Applications and Deployment of Neutron Scatter Cameras in Nuclear Safeguards Scenarios

Taylor Harvey and Andreas Enqvist
University of Florida, Gainesville, Florida USA

Katherine Bachner
Brookhaven National Laboratory, Upton, New York USA

Abstract

Neutron scatter cameras (NSCs) are a type of directionally sensitive neutron detector that rely on two consecutive neutron scattering events to localize a source of neutrons. NSCs can be used to locate, image, and identify unknown neutron sources or verify the geometry and identity of known sources. Much technical progress has been made in improving NSC designs, but little literature exists exploring the full range of practical application of neutron scatter cameras. This paper seeks to identify scenarios related to nuclear security and non-proliferation where deployment of NSCs may be useful. These situations could include: limited searches for sources during cargo screening, counting nuclear warheads for treaty verification, verification of special nuclear material during inspections, imaging nuclear contamination, imaging nuclear reactor cores, searching for lost sources, and matching neutron images in shipper/receiver or inventory management scenarios. These scenarios are examined with respect to existing NSC designs and proposed designs in terms of usefulness and practicality of deployment when compared to currently used detection systems.

Introduction

The field of nuclear safeguards seeks to stop the spread of nuclear weapons by developing technologies and polices intended to prevent the misuse of nuclear materials and technology.[1] Essential to the nuclear safeguards paradigm is the use of radiation detectors to monitor and verify the quantity, identity, and movement of radioactive sources relevant to both peaceful and weapons programs. Of particular interest is Special Nuclear Material (SNM), such as uranium and plutonium, which can be monitored and identified using a variety of gamma[2] and neutron[3] detection techniques. Detection systems can also be used to address accident scenarios involving nuclear reactors or nuclear material.

Neutron detectors are attractive for safeguards and accident scenarios because of the long attenuation length of neutrons when compared to gamma rays and the low natural background for neutrons. The high cost of helium-3 has led to several alternatives to gas proportional counters in safeguards detection systems.[4] A subtype of neutron detector that has seen increased interest in the last decade is the neutron scatter camera (NSC), a detector type that can provide data on the direction of a source of neutrons along with count rate and spectroscopic data. This paper seeks to survey the existing and proposed designs for neutron scatter cameras and identify measurement scenarios in which such detectors may be useful within the nuclear safeguards regime. Neutron scatter cameras may prove useful in a number of measurement scenarios, as they can provide directional information on neutron sources, can perform fast neutron spectroscopy, can discriminate between gamma rays and neutrons, can be made portable, can be powered by batteries, and contain no moving parts.

Neutron Scatter Camera Technical Overview

Neutron scatter cameras operate by detecting two consecutive elastic scatters of a single fast neutron emitted by a nearby source. The kinematic principle involved in determining the original particle trajectory from two consecutive scattering events is similar to the operating principle of Compton Cameras,[5] though NSCs use fast neutrons rather than gamma rays. The detector active volume present in all currently existing NSCs use either organic liquid or plastic scintillators. The initial trajectory of individual neutrons is determined by finding the approximate (x,y,z) position of both the first and second scatter in the scintillator volume. The position of each scatter is found by either using spatially separated volumes of scintillators or by comparing the position and timing of the arrival of light to a series of photodetectors within the same scintillator volume. Spatially separated arrays of scintillators may be arranged in either two or more planes or positioned in a radially symmetric arrangement. Examples of the three general types of neutron scatter cameras are shown in Figures 1, 2, and 3. Mascarenhas et al.,[6] Goldsmith et al.,[7] and Weinfurther et al.[8] provide detailed technical discussions of the kinematics of scattering in plane-based, radial, and single volume designs respectively. After the determination of two consecutive scatter positions, the cones encompassing the possible trajectories of individual neutrons are back projected in 3-D space. The region of space where the surfaces of all the back projected cones overlap is determined to be the direction of the neutron source.

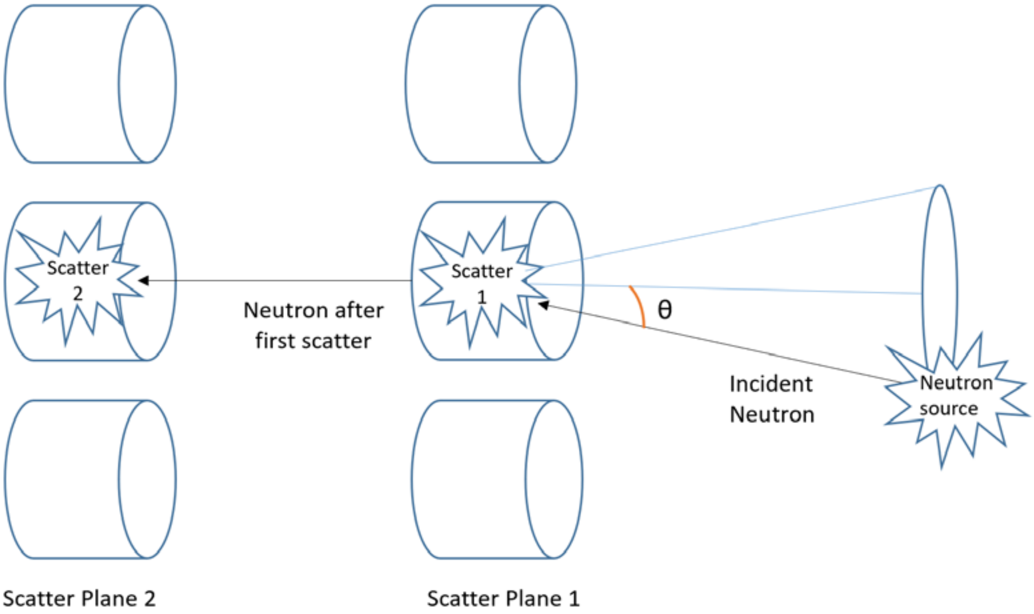

Figure 1. Two-plane Scatter Camera, Multiple Scintillator Volumes

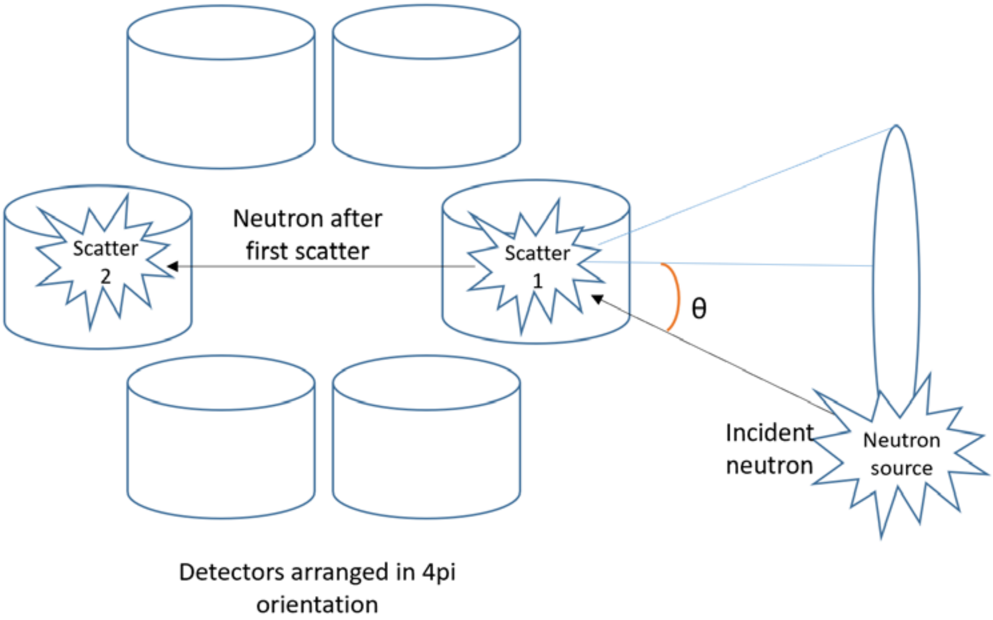

Figure 2. Radially Symmetric Scatter Camera, Multiple Scintillator Volumes

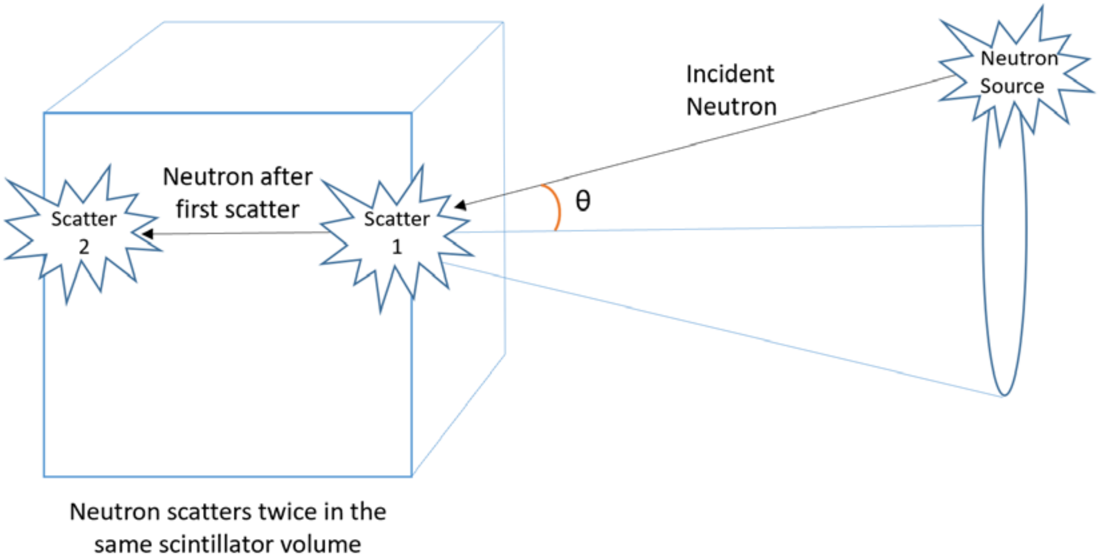

Figure 3. Single Volume Scatter Camera, Requiring Fast Timing and a Special Arrangement Of Photodetectors

