Low-resolution Gamma-ray Spectrometry for an Information Barrier Based on the Template-Matching Approach

Malte Göttsche and Alexander Glaser

Program on Science and Global Security
Princeton University, Princeton, NJ

ABSTRACT. Gamma-ray spectrometry has been successfully employed to identify unique items containing special nuclear materials. The technique is particularly sensitive to the isotopes near the surface of an inspected item and its projected surface area (or its minimum mass). Here, we present a warhead authentication system based on low-resolution measurements, which, by design, reduces the extent of revealed sensitive information. A polyethylene insert can be placed in front of the detector in order to detect important evasion attempts and to assess in particular whether an item’s absolute mass of fissile material correspond to the mass of a reference item. Neutrons from spontaneous or induced fission events in the item produce 2.22 MeV gammas from \((n,\gamma)\) reactions in the insert. This supplementary gamma signature scales with the mass of the item and provides extra sensitivity of the inspection system. While the intensity of spontaneous fission neutrons from plutonium is sufficient to confirm the item’s mass, a californium-252 source can be added to obtain a neutron signature from induced fission in uranium items.

Background

Current nuclear arms-control agreements between the United States and Russia limit the number of deployed strategic nuclear weapons each party can have. In the future, however, nuclear arms-control agreements will most likely also place limits on the number of nuclear weapons and warheads that a country can maintain in its arsenal. Such agreements would require the inspection and verification of warheads that are in storage and queued for dismantlement, including confirming their authenticity. One of the authentication concepts, designed to prevent the leakage of sensitive information, is the template-matching approach. The method seeks to detect significant differences between two items, for example by means of gamma spectroscopy. Despite the approach’s strengths, few such systems have been proposed and built;\(^1\) among these, the Trusted Radiation Inspection System (TRIS) developed at Sandia National Laboratories is the most prominent and widely tested one.\(^2\)

In this paper, a concept is proposed and evaluated based on its capability to detect the most relevant evasion scenarios. One of them is the diversion of fissile material. While
passive gamma spectrometry is generally not well suited for determining the fissile mass in a nuclear component due to self-shielding effects, we examine conditions under which the technique is able to detect significant differences in the mass, in addition to isotopic composition and the size of the item’s surface, in simple configurations using simulated gamma spectra. This is done using MCNP simulations. To benchmark the simulated data, we have compared our results with extended measurements for a 4484-gram sphere of alpha-phase, weapon-grade plutonium (BeRP ball, 0.02 wt% Pu-238, 93.27 wt% Pu-239, 5.91 wt% Pu-240, 0.07 wt% Pu-241, 0.03 wt% Pu-242), surrounded by a 3.0 inch polyethylene reflector. These were previously conducted as part of the SINBAD exercise using a High-Purity Germanium detector. The MCNP results are in agreement with the measurement data.

Concept

In order to limit the amount of sensitive information acquired, we examine whether sufficient results can be obtained with low-resolution detectors. While the information barrier concept prevents inspectors from accessing the spectral data, acquiring low-resolution spectra adds an additional layer of security. Just as TRIS does, the proposed setup uses a sodium-iodide (NaI) detector with a 2-inch by 2-inch crystal. Its resolution has been determined and implemented by measurements of various radioactive sources with the Canberra Model 802 NaI detector. A polyethylene mask with a thickness of 15 cm is placed between the source and the detector to moderate and capture neutrons in hydrogen (Figure 1). In this process, 2.22-MeV gamma rays are emitted, which can be detected by the inspection system. As the polyethylene also acts as gamma shielding, the mask has a central drilling to allow gammas to pass through without attenuation. A 5 cm thick steel plate (with a corresponding drilling) serves to attenuate gammas that would otherwise scatter in the polyethylene and arrive in the detector, *inter alia* contributing to Compton background. The mask has an outer radius of 20 cm and a polyethylene mass of 17.6 kg. The detector is positioned 10 cm behind the plate.

