DOE/SC-0062

Report on the *Workshop on the Role of the Nuclear Physics Research Community in Combating Terrorism*

Washington, D.C.

11–12 July 2002

U.S. Department of Energy
Division of Nuclear Physics
Office of Science

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Executive Summary

The *Workshop on the Role of the Nuclear Physics Research Community in Combating Terrorism*, convened in Washington D.C., July 11–12, 2002, brought together scientists from the nuclear science research community and many representatives of U.S. government agencies charged with protecting the nation in an attempt to generate new ideas and new connections for nuclear science in the service of national needs. The workshop was organized and sponsored by the Department of Energy (DOE), Office of Science, Division of Nuclear Physics and included scientists supported by the Division of Nuclear Physics and by the National Science Foundation (NSF—Physics Division), the two principal federal agencies charged with supporting the Nation's basic research in nuclear physics. This report is based on discussions by the Workshop's two working-groups—*Conventional Explosive and Weapon Detection*, and *Radiological and Nuclear Threats*—and on the Workshop's poster presentations. It covers a broad expanse of topics ranging from the very speculative to technologies that have been in the national and homeland defense research portfolios for years. The primary objectives of the workshop focused on communication:

- introduce scientists in the nuclear physics research community to the technological challenges of combating terrorism facing U.S. government organizations charged with protecting the nation,
- introduce leaders of U.S. government organizations to the capabilities of the nuclear physics research community for addressing the technological challenges to combating terrorism, and
- understand the mechanisms and opportunities for involvement of the nuclear physics research community on problems related to preventing terrorism.

An overview of the full report may be obtained by reading the first three sections, 1. *Introduction*, 2. *Summary of the Working Group Reports*, and 3. *Recommendations*. Sections 4 and 5 cover the more detailed discussions of the working groups and refer to a large quantity of tabulated information in references, tables, and appendices. For convenience we include the principal recommendations below. Section 3 elaborates on these recommendations. A color version of this document can be found at the DOE Nuclear Physics Division Website (http://www.sc.doe.gov/production/henp/np/index.html).

Recommendations

A. *The basic nuclear physics research community has much to contribute to the quest for new science and technology for combating terrorism.*

Recommendation A: The basic nuclear physics community should increase its involvement in counterterrorism research.

B. *The basic nuclear physics community is a unique national resource in the experimental, theoretical, and computational methods of nuclear physics.*

Recommendation B1: The DOE Division of Nuclear Physics, the Physics Division of the NSF and the APS/DNP should explore ways of better communicating to all interested groups and agencies the knowledge of nuclear physics and the broad range of expertise that resides within the basic research community.

Recommendation B2: A special effort needs to be undertaken to ensure that the nuclear data needs for the development of counterterrorism measures are thoroughly identified and promptly addressed.

C. *To quote from the 2002 National Academies' study*, Making the Nation Safer: The Role of Science and Technology in Countering Terrorism: *"Indeed, America's historical strength in science and engineering is perhaps its most critical asset in countering terrorism without degrading our quality of life.... The nation's ability to perform the needed short- and long-term research and development rests fundamentally on a strong scientific and engineering workforce. Here there is cause for concern as the number of American students interested in science and engineering is declining, as is the support for physical science and engineering research.*"

Recommendation C: The federal support of the basic physical sciences must ensure that the nation has an effective future workforce trained in the full spectrum of technologies related to the mission of countering the terrorist enemy.

1. Introduction

The methods of nuclear science are applicable to a wide variety of problems that face a nation trying to counter the threats of terrorism. The technologies associated with nuclear arms control and safeguards associated with nuclear power have been in place for decades. Nuclear technologies have also been applied to the detection of conventional explosives, with a resurgence of interest in the past 15 years in response to threats to commercial aviation.

The terrible events of September 11, 2001, have made it abundantly clear that there are new terrorist enemies and that it is timely to ask the question, "Are there new nuclear-physics-based technologies developed by the basic-research community that can help mitigate their threats?" It is equally important to ask, "In what new contexts can a deployment of the techniques of nuclear physics help reduce the threat of terrorism?"

The *Workshop on the Role of the Nuclear Physics Research Community in Combating Terrorism*, convened in Washington D.C., July 11–12, 2002, brought together scientists from the nuclear science research community and many representatives of U.S. government agencies charged with protecting the nation in an attempt to generate new ideas and new connections for nuclear science in the service of national needs. The agenda for the workshop is given in Appendix I; the agencies represented are listed in Appendix II.

The workshop was organized and sponsored by the Department of Energy (DOE), Office of Science, Division of Nuclear Physics and included scientists supported by the Division of Nuclear Physics and by the National Science Foundation (NSF—Physics Division), the two principal federal agencies charged with supporting the Nation's basic research in nuclear physics. Attendance at the workshop was by invitation only, but with a broad solicitation made for participation by all of the universities and national laboratories involved in the basic nuclear physics research program. The solicitation included a request "to describe current or proposed projects relevant to combating terrorism." These submissions, which represent a sample of the community's capabilities, were then presented at the workshop's poster session. The poster presentations (Appendix III) formed the basis for the working groups that met the second day of the workshop. The working groups focused on two areas of technology: *Conventional Explosive and Weapon Detection*, and *Radiological and Nuclear Threats*. Both groups (memberships are listed in Appendix IV) had experts in a range of nuclear-physics technologies—detectors, accelerators, theory, simulation tools—as well as three representatives from agencies with knowledge and responsibilities for protection of the public. We also note the active participation of a number of nuclear physicists from the private sector, universities, and the national defense laboratories, who had extensive experience working with many of the agencies represented at the workshop.

The primary objectives of the workshop focused on communication:

- introduce scientists in the nuclear physics research community to the technological challenges of combating terrorism facing U.S. government organizations charged with protecting the nation,
- introduce leaders of U.S. government organizations to the capabilities of the nuclear physics research community for addressing the technological challenges to combating terrorism, and
- understand the mechanisms and opportunities for involvement of the nuclear physics research community on problems related to preventing terrorism.

This workshop was a strong first step toward achieving these objectives. Additional effort and wider input from the basic nuclear physics research community are needed in order to benefit the nation and its homeland security needs.

Because of the short time scale for the call for poster submissions, the short duration of the workshop itself, and the complexity of the new security issues facing the nation, we did not attempt to endorse new technology or to assign priorities to research and development (R&D). We note that prototype inspection systems employing some of the techniques discussed have been extensively examined by the National Academy of Sciences and other review processes, sometimes with the recommendation that the technology needed further development before finding service in the field. A discussion of a wide variety of potential techniques was carried out, in part to set the context for members of the basic research community who had not been actively working in these areas. All workshop participants recognized the difficulty of translating new and emerging technologies from the laboratory to actual devices for the protection of the public.

Sections 2 (Summary of the Working Group Reports) and 3 (Recommendations) of this document provide a short overview of the important conclusions and recommendations that followed from discussions that took place at the workshop's parallel sessions and the subsequent interactions with the two writing groups. The short form of this document is thus Sections 1–3 plus the appendices. A more detailed discussion of the issues can be found in Sections 4 and 5 that describe the deliberations of the two working groups. These sections also contain additional references and tabular summaries of nuclear inspection techniques.

2. Summary of the Working Group Reports

Nuclear physics has provided many of the techniques and tools applicable to national defense for decades. Since September 11, 2001, the context of national defense has, however, taken on a greatly expanded range of opportunities for the applications of the technology of nuclear physics. An important objective of the workshop was to explore the potential application of the more recent technological advances of the basic nuclear physics community to the new needs of national and homeland defense. Table 1 summarizes the relevant capabilities of the community.

We have chosen to highlight a few techniques as "sidebars" to give examples of promising territory for further development. This section, as well as the more detailed discussions presented in Sections 4 and 5, is intended to elicit further inquiry, investigation, and contact both from the basic nuclear physics community and the government agencies charged with protecting the nation. References in this section (marked with {}) refer to the poster presentations (Appendix III).

A. Improvements in Accelerator-Based Radiation Sources

The search for conventional explosives often involves active interrogation of luggage, containers, and vehicles using accelerator-based sources of x-rays, gamma rays, and neutrons. Active interrogation is also required in the search for special nuclear materials (SNM) such as highly enriched uranium (HEU, greater than 20% concentration of ^{235}U) which is only slightly radioactive.

Advancements in accelerator technology are the lifeblood of a large array of DOE Office of Science and NSF research facilities. Thus, it is not surprising that recent advances in this area could potentially have a large impact in counterterrorism applications.

Neutron-Based Inspection Techniques in Service of Counterterrorism

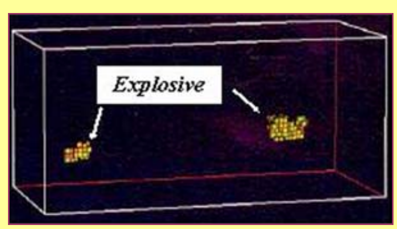
The key to distinguishing explosives from benign material is the use of elemental analysis. While x-ray-based systems (in particular, computerized tomography) can give high-precision charge density measurements with high-resolution three-dimensional images, these systems provide at best only gross information about the elemental content of the inspected item (low atomic number, Z, vs. high atomic number). Neutron interrogation offers the possibility of measuring the elemental density of most elements in materials. Of particular interest in the detection of conventional explosives are the densities of (in order of importance) nitrogen, oxygen, carbon, and hydrogen.

Various neutron-analysis techniques are at different states of development, ranging from conceptual design to operational status. The choice of the technique to employ is highly dependent on the nature of the inspection problem. Pulsed Fast Neutron Analysis (PFNA) is one of the promising techniques for cargo inspection for explosives and contraband. PFNA uses a nanosecond-wide pulsed and collimated beam of mono-energetic neutrons. The inspected object is scanned by moving the collimated beam up and down in a vertical plane (rastering) while the object is moved horizontally. The neutrons interact with the nuclei of the inspected object to produce characteristic gamma rays and the time-dependant gamma-ray spectrum can be unfolded to create a three-dimensional map of the object. The characteristic energy spectra for the gamma rays emitted by key elements are shown. Such spectra are combined to produce unique material signatures, which are stored in computer libraries and used for automatic material identification. Typical images obtained in the inspection of a truck with high-energy x-rays and a car carrying explosives with PFNA are compared (right).

High-energy x-ray image

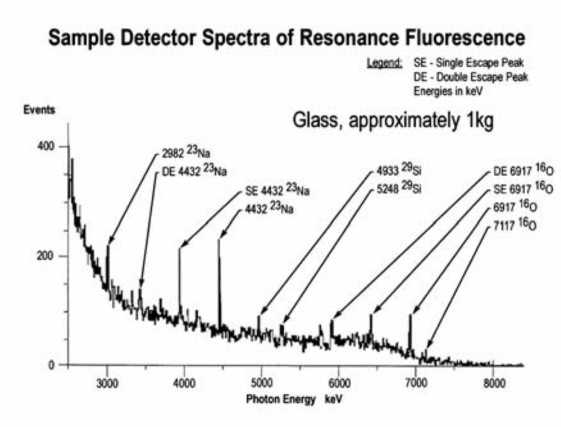
- Requires operator to decide
- Can't see behind engine
- Can't distinguish concealed explosives

X-ray and neutron images of motor vehicles. The neutron image (below) can highlight suspected explosive material with elemental analysis.



PFNA automatically and precisely locates concealed explosive behind engine and among cargo in rear of automobile

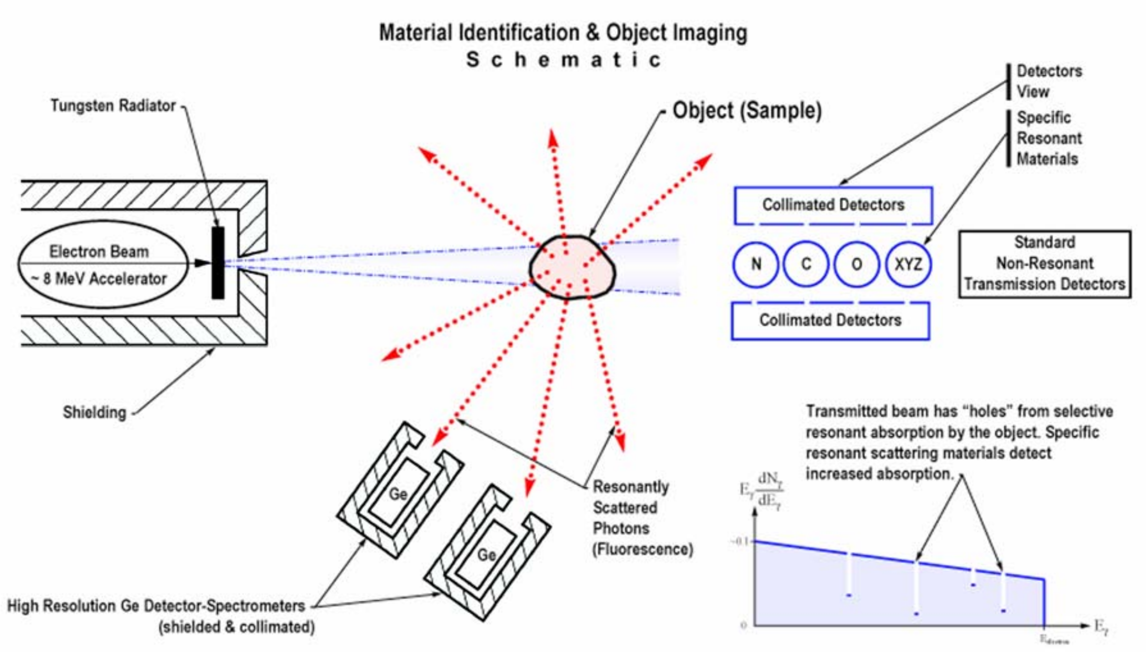
Nuclear Resonance Fluorescence in Material Detection and Object Imaging



Resonance fluorescence gamma-ray spectra of glass

All nuclei have characteristic excited states at energies that are unique. Many of these states have strong probabilities for electromagnetic excitation and can usually be found in the lowest 7 MeV. By using a beam of photons that is continuous in energy (bremsstrahlung), one ensures that there are photons at all energies and all elements in the beam can be excited to their characteristic states (resonance absorption). These states then decay mostly back to the ground states with the emission in all directions of photons of the characteristic energies (resonance fluorescence or resonant gamma scattering). Detecting these characteristic photons provides a signal that identifies the elements in the sample uniquely. Collimating both the photon beam and the viewing direction of the detectors provides spatial imaging. An object can be identified by its spatial position and its elemental composition.

The resonant absorption makes a “hole” in the transmitted spectrum of photons and this is also a signal of great importance. Typically, for a 5-MeV photon the resonant cross section has a peak value of about 500 barns (10^{-24} cm^2), depending on the angular momentum of the states involved. Because of thermal Doppler broadening, the effective peak cross sections are typically reduced by a factor of about 200, depending on the photon energy, but these resonant nuclear cross sections are still significantly larger than the photoelectric, Compton, and pair-production cross sections that normally absorb photons out of the incident beam. The resonant absorption that makes these “holes” can be measured by detecting the resonant fluorescence (scattering) of the transmitted beam by a sample that contains all the elements of interest. A separate shadow image results for each resonant energy. Each image is like a standard x-ray shadow image, but now each of these images is element-specific. For a single object, these element-specific images all coincide in the shadow.



Elements of nuclear resonance fluorescence imaging

- **Neutron Generators**

  Substantial advances in neutron-source technologies are expected in the next five years. Commercial suppliers of portable neutron generators are making sources more compact and more reliable at an impressive pace. Over the next few years the lifetime of sealed-tube deuterium-tritium (DT) neutron generators is expected to increase from about 1000 to 3000 hours. Compact sealed-tube sources are well suited for portable systems such as those being used for searching for car bombs. Greater output of neutron sources will increase the stand-off distance of the detection system. Source development work {15} holds the promise for increases in neutron intensities about a thousand times greater than what is commercially available today. Similarly, basic research in increasing the primary intensities of electrostatic {10} or other charged-particle accelerators could lead to increased neutron intensities via the D(d,n) reaction while retaining the characteristic high beam quality, energy, and time resolutions: This will further advance the high performance neutron-based inspection systems.