If the neutron source is sufficiently far enough from the detector to be approximated as a point source, then the back projected cones will converge on a point which can be described by the ordered pair (θ, ϕ), where θ is the azimuthal and ϕ is the polar coordinate in a spherical coordinate system with the position of first scatter within the detector as the origin. The standard neutron scatter camera design cannot determine the radial distance from detector to source, though the application of a coded aperture system or multiple measurements at different locations can give some information about the distance to the source.[9] If the neutron scatter camera is close enough to the source so that it cannot be approximated as a point source, then the scatter camera can perform a rough imaging of the neutron-emitting parts of the source given a sufficiently long measurement time. Figures 4a and b show simulation results from a neutron scatter camera localizing a distant source approximated as a point with an increasing number of cones, while Figures 5a and 5b show a nearby, distributed source measured for a “long” counting time.

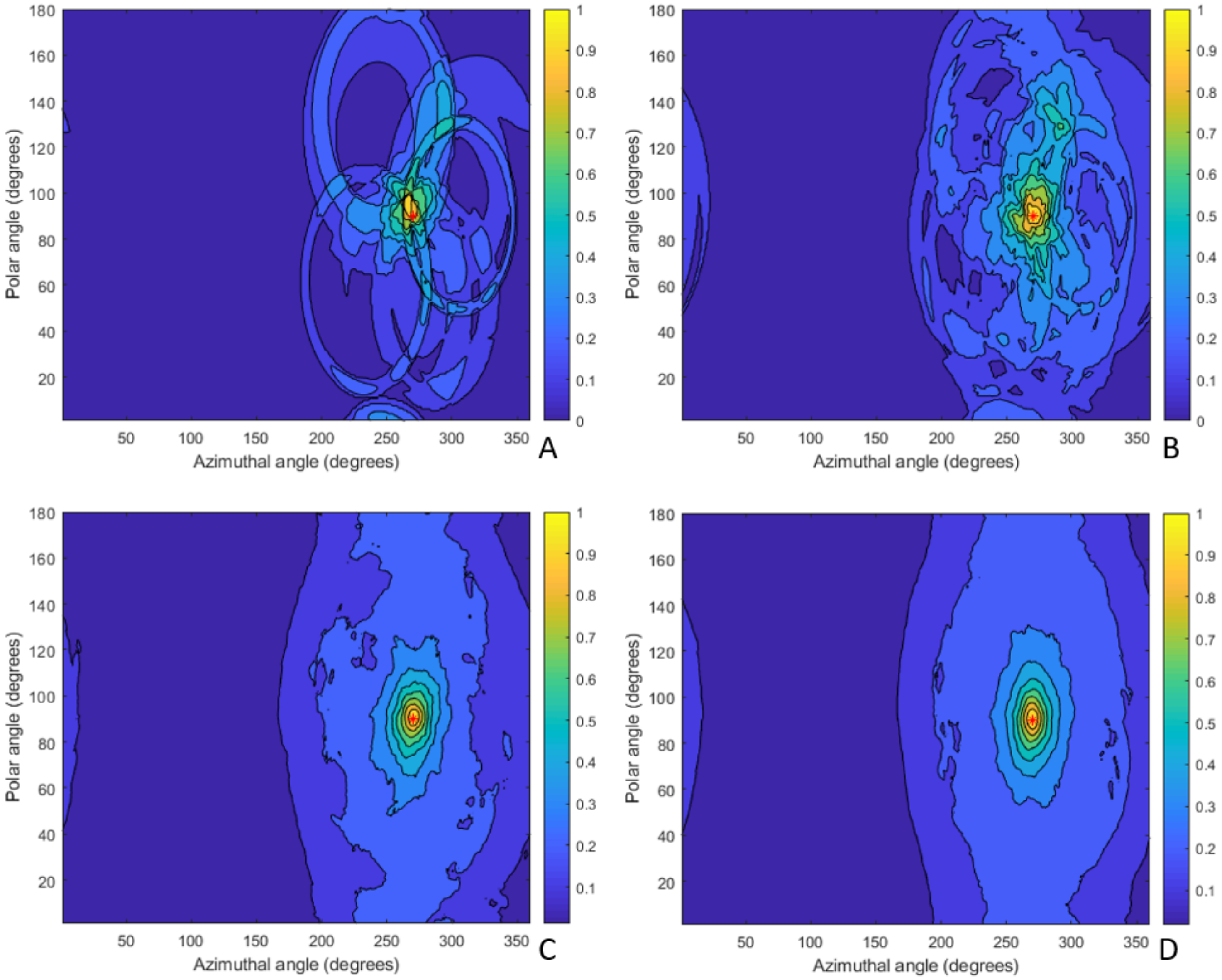

Figure 4a. Simulated Localization of a Distant Neutron Source at (270,90) with A) 10 B) 30 C) 300 and D) 1000 Back Projected Cones

