DOE/NV/25946--416

Can handheld plastic detectors do both gamma and neutron isotopic identification with directional source location?

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Keywords – gamma, neutron, spectrometry, directional, multiplicity, hand held

Abstract

This paper demonstrates, through MCNPX simulations, that a compact hexagonal array of detectors can be utilized to do both gamma isotopic identification (ID) along with neutron identification while simultaneously finding the direction of the source relative to the detector array. The detector array itself is composed of seven borated polyvinyl toluene (PVT) hexagonal light pipes approximately 4 inches long and with a 1.25 inch face-to-face thickness assembled in a tight configuration. The gamma ID capability is realized through judicious windowing algorithms as is the neutron spectral unfolding. By having multiple detectors in different relative positions, directional determination of the source can be realized. By further adding multiplicity counters to the neutron counts, fission events can be measured.

Introduction

Often, neutron detection is carried out using gaseous detectors through absorption by helium-3 (He-3), lithium-6 (Li-6), boron-10 (B-10), or some fissile isotope (Knoll 1989). Often, these neutron absorbing materials are gaseous in form where the tube holding this gas would be adjacent to a neutron moderating material. Alternatively, some scintillators can utilize recoil protons from the moderation of fast neutrons as a means of detection. If assay is desired, then appropriate detector system calibration is required. To further enable discrimination of fission (or spontaneous fission) neutrons from other more common neutron sources (such as alpha induced emission or cosmogenic neutrons), then multiplicity counters can be employed to histogram an appropriate Rossi alpha distribution (Reilly et al. 1991). Further neutron source ID can be accomplished, or assisted, by neutron spectrometry which requires multiple detectors. One attractive aspect of the proposed detector system is that it would simultaneously utilize all of these detection forms for neutrons. The system has multiple detectors for spectral unfolding, it counts proton recoils caused by the neutron thermalization, and it is borated so that the energy released in the $B^{-10}(n, \alpha)Li^{7}$ reaction can be also measured.

Gamma detection typically measures the gamma rays based on measurements of the ionized particles generated by the radiation interacting with matter. When isotopic ID is intended, this often is accomplished through using detectors with a high Z and high density to promote total energy deposition of the incident gamma into the detector itself. Many photons will only interact once or twice (often through Compton scattering) and leave the detector at a lower energy (although typically the Compton generated electron will deposit all of its energy in the detector) and so do not contribute to the photopeak

resulting in them not being utilized for ID purposes. This applies both for scintillation detectors as well as other solid state spectrometry systems. Another not so well known method is that of windowing (Lyons and Hendricks 2006). Windowing has been shown to be a very powerful method to accomplish rigorous background compensation for detection systems that are used in conditions where the background is continually changing (such as aerial detection systems, Hendricks 2001). In this approach, low resolution detectors can be made to attain comparable selectivity as that realized with high resolutions systems if the latter rely solely on photopeak quantification. The windowing can be made to utilize the Compton scattered photons so that man-made activity can be readily discriminated from natural radioactivity or even NORM sources, such as uranium tailings (Hendricks 2001) and Americium-241 (Am-241) contamination along with Europium-152 (Eu152) and cesium-137 (Cs137) (Hendricks and Riedhauser 1994). Although this approach can be done in tandem with high resolution systems (Hendricks and Hayes 2006), it is fully capable of seeing surface activity perturbations from aerial systems at levels reaching a fraction of natural background, demonstrating the full power of windowing methods to high selectivity even with low resolution as demonstrated at the Remote Sensing Laboratory (RSL) over the past few decades. Although the detector system proposed here would be low Z and low density, it partially corrects for this with a nominally large size (approximating a 4-inch right circular cylinder) but even more importantly, by using appropriate windowing algorithms.

In addition to the very sensitive gamma and neutron capabilities described above, the proposed detector system uses a compact array of detectors allowing directional source determination for both gamma and neutron sources in a single system. In

summary, this paper describes a system argued to be capable of carrying out gamma ID, neutron ID, rudimentary gamma spectrometry, neutron spectrometry and directional determination of either the gamma or neutron source being measured.

