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Spectral Relative Absorption Difference Method

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Abstract

When analyzing field data, the uncertainty in the background continuum emission produces the majority of error in the final gamma-source analysis. The background emission typically dominates an observed spectrum in terms of counts and is highly variable spatially and temporally. The majority of the spectral shape of the background continuum is produced by combinations of cosmic rays, ^{40}K, ^{235}U, and ^{220}Rn, and the continuum is similar in shape to the 15%-20% level for most field observations. However, the goal of spectroscopy analysis is to pick up subtle peaks (<%5) upon this large background. Because the continuum is falling off as energy increases, peak detection algorithms must first define the background surrounding the peak. This definition is difficult when the range of background shapes is considered. The full spectral template matching algorithms are heavily weighted to solving for the background continuum as it produces significant counts over much of the energy range. The most appropriate background mitigation technique is to take a separate background observation without the source of interest. But, it is frequently not possible to record a background observation in the exactly location before (or after) a source has been detected. Thus, one uses approximate backgrounds that rely on spatially nearby locations or similar environments. Since the error in many field observations is dominated by the background, a technique that is less sensitive to the background would be quite beneficial. We report the result of an initial investigation into a novel observation scheme for gamma-emission detection in high background environments. Employing low resolution, NaI, detectors, we examine the different between the direct emission and the "spectral-shadow" that the gamma emission produces when passed through a thin absorber. For this detection scheme to be competitive, it is required to count and analyze individual gamma-events. We describe the unique instrumental setup which we assembled to make these measurements.

Introduction

Handheld NaI(Tl) detectors are the most prevalent radioisotope identifying instruments on the frontlines of nuclear homeland national security. However, the embedded algorithms in commercial detectors perform poorly at isotope identification in laboratory environments and even worse in the field. Both Los Alamos National Laboratory and National Institute of Standards and Technology have conducted studies to evaluate the performance of commercial off-the-shelf (COTS) handheld NaI(Tl) detectors. Both groups determined that the embedded algorithms in current COTS hardware perform quite poorly compared to the ANSI benchmark (Blackadar et al. (2004), Pibida et al. (2004)). The question arises whether this poor performance is a limitation of the modest energy resolution of NaI, or if the implemented algorithms are underdeveloped. In an evaluation of research-grade algorithms, Nelson and Sokkappa (2004) find that routine signal processing methods (template matching, maximum likelihood, principal component analysis) perform vastly better than COTS hardware embedded algorithms. In controlled environments, these research grade algorithms would likely meet the 80% identification rates specified by the ANSI 42.34 and 42.12 standards for handheld radioisotope detectors. However, the authors express concern about the "lack of adaptability to real world conditions," because the algorithms perform much worse (at least 25% lower correct isotope identifications) when subjected to data taken in the field.

The major difference between the lab and the field is the background radiation. In the field, background radiation is frequently the dominant source of emission. Further, the background is dynamic both temporally and spatially. The spatial size scale is on the order of a meter (Scott (2003)) and can vary by a factor of 50 from different locations on Earth (Nelson (2003)). The temporal time scale is on the order of an hour and can change in amplitude by a factor of two diurnally (Zahorowski et al. (2004)). This dynamic behavior of the background radiation presents a challenging obstacle for radioisotope analysis. The most effective method for addressing the background radiation is to take an independent background observation without the source in the area of interest. In field applications, this is rarely an option, and approximate backgrounds are used that are derived from nearby locations or similar environments. These background approximations frequently dominate the error in the final spectroscopic analysis.

Fundamentally, there is a difference between the emission from background continuum and line emission. Most of background gamma photons are either from non-energy-discrete cosmic ray events or are gamma-photons that have undergone a very large number Compton scatterings, rendering them non-discrete in energy. These background photons are continuous in energy (but are not uniform in intensity) and produce the background continuum. This contrasts with spectral emission profile for radioisotope photo-peaks and other distinct energy events where the spectral effects are more pronounced and concentrated in energy. Below we propose and demonstrate a concept that exploits the difference between: a) source distributions that are discrete in energy and b) background distributions that are continuous in energy. The outline of the papers is as follows: We first sketch out a thought experiment to illustrate the spectral absorption difference analysis as a concept. Then, a description of a real-world detector system is described along with the data products generated. An analysis and discussion of this lab data is presented as a proof of concept of the spectral absorption difference method. In the paper conclusion, we describe the utility of this novel observation scheme and outline further work required for a full assessment.

