Nuclear Science

Enhancing American Competitiveness through Basic Research

Submitted to the Nuclear Science Advisory Committee
by the organizers of the Workshop on American
Competitiveness, Chicago, ILL (January 2007)

Revised: April 27, 2007

Contents

List of Figures

List of Tables

Preamble

In July 2006 the Department of Energy (DoE) and the National Science Foundation (NSF) charged the Nuclear Science Advisory Committee (NSAC) to develop a new long-range plan (LRP) for the field. Earlier that year President Bush, in his state of the union address, boldly announced The American Competitiveness Initiative (ACI). The President called for doubling over ten years the investment in key Federal agencies which support basic research in the physical sciences and engineering that have potentially high impact on economic competitiveness. These agencies include the NSF, the Office of Science at the DoE and the National Institute of Standards and Technology at the Department of Commerce.

In preparation for developing the LRP four town meetings were organized by the American Physical Society's Division of Nuclear Physics in January 2007 to gather broad community input. Prior to that, a number of meetings were held in the fall of 2006 to prepare for the town meetings. As part of the planning process a workshop on American Competitiveness was held on January 19 – 21, 2007, at the Hyatt Regency Hotel in Chicago, Illinois. This workshop was run in parallel with the town meetings on "Nuclear Astrophysics and Structure of Nuclei" and "Neutrinos, Neutrons and Fundamental Symmetries." The main goals of the workshop were:

(1) To provide a venue for gathering input from the broad nuclear science community detailing how the activities of this field enhance the Nation's competitiveness in the physical sciences, develop innovative technology, and advance the Nation's abilities to address challenges in national security, energy, education and medicine.

(2) To collect examples of how the nuclear science community is contributing to the areas of energy, medicine and national security.

(3) To identify opportunities for the nuclear science community to contribute in areas relevant to the Nation's competitiveness for the next decade.

(4) To devise recommendations regarding how the Office of Nuclear Physics at the DoE and the Nuclear Physics Program Office at the NSF might better facilitate the engagement of the nuclear science community in addressing means to enhance the economic competitiveness of the Nation.

The American Competitiveness workshop opened on Friday evening (January 19, 2007) with a plenary session devoted to nuclear energy. Plenary sessions on Saturday morning focused on national security and applications of nuclear science in medicine. Two working group sessions ran in parallel on Saturday afternoon. One covered nuclear energy and nuclear data, while the other focused on national security, nuclear medicine and industry. The former session was arranged jointly with the organizers of the nuclear astrophysics town meeting working group. All sessions encouraged in depth discussions. In addition, the working group session on nuclear energy and nuclear data included time slots for short presentations from participants. All sessions were well attended with a mixture of speakers and participants from national laboratories, universities, government agencies, and industry. The program agenda and presentations are posted at http://www-mep.phy.anl.gov/atta/dnp/program_ac.htm, and this whitepaper can be found at http://www-mep.phy.anl.gov/atta/dnp/home_ac.htm. The sections in this report are based largely on the content of presentations made at the workshop and the participant discussions.

Executive Summary

Support for curiosity-driven research is inherently an investment in securing a nation's long-term scientific and technological future. These investments become increasingly more important as more nations' economies evolve from being manufacturing based toward being driven by products that spring from technological innovations. To be internationally competitive in advancing knowledge at a scientific frontier several basic infrastructural features must be solidly maintained and evolved in response to the changing landscape at the cutting edges of science. These include: (1) a well established and consistently supported enterprise for sustaining high-quality expertise at all professional levels in the field, from undergraduate research assistants to senior scientists, (2) access to world class facilities and opportunities to develop such facilities and the instrumentation that enable advances in the field, (3) mechanisms for establishing mutually beneficial relationships between scientists and technologists, and (4) regular exercises to identify important questions in the field and develop strategies to effectually pursue answers and respond to opportunities for discovery. The nuclear science community is currently developing a new long-range plan (LRP) for the next decade. The plan will identify discovery opportunities for which the USA can have leadership and will recommend to the DoE and NSF scientific priorities for the field. The development and implementation of strategies to attract and cultivate the next generation of nuclear scientists are paramount for achieving the scientific goals of the plan, for sustaining American's leadership in this important field, and for securing American's competitiveness in technologies and services that are built on nuclear science.

The recommendations made in this report are based on the presentations and discussions at the workshop and on subsequent electronic exchanges.

Recommendation #1

The nuclear science community recognizes that this LRP is being developed during a period when our nation is at war and is facing serious challenges in several areas essential for sustaining American economic competitiveness. Recent studies have called for long-term planning and increased investments and new initiatives in national security [1], nuclear energy [2] and education in the fields of science, technology, engineering and mathematics [3]. The nuclear science community is committed to enhancing American competitiveness through research to advance fundamental understanding of the origin of baryons and the structure of nuclear matter. Intrinsic in the research vision is education of the next generation of nuclear scientists, many of whom will provide the scientific and technological expertise in the field needed by the Nation. In addition to long-term benefits, there are opportunities for nuclear science research to have direct impact on R&D projects that address current societal needs. Workshops were held recently to identify areas where capabilities of the nuclear science community can contribute in important ways to achieving the goals of Federal agencies with mission responsibilities in nuclear stockpile stewardship, homeland security [4] and the Global Nuclear Energy Partnership (GNEP) [2] . For the first time a workshop dedicated to discussions of the broader impact of nuclear science activities on society was held as part of the information gathering stage of the planning process in nuclear science.

We recommend that the nuclear science community in alliance with the Nuclear Physics Programs at the DoE Office of Science and the NSF include in the input gathering stage of the LRP process scientists supported by other R&D efforts and government organizations for which nuclear science is an important program component; e.g., the National Nuclear Security Agency, DOE Office of Nuclear Energy, Department of Defense, and the Department of Homeland Security.

Recommendation #2

The Nuclear Physics Programs at the DoE Office of Science and the NSF operate world-class accelerator facilities for basic research in nuclear physics. These facilities provide users with an assortment of particle beams, including photon, electron, hadron, stable heavy ion and radioactive ion beams, over broad energy ranges. The research infrastructure of these facilities include sophisticated particle detection systems, start-of-the-art electronics and data acquisition systems, and technical staffs with expertise in supporting nuclear physics research. In addition to providing an essential component of the research infrastructure for the nuclear physics community, these facilities are becoming important resources for other communities of scientists and technologists who apply basic nuclear science in the development of technologies and services for security and energy and for organizations that require particle beams in R&D projects; e.g., single-event failure testing of electronics and evaluation of novel particle detection concepts by research teams supported by Federal agencies and industry. Because of the investments made by the DoE and NSF and the nuclear physics community in particle-beam accelerator facilities and accelerator and particle detection R&D and construction for accelerator- and non-accelerator based experiments, these facilities offer cost-effective resources that can be utilized to support the missions of other Federal agencies. Of course, the usage of these facilities to support the programs of other Federal agencies should be modest relative to normal operation for nuclear physics research.