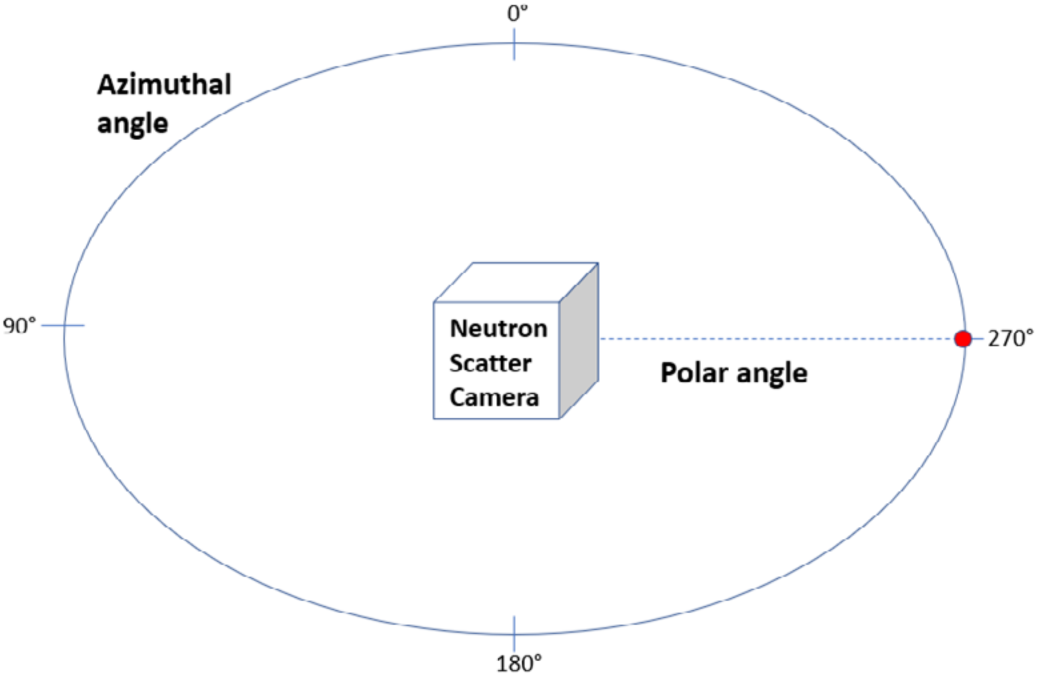

Figure 4b. Diagram of Simulated Measurement Setup for Distant Point Source

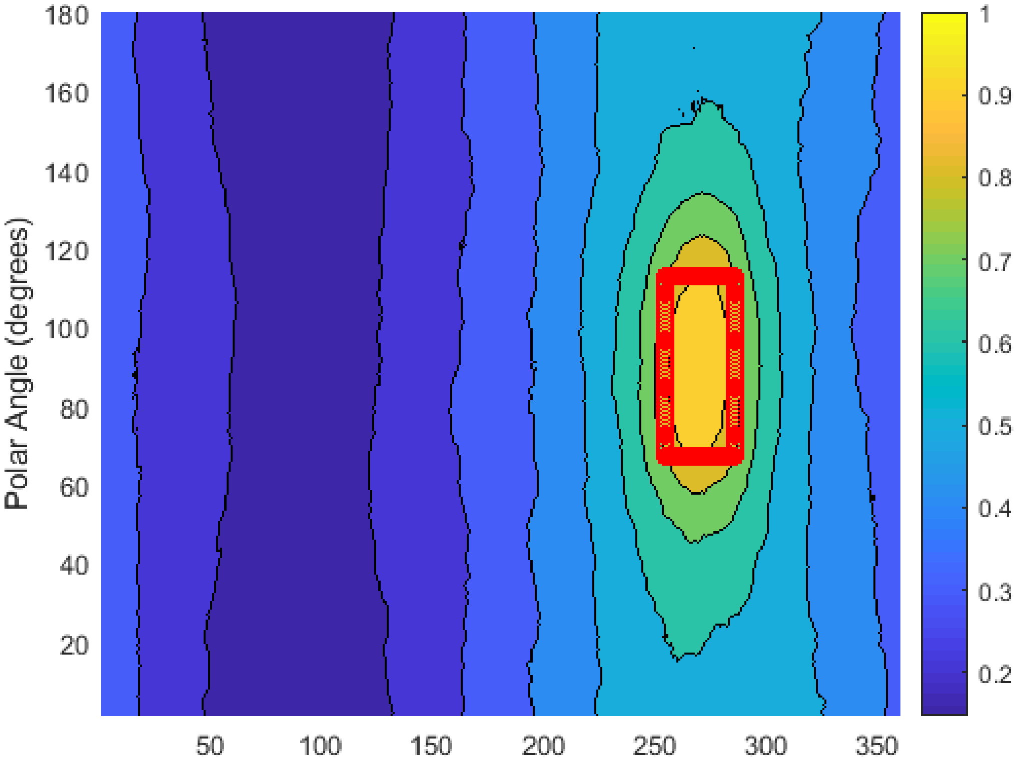

Figure 5a. Simulated Distributed Spontaneous Fission Source in Shape of a Barrel Placed One m from Detector Over a Long Measurement Period

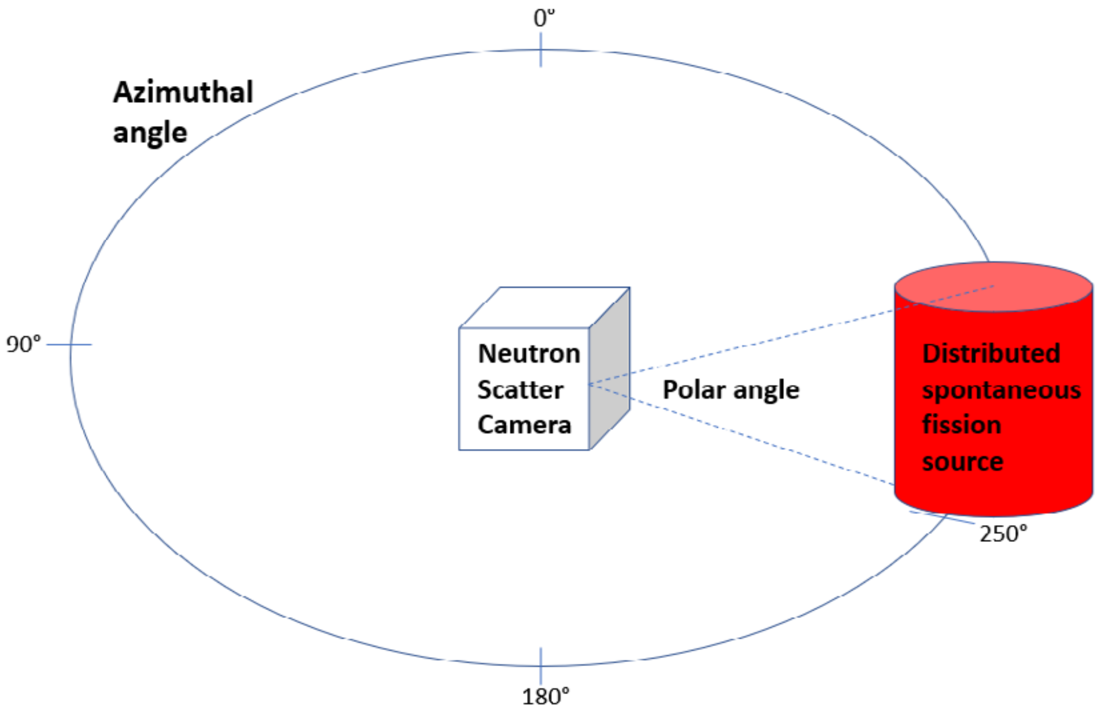

Figure 5b. Diagram of Simulated Measurement Setup for Distributed Source

Neutron scatter cameras are not the only neutron detection systems with source imaging capabilities. Coded aperture systems[9] and time projection chambers[10] also allow for neutron source localization, though neutron scatter cameras offer several advantages over these systems. Neutron scatter cameras are capable of comparable imaging resolution given sufficient measurement time and can identify the general direction of an unmoderated source in only minutes.[11] NSCs using scintillators are also capable of low-resolution neutron spectroscopy, which can be useful in identifying unknown sources, and can distinguish neutrons from gammas by either using pulse shape discrimination or through time-of-flight methods. NSCs with a radial multi-volume arrangement or single volume designs are capable of 4π fields of vision, which can be useful if the source direction is totally unknown. Low numbers of output channels and the potential for photodetectors to be powered with mobile batteries[7] are features promising for deployment in measurement scenarios where power is scarce. NSCs can also be made relatively compact and low weight at the expensive of lower sensitivity.[7,8,12,13] Finally, most NSCs contain few to no moving parts and do not require pressurization of the detection medium, making them relatively simple and safe to transport and operate.

Survey of Existing and Proposed Neutron Scatter Cameras

The first camera-type detectors to rely on fast neutron double scatters were used to determine the primary direction of the flux of solar neutrons. The first such detector, developed by Grannan et al., used two planes of liquid scintillators separated by 1 m to detect double scatters for neutrons in the range of 2 to 100 MeV.[14] A similar design by Herzo et al. added the capability to determine the gamma flux direction by using the scintillator volumes as both gamma and neutron detectors.[15] Neutron imaging using a two-plane design was proposed for use in nuclear warhead measurement by Sailor et al. and was explored with a series of Monte Carlo simulations and prototype measurements. This project found that a warhead emitting 10^5 n/s could be imaged in about 2 minutes.[16] Several decades later, the SONTRAC imaging spectrometer presented a device utilizing stacked scintillation plastic fibers to image neutrons between 20 and 200 MeV.[17] This design was the first to focus on a compact design where the scintillation volumes were not spatially separated but were instead optically columnarized. A similar design featuring segmented layers of plastic scintillators was used by the Fast Neutron Imaging Telescope.[18] The FNIT was able to locate 98g of weapons-grade plutonium 1 m away from the detector with approximately 80 double scatter events.[19] Around the same time, Vanier et al. achieved similar imaging results using eight separate scintillator volumes arranged in a two-plane configuration.[20] All of these systems most closely resemble the two-plane, multi-volume design shown in Figure 1, save the SONTRAC, which more closely resembles the schematic of the single-volume design shown in Figure 3.

A major improvement in the neutron scatter camera design (and the first device to be called such) was the system developed at Sandia National Laboratory to image neutron sources in the fission energy range.[6] Improvements to the sensitivity of the Sandia NSC were made by increasing the number of detector volumes used, lowering the energy deposition threshold, and implementing more effective neutron-gamma discrimination by using both pulse shape discrimination and time-of-flight methods.[21] Further results showed that the Sandia NSC could locate a hidden ^{252}Cf source within the hold of a tanker ship with 5 minutes of measurement time, and could locate the same source at a standoff distance of 30 m.[22] Later results claimed that the Sandia NSC could be applied to warhead monitoring and treaty verification through the implementation of a track to adjust the spacing between the detector planes and the use of maximum likelihood estimation methods (MLEM).[23] The adjustable track allows the NSC to switch between a high efficiency mode, in which the detector planes are closer together, and a high angular resolution mode, when the detector planes are farther apart, as demonstrated by Figure 6. MLEM, often used in astronomy and medical imaging, can be applied to images generated by the camera to improve the imaging resolution without any changes to the hardware itself. This technique is especially useful when more than one neutron source is present.

