AN ASSESSMENT OF THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY PHYSICS LABORATORY

FISCAL YEAR 2008

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Panel on Physics

Laboratory Assessments Board

Division on Engineering and Physical Sciences

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Richard G. Brewer, Stanford University,
John H. Bruning, Corning Tropel Corporation,
Laura H. Greene, University of Illinois,
Steven M. Larson, Memorial Sloan-Kettering Cancer Center, and
David R. Schultz, Oak Ridge National Laboratory.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Alton Slay, Warrenton, Virginia. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Summary

The overall mission of the National Institute of Standards and Technology (NIST) is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve the quality of life. The institutional vision is to be the world's leader in creating critical measurement solutions and promoting equitable standards with core competencies in the areas of measurement sciences, rigorous traceability, and standards. The mission of the NIST Physics Laboratory is to support U.S. industry, government, and the scientific community by providing measurement services and research for electronic, optical, and radiation technology. In this respect, the laboratory provides the foundation for the metrology of optical and ionizing radiations, time and frequency, and fundamental quantum processes, historically major areas of standards and technology.

The organizational structure of the Physics Laboratory for accomplishing its mission and goals includes six vertically integrated divisions:

- Atomic Physics Division
- Electron and Optical Physics Division
- Ionizing Radiation Division
- Optical Technology Division
- Quantum Physics Division
- Time and Frequency Division

The laboratory also includes an Office of Electronic Commerce in Scientific and Engineering Data to facilitate the electronic dissemination of technical information through the Internet. In line with the vertical integration of the laboratory, each division is further divided into groups and projects.

The Panel on Physics visited the six divisions of the laboratory and reviewed a selected sample of their programs and projects. As described in the next chapter, "The Charge to the Panel and the Assessment Process," the panel's assessment included the following four criteria: (1) the technical merit of the current laboratory programs relative to the current state of the art worldwide; (2) the adequacy of the laboratory facilities, equipment, and human resources, as they affect the quality of the laboratory technical programs; (3) the degree to which the laboratory programs in measurement science and standards achieve stated objectives and desired impact; and (4) the extent of the progress of all of the fiscal year (FY) 2007 programs funded under the America COMPETES Act of 2007 (which supports the President's American Competitiveness Initiative [ACI])[1] relevant to the laboratory.

[1] See Domestic Policy Council, Office of Science and Technology Policy, 2006, *American Competitiveness Initiative,* Washington, D.C. "America COMPETES Act" is the short title for the America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act of 2007 (Public Law 110-69).

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

The overall quality and productivity of the Physics Laboratory are comparable to or better than those of other peer institutions, an accomplishment that is being achieved with an infrastructure that is smaller in both size and funding than the size and funding of most national and agency laboratories in the United States.

The laboratory has responsibilities for the maintenance and improvement of the U.S. national standards for the Système International (SI) base and derived units, including those for time (the second), light (the candela), light output (the lumen), power (optical watt), thermometry (the kelvin), radiation (the gray), and radioactivity (the becquerel), as well as many other quantities, units, and data compilations. Following are some of the responsibilities of the laboratory's six divisions:

- The Atomic Physics Division compiles fundamental constants and spectroscopic data for atoms from the far infrared to the x-ray spectral region. It maintains the Atomic Data Center, the only center of its kind, and it sets the standard worldwide for these data.
- The Electron and Optical Physics Division has the primary responsibility for the national primary radiometric standards for extreme ultraviolet (EUV) radiation.
- The Ionizing Radiation Division is primarily responsible for radiation dose (gray) and radioactivity (becquerel) as well as calibrations and standards in industry and medicine.
- The Optical Technology Division maintains primary standards for the candela and associated photometric, colorimetric, pyrometric, and spectral radiometric quantities.
- The Quantum Physics Division conducts research in support of the length scale for mechanical measurements along with establishing a direct connection between optical and radio frequencies.
- The Time and Frequency Division maintains time and frequency standards with the accuracy, continuity, and stability essential for supporting U.S. commerce and scientific research; provides an official source of time for U.S. civilian applications; and supports the coordination of international time and frequency standards, including realization of the SI second.