We extend the standard template approach, which relies on a comparison of gamma spectra, by including two additional criteria in order to be more sensitive to important diversion scenarios that may otherwise be missed. Combined, the current criteria are:

**Spectral features.** The level of similarity between the acquired gamma spectrum and the template is determined by an “empirical” Kolmogorov-Smirnov (KS) test. In statistics, the standard two-sample KS test is a nonparametric hypothesis test that measures the similarity of two distributions. To do this, the test uses the largest absolute difference ($D_{KS}$) between the two cumulative distribution functions of the datasets as a measure of disagreement (see Figure 2). It accepts the hypothesis that the distributions are equal if $D_{KS}$ is less than the threshold value $D_T$, which is determined by choosing a
significance level. Directly applied, this test will reject the hypothesis for two measured spectra, if the measurement configuration, e.g. the source and detector position, the detector voltage, or other experimental conditions vary to a very small extent. To have a test that allows for such slight variations, we empirically determine the $D_T$ for a series of measurements on the same items to meet a specified false positive rate. Preliminary experimental results we obtain with standard calibration sources suggest selecting $D_T = 0.010$ results in negligible false positive rates for measurements with 100,000–200,000 counts. Measurements on plutonium and uranium items are required to confirm this assessment.

**Total gamma count rate.** The features of a gamma spectrum are largely determined by the isotopics of the source and only weakly depend on the size of the object. In order to be directly sensitive to size, we therefore also compare the total gamma count rates observed for the template and the inspected item. To first order, these count rates scale with the projected surface area of the items and provide a useful indicator for the similarity of their shapes.

**Total neutron count rate.** The gamma signature of massive objects, i.e., objects with thicknesses that exceed several millimeters, is dominated by the isotopics near the surface. The signature is much less sensitive to the presence of radioactive material away from the surface. For this reason, simple gamma measurements cannot be used for estimating the mass of an inspected item; at best, they can provide a minimum mass estimate. Most diversion scenarios involve removing fissile material from an item, and an indicator that scales with mass would therefore be highly valuable. Here, we use neutron emissions from the item for this purpose. While plutonium components emit enough neutrons passively, an active configuration, using for example a californium-252...
Figure 2: Quantifying the differences between two radiation spectra. Simulated gamma spectra measured of the original BeRP ball compared against the spectrum of a similar ball made of reactor-grade plutonium (top). The cumulative distribution function is equivalent to the fraction of the counts that have already been observed as a function of energy.

source, is required for uranium components. The neutron rate is indirectly assessed by the 2.22 MeV peak intensity produced in the polyethylene mask. The strength of this gamma line will be used as an indicator scaling with the mass of the object (Figure 3). If neutron multiplication in the inspected item is significant, then the dependency can be nonlinear. Since, for the template approach, we only compare the equivalence of radiation signatures and are not interested in absolute mass measurements, understanding the functional relationship is not necessary.

The Uranium Case

As an approximation to a collimated californium-252 source, we simulate a neutron beam with an intensity of $10^5$ n/s directed at the uranium item. The polyethylene mask
Figure 3: Gamma peak at 2223 keV following neutron absorption in hydrogen. Shown are the detector counts for the solid BeRP ball and for a hollow ball from which 15% of the material has been removed (3830 grams vs 4484 grams). The relative peak area drops by about 40% due to reduced mass and lower neutron multiplication in the hollow item.

and the detector are placed at a 90° angle from the beam, facing the uranium item, in order to minimize detected neutrons originating from the Cf-252 source as opposed to induced fission. Figure 4 shows the simulated spectrum of a weapon-grade uranium metal sphere (23.2 kg, 1.02 % U-234, 93.16 % U-235, 0.47 % U-236, 5.35 % U-238) and a spectrum with the same sphere, but with a 20%-reduction in the uranium-235 content (73.16 % U-235, 25.35 % U-238). Only gamma rays above 100 keV are shown as lower energy gammas are very easily shielded and do not provide a robust signature. The intense U-235 peak at 186 keV clearly dominates both spectra. The configuration with the larger U-238 content can be distinguished from the other by the reduced 186 keV peak intensity, and a larger peak intensity of the U-238 daughter nuclide Pa-234m peaks at 766 keV and 1001 keV.

The spectra would be difficult to distinguish using the cumulative distribution function: The intensities of the Pa-234m peaks are very low compared to the 186 keV peak and therefore have a very small influence on the distribution function. Because the function is normalized and the 186 keV dominates the normalization to such a large extent, differences in the 186 keV peak intensity are hardly seen with the cumulative distribution function as they are offset by the normalization ($D_{KS} = 0.007$).

