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Spectral analysis of shielded gamma ray sources using precalculated library data

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HIGHLIGHTS

- Shielded gamma emitting radioactive source intensity is determined.
- MCNP generated precalculated spectra used to make comparisons to the unknown.
- Determined the shielding material thicknesses to an extensive test suite.

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ABSTRACT

In this work, an approach has been developed for determining the intensity of a shielded source by first determining the thicknesses of three different shielding materials from a passively collected gamma-ray spectrum by making comparisons with predetermined shielded spectra. These evaluations are dependent on the accuracy and validity of the predetermined library spectra which were created by changing the thicknesses of the three chosen materials lead, aluminum and wood that are used to simulate any actual shielding. Each of the spectra produced was generated using MCNP5 with a sufficiently large number of histories to ensure a low relative error at each channel. The materials were held in the same respective order from source to detector, where each material consisted of three individual thicknesses and a null condition. This then produced two separate data sets of 27 total shielding material situations and subsequent predetermined libraries that were created for each radionuclide source used. The technique used to calculate the thicknesses of the materials implements a Levenberg–Marquardt nonlinear search that employs a tri-linear interpolation with the respective predetermined libraries within each channel for the supplied input unknown spectrum. Given that the nonlinear parameters require an initial guess for the calculations, the approach demonstrates first that when the correct values are input, the correct thicknesses are found. It then demonstrates that when multiple trials of random values are input for each of the nonlinear parameters, the average of the calculated solutions that successfully converges also produced the correct thicknesses. Under situations with sufficient information known about the detection situation at hand, the method was shown to behave in a manner that produces reasonable results and can serve as a good preliminary solution. This technique has the capability to be used in a variety of full spectrum inverse analysis problems including homeland security issues.

1. Introduction

Analysis of collected gamma spectra is a subject that has been gaining more attention in recent years as the fear of clandestine nuclear material transportation rises. In some situations, a hidden source activity is unknown due to unknown shielding materials and their associated unknown shielding thicknesses. This scenario can become more complicated by only being able to use passive collection of the emitted gamma-rays as a means to determine the contents and composition of the shielding container. These two factors are influential in determining the overall source activity which is proportional to radiation exposure and can be used as a metric for public concern. With this possibility in mind, it would only make logical sense to use the most accurate tools available for more precisely assessing the potential presence and strength of malicious nuclear materials within any container.

The problem of analyzing unknown containers used to transport ionizing radiation can often be modeled in a combination of

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linear and non-linear parameters in terms of the radionuclides present, their source activity and the shielding materials at hand. Several approaches for determining the various radionuclides within any given spectrum have implemented the method of least squares analysis. Salmon (1961) was a primary contributor to this approach where he established its ability to successfully determine the composition and contribution of a spectrum with six separate sources and their associated spectra. He was able to complete this task by recognizing that the Compton continuum of the higher energy photo peaks impacted the shape of the lower energy peaks. To account for this, he used the entire spectrum of all of the radioisotopes found within the spectrum in his calculations. This successful demonstration of the least squares approach has lead to similar techniques that have been applied previously at NC State University for the measurement applications of prompt gamma-ray neutron activation analysis and X-ray fluorescence spectroscopy for elemental analysis (Guo et al., 2004).

There is a fundamental issue when attempting to resolve these various unknown shielding materials and their associated unknown thicknesses when given a spectrum of an unknown source and activity, which is centered on the idea that the peak value does not contain all of this information. The principal means by which to identify a source is by its photo-peaks with a high number of counts but in the situation that there is little to no knowledge of several shielding materials and the source activity, a complex density transmission gage using these photo-peaks is not possible. The most appropriate means to determine the shielding material is to consider the portion of the energy spectrum that represent the photons that have interacted with the material, scattered and then been collected by the detector. Due to the range of incident energies considered in this application, the region that needs to be considered for shielding material identification is from incoherent scattering events that reside below the full energy photo-peak.