The success of the laboratory, its relevance, and the quality of the work are exemplified by the Nobel Prizes in physics awarded to three of its staff during the past decade, an accomplishment not duplicated by government laboratories and academic research institutions that are much larger and funded at a higher level. Such honors should be taken as an affirmation of the importance and success of the overall standards, services, and research being performed within this laboratory and provided nationwide and worldwide as well as an acknowledgment of the unique and relevant accomplishments of the Nobel laureates themselves. It is worth noting that the research on which the three awards were based is directly related to improvements in measurements and standards.

ADEQUACY OF INFRASTRUCTURE

Staffing

The quality and productivity of the research staff in all of the laboratory's divisions are impressive, and the laboratory appears to be moving well toward the NIST 3-year goal for attracting and retaining excellent staff. The vast majority of the projects are well conceived and relevant to the mission of the divisions and to the needs of those who use the calibrations, standards, and research results. A major strength of the laboratory is the receptiveness of the researchers and administrative staff to input from the user community and a willingness to address new and evolving technological and metrological issues.

Some groups in the divisions are staffed heavily with retired and/or emeritus employees, contractors, and visitors. Visiting researchers are major contributors to the quality and productivity of the laboratory, bringing in new ideas, establishing close working relationships that continue after the individuals have returned to their own institutions, and filling gaps in expertise in particular projects. A policy involving the use of nonpermanent personnel can, at the same time, be disruptive, because such a policy can jeopardize continuity and flexibility if not effectively implemented. Capabilities appear to be threatened in some areas by the staffing trends of the past few years.

A relatively low permanent staff population appears to be partially related to the NIST overhead structure, which assesses the salaries of permanent staff but not the costs of contractor personnel. A related factor appears to be the extent to which support depends on external funding sources, a factor that has led to a situation in which the hiring or maintaining of temporary appointments is preferred over permanent appointments because of lower costs. A NIST committee is addressing the NIST overhead structure and how it is allocated.

Security Procedures for New Personnel

There has been notable improvement in the ability of the NIST facility at Boulder, Colorado, to engage guest scientists. A highly effective program enables both foreign and domestic scientists to work at NIST Boulder on contract through a new scientific services company. Programs through several universities in Colorado enable collaborative work by foreign and domestic scientists with the Physics Laboratory.

The security-related background checks of new employees and visitors to the laboratory should be expedited as much as possible. The scientists at NIST work on complex experiments that often involve measurements being made after regular business hours when vibrations and temperature fluctuations in the building are minimized. Therefore, it is a serious impediment to both progress and a collaborative spirit that new employees, and particularly foreign visitors and employees, often face 5 to 14 months for background checks by an agency outside of NIST before being allowed to run their experiments after hours. The resolution of this issue would be in line with the ACI goal of increasing the ability of the United States to compete for and retain the most highly skilled workers from around the world.

New Facilities and Equipment

An impressive building program has continued since the 2005 assessment by the previous National Research Council (NRC) Panel on Physics.[2] As noted in that assessment, the addition of these new facilities should alleviate many problems arising because of insufficient space. Although new buildings generally require less maintenance, they do not eliminate the need entirely, so maintenance issues must still be resolved both in the short and long terms, particularly in the case of existing facilities.

A main concern is the condition of the physical plant that houses the Radiation Interactions and Dosimetry Group and the Radioactivity Group in the Ionizing Radiation Division, as well as aging equipment that must be replaced. A serious problem arises from the fact newer equipment must be housed in heavily (radiation) shielded bunkers, but the division is housed in an older building whose shielded facilities do not meet these requirements. This is a major issue that may require the construction of a new building. Funding for a major renovation, or preferably a new building, should be established for the Ionizing Radiation Division. Shielded radiation cells should be constructed to house modern radiation equipment and the high-dose-rate calibration equipment needed for industrial-scale dosimetry and medical imaging and calibrations.

