Applications of Antineutrino Detector Technology to Counterterrorism

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The threat of highly organized and well-financed international terrorism requires the development of more sensitive, more versatile, and less expensive methods of detecting the presence of illicit radiological materials. The basic physics community has pioneered very large volume (kiloton) liquid-scintillator detector technology in recent years with the development of detectors for antineutrino physics.[1,2] Smaller-scale versions of "neutrino" detectors offer significant advantages over conventional detector technology for both stand-alone radiation monitoring and for use in active interrogation systems. The concept as applied to counterterrorism problems is called VLAND (Very Large Area Neutron Detector; the same acronym is used whether the application is for neutron or gamma-ray detection).[3]

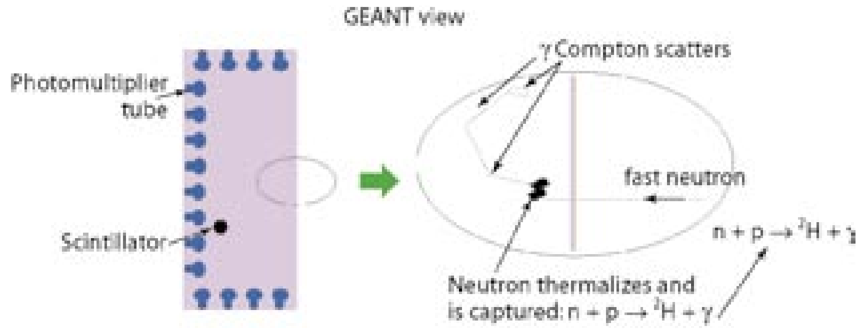
Advantages of Neutrino-Detector Technology

Current radiation monitors deployed at ports of entry and sensitive facilities such as military bases, reactors, and accelerators employ mature technology, typically plastic scintillators, ^{3}He proportional counters, or ^{6}Li-loaded glass for neutrons, and plastic scintillators and NaI(Tl) scintillators for gamma rays. Scaling this technology to large areas, required for increased detection sensitivity, is exceedingly expensive and cumbersome.

Some of VLAND's advantages as a replacement for the older technology are listed below.

- It can be readily fabricated with large areas, 10 to 100 m^2 or more. This is an enormous advantage in detecting weak signals in passive applications. VLAND is inexpensive compared to competing detector technologies of comparable size and efficiency.
- Because it can be scaled to large sizes, VLAND is a logical component of future active-interrogation and neutron-radiography systems.
- VLAND is highly efficient for both fission neutrons (~ 30%) and MeV-range gamma rays (~ 70% full-energy peak). For detecting fission neutrons, VLAND employs a distinctive signal—a fast-neutron moderation pulse followed by the delayed capture of the 2.22-MeV gamma ray from the $n + p \rightarrow {}^2H + \gamma$ reaction. The spatial distribution of this coincidence is also a strong discriminant against background events.
- Cosmic-ray muons are readily detected and identified as such by VLAND. Thus, variations in neutron backgrounds that follow variations in the cosmic-ray flux can be anticipated and valid-event selection can be correspondingly adjusted.
- VLAND is robust; simple to maintain; and may be easily calibrated, monitored, and operated remotely. Neutrino detectors using this technology have operated with virtually no component failure for five-plus years.

Figure 1. Schematic of VLAND. The enlargement at the right shows a simulated event using the CERN program, GEANT.[4] A neutron quickly moderates (thermalizes), followed by capture, which produces a 2.22-MeV gamma ray. The gamma-ray energy is absorbed by multiple Compton scattering.



Neutrino-Detector Technology Applications

The basic unit thickness of VLAND is about a meter, set by the ~ 30-cm mean-free path of 2.22-MeV photons in a liquid scintillator. Given this condition, any number of configurations of VLAND are conceivable—depending on the specific application. Four possible applications are described below.

As a fast-neutron portal monitor. Figure 1 illustrates the concept for fast-neutron detection. The detector is a meter thick (horizontal dimension) with no photomultipliers on the sensitive (right) face. The detector's height and width may extend several meters. Fast neutrons enter and are moderated within 10 cm of the sensitive face, as is illustrated in the simulation detail at the right of Figure 1. The moderation signal (from recoiling protons) is detected for 25% to 75% of the fission neutron spectrum, depending on the number of photomultipliers and on the light-production efficiency of the scintillator.

Use of a several-square-meter fast-neutron detector would permit more stringent limits be placed on the amount of plutonium passing undetected through transportation portals than is possible with commonly used ^{3}He proportional tubes. We could easily achieve gains in sensitivity by factors of 10 to 100. The fast-neutron signal is not subject to the large variation in background and innocent-radiation rates that plague gamma-ray-portal monitors.

As a gamma-ray detector. When used as a very large area gamma-ray detector, VLAND does not require the one-side-open geometry of Figure 1. Figure 2 shows a configuration that possesses directional sensitivity; such a detector could be mounted on a truck or a boat for large area search operations. In order to be competitive with NaI(Tl) crystals, configurations that favor good energy resolution would be desirable. Because energy resolution is usually dominated by photon statistics, important factors in its optimization are large photomultiplier coverage and the use of an efficient scintillator. The KAMLAND collaboration[2] has already demonstrated an energy resolution of 7.5%/√E—about a factor of two inferior to that of 4 × 4 × 16 in^3 NaI(Tl) crystals commonly employed in search applications. However, VLAND technology has a distinct advantage over NaI(Tl) because of its much more favorable peak-to-Compton-edge ratio. Within its fiducial volume, simulations show that VLAND would have a 70% photopeak efficiency. This would lead to spectral simplicity that facilitates separation of signal from background and from anthropogenic radiation sources.

