Two-Color Neutron Detection for Zero-Knowledge Nuclear Warhead Verification

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ABSTRACT. We have previously proposed an inspection system for nuclear warhead verification combining 14-MeV neutron radiography with a zero-knowledge protocol. We confirmed that transmission radiography is particularly sensitive to geometric and elemental differences of inspected items. Distinguishing different isotopic compositions of the same element, however, can be more challenging. In this paper, we propose an upgraded system that uses neutrons in the 100-keV range to illuminate a test object. Fissile isotopes, like plutonium-239 and uranium-235, exposed to these neutrons undergo fission and produce neutrons in the MeV-range. These neutrons can be counted using detectors that are blind to lower energy neutrons in the direct beam. We model the neutron source for this setup based on the $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$ reaction in a lithium target coupled to the open source Monte Carlo particle transport toolkit *Geant4* to simulate neutron interactions in the inspected item and neutron detection in the detector bank. Preliminary results for this "two-color setup" using neutron detectors with different energy thresholds (100 keV and 500 keV) demonstrate a good intrinsic discriminability for different materials, which could make this a promising method for a nuclear warhead verification system.

Background

Verification of future arms control agreements is likely to face some fundamentally new and complex verification challenges. Most importantly, next-generation nuclear disarmament treaties may place limits on the total number of nuclear weapons in some arsenals. Verifying these limits would likely require confirmation of the authenticity of warheads prior to their dismantlement. Inspection systems using radiation detection techniques are in principle well-suited to accomplish this task, but they can also reveal highly classified information. Traditionally, the concept of the "information barrier" is used to prevent from disclosure the data acquired during an inspection, but certifying and authenticating such equipment has proven to be an extremely challenging undertaking.[1] To resolve this dilemma, we have proposed a fundamentally different approach featuring a "zero-knowledge protocol" to avoid the measurement of sensitive information at the outset to address concerns about its potential leakage.[2] The viability of this approach has been examined in simulations of a system based on active neutron interrogation of radiographic test objects using a template-matching approach. Experimental demonstration using 14-MeV neutrons is currently underway.[3] In this study, we examine the viability of a complementary approach using neutrons in the 100-keV range to illuminate test objects; combining results from two different energy ranges, we have call this approach a "two-color setup."

Two-Color Setup

Transmission radiography has been shown to be particularly sensitive to geometric and elemental differences of tested objects. Since the fission cross sections for high-energy (14 MeV) neutrons can be very close for isotopes of the same element, however, this concept is generally less sensitive to isotopic changes. Using a p-Li neutron source with neutron energies in the 100-keV energy range could present an efficient complementary strategy for interrogation of nuclear materials because the neutrons from induced fission events have a typical energy on the order of 1 MeV, which can be distinguished from the source neutrons.[4] As shown in Figure 1, fissionable isotopes have negligible (U-238) or small (Pu-240) fission cross sections for neutron energies of 500 keV and below; this is in stark contrast to the fissile isotopes U-235 and Pu-239.

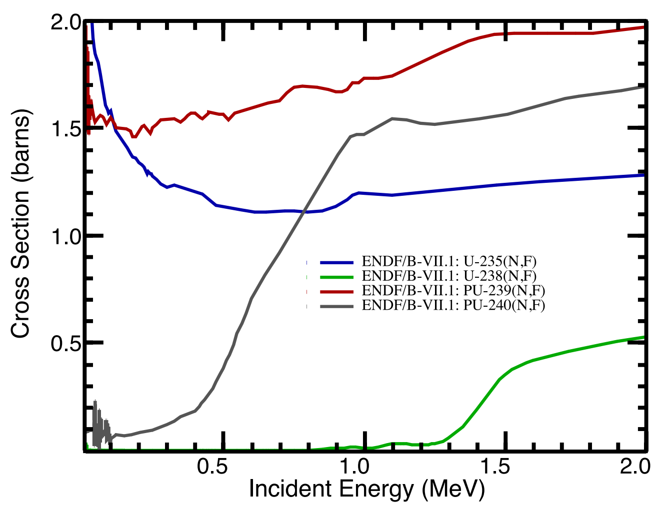

Figure 1: Fission cross-section of U-235, U-238, Pu-239, and Pu-240.

