Verification of Arms Control Treaties with Resonance Phenomena

Nuclear disarmament treaties are not sufficient in and of themselves to neutralize the existential threat of nuclear weapons. Technologies are necessary for verifying the authenticity of the nuclear warheads undergoing dismantlement before counting them toward a treaty partner’s obligation. Here we present a review of concepts involving isotope-specific resonance processes, Nuclear Resonance Fluorescence (NRF) [1] and Neutron Resonance Transmission Analysis (NRTA) [2, 3], used to authenticate a warhead’s fissile components by comparing them to a previously authenticated template. All information is encrypted in the physical domain by the addition of an encrypting filter to the target, leading to measurements with an outcome similar to an equation with two unknowns. Using Monte Carlo simulations and experiments, we show that the measurements readily detect hoaxing attempts, while no significant isotopic or geometric information about the weapon is released. These nuclear techniques can be used to dramatically increase the reach and trustworthiness of future nuclear disarmament treaties.

Introduction

As of 2019 there are an estimated 13,000 nuclear weapons that make up the nuclear arsenals of the United States and Russia [4, 5]. Such large arsenals may be one of the greatest threats to our civilization. While high, these numbers are a significant reduction from the Cold War era, as a result of a series of arms control treaties. The past treaties between the United States and Soviet Union/Russia, however, primarily focused on the verified dismantlement of the delivery systems, such as ballistic missiles and strategic bomber aircraft. This approach has left behind large stockpiles of surplus nuclear weapons, exposing them to the risk of theft and unauthorized or accidental use, as well as transfer to third countries. Furthermore, there are increased worries that, unless new treaties are implemented, the current arsenal sizes will stagnate at the current numbers [5–7]. New types of technologies are necessary to enable new arms control treaties. These technologies will have to detect hoaxing attempts, clear honest warheads as such, while simultaneously protecting sensitive information about the weapon designs.

But how does one verify that an object is a weapon without inspecting its interior? Past U.S.– Russia lab-to-lab collaboration included the research and development of so-called information barriers [8]. These are devices that rely on software and electronics—which can be hacked and that themselves need to undergo verification—to analyze data from radiation detectors and compare the resulting signal against a set of attributes in a so-called attribute verification scheme [9, 10]. Unlike these past methods, which relied on electronics and computers, we propose to use physical cryptography, which relies on the immutable laws of physics instead. An early attempt using physical cryptography and template verification was proposed by researchers at Princeton University [11–13]. The Princeton concept has strong information security in the form of a zero-knowledge (ZK) proof. It relies primarily on the non-resonant scattering of fast neutrons, a process that is almost identical for most actinides, making it prone to some isotopic hoaxes. Neutron elastic scattering in the MeV scale primarily depends on the size of the nucleus, and as such is a very poor differentiator between nuclei of similar A and Z. A much stronger isotopic sensitivity can be achieved by measurements which are sensitive to resonances in the nucleus: even small change in the number of nucleons results in drastic changes in the resonance parameters and energies. An NRF-based concept was proposed and tested via Monte Carlo simulations and proof of concept experimentation [1, 14–16]. The reliance on isotope-specific NRF signatures offers strong hoax resistance. However, it is not fully ZK, and thus needs to undergo thorough checks for information security. A second idea was proposed later, which makes use of NRTA to achieve isotopic imaging and tomography, while achieving a near-ZK level of information security [2, 3]. This technique uses resonance phenomena to achieve iso-specific data signatures, which can be used to obtain a unique fingerprint of the object. This is achieved by exploiting nuclear resonances in actinides when interacting with epithermal neutrons in the 1–10 eV range. Unlike fast neutrons, which do not have this isotope specificity for high Z nuclei, the epithermal neutron transmission signal can be made highly specific and sensitive to the presence and abundance of individual isotopes. These include $^{235}$U and $^{239}$Pu in highly enriched uranium and WGPu [17]. Also unlike NRF, the resonant absorption of epithermal neutrons in the beam can be observed directly with very high resolution (less than eV). This can be done by using...
time-of-flight (TOF) techniques, as described in detail in Ref. [2], Supplementary Note 1. These characteristics allow for direct measurements of resonant absorption.