We recommend that the DoE Office of Science and the NSF continue to make the nuclear-physics research facilities for which they have major stewardship responsibilities available to scientists whose work supports the missions of other Federal agencies and programs, in particular those that have missions in the areas of national security and energy security.

Recommendation #3

A program for vigilant evaluation and effectual dissemination of nuclear data is essential for sustaining American leadership in basic nuclear science research and American competitiveness in applying basic nuclear science to develop technologies and services for general use in society. The nuclear data are produced by programs that are supported by a number of government agencies (e.g., DoE, NSF, NNSA, DHS and NIST) and evaluated by nuclear scientists. These data are essential to meeting the diverse missions of a number of organizations: governmental, international, educational, commercial and medical. The nuclear science community serves a number of these organizations separately, but a more coherent approach may be beneficial in providing the best and most timely data as well as ensuring that the future needs of the interested organizations are considered in the planning process for this important national service.

We recommend that the DoE Office of Science continue to provide strong support for the nuclear data program and to engage other relevant organizations in evaluating and planning the direction of the nuclear data program.

Recommendation #4

The most valuable assets in the field are the scientists. Sustaining leadership in basic nuclear-science research and American competitiveness in applications of nuclear science for the benefit of society requires maintaining a critical number of practitioners at all levels of the professional development line from undergraduate student to senior scientist. For this reason, basic science research is conducted in an apprenticeship style with the more experienced practitioners passing on their knowledge of the field and research expertise to the younger participants.

The participants of the American Competitiveness workshop fully endorse the recommendations of the Education whitepaper and recommend that the nuclear physics programs at the DoE Office of Science and the NSF continue strong support of graduate education and expand their support for undergraduate research participation, outreach and professional development activities.

Executive Summary Endnotes

[1] *Making the Nation Safer: The Role of Science and Technology in Countering Terrorism*, A report of the National Academy of Sciences, 2002, http://www.nap.edu/catalog/10415.html.

[2] *Nuclear Physics and Related Computational Science R&D for Advanced Fuel Cycles*, the report of the DoE sponsored workshop held in Bethesda, Maryland, on August 10–12, 2006, http://www-fp.mcs.anl.gov/nprcsafc.

[3] *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* A report of the National Academy of Sciences, 2006, http://www.nap.edu/catalog/11463.html.

[4] *The Role of the Nuclear Physics Research Community in Combating Terrorism*, report of the workshop convened in Washington D.C., July 11–12, 2002, http://www.sc.doe.gov/henp/np/homeland/CombatTerrorismFinal110602.pdf

Introduction

The fundamental physical description of the nucleus represents the goal of nuclear science. The understanding derived from this description provides the knowledge base essential for creating nuclear technologies. Technologies such as nuclear energy, nuclear medicine, particle accelerators, particle detects, and nuclear weapons all rest on the foundation of understanding provided by nuclear physics and nuclear chemistry and on the activities of a research community engaged in the extending this knowledge and producing scientific insight and physical data. United States competitiveness depends on the creation of technologies resulting in economic growth. The preeminence of the United States in all economic areas is driven, in part, by technical innovation, which is the result of knowledgeable people engaging in a host of research activities. While the explicit connection between fundamental research and economic well-being is yet to be described, however, it is clear that the people who engage in basic research participate in technological innovation in a number of ways in the long process that brings original ideas of a fundamental nature to products in the market place. Nuclear science provides both the foundation required for a diverse set of important technologies crucial to the future competitiveness of the United States and the workforce trained to create those technologies.

Sustaining leadership in basic science research is important for sustaining American economic competitiveness. Development of this long-range plan (LRP) provides the nuclear science community with opportunities to reflect on accomplishments in advancing understanding of nature at the distance and energy scale of atomic nuclei and in developing technologies that create new discovery capabilities in the field. A primary goal of this planning exercise is to lay out a research agenda that will optimize the chances for significant discoveries during the next decade and position the US for leadership on key scientific issues in the field. Successful execution of the plan will affirm America's prominence in the global scientific community and help secure our economic place in a technology-driven global economy. Table 1 summarizes areas in which nuclear science is applied to produce technologies and provide services that benefit society. Potential applications of state-of-the-technologies that were recently used in nuclear physics research are listed in Table 2. Some examples of applications of nuclear science in national security and medicine are presented in the sections to follow.

The execution of the research envisioned in this LRP at a pace required to sustain American leadership in basic nuclear science is predicated on attracting and educating the next generation of nuclear scientists. In addition, this community is the primary source of scientists and technologists who have the educational background to innovate and implement technologies and services that are based on nuclear science. In developing this LRP the community prudently threaded the issue of education through all forums for discussing the science. This places the development of strategies for attracting talented students into the field at the onset of the planning process rather than at the tail end, which is a different approach from previous plans. Strategies for developing the talent base to sustain American competitiveness in nuclear science are discussed in the Education whitepaper [5], and therefore, are not included in this report.

Technologies required to execute the basic research program in nuclear science have proven to be extremely important in other areas, both in other areas of basic science as well as in applications. Particle accelerator technologies that are developed for the nuclear science research, such as the proposals for a U.S. Facility for Rare Isotope Beams, provide capabilities to study material science through isotope implantation, produce radio-isotopes for medical research and nuclear data for national security. Detector development is an essential component of executing basic experimental research where the ability to "see further" is crucial to advance knowledge. Our ability to respond to the nation's acute need for radiation detector technologies and for people with the science and technical backgrounds needed to develop new technologies is a direct result of investments made in basic science research. The products of these investments are now available to bring to bear on applications that are important for homeland security and other national priorities. It is important for this LRP to make the connection between the long-term investments made for basic research and the need to assure a technological capability ready to respond to national needs.

Data describing the nucleus and the reactions involving nuclei are a direct product of nuclear science basic research. These data have a direct application to many of the technologies based on the nucleus. The data are managed in multiple, international, databases and the National Nuclear Data Program is the U.S. effort supported by the DoE. While extensive, the database does not span the entire range of applications anticipated in the near future, particularly to support the resurgent nuclear energy program. In addition, the application of these data to homeland security will become more important in the near future. The LRP should address the issues of making available the data from the broad range of research activities into a useful database.