In general, one could envision two different kinds of two-color setups: one emphasizing the energy of the interrogating neutrons, i.e., the energy of the source neutrons, and one emphasizing the energy of the detected neutrons. The first kind could use two separate neutron sources with different neutron energies: for example, a 14-MeV DT neutron source could be used for transmission radiography, while a p-Li neutron source could produce neutrons in the 100-keV range energy to detect neutron-induced fission in the fissile material for the distinguish of different isotopic composition. The second kind of the two-color setup would use only one neutron source but a neutron detection system with two distinct energy thresholds. In this case, the higher energy threshold can be blind to the neutron source, but sensitive to the fission neutrons coming from the nuclear material, while the lower energy threshold can be used for the transmission radiography.

In this study, we model and analyze the second two-color setup (one source and two detector thresholds) because of its simplicity. We analyze the viability of using neutrons in the 100-keV range to examine isotopic substitution scenarios, in which the elemental composition, mass, and geometry of the test items remain unchanged; but we also discuss the sensitivity to differences in the geometry.

Zero-knowledge Protocol

As in our earlier studies, we follow the general idea of a template approach, in which active neutron interrogation is used to generate a unique fingerprint of an inspected item. This fingerprint is then compared against the fingerprint of a reference item to confirm that both items are quasi identical. Neutron radiographic images could contain highly classified information, but in our case they are actually never measured. To achieve this, bubble detectors are preloaded with the negative of the radiograph. Preloaded detectors are supplied with the submitted items and shuffled at random by the inspector between the reference item and the inspected item.[5] The neutron counts obtained in any measurement on the reference item or on any valid item are normally distributed with a mean value of N_{max} and the corresponding standard deviation of $\sqrt{N_{max}}$. The value of N_{max} is jointly chosen in advance by both parties, and so neither the measurement nor its noise reveals any new information.

Simulated Experimental Setup

Figure 2 shows the simplified experimental setup of the proposed inspection system modeled with the open-source Monte Carlo toolkit *Geant4*.[6] It consists of the neutron source, the test item, and the detector bank. The neutron cross section libraries used for all simulations are from the evaluated data libraries ENDF-B/VII.0 converted into the *Geant4* format using CIEMAT.[7]

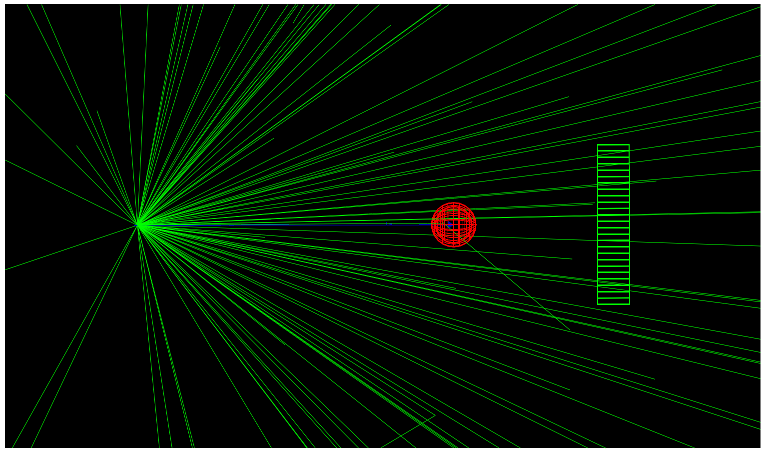

Figure 2: Simplified experimental setup (*Geant4*).

Neutron source. The p-Li neutron source requires an intense source of protons and a lithium target to drive the $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$ reaction. Even for actively cooled targets, the beam current is generally limited by the relatively low melting points of metallic lithium and its main compounds such as lithium fluoride. Proton currents on the order of 100 μA are achievable and can produce 10^{9}–10^{10} neutrons per second. For this analysis, the proton interaction in the metallic lithium target has been simulated using the Monte Carlo code SimLiT.[8] The neutron spectrum can be tailored by varying the target thickness and the incident proton energy. Some typical forward-directional ($< 10^{\circ}$) neutron energy distributions from the modeled p-Li reaction in the laboratory coordinate system are shown in Figure 3. For the simulations discussed below, a proton energy of 2040 keV and a target thickness of 10 μm has been chosen. These parameters produce neutron energies between 180 keV and 290 keV, which is an excellent energy range for discriminating nuclear materials.