**Template Verification Protocol**

The key to any verification procedure is a protocol that can guarantee that no treaty accountable item (TAI) undergoing verification is secretly modified or replaced with another object. Significant thinking has been invested into the concept of template verification, particularly at the U.S. national laboratories and think tanks [9, 18, 19].

The high-level protocol has been either outlined in or been the basis of prior warhead verification publications in academia [10–12, 14] and in U.S. national laboratories [19–22]. Its basic steps can be summarized as follows:

1. The inspection party makes an unannounced visit to an intercontinental ballistic missile site and randomly chooses a warhead from one of the missiles. This warhead can be treated as the “golden copy” (i.e., the reference for all future comparisons).
2. The template is transported under the joint custody of the hosts and inspectors to the site where the candidate warheads will undergo dismantlement, verification, and disposition.
3. The golden copy and the candidate undergo the measurement in question, whether it is NRF or NRTA. The signals are compared in a statistical test. An agreement confirms that the candidate is identical to the template and thus can be treated as authentic. A disagreement indicates a hoaking attempt.

The last step is key to the whole verification process and is the focus of this review.

**NRF-Based Verification**

NRF describes the $X(γ, γ′)X$ reaction in which a photon $γ$ is resonantly absorbed by the nucleus $X$ and then re-emitted as the excited nucleus subsequently decays to its ground state [23, 24]. The cross-section for an NRF interaction with absorption via the resonant energy level $E_r$ is given by the Breit-Wigner distribution:

$$
\sigma(E) = \frac{2\pi g_r}{E_r} \left(\frac{\rho c/\hbar}{(E-E_r)}\right)^2 \left(\Gamma/(\Gamma/2)^2 \right)
$$

where $\Gamma_r$ is the width of the level at $E_r$, $\Gamma_{r0}$ is the partial width for transitions between $E_r$ and the ground state, and $g_r$ is a statistical factor. For high-Z isotopes of interest, these fundamental widths are typically $\sim10$ meV, but the effective width of the cross-section is increased to $\sim1$ eV through Doppler broadening by thermal motion of the target nuclei. Imperfect detector resolution further broadens the measurable NRF resolution to widths of $\sim1$ keV. Since the NRF lines of an isotope are still typically $\sim10$ keV apart, the set of resonance energies $E_r$ provides a resolvable, one-to-one map between measurement space and isotopic space.

The MIT NRF verification protocol exploits the isotope-specific nature of NRF to make a template measurement of the mass and geometry of the isotopes of interest to the inspector. The measurement uses a broad-spectrum bremsstrahlung photon source to irradiate the measurement object; NRF interactions in the object preferentially attenuate the photon flux at specific energies determined by the unique nuclear energy–level structure of each isotope according to how much of the isotope is present in the warhead. The remaining transmitted flux at these energies goes on to induce further NRF interactions in an encryption foil, leading to NRF emission into high-purity germanium (HPGe) photon detectors at an observed rate (see Ref. [1], Supplementary Information, Eq. S8) that has been reduced by the presence of the NRF isotope in the warhead. The hashed measurements required for the template verification protocol are thus the recorded spectra, since it is impossible to precisely determine the warhead composition from the height of the NRF peaks in the observed spectrum without knowledge of the detailed composition of the foil. The exact foil design is therefore decided by the host and kept secret from the inspector. The influence of the warhead composition on the height of the NRF peaks—and thus any sensitive warhead design information—is then said to be physically encrypted by the foil. As an additional layer of information security, the host may add optional “encryption plates” of warhead materials to the measured object so that even if precise inference about the measured object is possible, it is impossible to infer anything about the warhead alone.

Following the design depicted in Figure 1, a bremsstrahlung beam was used to illuminate a circular section of the object undergoing interrogation. Since no real nuclear warheads were available in an academic setting, several proxy warheads were constructed. The proxy warheads were objects with a set of isotopes—$^{238}U$ and $^{27}Al$—that form the basis for proof-of-concept NRF experiments and subsequent extrapolations to more realistic settings involving weapon isotopes, such as $^{235}U$, $^{239}Pu$, and $^{240}Pu$. For each measured object, photon spectra from multiple acquisition periods and three separate detectors are combined into a single spectrum. Each spectrum is then fit with a series of Gaussian functions for the eight observed NRF peaks in the signal region near 2.1–2.3 MeV, on top of an exponentially decaying continuum.
background. $^{238}$U contributes the 2.176, 2.209, and 2.245 MeV peaks; the branched decays 45 keV below each of these three; and a small peak with no branch at 2.146 MeV. $^{27}$Al contributes the intense 2.212 MeV peak.