  Table 2 summarizes current neutron inspection technology.

Terahertz Imaging and Nuclear Accelerator Development

Terahertz (THz, 10^{12} Hz) electromagnetic radiation in the frequency range 0.1–10 THz is the new frontier in imaging science and technology. Terahertz beams can penetrate plastic, concrete, and other common materials, and can recognize and identify biologic and plastic materials as well as concealed weapons. Terahertz waves have been used to characterize the electronic, vibrational, and composition properties of solid-, liquid-, and gas-phase materials.

Until recently, initiatives and advanced technological developments in the THz band have been limited for high-power applications such as imaging. However, a high-power (100s of Watts) source using coherent synchrotron radiation emission from subpicosecond bunches of electrons has been developed at the Thomas Jefferson National Accelerator Facility based on technology developed for nuclear physics research. This development will allow full-field, real-time, image capture.

Unlike many other forms of radiation, THz beams are nonionizing. This gives them a unique counter-terrorism niche, and makes them extremely well suited for inspecting packages and people for concealed chemical and biological weapons, plastic explosives, or other contraband. They could also be used for through-wall imaging, or for mine detection and localization.

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Spot the knife? Millimeter waves, close to THz, show their ability to see through clothes and paper.

Superconducting acceleration cavity which was developed at Jefferson Laboratory for the U.S. DOE Nuclear Physics Program. These cavities have also shown great utility for generating high-power light from the THz to UV range for defense, industrial, and scientific applications.

- **Gamma-Ray Sources**

  Many of the same advances in ion and electron accelerators can greatly enhance the production of gamma rays for nuclear resonance absorption and scattering measurements {10,39,42}. Continuous gamma-ray beams can employ the progress in basic research in electrostatic, microtron, and linear accelerator development. Laser backscattering from electrons in storage rings, such as the Triangle Universities Nuclear Laboratory (TUNL) High-Intensity Gamma-ray Source (HIGS) facility at Duke University {42}, can now provide high-intensity monochromatic photon beams with energies in the tens of MeV range appropriate for active interrogation. This facility is a significant advance for basic nuclear data measurements relevant to photon interrogation.

- **Other Accelerator-Based Radiation Sources**

  The Jefferson Laboratory (JLAB) energy-recovering free-electron laser (FEL) {40} is opening new industrial possibilities in high power using high-power ultraviolet, infrared, and electron radiation for material processing such as the preparation of antimicrobial surfaces. JLAB has also created a potent source of terahertz radiation that could significantly advance the capability for imaging hidden weapons or explosive packages {1,38}.

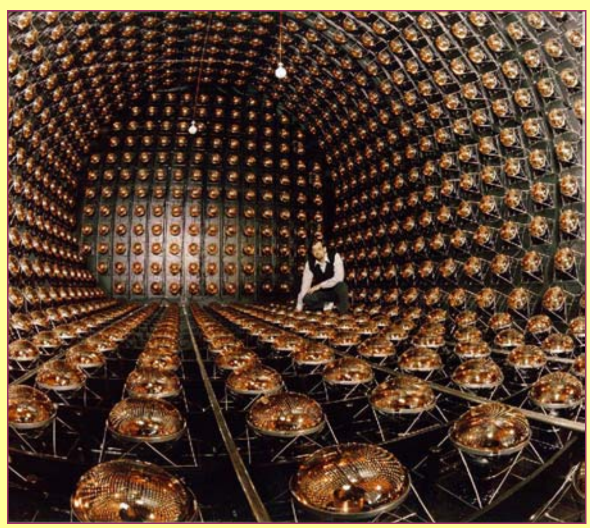
B. Improvements in Gamma-Ray Detection

In recent years spectacular advances have been made in the detection of gamma rays using large arrays of high-resolution intrinsic germanium crystals. The largest of these, Gammasphere, uses 110 germanium crystals to obtain unprecedented sensitivity. The newest development from the research community is gamma-ray energy tracking to greatly increase the efficiency and resolving power of germanium detector arrays {5, 13}. The tracking project involves the development of segmented germanium detectors, digital signal processing electronics, and fast algorithms. Gamma-ray tracking promises orders-of-magnitude improvement in weak signal detection for nuclear spectroscopy. Its application to homeland-defense

Very Large Area Neutron Detector (VLAND)

The design of VLAND is based upon new technologies developed for neutrino physics experiments such as the Liquid Scintillator Neutrino Detector (LSND) experiment at Los Alamos. The concept employs large neutron detection modules filled with mineral oil and scintillator and instrumented with photomultiplier tubes (PMTs) to provide significantly improved solid-angle coverage at reduced cost as compared to competing technologies. This would allow the detection of neutron-emitting materials or devices in venues such as highways, tunnels, bridges, airports, border crossings, or nuclear facilities. The applications are in a) detection of smuggled neutron-emitting special nuclear materials (SNMs), such as weapons-grade plutonium and certain uranium compounds, b) terrorist nuclear-weapon threat detection, and c) weapon accountability.

The characteristic that makes VLAND unique is the ability to fabricate very large area detectors cost effectively. As the likely targets of interest would emit low fluxes of neutrons and would be detected at relatively long distances with short dwell times, any effective neutron detection system would be detected at relatively long distances with short dwell times, any effective neutron detection system would need to have a large surface area. Recent neutrino physics experiments have successfully instrumented with PMTs from tens to thousands of tons of liquid scintillator detectors, which detect the light emitted from the incident neutron as well as the light from the subsequent neutron capture with high efficiency. The technology is now sufficiently mature that an eight-inch diameter PMT costs less than a thousand dollars and can be expected to operate unattended for more than ten years.



The liquid scintillator neutrino detector at Los Alamos.

problems could be equally significant, given dedicated R&D coupled with realistic simulations of the possible contexts of a more complex technology.

A technological step beyond gamma-ray tracking with germanium is the development of a Compton telescope with electron tracking and photon conversion. Conceptually, with the advent of microposition detectors (silicon, gas filled, etc.) and highly miniaturized electronics with distributed intelligence, such a detector could be built today. Indeed, collaborations at several institutions have active research programs including applications to gamma-ray astronomy and nuclear nonproliferation. Scalability to large volumes and cost are issues that need to be addressed in the context of particular applications.

For years the nuclear research community has recognized the need for gamma-ray detectors whose performance lies between that of germanium diodes and sodium iodide scintillators. One approach under development is large-volume, high-pressure inert gas (such as xenon) ionization chambers {9}. These promise high sensitivity and relatively low cost with an energy resolution better than sodium iodide, but less than germanium.

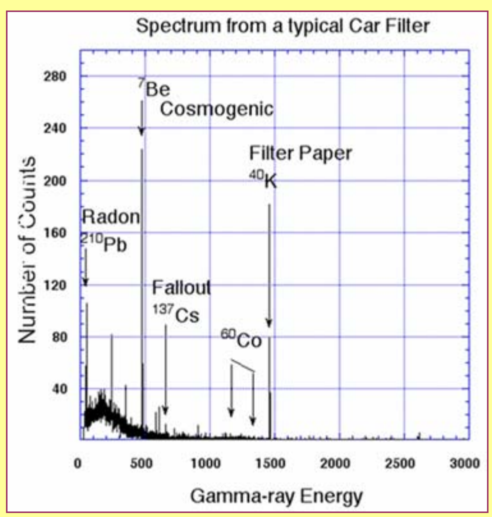
Finally, we note the development of a field-portable germanium detector system {20} that uses a small low-power Stirling-cycle cooler, instead of liquid nitrogen, to achieve the required operating temperature. At the present stage of development, there is degradation in energy resolution of about a factor of two.

Table 3 summarizes the current gamma-ray detection technology.

Automotive Air filters Determine the Extent and Severity of a Nuclear Terrorist Attack

In 1986, the Chernobyl incident spread a cloud of radioactivity around the world. As far away as California, automotive air filters were found to be nearly as effective as dedicated sampling stations in detecting this radioactivity in the air.

Rather than deploy a widespread series of dedicated air sampling stations to search for nuclear, chemical, or biological agents in the air, we prefer the less expensive, but equally effective, use of automotive intake air filters as sample collectors. Hundreds of lead-shielded gamma-ray spectrometers exist at universities, national laboratories, and reactor facilities. These facilities can serve as primary analysis centers. The examination of 150 automotive air filters at the low-background facility at Lawrence Berkeley National Laboratory has detected the naturally occurring ^{7}Be and ^{210}Pb, verifying the performance of these filters. Activities expected from a terrorist attack would be orders of magnitude greater than these naturally occurring activities.



Public service Vehicles are excellent air sample collectors since they typically are concentrated in population centers and are driven in well-documented patterns. Police departments are the first response teams to any disaster.

A national network of air sampling and analysis centers can be established in a matter of months utilizing public-service vehicle air filters as sample collectors and existing laboratory facilities for analysis. A pilot program could consist of ten metropolitan areas.

Every car on the road is a potential mobile air-sample collector!

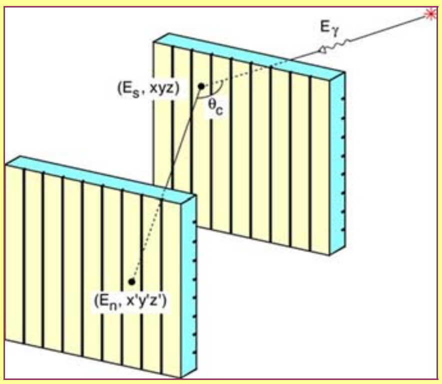
C. The Search for Illicit Nuclear and Radiological Materials

The development of cheaper, more versatile (with on-board intelligence), and efficient neutron detectors has the potential for large impact in many areas of counterterrorism. It is absolutely crucial for the most difficult mission—the (active) detection of special nuclear material, the most insidious of which is HEU because of its low specific activity.

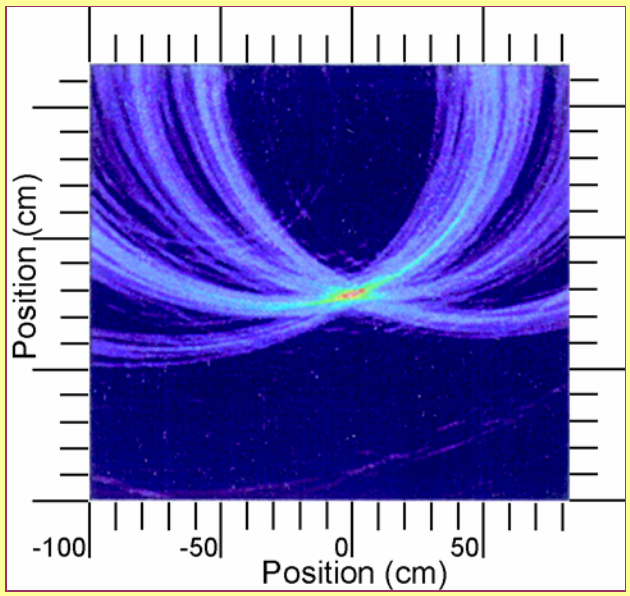
The nuclear physics and high-energy physics communities have pioneered very large volume (kiloton) detector technology in recent years with the development of detectors for neutrino physics {25}. These include water Cerenkov detectors and liquid scintillator tanks viewed by large (8-inch diameter) but comparatively inexpensive photomultipliers. With suitable modification this technology could be applied to both neutron and photon detection. The combination of inexpensive materials and construction techniques that are versatile (many possible configurations) and robust bodes well for new applications such as those indicated in the recommendations of the recent National Academy of Sciences report,

Gamma-Ray Tracking

Gamma-ray tracking using high-purity germanium detectors with segmented electrodes yields huge improvements in signal-to-background ratios. Shown below are results from a collaboration involving Argonne National Laboratory, AMETEC/ORTEC, Naval Research Laboratory, DePaul University, University of Massachusetts, and Purdue University. Here two planar segmented-electrode germanium detectors, shown schematically at the left, are used to determine the "Compton circles" for gamma-rays emerging from a point source. The intersection of three or more circles determines the source location as is shown at the right.



Schematic layout of gamma-ray tracking system



Compton circles from the gamma-ray tracking system at the Naval Research Laboratory. Source is located 120 cm from the detectors.

The technique works best for relatively high-energy photons (~ 1 MeV) where signals are large and Compton scattering is the dominant interaction process. Current applications include computer-assisted tomography, high-resolution absorption mapping, and high-resolution emission maps.

Making the Nation Safer: The Role of Science and Technology in Countering Terrorism.[1] We quote recommendation 2.6, "A focused and coordinated near-term effort should be made by the DOE, through its National Nuclear Security Administration, and by the Department of Defense, through its Defense Threat Reduction Agency, to evaluate and improve the efficacy of special nuclear material detection systems that could be deployed at strategic choke points for homeland defense."

Radioactive substances including some forms for SNM advertise their presence by gamma-ray emission. But when surrounded by heavy shielding such as lead, the detectable activity is reduced many orders of magnitude. However, the presence of the shielding itself could be an indicator of a smuggling attempt. Absorption radiography with high-energy x-rays or gamma-rays is useful in this context if the object to be interrogated is not very thick. However, a new concept {24}, which uses the natural and very penetrating but weak flux of cosmic rays muons may add an additional advantage in circumstances where longer inspection times (to accumulate statistical precision) are permitted.

D. Forensics and Attribution

- **Accelerator-Based Techniques**

  Identifying the origin of terrorist materials could be assisted using a number of accelerator-based techniques {2, 4, 33}. Accelerator mass spectroscopy (AMS) yields trace isotopic ratios of material

Gamma-Ray Spectroscopy—A Tool for Basic Research and Security Applications

Advances in gamma-ray spectroscopy have enabled major discoveries in basic nuclear physics, while making critical contributions to medical imaging, characterization of radioactive materials, and nuclear safeguards. Central to these achievements has been the development of advanced nuclear instrumentation. Starting in the 60s, the basic research community developed spectrometers based on germanium detectors for many applications, replacing the earlier NaI(Tl) detectors. These detectors provide much higher energy resolution for radioisotope identification and high selectivity above background—the trade-off being higher cost, limited crystal size, and need to operate cryogenically. Since the 80s arrays of germanium detectors have evolved to their current 4π scale, as shown by the 110 element Gammasphere detector—seen being worked on by two technicians.

However, for gamma-ray identification in the field, e.g., by first responders to a radiological or nuclear threat, portability and ease of operation are essential. To go from a Gammasphere-scale device to a hand-held detector requires a team approach involving both science and engineering. For example, a portable spectrometer, CRYO-3 (at right), recently developed, has light weight (10 lbs.), requires low power (15 W DC) and is long-lived (6 months before a 4-day warm-up/cool-down cycle). Current R&D efforts in developing detectors with higher efficiency, lower-background and better position and directional sensitivity will have application in many applied areas.

Gammasphere

CRYO-3

[1] http://books.nap.edu/books/0309084814/html/39.html#pagetop

that may be unique to a particular material-processing path. Measurement of isotopic ratios as low as $5x10^{-17}$ has been demonstrated for some elements. Detection of actinide isotopes with concentrations as low as 10^8 atoms/gm has also been demonstrated. Most of this work has taken place at large complex heavy-ion linear accelerators or high-voltage tandem accelerator facilities. Recently, detection of ^{244}Pu was demonstrated at a small 3 MV tandem AMS facility. AMS also has potential use in the identification of nuclear fuel reprocessing by monitoring the trace concentrations of ^{36}Cl or ^{85}Kr in air samples. AMS with these isotopes requires the use of relatively large (10–30 MV) heavy-ion accelerator facilities in order to clearly separate the trace isotopes from stable isobars. At this time, the use of existing, complex heavy-ion accelerator facilities is the only option for these AMS measurements. Another new technique for high-sensitivity mass spectroscopy is the atom trap trace analysis (ATTA) system. Low-level detection of ^{85}Kr has already been demonstrated with ATTA.

An entirely different approach that is applicable even to molecular species is the multipass time-of-flight mass spectrometer {34}. With this device it is possible to distinguish more than 90% of all organic substances from each other without the use of time consuming chromatographic techniques.