A new laboratory building for the Time and Frequency Division at Boulder has been funded, and construction bids have been solicited. Initiatives to construct this new laboratory should be completed as planned. There remains, however, the problem of the inability to repair and maintain the present facility in a timely manner.

It is critical for the Quantum Physics Division that funding for the new JILA building be provided and that the plans for design and construction move forward in a timely fashion, both to relieve the space crunch at JILA and to maintain the high morale and productivity that are key in making JILA an attractive place to work for highly talented staff members who are actively recruited by other institutions.

In the Optical Technology Division, several laboratories are in new locations in the Advanced Measurements Laboratory (AML), and in general the overall increase in floor space offers much more flexibility and a much improved environment for the researchers to work with their equipment. Unfortunately the occupants of the AML, many of whom are in the new Biophysics Group, will have to move in order to create space for a new NIST center. Laboratory moves are always disruptive. Although the affected staff are facing this change with a positive attitude, it will slow the progress of their research for a time. It is important to have a plan in place that will adequately prepare their destination laboratories prior to the move.

The Optical Technology Division is also investigating the possibility of developing an x-ray facility using a compact source based on inverse Compton scattering. There needs to be a detailed cost-benefit analysis of the development and operation of this facility compared with the development of beam lines at an existing synchrotron radiation facility. If the proposal is thought to be viable, a more focused review by a diverse panel of experts should be undertaken.

The laboratory of the Laser Cooling and Trapping Group in the Atomic Physics

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[2] National Research Council, 2005, *An Assessment of the National Institute of Standards and Technology Measurement and Standards Laboratories, Fiscal Years 2004-2005,* Washington, D.C.: The National Academies Press.

Division is maintained and used at a high level with the addition of significant outside funding—a recognition of the importance of the research of this group to outside funding agencies. The Joint Quantum Institute has plans for a new building that will provide new laboratory space for the Laser Cooling and Trapping Group; these plans should be brought to completion expeditiously.

Maintenance and Upgrading of Existing Facilities and Scientific Equipment

Routine maintenance, repairs, and upgrades of existing facilities and equipment vary considerably among the different laboratory divisions and sites. The panel requested and received a meeting with the Chief Facilities Management Officer to discuss routine maintenance. The available annual funding is substantially less than the estimated costs.

The capacity and capability of the instrument shops of the NIST facility at Boulder have continued to decline over many years and are now at the point that NIST Boulder researchers, particularly in the Time and Frequency Division, must regularly use external machining services, including commercial services, and must sometimes use JILA instrument shops. The absence of stronger in-house fabrication services impedes NIST Boulder research and metrology. JILA, in contrast, has top-notch mechanical and electronic shops, and this infrastructure is vital to the productivity and success of the Quantum Physics Division. The inadequacy of the NIST instrument shops constitutes an unsatisfactory situation that should be addressed and corrected. The strong emphasis on nanotechnology in many of the projects at JILA has led to the need for a new, high-resolution scanning electron microscope (SEM) with a state-of-the-art field emission source for imaging of the nanostructures and for nanolithography; the present SEM at the laboratory is not state of the art.

Infrastructure and facilities for the Time and Frequency Division have shown improvement since 2005. A central heating, ventilation, and air-conditioning (HVAC) facility is being installed to provide improved environmental controls within the existing buildings. A power-conditioning unit is being installed to improve the reliability and quality of the alternating current power to the laboratories on the site. The room in which the new time standard (F2) is being assembled is a significant improvement over the space that housed the current time standard (F1) in 2005. However, these facilities need further improvement, and there remains the problem of the inability to repair and maintain the facility in a timely manner and to an acceptable standard. This problem affects employee safety, efficiency, and morale and should be immediately resolved satisfactorily. The initiative to construct a new laboratory, mentioned above, is laudable; this construction should be completed in a timely fashion as planned, and the present facility must be maintained in an acceptable fashion in the interim.

