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Passive one-dimensional self-transmission imaging of subcritical metallic plutonium assemblies

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ABSTRACT

We present a new passive technique to assess the spatial extent of subcritical metallic assemblies of plutonium. This technique could be used in disarmament verification where the size of the assembly is a verification attribute. The technique is based on measurements of neutron and gamma-ray coincidences from fission events within special nuclear material (SNM) and is analogous to active transmission imaging where the interrogating source is the SNM itself. Experimental measurements were performed using a ^{252}Cf source and a 4.5 kg sphere of weapons-grade plutonium metal. These measurements and Monte Carlo simulations demonstrate that this technique is highly sensitive to the outer radius of metallic spherical assemblies of plutonium and moderately sensitive to the presence of a void inside the plutonium.

1. Introduction

The aim of disarmament verification is to ensure that warheads dismantled over the course of an arms control treaty are authentic nuclear warheads. Broadly, there are two categories of proposed methods of disarmament verification: template approaches and attribute approaches [1]. In template approaches, measurements of an unknown warhead are compared to measurements of a template warhead which is known to be authentic. In attribute approaches, specific attributes of the warhead are measured, such as its mass or isotopic composition, and the results are compared to what would be expected for a possible mock warhead. The inspected item is assumed to be authentic if a sufficient number of attributes are inconsistent with mock warheads.

We propose a new passive technique to measure the size of the dismantled plutonium assembly as one component of an attribute approach to disarmament verification. The proposed technique is similar to 1-D transmission imaging where the interrogation source is spontaneous fission within the assembly itself. Our novel technique is capable of distinguishing a fissioning SNM assembly with some spatial extent from a point-like fissioning source, and it has some capability of detecting a void inside the assembly. The sensitivity to inner voids can confirm that no material has been diverted from the interior of the SNM assembly.

The technique relies on measurements of correlated prompt fission neutrons and prompt fission gamma rays from the assembly. We use a similar technique as the one developed in Ref. [2] to estimate an average distance to the assembly from measurements of correlated gamma ray and neutron pulse height and timing distributions. However, in our work the fitting procedure is repeated for different combinations of detectors located on two opposite sides of the assembly. For each combination, the extracted average distance to the assembly is inherently weighted by the escape probability of the gamma ray, which for high-Z assemblies is greatest at the surface of the assembly. Therefore, in effect we measure the average distance to the surface of the assembly on opposite sides, giving an estimate of the diameter for metallic fissioning assemblies. The interior of the assembly can be probed by varying the gamma-ray threshold. For the purposes of disarmament verification, these attributes (outer diameter, inner diameter) would have to be hidden behind an information barrier [1].

2. Previous work on imaging of SNM and time correlated pulse height analysis

2.1. Selected previous work on imaging of SNM

In general there are two techniques commonly used to passively image gamma rays or neutrons from SNM: coded aperture imaging [3–6] and scatter/Compton imaging [6–8]. For the particular application of resolving the spatial extent of assemblies of SNM in disarmament verification, scatter/Compton imaging may not have sufficient angular resolution to assess the size of the assembly [3,6–8]. In comparison, coded aperture imaging has a smaller field of view but superior angular resolution. Previous experiments have demonstrated that gamma ray

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and neutron coded aperture imaging or time encoded imaging can obtain angular resolutions of a few degrees which could be sufficient to assess the outer diameter of an SNM assembly [3,4,6].

It is not clear if coded aperture imaging techniques can assess the presence of voids inside the SNM. Coded aperture imaging and time encoded imaging both rely on the detection of singles events from the source. For gamma-ray imaging, these techniques will not be able to image the interior of metallic assemblies of SNM because of the short attenuation length of gamma rays within metallic SNM. For neutron imaging, the mean free path of fission neutrons in metallic SNM is typically a few centimeters so neutrons can escape from deeper within the assembly. However, it is not clear if a void will cause a significant enough variation in intensity in the image to be detected. It is unlikely that measured count rates alone from these systems will be able to determine the presence of inner voids. The significant self-attenuation within metallic SNM means the gamma-ray count rate will largely be unaffected by an inner void. The neutron count rate would be affected by a void, but the rate also depends on the isotopic composition and multiplication of the assembly, neither of which would be known to the inspector during disarmament verification.

Coded aperture imaging also requires significant preparation including optimizing and fabricating the mask, instrumenting the imaging plane, and careful alignment of the focal length. In contrast, the technique presented in this paper could be performed with as few as three detectors and does not require any type of mask.

Active transmission measurements are sensitive to both the inner and outer radius of metallic SNM [9]. In the case of plutonium assemblies, the spontaneous fission rate of ^{240}Pu may provide a sufficient self-interrogation source that external sources would not be required. The advantages of transmission imaging, such as sensitivity to inner voids, could be realized without the need for external sources.