Figure 2 shows the comparison between the “golden copy” and the hoax. In Figure 2 (left) the NRF peaks from $^{238}$U and $^{27}$Al are plotted. Figure 2 (right) subsequently shows the 26-parameter fits to the two spectra. The counts from the two peaks are compared in a Z-test, with the resulting score of $z=10.7$, indicating a clear disagreement. The discrepancies for all verification scenarios are shown in Table 1 of Ref. [1]. In all four hoax scenarios, a discrepancy in counts greater than an alarm threshold of $z^*=3$ was attained in ~20 µA·h (live, on three detectors) per measured object, indicating diversions in the uranium component. In the genuine candidate scenario, the 1.7 σ discrepancy in uranium (primarily a result of day-to-day beam variations) does not trigger the alarm at $z^*=3$, and is clearly delineated from the much larger observed discrepancies in the hoax cases. Similarly, the $^{27}$Al comparisons all exhibit $|z|<2$, indicating consistency in the aluminum component across all measurement scenarios.

The work reported by Vavrek et al. [1] shows the usability of NRF for warhead verification. The extrapolations based on experimental conditions and expected weapon geometries indicate that a realistic warhead verification exercise, using state-of-the-art commercial instrumentation, can be achieved in hours, which is satisfactory for most verification settings.

**NRTA-Based Verification**

The epithermal range refers to the neutron energy domain encompassed between the thermal energies of ~40 meV and fast neutron energies of ~100 keV. The energies of interest for our methodology, previously reported in detail in Hecla and Danagoulian [2] and Engel and Danagoulian [3] are those in the range of $1 \leq E \leq 200$ eV. While the neutron interactions in the thermal regime are described by monotonic changes in cross-sections, in the epithermal range the neutrons can trigger various resonant responses in uranium and plutonium. These are typically (n,fission), (n,n'), and (n,γ) reactions, resulting in the loss of the original neutron from the beam. A plot of total interaction cross-sections in the epithermal range for five plutonium isotopes of interest can be seen in Figure 3. The data plotted in Figure 4 show the absorption lines that correspond to the resonances in molybdenum and tungsten isotopes, such as the 0.13 eV–wide line at 70.9 eV from $^{97}$Mo. For a transmission configuration these interactions selectively remove the original neutrons of resonant energies from the transmitted beam and give rise to an absorption spectrum, resulting in unique sets of ~0.3 eV–wide notches specific to each isotope. While the resonances are the most prominent features of the cross-section, the continuum between the
resonances also encodes information about the isotopic compositions of the target. These combined absorption features yield a unique fingerprint of a particular configuration of isotopes, geometry, and density distribution.

Our most recent work, in Engel and Danagoulian [3], focused on a sensitivity study, experimentally demonstrating the feasibility of the comparison. This study thus focuses on an inspection scenario where the plutonium pit has been extracted in a controlled environment and undergoes verification, as described in prior work [2]. Using molybdenum and tungsten proxies for plutonium (due to the former’s similarity in resonance energies to those of plutonium), the technique is shown to be capable of clearing objects identical to the genuine reference object and rejecting objects that are isotopically or geometrically different. Instead of hollow spheres, which are typical of nuclear weapon pits, simpler cylindrical geometries were chosen, such that the genuine proxy object is a cylinder of 50.8 mm diameter and 30 mm length, with the first 27 mm consisting of molybdenum and 3 mm consisting of tungsten. Such a combination was chosen to mimic the ~90% enrichment of WGPu. Unlike molybdenum or tungsten, the actinide targets would produce additional neutrons via the $(n,fission)$ reaction. However, the resulting neutrons would be of the ~MeV energies, making the $^6\text{Li}$ detector insensitive to them. The encrypting filters were assembled from 3 mm– and 6.35 mm–thick tungsten and molybdenum plates, respectively, that had 76.2 mm × 76.2 mm outer dimensions.