Modeled configuration

A gross schematic of the detector array is shown in Figure 1. The detectors themselves are 5 percent borated polyvinyl toluene (PVT) with tightly fitted hexagonal photomultiplier tubes (PMT). The detector systems were assembled by Scionix from other commercially available products. The electronics used to drive the system are custom built for this application in house. At present, the multiplicity circuit has not been completed but this is not considered to be either a difficult or challenging effort based on the simplicity of currently utilized systems at the National Laboratories (Reilly et al. 1991). Currently, circuitry is already built for summing the outputs from four detectors at the RSL; modifications are in process for these changes. It should be noted that this paper only covers the computer modeling of this system to demonstrate a sound theoretical basis for the detector application and operation.

Results

Correction for Background Spectra

The predicted spectrum obtained from summing all the detectors is shown in Figure 2 using the reference background spectrum of (Novikova et al. 2007) as a source term. The predicted spectrum was generated using MCNPX (Pelowitz 2005) and so the activity normalization was not needed and would only affect the noise seen in Figure 2 as a function of the integration time utilized in obtaining the spectrum. What is of interest here is that the spectrum is generated from the naturally occurring radionuclides in

equilibrium. Typically, the dominant relative changes below 2.5 MeV are those of overall amplitude with certain window ranges showing higher stability of this ratio than others. Any ratio of counts in any two windows below this energy will give a constant value when only natural background is present. Perturbations can be realized due to radon fluctuations but these can be corrected. Furthermore, at 1.4 MeV, the potassium-40 (K-40) peak provides a very nice real-time energy calibration standard (although in the spectrum shown in Figure 2, the Compton edge is the dominant feature) and so could be measured for this application. It is typically not utilized in a window as the relative concentration of K-40 to either the uranium or thorium decay series is not a precisely constant proportion, although the shape of its Compton continuum is generally a fixed shape and so partially falls out of energy windowing ratios constructed solely below its photopeak. As seen in Figure 2, there are effectively no gamma lines above 2.6 MeV such that largely anything above 2.6 MeV is cosmic in origin in the absence of anthropogenic sources. The two spectra shown in Figure 2 represent the actual energy deposition in the detector array (raw) and the smeared spectrum approximation that would be seen from the multi channel analyzer (MCA).

Using the generic energy windows of all counts in the energy bins of 0.1 to 0.5 MeV to the sum of all counts in the energy bins ranging from 0.5 to 1.0 MeV would give the window ratio a value of 0.64. The final algorithm would be composed to account for the presence of K, U series and Th series radionuclides, such that the weighted window of the spectrum gives zero for all natural background variants. This value would then be statistically indistinguishable from zero with variations dependent on total count times.

Basic Gamma Spectrometry

The low resolution of the detector array can be seen in Figure 3 for a Cs-137 spectrum both with and without the GEB feature implemented. As seen here, there is a small photopeak in the raw energy deposition spectrum, but with the light smearing function approximation of the GEB feature, no photopeak is resolved in the resultant spectrum. This provides an excellent example of the potential capability realized by the energy windowing approach. If the total initial photon fluence to the detector were in equal portions of both the background gamma radiation shown in Figure 2 and that of the Cs-137 shown in Figure3, the generic window ratio is increased from the background value of 0.64 up to 1.5 with statistical significance dependent on total number of counts (i.e., count time). Typical portal monitors for nuclear workers (which are thin strips of PVT) will have count rates in excess of 100 cps for background, so a one minute integration time should be more than adequate to make this discrimination. This is not meant to be the only suggested algorithm but rather a simple example of how windowing can take the output of a low resolution system and obtain final selectivity comparable to higher resolution systems. In this case, all that is argued is that selective identification of excess anthropogenic activity being present of a broad category (e.g., intermediate energy emitters) would be assessed by a simple window algorithm as described. Ultimately this approach will have to be accompanied by extensive analysis with verification and validation that the algorithms truly represent effective discrimination of anthropogenic activity from that of NORM (although this has been done consistently for many years at RSL with NaI detector arrays, Colton 1999).