2.2. Previous work on time correlated pulse height analysis

Our technique relies on extracting the distance to the average fission location within the assembly conditioned on coincident detections of a prompt fission neutron and a prompt fission gamma ray. The distance to the average fission location is extracted by fitting 2-D histograms of the neutron pulse height and the neutron–gamma inter-arrival time. This analysis is referred to as time correlated pulse height (TCPH) and was initially developed in Ref. [10]. Later work investigated performing a time shifting of this histogram to increase its sensitivity to the source multiplication and other observables [11,12]. More recent work involved fitting the TCPH histogram to extract parameters related to the source multiplication, reflecting materials, and distance from the detector to the source [2,12]. In Ref. [2], the authors note that the most constrained parameter in the fits is the detector distance and they find a typical statistical uncertainty on the distance parameter of 1 millimeter. Our TCPH fitting procedure to extract the detector distances is described in more detail in Section 6 and is based on the concepts and procedure in Ref. [2].

3. 1-D self-transmission imaging concept

Here we present a simple proof-of-concept Monte Carlo simulation performed with GEANT4 [13]. The simulation consists of an assembly of weapons-grade plutonium metal with detector volumes on opposite sides of the assembly as shown in Fig. 1. The plutonium has a radius of 3.79 cm and is 94% ^{239}Pu with the remaining 6% as ^{240}Pu. Induced fission is disabled in the simulation for simplicity. Prompt fission neutron and gamma-ray coincidences in each detector are recorded along with the location of the fission event that generated those neutrons and gamma rays. GEANT4 was used for this simulation because of the relative ease in recording the sites of the original fission events.

First, consider spontaneous fission events where a prompt fission neutron and gamma ray are both detected on the left side of the assembly. The average fission location for such events will be located towards the left side of the source; this location results from the uniform distribution of fission sites weighted by the escape probability of both particles to the left. Quantitatively, the results of the simulation show that the average fission location for such events is approximately 2.6 cm to the left of the center of the source.

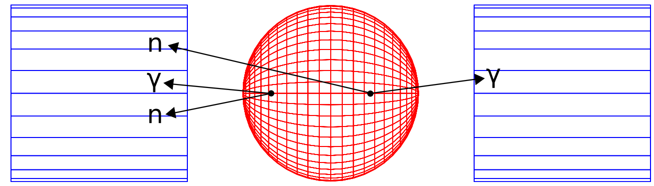

Fig. 1. A simplified GEANT4 simulation demonstrating our imaging technique. The sphere in the center is the plutonium assembly and the cylinders on the left and right are detectors. The points indicate average fission locations for coincident neutrons and gamma rays traveling into the detectors.

Next, consider spontaneous fission events where a prompt fission neutron is detected on the left side of the source and a prompt fission gamma ray is detected on the right side of the source. Again, the average fission location results from the uniform distribution of fission sites weighted by the escape probability, but in this case the neutron and gamma ray are traveling in opposite directions. Based on the simulation, this average fission location occurs approximately 1.7 cm to the right of the center of the source. The location is right of the center of the source because the attenuation length of the gamma ray is shorter than the mean free path of the neutron.

These two average fission locations are shown in Fig. 1. The difference between these average fission locations, 4.3 cm, is fundamentally related to the difference in attenuation for gamma rays and scattering of neutrons as they traverse the assembly. Therefore, this difference will depend on the outer diameter of the assembly and the presence of voids within the assembly.

The presence of fission chain reactions has a noticeable impact on these locations. Based on simulations with induced fission enabled, the average fission location for neutron and gamma-ray coincidences on the left side of the source is 2.1 cm to the left of the center. For coincidences where the gamma ray is detected on the right side of the source, the average location is 0.7 cm to the right of the center, yielding a distance difference of 2.8 cm.

In our experiments, we cannot measure the precise distance of the average fission locations relative to the center of the source. However, using TCPH analysis we can estimate the distance between the average fission location and the detector with the neutron event. We perform these estimates for coincidences with both particles on the left (d_s, same side) and neutrons on the left and gamma rays on the right (d_o, opposite sides) and take the difference $d_o - d_s$, which should match the difference in the average fission locations relative to the center of the source. The experimental results presented in Section 7.1 are in good agreement with this simple model.

4. Description of the experiment

We tested our technique by performing measurements of correlated prompt fission neutrons and prompt fission gamma rays from a subcritical plutonium metal assembly at the Device Assembly Facility (DAF) located at the Nevada National Security Site (NNSS). The assembly, referred to as the BeRP ball, is a 4.5 kg sphere of α-phase plutonium metal with a radius of 3.79 cm encased in stainless steel with a nominal thickness of 0.3 mm. The BeRP ball is composed of approximately 93.3% ^{239}Pu, 5.9% ^{240}Pu, and 0.2% ^{241}Am by mass [14]. The primary neutron source is the spontaneous fission of ^{240}Pu within the assembly itself which generates approximately 2.8 × 10^5 neutrons per second;