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Real-Time Zero-Knowledge-Protocol Radiography for Warhead Verification

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Abstract. Future arms control agreements may require verification of individual warheads, rather than counting of delivery vehicles. This presents the daunting challenge of verifying that an object presented as a warhead, or "Treaty Accountable Item," TAI, is truly as claimed – while at the same time learning nothing about its design or composition. To address this challenge, we propose to expose an object presented as a TAI to a beam from a 14 MeV neutron source, producing a real-time radiographic image on a 2D scintillator. In parallel with this, a second beam from the same neutron source would be imaged on a second identical scintillator, with no intervening object. This second scintillator would, however, be backed by a transparency carrying a printed complement of the image produced on the first. Adding these two images with a half-silvered mirror and presenting the summed image to a sensitive camera would provide a high-precision, real-time image corresponding to the signal to be seen from an open beam – for the case in which the printed complement is matched to the nominal TAI. Using the same complement for multiple nominal TAIs constitutes a form of real-time Zero-Knowledge-Protocol differential radiography, allowing the Inspector to be assured that all items, potentially including verified, so-called "golden," warhead(s), are indistinguishable. We denote this additive approach ZKP+. A subtractive, or ZKP–, version would be simpler, using a single scintillator with a printed complement of the TAI affixed to its back. A third variant would be to direct the two neutron beams through, for example, a nominal TAI and a golden warhead. These would be viewed by a photodiode through opposite sides of a rotating coded mask with anti-symmetry, such that identical images on opposite sides provide a steady signal, as in the CONFIDANTE concept for imaging neutron sources.

Introduction

Future arms control agreements may require verification of individual warheads, rather than counting of delivery vehicles, even complemented by on-site inspections. This presents the daunting challenge of verifying that an object presented as a warhead, or "Treaty Accountable Item," TAI, is truly as claimed – while at the same time learning nothing about its design or composition. The owner of the warhead will certainly not want such information revealed.

We have pursued Zero-Knowledge Protocol (ZKP) differential 14 MeV neutron radiography as a means to determine if an object presented for inspection can be distinguished from a "template" object, a verified Treaty Accountable Item (TAI). To date we have examined the use of superheated droplet, or "bubble" detectors[1] and ZnS(Ag)/PP scintillator backed by photographic film. In either case an honest "Host" (owner of both the verified TAI and the object presented for inspection) would pre-load the measurement medium with the complement of the radiographic image, with the result that the final image after exposure of the medium to the radiographic signal would be the same as if no object had been present in the neutron beam. This reveals no information about the object – again assuming the Host is honest. Since multiple objects are to be inspected, the Host must provide multiple preloads. It is key that the "Inspector" gets to select which preload goes with which object, thus making successful spoofing extremely unlikely if multiple items are tested or a few items are tested multiple times.

We have found that bubble detectors provided by Yale University[2] have adequate sensitivity for use with a collimated 14 MeV DT neutron source of strength in the range of $3\ 10^8$ n/s and can in principle provide spatial resolution in the few-mm range. Thus they remain attractive, and research is proceeding with them[3] for 2D imaging. On the other hand, we found that ZnS(Ag)/PP scintillator[4], backed with film, did not provide a strong enough image, due in part to low-intensity reciprocity failure[5].

Modern, cooled CCD and EMCCD cameras[6] are much more sensitive than film, and can have both very low background signal and no low-intensity reciprocity failure. However, it would be difficult to pre-load them with a complement image in a manner that could assure the Host, for example, that the preload was not erased by the Inspector, and at the same time assure the Inspector, for example, that the camera was not pre-loaded with a flat image and then not operated during the measurement. Thus, we present three concepts where the Zero-Knowledge Protocol is applied in real time, obviating the need for preloads.

Zero-Knowledge Protocol +, ZKP+

The Zero-Knowledge Protocol +, or ZKP+, approach shown in Figure 1 is a direct analog to the preload approach, in which the radiograph is combined with the preload. In this case we expose a presented item to a beam from a 14 MeV neutron source, producing a real-time radiographic image on a 2D scintillator. In parallel with this, a second beam from the same neutron source is imaged on a second identical scintillator, with no intervening object. This second scintillator is, however, backed by a transparency carrying a printed complement of the image produced on the first. Adding these two images with a half-silvered mirror and presenting the summed image to a sensitive camera provides a high-precision, real-time image corresponding to the signal which would be seen from an open beam – for the case in which the printed complement is matched to the nominal TAI.