Test item. The reference test item used for this study is the fissile core of a "hypothetical weapon model" previously proposed and used for benchmark analyses.[9] The selected component consists of a shell of weapon-grade uranium with an inside diameter of 11.5 cm and an outside diameter of 14.0 cm. The uranium mass is exactly 12 kg. The item is centered at a distance of 100 cm from the p-Li neutron source.

Detector bank. The detector bank is located 50 cm away from the center of the test item and has 625 detector positions (25×25 detectors on a square grid). Neutron reactions in the detectors are not directly simulated in this simplified model. Instead, the neutron track length is recorded and converted to bubble counts by assuming a detection efficiency of 1%, which is typical for state-of-the-art bubble detectors.[10]

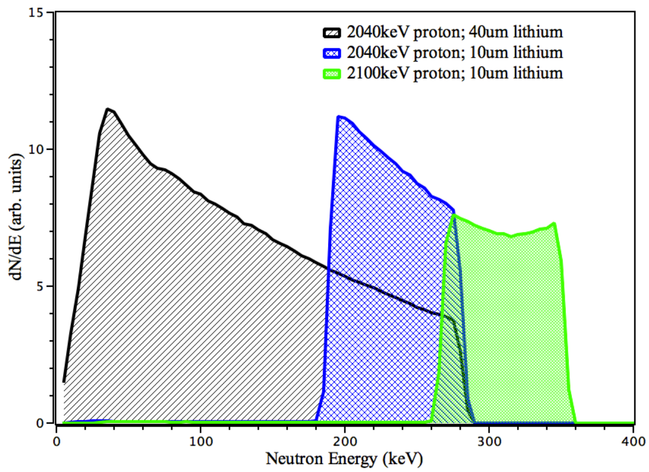

Figure 3: Simulated neutron energy distribution from p-Li source. The proton energy in the beam determines the upper energy cutoff; the thickness of the target determines the lower energy cutoff of the neutrons. The source-target configuration can be optimized for sensitivity to isotopic and geometric changes in the test item. Results below are for the blue distribution (2040 keV protons on 10 μm lithium target).

Results and Discussion

In order to examine the viability of the proposed two-color setup, we consider two situations: changes in the isotopic composition and changes in the geometry of the test item (Figure 4). In the first case, the U-235 concentration is reduced from its original value of 93.5% in the reference item to 75% and 85%; in the second case, the outer diameter of the item is increased from 14.0 cm to 15.0 cm while the thickness of the shell is reduced from 1.23 cm to 1.03 cm to retain the same mass of 12 kilograms.

For the selected neutron energy range of 180–290 keV, neutron detectors with two different energy thresholds have been selected for optimum system performance. First, we use detectors with a nominal energy threshold of 500 keV, which is well *above* the maximum source energy of 290 keV. These detectors are therefore completely insensitive ("blind") to neutrons from the source, but they will efficiently detect fission events driven by the source in the test item. Second, we use detectors with an energy threshold of about 100 keV, which is well *below* the minimum source energy of 180 keV. These detectors are sensitive to all neutrons from the source, while being largely insensitive to scattered neutrons from the laboratory environment.[11] The gap between the lowest relevant energy from the source and the detector threshold of $(180 - 100)$ keV $= 80$ keV ensures that slight variations in the value of the detector threshold do not affect the performance of the system.

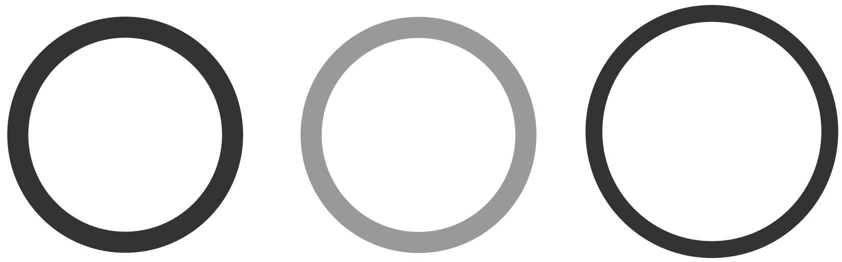

Figure 4: The reference test item is a simple 12-kg shell of weapon-grade uranium as first proposed in 1990.[8] To examine the sensitivity to diversions, we consider two variations: an item with the same geometry, but modified isotopics (75% and 85% U-235); and an item with a larger outer radius and reduced thickness, but with same mass and isotopics.