Basic Neutron Detection

Because the PVT detectors are simultaneously neutron moderators and scintilators, the proton recoils from the moderation process are able to be counted in the detection process. By further borating the material, a concomitant capability to measure the thermalized neutrons through the boron capture process is present. The resultant simulated detector response to a bare Cf252 source is shown in Figure 4. The spectrum shown is an average of only the outer detectors generated to obtain the total angular response function. Here the response shows a relatively large proportion of counts that are well above 1 MeV.

An example of a windowing algorithm here would be to evaluate the ratio of counts between 2.5 to 5 MeV to those counts between 1 and 2.5 MeV in conjunction with the ratio that would occur from superposition of the background spectrum. The ratio for the background spectrum alone would be 17.7 for these windows (which by the way is not changed for the Cs137 plus background spectrum). When the background spectrum is added to a neutron spectrum of equivalent integral, the ratio becomes 3.67. The normalization here is arbitrary as the calibration will ameliorate this effect if it is even chosen to be used.

The most definitive indication to quantify neutrons will be demonstrated by the presence of boron absorption peaks in the spectrum, these in and of themselves could be used to quantify incident neutron flux. Although some form of window ratio would likely be utilized to take some credit for the lower energy counts caused by proton recoils from the neutron thermalization process, this is not discussed further here.

Although gross counting above 2.5 MeV is a simple method in and of itself, combining this with multiplicity counting allows SNM assay capability to be realized once the system is appropriately calibrated. Effectively, this would be a traditional multiplicity counting circuit with a lower level cutoff threshold of 2.5 MeV or thereabouts.

Source Location Determination

The angular distribution of individual detector elements is shown in Figures 5a and 5b for Cs-137 photons and Cf-252 neutrons, respectively. Although there are multiple algorithm forms that can be applied to deconvolute the source location relative to the detector, due to the differential outputs from each detector given their known response functions (Figure 5), they all tend to have the limiting resolution metric of the maximum and minimum response levels attained in any two detectors in the array. In other words, the greater the difference between the maximum and minimum in Figures 5A and 5B, then the more precisely and accurately the source angle with respect to the detector reference frame can be reconstructed.

Discussion and Conclusions

If the source is not already known due to prior measurements or other forms of predictive intelligence, then matrix methods on multiple window algorithms must be applied to obtain results for multiple isotopes simultaneously, as done historically at the RSL on sodium iodide arrays. Often, one will already know from process knowledge, or even historical measurements, which isotopes could credibly be present and so enable the use of windowing algorithms customized for that isotope. Some applications would have a short qualitative list of radiation sources of interest such as might be utilized in

interdiction where the categories would consist of NORM, medical, industrial and SNM. These groups tend to be amenable to the windowing approach but with associated mathematical complexity requiring concomitant verification and validation efforts.

Given all this, the answer to the question in the title of this paper is therefore argued to be affirmative based on the theoretical and calculated results presented. Compact plastic detectors should be capable of both gamma and neutron isotopic identification with directional source location determination.

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Figure Captions

Figure 1. Schematic representations of a compact hexagonal PVT array of a dual gamma neutron ID and directional finder system. The design and principles for operation were conceived at RSL with the detection system assembled by Scionix, with final peripheral electronics to be engineered and built by RSL. The left image is a cross section of the PVT detectors taken from a VisEd (reference) screen shot with the right image showing a perspective image of the core detector assembly.

Figure 2. This figure illustrates both the raw energy deposition spectrum along with the Gaussian Energy Broadened (GEB) spectrum which simulates the empirical pulse height distribution measured by the PMT due to the stochastic spread in light output per incident photon (Knoll 1989).