Nuclear science is important to the execution of the missions, and the accomplishment of the goals of many organizations within the U.S. Government. To be specific, the Departments of Energy, Defense and Homeland Security all depend on the activities of the nuclear science community. This report provides some of the many examples of how the knowledge obtained and the technologies developed through basic nuclear science research are being applied to address national needs.

Table 1. Summary of current applications of nuclear science

Medical Diagnostics and Therapy Radiography Computerized tomography Positron emission tomography MRI (regular) MRI (with polarized noble gases) Photon therapy Particle-beam therapies	**Material Analysis** Activation analysis Accelerator mass spectrometry Atom-trap trance analysis Forensic dosimetry Proton-induced x-ray emission Rutherfold backgrounding Ion-induced secondary-ion emission Muon spin rotation
Safety and National Security Airport safety and security Large-scale x-ray scanners Arms control and nonproliferation Stockpile stewardship Tritium production Space-radiation health effects Food sterilization	**Environmental Applications** Climate-change monitoring Pollution control Groundwater monitoring Ocean-current monitoring Radioactive-waste burning
Energy Production and Exploration Nuclear reactors Oil-well logging R&D for next generation nuclear reactors **Art and Archaeology** Authentication Nuclear dating	**Materials Testing and Modification** Trace-isotope analysis Ion implantation Surface modifications Flux-pinning in high-T_c superconductors Free-electron lasers Cold and ultracold neutrons Single-event efforts Microphone filters

Table 2. Summary of potential applications of nuclear science.

Safety and National Security Large-scale neutron beam scanner Large-scale gamma-ray beam scanner Large-scale imaging with muons Nuclear reactor monitoring with antineutrino detector

Sidebar: Quark-gluon plasma meets spintronics

Quark-gluon plasma meets spintronics

The large masses of neutrons and protons are not due to the nearly massless constituents, quarks, but to the formation of chiral condensate. The chiral condensate melts at high temperature and density such as in the conditions achieved by the Relativistic Heavy Ion Collider at BNL. The chiral condensates are the result of the spontaneous breaking of the approximate chiral symmetry of Quantum Chromo-Dynamics (QCD) at the femtometer scale.

It turns out the chiral symmetry governs the dynamics of quasi-particles in exotic materials at the nanometer scale. Graphene – a single layer of carbon atoms arranged in a honeycomb lattice – can be the stage on which chiral condensate is formed by applying an external magnetic field.

This cross disciplinary work, the confluence of condensed matter theory and the theory of relativistic heavy ion collisions, result in an innovative proposal to create a class of nano-electronic devices based on Graphene-Magnet Multilayers (GMMs). The resulting US Patent 60/892,595 (pending) “Graphene-(Antiferro)Ferro-Magnet Multilayers” awarded to BNL scientists I. Zaliznyak, A. Tsvelik and D. Kharzeev describes the concept of re-writable nano-scale spintronic processors and storage devices that could be possible using GMM technology.

Nuclear Data: Accurate and Accessible

Nuclear data are produced by activities that are motivated by either basic research or the development of nuclear-based technologies. Globally, programs that generate nuclear data are supported primarily by government agencies (e.g., in the U.S., the DoE, NSF, NNSA, DHS and NIST are the major funding agencies for nuclear data measurements). It became clear early that international coordination of the collection, evaluation and dissemination of nuclear data that is produced world wide was essential for assuring quality control and effective utilization of this international resource. The International Atomic Energy Agency has taken the lead on coordinating nuclear data projects world wide through a network of core and specialized nuclear data centers. The dissemination of nuclear data and associated documentation to the consumers of nuclear data is the main goal of this international network. To accomplish this goal, the network conducts the following activities:

- Compilation of experimental nuclear data (EXFOR/CSISRS) and bibliographic information (CINDA)
- Collection of evaluated nuclear data (ENDF/EVA);
- Exchange of nuclear data of all types among the data centers;
- Promotion of the development of special purpose evaluated data files;
- Development of common formats for computerized exchange of nuclear data;
- Coordinated development of computer software for managing and disseminating nuclear data; and
- Documentation of current and future data needs in order to be able to meet changing user demands.

Information about nuclear data centers world wide can be found at http://www-nds.iaea.org/nrdc.html.

The National Nuclear Data Center (NNDC) is the core center for serving America. It serves as the hub facility for the U.S. Nuclear Data Program (USNDP) which is funded by the Office of Science at the Department of Energy. The mission of the USNDP is to collect, evaluate and disseminate nuclear physics data for basic nuclear physics and for applied nuclear technology communities in the United States. The USNDP includes nuclear data groups and nuclear data experts from national laboratories and academia, including Brookhaven National Laboratory (BNL), Argonne National Laboratory (ANL), Los Alamos National Laboratory (LANL), E.O. Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Oak Ridge National Laboratory (ORNL), Triangle Universities Nuclear Laboratory (TUNL), McMaster University, and the National Institute of Standards and Technology (NIST). The services provided by this national network of nuclear data groups are essential to organizations with missions that require access to nuclear data. The nuclear data infrastructure provided by the USNDP impacts governmental, educational, commercial and medical organizations in America, and is part of the U.S. commitment to the international nuclear data network.

It is evident that the need for convenient access to nuclear data is rapidly increasing. As shown in **Figure 1** the number of data retrievals from USNDP databases have increased

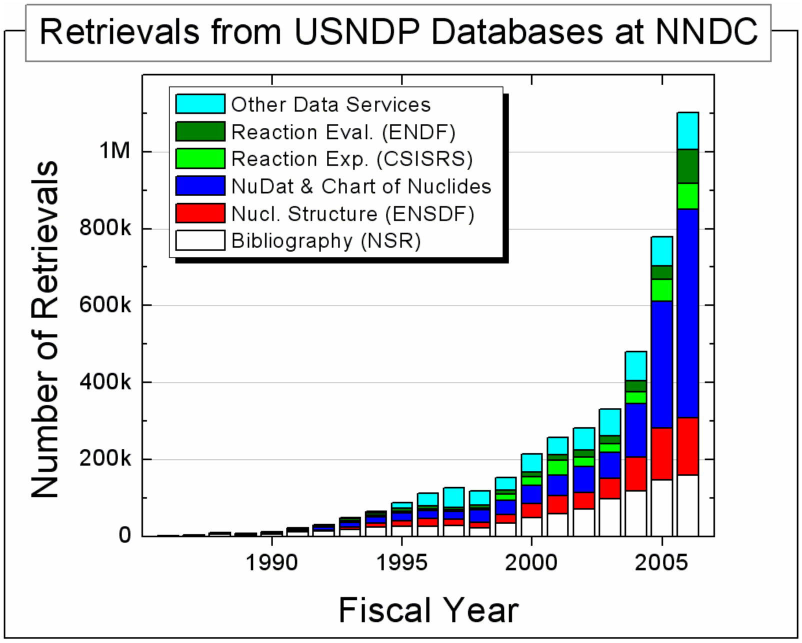

Figure 1. Number of retrievals from the USNDP databases at the NNDC from 1985 through 2006. This graph is from the USNDP Annual Report for FY2006.[1]