- **Low-Background Counting**

The detection of nuclear reactions induced by neutrinos and the search for extremely rare decay processes such as double nuclear beta decay has been made feasible in the past decade by the impressive confluence of new techniques {23}.

These include:

- few-atom, high-purity chemical separations,
- ultra-low-level gas counting systems constructed of materials nearly free of natural radioactive contaminants,

Nuclear Data for Homeland Defense and National Security

US Nuclear Data Program: Status

Mission. Collects, evaluates, and disseminates nuclear physics data of critical importance for basic research and nuclear-technology applications

US Nuclear Data Program. Involves national labs and universities; main product is nuclear structure database (ENSDF); sponsored by DOE-SC (26 FTE, $4.6M, FY2002).

Cross-Section Evaluation Group. Involves national labs, universities, and industry; main product is nuclear reaction database (ENDF), sponsored by DOE-SC, -NM, -NNSA.

National Nuclear Data Center. Core U.S. nuclear data facility, coordinates U.S. activities, archives, and disseminates databases.

National Resource. Nuclear databases contain data from more than 50 years of worldwide research in low-energy nuclear physics; they are both a national resource and a national treasure.

Importance for Homeland Defense.

Structure database (ENSDF) represents basis used to identify radioactive materials, including most popular Table of Isotopes (LBNL) and Nuclear Wallet Cards (BNL).

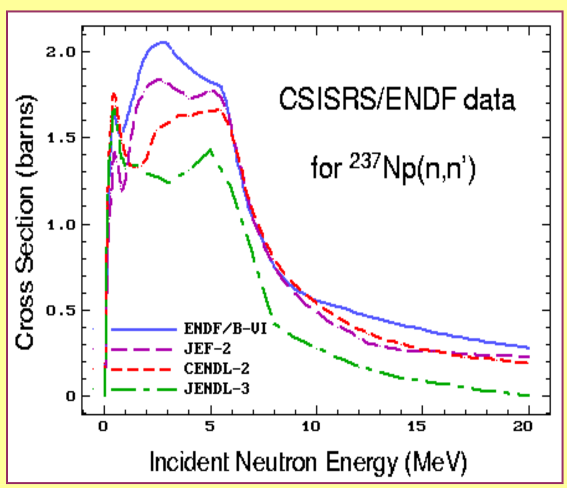
Reaction database (ENDF) is indispensable for all neutronics calculations, including widely used Monte Carlo simulation code MCNP (LANL).

US Nuclear Data Program: Initiative

Safeguards and NM Management.

Shorten update cycle for ENSDF.

Improve ENDF data to assess production of illicit nuclear device with ^{237}Np.



- near zero background germanium and scintillator detectors, and
- deep underground laboratory facilities where cosmic-ray backgrounds are reduced by many orders of magnitude.

  This technology has led, for example, to the measurement of the neutrino flux from the Sun where a few tens of atoms of ^{71}Ge are produced per month in 30 to 60 ton volumes (~10^{30} atoms) of gallium metal. These few ^{71}Ge atoms are then chemically extracted and their electron capture decays counted with close-to-zero background. There are numerous conceivable applications of this technology where samples collected at sites suspected of harboring illegal activities could be expedited to dedicated facilities. The technology is largely in hand; its application to national-security concerns remains to be developed.

E. Nuclear Data and Simulation

It is likely, given the large scope of counterterrorism measures to be implemented, that there are major gaps in our knowledge of essential nuclear data. As an example, consider the accurate determination of the critical mass of ^{237}Np {26}. Neptunium-237 is a possible candidate for construction of an illicit fission device, being outside of the International Atomic Energy Agency (IAEA) Special Nuclear Materials Atomic Energy Act (1954) and its amendments. Substantial improvements in nuclear data are needed for determining the critical mass of ^{237}Np and assessing its potential terrorist threat.

Nuclear databases and the supporting infrastructure built up over several decades are a significant contribution of basic nuclear physics to national security. These high-quality, standardized, and validated databases and the nuclear data evaluation community that can integrate experimental and nuclear theory/models to produce them are major resources.[2] In the context of counterterrorism, they are crucial components in passive and active interrogation schemes for detection of nuclear materials. They also play an important role in emergency response "home-team" code simulation capabilities to model (and render-safe) potential proliferant nuclear devices.

The uses of advanced simulation tools, such as the CERN package, GEANT, and the Los Alamos package, MCNP, that model the transport of radiation through complex assemblies of material is nearly ubiquitous in modern nuclear and particle physics experiments. Realistic models lend themselves to the optimization of almost any hypothetical counterterrorism situation consisting of a radiation source, detector, target, and a complex configuration of extraneous or background materials. This expertise should be sought in connection with proposal reviews and conceptual design studies of proposed counterterrorist systems.

[2] For example http://www.ndc.bnl.gov and http://www.ie.lbl.gov.

3. Workshop Recommendations

During the short time available for interaction between the nuclear physics research community and representatives from the federal agencies, it was possible to glean some important observations and recommendations:

A. *The basic nuclear physics research community has much to contribute to the quest for new science and technology for combating terrorism.*

Recommendation A: The basic nuclear physics community should increase its involvement in counterterrorism research.

There are clearly new venues where state-of-the-art technologies could be applied. Interested nuclear scientists should establish contacts and collaborations with knowledgeable personnel whose missions could be impacted by new techniques.

Funding for counterterrorism research is likely to go to specific government agencies with missions to protect the public. To accomplish the above goal, interested investigators involved in basic nuclear physics should seek new funding for applied research from the appropriate agencies. The large number of agencies with counterterrorism R&D responsibilities can be a bewildering barrier for research scientists trying to find their niche. The situation is likely to change rapidly as the Congress and the Executive Branch form the blueprint of the Department of Homeland Security. A central clearing-house for counterterrorism R&D proposals could enhance the ability of the basic-research community to become involved and could increase communication. Ideally there will be a symbiosis of effort provided the basic and applied projects have tools and technical resources in common.

B. *The basic nuclear physics community is a unique national resource in the experimental, theoretical, and computational methods of nuclear physics.*

Recommendation B1: The DOE Division of Nuclear Physics, the Physics Division of the NSF and the APS/DNP should explore ways of better communicating to all interested groups and agencies the knowledge of nuclear physics and the broad range of expertise that resides within the basic research community.

The basic nuclear physics community should organize and strengthen its involvement in communicating the methods of nuclear physics applicable to homeland and national defense. The expertise of the research community could be put to use in many areas ranging from peer review of technical proposals submitted to federal agencies, to advising and training local fire departments and police forces on the principles of nuclear physics and the use of radiation detectors. DOE and NSF should consider hosting a second workshop in the summer of 2003 to reexamine the application of the new techniques of nuclear physics to the rapidly changing landscape of homeland-defense challenges.

Recommendation B2: A special effort needs to be undertaken to ensure that the nuclear data needs for the development of counterterrorism measures are thoroughly identified and promptly addressed.

C. *To quote from the 2002 National Academies' study*, Making the Nation Safer: The Role of Science and Technology in Countering Terrorism: *"Indeed, America's historical strength in science and engineering is perhaps its most critical asset in countering terrorism without degrading our quality of life.... The nation's ability to perform the needed short- and long-term research and development rests fundamentally on a strong scientific and engineering workforce. Here there is cause for concern as the number of American students interested in science and engineering is declining, as is the support for physical science and engineering research.*"

Recommendation C: The federal support of the basic physical sciences must ensure that the nation has an effective future workforce trained in the full spectrum of technologies related to the mission of countering the terrorist enemy.

The nuclear physics research community develops scientific knowledge, technologies and trained manpower that are critically needed in developing a technically world-class and knowledgeable workforce that can effectively combat terrorism. A significant fraction of the scientists awarded Ph.D. degrees in nuclear physics follow career paths to defense-related nuclear research.[3] More specific examination of the complementary relationship between nuclear physics research and homeland security may further enhance the perspective of this future workforce. For example, universities and colleges might consider discussing this relationship within their current or future curriculum. This topic could also be incorporated into the meetings and summer schools of the American Physical Society's Division of Nuclear Physics (APS/DNP).

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[3] For example, the directors of the three DOE defense laboratories have Ph.D.s in nuclear physics—Paul Robinson, Ph.D. Florida State University, Sandia National Laboratory; John Browne, Ph.D. Duke University, Los Alamos National Laboratory; Michael Anastasio, Ph.D. State University of New York, Stony Brook, Lawrence Livermore National Laboratory.

4. Report of the Conventional Weapons and Explosives Working Group

Conventional weapons and explosives are the most ubiquitous of the terrorist's threats. Daily news reports from around the world highlight the physical and psychological damage that such weapons can inflict on a nation. While the hypothetical impact of nuclear or biological attacks may be more far-reaching, graphic recent examples in the United States, including the September 11, 2001, attacks on the World Trade Center and the Pentagon, and the Oklahoma City bombing, are vivid evidence of the destructive power of conventional threats.

The talents of nuclear scientists and the tools, techniques, and basic data of nuclear physics have extremely important roles to play in countering the terrorist threat. Table 1 lists a number of capabilities of nuclear science that could and should be brought to bear on these problems. In many cases, examinations of nuclear techniques in, for example, airline safety have been underway for some time as evidenced by a variety of National Academy studies and other reports [ref 4.1–4.3].

In basic terms, nuclear techniques can provide a means to determine the relative elemental and isotopic composition of materials by remote sensing employing the high specific sensitivity of the underlying nuclear reactions, radioactive decay properties, and nuclear detectors. Passive techniques can examine the unique decay products of unstable isotopes, which can be enhanced with the tagging of specific elements with radioactive tracers. For example, tagging of commercial igniters and explosives with radioisotopes has been proposed to reduce the threat of terrorist diversion. Active techniques can nonintrusively interrogate the inventory of stable isotopes in sealed containers. Gamma-rays, x-rays, and neutrons are typically the probes of choice as they are able to penetrate through significant amounts of material. Table 4 summarizes many of these techniques. In most cases, identification depends on unusual ratios of atomic composition, such as the relative fractions of hydrogen, carbon, nitrogen, and oxygen found in many explosives. In the other extreme, nuclear hyperfine interactions such as nuclear magnetic resonance and nuclear quadrupole resonance measurements can provide very specific chemical sensitivities to identify selected substances.

It is also clear from Table 1 that the tools, analysis structures, and social organization that the nuclear community has evolved to carry out sophisticated experiments and build state-of-the-art accelerator and detector complexes may provide skills and lessons that are extremely valuable in counterterrorism activities. It is now possible in a rare decay experiment to identify single important events in background of 10^{12} similar but less interesting events. Efficient analysis of terabytes of data is required by modern experiments. Such results require the detailed simulation of the effects of radiation in real materials and real instruments. On this scale, the problems in identifying the potential explosive device carried by one passenger in 500 million per year through customs may look tractable, but are clearly extremely difficult.

The range of threats under the category of conventional weapons and explosive detection is quite broad. To focus the discussion, the working group divided into four subgroups to examine areas of significant current and potential progress: 1) neutron-induced techniques, 2) gamma-ray-induced techniques, 3) gamma-ray detection, and 4) other applications. The first three focused on explosive detection. The typical threats addressed involved detecting and imaging explosives in luggage and/or cargo. The challenge is to find small (subkilogram) quantities of high explosives in suitcases and airfreight containers (of the order of 8'x8'x10') in the presence of normal cargo and, perhaps, deceptive shielding and to find large quantities (hundreds of kilograms) in maritime containers (of the order of 8'x8'x40'). In either case, the scanning would have to be done in a few seconds, or in special cases, minutes.

A related problem is to equip first responders to the threat of a mysterious-possible-terrorist-infernal-device with a portable or transportable interrogation system with which to examine the device without moving it. Here, however, because the device would be singular, a variety of imaging devices could be used and longer interrogation times, leading to improved sensitivity and resolution, could be exploited. If the device were chemical or biological in nature, ionizing radiation (at doses significantly higher than those used for diagnostic imaging and analysis) might be able to neutralize it; if it were a bomb—conventional, nuclear, or "dirty"—its components could be identified.

The fourth subgroup took a broader view of other potential applications of nuclear science to conventional weapons in counterterrorism. Many of these are applications of progress in accelerator, detector, or computational technology by the basic-research community.

The workshop identified areas where physicists doing basic nuclear research have made developments that should be of interest for counterterrorism applications and helped basic nuclear researchers understand how they can contribute to these vital problems of our nation. To assess the current situation, the progress of the broader nuclear community, the counterterrorism community, and industry was examined. The working group did not attempt to perform a detailed quantitative analysis of any of these techniques, nor does it endorse any specific technique as most promising. The results are to identify areas where the increased involvement of the basic research nuclear community shows promise of significant new developments. A summary of the common threads of these discussions is presented as the last subsection.

A. Neutron-Based Inspection Techniques for Counterterrorism

The key to distinguishing explosives from benign materials is the use of elemental analysis. While computerized tomography (CT) x-ray-based systems can give high-precision electron density measurements with high-resolution three-dimensional images, these systems provide limited information about the elemental content of the inspected item (low atomic number, Z, vs. high Z). Neutron interrogation offers the possibility of measuring the density of most elements in materials. Of particular interest in the detection of conventional explosives are the densities of (in order of importance) nitrogen, oxygen, carbon, and hydrogen; their ratios; and other functional relationships between them. A large body of knowledge has been accumulated and a number of well-established techniques have been developed for interrogating materials using neutrons over the years, especially in the last 15 years. However the full depth of this knowledge base is not yet reflected in what is being employed by end-user systems in the field.

This solid foundation of acquired knowledge and expertise provides the base on which new R&D programs can be launched. Neutron-analysis techniques can be divided into two broad types: "neutrons in-gammas out" and "neutrons in-neutrons out,"—that is those in which gamma-rays are detected and those in which neutrons are detected. For a brief review of the field including a representative bibliography on the topic see the article by Gozani [4.4]. Progress in neutron-based inspection systems is directly impacted by many factors; paramount among them are advances in neutron sources, gamma-ray and neutron detectors, advances in signal and data processing, feature analysis and pattern recognition, and issues in government and public acceptance of the use of radiation-based systems. This section briefly summarizes the existing neutron-interrogation techniques and the characteristics of the two primary hardware components. Table 2 gives a quick overview of existing and studied neutron-based interrogation techniques. The material provided here (see also [4.4]) and the vast amount of published information attest to the breadth and depth of the science and technologies already invested in addressing the problem.

Most neutron-based analysis techniques require a high-intensity source of neutrons that is either pulsed or emits a detectable time-correlated particle with the neutrons. The characteristics of currently available commercial neutron sources and the techniques in which they are typically used are given in Table 5 (see also Schulze [4.5]). With the exception of the radioisotopic sources that use the (α,n) and (γ,n) reactions, all other sources offer neutron timing capabilities.

While extensive information is available in the literature and data archives on the fundamental properties of these neutron sources, the existing databases on neutron source properties are not sufficient for neutron-interrogation applications. Consequently, the need to systematically measure (or re-measure) these properties and to accurately and comprehensively characterize realistic neutron sources for candidate reactions such as (p,n) and (d,n) on light nuclei, including neutron yield cross sections, neutron emission spectra, and neutron angular distributions, should be assessed.

Tables 6 and 7 summarize the detection systems used to measure the neutron and gamma-ray emissions following neutron radiation. The main characteristics to consider when choosing the type of gamma-ray detector to use in an inspection system are energy resolution, efficiency, cost, radiation resistance, stability, count rate capabilities, and ruggedness. Recent progress in gamma-ray detection will be discussed below. Commonly used gamma-ray detectors are typically large NaI(Tl) crystals and to a lesser extent BGO, BaF_2, CaF_2, and plastic scintillators due to their relatively high gamma-ray detection efficiency. Improvements in energy, time, and position resolutions and the availability of other promising high-energy gamma detectors could significantly extend the utility and range of applications of the current neutron-based techniques and allow for the development of new ones. Neutron detectors can be grouped into two categories based on the detection mechanism: 1) neutron detectors based on fast neutron interactions, like elastic scattering, and 2) those based on neutron moderation and reactions with thermal neutrons, like (n,α). An excellent general reference on this topic has been written by G. F. Knoll [4.6].