The Quantum Physics Division is housed in the JILA building on the campus of the University of Colorado. Laboratory and office space continues to be insufficient to adequately house current programs. Immediate steps should be taken to ensure that space limitations do not create potentially unsafe working conditions, are not detrimental to productivity, and do not affect the ability to attract, hire, and retain top-class scientists in the future. Funding to build additional space should be provided in a timely fashion.

Computer Security

The security rules for computers mandated through the Office of Management and Budget should be examined to address the specific needs of the laboratory. The Time and Frequency Division's staff and management have noted, for example, that an increasingly unhealthy fraction of the time and energy of scientists is consumed with various administrative burdens related to information technology (IT) security, procurement, physical security, repeated inventories, required training on administrative issues, and other distractions. NIST should examine ways to comply with the governing laws, regulations, and mandates while minimizing the distraction of the scientists from their mission and fundamental enterprise and maintaining productivity and morale. In fact, NIST would appear to be the appropriate national institution to be examining and developing technologies that maximize security while minimizing interference to the user. The NRC's 2007 report by the Panel on Information Technology also notes, "There are problems with the interaction between mandated or desirable research activities and the standard computer-security policies that are widely respected at NIST and similar organizations."[3] Research at the NIST Information Technology Laboratory that would reduce these problems would serve not only the best interests of NIST but also the nation.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

The American Competitiveness Initiative identifies the National Institute of Standards and Technology in the Department of Commerce, the National Science Foundation (NSF), and the Department of Energy's (DOE's) Office of Science as three key federal agencies that support basic research programs in the physical sciences and engineering. NIST's Physics Laboratory is the only laboratory of its kind among these three agencies and, as such, represents a unique and essential national asset within an institute that is both unique and essential.

According to the *Strategic Plan: Fiscal Years 2007-2012* of the Department of Commerce, "NIST research laboratories focus on providing the measurements, standards, verified data, and test methods necessary to support the development of new technologies and to promote the competitive standing of the United States in the global economy."[4] The strategic plan document further notes that NIST's scientific and technical staff work closely with private industry, academic researchers, and other government agencies. In order for NIST to achieve these objectives, the NIST Physics Laboratory has provided unduplicated services and technology to business, industry, medicine, academia, and other government agencies in the areas of commerce, transportation, communication, defense, science, and research. In parallel with these responsibilities, it has carried out a research program, in many instances the only such research in the United States or the world, designed to continually improve and expand

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[3] National Research Council, 2007, *An Assessment of the National Institute of Standards and Technology Information Technology Laboratory: Fiscal Year 2007,* Washington, D.C.: The National Academies Press, p. 1.

[4] Department of Commerce, 2007, *Strategic Plan: Fiscal Years 2007-2012,* Washington, D.C.: U.S. Government Printing Office, p. 35.

its capabilities in standards and metrology so as to maintain the leadership position of the laboratory, NIST, and the nation.

Detailed observations and recommendations with regard to how well the Physics Laboratory and its divisions have achieved their responsibilities are discussed in the chapters that follow. The overall quality and productivity have continued to rise during the past several decades, including areas of standards originally dominated by other countries, and are now comparable to or better than that of other peer institutions, an accomplishment achieved with an infrastructure that is smaller in both size and funding than the size and funding of most national and agency laboratories. The external impact of the Physics Laboratory is well demonstrated by the fact that three of its staff have received Nobel Prizes in physics in the past decade. Within NIST itself, the Physics Laboratory has 9 of the total of 30 NIST Fellows. These achievements have been accomplished during a time when the lead of the United States in other areas has been diminishing or has vanished as a result of worldwide changes; the Physics Laboratory is dealing with these same changes.