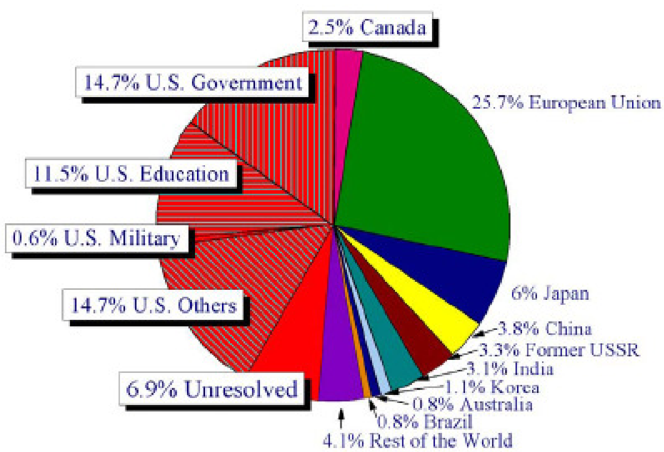

Figure 2. Demographic distribution of U.S. users and geographical distribution of international users of the USNDP nuclear databases as monitored by data retrievals through the NNDC. This graph is from a presentation given by B. Pritychenko.[2]

by a factor of 10 over the last decade. In FY2006 the NNDC web service reached the milestone of one million retrievals from the USNDP databases. The distribution of NNDC data retrievals shown in **Figure 2** shows that the users of the USNDP databases are mainly from the U.S. (42.9%) and Europe (25.7%). The U.S. users are almost equally divided among

[1] *U.S. Nuclear Data Program Annual Report for FY2006*, prepared by P. Oblozinsky, http://www.nndc.bnl.gov/usndp/docs/usndpfy06_fy08planfinal.pdf.
[2] B. Pritychenko, Overview of USNDP Products and Services, presented at CSEWG&USNDP 2005, Brookhaven National Laboratory, November 8-11,2005, http://www.nndc.bnl.gov/proceedings/2005csewgusndp/Wednesday/USNDPUserCommunity/03_Pritychenko.pdf.

government, education and all others users. Monitoring the trend of the usage of the USNDP databases by industry in the coming decade will provide a direct measure of a contribution by the USNDP on the U.S. economy.

Applications in National Security

In the area of national security, nuclear physics capabilities underpin a broad range of capabilities and applications. They support the work that the NNSA labs do in assessing and certifying the safety and reliability of the US stockpile. More recent efforts in building an "attribution" program also require extensive capabilities in nuclear theory, modeling, and experimentation. In this program the U.S. aims to use forensics to determine the design, fuel types, and possibly, the origin of a device that might be used against it from the post-explosion radiochemical isotope debris.

A common theme to these applications is the need for the ability to determine cross sections on short-lived nuclei.   These nuclear species can play an important role in high neutron fluence environments such as in the aforementioned applications, as well as in astrophysical environments. The methods being developed in the nuclear physics community play an important role here. For example, in theory, more microscopic methods for both light nucleus reactions (e.g., ab-initio predictions) as well as for heavier nuclei (e.g., in determining nuclear level densities, fission barriers, etc) are enhancing our predictive capability. In experimentation, methods such as the surrogate method (Livermore) are opening up the ability to infer previously unknown cross sections. Also, new detectors such as DANCE and the Lead Slowing Down Spectrometer at Los Alamos, combined with the ability to fabricate radioactive targets, is enabling a new set of important measurements to be made. Another high priority in many applications is a more precise and realistic set of covariance data, i.e., uncertainties and correlations on cross sections. These are needed in Stewardship applications, as well as in advanced reactor programs such as GNEP. Many of the statistical and theoretical methods needed to develop these databases have been supported by the Nuclear Data Program in the Office of Science Nuclear Physics Program. Indeed it is worth noting that this Nuclear Data Program is responsible for overseeing and maintaining the US national ENDF cross section database which is the basis of nuclear application simulations in a wide range of areas.

Applications in Homeland Security

At its beginning, nuclear science was an ambitious and risky wartime research effort that resoundingly succeeded in bringing World War II to a rapid conclusion and became the experimental foundation upon which quantum mechanics was launched. The promises of the nuclear age were breathtaking -- nuclear energy offered the possibility of abundant, cheap energy and other discoveries and inventions pointed to astounding medical and industrial applications. However, political problems in this new era lead to disillusionment – the nuclear arms race led to destabilizing developments and the world failed to find straightforward solutions to nuclear waste and safety issues. For better or worse, we have inherited and will pass on to our children a nuclear world. The knowledge of the nucleus creates tremendous opportunities for developing energy resources and applications in medicine. However, the promises of plentiful environmentally friendly energy sources and medical diagnostic and treatment technologies do not come for free. Because the same knowledge can be applied to develop destructive technologies, there are serious risks that must be understood and reduced to safeguard the Nation. The working group on national security at the American Competitiveness Workshop in Chicago brought together scientists from national labs, universities, government agencies and private companies for the purpose of identifying ways in which the research activities and expertise of the nuclear science community might be used in the next decade to help in the development of the technologies that will be needed for national security and homeland security. Many of the presenters provided examples of how basic nuclear science is being applied to provide new technologies relevant to national and homeland security and gave areas where the nuclear science community will have opportunities to contribute to this area. The agenda for the working group session is in the appendix of this report, and the talks can be obtained from workshop website at **http://www-mep.phy.anl.gov/atta/dnp/program_ac_wg2.htm**.

A recent Defense Science Board report noted that the risks of nuclear proliferation are severe and difficult to solve politically. Technical advances have lead to the proliferation of nuclear weapons technology. The Department of Homeland Security (DHS) was formed to help centralize the nation's efforts to reduce these risks. The country has evolved a multi-pronged research and development approach to addressing the proliferation threat, spearheaded by the DHS in addition to other agencies such as the Department of Energy. The main programmatic areas aim to develop new technologies in contraband detection, emergency response, incident assessment, and nuclear forensics. More specifically, the mission of the Domestic Nuclear Detection Office (DNDO), part of the DHS, is to improve the Nation's capability to detect and report unauthorized attempts to import, possess, store, develop, or transport nuclear or radiological material for use against the Nation, and to further enhance this capability over time. One of the objectives of DNDO to further its mission is to conduct an aggressive R&D program to develop technologies that will have a dramatic and demonstrable positive impact upon the cost, performance, and operational burden of nuclear material detection components and systems.