Table 8 indicates the present broad range of applications where the various existing techniques (or those being developed) can be applied providing significant potential security enhancements.

B. Gamma-Ray-Based Inspection Techniques for Counterterrorism

Gamma-ray beams have certain characteristics that are markedly advantageous to explosives and weapons detection:

- **Penetrability.** Gamma rays in the energy region of 1–10 MeV pass through matter, especially low-Z materials, with very little attenuation relative to other kinds of radiation. In this energy region, photoelectric absorption has fallen sharply from its high level at lower energies, pair production has not yet reached its high level at higher energies, and Compton scattering does not have a large cross section. This characteristic is particularly advantageous for rapidly probing large cargo containers, which frequently contain large amounts of low-Z material, such as food and textiles. Of course, cargo containers sometimes contain higher-Z materials, such as appliances and auto parts, but even these materials are usually characterized by low packing densities, and hence amenable to interrogation by gamma-ray beams. By contrast, the ability of neutron beams to penetrate to the center of large cargo containers is limited.

- **Insensitivity to hydrogen.** Gamma-ray absorption and scattering are minimal for hydrogen, unlike the case for neutrons. This characteristic is also particularly advantageous for large cargo containers, which often contain large amounts of hydrogenous material that tends to thermalize neutrons and then absorb them.

- **Low activation.** Gamma-ray beams of less than 10–12 MeV induce little activation in common low-Z materials (C, N, O, Al, Si), which have either high photonucleon thresholds (^{12}C, ^{14}N, ^{16}O, ^{27}Al, ^{28}Si) or else lead to stable nuclei through (γ, n) reactions (^{2}H, ^{13}C, ^{15}N, $^{17,18}O$, ^{29}Si, ^{30}Si). Gamma-ray beams of less than 7–8 MeV induce no activation in nearly all stable nuclides. Also, secondary neutrons from (γ, n) reactions do not have the high flux of a neutron beam. This is made apparent by the fact that U.S. and overseas regulatory agencies have approved MeV gamma-ray beams for food irradiation and they are used widely.

- **High intensity.** Intense gamma-ray beams from electron linacs and microtrons are a mature technology. Simplicity and robustness of operation make them well suited to counterterrorism applications at air and sea ports of entry. On the other hand, the size, complexity, and cost of these systems have thus far limited their use.

- **Ease of image processing.** Image processing, a vital requirement for explosives and weapons detection, is made far easier and more reliable with high-flux beams and the high counting rates they make possible. Spatial resolution of gamma-ray detectors is significantly higher than is the case for neutron detectors. Millimeter resolution without distortion is feasible, and while still not quite as fine as for x-ray film, the difference does not appear important.

- **Multi-functionality.** The same gamma-ray beams that can probe unknown materials in order to identify their isotopic composition can also serve to perform an imaging function.

- **Universality.** Gamma-ray beams can be used to identify any material, since photonuclear cross sections, including those for photoneutron production and photofission (of the actinides) are substantial (for sharp resonances and in the giant-resonance energy region) throughout the periodic table.

- **Specificity.** Virtually any isotopic species is uniquely identifiable, using resonant gamma absorption (RGA) or scattering (RGS, also known as nuclear resonance fluorescence (NRF)).

An essential criterion is creating a reliable device. Only a technology that is robust can be operationally deployed and entrusted with our safety.

A previous Air Force Tactical Applications Center report [4.8] outlines the underlying nuclear theory and compares and contrasts several of the gamma-ray-based techniques with regard to explosives and drug detection. A number of the poster presentations at the workshop provided more information on specific techniques.

There are two general classes of gamma-ray beams—**monochromatic** and **continuous**. **Monochromatic** gamma-ray beams are suited to transmission measurements like RGA. They are made by nuclear reactions of specific interest, and can be as narrow-band as the (thermally Doppler-broadened) nuclear energy levels themselves (See Table 9). For example, the $^{13}C(p, \gamma)^{14}N$ reaction is used to produce gammas that are absorbed preferentially by ^{14}N, a major component of most modern explosives. Use of compound (layered) targets can produce more than one energy beam, so that isotopic ratios (*e.g.*, ^{16}O:^{14}N) can be measured as well. This method thus has a high degree of *specificity* (for those elements for which it can be used), and is compatible with existing elemental-ratio databases for the most common types of explosives and drugs of abuse.

Continuous gamma-ray beams, well suited to scattering measurements like RGS and to pulsed-gamma analysis (PGA) can be produced as the familiar bremsstrahlung from an electron beam striking a radiator, usually a high-Z target. Because bremsstrahlung beams can be very intense, and because all elements emit characteristic “signature” gamma rays, either from scattering or following short-lived activation, these techniques can be used to interrogate a container to identify all of the materials contained therein by identifying the signature energies of the gammas measured with high-energy-resolution detectors. These methods, in addition to their specificity, thus have a high degree of *universality*.

Other gamma-ray beams, partly monochromatic, produced from positron annihilation in flight, tagged bremsstrahlung, or coherent radiation from crystals (*e.g.*, channeling radiation or coherent bremsstrahlung), can be used for special purposes. Over the years, all of these production techniques have been proven as sources of photons as well.

Finally, it should be noted that both the RGA and RGS techniques (as well as the techniques based on photofission for detection of ^{235}U and ^{239}Pu, as well as other fissionable materials, such as ^{233}U, ^{237}Np, and ^{241}Am) depend on having precise and reliable nuclear data, including the properties of nuclear energy levels and transitions (energy, width, multipolarity [to determine the angular distribution of scattered photons]), photonuclear cross sections [(γ, n), (γ, 2n), (γ, p), (γ, f)] and neutron multiplicities, and gamma-ray attenuation coefficients. At the workshop, a series of posters from the new HIGS facility at TUNL outlined the capability (present and future) of this facility to improve these kinds of needed input data, using the intense, polarized gamma-ray beam produced by the Compton backscattering of photons produced in their FEL. The capability exists for making substantial improvements to the existing body of such data, for many crucial isotopes throughout the periodic table, especially when the HIGS facility is able to realize its full potential in terms of intensity.

C. Gamma-Ray Detectors

Practical gamma-ray detectors measure energy lost by secondary ionizing particles produced through photoelectric absorption, Compton scattering, or pair production interactions. The relative importance of the three types of interaction depends on the energy of the gamma-ray and the Z of the absorber. The three basic types of detectors used are gas-filled ionization chambers, semiconductor, and scintillation counters. The first two types measure electrons and ions or holes produced by ionization energy loss of the secondary particle, while the third uses photodetectors to measure light produced by scintillation processes. Table 3 contains the characteristics of gamma-ray detectors in current use.

The choice of a detection system for a counterterrorism device is a complicated optimization of capability, cost, and reliability. The nuclear physics community has the skills and the track record to continue to push the state of the art in all of these three areas. Significant progress is being made. For example, large-scale integrated circuit fabrication techniques have led to substantially reduced cost of large highly pixelated systems, helping reduce the cost on larger systems and providing higher position resolution for imaging techniques with increased segmentation.

To obtain the highest specificity from identified gamma-ray transitions, solid-state detectors based on crystals of the semiconductor germanium are the choice for precision energy resolution, with a line width characterized by $\Delta E/E \sim 0.2\%$. Obtaining this resolution requires operation at liquid-nitrogen temperatures, which has been a disadvantage for remote deployment. A recently developed germanium detector system displayed in one of the workshop posters enables field portability for germanium detectors, by cooling the germanium crystal to ~100K with a small low-power Stirling cycle cooler. The downside is degradation in energy resolution to ~2 times laboratory resolution.

Current technology limits the size of the germanium crystals to cylinders ~10 cm long by 8 cm diameter. The efficiency of the detector for high-energy gamma rays is limited by the detector volume. Nuclear physicists have developed close packed arrays of individual detectors, *i.e.,* Gammasphere (see sidebar on page 9), greatly improving the detection efficiency for high-energy gamma radiation, as well as the ratio of signal to noise. The most promising major step forward is new research to add position sensitivity to the high energy resolution of germanium detectors [4.9]. This gamma-ray tracking technology enables both imaging a source by detecting the direction of the original gamma-ray and significantly increasing the total efficiency by following and summing up the multiple interactions of a gamma-ray in the crystals. Further, background radiation can be suppressed based on directionality. To take full advantage of such techniques requires significant digital signal processing and powerful reconstruction algorithms and processors. Over the past few years proof-of-principle of this technology has been demonstrated. Progress is underway on prototypes of two systems: 1) the gamma-ray energy tracking array (GRETA) [4.9] is a large-volume germanium detector array with position resolution of 1 mm, and good efficiency for high energy gamma rays and 2) double-sided planar germanium X-Y strip detectors are thin (2 cm) germanium detectors, recently capable of depth resolution. In this system, position resolution is about 1 mm. Efficiency is obtained by stacking frames of x-y strip detectors.

Scintillation crystals, such as NaI and BGO have been the workhorses of industrial gamma-ray detection as they offer large volumes and energy resolution of ~6–8%. These scintillators are also very efficient, especially for high-energy gamma radiation. There is an ongoing basic research effort to develop new scintillating materials to improve the performance or reduce the cost for specific applications.

Plastic and liquid scintillators offer large volume at the expense of energy resolution. Physical segmentation gives the possibility of rough position resolution, and the large volumes enable sum energy spectroscopy. Plastic and liquid scintillators are sensitive to neutrons as well as gamma-rays. Pulse-shape discrimination can distinguish neutron and gamma-ray events.

D. Other Nuclear Techniques: Nonionizing Techniques, Safeguards, and Forensic Applications

This subgroup gathered information regarding a variety of proposals not directly involving interrogation with ionizing radiation. Here a few attractive ideas and relevant work of interest are highlighted.

New imaging science initiatives and advanced technological developments in the terahertz (THz) electromagnetic radiation band were discussed. Beams from 0.1 to 10 THz at high powers (100s of Watts) using subpicosecond bunches of relativistic electrons exist. The available power could revolutionize THz applications by allowing full-field, real-time image capture. This is particularly relevant for counter-terrorism in that "T-ray" beams can penetrate plastic, concrete, and other common materials, and can recognize and identify biological and plastic materials as well as concealed weapons. Unlike many other forms of radiation, THz light is nonionizing. During the past decade, THz waves have been used to characterize the electronic, vibrational, and compositional properties of solid-, liquid-, and gas-phase materials. In addition, THz radiation could determine the structures of many complex chemicals. Possibilities exist for inspecting packages and people at ports of entry, in order to detect and characterize chemical and biological agents or plastic explosives, or for obtaining images through barriers such as concrete walls.

Another exciting suggestion was to use ultraviolet (UV), infrared (IR), or electron radiation for antimicrobial polymer surface treatments. Widespread low-level contamination accompanies biowarfare and bioterrorism; it may even be the focus of the latter. Because advance knowledge of the timing, location, and choice of pathogen in such incidents cannot be anticipated, it is appealing to provide broad-spectrum, antimicrobial activity to surfaces likely to be exposed. While the idea of adding toxic entities to surfaces is not new (consider, for example, the widely used antiseptic wipes), the ability to bind such substances to surfaces has been elusive. Considerable progress has already been made toward technology that transforms the nylon surface into highly active cytotoxicamines. Grafting of amines to polyester has been demonstrated. Using this type of technology, a large number of counterterrorist applications can be considered and were discussed in the workshop posters. Envelopes impervious to anthrax, for instance, provide a notable example.

A very promising advance was the development of portable, fast, wide-band, sensitive spectrometers for direct measurements of nuclear and molecular masses. A multipass time-of-flight mass spectrometer (MTOF-MS) uses a given geometric flight path repeatedly to achieve long flight times and, thus, high mass-resolving powers. An MTOF-MS can use all ions formed in an ion source to produce a mass spectrum, and thus can achieve higher sensitivity than scanning mass spectrometers. The compact geometry of an MTOF-MS allows for the design of a portable trace analyzer capable of producing a distinctive mass spectrum in just a few seconds. Gas admixtures of 0.1 parts per million (ppm) have been identified. It is possible to distinguish more than 90% of all organic substances from each other without the use of time-consuming chromatographic techniques, thus reducing the time required for a full sample analysis from many minutes to merely seconds. Potential applications of such devices in the area of homeland security include fast and sensitive detection of minute traces of either airborne or transported biological and chemical hazards. Particularly noteworthy is the ability to detect conventional explosives that are not rich in nitrogen. Furthermore, detection capability not only of conventional explosives that readily form negative ions (as utilized in mobility spectrometers), but also of those that form positively charged ions, allows for combination with complementary detection techniques to significantly reduce or even eliminate false alarms.

Other ideas presented in the context of radiological threats may have relevance to conventional weapons as well. Air sampling may prove to be useful both in forensic and early-alert applications. A variety of analysis and detection techniques could be employed for chemical, biological, and other agents either of direct harm or associated with the manufacture of elements of direct harm. One poster presented the interesting idea to sample air via the regular analysis of particulate matter trapped in the automotive air filters of municipal vehicles such as police cars and public buses which have known, regular, routes.

Another such crossover project was a report on the monitoring of a web page with nuclear data information. The number, type, and origin of hits was presented, making it possible to see, for example, which countries had a lot of activity from people looking up plutonium. This kind on monitoring could be extended to chemicals involved in explosives, biological toxins, etc.

Finally, in connection with the impressive efforts in gamma-ray tracking development discussed above, it should be stressed that "dual modality" or "image fusion" techniques between ideas presented here and photon images should be investigated. In this approach, simply put, images obtained via a variety of techniques are superimposed on top of one another. Different images may provide different pieces of information, and a combined approach such as that suggested here should provide the most diagnostic information, reducing some need for multiple separate measurements. An example from instrumentation development for nuclear medicine is useful: x-ray information providing density profiling may be combined with positron emission tomography (PET) imaging to provide metabolic activity information. In this, it is evident whether or not an area of increased density, suspicious of a tumor, is highly metabolically active and therefore truly indicative of disease. The "fused" image is more powerful then the two images utilized separately.

E. Outlook

This brief review of the status of nuclear techniques for the detection or neutralization of contraband explosives and drugs has enumerated a variety of techniques that can be used, and outlines the general status of development of the technologies. Many other examples were presented in the workshop posters. As a consequence of this survey, several areas of development look promising.

- **Accelerators:**

  The large investment in our field in accelerator technology offers the possibility of significant improvements in accelerator systems for these nuclear techniques. The key for counterterrorism applications is a greater attention to requirements of reliability, portability, and ruggedness than is usually required in research settings. Linking the technology improvements of the nuclear community with industrial partners is likely an important component of exploiting these advances.

  - **Accelerator-based neutron sources**—An important near-term potential for improved system performance exists through improvement in neutron sources. For example:

    Substantial advances in neutron-source technologies are expected in the next five years. Commercial suppliers of portable neutron generators are making sources more compact and more reliable at an impressive pace. Over the next few years the lifetime of sealed-tube DT neutron generators is expected to increase from about 1000 to 3000 hours. Compact sealed-tube sources are well suited for portable systems such as those being used for searching for car bombs.

Greater output of neutron sources will increase the stand-off distance of the detection system. The source development work done at Lawrence Berkeley National Laboratory (LBNL) has the promise of resulting in sources that can deliver average neutron intensities of 10^9 n/s for the D(d,n) reaction and 10^{11} n/s for the T(d,n) reaction. These intensities are about 1000 times greater than what is commercially available today. Similarly, basic research in increasing the primary intensities of 5–7 MeV tandem electrostatic or similar charged-particle accelerators would lead to increased neutron intensities via the D(d,n) reaction (with a goal of achieving average d^- currents >250–500 microamps, at 1–5 MHz, 1 ns pulsing) while retaining the characteristic high beam quality, energy, and time resolutions: This will further advance the high-performance neutron-based inspection systems.

- **Accelerator-based gamma-ray sources**

  Many of the same advances in ion accelerators can greatly enhance the production of gamma-rays for nuclear-resonance absorption and scattering measurements. One such development, a vacuum insulated tandem accelerator, was illustrated by a poster at the workshop.

  Continuous gamma-ray beams can employ the progress in basic research in electrostatic, microtron and linear accelerator development. Significant improvement in intensity, reliability, portability, and cost seems possible based on recent developments.