A Thought Experiment

The concept explored here is a background suppression method that examines the relative spectral shape of observations made by two detectors. One of the detectors is surrounded by a thin gamma-absorbing shield (such as 1/8″ of stainless steel) and the other detector is a traditional "unshielded" detector. (We note that all modern detectors have some internal shielding; here we are discussing significant shielding in excess of the standard shielding.) If two observations are made with these detector systems, then the difference in the *normalized* spectral shape of these two observations reveals the *relative spectral absorption profile* of the gamma sources. This spectral absorption profile will be specific to the absorbing material and it will take a longer integration to reach the same number of counts in the shielded observation versus the unshielded observation.

Consider the following thought experiment: A background continuum and, separately, a photopeak are observed through a thin gamma-absorbing material. In this idealized system, there are no energy dependencies in the detector or the absorbing material. Further, the background will be exactly equal in intensity across all energies: a flat background. For a gamma-absorber to be independent of energy, the mean free path must be constant over all energies. If this flat continuum passes through the absorber, gamma photons at energy E_i will experience some absorption in the gamma-shield and some of these photons will be reemitted via the Compton process. Any process that occurs to gamma photons at energy E_i will also occur at energy E_{i+1} and likewise at E_{i-1}. As long as the energy distribution of continuum photons extends over all energies (including above the energy range of the detector), then the *shape* of the absorbed gamma spectrum will be the same as the traditional observation --- flat. If the spectral shape of this absorbed observation is compared to a traditional observation, one would only see a bias offset in intensity. Subtracting a total-count normalized absorbed background spectrum from a normalized unabsorbed background spectrum will produce a line that is equal to zero (within the SNR) over all energies.

Now let us consider the same types of observations for an energy-concentrated distribution, such as a photopeak. We will ignore energy resolution and state that intensity, I=0 when energy, $E<>E_{peak}$ and I=1 when $E=E_{peak}$. When this source is observed through the thin gamma shield, some of photons at E_{peak} will be absorbed and reemitted at lower energies with the exact spectral shape determined by the Compton interactions and energies. If the normalized spectral difference is generated, the dominant feature will be the difference in the height of the peak at E_{peak}. The amplitude of this peak in the relative difference spectrum will be somewhat larger than the actual number of absorptions at energy E_{peak} as the shielded spectrum is normalized. This normalized spectrum includes all the newly produced lower energy emission, which suppresses the photopeak on a relative basis. In addition to the distinct feature at E_{peak}, the difference spectrum will also contain lower level spectral structure in the Compton region.

Continuing the thought experiment, a "field" observation is produced with this idealized system, with emission from both the flat background and the energy concentrated event combined. In the relative difference spectrum the peak will be detectable in this difference analysis regardless of background level. No prior or off-source information is required of the analysis as the background determination is taken in-situ. This difference method would function best in high background environments as it depends on a significant continuum emission.

The instrument setup for this difference analysis is similar to that of coincidence measurements, but the analysis mode is fundamentally different. In coincidence analysis mode, an inner detector is surrounded by an outer detector, and the inner detector's counts are gated by simultaneous detections in the outer. These coincidence detectors can be used in a summed mode or an anti-coincidence mode. The spectral absorption profile method is not comparing scattered events out of one detector and into the other, so coincident events are irrelevant. In fact, this difference method can be performed with sequential observations. The difference analysis examines the spectral shape of these shielded and unshielded observations.

As with any observation technique, there are costs and benefits to the spectral difference analysis method. The main cost of this method is having to make two observations, requiring either two detectors or sequential observations. An additional cost is that in the shield observation, counts are deliberately being absorbed. The benefits of the method are that the analysis becomes independent of the background continuum, and that an expectation value of zero results for all background energy regions. This means that a region of interest analysis would generate the same signal if the background level was 100x stronger than the source signal as an observation where the background level was equal to the source.

The real world adds many complications to this thought experiment, mainly due to the energy dependence of the background continuum, the gamma-absorber, and the detector sensitivity. To further validate this concept, we examined synthetic data generated by GADRAS and assembled a small instrument to acquire data in the laboratory.

Instrumentation and Data Generation

A custom instrument was assembled at SRNL to collect event-level data in shielded and traditional observations. A 2″x2″ NaI detector was coupled with digitizer that allowed for time tagging of individual events. A ¼″ steel enclosure was fabricated to completely and uniformly shielded the detector for the absorption observations. The unshielded spectra were observed with the same detector after the enclosure was removed but in the same physical location. The integrations for the shielded observation were approximately twice as long as the unshielded in order to obtain similar total counts.