The overall diagram of the measurement setup can be seen in Figure 3. The neutrons are produced in a pulsed mode from a pulsed electron linear accelerator, via a tantalum bremsstrahlung-photoneutron converter, which produces neutrons via the $(\gamma,n)$ reaction. A 2.54 cm polyethylene moderator degrades the neutrons’ energy from the ~MeV scale to the ~eV scale. As the epithermal neutrons traverse the object and the encrypting filter, their spectrum is modulated in accordance to the cross-sections and areal densities of the relevant isotopes, after which they are detected by a $^6\text{Li}$ glass scintillator detector. The detector produces a timing pulse, which is compared to the timing pulse of the linear accelerator. This comparison allows us to determine $t_{\text{tof}} = t - t_0$ of the neutrons. The energy of individual neutrons can then be reconstructed via $E = m(d/t_{\text{tof}})^2/2$, where $m$ and $d$ are the neutron mass and the flight path length, respectively. The transmission spectra are normalized to the incident neutron count, determined by a fission chan-
ber (not shown) upstream of the target object. To test the sensitivity of the technique to isotopic variations, the 90%:10% Mo:W genuine reference object’s transmission spectrum was compared to the transmission spectra of 50%:50% and 10%:90% Mo:W objects of the same cylindrical shape and overall dimensions. Figure 4 shows the plots and comparisons of the spectra. The comparisons show that, as the proportion of tungsten is increased, the tungsten absorption lines show increased absorption, while the molybdenum lines exhibit reduced absorption, as expected. A simple \( \chi^2 \) test can be applied, determining the values of \( \chi^2 \) and the corresponding probability \( p \) that the difference is merely due to random fluctuations. For these comparisons \( p \)-value is consistent with 0 to 10 significant digits, and thus indicates that a systematic difference is present. The \( \chi^2 \) test thus rejects the comparison and indicates a hoaking attempt. All measurements lasted approximately 5 minutes. See Table 1 in Engel and Danagoulian [3] for the full results of the template–hoax comparisons.

One of the important goals of the verification system is information security; that is, the inspectors’ inability to learn significant information about the TAI. In our prior work in Ref. [2] we showed via computational simulations that, while the inspectors can learn information about the combined content of the weapon component and the encrypting filter, they cannot learn anything specific to the weapon component itself. To extend this, we use experimental data from the measurements in combination with a Geant4 [26, 27] computational model of the experiment to simulate scenarios with a WGPu pit and an encrypting filter. In these data-driven simulations we show that various opposite combinations of the TAI and filter geometries produce statistically indistinguishable signals. It is demonstrated that using an encrypting filter of just 1.8 kg will result in an inferred range of the pit’s possible mass that spans from zero to a value that is significantly larger than the critical mass. This makes it impossible for the inspectors to learn information of value, similar (but not identical) to the concept of zero-knowledge proof. At the same time, additional simulations show that pairs of 5-minute-long measurements at an experimental facility similar to the one used in this study can readily detect cheating scenarios where the WGPu pit has been replaced with RGPu, or where its size has been reduced by 2 mm or less, depending on experimental conditions. See Supplementary Note 3 in Engel and Danagoulian for a detailed discussion and calculations [3].

Conclusions
Warhead verification requires high-precision comparisons of the isotopic-geometric compositions of two objects—the “golden copy,” which serves as the reference, and the candidate object. Resonance phenomena—whether triggered through epithermal neutrons, MeV photons, or via other particle interactions—serve as a great tool for achieving such comparisons due to their sensitivity to the isotopic makeup of an object. The concepts explored and tested via proof of concept experiments are based on NRF and NRTA. Both results show very strong dependence on isotopic composition. The advantage of the NRF system is the penetrating power of the MeV photons. Their downside is the information-rich content of the observed spectra, which are difficult to modulate and obscure, as well as the necessity for high-intensity photon beams and long measurements. Furthermore, the photon beams require specialized instrumentation. By comparison, neutron beams can be produced via multiple methods: nuclear reactors as high-intensity sources and choppers to enable TOF measurements; compact deuterium-deuterium and deuterium-tritium generators, as proposed in Ref. [28]; linear accelerators; and so on. Furthermore, the neutron beams allow very high-precision energy reconstruction via TOF techniques. Finally, pulsed sources, such as linacs, can then be combined by a second chopper, which can directly and physically obscure parts of the neutron spectrum, and thus allow for a high degree of information security. A future treaty can select from these options, possibly combining some along with concepts developed by other research groups [12].

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Areg Danagoulian
Massachusetts Institute of Technology