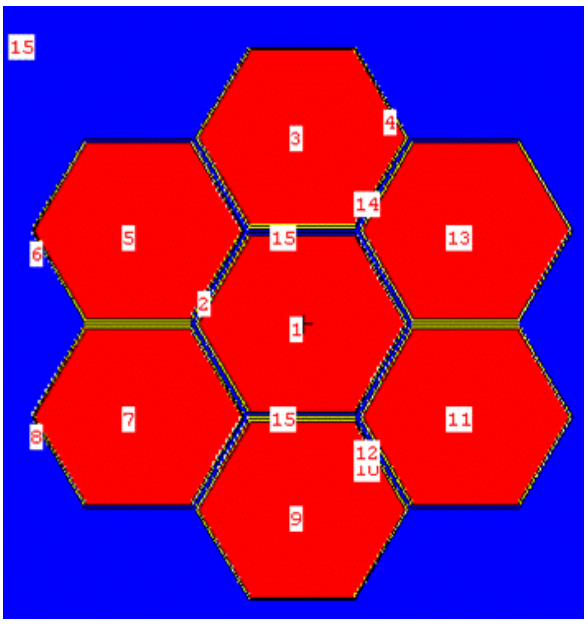
Figure 3. Comparison of the predicted actual energy deposition distribution (raw) and the expected measured spectrum (GEB) from the hexagonal array of PVT detectors. Both spectra have the same integral in this figure.

Figure 4. Predicted detector sum spectrum from a bare Cf252 source. This spectrum is the average angular spectrum obtained from the outside detector location used in generating Figure 5B. In this spectrum, proton recoils were modeled due to the unique capability found in the MCNPX software.

Figure 5. Angular response for a single detector element in the array to reference radiation forms.

Figure 5A shows the Cs-137 response for the outer element detectors and below this, **Figure 5B** shows the Cf-252 response for neutrons. The curve fit to each response is a 6^{th} order polynomial with the fitting function shown at the bottom of each figure.