As an element of an active interrogation system. In active interrogation, engineered sources of neutrons or high-energy photons are used to stimulate fission in SNM. Characteristic signatures of fission—delayed neutrons or gamma rays—are then recorded by a surrounding detection volume. Active interrogation is a known technology in the arena of nuclear safeguards; here long interrogation times are acceptable and comparatively small volumes need to be examined.

Currently no active interrogation system, even in the prototype stage, is applicable to the search for SNM in large transportation containers (truck trailers, shipping containers, etc.). Scaling the technology from the current ~1-m^3 object size to that of transportation containers requires at least two major advances—more intense radiation sources and large area neutron detectors, such as VLAND (whether the interrogating source is photons or neutrons). Because delayed neutrons are less energetic than those from fission, some optimization of the detection technology would be required. It may turn out, for example, that a modified VLAND using gadolinium-loaded scintillator would function better in this environment. Thermal-neutron capture on gadolinium yields readily identifiable ~ 8-MeV de-excitation gamma rays.

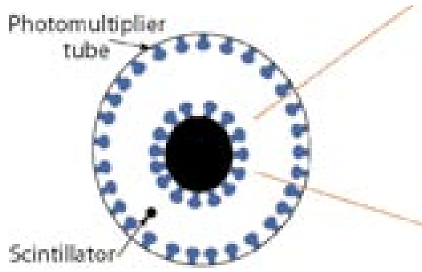


Figure 2. A possible configuration of a liquid scintillator tank for large area gamma-ray search application. The dashed lines indicate the approximate direction of sensitivity.

As an element of a fast-neutron radiography system. Conventional radiography using high-energy photons (nuclear gamma rays or bremsstrahlung from electron accelerators) is being increasingly deployed at critical transportation choke points to search for dense, heavy objects—objects that could be clandestine nuclear devices or components thereof. Muon radiography,[5] still in the research and development stage, promises sensitivity in this area as well.

Serious concerns remain about the ability of current radiographic methods (which were developed for conventional, not counternuclear, smuggling applications) to pick out small but significant quantities of SNM in transport containers in the presence of background clutter from legitimate cargo. A promising complement to current methods could be the radiographic application of fast neutrons.

Plutonium devices and kilogram-size quantities of plutonium are prolific sources of fast neutrons from spontaneous fission—readily detected by even unsophisticated portal monitors. However, when surrounded by a half meter of water or hydrogen-containing plastic, plutonium becomes nearly invisible to passive neutron detection. Highly enriched uranium (HEU, containing > 20% ^{235}U) presents a more complex challenge because it emits very few neutrons and primarily very low-energy gamma rays that are readily shielded by 1 cm of lead. However, the threat of active interrogation using neutrons and/or high-energy photons might well convince a would-be smuggler to protect his HEU with neutron shielding as well.

In contrast to photons, fast neutrons pass relatively freely through lead or iron, but are strongly attenuated in hydrogen-containing materials like water and polyethylene. This complementarity suggests the use of fast neutrons to search for the presence of neutron shielding in transportation vehicles. Figure 3 shows a simulated radiograph in which a shielded quantity of SNM in a 2- × 2-m^2 section of a shipping container is illuminated by a uniformly distributed source of 14-MeV neutrons.

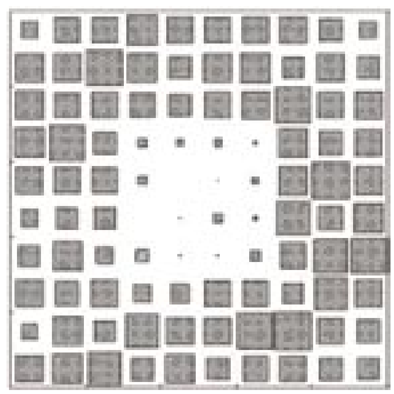


Figure 3. Simulated radiograph of a shipping container holding a shielded quantity of SNM surrounded by 50 cm of polyethylene. The white square in the center shows the outline of the neutron shielding. The contents of the container were simulated by a uniform mass of iron 10 cm thick (representing a container fully loaded to its 20-ton capacity).

Using fast neutrons to search for neutron shielding is fundamentally simpler than photon radiography for two reasons. First, moderation and containment of fission neutrons requires at least 50 cm of water equivalent, usually surrounded by a thin layer of thermal neutron absorber such as cadmium. Thus, the projected size of a shielded object is large—at least 1 m^2—leading to a modest number of pixels required to characterize the area of a shipping container. Second, unlike photons, 14-MeV neutrons have a substantial probability of passing through thick objects, like fully loaded shipping containers, unscattered. Thus, rather than scanning the object with a well-collimated beam in order to minimize in-scattering from adjacent pixels, a large area beam may be used. In Figure 3, 2.5×10^5 incident neutrons were used, which is a small fraction of the intensity available in one second from a commercial neutron generator.

A possible implementation of fast-neutron radiography could be as the second station following photon or muon radiography. A potentially threatening, but not completely convincing, dense object from the first radiograph would be examined at a second station with neutron radiography. The spatial overlap of the dense object in the photon radiograph with a region that contains substantial neutron shielding, likely to be a rare circumstance in normal cargo, would signal the need for more detailed inspection of the container. Because of the simplicity of the neutron source and detector, fast-neutron radiography could be implemented for a fraction (perhaps 10%) of the cost of current photon-radiography stations.

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