Current focus areas for this transformational R&D include:

- Passive and active systems with greater sensitivity and resolution
- Materials with greater sensitivity and resolution
- "Pocket" and hand-held systems with improved ID and enhanced operational effectiveness
- SNM verification
- Algorithms and phenomenology
- Detection at longer distance
- Remote emplaced sensors
- Modeling and measurement of operating environments
- Human-portable and re-locatable systems for active interrogation and improved passive detection performance

The main program drivers that result in these focus areas are:

- Detection of radiological and nuclear materials being transported into or through the US or its concerns
- Monitoring, detection, and analysis of nuclear explosions and nuclear weapons proliferation through radio-nuclide monitoring and other detection capabilities

Some related aspects of these programs drivers, including international treaty negotiations and emergency response, are clearly also important.

The nuclear science programs at DOE and NSF have an important role in helping plough new directions to take with nuclear detection technologies. A key role for the science community is in generating new concepts and approaches to detection. Many of the R&D projects currently underway have parentage in the basic research community. New approaches and ideas often grow out of the process of trying to extend our understanding of nature. This situation is particularly true for accelerator and detection technologies. There is very little support directly for advancing new ideas in these areas. Instead, developments in these areas are usually the outgrowth of the desire to achieve new physical insights about nature or to enhance detection sensitivities to physical processes that have not been measured before.

More parochially, there are many needs that crop up as specific technological approaches are developed. Projects often encounter nuclear physics issues when variant detection schemes or event scenarios are modeled using sophisticated simulation codes such as MCNP(X) or GEANT. These simulations are used to lay the groundwork for proposing and planning new projects and also to optimize the design or analysis of different configurations. Many calculations can be performed quickly, whilst individual experiments involving SNM require extensive authorization and are costly. Simulations of fielded experimental interrogation configurations can be used to interpret the measured data. And very importantly, simulations can extensively explore "what if?" questions.

The simulation capabilities are built upon high-quality fundamental nuclear cross section and decay databases, such as the ENDF nuclear data library developed by the US Nuclear Data Program which is supported by the DoE Office of Science. These evaluated databases incorporate the detailed information available from experiments and from nuclear models, and allow transport simulations to model the underlying physical phenomena accurately. Several of the projects surveyed had encountered the need for advances in simulation methods and in the underlying ENDF library. These needs range from particle correlations in energy, angle and multiplicity to improved data for photonuclear reactions to improved cross sections for neutron reactions involving unstable or rare isotopes to improved gamma-ray production data.

Some examples that could be developed:

- Passive detection of multiplying fission chains
- Gamma-ray imagers
- Nuclear resonance fluorescence with mono-energetic photon beams

Basic science also plays a key role in developing the nuclear physics knowledge base used for assessing and responding to new technical and political situations as they arise. For example, in the late 1990's it was reported that a high-energy isomer of 178-Hafnium could be used as an energy storage device or possibly as a new type of nuclear weapon technology. The state-of-the-art facilities of the basic science community were brought to bear to perform new measurements with sensitivities that were many orders of magnitude improved over the initial report, laying to rest concerns over this new technology and potentially saving billions of dollars in resources. Within the homeland security arena, nuclear forensics plays an important role in deterring rogue nations from using nuclear weapons and radiological dispersal devices. By extending our forensics capabilities, it becomes easier to accurately identify such nations and address the situation with an informed political process.

Applications in Medicine

Diagnostics

Radioactive atomic nuclei are used extensively in biology and medicine as radiotracers. Their chemical properties are identical to the stable isotopes of the same element, and they are incorporated into molecules and are metabolized. When they decay with known half-lives, they emit characteristic radiation that can be readily detected for diagnostic purposes. Alternatively, the radiation can be used for therapeutic purposes. Commonly used radiotracers (technetium-99m, iodine-123, indium-111) have short half-lives and are typically generated and handled by personnel trained in nuclear science.

Positron emission tomography (PET) imaging

The use of positron emission tomography (PET) imaging has become a major diagnostic modality. PET imaging provides metabolic information through use of radioactive isotope tagged molecules that have different rates of uptake, depending on the type and function of the tissue involved. Tomographic images are reconstructed from recording the positron decay of radioactive isotopes (e.g. carbon-11, nitrogen-13, oxygen-15, fluorine-18) that are incorporated into radiotracer compounds such as glucose, water, or ammonia, which are metabolized. Flourine-18 labeled fluorodeoxyglucose (FDG) has become a primary tracer because the half life of flourine-18 is long enough to allow for transportation of a few hours. Examples of such functional tomography images are shown in **Figure 3** and **Figure 4**. Other shorter-lived isotopes are produced by on-site cyclotrons. Increasingly often PET scanners are combined with computed tomography (CT) scanners to provide multimodal images that give both metabolic and anatomic information. More than 650 hybrid PET/CT scanners were installed worldwide in 2005. Hybrid PET/Magnetic Resonance Imaging (MRI) scanners are under development and provide a promising diagnostic modality due to better soft tissue resolution and lower radiation exposure compared to PET/CT. A commercial head-only PET/MRI fusion system will be available by the end of 2007 [5].

In the past 20 years (1986-2006) the reconstructed position resolution of commercial PET scanners has increased from 8 mm to 4 mm, while the axial extent has increased from 5 cm to more than 15 cm. New detector materials that have better energy and time resolution (to provide more stringent coincidences and reduce random background) have contributed significantly to progress in this area. Measuring the time-of-flight of the photons along the line-of-flight has allowed scientists to obtain additional improvement in reconstructed position resolution in scanners under development.

New PET isotopes are being explored in research settings. For example, metal complexes of gallium-67,68, indium-111, copper-60,61,62,63,64,67 are being investigated as imaging agents for patients following a heart attack or stroke to identify hypoxic tissue.