The Host could study the summed image with their own camera, to assure, for example, accurate alignment of the two component images, before directing the summed image to the Inspector's camera. Using the same complement for multiple nominal TAIs constitutes a form of real-time Zero-Knowledge-Protocol differential radiography, allowing the Inspec-

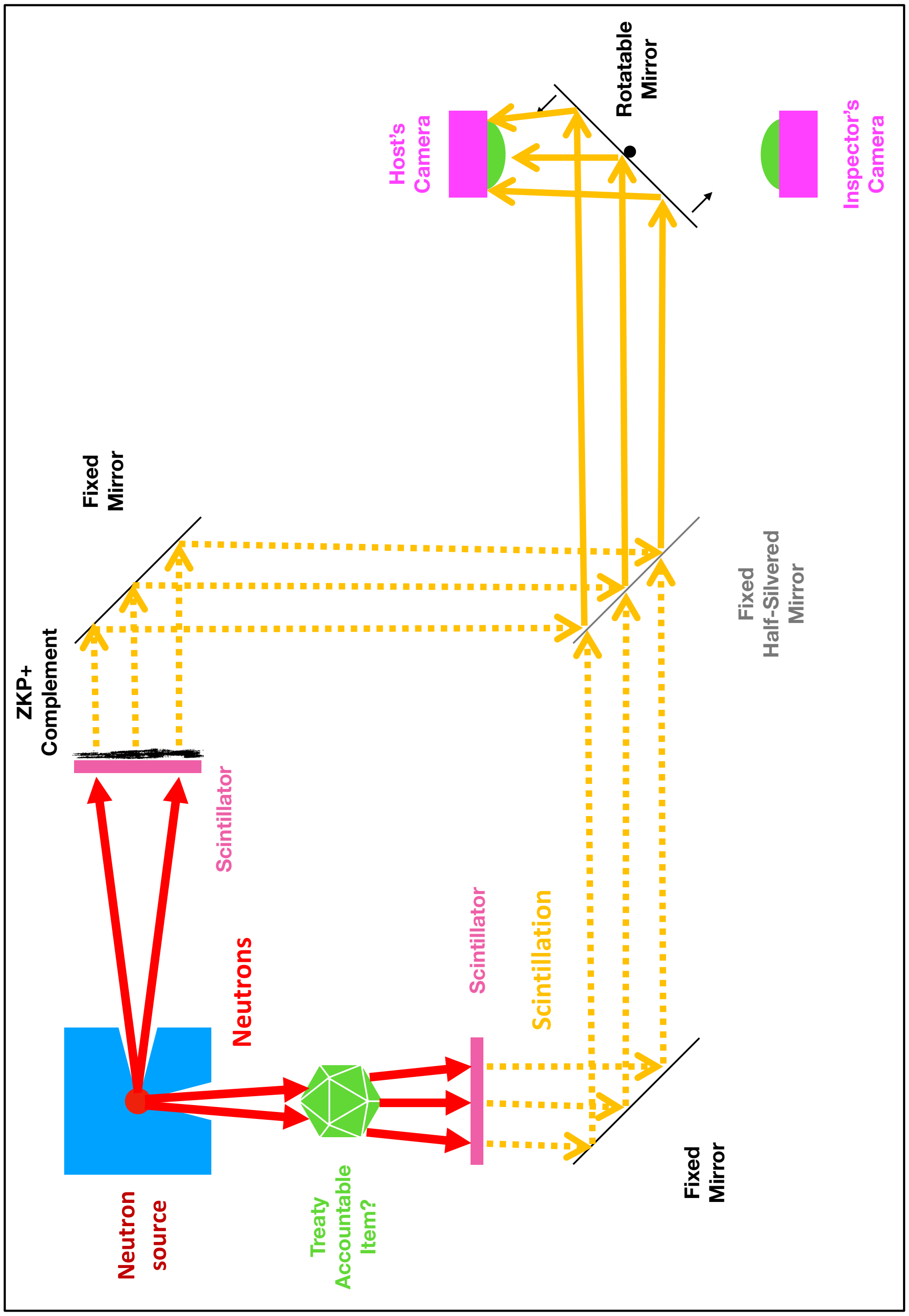

Figure 1: ZKP+ Configuration

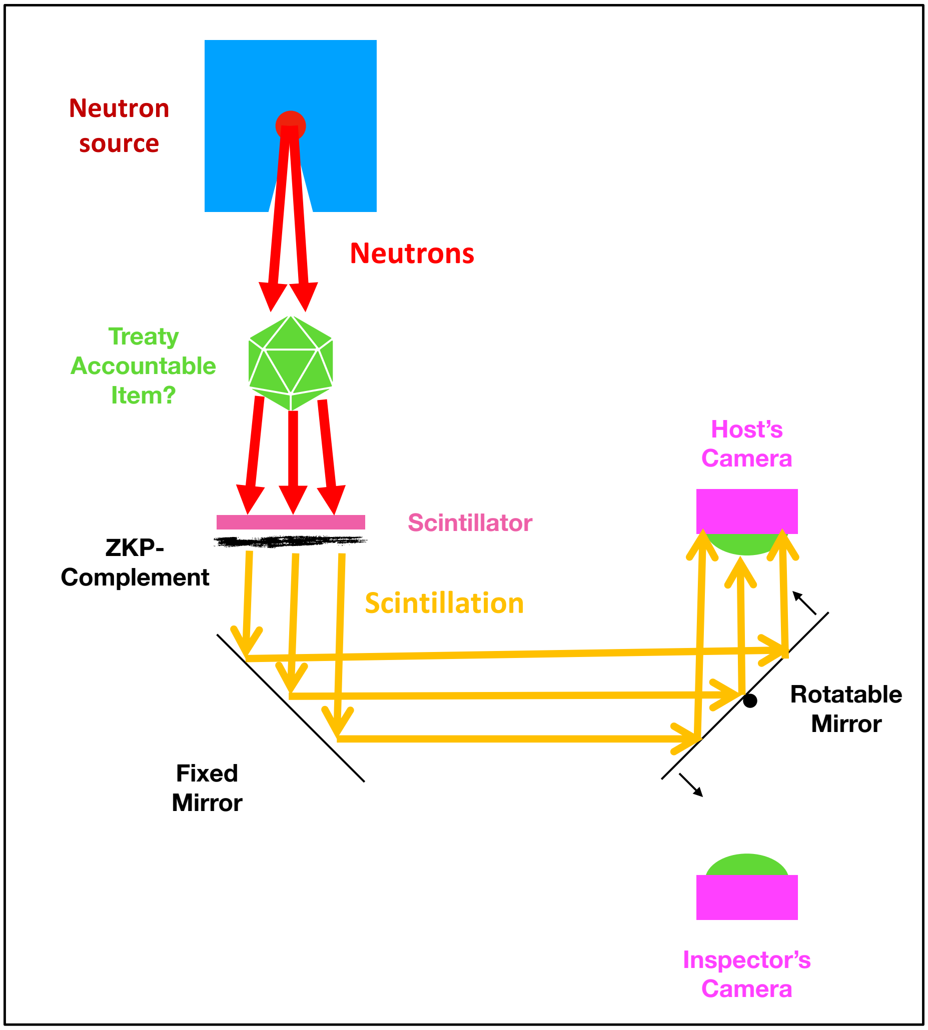

Figure 2: ZKP– Configuration

tor to be assured that all items, including verified, or so-called "golden," warhead(s) are indistinguishable. Using the same neutron source to produce both images assures that if the source fails, or varies in amplitude, no information is conveyed.

An advantage of this configuration is that, like the preload approach, the amplitude of the signal can equal the value expected from a scintillator with no intervening object. Agreement on this amplitude provides no information about the objects involved.