To maintain its international position, the Physics Laboratory has developed a strong network of collaborations with national and international groups that provide the laboratory with evaluations of national needs and recommendations of future directions as well as evaluations of the Physics Laboratory's performance. Following are examples of such collaboration:

- The NIST Measurement Services Advisory Group (MSAG) was recently created with a goal of bolstering measurement services within NIST. The MSAG selected the Atomic Physics Division's Atomic Spectroscopy Group to receive funds to enhance the Atomic Data Center, including an enhancement of the center's ability to collect and disseminate atomic data.
- The Council for Optical Radiation Measurements (CORM) is a body originally instituted by NIST to provide guidance and prioritization on technical needs in industry and research. It periodically evaluates national needs in optical metrology and provides feedback on the services and standards supplied by the Optical Technology Division.
- The Council on Ionizing Radiation Measurements and Standards (CIRMS) advises the Ionizing Radiation Division on potential projects. An external advisory committee should be appointed to help the Radioactivity Group select and prioritize both new research projects and the specific areas of service collaboration.

The Electron and Optical Physics Division should continue to pursue more collaborations and connections to the growing industrial base focused on EUV lithography. It should initiate a NIST EUV effort to couple existing, relevant expertise across the division.

The level of coordination or overlap of the Biophysics Group in the Optical Technology Division with other divisions should be clarified. Although this Biophysics Group fits into the Optical Technology Division, several other divisions include the activities of this group in their portfolios. The Physics Laboratory has the potential to play an increasingly important role in collaborating with other, external organizations to exploit the new technologies and methods in many facets of the biosciences. However, it will be necessary for the Physics Laboratory to elucidate a comprehensive plan for organizing and staffing its expanded role in this area if it is to optimize its effectiveness.

The terahertz research in the Optical Technology Division has outstanding measurement capabilities in terahertz research, but because these are developing technologies and because of reorganization within the laboratory, it is not obvious which applications are to be investigated and who the future customers are to be. The terahertz research technical leads and the division management should delineate applications areas and their potential applications for the laboratory's unusual capabilities in the area of terahertz research.

The Physics Laboratory should develop a strategic plan in quantum information because it has the potential to become a major innovator of such technology. Conversely, failure within the United States to develop a leadership position in this area could threaten U.S. competitiveness economically and scientifically and could undermine national security.

The Charge to the Panel and the Assessment Process

At the request of the National Institute of Standards and Technology, the National Academies, through its National Research Council, has since 1959 annually assembled panels of experts from academia, industry, medicine, and other scientific and engineering environments to assess the quality and effectiveness of the NIST measurements and standards laboratories, of which there are now nine,[5] as well as the adequacy of the laboratories' resources. In 2008, NIST requested that five of its laboratories be assessed: the Building and Fire Research Laboratory, the Manufacturing Engineering Laboratory, the Materials Science and Engineering Laboratory, the NIST Center for Neutron Research, and the Physics Laboratory. Each laboratory was assessed by a separate panel of experts, and the findings of the individual panels are summarized in separate reports. This report summarizes the findings of the Panel on Physics.

For the FY 2008 assessment, NIST requested that the panel consider the following criteria as part of its assessment:

1. The technical merit of the current laboratory programs relative to the current state of the art worldwide;
2. The adequacy of the laboratory facilities, equipment, and human resources, as they affect the quality of the laboratory technical programs; and
3. The degree to which the laboratory programs in measurement science and standards achieve their stated objectives and desired impact.

In addition, since NIST has begun to receive increases in funding through the America COMPETES Act of 2007, which supports the President's American Competitiveness Initiative, the Director of NIST requested that the assessment panels specifically examine and review the progress of all of the activities at the laboratories supported by funding under the America COMPETES Act of 2007 and that the panels comment on those activities in their reports.

The framework for this technical assessment is the mission of NIST, which is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve the quality of life. The NIST laboratories conduct research to anticipate future metrology and standards needs, to enable new scientific and technological advances, and to improve and refine existing measurement methods and services.