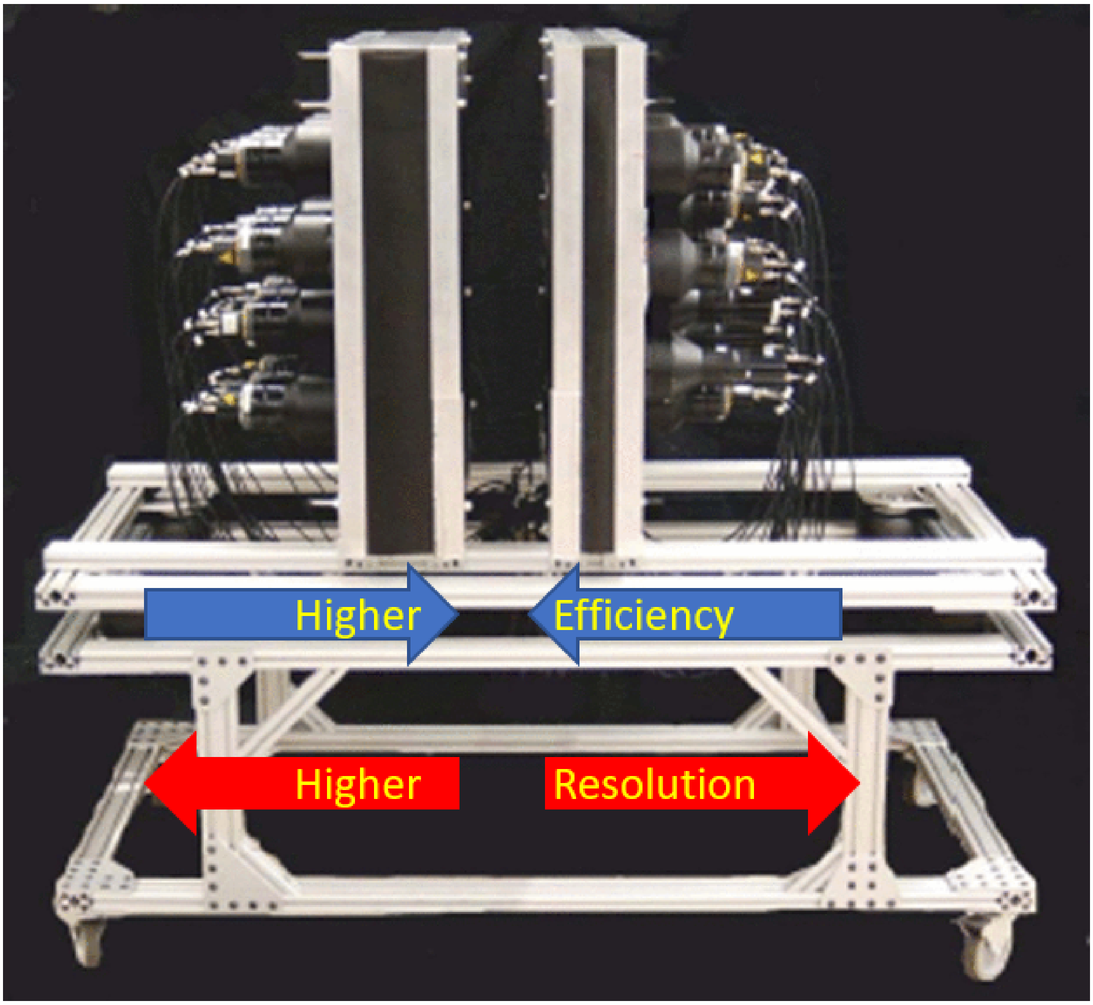

Figure 6. Sandia Neutron Scatter Camera with a Track Allowing Variable Spacing of Detection Planes.

When the planes are closer together, the system has a higher double scatter efficiency. When the planes are farther apart, the system has a high imaging resolution, as the greater time of flight between planes allows for more accurate cone back projection.

Another device with fast neutron imaging capabilities developed to detect and localize SNM is the Dual Particle Imager (DPI) introduced by Polack et al.[24,25] This system was designed to image both neutron and gamma sources with the hope of localizing and identifying sources in standoff scenarios. This design includes three arrays of detectors arranged into three seperate planes: two consisting of EJ-309 liquid scintillators and one of NaI scintillators. Both neutrons and gamma rays may scatter in the two liquid scintillator planes, while the NaI plane is only sensitive to gamma rays. The dual particle approach presents a few advantages when it comes to detecting and localizing sources. Only one of the two modes could be used to image a neutron- and gamma-emitting source with the presence of intervening shielding: high-Z shielding could be addressed using the neutron-only mode, while plastic or other low-Z shielding could be addressed using the gamma-only mode. Additionally, a neutron-only mode could provide a less noisy source image when the gamma background field is high. Neutron and gamma modes could be used simultaneously with dual-emitting sources to characterize the source identity with high confidence. Results with the DPI system demonstrated its ability to resolve two MOX canisters separated by 20° at a standoff distance of 2.5 m. This system was also able to distinguish between a spontaneous fission source and an (α,n) source, showing the applicability of such a system in safeguards and non-proliferation scenarios.[26]

Another advance in the development of neutron scatter cameras with nuclear security applications was the introduction of the Mobile Imager of Neutrons for Emergency Responders (MINER) by a group at Sandia National Laboratory[12] (also called a compact neutron scatter camera for field deployment, with the MINER name dropped in a later paper[7]). Improvements with the MINER system include a true 4π field of view and a compact, less massive design. Instead of separate planes of detectors, MINER uses radially configured scintillator volumes. MINER's mass is 40 kg, a significant reduction when comparing to the full-size Sandia NSC, which weighed around 330 kg including electronic racks. MINER, along with its electronics, can be transported in a single high-performance, injection-molded, watertight case and can be set up in 10 minutes. When fully set up, the system measures 0.9 m high and has a 0.4 m diameter. In an early test measurement, MINER was able to resolve an unshielded ^{252}Cf source at a standoff distance of 28 m in 30 minutes. MINER's features and capabilities could prove useful in a variety of field measurement scenarios that require a "portable" detector. The compactness of this system comes at the expense of imaging resolution, as this system consists of 12 large, unsegmented, closely-spaced scintillator volumes, an arrangement that leads to high uncertainties in time of flight and distance between scattering events.

Several proposed design changes have been made for further improvement of the results and versatility of neutron scatter cameras. One major area of interest is reducing the total detection system size and improving mobility while maintaining reasonable efficiency, spectroscopic capability, and imaging quality. One method for reducing the size of neutron camera systems is to use more compact photodetectors instead of relatively bulky photomultiplier tubes. Silicon photomultipliers (SiPM) have been considered as an alternative to PMTs with an eye toward creating a handheld NSC.[13] Ruch et al. demonstrated that SiPM coupled to stilbene scintillators showed similar timing resolution to PMTs, an important consideration when designing neutron scatter cameras that rely on accurate time-of-flight measurements for imaging and spectroscopy. Later work with a prototype eight-barred stilbene detector using SiPMs showed plutonium sources could be accurately localized with as few as 20 back-projected cones.[27]

More recent proposals have sought to make the NSC more compact by confining both neutron scatters to a single scintillation volume rather than spatially separated volumes. Chief among these proposals is the work done by the Single Volume Scatter Camera Collaboration, an alliance of several National Laboratories and universities.[28] This collaboration has produced prototype compact detectors using both monolithic and optically segmented concepts. In the monolithic design, light is emitted by scattering events in a single scintillator volume. The timing and arrival positions of light to a series of photodetectors mounted to the scintillator surface is used to reconstruct the original neutron direction and energy. In the optically segmented design, light is confined to pillars which in turn are coupled to individual photodetectors. Weinfurther et al. performed simulations on an optically segmented detector consisting of a 20 x 20 x 20 cm block of optically segmented pillars with a fast timing response coupled to either SiPM or Micro-Channel Plate Photomultipliers (MCP-PM). Both neutron scatters occur in the single plastic volume, but the scintillation light produced at each scatter location is confined to a single 1 cm x 1 cm column by total internal reflection. The x and y coordinates of each scatter are determined by the geometry of photodetectors coupled to each column that "see" scintillation light, while the z coordinate is found by comparing the intensity of light pulses collected at opposite ends of each column. The MCNP-PoliMi (for neutron transport) and GEANT4 simulation (for light transport) of this detector showed a root mean square error of the neutron-proton scattering position of <1 cm and an energy deposition error of <50 keV when proton recoils were confined to 1 MeV or greater. These low errors suggest a single volume scatter camera such as this one can still provide satisfactory imaging resolution while also increasing double-scatter efficiency, though due to the idealized nature of simulations actual results from such a detector are not expected to be so precise. The timing resolution of photodetectors and electronics also play a role in image quality, and such effects are not considered here.

Another detector that could potentially be used for directional neutron detection is the Segmented AntiNeutrino Directional Detector[29] (SANDD), which uses an 8 x 8 array of plastic scintillators coupled to 5 x 5 cm 64 channel SiPM arrays. The operational principle for this detector is very similar to the optically segmented Single Volume Scatter Camera. The SANDD system has recently demonstrated pulse-shape discrimination capabilities for distinguishing neutrons and gammas, lending credence to its usefulness as a directional neutron detector in addition to its primary use as an antineutrino detector.

Another proposal for a single volume scatter camera relying on a monolithic scintillator volume is the miniTimeCube, which has primarily been used as an antineutrino detector.[30] This design uses 24 MCP-PMs coupled to each of the six sides of a 13 x 13 x 13 cm cube of boron-doped plastic scintillator. The ratios of light arriving at the 1536 channels are used to localize the position of consecutive scatters. Consecutive scatters are resolved in time by using a plastic scintillator with a fast light pulse response and fast timing electronics. Geant4 and a MATLAB Monte Carlo algorithm were used to determine that this design could yield errors in scatter position of 5 mm and timing errors of 100 ps, though again this does not account for uncertainties in the timing of the photodetectors and electronics.

NSC designs that rely on many electronic readout channels can lead to more compact detectors, but these detectors can become prohibitively expensive and complex. One solution to reduce cost and digital pulse data produced is the use of signal multiplexing, in which the pulses from several readout channels are digitized into a single channel for analysis. Wonders and Flaska have demonstrated that an imaging array of 64 plastic scintillator coupled to SiPMs can be multiplexed into 8 or 16 digital channels at the expense of losing some meaningful events.[31] Despite the reduction in double scatter detection efficiency because of this, multiplexing could prove a useful tool in reducing the digitization equipment needed for an affordable and mobile system.

The existing and proposed neutron scatter camera designs surveyed here present a variety of capabilities in double-scatter efficiency, imaging resolution, neutron versus gamma discrimination effectiveness, portability, and cost. It is difficult to construct an NSC with good values for all these characteristics, as improving some have negative consequences for others. For example, the double-scatter efficiency of a detector can be improved by increasing the size or number of scintillation volumes, but doing this will require a larger and heavier detection system, thus decreasing portability and increasing cost. Similarly, increasing the average time of flight between consecutive scatters will lead to more accurate measurements of energy deposition, thus improving the imaging resolution, but only at the expense of a lower overall detection efficiency and longer measurement times.

