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Inspection System to Confirm the Absence of Nuclear Warheads Using Passive Gamma-Ray Measurements

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Abstract. Arms-control agreements between the United States and Russia negotiated after the end of the Cold War have imposed limits on the number of deployed strategic nuclear weapons. Verification of these agreements has relied on onsite inspections, sometimes supported by radiation detection techniques to confirm that an object is non-nuclear. Such absence-confirmation measurements, so far, rely on the detection of neutron emissions associated with the presence of plutonium, but they would be inadequate for uranium devices. Alternative instruments relying on the detection of gamma emissions could simultaneously confirm the presence or absence of both plutonium-based and uranium-based weapons, complementing existing systems that detect neutrons, which can only confirm the absence of plutonium devices. We propose a protocol for confirming the absence of nuclear warheads using only passive gamma-ray measurements. In support of developing and implementing the protocol, we have conducted extensive MCNP simulations, performed small-scale experiments using standard laboratory check sources, and developed a prototype device for use in verification exercises. Such a system would be particularly valuable for next-generation arms-control agreements that limit total numbers of weapons, including those deployed, in storage, and slated for dismantlement.

This work is based on E. Lepowsky, J. Jeon, and A. Glaser, "Confirming the Absence of Nuclear Warheads via Passive Gamma-Ray Measurements," Nuclear Instruments and Methods in Physics Research A, 990, 2021.

Motivation

The development of inspection systems that can confirm the authenticity of a nuclear weapon has been the focus of international research and development efforts. However, only limited progress has been made toward certifying and authenticating candidate systems to support a future treaty that requires verified disarmament, largely due to security concerns associated with such intrusive inspections.[1] Next-generation nuclear arms-control agreements could potentially place limits on all weapons in the stockpiles, including those that are non-deployed and in storage. The most basic approach to confirm numerical limits as part of such an all-warhead agreement could be to rely on baseline declarations followed by regular data exchange, akin to the approach under New START for deployed strategic nuclear weapons. During an inspection of an inspector-selected site, the host would identify the number of declared items, which will be accepted as treaty-accountable items and never accessed or inspected.[2] The inspector would then be allowed to confirm that other items on-site are in fact not treaty accountable. The host may be able to simply provide visual access or containers may have been previously flagged by the inspector as compliant. In cases where this approach is not feasible, the inspector could be allowed to take radiation measurements to confirm the "absence of a nuclear weapon" or, more generally, that a container does not contain sufficient amounts of plutonium or uranium to make a nuclear weapon.

Simple neutron detectors have been used for many years as part of New START to confirm that an object is "non-nuclear."[3] Only plutonium, however, emits neutrons in significant quantities; the technique can therefore not be used for uranium-only weapons or weapon components. Relying on the detection of gamma emissions, as a complement to neutron measurements, could simultaneously confirm the absence of both plutonium-based and uranium-based weapons. Since gamma rays are more easily shielded than neutrons, additional provisions in the inspection protocol may be necessary. While such gamma-based tools have not been used for arms-control verification purposes to date, the technology itself is straightforward and can be easily deployed. Absence measurements have several fundamental advantages as they can be non-intrusive by design. In a verification regime based on absence measurements, no weapons should ever be part of an inspection, thereby reducing safety and security concerns.

Analytical Basis for Absence Detection

We focus on passive detection of gamma rays and employ low-resolution gamma spectroscopy with regions of interest around selected gamma energies corresponding to prominent plutonium and uranium lines. Constraining the measurement to defined regions of interest minimizes background effects and increases the specificity of the measurement. For uranium, we consider the decay chain of U-238 to determine the relative concentrations of Th-234, Pa-234, and U-234, assuming the isotopes are in secular equilibrium.[4] For plutonium, we use a reference composition (DOE 3013) with a Pu-239 content of about 93.5% and no Am-241.[5]

Following the notation used by Fetter et al., the detected signal for a radiation source depends on the source emission rate, self-shielding and external shielding, and the solid angle and efficiency of the detector.[6] We use S_C to indicate the net signal from a containerized item and make two assumptions regarding shielding. First, the containerized item is assumed to be axially symmetric about its central vertical axis since a dishonest host would want to shield the inspected item equally well in all directions. Second, all observed attenuation, including that due to self-shielding of the nuclear material, is attributed to an equivalent thickness of "external" lead shielding. We use Currie's equation, $S_C\, T_M = z^2 + 2\,z \sqrt{2\,(S_B\, T_M)}$, to set a threshold for distinguishing a signal above the prevailing background, S_B, for measurement time, T_M, and the confidence parameter, z. The resulting minimum detectable quantity of weapon-grade plutonium (93% Pu-239) and highly enriched uranium (7% U-238) can then be evaluated for a range of measurement times and lead-equivalent effective shielding. Although we ideally seek to confirm the absence of a warhead, the maximum external shielding is calculated such that a warhead would be detectable, if present.