To accomplish the assessment, the NRC appointed a panel of 18 volunteers whose technical expertise matched that of areas of work being performed by the Physics Laboratory staff. Each panel member was further assigned to one of six division review teams, with each member's general field of expertise matching that of the work performed by staff in the relevant division. The six divisions are Atomic Physics, Electron and Optical Physics, Ionizing Radiation, Optical Technology, Quantum Physics,

[5] The nine NIST laboratories are the Building and Fire Research Laboratory, the Center for Nanoscale Science and Technology, the Chemical Science and Technology Laboratory, the Electronics and Electrical Engineering Laboratory, the Information Technology Laboratory, the Manufacturing Engineering Laboratory, the Materials Science and Engineering Laboratory, the NIST Center for Neutron Research, and the Physics Laboratory.

and Time and Frequency.

Selected members of the panel met for 1 day with the staff of the Time and Frequency Division and the Quantum Physics Division in Boulder, Colorado, on February 15, 2008. The remaining members of the panel separately visited the other laboratory divisions at Gaithersburg, Maryland, for 1 day on February 26, 2008. During both visits, the members of the panel, including the panel chair, attended presentations, tours, demonstrations, and interactive sessions with the laboratory staff. These sessions included interactive visits with the research and technical staff within their laboratories and research facilities. The entire panel assembled for a 2-day meeting at the NIST facilities in Gaithersburg on February 27-28, 2008. During that time they attended overview presentations by the Physics Laboratory management and participated in interactive sessions with the laboratory managers. The panel also met during this time in a closed session to deliberate its findings and to define the contents of this assessment report.

The panel's approach to the assessment relied on the experience, technical knowledge, and expertise of its members, who were chosen because their backgrounds matched the technical areas within which the laboratory activities are conducted. The panel reviewed examples of the standards and measurements activities and the technological research selected by the panel in consultation with NIST and NRC administration. It was not possible to review all of the laboratory's individual programs and projects exhaustively. The panel's goal was to identify, assess, and report salient examples of accomplishments and opportunities for further improvement with respect to the technical merit of the laboratory work, its perceived impact with respect to achieving the laboratory's own defined objectives, and specific elements of the laboratory's resource infrastructure that are intended to support the technical work. These highlighted examples, along with data from scientific and technical literature and supplemental information provided by each division, are intended to provide the basis of an overall evaluation of each division and of the laboratory as a whole, while preserving useful comments and suggestions specific to projects. The assessment is currently scheduled to be repeated biennially. While the panel applied a largely qualitative rather than quantitative approach to the assessment, it is possible that future assessments will be informed by further consideration of various analytical methods that can be applied.

The comments in this report are not intended to address each program within the Physics Laboratory exhaustively. Instead, this report identifies key issues and focuses on representative programs and projects relevant to those issues. Given the necessarily nonexhaustive nature of the review process, the omission of any particular Physics Laboratory program or project should not be interpreted as a negative reflection on the omitted program or project.

This report first summarized issues that apply broadly to several or all of the divisions or to the Physics Laboratory as a whole. Then, after this chapter on the charge to the panel and the assessment process, it presents observations specific to each Physics Laboratory division. Finally, it comments on the programs funded under the America COMPETES Act and provides overall conclusions.

Atomic Physics Division

DESCRIPTION OF THE DIVISION

Mission

The mission of Atomic Physics Division is to determine atomic properties and investigate fundamental quantum interactions in order to provide data and measurement support for national needs. The mission involves the development and application of atomic physics research methods, including those involving the interaction between atoms and electromagnetic fields, to achieve fundamental advances in measurement science—some at the quantum limit—relevant to industry and the technical community, and to produce and critically compile physical reference data.

Scope

The scope of the Atomic Physics Division includes the following three strategic elements.