Invalid Item: Wrong Isotopics

The template-matching results and the associated count distributions for the 500-keV detectors are shown in Figure 5. In this example, N_{max} is set to 5000, which is a practical upper limit for a modern bubble detector of the size considered here.[12] In the present case, and unknown to the inspector, the maximum bubble count obtained during the inspection of the test item is only on the order of 1000, i.e., most of the bubbles are added at the preload stage.[13] If the inspected item is valid, only natural statistical noise will be present and no information pertinent to the design of the inspected item is revealed. In contrast, if the weapon-grade uranium is replaced by uranium with a lower uranium-235 content, those invalid items can be easily identified. Figure 5 shows the cases of a reduced enrichment of 75% and 85% compared to the original value of 93.5%, which corresponds to a uranium-235 removal of 2.2 kg (20% of total U-235) and 1.0 kg (9% of total U-235), respectively. The bubble-count distributions are significantly different from the expected normal distribution with a mean value of N_{max}. Figure 5 also shows that even the change in geometry is easily detected with the 500-keV detector array. In this example, the uranium mass and isotopics are unchanged, but the thinner shell of the invalid item results in a significantly higher fission-driven neutron flux observed at the detector bank due to the reduced self-shielding of the item.

Invalid Item: Wrong Geometry

The template-matching results and the associated count distributions for the 100-keV detectors are shown in Figure 6. Again, N_{max} has been set to 5000.[14] As expected,

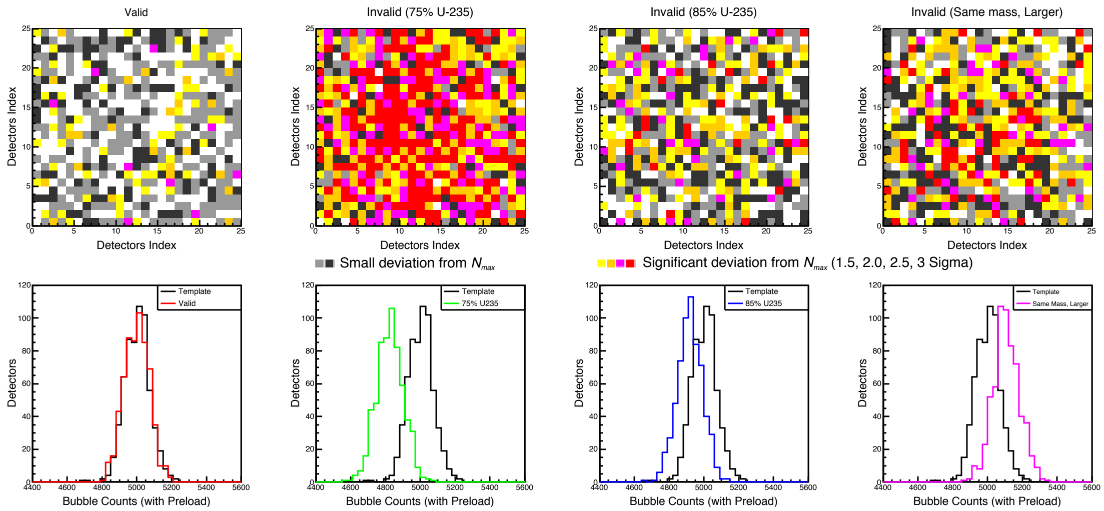

Figure 5: Diversion analysis for detectors with 500-keV threshold. In this example, N_{max} is set at 5000, but (unknown to inspector) the maximum bubble count during the inspection is only about 1000. All diversions are easily detected even when based on simple visual comparison of the bubble-count distributions. Statistical tests provide more robust quantitative assessments of the probabilities that an invalid item has been presented (*Geant4* simulations).

transmission neutrons are barely sensitive to the isotopics of the material, and items with the proposed differences in the isotopic composition (75% and 85% versus 93.5% U-235) cannot be distinguished using 100-keV detectors with the specified value of N_{max}. Changes in the geometry are now even more visible than in the previous case, however, and produce a radiographic image of the affected region. This is consistent with previous results obtained for a 14-MeV neutron source.[15] While a valid item produces normally distributed detector counts with mean and variance of N_{max}, an invalid item can reveal design information, e.g., in this case, information about the size of the object. This should be an additional strong incentive for the host not to cheat.