  One of the major advances in x-ray and gamma-ray production has been the progress on stimulated production systems at FELs. The JLAB energy-recovering FEL is opening new industrial possibilities in high-power x-ray production for material processing such as the antimicrobial surfaces discussed above. Such devices can lead to potent sources of THz radiation for imaging. The TUNL HIGS facility at the Duke FEL provides greatly enhanced capabilities for basic nuclear data measurements.

- **Detectors:** The most significant improvements in detector technology are likely to arise from developments in signal processing and tracking detectors, both for neutrons and gamma rays as was illustrated by several workshop posters. Position and angular resolution will greatly enhance the imaging capability over presently employed systems. For gamma-ray detectors, this is a major research activity of the field as recently reviewed by the report of the Gamma-Ray Tracking Steering Committee [4.9]. An example for neutron detectors would be the improved time (and therefore position resolution in pulsed systems) that could be achieved with improved signal processing.

- **Nuclear data:** Assessments of the basic nuclear database are needed to identify reactions where improved data would substantially benefit existing and future inspection systems. For neutron-induced systems this includes neutron-yield cross sections, neutron-emission spectra, and neutron angular distributions, not only for thin target sources but also for thick targets as well. Also important is an assessment of the neutron-induced reaction database, *e.g.,* $(n,n'\gamma)$ and (n,γ) reactions. This is a task that the low-energy nuclear physics research community is well equipped to undertake in the near term.

- **Advanced pattern recognition:** The experience accumulated in the nuclear physics community in identifying single or a few events in a huge background could be of potential help to the field of the neutron-based inspection where often very weak but significant signals are to be found in a high-background environment. Ways to use this experience need to be studied.

- **Simulations:** Improved simulation tools for radiation transport is a key element of proper modeling, device and/or proposal evaluation, and "training" of pattern-recognition algorithms. This progress must be exported in reliable, well-documented, and easily exportable modeling packages.

- **Education:** Training scientists to effectively employ nuclear techniques is one of the most essential functions of the basic-research community. Many of the techniques of direct application are regularly used in low-energy nuclear experiments. Higher-energy nuclear research also has an important role to play in accelerator, detector, analysis, and infrastructure development. A key is to open the eyes of students and their advisors to the value of this education for counterterrorism.

This section has summarized a broad role for nuclear science in the tapestry of countering terrorists' threats in the areas of conventional weapons and explosives. Many of these threads have significant common ground with the role of nuclear science in countering radiological and nuclear threats discussed in the following section. While progress is continuously being made by the broader nuclear community and industry, the talents and developments of basic nuclear research are achieving notable short-term and long-term advances that should be applied to these challenges. What is needed are new mechanisms to significantly enhance the linkage of the nuclear-research community with federal, state, and local agencies and private businesses actively engaged in countering terrorism.

5. Report of the Radiological and Nuclear Threats Working Group

For many, the workshop provided a first contact between the nuclear physics research community and the agencies charged with our national security. The communication begun at the workshop was an effective start in helping define ways in which the nuclear physics community can contribute to the national-security needs that have become even more important since Sept. 11, 2001.

The nuclear physics community provides basic research expertise, spanning universities, nondefense national laboratories, and defense laboratories. The radiation detectors and electronic circuits currently used to monitor radiation threats in and to the U.S. were largely developed by the nuclear science research community over a number of years. These include Geiger counters, scintillators of sodium iodide and other materials, semiconductor diode detectors using silicon and germanium, various detectors of slow and fast neutrons, pulse shaping circuits, analog-to-digital converters, and multichannel analyzers. In addition, the community has developed an arsenal of accelerator facilities supported by the DOE and the NSF (see Table 10). Past history shows that the nuclear research community will continue to develop new detector and accelerator systems in the future that will improve our ability to both identify and monitor radiation threats.

The nuclear research community (and the high-energy physics community) also pioneered the use of computers for real-time data acquisition and data analysis and developed the data-mining and pattern-recognition techniques to identify an event of interest in a background of $\geq 10^{12}$. In addition, the large body of knowledge and understanding the community has gained on basic nuclear reactions and structure is invaluable for determining how to best monitor, detect, and attribute various radiological and nuclear threats. Nuclear scientists have served in advisory positions, are leaders in our nation's universities and nonweapons and weapons laboratories, have helped establish standards, and play a large educational role—both in the research community and for the general public. The nuclear physics community is clearly involved and has much to offer in helping to combat terrorism.

The workshop has helped to inform this research community about the highest priority goals seen by the agencies charged with national security. As presented at the workshop these include:

- *Detection of kg quantities of fissile materials, particularly ^{239}Pu and ^{235}U in the form HEU (> 20% isotopic enrichment of ^{235}U).* HEU presents the greatest challenge because it is harder to detect and perhaps easier to obtain. As has been noted often in the past, HEU lends itself more readily to improvised nuclear devices, because a gun-type weapon is comparatively easy to design.

- *Detection and identification of Curie quantities of radioisotopes, especially those used in medical procedures, fire alarms, etc., that might be readily accessible.* The threat here is the coupling of an intensely radioactive substance to a conventional explosive creating a radiological dispersion device, to use recent terminology of the popular press.

- *Detection at a large standoff distance—100 m compared to near distances of 1–10 m.* This is driven by the need to monitor large quantities of imports and shipments around the country. Larger detectors with higher sensitivity would help address this goal.

- *A higher signal-to-noise ratio in order to reduce nuisance alarms.* We were repeatedly reminded of the high cost of nuisance alarms requiring further examination at facilities that are already operating at capacity.

- *Lower-cost and smaller-size radiation detection systems to allow more widespread use.*

- *Providing expertise in radiation detection to local emergency-response personnel.*

The wide range of detector needs to meet these goals can be summarized as follows:

- sizes ranging from handheld to that of freight containers;
- distances ranging from touching to large standoff;
- monitoring times ranging from a few seconds to ocean-crossing times;
- requirements of efficiency, energy resolution, and time resolution; and
- methods ranging from passive observation to active interrogation.

There was little time at the workshop to go into much detail in the two working groups—only two meetings of each working group were held. There is a substantial degree of overlap in the resulting reports of the two groups—not too surprising given the fact that the participants were all nuclear physicists or chemists with the common goal of using the community's expertise to aid the several agencies charged with working on issues associated with terrorism.

In an attempt to focus the discussion and to use the limited time to the best advantage, the Radiological and Nuclear Threats working group (see membership list in Appendix IV) divided into four subgroups to address the needs/goals presented by the agencies and to assess the possible role of nuclear research physicists in combating terrorism. Reports from the four subgroups are presented here. These are:

- detectors and electronics;
- accelerator applications in combating terrorism;
- databases, data analysis, and simulation; and
- education and outreach.

Some of the ways in which the nuclear science research community can help to meet these needs and goals are summarized in this report. In addition, the posters presented at this workshop[4] demonstrate ways in which the community is already working to improve homeland security.

A. Detectors and Electronics

- **Overview**

  Detectors for gamma-ray detection, neutron detection, and detection of fissile material as well as the associated electronics were reviewed by this group. Several techniques were identified for further research.

- **Gamma-ray Detection**

  Many of the security community's needs involve the detection of gamma rays. Beyond the simple Geiger counter that only indicates the presence of radiation, the workhorse appears to be the sodium-iodide scintillator. This mature technology still provides high sensitivity and large volume with moderate cost and energy resolution. The moderate resolution limits its ability to differentiate between different radioisotopes and between natural background and potentially more dangerous materials. An example of ongoing research progress is the development of compact scintillator-photodetector systems for greater portability.

  In contrast to the sodium-iodide scintillator, the germanium diode detector provides much higher resolution to allow definite radioisotope identification and high selectivity above background. Some of its drawbacks include higher cost, limited crystal size, and the need to operate at cryogenic

[4] http://www.sc.doe.gov/production/henp/np/homeland/posters.html

temperatures. The recent development of a handheld germanium detector system with a built-in refrigerator would be directly applicable to security monitoring [5.1]. An electronics challenge is to build suitably miniaturized electronics for signal processing and local intelligence in order to provide an instant readout of what radioisotopes have been detected.

The nuclear physics research community has worked hard on the limitation of germanium crystal size and has gained considerable experience in operating arrays of detectors. The largest of these, Gammasphere, uses 110 germanium crystals to obtain unprecedented sensitivity. The newest development is gamma-ray energy tracking to greatly increase the efficiency of germanium detector arrays. This ongoing development effort should provide important improvements applicable to the security arena. The tracking project involves the development of segmented germanium detectors, digital signal processing electronics, and fast algorithms. One important offshoot will be a greatly improved Compton gamma-ray camera. Its directionality and spatial resolution would be valuable for security monitoring.

For years the nuclear research community has recognized the need for gamma detectors whose performance lies between that of germanium diodes and sodium iodide scintillators. Such detectors would also be very valuable for security applications. One approach under development is large-volume, high-pressure inert-gas (such as xenon) ionization chambers [5.2, 5.3]. These promise high sensitivity and relatively low cost with an energy resolution better than sodium iodide, but less than germanium.

- **Neutron Detection**

  Neutron detectors are very valuable in the search for fissile materials. Nuclear science researchers continue to develop new high sensitivity neutron detectors. Examples are improved ^{3}He ionization counters and ^{6}Li loaded phosphors and scintillators. Large neutron detector arrays, such as Very Large Area Neutron Detector (VLAND) [5.4] and modular neutron array (MoNA) [5.5], have been developed for frontier-research purposes. This technology could easily be transferred to security applications for real-time monitoring of moving sources.

- **Fissile Material Detection**

  Fissile materials could be detected more easily by probing suspect containers with neutron or gamma beams. However, this technique is limited by the need to avoid irradiating the general public. An example of “thinking outside the box” is a proposal to use the ever-present cosmic-ray muons to probe containers [5.6]. While there are many technical questions about an approach such as this, it has been used to search for hidden rooms in Egyptian pyramids and could lead to valuable security applications in the future.

- **Electronics**

  An integral part of all the radiation detectors is the “front-end” electronic circuits needed to extract the maximum possible information from the sensor and to convert it to a digital format for analysis and display. Low-noise high-gain preamplifiers, filters, and signal processors have been pioneered by and for the nuclear science research community. Development of such state-of-the-art specialized electronic circuits will certainly continue apace with advances in detector and electronic component technologies.

  One facet of electronics in recent nuclear experimental instrumentation that has not been exploited by commercial vendors is large scale integration of “front-end” circuits. Custom integrated circuits have been designed to provide over 200,000 channels of state-of-the-art signal processing at a cost of only a few dollars per channel and very small area. This technology could have a major impact on the cost, size, and performance of imaging detectors for security applications. The possibility of incorporating pattern-recognition capabilities associated with the large detector systems used by today's basic-research community should be further studied for application to counterterrorism issues.

- **Summary**

The nuclear science community has already developed an impressive arsenal of detectors and associated electronics. New and better detectors are currently under development and several of these have been identified for further research for their potential use in homeland security. However, significant development is still needed to translate laboratory performance to specific systems that meet the needs of the counterterrorism community. The challenge is to design integrated detector systems that satisfy the requirements of size, portability, cost, reliability, and ease of operation. Continued dialogue between the nuclear science community and the agencies, followed by focused R&D, will be necessary in order to meet the homeland-security needs.

B. Accelerator Applications in Combating Terrorism

- **Overview**

The application of particle accelerators in combating terrorism falls into three major categories. These are inspection, forensics or attribution, and accumulation of basic nuclear and material-properties data. In each area a significant amount of development and, in some cases, deployment has already been undertaken. Nonetheless, further work is required to provide reliable, easy to use tools for inspectors; to fully develop the forensics tools needed to accurately and efficiently screen contraband materials; and to provide the basic material data necessary to design equipment and understand the data taken both for inspection and forensics.

- **Inspection**

The use of accelerators to provide active probes (mostly neutrons or photons) to rapidly and accurately inspect luggage, shipping containers, and personnel has received significant attention over the past two decades. However, presently available systems often fall far short of the desired level of intensity, reliability, portability, and ease of use. The desirability of interrogating ship containers will increase the neutron or photon beam size and flux demands to levels not previously considered.

Neutron interrogation of packages in the field have used neutron radiography and thermal neutron (activation) analysis (TNA). Recently proposed techniques include prompt gamma activation analysis (PGAA) and pulsed fast neutron analysis (PFNA). Neutron-induced fission is an especially attractive technique for identifying packages that contain fissile materials. In most of these applications, the accelerator and the detector are intimately related and must be designed as a system. The conflicting demands for these systems include small size, high flux, portability, and low cost. Neutron tube systems are being developed to address these issues. These consist of a radio frequency (RF) -driven ion source, an electrostatic accelerator, and a target. They produce neutrons via either D-D, D-T, or T-T fusion reactions. Presently available compact neutron tube systems are limited in flux (10^8 n/s), have operating lifetimes of less than 1000 hours, and are relatively expensive when considering massive deployment. Recently, new laboratory sources have been developed with gains of 100 to 10,000 in flux and are of a simple design suggesting rugged reliable operation is possible [5.7]. Cost reductions in high-voltage switching power supplies are necessary to address realistic budget constraints and new well-engineered tube designs are needed to increase the lifetime. Neutron beams with time structure of a few nanoseconds are necessary for neutron absorption spectroscopy. Presently such beams are available only in large laboratory settings. However, it seems feasible to build short, simple linac structures for field operations.

The proposed use of photons in package inspection covers a range from a few keV x-rays to MeV gamma-ray energies. Low-energy x-ray inspection of packages is a widely deployed technology and is not considered in this discussion. Techniques proposed for high-energy photon inspection include NRF, PGA, and uranium photofission. The systems in use and proposed mostly use either bremsstrahlung or synchrotron radiation requiring electron energies of only 10–20 MeV and beam currents with intensities generally in the few milliamperes or less. Simple, compact, and reliable linac S-band and X-band systems are available commercially but will need to be adapted for the explicit applications.

- **Forensics and Attribution**

Identifying materials confiscated in terrorism incidents, during routine inspections, or found during security raids, and their possible sources may be assisted using a number of accelerator-based techniques. AMS may be useful in comparing trace isotopic ratios of material that may be unique to a particular material-processing path. Measuring isotopic ratios as low as $5x10^{-17}$ has been demonstrated for some elements [5.8]. Detection of actinide isotopes with concentrations as low as 10^8 atoms/gm has been demonstrated [5.9]. Most of this work has taken place at large complex heavy-ion linear accelerator or high-voltage tandem accelerator facilities. Recently, detection of ^{244}Pu was demonstrated at a small 3MV tandem AMS facility creating the possibility of actinide detection at smaller, simpler, and cheaper installations than have been used to date.

AMS also has potential use in the identification of nuclear fuel reprocessing by monitoring the trace concentrations of ^{36}Cl or ^{85}Kr in air samples. AMS with these isotopes requires the use of relatively large (10–30 MV) heavy-ion accelerator facilities in order to clearly separate the trace isotopes from stable isobars. At this time, the use of existing, complex heavy-ion accelerator facilities is the only option for these AMS measurements. Another new technique for high-sensitivity mass spectroscopy is the ATTA system [5.10, 5.11]. Detection of ^{85}Kr has been demonstrated with ATTA at this point. Neither ATTA nor AMS hold any short-term promise for a simple portable easy to use facility, but ATTA may be considered as a large "table-top" system, albeit complex.

NRF may also be applied to forensic and attribution cases. Small portable systems using relatively low-energy electron beams are feasible as discussed above. If high-energy gamma rays are desired, then much higher beam energies are necessary and are not readily available. Only one facility in the U.S. is presently capable of providing gamma rays from 2–50 MeV with intensities up to 10^8 gammas/s (TUNL-HIGS). While not practical for field use, these beams can be used for specialized interrogations, and for developing a database for NRF and other investigations.