Zero-Knowledge Protocol –, ZKP–

A subtractive, or ZKP–, version would be simpler, using a single scintillator with a printed complement of the TAI affixed to its back, as shown in Figure 2. Again a flat image is produced if identical objects are presented for inspection. A disadvantage with this approach

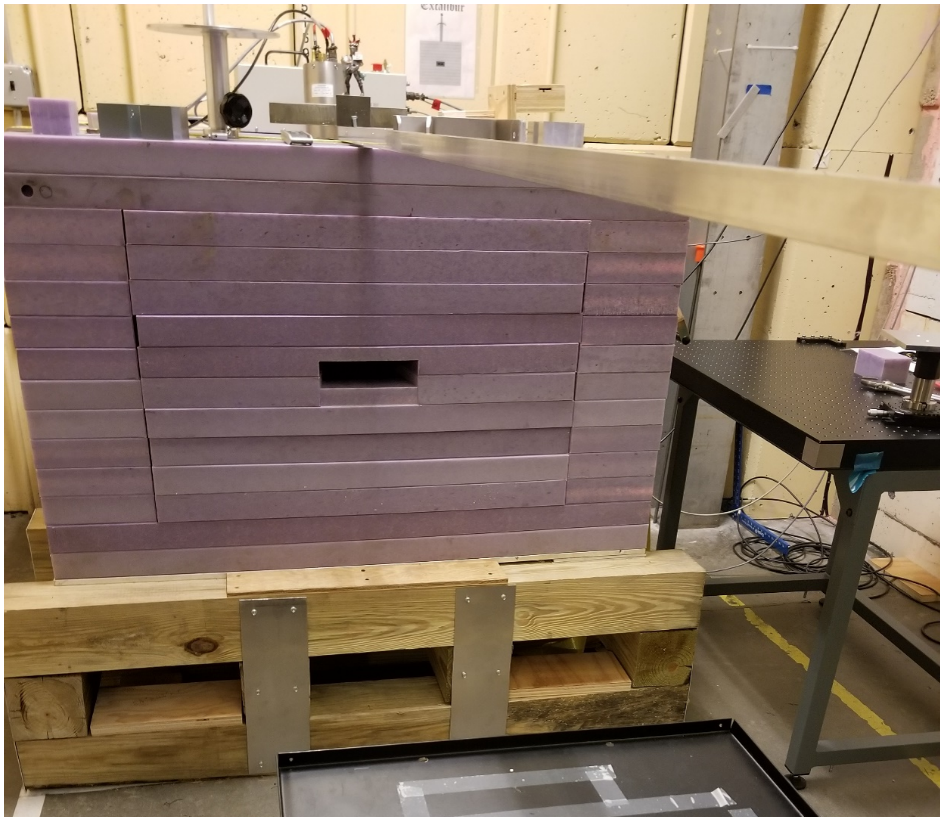

Figure 3: EXCALIBUR collimator with Thermo Scientific P-385 neutron generator

is that agreement on the amplitude of the image could be difficult to achieve, in that it would have to be below the signal that would be expected from the most opaque spot on the TAI, and the highest opacity of a warhead is likely a sensitive parameter. This problem could be mitigated by assuming a very high maximum opacity, but this might come at a high cost in signal level.

Expected Signal Level

We have available an f/1 lens with diameter and focal length of $\simeq$ 100 mm. If it is placed at a distance of 1 m from the scintillators, in order to be well out of the collimated neutron beam[7], in the thin-lens approximation the focal plane will be located at a distance of 111 mm behind the lens, with resulting demagnification of a factor of 9. We have available a 50 mm × 250 mm ZnS(Ag)/PP scintillator, whose image would be 5.5 mm × 27.7 mm at the focal plane, consistent with available cameras.

We also have available a Thermo Scientific DT neutron generator equipped with a A-3082 tube, which produces up to about 10^9 n/s. It is enclosed in a steel and polyethylene collimator, as shown in Figure 3, which minimizes stray neutrons. When the neutron generator is placed at a distance of 1.6 m from the scintillator, to allow approximately 1 m space for the TAI, the neutron flux in the absence of an object in the beam (equivalent to the ZKP+ signal) will be 3100 n/(s cm^2). With the expected detection efficiency of about 1%, and integrating for 1000 s, this comes to 31,000 events/cm^2. A 3 mm × 3 mm square, comparable to the expected spot size on the surface of the scintillator, would contain about 2800 events. This is a much greater number than can practically be measured with bubble detectors.