Note that the neutron flux $\phi(E_n > 100 \text{ keV})$ observed at the position of the detector bank is about one hundred times greater than the neutron flux $\phi(E_n > 500 \text{ keV})$ because it includes neutrons originating from the source (Figure 3). The bubble-generation rate in the 100-keV detectors is therefore much higher than the rate in the 500-keV detectors. In practice, this would result in very different inspection times, and both measurements are probably best carried out consecutively.

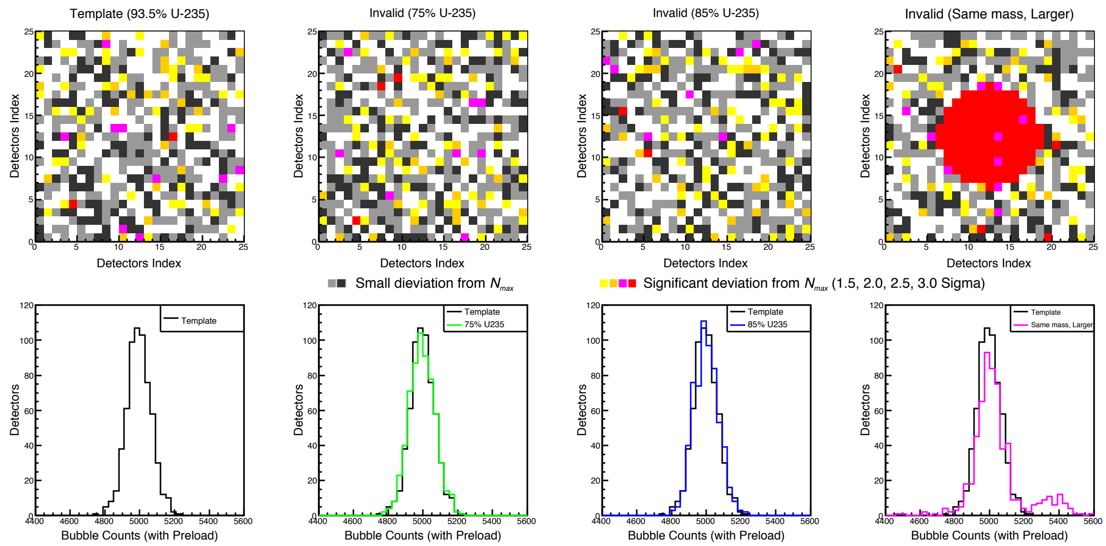

Figure 6: Diversion analysis for detectors with 100-keV threshold. In this example, N_{max} is set at 5000, about 10% higher than the maximum bubble count measured in the absence of a test item. As expected, isotopic changes are difficult or impossible to detect; in contrast, geometric changes are highly visible. Statistical tests provide more robust quantitative assessments of the probabilities that an invalid item has been presented (*Geant4* simulations).

Conclusion

Neutron transmission radiography based on active interrogation with high-energy neutrons provides an effective tool to detect geometric and elemental differences of inspected items. Distinguishing different isotopic compositions of the same element, however, can be more challenging because differences in the fission cross sections of relevant isotopes can be small for 14-MeV neutrons. Here, we have proposed and examined a complementary approach, dubbed a "two-color setup." The basic idea is to illuminate the inspected item with neutrons in the 100-keV range. Fissile isotopes that are exposed to these neutrons undergo fission and produce neutrons in the MeV-range. These neutrons can be counted using detectors that are blind to lower energy neutrons in the direct beam. In addition, detectors with a lower energy threshold, i.e, detectors that are sensitive to neutrons directly from the source, can be used for basic radiography measurements.

To assess the viability of this concept, we have modeled a neutron source for this setup based on the $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$ reaction in a lithium target coupled to the open source Monte Carlo particle transport toolkit *Geant4*. We have examined isotopic substitution scenarios, in which the elemental composition, mass, and geometry of the test items remain unchanged. We have also examined the sensitivity to differences in geometry. In both cases, we find excellent sensitivity of the concept to all diversion scenarios considered: Detectors with a threshold well above the neutron energies from the source readily detect isotopic shifts by less than 10% (from 93.5% down to 85%); in our test case, this corresponds to a U-235 removal of only 1 kg or less than 10% of the total uranium in the item. Similarly, small geometric changes in the inspected item are detectable by their radiographic signature, but also by their fission-neutron signature. By integrating this concept with the zero-knowledge protocol using preloaded bubble detectors, we can confirm the authenticity of valid items without revealing any information to the inspector.