Figures



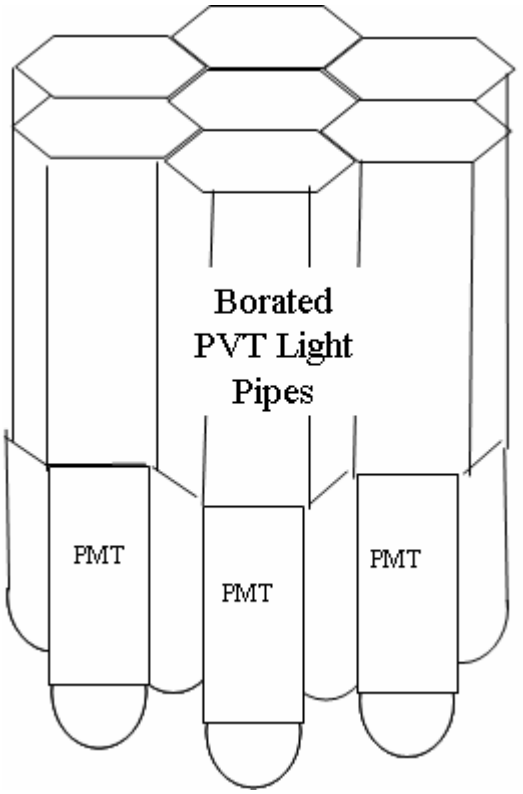


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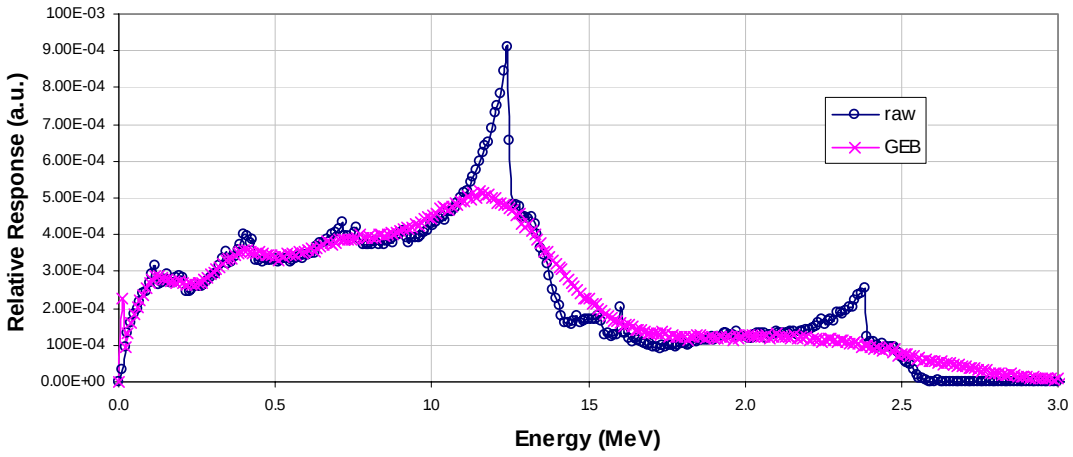
Figure 1



Can handheld plastic detectors do both gamma and neutron isotopic identification with directional source location?
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Figure 2

Can handheld plastic detectors do both gamma and neutron isotopic identification with directional source location?
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Figure 3

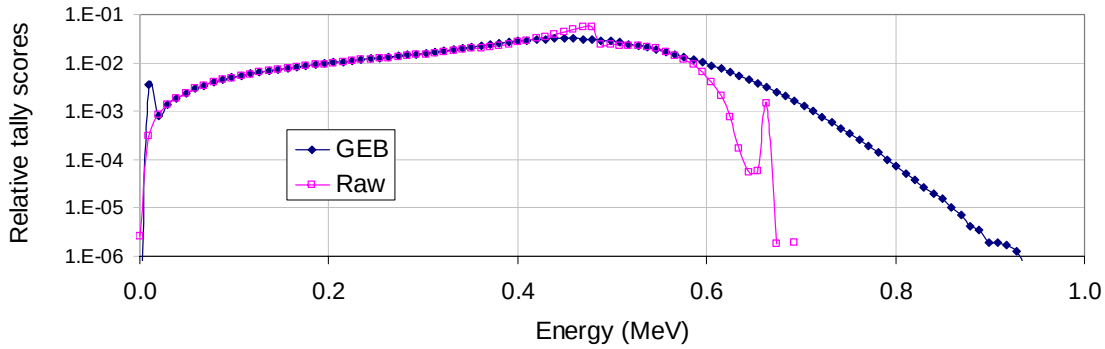

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Figure 4

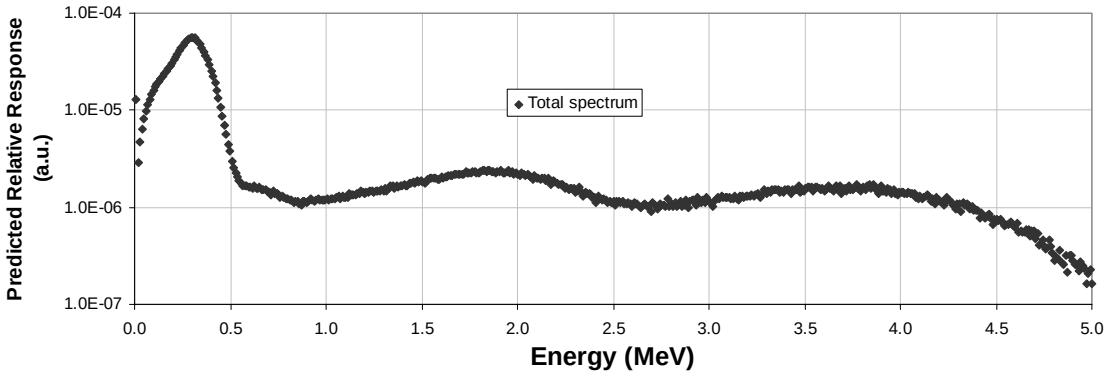

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Figure 5