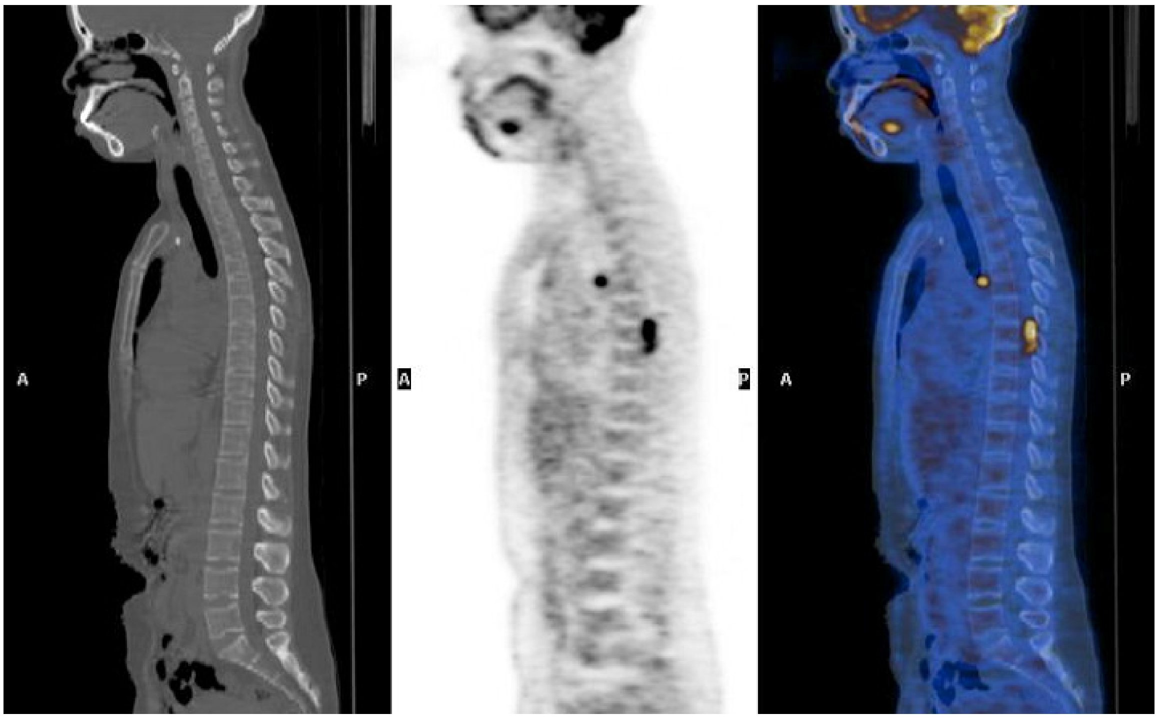

Figure 3. Images of the same patient taken simultaneously in different modalities: CT (left), PET (middle), and PET/CT fusion (right). While the CT scan displays the patient's anatomy, the PET scan shows (in black) areas of increased 18F-FDG uptake in the lung and spine of the patient. The fusion image shows the cancerous areas overlaid with the patient's anatomy. (Image courtesy of Kevin Berger, MD, Michigan State University)

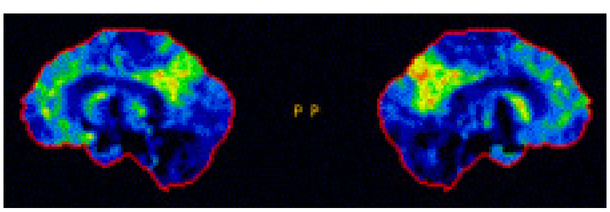

Figure 4. Brain images of a patient with Alzheimer's disease. Following brain 18F-FDG PET imaging, the images were normalized to a stereotactic brain template. Deviations in metabolism from that in a healthy brain are indicated in colors. The light colors indicate areas of reduced metabolism in this patient. (Image courtesy of Kevin Berger, MD, Michigan State University)

Novel detection concepts

Organ-specific PET imagers developed by nuclear scientists at Jefferson Laboratory could improve detection sensitivity to certain types of tumors over devices that are currently commercially available. The increased sensitivity should lead to earlier detection capabilities and consequently to more effective treatments. The cost per unit is still high relative to current devices. However, enhancements in the effectiveness of the treatment should stimulate increased use of the new device and eventually lead to a reduced cost to the patient. An example of a mammogram taken with the device is shown in **Figure 5**.

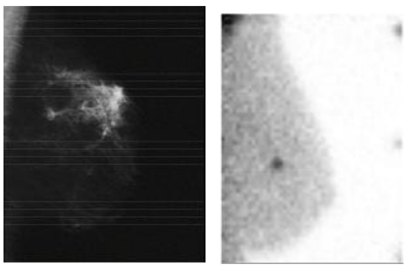

Figure 5. Mammogram of breast (left) showing stable nodular density. The gamma image (right) clearly shows a suspicious lesion, which was later confirmed by biopsy to be cancerous. (Image courtesy of Stan Majewski, Jefferson Laboratory).

This same group at JLab is making substantial improvements in the resolution of imagers that are based on the detection of single γ-rays by correcting for motion during imaging. These advances in medical imaging technologies were spurred by the experience of this group with radiation detection systems and real-time data acquisition and analysis in support of the basic nuclear physics research program at JLab. An example of the resolution improvement is shown in **Figure 6**.

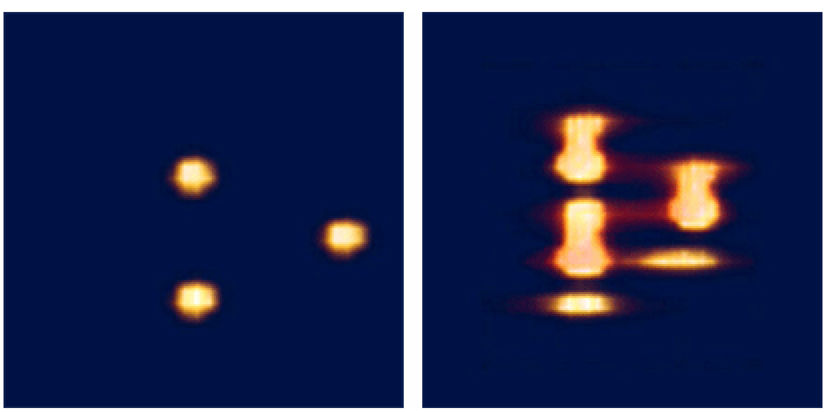

Figure 6. Three-dimensional rendering of reconstructed SPECT volumes of a mouse with motion correction (left) and without motion correction (right). (Image courtesy of Stan Majewski, Jefferson Laboratory).

Hyperpolarized gas magnetic resonance imaging

Magnetic resonance imaging with polarized noble gases allows one to image of the internal gas spaces of lungs or sinuses [6]. Due to limited water content, air spaces are usually poorly seen with hydrogen-based MRI. High resolution imaging of the steady-state distribution of laser-polarized helium-3 or xenon-129 allows one to directly visualization of airways. Time-resolved images of gas flow can provide functional assessment. Since the last long-range plan, Phase 2 clinical trials have begun with hyperpolarized xenon imaging in humans and hyperpolarized xenon production systems have become commercially available [7]. Research on hyperpolarized magnetic imaging grew directly out of the developments at universities and national laboratories of polarized targets for nuclear science experiments.