1. The Laser Cooling and Trapping strategic element focuses on the physics and applications of laser cooling and the electromagnetic trapping of neutral particles, the manipulation of Bose-Einstein condensates, and the use of optical dipole forces as a new tool for analyzing microscopic objects in biochemistry. It includes both fundamental studies, such as the investigation of superfluidity, and applied studies, such as quantum information processing and manipulation techniques for biomolecular systems. A strong theoretical-experimental collaboration is aimed at interpreting experimental results and providing guidance for new experiments.
2. The Atomic Spectroscopy strategic element has as its objective to critically compile fundamental constants and spectroscopic data for atoms from the far infrared to the x-ray spectral region. Such reference data are disseminated through the NIST Physics Laboratory Web site. When reliable data do not exist for high-priority needs, specific measurements or calculations are undertaken to produce them.
3. The Quantum Processes and Metrology strategic element focuses on developing and exploiting precision metrology at the interface between atomic and nanoscale systems. Systems under study include quantum dots and wires, the quantum optics of nanosystems, ultracold atomic quantum gases, metallic nanoparticles, and those systems with nanoscale features induced on surfaces by highly charged ions.

Projects

Laser Cooling and Trapping

The Joint Quantum Institute is a major new project for the division since the

NRC's previous review.[6] This institute was formally established with the University of Maryland and the National Security Agency (NSA) in the fall of 2006, modeled in part along the lines of JILA. The purpose of this partnership is to create an institute of the caliber that will attract top scientists and students into the field of coherent quantum phenomena. This cross-disciplinary effort combines atomic/molecular/optical physics, condensed-matter physics, and quantum information in a single institute to capitalize on the different strengths of these fields through interdisciplinary collaboration.

In 2007, the Joint Quantum Institute benefited from about $2 million of funding under the America COMPETES Act of 2007, helping to enhance the position of the United States in this emerging technology. New laboratories are being designed for NIST researchers, and several collaborative projects have been initiated. Two staff members taught a graduate course in quantum information at the University of Maryland, 25 Fellows have been appointed, and a new staff member was hired. An additional benefit of the institute will be the opportunity for NIST to share its expertise by the training of students through the graduate program at the University of Maryland, which will leverage the capabilities of the Laser Cooling and Trapping Group in the exploration of this new frontier. Quantum information has the potential to spur major innovations. Failure to develop leadership in this area could threaten U.S. competitiveness economically and scientifically and could undermine national security. This effort should receive continued support.

Atomic Spectroscopy

A second major project in the Atomic Physics Division, the Atomic Data Center, is the only center of its kind. Its mission is to critically compile fundamental constants and spectroscopic data for atoms from the far infrared to the x-ray spectral region. As a unique center, it sets the standard worldwide for these data. These results are disseminated on the NIST Physics Laboratory Web site to produce high-quality data for immediate scientific or technological needs. When such data do not exist for high-priority needs such as fusion energy, space astronomy, or microlithography, specific measurements or calculations are undertaken at the center to produce them. Improved measurements have also been initiated in support of fundamental constants. This database experiences more than 50,000 requests for data each month. An online collisional-radiative modeling system of hot plasmas was added in conjunction with the Lawrence Livermore National Laboratory.

Quantum Processes and Metrology

A third major project in the division involves a leading-edge optical lithography effort. This work in the precision measurement of materials is unique and is much appreciated by a community of users such as Intel Corporation and ASML, a provider of lithography systems for the semiconductor industry. The division's work also includes the most accurate diffraction measurement capability, work to make an absolute standard

[6] National Research Council, 2005, *An Assessment of the National Institute of Standards and Technology Measurement and Standards Laboratories, Fiscal Years 2004-2005,* Washington, D.C.: The National Academies Press.

of current, and the development of new magnetic material for read heads in magnetic data storage devices. The theoretical work in this group is strong, supporting experiments throughout the laboratory, including theoretical support for optical lattices, the atomic clock work at NIST Boulder and JILA, and the preeminent effort in cold collision Feshbach resonances important at present in Bose-Einstein condensation (BEC) research.

Staffing

The Atomic Physics Division has seen a healthy turnover in staff as two scientists in atomic spectroscopy have retired and three new scientists have been hired. Fifty percent of the scientists were new to the division in the past decade. The Laser Cooling and Trapping Group completed a successful bid to hire a new experimentalist. The Quantum Processes and Metrology Group has completed two hires since the previous assessment, one a transfer within NIST and one hired from a university. These impressive hires, which show a small amount of growth for the division, have been successful because of both the funding related to the America COMPETES Act and the first-rate reputation of this division in the scientific community.