- **Nuclear Data/Material Interaction Data**

Improved data in many areas are desirable to facilitate a number of detection and forensic approaches and to reduce the false positive and error rates. For example, accurate gamma-ray attenuation coefficients are needed in order to develop the technique of gamma-ray radiography. Current values are known to 2–3%, while values of 0.2–0.5% are needed, especially on actinide nuclei. In order to develop and refine the technique of gamma-ray interrogation, especially for the actinide nuclei, accurate spectra from (γ,n), $(\gamma,n\gamma)$, and (γ,γ) reactions are needed. Other requirements include improved photon attenuation coefficients, (γ, xn) cross sections, neutron absorption and scattering cross sections, and neutron amplification in bulk materials. Existing facilities (see Table l0.a and l0.b), in some cases with enhanced beamlines or detection systems, are generally capable of providing beams with the required characteristics.

- **Summary**

  For the applications presently identified in this workshop, the properties of existing accelerator systems have either already demonstrated the ability to deliver the required beam properties or developments in progress seem likely to achieve the necessary capabilities. In addition, development activities underway should soon demonstrate significantly increased neutron fluxes from simple systems. Even higher gamma-ray energies will soon be available for measuring additional nuclear and material properties.

  Significant engineering development is needed to translate laboratory performance to specific systems that meet the needs of the counterterrorism community. The challenge is not in demonstrating specific beam characteristics and matched detector performance but designing integrated systems that deliver application-specific beam parameters in a configuration that satisfies the system requirements of size, portability, cost, reliability, and turnkey operation. Each application comes with a different set of system specifications and therefore a different set of physics approaches and different engineering solutions. Continued dialogue between the nuclear and accelerator community and the potential customers, followed by focused R&D, will be necessary in order to meet the actual needs of homeland security.

C. Databases, Data Analysis, and Simulation

- **Overview**

  Nuclear databases[5] and the supporting infrastructure built up over several decades are a significant contribution of the field to the area of national security. These high-quality, standardized, and validated databases, and the nuclear data evaluation community that can integrate experimental and nuclear theory/models to produce them, are major resources.

  Databases. Evaluated nuclear databases, developed over the past five decades, represent a major national resource, largely supported by the DOE, Office of Science, Nuclear Physics Division. These databases contain validated and standardized information on nuclear structure and decay properties, as well as nuclear reaction cross sections. In the context of counterterrorism, they play an important role; they are crucial components in passive and active interrogation schemes for detection of nuclear materials. They also play an important role in emergency response “home-team” code simulation capabilities to model (and render-safe) potential proliferant nuclear devices.

  Data analysis and simulation. Nuclear databases represent a key element in data analysis and simulation. For example, the Evaluated Nuclear Structure Data File (ENSDF) and its derivatives such as the LBNL Table of Isotopes are of critical importance in analysis of complex spectra to identify radioactive materials. On the other hand, reaction databases are indispensable in neutronics calculations. For example, the Evaluated Nuclear Data File (ENDF) database is an inherent part of the Los Alamos MCNP Monte Carlo simulation code used widely in nuclear simulations.

  Organization. A major element in the U.S. nuclear data effort is the U.S. Nuclear Data Program sponsored by the DOE Office of Science, Division of Nuclear Physics (26 full-time employees [FTE], $4.9M in FY02). This program has lead responsibility for the structure and decay databases, as well as an important role in the reaction databases. The U.S. Cross Section Evaluation Working Group is focusing on development of nuclear-reaction databases. A focal point for U.S. nuclear-data activities is the National Nuclear Data Center at Brookhaven National Laboratory (BNL), responsible for

[5] The databases can be accessed at http://www.ndc.bnl.gov and http://www.ie.lbl.gov.

coordination, as well as for the archiving, maintenance, and dissemination of all nuclear physics databases.

- **Accomplishments**

Nuclear structure database (ENSDF). This national resource provides evaluations, based on experimental data of nuclear structure and decay properties, for stable and unstable nuclides. This decay information is important for identifying nuclear materials through characteristic gamma rays and other types of radiation. This "standard" database is used widely by workers in emergency response, counterterrorism, etc. in passive diagnostics for detection of nuclear materials. As of June 2002, the database contained information on nuclear structure properties for all known 2,898 nuclides, covering information for 130,065 nuclear levels and 187,506 gamma transitions.

Nuclear reaction database (ENDF). This database is used in simulation codes for identification of potential proliferant nuclear weapons. This national resource is a compilation of cross sections, based on experiment, theory, and modeling, for nuclear reactions on stable (and some unstable) nuclides. Data libraries are available primarily for neutrons, though recent work has provided new databases for photon and proton reactions. These physics data are used by emergency-response "home teams" in nuclear radiation transport simulation codes to construct models of proliferant devices based on experimental measurements of neutron and gamma-ray leakage.

Nuclear Wallet Cards. These contain a subset of information from the aforementioned ENSDF nuclear structure database, and provide a convenient and accurate "standard" set of information needed by people who work with nuclear materials. In March 2002, the DOE Office of Security, Nuclear Materials Management and Safeguards System adopted the Nuclear Wallet Cards as a standard for radioactive decay data.

Ongoing activities and ideas of the nuclear data community in combating terrorism were illustrated on three posters presented at the workshop.

  - *Nuclear data for homeland defense and national security.* The poster summarized current activities of the U.S. Nuclear Data Program and explained its ideas for future nuclear data developments, including safeguards and nuclear materials management, nuclear interrogation, stockpile stewardship and radiochemical analysis, and a new generation of reactors.

  - *Accurate determination of the critical mass of ^{237}Np.* Neptunium-237 is a possible candidate for construction of an illicit fission device, being outside of the IAEA Special Nuclear Materials Atomic Energy Act (1954) and its amendments. Substantial improvements in nuclear data are needed for determining the critical mass of ^{237}Np and assessing its potential terrorist threat.

  - *WWW search for nuclear terrorism activities*. This is an interesting idea to use the website of the LBNL Isotopes Project that provides the most widely used international source of nuclear structure data. Correlations have been found between usage of the website and the location of the users.

- **Summary**

The nuclear data community can provide and further develop/improve standards important in measurements of fissile and radioactive materials, such as the decay standards included in the Nuclear Wallet Cards, and detector calibration standards. The data community can also provide new references such as the proposed handy Wallet Card, with basic decay data for a selected list of radionuclides, along with agency contacts in case of nuclear emergencies.

Monte Carlo simulations are of critical importance for homeland-defense applications, and the nuclear data community has long-term experience and expertise in this area, such as the MCNP code and related databases like the reaction database ENDF. This expertise should be more effectively utilized through collaborations between the transport/diagnostics communities and the cross section/data communities, to ensure that cross-section database advances are well aligned with needs in the counterterrorism community.

D. Education and Outreach

- **Overview**

Applications of the many tools and skills of the nuclear science community to aid in combating terrorism and its threats will require skilled scientists and technicians, current and future, and closer connections to new communities and customers. A first need is to connect capable nuclear scientists concerned with terrorism issues more closely to existing federal agencies charged with homeland security. A significant step was taken at this workshop, and agencies now know quite a few scientists they may call upon. Other efforts within our community should provide materials to enable our community to answer questions, help meet the needs of all agencies, and strengthen our efforts in all phases of education, in particular, increasing the "awareness" of the general public.

- **Accomplishments**

Previous actions taken by the basic nuclear physics research community have provided the bases for the outreach and education needs we face. Most direct is the longstanding role of colleges and universities in nuclear research and education that has provided a strong pool of well-educated nuclear scientists.

Educational materials have been developed, including the Nuclear Science Wall Chart and Teachers Guide, wallet cards from the U.S. Nuclear Data program, and web sites such as "The ABCs of Nuclear Science."[6] From the experience gained in these activities, the nuclear physics research community is confident that its role in education and outreach relevant to homeland security can be successfully expanded.

- **Examples of Possible Future Activities**

Many federal, state and local agencies are newly faced with the need to assess and address threats or events. Many have few resources and little training. The community could provide nuclear scientists, for instance members of the American Physical Society, Division of Nuclear Physics (APS/DNP), with the means to assist local agencies, principally with nuclear issues, but also with advice on applications of nuclear science that may apply to other threats. Scientists could then initiate conversations, enhance understanding, and be ready for calls on short notice. The expertise of the research community could be very useful in advising and training local agencies such as police forces or fire departments on the principles of nuclear physics and the use of radiation detectors. The specific needs could require more precise materials. The following is recommended:

  - *Creation of a new wallet card, with basic decay data for a selected list of radionuclides, and agency contact telephone numbers in case of nuclear emergencies.*
  - *Creation of informational materials suitable for a nuclear scientist to give a short course or briefing, perhaps only one hour, to concerned but nontechnical responders or local authorities on the principles of nuclear physics and radiation detection.*

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[6] http://www.lbl.gov/abc

- *Creation of a web site, suitable for use by a nuclear scientist, for familiarization with the issues.* This must be relevant to the likely questions arising from responding state or local agencies.

Many vendors are offering gear to federal, state, and local responders. Some may be ineffective or inappropriate, and some may be hard to use. The research community has the expertise to review these offerings, and needs to find ways to provide advice. The nuclear physics research community could also assist the relevant agencies in creating a list of questions that a potential purchaser should ask.

The nuclear physics research community develops scientific knowledge, technologies, and trained manpower that are critically needed in developing a technically world-class and knowledgeable workforce that can effectively combat terrorism. A significant fraction of the scientists awarded PhD.s in nuclear physics follow career paths to defense-related nuclear research. More specific examination of the complementary relationship between nuclear physics research and homeland security may further enhance the perspective of this future workforce. For example, universities and colleges might consider discussing this relationship within their current or future curriculum. This topic could also be incorporated into the meetings and summer schools of the APS/DNP. The Education Committee of the APS/DNP might consider developing a course for remote delivery, suitable for credit as a special topic. University and laboratory departments may consider becoming better acquainted with the problems and issues of nuclear terror. One way to raise awareness level is through invited colloquium speakers.

Civic education on nuclear matters also needs to be improved. Lesson plans and teaching materials could be prepared, and use of the Nuclear Science Wall Chart and other tools for high-school science classes could be expanded in collaboration with schools of education.[7]

It is not only the U.S. nuclear research community that is concerned with terror. Avenues to include appropriate foreign scientists into our efforts should be explored.

- **Summary/Resources**

The Department of Energy Division of Nuclear Physics and the Physics Division of the National Science Foundation are the two federal agencies charged with supporting the Nation's basic research in nuclear physics. In recent years, federal funding has not kept pace with the actual ~4% cost of living increases for nuclear physics research at universities, national laboratories, and research facilities. As a result, university research groups have been hard hit, with high-quality grants reduced or terminated and many promising initiatives rejected; the number of graduate students has been declining from its value that peaked in the early 90s. State-of-the-art accelerator facilities to address forefront physics are essential for the U.S. to maintain its world leadership role in nuclear physics research. The facilities are necessary not only to make progress in our understanding of fundamental nuclear physics and generate new accelerator and detector technologies, but also to provide scientific opportunities for discovery that generate sufficient interest and excitement to attract the brightest students. Constrained funding has resulted in less than optimal operations and loss of personnel.

In recent years, ~20% of nuclear science Ph.D.s have chosen to pursue careers in national security. However, as stated in the Nuclear Science Advisory Committee 2002 Long-Range Plan for Nuclear Science, “The total number of physics Ph.D.s awarded in the U.S. has been declining in the past five years, with a somewhat more rapid decline in the number of nuclear science Ph.D.s. Allowing this trend to continue will imperil our leadership position in nuclear science research, as well as impede progress in such related areas as nuclear medicine and national defense.”

[7] One example of such a joint effort is found at http://www.colorado.edu/sciencediscovery.

The federal support of the basic physical sciences should be sufficient to ensure that the nation has a future workforce trained in the full spectrum of technologies related to the mission of countering the terrorist enemy. Adequate support would enable enhanced education/outreach activities such as those proposed above to be effectively implemented.

E. Summary

The greatest resource of the nuclear science community is its people—the highly trained, experienced, and motivated researchers and support personnel who are distributed across the nation in universities and national laboratories. This may be the greatest contribution from the basic research community to national security.

The laboratories and universities are also equipped with a wide range of state-of-the-art accelerators and detectors. Development is still needed to translate laboratory performance to specific systems that meet the needs of the counterterrorism community. The challenge is to design integrated accelerator and detector systems that satisfy the requirements of size, portability, cost, reliability, and ease of operation. Continued dialogue between the nuclear science community and the agencies, followed by focused R&D, will be necessary in order to meet the needs of homeland security.

In addition to developing better and more portable detectors and electronics that can be used by the security services, the community can contribute to homeland security in a number of ways. We can give expert advice to the agencies; provide independent, unbiased evaluations of proposals and detection equipment and techniques; provide training; and help with attribution by using knowledge and laboratory capabilities to identify and "fingerprint" radionuclides.

The Nuclear Data Program is an essential element in providing for national-security needs. The nuclear data community can provide and further develop/improve standards and databases important in measurements of fissile and radioactive materials, in Monte Carlo simulations, and in providing specific resources such as the Table of Isotopes and the Nuclear Wallet Cards.

A big issue ahead is the education and "awareness" training of the general population. The nuclear science community can be a prime resource for the education and outreach activities outlined in the section on outreach. The APS/DNP could help provide the leadership to coordinate these activities through the Education Committee.

The discussions at this workshop were a good first step in establishing a dialogue between the nuclear science community and the agencies charged with national security. It is important to continue these dialogues. Motivation should be maintained, and a follow-up meeting is recommended within the next year.

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Table 1: Capabilities of the Nuclear Community Relevant to Counterterrorism

Detectors of nuclear radiation
Accelerators
Decontamination and sterilization
Forensics
Basic nuclear data
Modeling radiation transport in materials
Simulation and appraisal of new techniques and apparatus
Supervisory control and data acquisition
Data analysis and mining techniques
Expertise for proposal review, first responder and local government agency training
Training the scientific work force for future challenges
Membership in radiological assistance programs
Safeguarding the hazardous material under our control
Skills in system (detectors/accelerator) design, construction, and implementation

Table 2: Summary of Neutron-Based Interrogation Techniques

Technique Name	Probing Radiation	Main Nuclear Reaction	Detected Radiation	Sources	Primary/ Secondary Detected Elements
TNA(Thermal Neutron Analysis)	Thermalized neutrons	(n,γ)	Neutron capture γ-rays (prompt & delayed neutrons for SNM*)	^{252}Cf, also accelerator based sources (ENG**)	Cl, N, SNM H, Metals, P, S
FNA(Fast Neutron Analysis)	Fast (high energy, usually 14 MeV) neutrons	(n,n'γ)	γ-rays produced from inelastically scattered neutrons	ENG based on (d,T)	O, C (N) (H) Cl, P
FNA/TNA (also appears under other names: Gated TNA, or PR/TNA)	Pulsed neutron source; fast neutrons during the pulse, thermal neutrons between pulses	(n,n'γ) + (n, γ)	During pulse #2 + . after pulse - #1	μs pulsed ENG based on (d,T)	N, Cl, S, SNM H, C, O, P, N
PFNA(Pulsed Fast Neutron Analysis)	Nanosecond (ns) pulses of fast neutrons	(n,n'γ)	Like FNA (#2) (prompt & delayed neutrons for SNM)	ns pulsed (d,D) accelerator with E_d ~6 MeV	O, C, N, Cl, Others, SNM H, Metals, Si, P, S, Others
API (Associated Particle Imaging)	14 MeV neutrons in coincidence with the associated α-particles	(n,n'γ)	Like FNA in delayed coincidence with α	(d,T)	O, C, N Metals
NRA (Neutron Resonance Analysis) also known under other names, *e.g.,* PFNTS	ns pulsed fast neutrons (0.5-4 MeV), broad energy spectrum	(n,n)	Elastically and resonantly scattered neutrons	ns pulsed (d,Be) accelerator, with E_d #4 MeV	H, O, C, N (Others)

*) special nuclear materials—^{235}U and ^{239}Pu.
**) electronic neutron generator—can be based on neutron production processes such as (d,D), (d,T), (d,Be), (P,Li)), (P,Be).