Implementation in Nuclear Safeguards and Non-Proliferation Scenarios

Most of the research into neutron scatter cameras and similar directional fast neutron imaging systems has focused on the technical capabilities of such systems, with the actual usefulness and versatility mentioned mostly as an afterthought. The goal of this section is to identify scenarios where the use of neutron scatter cameras or similar systems capable of neutron source localization and imaging may be useful, particularly in the realm of nuclear materials safeguards and non-proliferation. A list of possible measurement scenarios follows, with a brief speculative description of how an NSC system could be used in each scenario.

1. Neutron Source Localization in Limited Search Scenarios

Radiation portal monitors are large-volume detectors designed to detect radioactive sources passing through chokepoints along roads, railroad lines, or pedestrian walkways. These detectors may also be put in place at the entrances of nuclear facilities, at international borders, or other areas where the illicit transport of nuclear material may be a concern.[32] The high sensitivities of these detectors make them excellent at detecting the presence of both neutron and gamma-emitting radioactive sources hidden in large vehicles or shipping containers. If a portal monitor were to identify the presence of an unexpected source in a vehicle, container, or other object moving through the portal, a limited search would be needed to identify and secure the source. Checking a large vehicle or shipping container “blind” could be both hazardous and inefficient for searchers, so having some prior knowledge about the exact location of the source within the larger container would be desirable. Imaging radiation detectors, like Compton or neutron scatter cameras, could be used to pinpoint compact sources within large containers. Neutron imagers may be of special interest as neutrons are far more penetrating in shipping containers due to the presence of high-Z materials, which shield gamma rays. Several of the systems discussed above have already been employed to this end in mock search scenarios for locating neutron sources, most notably the MINER system. That system was also able to distinguish between ^{252}Cf and AmBe sources and localize those sources at a standoff distance of 28 m.

In limited search scenarios of containers or vehicles, measurement times of 30 minutes may be unacceptably long in urgent situations. Measurement times with an NSC system could be reduced by adaptably changing the location of the NSC as measurements go on. A brief measurement with an NSC or other portable radiation detector could be used first to establish the general direction of the source, whether it be on the left, right, or center of a shipping container, for example. Next, the NSC could be moved closer to the area of interest with the goal of pinpointing the position of the source inside the container without going inside of it. The neutron image generated from a few minutes of measurement time could be coupled with an infrared, gamma or x-ray radiographic image[33,34] of the container to ascertain the source location and distribution along with the internal components of the area of interest. Knowing the general location of the source and the internal components surrounding it in advance would then make the task of retrieving and securing the source safer and more effective for the search team.

2. Verification of Nuclear Warheads

Counting nuclear warheads is a vital component of the New START treaty[35] between the United States and Russian Federation, which limits the number of warheads that can be present on intercontinental ballistic missiles (ICBMs) and submarine-launched ballistic missiles (SLBMs). The possibility of using an NSC to verify the presence of nuclear weapon warheads has been explored by Brennan et al.[23] The use of NSCs to this end is particularly interesting because a neutron imager with suitable angular resolution could identify the number of warheads present in a reentry vehicle without revealing classified, proprietary, or other sensitive information about the specific design of the weapons, information that could be revealed when using gamma detection methods. Utilizing an NSC without utilizing gamma spectroscopic abilities can act as an information barrier,[36] a method that can verify the presence and number of warheads without giving away classified or proprietary information. NSC systems could be integrated into the existing framework of arms control verification that already utilizes neutron multiplicity counting and high-purity germanium detectors. Parties subject to an arms control treaty must mutually agree that such imaging neutron systems as NSCs are not too intrusive but still provide information valuable to treaty inspectors.

As a technical consideration, NSCs may be desirable in the measurement of warheads because neutrons have a better chance of fully penetrating the high-Z structural materials present in reentry vehicles containing the missile-mounted warheads. By applying MLEM, Brennan et al. have shown promising results in resolving individual sources, even at stand-off distances realistic to treaty-enforced verification.

3. Verifying the Presence and Movement of Nuclear Material in Inspection Scenarios

Nuclear facility inspectors, such as those employed by the International Atomic Energy Agency (IAEA), are tasked with performing regular and special inspections of nuclear facilities to confirm proper use of materials and technologies.[37] Such inspections generally involve the verification of declared quantities of nuclear material, with a focus on fissionable, fissile, and fertile isotopes due to their significance in nuclear proliferation. Inventories are usually verified by visual inspection (counting of materials) and by measurement using several non-destructive assay (NDA) techniques, including using radiation detectors. Because of the time constraints placed on inspectors, it is often impossible to verify each inventory item separately, so typically a random sample of material is selected for analysis by NDA. When dealing with neutron-active materials in such an inspection situation, the employment of an NSC could be useful in completely verifying an inventory. Say, for example, an inspector wished to verify that a waste storage room contains 30 drums containing plutonium. Standard protocol would call for the random selection of several of these barrels for individual analysis, with the hope that these will be a representative sample of the waste. Instead of employing this approach, an NSC could be set up in this room and left to measure while the inspectors continued to inspect the rest of the facility. The neutron image generated at the end of a sufficient measurement period could then be cross referenced against the declarations made of the plutonium content of each of the drums to discover any irregularities in the declared quantities based on the image, which could indicate a diversion of material.

Inspectors may also find that their access to certain parts of a facility is restricted by the personnel of the host facility for safety-related or other reasons. NSCs or other imaging detectors could then be used to confirm the presence of sources from a distance, without the need to enter an inaccessible area. Neutron images would not need to stand on their own in inspection scenarios: data collected from visual cameras, count rate data, and specifics about facilities would need to be coupled with the neutron images for inspectors to draw useful conclusions about the nuclear material subject to inspection.

4. Wide-area Search in Accident or Lost Source Scenarios

A portable NSC system could also be of use in a wide-area search for lost sources or in mapping the distribution of widely dispersed sources from an accident or attack. The IAEA has published guidelines[38] aimed at providing inspection for search of lost radioactive sources, indicating that there is some need for devices that can grant the searchers some footing in such scenarios. If a neutron source was lost within a nuclear facility, NSC measurements at several points in the facility could help searchers narrow down search areas by comparing the 4π images generated at different points in the facility. Neutron sources could also be spread over a large area in nuclear reactor or in nuclear material shipping accidents. A neutron image produced by an NSC system could be useful when coupled with visual identification and more traditional radiation detectors for the radiological response team tasked with securing the sources in such an accident scenario. NSC measurements need not be taken at a single fixed point; neutron imaging in the field could be adaptive. A short initial measurement near the center of the identified search area could show which radial directions are most “neutron hot.” Next, the NSC could be moved in the direction of an area of interest identified by the initial measurement and another short measurement could be taken to further zero in on any sealed sources or areas of contamination. The iterative process of measurement-move-measurement could be done across a wide search area as many times as necessary to locate any and all nuclear material in the accident area.

5. Mapping Neutron Source Contamination in an Enclosed Space

An NSC could be used to map the distribution of a diffuse neutron source that has contaminated a room or other enclosed space at a nuclear facility. Typically, the distribution of contamination in a room or enclosed space must be mapped by moving a radiation detector throughout a room and recording the relative count rate at different locations. This process is problematic because it unnecessarily exposes the operator of said detector to possible high dose rates and could lead to the spread of contamination. To reduce exposure time in contaminated areas, an NSC or other imaging device could be set up in an area of interest and left to measure for an appropriate counting time, as it would not require an operator to move the system around. The 4π neutron image produced could be coupled with a 4π 3-D image of the room in question to surmise the relative levels of contamination throughout the room. In 2014, Kishomoto et al.[39] demonstrated a novel Compton camera capable of identifying gamma source hotspots in contaminated zones, lending credence to the analogous use of an NSC or dual particle system in a similar way to identify zones of neutron source contamination.

6. Monitoring of Diversion of Nuclear Fuel

A large effort in nuclear safeguards focuses on securing and analyzing spent nuclear fuel, as fuel contains large amounts of material that is of concern for nuclear proliferation. Cherenkov cameras,[40] passive neutron/gamma detectors,[41] muon tomography,[42] and guide-tube-based partial defect detectors[43] have all been employed to check for fuel pin diversion for spent fuel residing in pools. Measuring fuel using these methods may not be applicable in all cases, as some require fuel to be placed in accessible positions, require clear water, or may not function properly after long cooling times. Neutron emission tomography has also shown promise for detecting missing pins, though this method requires access to the ends of the fuel assemblies and requires collimation of individual pins.[44] An NSC could function in much the same way as currently existing neutron tomography systems, though it would not necessarily require neutron collimation or even be next to the assembly, given enough measurement time. Both axial and radial neutron images of a measured assembly could be generated to check for diversion of entire rods or individual pellets along the length of the assembly. Generating images detailed enough to make determinations about fuel diversion would require long measurement times, on the order of hours or days, depending on the fuel’s activity and the distance from NSC to fuel, so this method would likely not be appropriate in a time-constrained measurement situation. Additionally, performing this type of measurement would work best with a large NSC system with widely separated detector volumes to ensure proper angular image resolution, which in turn will make the system less portable. This reality makes a case for there being no one-size-fits-all NSC system: applications such as fuel assays require high resolution, while search applications favor a mobile system with shorter measurement times.