Hadron therapy

During the period of the last long-range plan, hadron-therapy to treat cancer has shifted from pilot projects at accelerator facilities to hospital-based or dual centers. As of July 2005 over 48,000 patients had been treated with hadrons for various forms of cancer worldwide [8]

Proton therapy

Radiotherapy with energetic protons (> 230 MeV/nucleon) allows one to design fine-tuned three-dimensional treatment plans and to achieve better conformality compared to photon treatments, because charged particles deposit most of their dose in the well-defined Bragg peak. This allows one to obtain a dose escalation in the tumor relative to photon treatments while limiting the integral dose and makes proton radiotherapy suitable for pediatric applications. Proton radiotherapy was pioneered at the Harvard Cyclotron Laboratory and five proton therapy facilities in clinical settings are in operation in the United States. A 250 MeV proton therapy superconducting cyclotron was designed at the National Superconducting Cyclotron Laboratory using technology developed for building cyclotrons for nuclear science. Several of these cyclotrons have been built and installed by ACCEL Corporation in Europe and are now being offered in the United States through Varian Medical Systems. Worldwide, around 45,000 patients had been treated with protons beams at the beginning of 2006, in twelve physics laboratories and more than ten hospital-based proton-therapy centers. The locations of the proton beam therapy sites are indicated by the circles in

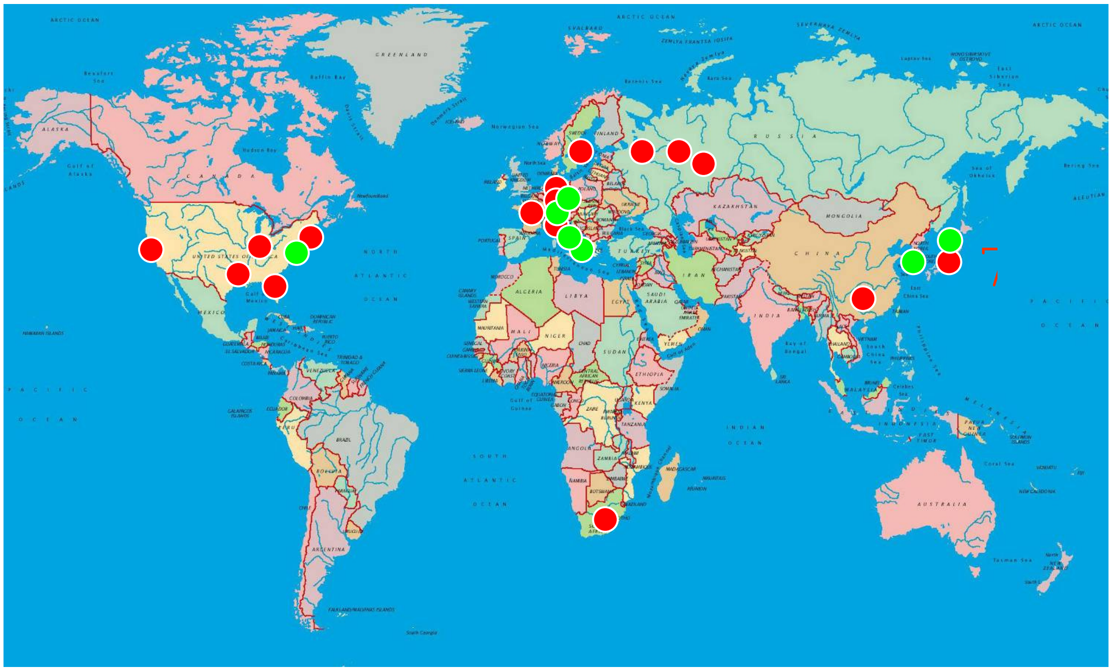

Figure 7. Proton therapy centers (< 200 MeV) in operation (red dots) and under construction (green dots. Proton radiotherapy centers are in operation in the United States at Loma Linda University Medical Center, the Northeast Proton Therapy Center, theMidwest Proton Radiotherapy Institute, the University of Texas M.D. Anderson Cancer Canter, and the University of Florida Proton Therapy Institute [9].

Future technological advances in proton radiotherapy are closely tied to technical advances in accelerator physics. A prototype for a compact dielectric wall accelerator with acceleration gradients of up to 100 MV/m is under development and would reduce the accelerator cost significantly. Concepts of laser-based acceleration are being explored and a scanning proton beam concept is being proposed

Neutron therapy

Fast neutrons have a biological advantage over x-rays and are used at neutron facilities at the University of Washington and at Harper hospital in Detroit. The latter facility employs a small superconducting cyclotron (designed and constructed at Michigan State University's NSCL) that is rotated around the patient.

Heavy-ion therapy

Heavy-ion beams provide higher dose conformality than do protons (the beam profile has a sharper lateral falloff) and have a similar biological advantage (as measured in the Relative Biological Effectiveness) compared to neutrons. Because the ionization of heavy ions is larger than that of protons, the damage to tumor cells is more severe. This makes heavy-ion therapy the modality of choice for slow-growing tumors, which are resistant to proton and photon therapy.

Following the development of heavy-ion radiotherapy at Lawrence Berkeley National Laboratory in 1977, three synchrotron-based facilities are currently treating patients with carbon ions in Japan and Europe. In Japan, the Heavy Ion Medical Accelerator in Chiba (HIMAC) and the Hyogo Ion Beam Medical Center (HIBMC) provide treatments in a clinical setting; in Germany, a research therapy facility is in operation (GSI Darmstadt) and a fourth facility in a clinical setting is nearing completion (DKFZ Heidelberg). Additional heavy-ion therapy facilities have been proposed in Austria, Italy, and Germany [10].

Sidebar: Development of particle radiotherapy in the US

Development of particle radiotherapy in the US

Foundation of heavy-ion radiotherapy

Heavy-ion radiotherapy was pioneered at the Bevalac at Lawrence Berkeley National Laboratory starting in 1977. A radiation therapy program was developed with a variety of heavy-ion beams, including carbon, nitrogen, neon, and argon at energies of several hundred MeV/nucleon. Human patient protocols for various cancers were carried out with several hundred patients treated during the lifetime of the program (which ended with the shutdown of the Bevatron in 1993). The therapy community learned how to develop, shape, and deliver the beams for radiotherapy procedures and developed the instrumentation to monitor the beam and patient during treatment. This pioneering program laid the foundation for the heavy-ion radiotherapy programs presently in place in Germany (GSI in Darmstadt) and Japan (HIMAC in Chiba and IBMC in Hyogo).

