be helpful, in which the detection of SNM that emits neutrons and gamma rays is implemented in one device. Hence, both gamma spectroscopy and neutron detection can be influenced by the presence of each other's sources. Neutrons interact with environmental materials and produce gamma or X-ray by a reaction of (n, n'), which affects the main spectrum of gamma detector. The effects of neutrons on a traditional scintillator, such as NaI(Tl), are also described in [2], where new energy lines are added to gamma-ray spectrum due to the neutron interacts with NaI(Tl) detector. Examples of these spectral lines are seen in 58 keV and 202 keV energies owing to the recoil of ^{127}I nuclei. As an alternative, a common method for the detection of gamma-rays in the gamma/neutron environment is to separate neutron and gamma-ray pulses utilizing the pulse shape discrimination technique with the use of organic scintillators, such as stilbene and EJ-276 plastic scintillator. Nonetheless, in this case, the gamma-ray detection efficiency is dramatically reduced, leading to no feasibility of radiation imaging in real-time. Therefore, we look at the ability of the spectrum analysis and the real-time imaging of neutron/gamma sources using a coded-aperture based gamma camera developed in the Jeju National University.

2. Methods and Results

This section describes the components and performance of the developed gamma camera and covers the technology and measurement results of the gamma/neutron sources to be measured.

2.1 Epsilon-G

The developed gamma camera, termed EPSILON (**E**nergetic **P**article **S**ensor for the **I**dentification and **L**ocalization of **O**riginating **N**uclei)-G(gamma), can read-out 12 × 12 silicon photomultipliers (SiPMs), resulting in an instrument with 144 pixels which is coupled with 4 × 4 × 20 mm_t cerium doped gadolinium aluminum gallium garnet ($Gd_3Al_2Ga_3O_{12}$(Ce) or GAGG(Ce)) scintillator array and an intercepts area of 50.2 × 50.2 mm^2. GAGG(Ce) is a high-density, high absorption coefficient material and can provide scintillation performance characteristics that are competitive with both traditional scintillation solids (NaI(Tl), CsI(Tl)) as well as advanced cerium doped silicates such as LYSO(Ce) and $LaCl_3$(Ce). The use of this scintillator with these excellent properties allowed them to have excellent sensitivity and the ability to analyze nuclides. In addition, unlike the Compton camera, the application of the coded-aperture mask allowed excellent angular resolution and linearity to dose to be competitive [3].

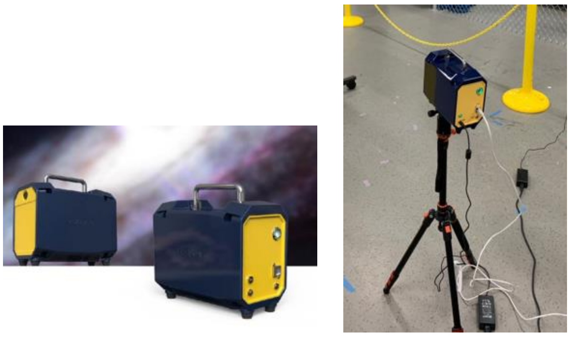


Fig. 1. Design of EPSILON-G (left) and illustration of use examples of equipment (right)

2.2 The Characteristics of Gamma/Neutron Sources

Table I. The characteristics of gamma/neutron sources used in this study.

	^{239}PuBe	**^{241}AmLi**	**^{252}Cf**
Half-life	2.4 × 10^{30} yr	432 yr	2.65 yr
Decay mode(s)	^{9}Be(α, n)^{12}C	^{7}Li(α, n)^{10}B	α (96.9%) SF (3.09%)
Neutron Energy	0.5 - 11.5 MeV E_{ave}: 4.4 MeV	0.02 - 2 MeV E_{ave}: 0.54 MeV	0.2 - 7 MeV E_{ave}: 2.13 MeV
Average # emitted neutrons	1.7 × 10^{6} n/s-Ci	60,000 n/s-Ci	3.757 per SF
Gamma-ray Energy	4.4 MeV	59.5 keV 102.97 keV ($NpK_{\alpha 1}$: 101.66 keV)	0.14 - 10 MeV E_{ave}: 0.8 MeV