7. External Imaging of Reactor Cores

Knowledge of the neutron distribution within a nuclear reactor core is vital in ensuring the safe operation in standard and accident scenarios. Normally, in-core neutron monitors relay information about neutron distribution to reactor operators, though these systems may be damaged in accidents, making operators “blind” to the full situation inside a core. Beaumont et al. have presented a method of monitoring the neutron and gamma distribution inside a reactor core externally using a scintillator equipped with a moving slit collimator capable of determining the particle distribution in space.[45] An NSC system could potentially be used to these same ends, as a reactor could be imaged using fast neutrons escaping from the core and moderator by using double-scatter back projection. It is unknown how long the measurement time for imaging an entire reactor core with an NSC system would be when compared to the slit-collimated method discussed by Beaumont et al, but a Monte Carlo simulation of a small research or test reactor and neutron scatter camera could be done to gauge if experimental measurements are worthwhile. An external neutron image of a reactor core could be useful to reactor operators if data from in-core instruments are temporarily unavailable, or in reactor designs lacking internal instruments.

8. Neutron Image Matching in Shipping/Receiving and Facility Management

An NSC, like any imaging system, can provide a “snapshot” of how the radiation distribution for a particle source or location “looked” at a particular moment in time. When producing a neutron or gamma image of a source distribution, it is vital to also record factors such as the location of the detector system relative to the source being measured, the source’s position in the room being analyzed, the measurement time, and the various energy threshold and neutron/gamma discrimination settings. A radiation image, along with this set of information about its production, could be of use in detecting diversion of nuclear material during shipping or between two inspection times at a facility by a system of image matching. For example, a source or set of sources could be imaged by an NSC upon being loaded into a truck for transport, with special attention paid to the position of the NSC relative to the source or sources and the measurement time. Following transport and the arrival at a new nuclear facility, another image could be generated with the same measurement parameters. The before-shipping and after-shipping images could be visually or algorithmically compared to detect any diversion of material during the transit process. Before-and-after comparison of shipments of nuclear material are already performed, though these processes often focus on visual inspection and mass comparisons, which could be spoofed.[46] This image matching technique would naturally need to be implemented in tandem with visual and mass-based inspection of shipped materials as a sort of “triple check” for radioactive material, along with tamper-indicating seals on vehicle and facility doors. Implementing such a system would require both the shipper and the receiver to operate identical or near-identical NSC systems and measure the source or sources with the exact same parameters to ensure that the pre- and post-shipment images will indeed match when they should.

In analogy to shipper-receiver image matching, a similar system could be implemented to verify inventories within a single nuclear facility. When taking inventory of nuclear materials, facility material managers could also take a neutron image of the room or rooms where the radioactive material is stored. This image, along with the relevant parameters concerning its acquisition, could be saved along with more typical inventory data such as the number, identity, volume, mass, and activity of sources present. Having such a radioactive “snapshot” of a collection of sources at particular moment could be useful for nuclear material managers in maintaining a continuity of knowledge about sources and their arrangement, which could be useful as a historical record to consult in the event of an instance of material unaccounted for.

Strength and Shortcomings of Neutron Scatter Cameras When Compared to Alternative Systems

Neutron scatter cameras are not the only type of directional radiation detector that could be of use in safeguards scenarios. Neutron or gamma-coded aperture systems, Compton scatter cameras, and time projection chambers can also be used to gain information about the spatial distribution of radiation sources of interest. Additionally, suites of spatially-separated detectors and iteratively moved non-directional detectors have long been used to map source distributions in safeguards contexts. Fully evaluating NSCs for use in safeguards must also account for these alternative methods of source localization and imaging.

Several neutron-detecting coded aperture systems have been applied to nuclear safeguards and security applications.[9,47,48,49,50.51,52] Coded aperture systems image sources by using a mask featuring a known pattern placed in front of a detector. In neutron coded aperture systems, the mask can be made a neutron absorbing shield or can be another detector. The “shadows” of neutrons that pass through the mask to the detector can be convolved to form an image of the radiation source, providing both direction and distance information about the source. Gas detectors and liquid and plastics scintillators have been used as the detectors in various neutron coded aperture systems. In general, neutron coded aperture systems demonstrate superior imaging resolution when compared to neutron scatter cameras, typically <5°. This excellent imaging resolution makes coded aperture systems desirable in situations when multiple nearby sources are present, when the source location needs to be known to a precise degree, or when the radial distance to sources is relevant. Coded aperture systems require longer exposure time to neutron sources to generate images when compared to NSCs. It is also more difficult to gain real-time imaging results from coded aperture systems because of the high amount of data processing needed for image convolution when compared to the event by event back projection used by NSCs. The large size of several[9,47,48,50] of the neutron coded aperture systems makes application where system mobility is a concern challenging, though several more compact and transportable time-encoded systems have been demonstrated.[50,52]

Compton scatter cameras and gamma coded aperture systems have wide applications in the field on nuclear safeguards because of their high accuracy and efficiency in localizing gamma sources and the portable size of several designs.[5,24,53-55] Gamma imagers can provide accurate images of spatial gamma source distribution within minutes, making them useful in a variety of safeguards settings. The main drawbacks of using gamma imagers are mostly due to the nature of gamma ray's measurement environments rather than the systems themselves: the natural gamma ray background is much higher than the neutron background and gammas are less penetrating than neutrons for most intervening materials. Gamma spectroscopic capabilities provided by such imagers can also be detrimental in safeguard scenarios where gamma spectra can reveal classified or proprietary information about source or weapon design.

Time projection chambers have also been shown to be capable of directional neutron measurement by tracking ionization paths created by fast neutrons traveling in a gas.[10] Though this type of design is not as well-researched as NSC or coded aperture systems for directional neutron measurements, results from Bowden et al. suggest that such system may provide comparable resolution and sensitivity results to NSCs.

Non-directional neutron and gamma detectors can also be used to gain spatial information about source distribution in safeguards scenarios. Portable, non-imager detectors can be iteratively moved by individuals[38] or unmanned vehicles[55] to map the radiation field of an area. Arrays of radiation sensors can also be used to passively monitor source distribution and movement through facilties.[56] These methods do not provide data equivalent to that of true imaging systems and are in many cases limited by the physical accessibility of sources, but data from these methods can be valuable when paired with directional radiation and other spatial data.

When compared to these other directional detection methods for safeguards applications, NSCs feature a unique set of strengths and shortcomings. They are summarized as follows:

Strengths

- Can construct neutron images using individual particle scattering events rather than a flux: only 10s of acceptable counts are needed for a general indication of source direction
- Statistical uncertainty can be calculated for each event based on energy deposition and time of flight uncertainty
- Low cost when compared to other options: plastic and liquid scintillators are typically inexpensive when compared to He-3 gas or semiconductor-based detectors
  - Cost can be increased if compact NSC use more expensive electronics like SiPMs or MCPs rather than standard PMTs
- NSC systems have been made transportable, with some prototype systems approaching handheld size
- Sensitive to wide energy range of fast neutrons; no moderator needed to slow neutrons
- NSC systems can be made into dual particle imagers, sensitive to both neutrons and gammas, by using the appropriate scintillator materials
- Because of the low amount of data processing needed per scattering event, real-time image back projection is possible

Shortcomings

- Poor energy resolution of organic scintillators leads to uncertainties in cone overlap
  - Poor spatial imaging resolution when compared to Compton scatter cameras and coded aperture systems
  - Trouble with situations featuring multiple, close together sources
- Poor energy resolution leads to poor spectroscopic capabilities compared to semiconductor detectors and other detectors with better energy resolution
- Cannot gauge radial distance to source without moving the camera
- Some NSC designs may use scintillators without strong pulse shape discrimination capabilities and must rely on time of flight to short pulses into neutrons or gammas, leading to some particle misclassification

- In some cases, localization of a source in a search scenario can be performed faster by adaptively moving a non-imaging detector in the direction of greater count rate

The information in Table 1 provides some estimates for the expected measurement range, target measurement time, target spatial imaging resolution, and alternative methods that can approximate each of the safeguards scenarios discussed in the section, "Implementation in Nuclear Safeguards and Non-Proliferation Scenarios." The target measurement times and resolutions are estimates based on both the demonstrated efficiency and imaging resolution of the systems surveyed above and the needs for each scenario. In general, source search applications require systems with higher efficiency and lower resolution, whereas scenarios that involve determining the absence or presence of one source among many emitters require better resolution.