Table 3: General Characteristics of Commonly Used Gamma-Ray Detectors in Inspection Systems

Detector Type	Characteristics	Sensitivity and Resolution	Utilization
NaI(Tl)/BGO	• Inorganic Scintillator • Typical size used in inspection 3” dia. x 3”high to 6” to 6”high (larger sizes available)	• Very High efficiency • Medium resolution: 6–7%/10–13% @ 662 keV	• Rugged, field portable systems available • Low/moderate (high for large size) cost
CdZnTe (CZT)	• Solid state charge collection • Sizes available 1 cm^3 • Room temperature	• Medium sensitivity • Good resolution: 2% @ 662 keV	• Still in R&D stage • High potential for future field systems
High Purity Germanium	• Solid state charge collection • Sizes in excess of 300 cc • Mechanical or cryogenic cooling to ~77K required	• Good sensitivity • Very high resolution <0.2% @1332 keV	• Relatively high system cost: ~$50K • Currently available systems require expert use and maintenance
Plastic Scintillator	• Organic scintillator • Large sizes (1m x 2m x 1cm) available	• Poor energy resolution • High sensitivity due to large area and volume • Fast time response: ~1ns	• Good for portals and other application not requiring energy resolution • Very low cost
Ion chambers, proportional counters, Geiger counters	• Gas filled ionization charge collection with gas gain for proportional and Geiger counters	• Poor sensitivity at gamma-ray energies • Good resolution	• Little utility for applications discussed in this report
Liquid Xenon	• High pressure (40atm) gas/liquid • Volume 160 cm^3	• Good sensitivity • High resolution: 2.5% @ 662 keV	• R&D portable unit built at BNL

Table 4: Synopsis of Existing/Studied Nuclear-Based Inspection Techniques

TNA (Thermal neutron analysis): Method based on the capture of thermal neutrons by nuclei creating high-energy gamma rays characteristic to the specific nuclei. Thermal neutrons are produced by the slowing down of fast neutrons generated by sources or accelerators in specially designed moderators and in the interrogated object itself. The gamma rays are detected by an array of detectors near ("one-sided" configuration) or surrounding the object ("inspection tunnel or cavity" configuration). Spatial information on the interacting nuclei of interest (e.g., nitrogen, chlorine, hydrogen, etc.), to determine, for example if they appear in a lump or sheet forms, can be obtained by processes akin to emission tomography.

GTNA (Gated TNA): A TNA-like technique, but with a pulsed neutron source (typically "on" for 5 to 100s microseconds with a repletion rate of 100 to 10,000 Hz). The gamma rays measured after the neutrons are switched off, are generated by the capture process of the decaying thermal neutrons. The temporal behavior of the neutron population ("neutron die away") is related to the geometry and material absorption properties of the inspection system and inspected object.

FNA (Fast Neutron Analysis): Method based on fast neutron interactions, mostly inelastic neutron scattering. Characteristic gamma rays from carbon, oxygen, chlorine, nitrogen, and other elements can be measured. Arrays of gamma-ray detectors and analysis similar to the TNA technique are employed. Neutrons are usually generated by small 14 MeV neutron generators.

PF/TNA (Pulsed Fast/Thermal Neutron Analysis): Combination of GTNA with FNA. The latter is done when the source is on and the former when the source is off.

PFNA (Pulsed Fast Neutron Analysis): Method based on highly collimated beam of fast monoenergetic (typical 6–9 MeV) neutron interactions with nuclei yielding characteristic gamma rays and full three dimensional material mapping. The neutrons are generated in nanosecond-wide pulses (1–10 MHz frequency) and time of flight (TOF) is employed to determine the spatial distribution of the signal, and hence the material present.

API (Associated Particle imaging): A technique to tag source in time and direction, by the associated particle emitted simultaneously in the nuclear reaction that generated the neutrons, e.g., alpha particle and ^{3}He in the (d,D) or (d,T) reactions respectively.

NRA (Neutron Resonance Absorption): A technique to measure the areal density (density x thickness) of elements present in the interrogated object. The technique takes advantage of relatively sharp resonances and other features in the neutron total (mostly elastic) cross-section in the energy range of 0.5–5 MeV. Two-dimensional projection of the areal density of N, C, O, and H can be obtained using fast neutrons with a broad energy spectrum, generated in narrow pulses, to perform neutron TOF energy measurements.

NES (Neutron Elastic Scattering): A technique to measure elemental concentration using the different structures and angular distribution of the neutron elastic scattering cross sections. In the NES the scattered (mostly in backward angles) neutrons are measured.

RGS, NRF, RGA (Resonance Gamma Scattering or equivalently Nuclear Resonance Fluorescence and Resonance Gamma Absorption): A technique that uses the ability of nuclei, (*e.g.,* ^{14}N) to resonantly scatter/absorb gamma rays of specific and precisely defined energy (^{14}N: 9.17MeV). In RGS the scattered gamma rays are detected while in RGA the attenuation of the gamma-ray beam is measured. The resonant gamma rays are also scattered/absorbed, but in nonresonant ways (mostly through Compton scattering), in all material present. With a rastered beam these provide a two-dimensional areal density of the element of interest (nitrogen, for explosives). With an angular tracking or high-time resolution detectors, three-dimensional imaging is possible.

Photonuclear Activation and Pulsed Gamma Analysis (PGA): A technique whereby specific nuclei (*e.g.,* ^{14}N) are selectively made radioactive by a photonuclear reaction using >10 MeV high-power electron linacs. The measurement of the induced radioactivity indicates the presence of an element of interest. Spatial distributions of the activation can, in principle, be determined by the Positron Emission Tomography (PET) following positron decays.

NMR and NQR (Nuclear Magnetic Resonance and Nuclear Quadrupole Resonance): Hyperfine interactions between the intrinsic nuclear magnetic moment or quadrupole moment can be detected through the interaction with the intrinsic magnetic field or electrical field gradients of the host material. Because these intrinsic fields depend on the chemical form and phase of the material, NMR and NQR can provide specific chemical identification with induced radiofrequency probes.

Table 5: Commercial Neutron Sources for Neutron-Based Inspection Techniques

	Nuclear Reaction	Examples/ Manufacturer	Strength (n/s)	Neutron Energy (MeV)	Neutron Spectrum	Pulsing Capabilities	Typical Repetition Rate	Possible Applications	Comments
Radioisotopic sources									
Sources based on charged-particle interactions from isotopic sources	(γ,n)	(^{241}Am, Be)	$<10^8$	5	broad	no	dc	TNA, FNA	
Sources based on photonuclear reactions from isotopic sources	(γ,n)	(^{124}Sb, Be)	$<10^9$	0.03	narrow	no	dc	Fissile detection	
Sources based on spontaneous fission	fission	^{252}Cf	$<10^{12}$	<2.3>	fission spectrum	yes, trigger w/fission events	dc	TNA	
Accelerator based: low energy (<200KV)									
Sealed tube type	(d,D)	MFP, Sodern	$<10^8$	3.2	narrow	> μs	dc–10 Khz	TNA, GTNA fissile	Under development 10^9 source
Sealed tube type	(d,T)	MFP, Sodern	$<10^9$	14	narrow	> μs	dc–10 Khz	TNA,FNA,PR/TNA, fissile	Under development 10^{11} source
Accelerator based: medium energy (>500KV-2MV)									
Van De Graaff, RFQ,	(p,Li)	NEC, Accys	10^8–10^{10}	0.15–1	narrow	dc–ns; μs	RFQ-180 Hz	TNA,GTNA fissile	
Van De Graaff, RFQ,	(d,Be)	NEC, Accys	10^9–10^{11}	variable	broad	dc–ns; μs	RFQ-180 Hz	TNA, fissile	
Accelerator based: "high" energy (>2MV)									
Van De Graaff	(d,D)	NEC	10^9–10^{11}	variable	mono-energetic	ns	1–10 MHz	PFNA, fissile	
Van De Graaff, Cyclotron	(d,Be)	NEC,EBCO, IBA	10^9–10^{12}	variable	broad	ns	1 MHz	NRA	
Others									
Medium energy (E<10MeV) electron linac, using Bremsstrahlung photo nuclear reaction w/converter	(γ,Be), (γ,D)	Varian (linac)	10^9–10^{11}	"fission" like	broad	μs	180 Hz	TNA, fissile	

Table 6: Neutron Detectors Based on Fast Neutron Interactions.
This is adapted from Humphry ref. [4.7]

Detector	Time Resolution	Efficiency	Gamma Sensitivity	Cost $	Comments
^{4}He	μs	1%	Very Low	650	1" dia. × 8" long
Organic Scint.	< 0.5 ns	>10%	Very High	600	2" dia. × 2" thick w/PMT
Liquid Scint.	< 1 ns	> 10%	Very High/low w/PSD (but count rate limited)	6,000	2" dia. × 2" thick w/PMT+PSD module
Recoil Telescope	5 ns	~10^{-3}	Extremely Low	2,000	

Table 7: Neutron Detectors Based on Neutron Moderation. This is taken from ref. [4.7]

Detector	Time Resolution	Efficiency	Gamma Sensitivity	Cost $	Comments
^{3}He (Cd wrapped poly, 3–2 in tubes)	10–100 µs	1–10% for ^{252}Cf neutrons	Very Low	~5,000	3 tubes, 2" dia. × 24" long
^{6}Li doped Glass, Ce activated	1 ns	~10% for ^{252}Cf neutrons	Low/medium		

Table 8: Applicability of Neutron-Based Inspection Techniques

Threat	Location	Nuclear Techniques
Small explosives (solid or liquid, sheet, bulk, or powder), drugs, chemicals and nuclear material in luggage and parcels (medium to high throughput required)	Airport (checked and carry-on luggage), post office, border inspections	TNA with imaging TNA/FNA, PR/TNA) with imaging, NRA (PFNTS), with multiple angle views
Small explosives (solid or liquid, sheet, bulk or powder), and drugs concealed in carry-on items: laptop computers, electronics, briefcases (low–medium throughput acceptable)	Airport security check points, courthouses, government and corporate headquarters, airport lobbies	TNA, TNA/FNA, PR/TNA
Buried antivehicular and antipersonnel mines	Military base cleanup, and war zones	TNA, TNA/FNA or PR/TNA (confirms or clears alarms by metal detector, ground penetrating radar or by other means)
Verification of unexploded ordnance (UXO)—conventional or chemical	Range, military bases, or war-zone environmental cleanup	As above
Bulk explosives (and/or drugs and other chemicals) in trucks or cars ("truck/car bombs"). Threats include nuclear and radiological devices.	Inspections at border, seaports; inspections at parking garages and entrances to sensitive facilities. Inspections of parked cars.	TNA, TNA/FNA or PR/TNA
Explosives, drugs, environmentally hazardous materials, smuggled dutiable goods, nuclear material in trucks, containers, air cargo	Customs inspection at land and sea ports of entry, air cargo, high-speed luggage inspection.	PFNA (= ns pulsed collimated FNA)
Nuclear and hazardous chemical ("mixed") wastes in 55 gal. drums or larger boxes	Nuclear reprocessing plant, facilities in the nuclear fuel cycle, clean up of previous nuclear sites	PFNA, TNA, TNA/FNA or PR/TNA

See Table 4 and 2 for definitions of the techniques.

Table 9: Key Nuclear Reactions Used to Produce Photons and Neutrons

Reaction	Energy (MeV)	Application
$^{13}C(p,\gamma)^{14}N$	1.7476	MeV photons for Nuclear Resonance Absorption (NRA)
$^{19}F(p,\alpha e^{+}e^{-})^{16}O$	1.8–2.3	Positrons for producing tunable source of MeV photons by in-flight annihilation for NRA
$^{19}F(p,\alpha\gamma)^{16}O$	1.8–2.5	MeV photons for Photon-Induced Positron Annihilation (PIPA)
$^{7}Li(p,n)^{7}Be$	1.8–2.5	Epithermal to MeV neutrons

Table 10.a DOE Nuclear Physics Division: Supported Accelerator Facilities Description

Institution	Facility	Accelerator Description	Beam Type(s)	Maximum Energy (MeV or MeV/u)	Max Current (μA or pμA)	Contact Person
Argonne National Laboratory	ATLAS	Tandem - Superconducting Linac	all heavy ions	20 MeV/u	5 pμA	Richard Pardo 630 252-4029 Pardo@phy.anl.gov
Brookhaven National Laboratory	RHIC	Collider (2 synchrotron rings)	protons-gold	Protons-500 GeV (cm) Gold-200 GeV/u (center of mass)	Luminosità (cm^{-2} s^{-1}) Au: 2 x 10E26 Proton: 10E32	Derek I. Lowenstein 631 344-4611 Lowenstein@bnl.gov
Brookhaven National Laboratory	Tandem	Tandem - Dual Tandem	protons-gold	1 MeV/u–30 MeV (gold-proton)	1 pμA-.05 pμA (proton-gold)	Derek I. Lowenstein 631 344-4611 Lowenstein@bnl.gov
Brookhaven National Laboratory	Linac	Linac	Protons	200 MeV	25 ma	Derek I. Lowenstein 631 344-4611 Lowenstein@bnl.gov
Brookhaven National Laboratory	Booster	Synchrotron	protons-gold	0.3 GeV/u-3 GeV (gold-proton)	2 x 10E13 / pulse, 7.5 Hz, 2.5 μs spill	Derek I. Lowenstein 631 344-4611 Lowenstein@bnl.gov
Brookhaven National Laboratory	AGS	Synchrotron	protons-gold	0.6 GeV/u-28 GeV (gold-proton)	7 x 10E13 / spill, 0.5 Hz	Derek I. Lowenstein 631 344-4611 Lowenstein@bnl.gov
Lawrence Berkeley National Lab	88-Inch Cyclotron	Sector-focused Cyclotron	light ions heavy ions + selected radioactive beams: see http://user88.lbl.gov/	55 MeV/u 32.5 MeV/u	10 pμA 3 pμA	Claude Lyneis 510-486-7815 cmlyneis@lbl.gov
Massachusetts Institute of Technology	Bates	Linear Accelerator and Storage Ring	Electrons	1.1 GeV	50 μA	Christoph Tschalaer 617-253-9200 chris@bates.mit.edu
Oak Ridge National Laboratory	HRIBF	k=100 Cyclotron – 25 MV Tandem	most stable heavy ions + radioactive beams: see list at http://www.phy.ornl.gov/hribf/users/beams/	15 MeV/u, A~12 8 MeV/u, A~60 5 MeV/u, A~130	1 puA	Carl Gross 865 576-7698 grosscj@ornl.gov

Thomas Jefferson National Lab	CEBAF	Recirculating superconducting linac	Electrons	6 GeV		
Texas A&M University	Cyclotron Institute	K500 Superconducting Cyclotron	all ions – ^{1}H-^{238}U, + selected radioactive beams	70 MeV/u at ^{1}H 20 MeV/u at ^{238}U	1 pμA	Henry Clark Clark@comp.tamu.edu
Triangle Universities Nuclear Lab	TUNL	FN-Tandem Van de Graaff	p,d,^{3}He,^{4}He , and heavier, DC and pulsed; polarized p,d; n from reactions	20 MeV	5 μA unpol. 3 μA polarized p,d DC or pulsed	Werner Tornow 919 660-2637 tornow@tunl.duke.edu
Triangle Universities Nuclear Lab	TUNL	FN – Van de Graaff	p,d, ^{4}He	4.0 MeV	100 μA	Garry Mitchell 919 660-2638 Mitchell@tunl.duke.edu
Triangle Universities Nuclear Lab	TUNL	LEBAF	p,d, ^{3}He, ^{4}He, polarized p,d	680 keV	400 μA unpol. 50 μA pol 3 μA (-) pol	Ed Ludwig 919 660-2606 ludwig@tunl.duke.edu
Triangle Universities Nuclear Lab	TUNL	LENA Two simul-taneous beams ECR Source + Van de Graaff	Protons	200 keV/1 MeV	5 mA/100 μA	Art Champagne 919 660-2607 aec@tunl.duke.edu
Triangle Universities Nuclear Lab	TUNL/ DFELL	HIγS – an FEL back- scattered γ-ray source	γ rays linearly (circularly) polarized	50 (225 MeV after upgrade)	10^{6} – 10^{8} γ/s (>10^{9} γ/s after upgrade)	V. N. Litvinenko 919 660-2658 vl@fel.duke.edu H.R. Weller 919 660-2633 weller@tunl.duke.edu
University of Washington Center for Experimental Nuclear Physics and Astrophysics	Tandem	FN- Tandem with negative ion sources and terminal ion source	all ions, helium and hydrogen ions at low energy, high intensity	p: 18 MeV He: 27 MeV *e.g.,* Oxygen: 63 MeV, heavier ions approx 100 MeV	30 μamps for He or H at low energy, ~1 μ amp at higher energy	Derek Storm 206-543-4085 storm@npl.washington.edu