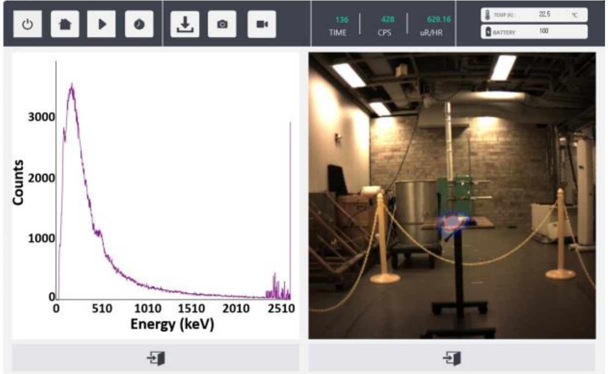
A very popular gamma/neutron source is a nuclear reaction of type (α, n) induced in certain isotopes using alpha particles coming from alpha decay of the other isotopes. For example, the ^{239}PuBe source emits the neutrons from reaction ^{9}Be(α, n)^{12}C. The neutrons have an energy range of 0.5 - 11.5 MeV with an average of about 4.4 MeV. It is not only a common neutron source but also a gamma-ray source that produces 4.438MeV photons. Furthermore, the ^{241}AmLi source emits the neutrons from reaction ^{9}Li(α, n)^{12}C. In addition, this ^{241}AmLi source emits gamma-rays with an energy of 59.5 keV and 102.97 keV. Neptunium X-rays with an energy of 101.66 keV also arise from the decay of ^{241}Am. On the other hand, ^{252}Cf is a spontaneous fission (SF) source, which emits a burst of time-correlated neutrons each time it fissions, resulting in the energy spectrum of prompt neutrons that can be described as a Maxwell distribution with the temperature parameter (T = 1.42 MeV). The energies of gamma-rays emitted from ^{252}Cf range from a few tens of keV up to 10 MeV. The characteristics of the aforementioned gamma/neutron sources are summarized in Table I.

2.3 Measurement setup for Gamma/Neutron Sources

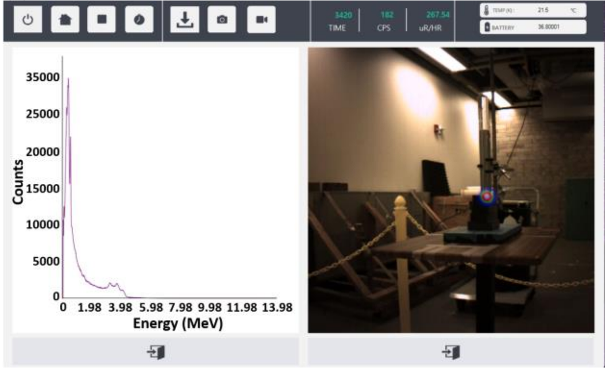
Specimens used for testing the detection capabilities and imaging performance in neutron and gamma environments are 5.37 × 10^{6} n/s ^{252}Cf, 1.7 × 10^{6} n/s ^{239}PuBe, and 5.57 × 10^{5} n/s ^{241}AmLi. These three sources were developed at the Michigan University, U.S.A. The prepared gamma/neutron sources were located two meters away from the camera and tested for the possibility of image acquisition and the time required for acquisition. The ^{239}PuBe source was exceptionally located at a distance of one meter away from the camera due to the source's low intensity of gamma-ray emission.