One can then ask what fraction of these events will be observed by the camera. The scintillation process begins dominantly with elastic scattering of 14 MeV neutrons on protons, and photon production is expected to be about 50,000 per MeV of the protons[8], giving an average of 350,000 photons per event. Many of these will be absorbed before escaping, so we can make an extremely rough estimate of 100,000 photons at 450 nm per event. At a distance of 1 m the 100 mm diameter lens should gather about 20 photons per event, which should be detectable with a modern camera having a quantum efficiency at 450 nm of 0.8, giving 16 electrons per event, suggesting a viable measurement.

CONFIDANTE-like System

The expected count of 16 electrons per event on a ZnS(Ag)/PP scintillator should be taken with a (large) grain of salt until we have data in hand. One could nonetheless be concerned that an Inspector might have a sufficiently sophisticated camera that they could make a pulse-height spectrum of the photon counts. Even without this one could be concerned that if the incoming photons are correlated in large pulses the statistical noise will be higher than for individual photons or smaller pulses. Since the dark parts of the ZKP complement will shift the pulse height spectrum downwards, it might be possible to distinguish smaller bursts of photons from larger ones, and thus distinguish complement signal from radiographic signal. On the other hand, practical sources of noise, including dark current and readout noise, as well as signal due to neutron and/or gamma interaction with the camera, may make this impossible. One could also provide the Inspector with a small enough aperture, at a sufficient distance, that the dominant signal comes from single-photon events.

This potential problem can be mitigated by using a variant on the CONFIDANTE (CONfirmation using a Fast-neutron Imaging Detector with Anti-image Null-positive Time Encoding)[9] system, which uses a single neutron detector to view two neutron-emitting objects through a rotating coded aperture mask. The mask is configured anti-symmetrically in the azimuthal direction, such that for any spot in z, θ that is opaque to neutrons, the spot in $z, \theta + \pi$ is transparent. Thus in principle if the two sources are identical, the signal at the neutron detector is steady, with only statistical noise.

We would exploit this concept by using mirrors to place the radiographic images of two objects on opposing sides of a rotating mask, with mirrors aiming at a single photodiode, as shown in Figure 4. Our mask could be much lighter and thinner than required for stopping neutrons. As before, the Host can look at the signal from the photodiode first, and assure that that the objects are properly aligned before handing the signal over to the Inspector, who could even bring their own photodiode.