Neutron therapy superconducting cyclotron

The first superconducting cyclotron for medicine was designed and constructed at the NSCL at Michigan State University and is now in use for cancer treatment at the Gershenson Radiation Oncology Center at Harper University Hospital in Detroit. It was completed at the NSCL in 1990 and was then moved to Detroit to be installed in the hospital. The cyclotron itself accelerates deuterons, which are stopped in a target of beryllium just before their exit from the cyclotron. This produces a beam of high-energy neutrons, which is then directed against the cancer patient's tumor. Since the cyclotron is superconducting, its physical size is much smaller than a comparable room-temperature cyclotron would be. This "miniaturization" allows the cyclotron to be mounted on gantry rings that rotate around the patient so that the cancer can be irradiated from several angles. The Harper facility has become the most active neutron-therapy center in the world.

References

[5] *Announcement that Siemens will be releasing a commercial head only with MR/PET systems this year*, Applied Radiology Today Vol 8 No 3 p. 17 (Feb 12, 2007).

[6] *Metabolic Magnetic Resonance Research and Computing Center*, University of Pennsylvania, http://www.mmrrcc.upenn.edu/research/hyper.html.

[7] *Announcement that MagniXene received US FDA start the next phase of human testing*, Feb. 3, 2006, http://www.xemed.com/news/recent.

[8] *Particles*, July 2005, http://ptcog.web.psi.ch/ptles36.pdf

[9] *Advances in Charged-particle Beam Therapy*, talk given by Jonathan Farr at the Workshop on American Competitiveness, Chicago, ILL, Jan. 20, 2007, http://www-mep.phy.anl.gov/atta/dnp/program_ac.htm.

[10] *Particle Therapy Co-Operative Group*, http://ptcog.web.psi.ch/newptcentres.html

Appendix A. Workshop Organizing Committee

Mark Chadwick	Los Alamos National Laboratory
Ben Gibson	Los Alamos National Laboratory
Thomas Glasmacher	Michigan State University and NSCL
Ed Hartouni, co-chair	Lawrence Livermore National Laboratory
Calvin Howell, co-chair	Duke University and TUNL
Dennis McNabb	Lawrence Livermore National Laboratory
J. David Robertson	University of Missouri-Columbia

Appendix B. Workshop Agenda

Friday, January 19, 2007

Plenary Session I: Energy - Chair: Calvin Howell (Duke/TUNL)

8:30 PM - 8:45 PM Welcoming remarks and description of the goals of the workshop, Ed Hartouni (LLNL)

8:45 PM - 9:15 PM Global Nuclear Energy Partnership, John Herczeg (DOE)

9:15 PM - 9:45 PM Advanced Fuel Cycle and nuclear data needs, Phillip Finck (INL)

Saturday, January 20, 2007

Plenary Session II: National Security - Chair: Ed Hartouni (LLNL)

8:30 AM - 9:00 AM National Nuclear Security, Mark Chadwick (LANL)

9:00 AM - 9:30 AM From building bombs to finding them: New frontiers in nuclear physics, Dennis McNabb (LLNL)

9:30 AM - 10:05 AM Radiation Effects Testing, Peggy McMahan Norris (LBNL)

10:05 AM - 10:30 AM Coffee Break

Plenary Session III: Medical Applications - Chair: Thomas Glasmacher (MSU/NSCL)

10:30 AM - 11:00 AM Advances in Charged-particle Beam Therapy, Jonathan Farr (MPRI)

11:00 AM - 11:30 AM Advances in Medical Imaging Using Nuclear Physics Techniques, Stan Majewski (JLab)

WG Nuclear Energy and Nuclear Data
Convener: David Robertson (U. Missouri)

1:30 PM Opening remarks by David Robertson

1:35 PM Opportunities for the Nuclear Science Community to Contribute to the Nation's Energy Future, Lee Schroeder (LBNL)

2:05 PM Nuclear Decay Data for Neutron Neutron-rich Fission Products: Challenges & Opportunities, Filip Kondev (ANL)

2:19 PM Status of ORELA Measurement Capabilities for Astrophysics and Nuclear Energy Research, Michael Dunn (ORNL)

2:33 PM Planning for Nuclear Science Utilization of the National Ignition Facility (NIF), Mark Stoyer (LLNL)

2:47 PM MIX: An Example of Applied Nuclear Physics, Jerry Wilhelmy (LANL)

3:01 PM Preparing PhD Nuclear Scientists for National Needs, Jolie Cizewski (Rugers)

3:15 PM Short Presentations and Discussion

4:00 PM Break

4:30 PM Nuclear Data for Reactor Physics, Mike Herman (BNL)

4:55 PM Nuclear structure: Emergent phenomena revealed through high high-quality data, Davis Kulp (Georgia Tech)

5:09 PM Nuclear Information Science for Nuclear Astrophysics, Michael Smith (ORNL)

5:29 PM Short Presentations and Discussion

6:00 PM Session Adjourned

WG National Security and Other Applications

Convener: Thomas Glasmacher (MSU/NSCL)

1:30 PM Opening remarks by Thomas Glasmacher

1:35 PM Transformational R&D at the Domestic Nuclear Detection Office, Bill Hagan (DNDO)

2:00 PM Charged Particle Radiography, Chris Morris (LANL)

2:20 PM National Security Research at Pacific Northwest National Laboratory, Harry Miley (PNNL)

2:34 PM DOE Radiological Emergency Response Assets, E. Frank Moore (ANL)

2:48 PM A Startups perspective on the role of the nuclear physics community in national security applications, Robert Ledoux (Passport Systems, Inc.)

3:02 PM Building R&D Teams for National Security Applications, Naresh Menon (Physical Optics Corp.)

3:22 PM Discussion

4:00 PM Break

4:30 PM Nuclear Physics and Chemistry Workforce Needs, Brad Sherrill (MSU/NSCL)

4:40 PM Applied Nuclear Science Research at the Los Alamos Neutron Science Center, Steve Wender (LANL)

4:05 PM Nuclear Science for Stockpile Stewardship, John Becker (LLNL)

5:30 PM Recent Nuclear Data Efforts Using the DANCE 4 pi BaF2 Array, Todd Bredeweg (LANL)

5:44 PM Applied Nuclear Physics at Ohio University, Carl Brune (Ohio University)

6:00 PM Break

6:15 PM A tunable neutron beam at the 88" Cyclotron, Peggy McMahan (LBNL)

6:29 PM Surrogate Reaction Techiques for Advanced Fuel Cycle Studies, Rod Clark (LBNL)

6:43 PM Discussion

7:00 PM Adjourn Session

Sunday, January 21, 2007

Closeout Session: Summary and Recommendations

Chairs: Ed Hartouni (LLNL) and Calvin Howell (Duke/TUNL)