IPNDV Working Group 3: Technical Challenges and Solutions
High Explosives/Nuclear Material (1)—Technology Data Sheet

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Nuclear Material (NM)/High Explosives (HE) Technology Name: Nuclear Resonance Fluorescence (NRF)

Physical Principle/Methodology of Technology:

Nuclear Resonance Fluorescence (NRF) is an active interrogation technique that provides the isotopic information of a target under investigation. The technique works by irradiating a material with high-energy photons and then detecting the photons that are subsequently emitted by the material.

Each isotope has unique energy states within the nucleus (known as a *resonant energies*). When nuclei are irradiated by high-energy photons that have an energy matching one of these energy states, the probability (cross-section) for absorption of the photon by the nucleus is significantly increased. Absorption of the photon raises the nucleus to an excited state; de-excitation then occurs by re-emission of the photon with the same discrete resonant energy (known as *resonance fluorescence*). The information of the specific resonant energy is used to identify the isotopic constituent of the material, because the resonant energies are unique to each element and indeed each isotope of an element. The only element that cannot be detected in this manner is hydrogen.

The detection of NRF can be achieved by detection of either scattered or transmitted photons. The resonance fluorescence photons that are scattered out of the main stimulating photon beam can be directly detected by a spectroscopic detector and the peaks of the resonant energies used to identify the isotopes present. Because the fluorescence photons are scattered over a wide angle, it is possible to detect photons travelling back in a direction toward the stimulating source. An NRF system using this geometry would therefore be a single-sided technique.

The major resonance energy levels are typically much greater than 1 MeV. Thus, the technique is particularly suited to the interrogation of substances that are surrounded by thick layers of obstructing materials or even stored within dense containers. The isotope specific information, provided by NRF, has previously been used to identify high-*Z* materials such as ^{235}U and ^{239}Pu even when shielded.[1]

Additionally, the direct detection of low-*Z*, low-density materials that are shielded by high-*Z*, dense materials has already been observed.[2] The ratio in abundance of specific elements in a target material has been estimated from an NRF signal, potentially allowing for discrimination between benign and threat materials. A proof-of-principle experiment has previously investigated the determination of the C to N abundance ratio by using the ^{12}C and the ^{14}N resonances.[3] The determination of the Oxygen to Nitrogen ratio has also been demonstrated for a simulated explosive (RDX) target.[4]

The specific energies required within the photon beam of an NRF system depend on the isotopes that are of interest for detection and, thus, the performance of the system is reliant on the properties of the photon beam source. The use of a Bremsstrahlung generator produces a broad spectrum of photon energies and it is therefore possible to excite any number of fluorescence lines without requiring specific tuning and hence detect many different isotope species simultaneously.[5] An alternative and new type of X-ray source, based on laser Compton scattering, has the potential to form mono-energetic beams that can be tuned or selected for a specific energy range (and therefore a specific isotope).

Potential Monitoring Use Cases (pre-dismantlement, dismantlement, post-dismantlement, storage stage):

All

Used to measure U, Pu, or U and Pu:

U and Pu

For detection technologies, what does the method determine/measure (e.g., presence of nuclear material, isotopics, mass, etc.):

For NM detection: NRF determines the isotopes present within an irradiated target and will therefore determine the presence of NM.

For HE detection: NRF can determine the C/N and C/O ratios, which can be used to determine the presence of HE.

Physical Description of Technology (e.g., approximate size, weight):

The essential components of a NRF system are an X-ray generator and a detector array. The appropriate X-ray generators can have a foot print in the order of 1 m^2 and weight in excess of 100 kg. The detector component would have a similar footprint. A significant amount of shielding would also be required to reduce the dose rate within the vicinity of the equipment.

Time Constraints (e.g., measurement times including distance from object):

Measurement time: The measurement time required to collect sufficient counts for an unambiguous detection depends on the incident photon intensity at the resonant energy (the *spectral density*), the NRF cross-section, the solid-angle subtended by the detector with respect to the target material, and the intrinsic efficiency of the detector.