2. Methodology

In the past, solutions for determining the presence of nuclear materials within shielded containers considered that the shape of the various components used to shield or hide the source of radiation from detection was negligible when constructing the database of simulation results (Gardner and Verghese, 1991). This is known as a one dimensional (1D) approach. The proposed updated approach discussed here builds on this previous idea but in this modified instance, the shape of the various components used to shield the source was taken into consideration in a more complete three dimensional (3D) approach. A primary reason that this advance was deemed as an essential component in the detection of nuclear materials was due to the increased accuracy of the measurements. To demonstrate the differences in these two approaches, general-purpose Monte Carlo N-Particle (MCNP5 v. 1.51) simulations were performed where the shape of two otherwise identical systems were constructed with one in a 1D fashion and the other in a 3D fashion (Brown et al., 2009). Lead, aluminum and wood were used as shielding materials and kept at their same respective thicknesses where the 1D simulation consisted of concentric spheres of shielding material and the 3D simulation used lead and aluminum in the shape of right circular cylindrical cans and wood in the shape of a square box. ^{137}Cs was used as a source placed in the center of the shielding scenario and a 2 in. × 4 in. × 16 in. NaI(Tl) detector was used 75 cm away from the source. The thicknesses of the materials were in the “mmp” configuration based on the authors previous work (Holmes et al., 2011). The simulated results are found in Fig. 1 and demonstrate the differences along the Compton continua which were directly

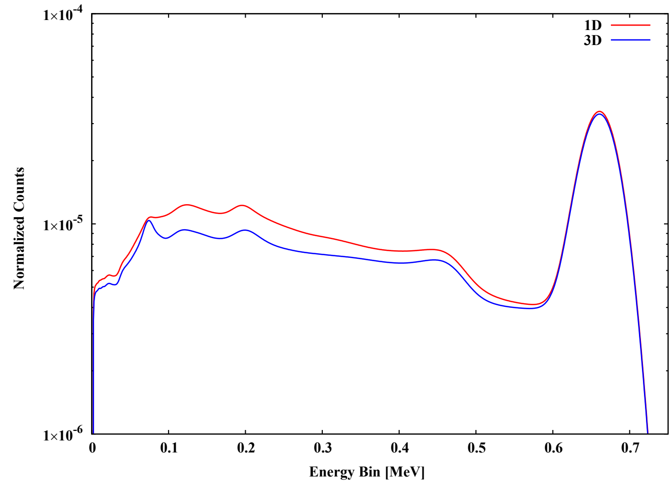

Fig. 1. Comparison of the 1D and the 3D simulations. The materials were in the “mmp” configuration where the lead, aluminum, and wood are 0.1792 cm, 1.1408 cm, and 10.7241 cm respectively.

related to the geometric differences as well as a difference in the number of counts at the full energy peak which can be seen more clearly in the normalized counts portion of the figure. Within this figure, the scale is normalized to the total number of histories ran against the number of tallied histories.

The primary tool used in the evaluation of the differences in the shielding materials employs the Monte Carlo Library Least Squares (MCLLS) method. This approach uses a series of libraries based on a very accurate pre-calculated forward models to fit an unknown data set (Gardner et al., 1997). This method is very useful in evaluating inverse spectral problems and while it may require more computational effort than peak transmission gauges, it is more advantageous in that it uses the entire spectral data available and is able to generate a solution with a higher degree of accuracy (Metwally et al., 2004).

As a means to use the MCLLS process, a generalized FORTRAN code has been developed by Gardner for determining the parameters of a fitting model for a given data set. This package has been called CURMOD, which is based on the CURFIT subroutine developed by Bevington, and has served as the backbone for many specialized code developments. CURMOD can be used to describe a data set using any combination of linear and non-linear parameters. Accurate guesses are required for each non-linear parameter but they are not required for the linear parameters. CURMOD uses the Levenberg–Marquardt non-linear search method for finding a solution to the non-linear parameters and a multiple linear regression in determination of the linear parameters. It uses a minimized reduced X^2 to select the best fit for all of the parameter values and also quantifies the error associated with each found parameter for the final fit to the input unknown spectrum.

To create the libraries used by CURMOD, it is essential to accurately determine the photon spectral fluence distribution entering the detector though the forward simulation. These calculations were performed using MCNP5 to more accurately represent the environment that was under investigation with the F8 tally to collect the simulated radiation events (Sood et al., 2004). This design uses three different shielding materials of lead, aluminum and wood with each having three equally thick shielding components and a null condition where the material is entirely removed, thus creating a total of 46 separate configurations. The structure, dimensions and naming conventions for these simulations was based off of previous work by the authors (Holmes et al., 2011). A 2 in. × 4 in. × 16 in. box style NaI(Tl) detector was placed one