Two data runs generated time-tagged, event-list mode data in both a shielded and unshielded mode for four isotopes (^{60}Co, ^{137}Cs, ^{133}Ba, ^{228}Th). These observations were made at four different distances from the detector (5cm to 13cm). In addition, a high-count background observation was generated for both the shielded and unshielded detector configuration. We use the event list mode data to enable low count peak finding statistical tests and to enable summations over different time periods to simulate different integration times.

Initially the gain on the detector was not locked to a value and was allowed to drift during the long integrations. This was due to a limitation in way the digitizer was run to obtain the list-mode data. After several communications with the manufacturer, we were able to operate the gain in closed mode. The majority of the data acquired was with the gain open. The gain drift presented some difficulty in characterizing the performance of this analysis. We attempted to mitigate this effect by screening 2500-block regions in the event list file for regions where photopeaks were centered in consistent energy ranges.

We probed the sensitivity of the spectral relative absorption difference analysis by using the real data to generate synthetic observations from permutations of the original observation. To generate different integration times, intervals from the full event list were selected. By starting at random locations in the event list we could also sample the stochastic process of low count observations. The background-to-source mixture ratio was varied by mixing the background and isotope event lists in proportion to their respective count rates. The shielded observations were always mixed with the shielded background. Likewise, the unshielded observations were always mixed with the unshielded background. Employing these large count files, many distinct observations could be generated for any mixture-ratio of isotope and background.

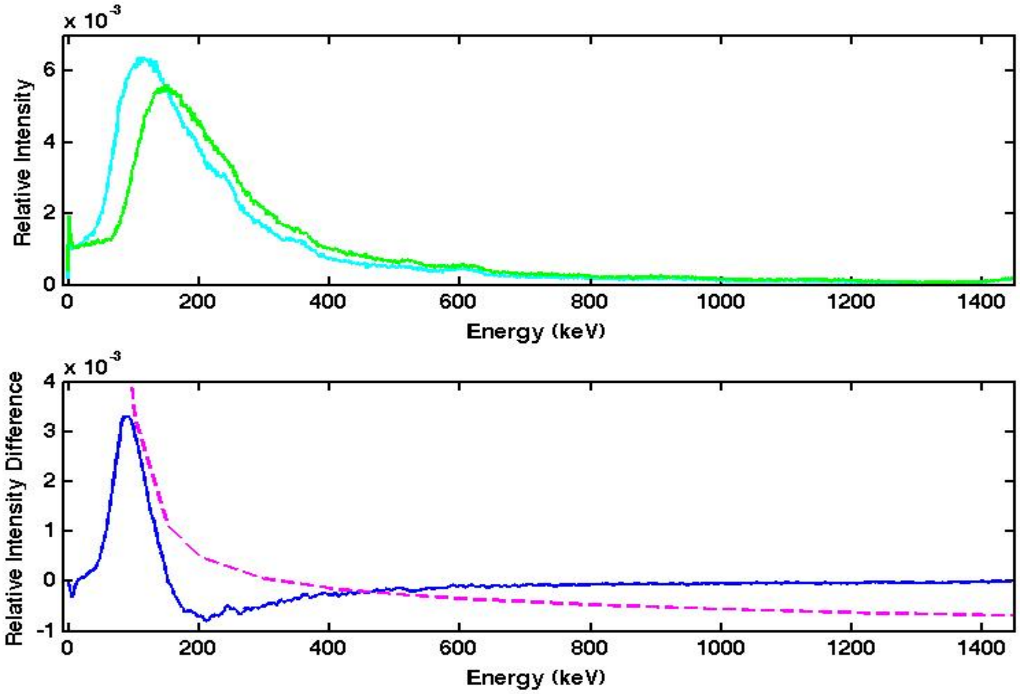

Figure 1. Shielding Difference Analysis Applied to Background. The top panel displays very high count observations of the background in both an unshielded (cyan) and shielded (green) configuration. The normalized difference of these observations is shown in the bottom panel (blue). The background is most void of small-scale spectral features. The large-scale feature from 50 keV - 400keV is due in part to the energy dependence of the gamma-absorbing shield. The mean free path of iron is shown in magenta as a visual confirmation of this energy dependence.