2.4 Spectrum Analysis for the gamma/neutron sources

(a)



(b)



(c)

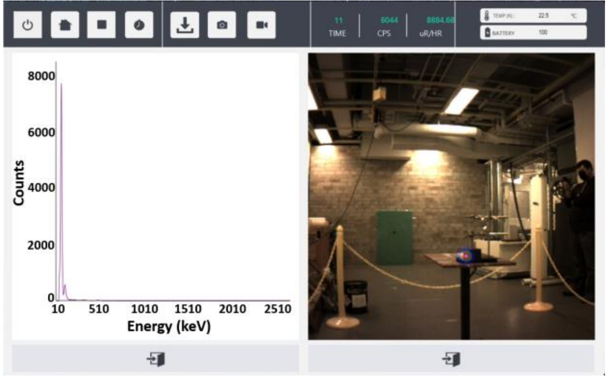


Fig. 2. Spectral and imaging results for gamma/neutron sources that are dropped at a distance of 2 meter using EPSILON-G: (a) 5.37 × 10^{6} n/s ^{252}Cf, (b) 1.7 × 10^{6} n/s ^{239}PuBe, and (c) 5.57 × 10^{5} n/s ^{241}AmLi.

Figure 3 shows the graphical user interface (GUI) screens, where the gamma-ray spectrum is presented on the left and the optical image superimposed by the radiation distribution map on the right. The elapsed time in the unit of second during the demonstration is given at the top of the GUI screens. In Fig. 3(a), it is challenging to recognize prominent full-energy peaks as explained above. In Fig. 3(b), the 4.44 MeV gamma-rays associated with the de-excitation of the first-excited state of ^{12}C can be observed. At the same time, the corresponding first- and second-escape peaks appear at 3.93 MeV and 3.42 MeV, respectively. In, Fig. 3(c), the energy spectrum showed a predominance of the full energy peaks at 59.5 keV and 102.97 keV. The reason why gamma-ray spectra analysis is possible in the neutron and gamma environments is due to the fact that neutron interaction with environmental materials can be mitigated by tungsten bars, with a thickness of 1 cm, surrounding the lateral side of the GAGG(Ce) scintillator array. There is another tungsten shield with a 5 mm thick at behind the sensor module. GAGG(Ce) scintillators also show a negligible interaction with the fast neutrons incident through the tungsten-based coded aperture that scatters fast neutrons.

2.5 Real-Time Gamma Camera Imaging for Gamma/Neutron Sources

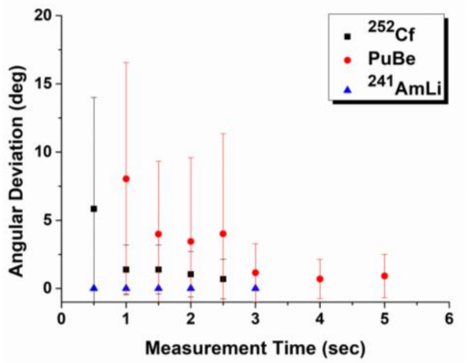


Fig. 4. Spectrum comparison with different ^{235}U enrichments samples

We also examined the time required to obtain an image to determine the exact source location using the acquired data. The angular deviation of the radiation distribution from the exact source location over the measurement time is presented in Fig. 4, and the result was that EPSILON-G can obtain valid images for the three gamma/neutron sources within 1.5 seconds considering the system's angular resolution of 6.8°. Because the 12 × 12 pixelated GAGG(Ce) scintillator array has a high detection efficiency as described in [3], it is feasible to implement the real-time imaging of the location of the gamma-ray sources in the complex gamma-ray/neutron environment. As a result, we confirmed that EPSILON-G is a portable gamma camera for accurate real-time visualization and localization of radioactive markers in neutron and gamma-ray environments. We will present more details at the conference.

3. Conclusions

Several technologies have been developed for nuclear safety and security in terms of nuclear nonproliferation. In particular, technologies that directly detect gamma rays emitted from gamma/neutron sources are still actively being studied. To this end, we developed a gamma camera equipped with the coded-aperture mask, which provides a successful analysis of gamma-ray spectra for ^{252}Cf, ^{239}PuBe, and ^{241}AmLi. It is also expected that the developed gamma camera using sensors with very high sensitivity would be able to identify the accurate location of gamma-ray sources in real-time in a complex environment where gamma-rays and neutrons coexist.

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