The modified KS-test is effective, however, when separately calculating cumulative distribution functions for two or more energy regions. The results for two regions are shown in Figure 5. We obtain $D_{KS} = 0.004$ for the 100–600 keV, which is not sufficient to
Figure 4: Sodium iodide detector gamma spectra of weapon grade uranium (black) and a uranium item with a lower enrichment level (red), simulated using MCNP.

distinguish the spectra based on our criteria; in contrast, we obtain $D_{KS} = 0.058$ for the 600–1100 keV region. Using even smaller regions of interest, one obtains $D_{KS} = 0.002$ for 100–350 keV, $D_{KS} = 0.047$ for 350–600 keV, $D_{KS} = 0.063$ for 600–850 keV and $D_{KS} = 0.132$ for 850–1100 keV, which is also suited to distinguish the spectra.

Figure 5: Cumulative distribution functions of two spectral regions of the two gamma spectra shown in Figure 4.

Figure 6 shows the 2223 keV peak of the two configurations. There are $2120 \pm 50$ peak counts for a 30-minute measurement of the weapon-grade sample and $1400 \pm 40$
Figure 6: The 2223 keV peak of the weapon-grade uranium item (black) and the item with a lower enrichment level (red) and a californium-252 source, which is the result of neutron capture in the polyethylene mask. The counts correspond to a 30-minute measurement.

peak counts for the other, which means that they can be distinguished. The reason why the number of counts is larger for the weapon-grade item is the higher induced fission cross-section of U-235 compared to U-238 for fast neutrons and therefore a larger neutron multiplication \( M = 6.72 \) compared to \( M = 4.40 \). While for these two configurations, the “empirical” KS test alone is sufficient to distinguish between them, a hollow sphere with diverted uranium, but the same isotopic composition, would perhaps not be detected by the KS-Test, but by this one. The 2223 keV peak intensities would differ, as the hollow sphere’s neutron multiplication would also be smaller due to the lower (most significantly U-235) mass. For two items with more similar isotopic compositions, or items with only small material diversions, the required measurement time would be larger or the californium-252 source would need to be stronger to obtain unambiguous results.

The total gamma count rate of the weapon-grade uranium measurement is \( 1714 \pm 41 \) counts compared to \( 1364 \pm 37 \) counts per second for the ideal detector modeled here (100-1100 keV window). The total count rate is accordingly also an effective measure to distinguish different isotopics, and would also be suited for detecting different surfaces.

The Plutonium Case

The goal is an authentication algorithm that does not require assumptions, such as the fissile material type. Therefore, the same modified KS test windows should be used
for plutonium items. They also work well with plutonium, as can be seen in Figure 7, as plutonium emits gamma rays in both energy regions ($D_{\text{ks}} = 0.018$ for the 100-600 keV and $D_{\text{ks}} = 0.023$ for the 600-1100 keV window). Note that the differences in the simulated isotopics are small. Our simulations also show that the analyses of the 2223 keV peaks as well as the total count rates function well. For plutonium items, no californium-252 source is required for a sufficient neutron signature. If it is unknown, however, whether a plutonium or uranium item is examined, a Cf-252 could be used in any case.

Conclusion

In this paper, we examine the potential of low-resolution gamma spectrometry for an information barrier based on a template-matching approach combining three different criteria: spectral similarity, neutron emissions (indirectly via gamma emissions after neutron capture in hydrogen), and total gamma count rate. The analysis of the simulation results suggests that the three proposed tests could be effective in distinguishing valid from invalid nuclear components. They can be applied in similar form to both uranium and plutonium, but a separate neutron source is needed in the case of uranium to drive fission events in the inspected item and generate a robust neutron signature. As a next step, experimental testing with plutonium and uranium items of relevant masses is required to obtain a nuanced understanding of uncertainties.

Compared to previously built template-matching information barriers, our proposed setup can be expected to be more robust in detecting important evasion scenarios that might not have been detectable before. In particular, one such scenario is the diversion
of fissile material from the interior of an item, which is unlikely to be detected by standard gamma spectrometry without the polyethylene mask.
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Endnotes


3*Shielding Integral Benchmark Archive and Database, Version December 2013, SINBAD-2013.12.*


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