Analysis

For a combination of isotopes and background mixtures we perform the spectral difference analysis as described above. Briefly reiterating, both the shielded and unshielded are normalized by their respective total counts and then the difference between the spectra is produced. The difference spectra is then analyzed in regions of interest for indications of narrow-band energy. The goal of the analysis presented here is to provide proof of a concept for the spectral absorption difference analysis and is not a general solution.

In order to develop an understanding of the spectral absorption difference analysis, it is instructive to examine very high SNR observations of just the background. Figure 1 shows the two background observations (top panel) and their relative difference (bottom panel). These are very high count observations with roughly 1 million counts in each of the shielded and unshielded observations. There are a couple of notable features. The large scale structure from 40 to 200 keV is produced by the combination of the changing spectral shape of the absorber and the intrinsic shape of the background. We suspect, but have not confirmed, that it is possible to flatten this spectral region based purely on the physics of the absorbing material. All of the elements in modern steel (Fe, Cr, Ni, and Mn) have a *knee* in their absorption profile in the 5-10 keV and this resultant spectral feature appears in the lowest end of the spectrum. Discontinuities in the absorption profile could provide an interesting approach to energy-calibrate the data in situ as this is energy specific data imprinted on the observation. Somewhat counter-intuitively, the lower energy is dominated by the unshielded observation. This phenomena is occurs because the energy dependence absorption dominates over the downward energy scattering of the gamma-photons. The background from 300 keV to 1500keV is remarkably smooth and void of any distinct spectral features.

To continue developing an understanding of the spectral absorption difference analysis, a high count observation is examined where half of the counts originate from the background and half are from ^{60}Co. This analysis is presented in Figure 2 and we note the smooth background at higher energies, allowing for the clean detection of the two photopeaks. Another interesting feature can be observed, in that the photopeaks present as positive deviations from the spectral difference and the background continuum appears a negative deviation. The photopeaks will always create positive deviations as their relative magnitude is reduced in the absorption process. Where the background is at least 50% of the total counts, the background always produces negative deviations.

Of course with the high count observations, there is no need to perform such a difference analysis; traditional spectral analysis could handle these observations. There are two scenarios where the spectral absorption difference analysis will be particularly effective and have the potential to outperform traditional observational techniques. The first scenario is in extremely high count

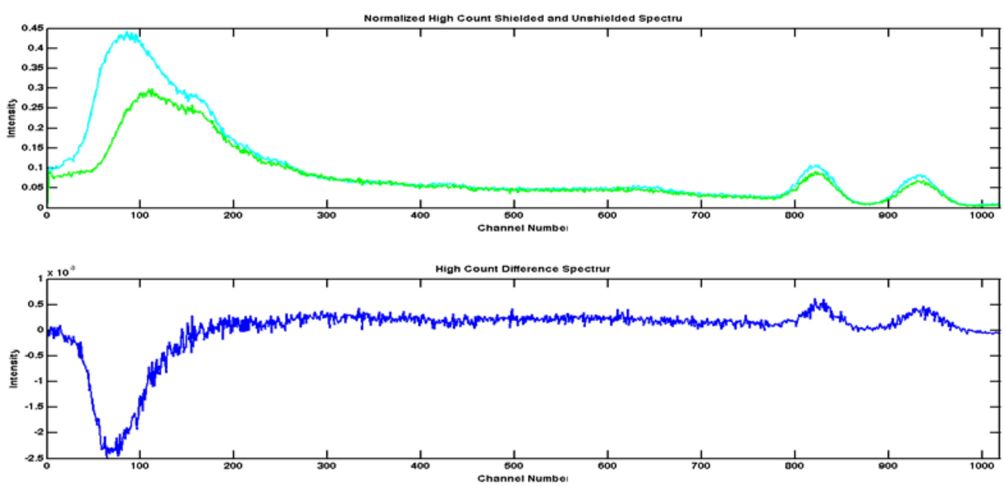

Figure 2. Shielding Difference Analysis Applied to ^{60}Co. The top panel displays very high count observations of background (~50% of total counts) and ^{60}Co (~50% of total counts) in both an unshielded (cyan) and shielded (green) configuration. The normalized difference of these observations is shown in the bottom panel (blue). Clearly in such high count observations, traditional isotope identification algorithms would easily detect the ^{60}Co emission and the main point illustrated is the clean nature of the signal detection in the difference analysis.

backgrounds environments where the source is contributing less than 5% of the total counts. If prior radiation background measurements are unavailable for such an environment and a long integration time is possible, then the spectral absorption difference analysis has the potential to reveal the signatures of isotopes beneath the overwhelming background. The concept of *detection at a large standoff distance* falls under this first scenario. The second scenario where the spectral absorption difference analysis will be competitive with traditional analysis is in very low count spectra (<1000 total counts) where the background is at a comparable level with the source. Below, we provide some examples of spectral analysis for these two scenarios.