Measurement time to measure 500 g of Pu (0.1 ^{239}Pu/^{240}Pu) or 500 g of ^{235}U at 1 m from the surface of the container (order of magnitude: seconds, minutes, hours, days):

Not known.

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[1] W. Bertozzi, "Nuclear Resonance Fluorescence Excitations Near 2 MeV in 235U and 239Pu," *Physical Review C* 78 (2008).

[2] F. Albert, "Isotope-Specific Detection of Low Density Materials with Mono-Energetic Gamma-Rays," *Lawrence Livermore National Laboratory Report*, no. LLNL-TR-411369 (2009).

[3] T. Hayakawa, "Nondestructive Detection of Hidden Chemical Compounds with Laser Compton-Scattering Gamma Rays," *Review of Scientific Instruments* 80 (2009).

[4] H. Toyokawa, "Nondestructive Inspection of Explosive Materials Using Linearly Polarized Two-Colored Photon Beam," *Nuclear Instruments & Methods in Physics Research Section A* (2011).

[5] W. Bertozzi and R. J. Ledoux, "Nuclear Resonance Fluorescence Imaging in Non-Intrusive Cargo Inspection," *Nuclear Instruments & Methods in Physics Research Section B-Beam Interactions with Materials and Atoms* 241, no. 1–4 (December 2005): 820–25; and J.O. Perry, Xiao, S., and Jevremovic, T, "iMASS: Evolved NRF Simulations for More Accurate Detection of Nuclear Threats," *17th ICONE International Conference on Nuclear Engineering* (2009).

Will this method work in the presence of shielding? If so, what is the maximum amount of shielding that will still allow the method to work?

The resonance photon energy levels are typically much greater than 1 MeV, which can penetrate reasonable levels of shielding.

Technology Complexity (e.g., hardware, software, and ease of use by personnel):

The technology may involve the integration of the following components:

- Detector material
- X-ray generator
- Radiation shielding
- Computer

The complexity of the system would be hidden from the end user.

Infrastructure Requirements (e.g., electrical, liquid nitrogen, etc.):

Radiation shielding, power (Passport system SMARTSCAM requires 480VAC, 3 phase @ 1,200 amps), potentially liquid nitrogen.

Technology Limitations/Variations (e.g., detection limits for nuclear material, operational temperature range, differences in technology detector materials):

Specific equipment limitations include:

- The cross-section efficiency is low, especially for continuous wave X-ray generators. Increased efficiency could be achieved with laser-based Compton scattering X-ray sources. These developmental X-ray sources can generate mono-energetic beams of radiation.
- Hydrogen is the only element that can’t be detected.
- In the transmission configuration, the measurement is aided by a “witness or detection” foil that consists of the isotope of interest.

Information Collected by the Technology (used to help determine if an information barrier is required for use):

Gamma-ray spectrum, isotope information, C/N and C/O ratios for explosives determination, potential for SNM mass determination.

An information barrier would be required.

Safety, Security, Deployment Concerns:

NRF is an active detection technology, so there will be a radiation safety concern.

Security concerns may arise from the technology being able to detect sensitive information.

The broad range of photon energies, for Bremsstrahlung X-ray generators, will lead to higher operational dose rates. Laser-based inverse Compton scattering X-ray generators are at a lower TRL level, but would offer lower operational dose rates.

HPGe detectors require cryogenic cooling, through either the use of liquid N or mechanical cooling. The use of mechanical cooling would have fewer deployment concerns.
Technology Development Stage (Technology Readiness Level, TRL): There is one known COTS items (TRL 9) that is available. National labs and universities are also developing technologies that are at the various TRL levels.
Additional System Functionality (e.g., outside the monitoring use case): X-ray backscatter imaging functionality could be simply combined with an NRF system. Other detection modalities could be added to the system. Passport Systems Inc. has developed such a multi-modality system that includes NRF, transmission X-ray, and the detection of prompt neutrons from photo-induced fission.
Where/How the Technology Is Currently Used (e.g., international safeguards, border protection): Safeguards National Security
Examples of Equipment: Passports Systems Inc. uses NRF technology as part of a fixed cargo screening technology called "SmartScan 3D."