Verification Protocol

To apply the theory supporting absence detection, we propose a simple five-step measurement campaign (Figure 1); the only non-standard requirement is a check source with an activity in the 1 mCi range. The verification protocol begins with background acquisition and detector calibration. Ideally, the inspection should be conducted in a low-background environment to expedite the measurement and avoid inconclusive outcomes. The background is acquired before calibration so that the presence of an acceptable calibration source can be confirmed. A reference source is then placed on the "far side" of where the inspected container will be placed later in the protocol. This reference source is used to estimate the shielding present in the inspected container. Similar to the calibration source, the presence of an adequately strong reference source is verified by comparing the count rates near the expected peak to the background. If the source is deemed sufficiently strong, the container to be inspected is moved into position between the detector and the reference source. The reduction in signal due to the inspected item is used to estimate the total lead-equivalent effective shielding.

The final step is to remove the reference source and measure the gamma rays emitted from the container itself. At this stage, the effective shielding thickness is calculated based on the spectra acquired in the last three steps. Using the background and the counts of a notional bare source, the maximum shielding thickness is also calculated.

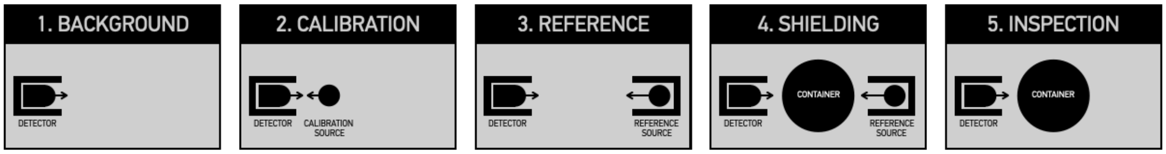

Figure 1: Steps of the verification protocol for absence measurements, including: background acquisition; detector calibration; characterization of a reference source; shielding estimate of the inspected container; and inspection of the container itself.

The final inspection result is then deduced by simple comparison with these threshold values in each region of interest. If the inspection spectrum exceeds the critical level corresponding to Currie's equation, $L_C = z\sqrt{2\,(S_B\,T_M)}$, then an anomaly is detected; however, detecting an anomaly does not guarantee the presence of the threshold quantity. If the inspected spectrum is below the critical level and the estimated shielding thickness exceeds the calculated maximum shielding, then the result is inconclusive; this may be due to a combination of high background, excessive shielding, and insufficient measurement time. Otherwise, absence is confirmed if the detected counts are below the critical level without exceeding the maximum shielding.

ACX: Absence Confirmation eXperimental Device

We have developed the ACX (Absence Confirmation eXperimental) device – based on a Raspberry Pi computer with a 7-inch touchscreen display and housed in a portable Pelican case (Figure 2) – to demonstrate the proposed verification protocol. A rechargeable power-over-ethernet (POE) battery contained within the case supplies power to the computer and an external detector which connects via ethernet. We used a collimated 2-inch Mirion/Canberra NaI scintillator (Model 802) connected to an Osprey Digital MCA Tube Base. The device has minimal user-accessible inputs/outputs: charging port, ethernet port, and universal power switch. A graphic user interface (GUI) guides the user through the verification protocol. A video demonstration of the protocol and GUI can be found at youtu.be/JuNA6D4kGe4. To initiate a measurement campaign, the start screen asks the user to input the agreed upon thresholds (in terms of mass for special nuclear material or activity for laboratory check sources), the measurement time, and the level of confidence in the inspection result. For each step of the protocol, the device instructs the user to position/remove the calibration source, reference source, and/or inspected objects. During data acquisition, the GUI provides a countdown clock. After data is acquired for a given step, the user has the option to redo the measurement or proceed; at no point can the user deviate from the prescribed order, reducing the possibility of human error. For the calibration and reference steps, an error message is included if the source is too weak to provide a reliable inspection. The GUI also provides the final inspection result (absence confirmed, inconclusive, or anomaly detected); no other information or data is ever revealed to the user.