In the first of our two scenarios, a challenge observational task is presented where 3% of the total counts in an observation originate from an isotope with the rest of the counts being background continuum. An example of such an observation is displayed in Figure 3. In the traditional spectra (top panel in blue) there is a hint with a very good background determination that the 1173keV might be detectible. However, the 1332 keV line is completely buried. Additionally, there is a spectral bump of emission in the mid-600 keV range, which would suggested to an experienced spectroscopist a potential for low level emission from the 662 keV of ^{137}Cs. The difference analysis shows no evidence of this emission. Because the background measurement is taken in-situ, there is no ambiguity in the spectral relative difference analysis determination of any low level ^{137}Cs. However in traditional analysis, the background would have to better than 3% over the 662 keV region to make the same determination. Further, it is not physically possible to determine how

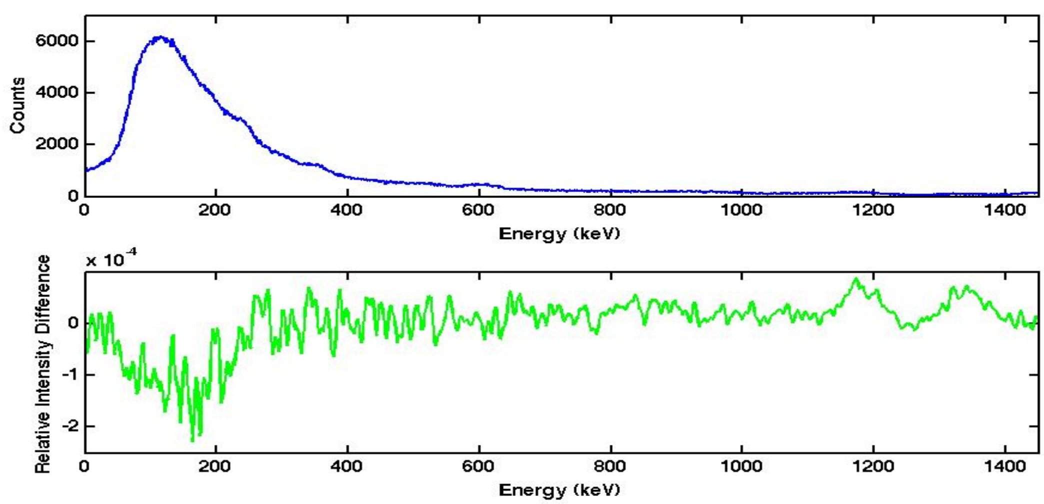

Figure 3. Shielding Difference Analysis Applied to ^{60}Co. Displayed is the difference analysis applied to a very high count observation of background (~97% of total counts) and ^{60}Co (~3% of total counts). The top panel displays the unshielded observation (blue). The bottom panel displays the difference analysis (green). We have subtracted off the shape of the pure background for flattening the difference spectrum. This has no impact on algorithm performance, but makes the figure more readable. In the future, we will develop flattening techniques that rely on the fundamental physics. Without a prior measurement of the background, traditional isotope identification would have difficulty identifying the ^{60}Co emission in this measurement.

accurate a nearby background measurement is to the radiation measured in the target observation. In the introduction, several studies were mentioned which reviewed how dynamic the background continuum is spatially and temporally. Those studies were for total counts. We are unaware of any studies indicating the spectral stability of background measurements. But for most field applications, it is unlikely to be better than 10%.

In the second scenario, the challenge is to determine the presence of an isotope when 30% of the counts originate from the source, but there are only 750 counts total in the spectrum. In traditional spectroscopic analysis, there are a minimum number of counts required before a photopeak looks like a peak. For the low count spectral analysis we combine the difference analysis with statistical test on the events list.