University of Washington Center for Experimental Nuclear Physics and Astrophysics		Superconducting booster (presently mothballed)	heavy ions up to mass 64	10 MeV/u for mass up to about 40		Derek Storm 206-543-4085 storm@npl.washington.edu
Yale University	WNSL	20-MV tandem	all ions: H to Pb	H: 40 MeV/u Pb: 2 MeV/u	5 pμA	Jeff Ashenfelter 203-432-3090 ash@mirage.physics.yale.edu

Table 10.b NSF: Supported Accelerator Facilities Description

Florida State University	Super-conducting Acc. Lab	Tandem+Super-conducting Linac	A< 50	10 MeV/u	1 pμA	Sam Tabor 850-644-5528 tabor@nucmar.physics.fsu.edu
Michigan State University	National Super-conducting Cyclotron Lab	K500 and K1200 Coupled Superconducting Cyclotrons	hydrogen to uranium	200 MeV/u	1 pμA	Brad Sherrill 517-333-7322 sherrill@nscl.msu.edu
University of Notre Dame	Nuclear Structure Lab	FN Tandem KN Van de Graaff JN Van de Graaff	A< 50 A< 16 A< 16	11 MeV/u 4 MeV/u 1 MeV/u	10 μA 150 μA 150 μA	Ani Aprahamian 574-631-7716 lab 574-631-8120 office aprahamian.1@nd.edu
SUNY at Stony Brook	Nuclear Structure Lab	Tandem + Superconducting Linac	1<A< 90	15 MeV/u	1 pμA	Gene Sprouse 631-632-8115 gene.sprouose@stonybrook.edu

Appendix I: Workshop Agenda

Workshop on the Role of the Nuclear Physics Research Community in Combating Terrorism

July 11

Plenary Session

Sphinx Club Grand Ballroom, Almas Temple, adjacent to Crowne Plaza Hotel on K Street

8:00 am	Coffee
8:30 am	Welcome and Opening remarks - DOE and NSF
8:45 am	Introduction and Purpose – Joel Moss, Chair, Los Alamos National Laboratory
9:00 am	***Keynote Lecture:*** Technological Challenges in Combating Terrorism – Penrose Albright, Office of Homeland Security Senior Director for Research and Development and Assistant Director for Homeland and National Security, Office of Science and Technology Policy
10:00 am	Break
10:30 am	Capabilities of the Nuclear Physics Research Community – James Symons, Lawrence Berkeley National Laboratory and Chair of Nuclear Science Advisory Committee
11:30 pm	Accelerator Applications to Combating Terrorism – Donald Prosnitz, Chief Science and Technology Advisor, Department of Justice
12:15 pm	Lunch
1:30 pm	Conventional Explosive and Weapon Detection - Lyle Malotky, Scientific Advisor, Transportation Security Administration
2:30 pm	Radiological and Nuclear Threats - Michael O'Connell, National Nuclear Security Administration, DOE
3:30 pm	Break
4:00 pm	Challenges in Transitioning from R&D to Operations – John Pennella, Executive Director of Applied Technology Division, U.S. Customs
4:45 pm	Closing Remarks of Plenary Sessions - James Decker, Principal Deputy Director of the Office of Science, DOE
5:00 pm	Breakout into working groups *(Sphinx ClubGrand Ballroom and Oasis Room, Almas Temple)*
6:00 pm	Poster and social session, *Hamilton Ballroom, Crowne Plaza Hotel*
7:30 pm	Dinner, Hamilton Ballroom, Crowne Plaza Hotel

July 12

Session 1: Conventional Explosive and Weapon Detection Working Group

(Chair, Donald Geesaman, Argonne National Laboratory) *Oasis Room, Almas Temple*

8:00 am	Discussion of R&D on Conventional Explosive and Weapon Detection—Anthony Fainberg, Special Assistant for Technology, Transportation Security Administration
9:00 am	General Discussion

Session 2: Radiological and Nuclear Threat Working Group

(Chair, Lee Schroeder, Lawrence Berkeley National Laboratory) *Hamilton Ballroom, Crowne Plaza*

8:00 am	Discussion of R&D on Radiological and Nuclear Threat Detection—Paul Evancoe, Director of Office of Emergency Response, National Nuclear Security Administration, DOE
9:00 am	General Discussion

Session 3: Both Working Groups

12:00 pm	Lunch
2:00 pm	Report from Working Groups/Large room discussion, *Hamilton Ballroom, Crowne Plaza*
4:00 pm	Closing remarks from agency representatives
4:30 pm	Adjourn

Appendix II: U.S. Government Agencies Represented at the Workshop

Army Research Laboratory

Central Intelligence Agency

Defense Threat Reduction Agency

Office of Science, DOE

Department of Justice

Department of State

Environmental Protection Agency

Federal Bureau of Investigation

National Aeronautics and Space Administration

National Institute of Standards and Technology

National Armed Forces Radiobiological Research Institute

National Nuclear Security Administration

National Science Foundation

Naval Research Laboratory

Office of Science and Technology Policy

Senate Foreign Relations Committee

Technical Support Working Group, Department of State

Transportation Security Administration

United States Air Force

United States Customs

Appendix III: Workshop Poster Listing
(Posters are available at: http://www.sc.doe.gov/production/henp/np/homeland/posters.html)

Title of Poster	Point of Contact	Institution
1. Identification of Biological Agents and Contraband with Terahertz Imaging	Alan Todd	Advanced Energy Systems, Inc.
2. Accelerator Mass Spectroscopy: Measurement of Extremely Low isotopic Ratios in Small Samples	Richard Pardo	Argonne National Laboratory (ANL)
3. ATLAS—Facility Description	Richard Pardo	ANL
4. Atom Trap Trace Analysis: An Ultrasensitive Isotope Analyser	Don Geesaman	ANL
5. Gamma Ray Tracking with Large Area Planar Germanium Detectors	Christopher Kim Lister	ANL
6. Use of Gamma Resonance Imaging for Detection of Explosives	Lucien Wielopolski	Brookhaven National Laboratory (BNL)
7. Advanced Detectors for Gamma-rays and Neutrons	Peter Bond	BNL
8. Microelectronics for Highly Segmented CdZnTe Gamma-ray Detectors	Pavel Rehak	BNL
9. Capabilities with Accelerators at Brookhaven National Laboratory	Peter Bond	BNL
10. A Novel High Current Tandem Accelerator for Antiterrorism Applications	Paul Farrell	Brookhaven Technology Group
11. Identification of Fissile Materials from Fission Product Gamma-ray Spectra	Edward Cecil	Colorado School of Mines
12. Gulf-Caribbean Radiological Defense	Samuel Tabor	Florida State University
13. GRETA (Gamma-Ray Energy Tracking Array)	I Yang Lee	Lawrence Berkeley National Laboratory (LBNL)
14. Automotive Air Filters as Samplers to Detect and Measure the Severity and Extent of Radioactivity Released in a Terrorist Attack	Eric Norman	LBNL
15. Prompt/Delayed Gamma-ray Neutron Activation Analysis (PGAA/NAA) System for Total, Nondestructive, in situ, Elemental Analysis using a Neutron Generator	Eric Norman	LBNL
16. A Cyclotron-based Pulsed Fast Neutron Endstation for Studies in Support of Neutron-based Nonintrusive Inspection Techniques	Claude Lyneis	LBNL

17. WWW Search for Nuclear Terrorism Activities	Eric Norman	LBNL
18. 88-Inch Cyclotron Capabilities and Applications	Claude Lyneis	LBNL
19. Compact, Powerful Neutron Source for Rapid Screening of Cargo	Bill Barletta	LBNL
20. Portable Germanium Gamma-ray Spectrometer Detector	John Becker	Lawrence Livermore National Laboratory
21. SQUIDs for Detection of Underground Activities	William Louis	Los Alamos National Laboratory (LANL)
22. Detector for Advanced Neutron Capture Experiments (DANCE)	Richard Shirato	LANL
23. Ultra-low-level Counting for National Defense	Thomas Bowles	LANL
24. Muon Radiography	Chris Morris	LANL
25. Very Large Area Neutron Detector (VLAND) Based on LSND and MiniBooNE	William Louis	LANL
26. Accurate Determination of the Critical Mass of ^{237}NP	Mark Chadwick	LANL
27. Material Identification and Object Imaging Using Nuclear Resonance Fluorescence	William Bertozzi	Massachusetts Institute of Technology (MIT)
28. Solid State Switch Pulse Modulator for Radar Systems	Abbi Zolfaghari	MIT Bates Linear Accelerator Center
29. The MIT/Bates Laboratory: An Overview	Richard Milner	MIT Bates Linear Accelerator Center
30. Nuclear Science Research and Education at the National Superconducting Cyclotron Laboratory at Michigan State University	Paul Mantica	Michigan State University
31. Technical Capabilities of the University of Notre Dame Accelerator Facility	Larry Lamm	Notre Dame University
32. Nuclear Data for Homeland Defense and National Security	Pavel Oblozinsky	Nuclear Data Center/Brookhaven National Laboratory
33. Opportunities for Accelerator Mass Spectrometry using HRIBF	Alfredo Galindo-Uribarri	Oak Ridge National Laboratory (ORNL)
34. Detection of Traces of Toxic Vapors by Mass Spec	Alfredo Galindo-Uribarri	ORNL
35. HRIBF Capabilities and Applications	James Beene	ORNL

36. Education, Training, and Careers of Nuclear Scientists	Jolie Cizewski	Rutgers University
37. Texas A&M Radiation Effects Facility	Henry Clark	Texas A&M University
38. Multimodality Sensor Systems for Detection of Contraband, Concealed Weapons, and Biological Agents	Stan Majewski	Thomas Jefferson National Laboratory (JLab)
39. Identification of Explosives and Fissile Materials using Pulsed Gamma Analysis	Andrei Afanasev	JLab
40. Production of Antimicrobial Polymer Surfaces using High-Power UV, IR, or Electron Radiation	Michael Kelley	JLab
41. Jefferson Laboratory Contributions to National Security	Fred Dylla	JLab
42. Detection and Isotopic Identification of Nuclear Materials using Monoenergetic Gamma-ray Beams	Henry Weller	Triangle Universities Nuclear Laboratory/Duke University (TUNL)
43. Precision Measurements of Gamma-ray Attenuation Coefficients at HIGS	Henry Weller	TUNL
44. Transmutation of Radioactive Materials using Thermal Neutrons	Calvin Howell	TUNL
45. Detection of Explosives using Monoenergetic Gamma Rays and Monoenergetic Fast Neutrons	Werner Tornow	TUNL
46. International Working Group on Nuclear Physics Technology and Reduction of Terrorism Threats	Jerry Peterson	University of Colorado at Boulder
47. Mobile Accelerator-based Neutron Diagnostics Instrumentation	Jan Toke	University of Rochester
48. Technical Capabilities of the University of Washington Center for Experimental Nuclear Physics and Astrophysics	Derek Storm	University of Washington
49. Wright Nuclear Structure Laboratory: An Overview	Cornelius Beausang	Yale University

From http://www.sc.doe.gov/production/henp/np/homeland/posters.html

Appendix IV: Membership of Working Groups

1. Conventional Explosive and Weapon Detection

Don Geesaman, Chair	Argonne National Laboratory
Barry Berman	George Washington University
Claude Lyneis	Lawrence Berkeley National Laboratory
William Bertozzi	Massachusetts Institute of Technology
Pavel Rehak	Brookhaven National Laboratory
Jolie Cizewski	Rutgers University
John Becker	Lawrence Livermore National Laboratory
Cythia Keppel	Hampton University/Jefferson National Laboratory
Joseph Natowitz	Texas A&M University
Michael Kelly	William and Mary/Jefferson National Laboratory
Cyrus Baktash	Oak Ridge National Laboratory
Donald Smith	Argonne National Laboratory
Robert Scarlett	Los Alamos National Laboratory
Calvin Howell	Triangle University Nuclear Laboratory/Duke University
Christopher Kim Lister	Argonne National Laboratory
Cornelius Beausang	Yale University
Peter Thieberger	Brookhaven National Laboratory
Jan Toke	University of Rochester
Edward Bilpuch	Duke University
Brad Sherill	Michigan State University
Andrei Afanasev	Thomas Jefferson National Laboratory
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Appendix VI. Acronym List

Acronym	Meaning
AGS	Alternating Gradient Synchrotron (BNL)
AMS	accelerator mass spectroscopy
ANL	Argonne National Laboratory
API	Associated Particle Imaging
APS/DNP	American Physical Society—Division of Nuclear Physics
ATLAS	Argonne Tandem Linac Accelerator System (ANL)
ATTA	atom-trap trace analysis
BGO	bismuth germanium oxide
BNL	Brookhaven National Laboratory
BooNE	Booster Neutrino Experiment (FNAL)
CEBAF	Continuous Electron Beam Accelerator Facility (JLAB)
CT	computerized tomography
DANCE	Device for Advanced Neutron Capture Experiments
DFELL	Duke (University) Free-Electron Laser Laboratory
DOE	Department of Energy
DT	deuterium-tritium
ECR	electron cyclotron resonance
ENDF	Evaluated Nuclear Data File
ENG	electronic neutron generator
ENSDF	Evaluated Nuclear Structure Data File
FEL	free-electron laser
FNA	Fast Neutron Analysis
FNAL	Fermi National Accelerator Laboratory (Fermilab)
FTE	Full-time (equivalent) employee
GRETA	Gamma-ray Energy Tracking Array (LBNL)
GTNA	Gated Thermal Neutron Analysis
HEU	highly enriched uranium
HIGS	High-Intensity Gamma-ray Source (TUNL)
HRIBF	Holifield Radioactive Ion Beam Facility (ORNL)
IAEA	International Atomic Energy Agency
IR	infrared
JLAB	Thomas Jefferson National Accelerator (Laboratory) Facility
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Science Center (LANL)
LBNL	Lawrence Berkeley National Laboratory
LEBAF	Low Energy Beam Accelerator Facility (TUNL)
LENA	Laboratory for Experimental Nuclear Astrophysics (TUNL)
LSND	Liquid Scintillator Neutrino Detector (LANL)
MCNP	Monte Carlo Neutron and Photon (transport code)

MIT	Massachusetts Institute of Technology
MoNA	Modular Neutron Array (NSCL)
MSU	Michigan State University
MTOF-MS	Multipass Time-of-Flight Mass Spectroscopy
NES	neutron elastic scattering
NMR	nuclear magnetic resonance
NQR	nuclear quadrupole resonance
NRA	Neutron Resonance Analysis
NRF	Nuclear Resonance Fluorescence
NSCL	National Superconducting Cyclotron Laboratory (at MSU)
NSF	National Science Foundation
ORNL	Oak Ridge National Laboratory
PET	Positron Emission Tomography
PF/TNA	Pulsed Fast/Thermal Neutron Analysis
PFNA	Pulsed Fast Neutron Analysis
PGA	Pulsed Gamma-ray Analysis
PGAA	Prompt Gamma-ray Activation Analysis
PMT	photomultiplier tube
ppm	parts per million
PSD	pulse shape discrimination
R&D	research and development
RF	radio frequency
RGA	Resonant Gamma-ray Absorption
RGS	Resonant Gamma-ray Scattering
SNM	special nuclear material
SQUID	superconducting quantum interference device
SUNY	State University of New York
THz	terahertz
TNA	Thermal Neutron (activation) Analysis
TOF	time of flight
TUNL	Triangle Universities Nuclear Laboratory
UV	ultraviolet
UXO	unexploded ordinance
VLAND	Very Large Area Neutron Detector (LANL)
WNR	Weapons Neutron Research (facility-LANL)
WNSL	Wright Nuclear Structure Laboratory (Yale)
Z	atomic number (low-Z, high-Z)