Overall, the simulated results suggest that a system based on this "two-color setup" could be a promising method for nuclear warhead verification. In contrast to 14-MeV neutrons, which can be efficiently (and affordably) produced with compact DT neutron generators, the concept requires an intense proton beam to produce neutrons with an adequate energy spectrum and well-defined lower and energy cutoffs (200–300 keV). To validate the concept experimentally would require a well-characterized, intense, and robust source of neutrons driven by a proton beam from a cyclotron or linear accelerator.

Acknowledgements

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Endnotes

[1]Certification ensures the host that the system cannot reveal classified information, while authentication ensures the inspector that the system works as designed and displays genuine measurement results. D. Spears (ed.), *Technology R&D for Arms Control,* U.S. Department of Energy, Office of Nonproliferation Research and Engineering, Washington, DC, 2001, www.fissilematerials.org/library/doe01b.pdf.

[2]Alexander Glaser, Boaz Barak, and Robert J. Goldston, "A Zero-knowledge Protocol for Nuclear Warhead Verification," *Nature,* 510, June 2014, pp. 497–502.

[3]Sebastien Philippe, George Ascione, Francesco d'Errico, Charles Gentile, Alexander Glaser, and Robert J. Goldston, "Experimental Demonstration of a Physical Zero-knowledge Protocol for Nuclear Warhead Verification," *Proceedings of the 56th Annual INMM Meeting,* Indian Wells, California, July 2015.

[4]R. J. Goldston, F. d'Errico, A. di Fulvio, A. Glaser, S. Philippe, and M. E. Walker, "Zero-knowledge Warhead Verification: System Requirements and Detector Technologies," *Proceedings of the 55th Annual INMM Meeting,* Atlanta, GA, July 2014.

[5]For a more detailed discussion, see Glaser, Barak, Goldston, *Nature, op. cit.*

[6]S. Agostinelli et al., "Geant4: A Simulation Toolkit," *Nuclear Instrumentation and Methods in Physics Research A,* 506 (3), 2003, pp. 250–303.

[7]E. Mendoza, D. Cano-Ott, C. Guerrero, and R. Capote, IAEA technical report INDC(NDS)-0612, Vienna, 2012. Data available online at www-nds.iaea.org/geant4; and E. Mendoza, D. Cano-Ott, T. Koi and C. Guerrero, *IEEE Trans. Nucl. Science,* 61, 2014.

[8]M. Friedman et al., "Simulation of the Neutron Spectrum from the ^{7}Li(p, n) Reaction with a Liquid-lithium Target at Soreq Applied Research Accelerator Facility," *Nuclear Instruments and Methods in Physics Research A,* 698, 2013, pp. 117–126. See also www.phys.huji.ac.il/SimLiT.

[9]Steve Fetter, Valery A. Frolov, Marvin Miller, Robert Mozley, Oleg F. Prilutsky, Stanislav N. Rodionov, and Roald Z. Sagdeev, "Detecting Nuclear Warheads," *Science & Global Security,* 1 (3–4), 1990, pp. 225–253, scienceandglobalsecurity.org/archive/sgs01fetter.pdf

[10]Francesco d'Errico, "Radiation Dosimetry and Spectrometry With Superheated Emulsions," *Nuclear Instruments and Methods in Physics Research B,* 184, 2001, pp. 229–254.

[11]Note that the full room environment was not modeled in these simulations.

[12]The active volume of the modeled detectors is on the order of 10–30 cm^3.

[13]The number of fission events driven in an inspected nuclear warhead or warhead component has to be considered extremely sensitive information. We assume that both parties could agree on an upper bound of N_{max}. For example, the value could be determined by the inspection of an unshielded significant quantity of weapon-grade uranium or plutonium.

[14]N_{max} for transmission could reasonably correspond to the maximum number of counts that is expected in the absence of a test item. Counts observed during an inspection can be close to this upper limit.

[15]Glaser, Barak, Goldston, *Nature, op. cit.*