Although the majority of radioisotope identification algorithms analyze the gamma-ray energy spectra, stronger statistical tests can be used when the event-level data are considered. For example, each event that arrives in each energy bin can be treated as a separate statistical entity, instead of merely the sum of the number of events that arrive in each energy bin. Wurtz (2004) has shown the benefit of a Kolmogorov-Smirnov (K-S) analysis when performed on simulated event-level data in a region of interest (ROI)-type analysis. An analogous test on the event arrival times can be performed to test if two populations arise from the same underlying distribution. The Mann-Whitney U-Test (Mann & Whitney (1947), Wilcoxon (1945)) is a non-parametric test that is particularly well suited for extremely low count data. This method has the capability to assign

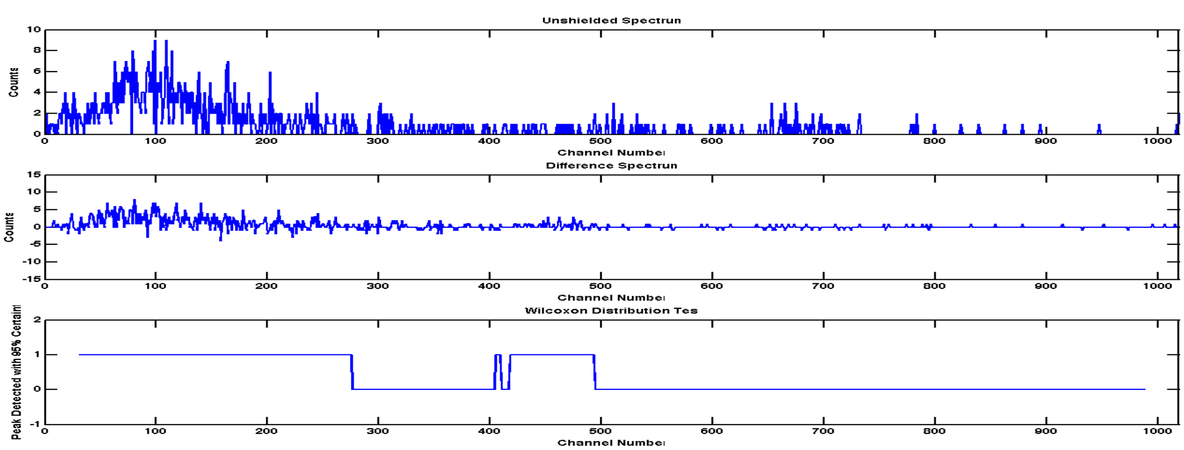

Figure 4. Low Count Shielding Difference Analysis Applied to ^{137}Cs. Displayed is the difference analysis applied to a very low count observation of background (~70% of total counts) and ^{137}Cs (~30% of total counts). The top panel displays the unshielded observation. The middle panel displays the difference analysis. In the bottom panel a statistical test (Wilcoxon or U-Test) is performed on the difference spectrum, where a value of 1 represents a 95% probability of a photopeak in this region. We have assumed a background region from channel number 500-700. Such a broad peak detection is not useful for isotope identification and this only represents the first step in peak determination. In this analysis, we did not attempt to address the systematic issues with the region below channel number 300.

confidence levels to low count detections in specified spectral regions of interest. The main limitation of this method is that an expected value or population is required to define the background. However, in the spectral difference analysis, we have an expected value of zero for every region that is background.

We have conducted some preliminary work on low count data with high background levels (See Figure 4). We have been using the difference spectral analysis on very low count data (750 counts), where up to 70% of the counts are due to background. In a 750 count spectrum (70% Background, 30% ^{137}Cs) when the difference method is applied, we are able to use the Wilcoxon statistical test to detect the 663 keV peak at the 95% confidence level. We assume a background region from channel number 500-700 and the detection algorithm picks up the 662keV peak, but as a broad energy range. A further investigation of this peak detection method could be used to determine the low count limit necessary for useful identification with some isotope identification application.

Conclusion

The spectral absorption difference analysis method is intriguing and fundamentally different from any previous work we have found in the literature. There are numerous issues to address going forward, as this work just provides a proof of concept. By considering all the absorption and detection efficiencies in the difference method it is likely that the low energy range of the spectrum can be flattened. It would be interesting to explore other gamma-absorbers, particularly ones that contain multiple mean-free path “knees” in the 10-1500 keV range for energy calibration. To provide gains over traditional observations and analysis, the spectral absorption difference analysis requires a high background environmental situation and either very long integrations or very low count observations. Frequently, it is not possible to know whether the observations, yet to be taken, are in either of these scenarios. In future work we hope to quantify the gains of this novel observing scheme and further explore its utility.

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