Table 1. Neutron Scatter Camera Characteristics for Safeguards Scenarios

Safeguards Scenario	Typical Measurement Distance Range [m]	Target Measurement Time	Target Resolution	Alternative Methods for Achieving Similar Goal
Neutron source localization in limited search scenarios	1 to 30	<2 minutes before each iterative movement of system, <5 minutes for more detailed neutron image once source is localized	<30°	Iteratively moving non-imaging neutron detector, Compton camera, transportable coded aperture
Verifying nuclear warheads	~1	<1 hour	<5°	Coded aperture system
Verifying the presence and movement of nuclear material in inspection scenarios	1 to 5	<10 minutes	<5°	Coded aperture system, Compton camera
Wide-area search in accident or lost source scenarios	highly variable	<30 seconds before each iterative movement of system	<45°	Handheld Compton camera, handheld or unmanned vehicle-mounted non-imaging detector
Mapping neutron source contamination in an enclosed space	0.1 to 10	<1 hour	<10°	Coded aperture, Compton camera
Monitoring of diversion of nuclear fuel	1 to 10	<1 hour	<5°	Coded aperture, Compton camera, count rate matching with non-imaging detector
External imaging of reactor cores	2 to 10	<24 hours	<10°	Coded aperture, Compton camera
Neutron image matching in shipping/receiving and facility management	0.1 to 2	<5 minutes	<5°	Coded aperture, Compton camera, count rate matching with non-imaging detector

Conclusion and Proposals for Future Work

The measurement scenarios described here are proposals for where the emerging technology may prove useful, though it is important to note that the practicality of many of these proposed scenarios has not been experimentally explored by existing technology. Laboratory experiments that approximate standoff detection similar to a limited search scenario and monitoring of nuclear warheads have demonstrated promising results in the practical application of already-existing designs to scenarios one and two. The application of NSC systems to the remaining six scenarios are yet to be explored with simulation or experiment and may be fertile ground for future work for teams researching directional neutron detection systems.

Implicitly throughout this paper it has been assumed that all measurement with the NSC systems discussed are passive neutron measurements: that is, they detect and image sources with significant spontaneous fission or (α,n) rates. Relying only on passive neutron measurements would preclude the detection and localization of nuclear material with lower passive neutron rates, such as uranium sources, which would require active neutron interrogation to properly image. An NSC system could indeed be coupled with an active interrogation source, though no example of such a system has yet been reported in the literature. Additionally, active interrogation is not a viable method for source localization or imaging if the location of the source is unknown, such as in search scenarios. Still, imaging an induced fission source like a drum of uranium at close range with an active integrating NSC could be possible, though the usefulness of such a setup is questionable.

A clear concern when surveying NSC measurement scenarios is the inherent tradeoff between imaging resolution and detection efficiency. Small, compact detectors are more portable and have a higher double scatter efficiency, while large, less mobile detectors can provide better resolved images with fewer total counts. This reality suggests that a "one-size-fits-all" NSC design applicable to all measurement scenarios may not be desirable. Wide- and limited-area searches, as described in scenarios one and four would naturally require a portable or at least transportable system, preferably one that could be moved and set up by a single person or a small vehicle. Systems for these applications would also benefit from a wide-field of view, making radially arranged designs, like the MINER/Compact Neutron Scatter Camera, or single volume designs–like the Single Volume Scatter Camera, the miniTimeCube System, or the handheld stilbene camera–most practical for applications in which the detector is moved for a series of consecutive measurements. Larger detector systems consisting of planar arrays of detectors–like the original Neutron Scatter Camera and the Dual Particle Imager system–could still prove useful in scenarios where frequent transport of the detector system is not a concern, such as measuring inventories in nuclear facilities, externally imaging reactor cores, or producing images for shipper-receiver records.

As electronic pulse timing becomes better time-resolved and new scintillation materials are developed, the technical capabilities of neutron imaging systems may further improve, making the practicality of the measurement scenarios explored here increasingly more relevant to those working in the field of nuclear safeguards and non-proliferation. Current scatter camera technology has shown promising results in localizing and identifying neutron sources, though more experimental studies and Monte Carlo simulations should be performed to verify the feasibility of the measurement scenarios outlined in this paper.

Keywords

Neutron scatter camera, neutron imaging, nuclear safeguards, detection applications, image matching, source search

References

1. International Atomic Energy Agency. Basics of IAEA Safeguards, available at: www.iaea.org/topics/basics-of-iaea-safeguards. Accessed June 7, 2019.
2. United States Nuclear Regulatory Commission. Special Nuclear Material, available at: www.nrc.gov/materials/sp-nucmaterials.html. Accessed June 7, 2019.
3. Runkle RC, Bernstein A, Vanier PE. 2010. Securing Special Nuclear Material: Recent Advances in Neutron Detection and Their Role in Nonproliferation. *Journal of Applied Physics,* Vol. 108, N. 11, 11101. doi.org/10.1063/1.3503495.
4. Kouzes RT, Lintereur AT, Siciliano ER. 2015. Progress in Alternative Neutron Detection to Address the Helium-3 Shortage. *Nuclear Instruments and Methods in Physics Research*, Vol. 784, pp. 172-175. doi:10.1016/j.nima.2014.10.046.
5. Xu D, He Z, Lehner CE, Zhang F. 2004. 4-pi Compton Imaging with Single 3D Position Sensitive CdZnTe Detector. *Proc. SPIE 5540, Hard X-Ray and Gamma-Ray Detector Physics VI.* doi.org/10.1117/12.563905.
6. Mascarenhas N, Brennan J, Krenz K, et al. 2006. Development of a Neutron Scatter Camera for Fission Neutrons. *2006 IEEE Nuclear Science Symposium Conference Record.*
7. Goldsmith JE, Gerling MD, Brennan JS. 2016. A Compact Neutron Scatter Camera for Field Deployment. *Review of Scientific Instruments,* Vol.87, 083307. doi.org/10.1063/1.4961111.
8. Weinfurther K, Mattingly J, Brubaker E, Steele J. 2018. Model-Based Design Evaluation of a Compact, High-Efficiency Neutron Scatter Camera. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* Vol. 883, pp. 115-135.
9. Marleau P, Brennan J, Brubaker E, Steele J. 2010. Results from the Coded Aperture Neutron Imaging System. *IEEE Nuclear Science Symposuim & Medical Imaging Conference.*
10. Bowden NS, Heffner M, Carosi G, et al. 2010. Directional Fast Neutron Detection Using a Time Projection Chamber. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* Vol. 624, pp. 153-161.
11. Brennan, J, Cooper R, Gerling M, et al. 2010. Results with a 32-Element Dual Mode Imager. *IEEE Nuclear Science Symposuim & Medical Imaging Conference.*

12. Gerling MD, Goldsmith JE, Brennan JS. 2014. MINER–a Mobile Imager of Neutrons for Emergency Responders. 2014. *IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC).*
13. Ruch ML, Nguyen J, Flaska M, Pozzi, SA. 2015. Time Resolution of Stilbene Coupled to Silicon Photomultipliers for Use in a Handheld Dual Particle Scatter Camera. *IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC).*
14. Grannan RT, Koga R, Millard WA, et al. 1972. A Large Area Detector for Neutrons Between 2 and 100 MeV. *Nuclear Instruments and Methods,* Vol. 103, pp. 99-108.
15. Herzo D, Koga R, Millard WA, et al. 1975. A Large Double Scatter Telescope for Gamma Rays and Neutrons. *Nuclear Instruments and Methods,* Vol. 123, pp. 583-597.
16. Sailor WC, Byrd RC, Gavron R, Hammock R, Yariv Y. 1992. A Neutron Source Imaging Detector for Nuclear Arms Treaty Verification. *Nuclear Science and Engineering,* Vol. 109, No.3, pp. 267-277.
17. Miller RS, Macri JR, McConnell ML, et al .2003. SONTRAC: An Imaging Spectrometer for MeV Neutrons. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* Vol. 505, pp. 36-40.
18. Bravar U, Bruillard PJ, Flckiger EO, et al. 2006. Design and Testing of a Position-Sensitive Plastic Scintillator Detector for Fast Neutron Imaging. *IEEE Transactions on Nuclear Science,* Vol. 53, pp. 894-3903.
19. Macri JR, Bravar U, Legere JS, et al. 2007. The Fast Neutron Imaging Telescope (FNIT)-Hardware Development and Prototype Testing. 2007. *IEEE Nuclear Science Symposium Conference Record.*
20. Vanier PE, Forman L. 2005. Demonstration of a Directional Fast Neutron Detector. 2005. *IEEE Nuclear Science Symposium Conference Record.*
21. Marleau P, Brennan J, Krenz K, Mascarenhas N, Mrowka, S. 2007. Advances in Imaging Fission Neutrons with a Neutron Scatter Camera. 2007. *IEEE Nuclear Science Symposium Conference Record*.
22. Mascarenhas N, Brennan J, Krenz K, Marleau P, Mrowka S. 2009. Results with the Neutron Scatter Camera, *IEEE Transactions on Nuclear Science*, Vol. 56, pp. 1269-1273.
23. Brennan J, Cooper R, Gerling M, Marleau P, Mascarenhas N, Mrowka S. 2010. Applying the Neutron Scatter Camera to Treaty Verification and Warhead Monitoring. *IEEE Nuclear Science Symposuim & Medical Imaging Conference.*
24. Polack JK, Poitrasson-Riviere A, Hamel MC, et al. 2011. Dual-Particle Imager for Standoff Detection of Special Nuclear Material. 2011. *IEEE Nuclear Science Symposium Conference Record.*
25. Poitrasson-Rivière A, Hamel MC, Polack JK, et al. 2014. Dual-Particle Imaging System Based on Simultaneous Detection of Photon and Neutron Collision Events. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* Vol. 760, pp. 40-45.
26. Poitrasson-Rivière A, Polack JK, Hamel MC, et al. 2015. Angular-Resolution and Material-Characterization Measurements for a Dual-Particle Imaging System with mixed-Oxide Fuel. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* Vol. 797, pp. 278-284.
27. Steinberger WM, Ruch ML, Giha N, et al. 2020. Imaging Special Nuclear Material Using a Handheld Dual Particle Imager. *Scientific Reports,* Vol. 10, 1855.
28. Brown J. 2018. Single Volume Scatter Camera: Development Towards a Compact Neutron Imager. *Applied Antineutrino Physics 2018 Workshop*.
29. Li VA, Classen TM, Dazeley SA, et al. 2019. A prototype for SANDD: A Highly-Segmented Pulses-Shape-Sensitive Plastic Scintillator Incorporating Silicon Photomultiplier Arrays. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 942*.
30. Jocher GR, Koblanski J, Li VA, et al. 2019. MiniTimeCube as a Neutron Scatter Camera, *AIP Advances,* Vol 9, Issue 3, 035301. doi.org/10.1063/1.5079429.
31. Wonders MA, Flaska M. 2019. Simulation and Optimization of a Neutron Scatter Imager Based on Silicon Photomultipliers and Signal Multiplexing, *Proceedings of the 2019 INMM Annual Meeting*.
32. Kouzes RT, Siciliano ER, Ely JH, Keller PE, McConn RJ. 2008. Passive Neutron Detection for Interdiction of Nuclear Material at Borders. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* Vol. 584, Nos. 2-3, pp. 383-400.
33. Bendahan J. 2017. Vehicle and Cargo Scanning for Contraband, *Physics Procedia*, Vol. 90, pp. 242-255.
34. Orphan VJ, Muenchau E, Gormley J, Richardson R. 2005. *Applied Radiation and Isotopes*, Vol. 63, Nos. 5-6, pp. 723-732.
35. Arms Control Association. New START at a Glance, available at: www.armscontrol.org/factsheets/NewSTART. Accessed July 5, 2019.
36. Bachner K, Verdugo D. 2013. Information Filters for Safeguards Applications: A Scoping Study, Brookhaven National Laboratory Manuscript, available at: https://www.bnl.gov/isd/documents/81688.pdf. Accessed July 5, 2019.
37. International Atomic Energy Agency. IAEA Safeguards Overview: Comprehensive Safeguards Agreements and Additional Protocols, available at: www.iaea.org/publications/factsheets/iaea-safeguards-overview. Accessed July 5, 2019.
38. Methods to Identify and Locate Spent Radiation Sources: IAEA Technical Document 804, available at: https://www-pub.iaea.org/MTCD/publications/PDF/te_804_prn.pdf. Accessed July 5, 2019.
39. Kishomoto A, Kataoka J, Nishiyama T, et al. 2014. *Performance and Field Tests of a Handheld Compton Camera Using 3-D Position-Sensitive Scintillators Coupled to Multi-Pixel Photon Counter Arrays*. *Journal of Instrumentation*, Vol. 9, Issue 11, P11025.