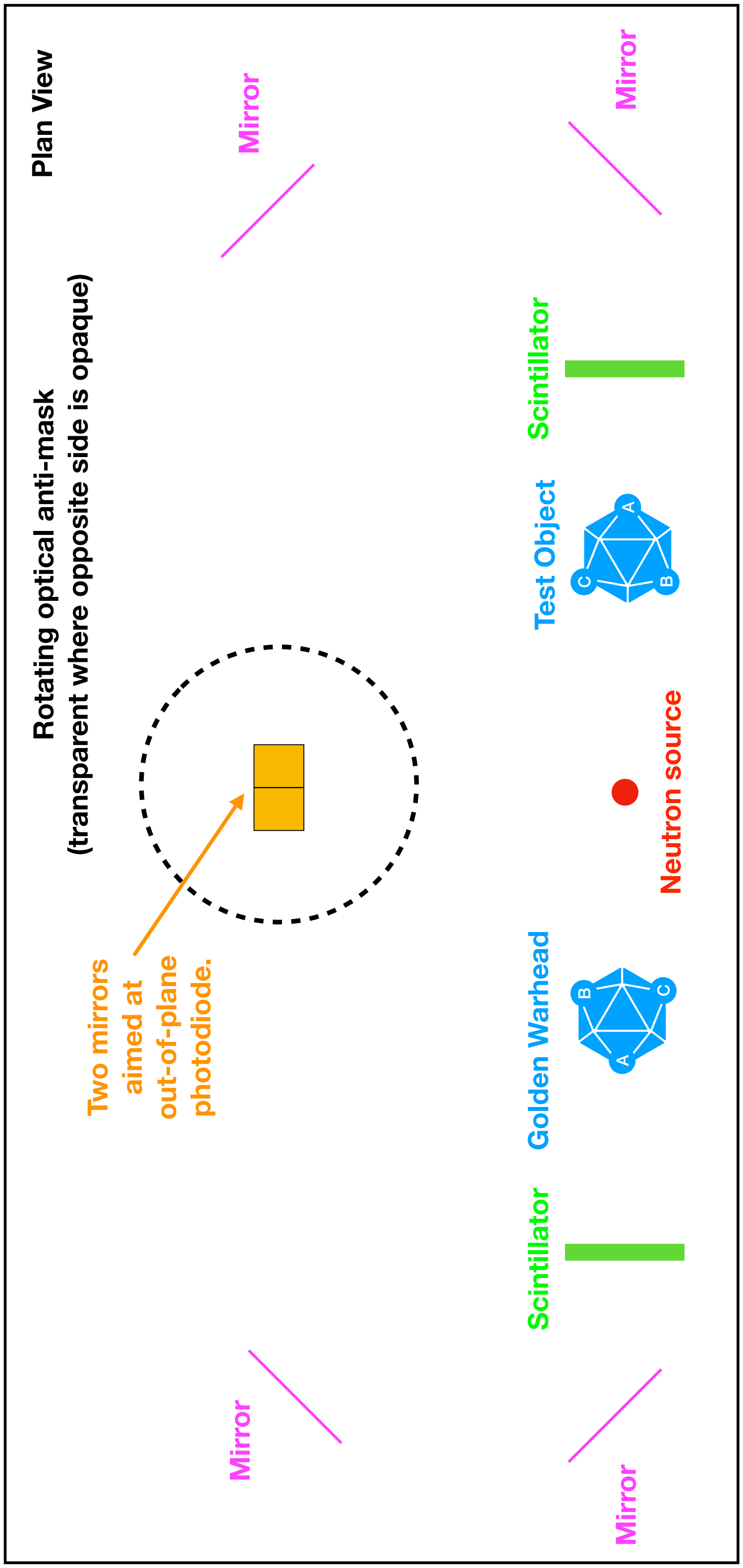

Figure 4: CONFIDANTE-like Configuration

We can have a concern, similar to the ZKP− configuration, that the Inspector can learn about the mean transparency of the two objects from the time-average signal. (CONFIDANTE itself presents a similar concern with regard to total neutron emission.) This concern can be mitigated by agreeing that the time-average signal should be that which would have occurred if no object were in either of the two beams. The Host can expose the photodiode to a third scintillator that is irradiated directly by the neutron source, such that the agreed time-average signal is observed, and no information leaks even if the neutron source faults.

Discussion & Future Work

It appears that real-time Zero-Knowledge-Protocol differential radiography should be possible, using a modest-flux 14 MeV neutron source. It has the promise of higher performance than other techniques investigated to date. Clearly the next step, however, is to acquire data using a high-performance camera. The projected signal level requires experimental validation, and the sources of noise need to be evaluated.

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Endnotes

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[2] F. d’Errico, “Radiation dosimetry and spectrometry with superheated emulsions,” Nuclear Instruments and Methods in Physics Research B 184 (2001) 229-254

[3] J. Jeon et al., “Solving the Rubik’s Cube: two dimensional neutron radiography with superheated droplet detectors,” Proceedings of INMM & ESARDA Joint Annual Meeting May 22–26, 2023

[4] See RC Tritec, Scintillators, ZnS

[5] J. Jeon et. al, “Scintillator Coupled with Photographic Film for Application to Zero-Knowledge Verification,” Proceedings of the INMM & ESARDA Joint Virtual Annual Meeting August 23-26 & August 30-September 1, 2021

[6] See Teledyne Princeton Instruments PyLoN and Andor iXon Ultra cameras

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