40. Attas EM, Chen JD, Young GJ. 1990. A Cherenkov Viewing Device for Used-Fuel Verification. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors, and Associated Equipment*, Vol. 299, Nos. 1-3, pp. 88-93.
41. Willman C, Håkansson A, Osifo O, Bäcklin A, Svärd SJ. 2006. Nondestructive Assay of Spent Nuclear Fuel with Gamma-Ray Spectroscopy. *Annals of Nuclear Energy*, Vol. 33, No. 5, pp. 427-438.
42. Jonkmans G, Angel VNP, Jewett C, Thompson M. 2013. Nuclear Waste Imaging and Spent Fuel Verification by Muon Tomography. *Annals of Nuclear Energy*, Vol. 53 pp. 267-272.
43. Ham YS, Sitaraman S. 2011. Partial Defect Tester: A Novel Approach to Detect Partial Defects in Pressurized Water Reactor Spent Fuel. *Nuclear Technology*, Vol. 175, No. 2 pp. 401-418.
44. Hausladen, PA, Blackston MA, Brubaker E, Chichester DL, Marleau P, Newby RJ. 2012. Demonstration of Emitted-Neutron Computed Tomography to Count Fuel Pins. *Proceedings of the 53rd Annual INMM Meeting*.
45. Beaumont JS, Mellor MP, Villa M, Joyce MJ. 2015. High-Intensity Power-Resolved Radiation Imaging of an Operational Nuclear Reactor. *Nature Communications*, Vol. 6, 8592.
46. Lovett JE. 1974. *Nuclear Materials: Accountability, Management, Safeguards*, American Nuclear Society, Hinsdale, IL, USA.
47. Gottesman, SR. 2007. Coded Apertures: Past, Present, and Future Application and Design. *Adaptive Coded Aperture Imaging and Non-Imaging Sensors*. 671405. doi: 10.1117/12.735494.
48. Woolf RS, Phlips BF, Hutcheson AL, Wulf EA. 2015. Fast-Neutron Coded-Aperture Imager. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors, and Associated Equipment*, Vol. 784, pp. 398-404.
49. Hausladen P, Newby J, Liang F, Blackston M. September 2013. The Deployable Fast-Neutron Coded-Aperture Imager: Demonstration of Locating One or More Sources in Three Dimensions. Oak Ridge National Laboratory, Oak Ridge, TN, USA, TM-2013/446.
50. Brennan E, Brubaker E, Gerling M, et al. 2015. Demonstration of Two-Dimensional Time-Encoded Imaging of Fast Neutrons. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors, and Associated Equipment*, Vol 802, pp. 76-81.
51. Griffith CV, Woolf RS, Philips BF. 2017. 64-Element Fast-Neutron, Coded-Aperture Imager. *2017 IEEE International Symposium on Technologies for Homeland Security.*
52. Liang X, Pang X, Cao D, et al. 2020. Self-Supporting Design of a Time-Encoded Aperture, Gamma-Neutron Imaging System. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, Vol. 951, 162964.
53. Park JH, Kim YS, Kim CH, Seo H, Park SH, Kim HD. 2014. Development of a Compton Camera for Safeguards Applications in a Pyroprocessing Facility. *Journal of the Korean Physical Society*, Vol. 65, No. 9, pp. 1360–1366.
54. Kim YS, Kim JH, Lee J, Kim CH. 2018. Large-Area Compton Camera for High-Speed and 3-D Imaging. *IEEE Transactions on Nuclear Science*, Vol. 65, No. 11, pp. 2817–2822.
55. Pavlovsky R, Haefner A, Joshi T, et al. 2018. 3-D Radiation Mapping in Real-Time with the Localization and Mapping Platform LAMP from Unmanned Aerial Systems and Man-Portable Configurations, available at: https://arxiv.org/abs/1901.05038. Accessed March 25, 2020.
56. Gomaa R, Adly I, Sharshar K, Safwat A, Ragai H. 2013. ZigBee Wireless Sensor Network for Radiation Monitoring at Nuclear Facilities. *6th Joint IFIP Wireless and Mobile Networking Co.*

Taylor Harvey is a third-year nuclear engineering PhD candidate and research assistant at the University of Florida, where he works in the group of Dr. Andreas Enqvist. He holds a bachelor's degree in Nuclear Engineering from the University of Florida. He has completed internships in nuclear non-proliferation and safeguards at Los Alamos National Laboratory in 2017 and Brookhaven National Laboratory in 2019. His research interests include neutron imaging systems, pulse shape discrimination techniques, scintillator characterization, and neutron multiplicity counting. Taylor is a member of the student chapters of INMM and ANS at the University of Florida. His author contact information is:

Email: taylor.harvey250@ufl.edu
Mailing address: 1698 Gale Lemerand Dr, Gainesville, FL, USA
Telephone: (850) 933-3937

Katherine Bachner is the group leader for the Nonproliferation Policy and Implementation Group at Brookhaven National Laboratory's Nonproliferation and National Security Department. Prior to her time at BNL, Katherine was based at the U.S. Department of Energy/National Nuclear Security Administration, supporting nuclear security efforts in Russia and the former Soviet Union. Prior to that time, she worked at the United Nations Office of Disarmament Affairs in both Geneva and New York. Katherine has graduate degrees in international policy from the Monterey Institute of International Studies, in cultural anthropology from Columbia University, and in nuclear engineering from Penn State University. Katherine has lived and studied in Switzerland, India, Madagascar, Mexico, and Russia. Katherine is the INMM Northeast Chapter President, and the Long Island ANS Chapter President.

Andreas Enqvist is a Florida Power & Light Associate Professor in the Nuclear Engineering program in the Department of Materials Science and Engineering, and the Director of the Nuclear Engineering program at the University of Florida in Gainesville, FL. Dr. Enqvist received a MSc in Physics at Gothenburg University, Sweden. He graduated with a PhD at the Department of Nuclear Engineering at Chalmers University of Technology (Sweden) in 2010. Dr. Enqvist has previously worked at the University of Michigan and Oak Ridge National Laboratory. His expertise areas include radiation detector characterization and radiation measurements, with emphasis on neutron detection and nuclear safeguards applications. As a faculty member at the University of Florida, Dr. Enqvist has conducted funded research for the Department of Energy, Department of Homeland Security, and National Nuclear Security Administration, as well as industry sponsors. He is a recipient of the 2017 Institute of Nuclear Materials Management Early Career Award. He has authored or co-authored over 40 journal publications and has over 100 presentations and contributions at professional conferences, workshops, and seminars. He is a member of numerous professional societies, including ANS, IEEE, and INMM.