The Atomic Spectroscopy Group, which has had two retirements in the past 3 years, currently functions by leveraging its effort with emeritus staff, contractors, and visitors. This appears to be a highly effective means to maintain productivity and to retain expertise, although it jeopardizes continuity if not effectively implemented.

Major Equipment, Facilities, Ancillary Support, and Resources

The status of equipment, facilities, and ancillary support and resources in the division appears to be good. Much of the current equipment of the division is state of the art. The facilities are between good and excellent and are well maintained. The Advanced Measurements Laboratory building provides state-of-the-art facilities for the Laser Cooling and Trapping Group and for parts of the Quantum Processes and Metrology Group. This laboratory is maintained and used at a high level with the addition of significant outside funding—a recognition of the importance of the research of this group to outside funding agencies. The Joint Quantum Institute has plans for a new building that will provide new laboratory space for this group.

ASSESSMENT OF THE DIVISION

As stated above, the mission of the Atomic Physics Division is to determine atomic properties and investigate fundamental quantum interactions in order to provide data and measurement support for national needs. The major projects of the division reflect this mission, striking a healthy balance between applied studies targeting high-priority needs of industry, the fusion energy community, and the space astronomy program, and more fundamental studies that may lead to new technologies that could affect U.S. leadership economically and scientifically; they could also affect national security issues.

The major accomplishments since the previous assessment, in 2005, include both institutional progress and technological accomplishments. Examples of institutional progress include the following:

- The NIST Quantum Information Program, started in 2000, is a cross-laboratory effort in quantum information science. This program is a coordinated effort aimed at producing a prototype quantum logic processor. Initiative funds from the FY 2007 budget significantly enhanced the program that currently supports 10 divisions in three NIST laboratories: the Physics Laboratory, the Electronics and Electrical Engineering Laboratory, and the Information Technology Laboratory.
- A new entity in the Quantum Information Program, the Joint Quantum Institute, was formally established with a cooperative agreement and Memorandum of Understanding in September 2006. As discussed above, this institute creates a partnership between NIST, the University of Maryland, and NSA to study coherent quantum phenomena (quantum information science), an area that has the potential to become a revolutionary technology that will affect the United States economically and in national security issues. Supported by America COMPETES Act funding, the goal of this institute is to keep the United States in the forefront of quantum information science.
- The NIST Measurement Services Advisory Group was recently created with a goal of bolstering measurement services within NIST. The MSAG selected the division's Atomic Spectroscopy Group to receive funds to enhance the Atomic Data Center, including its ability to collect and disseminate atomic data.

Technological accomplishments in the division since the previous NRC assessment of the Physics Laboratory include the following:

- A theoretical and experimental study was done to examine ionized states of heavy atoms, which have several critical applications, including the obtaining of diagnostics of the conditions in the International Thermonuclear Experimental Reactor, a joint international research and development project that aims to demonstrate the scientific and technical feasibility of fusion power.
- New magnetic materials for ultrasmall read heads in magnetic data storage devices were developed. A patent is pending for this valuable contribution to the data storage industry.
- A neutral atom swap gate for quantum computation was demonstrated using a novel, two-period lattice. This work, published in *Nature*,[7] represents a significant step forward for neutral atom quantum computing.

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[7] Marco Anderlini, Patricia J. Lee, Benjamin L. Brown, Jennifer Sebby-Strabley, William D. Phillips, and J.V. Porto, 2007, "Controlled Exchange Interaction Between Pairs of Neutral Atoms in an Optical Lattice," *Nature* 448 (July 26): pp. 452-456.

Technical Merit Relative to State of the Art

Laser Cooling and Trapping

The area of atom cooling and trapping was pioneered at NIST in the Laser Cooling and Trapping Group, leading to a Nobel Prize in 1997. This group also pioneered confining cold atoms in optical lattices formed by the interaction of the atom with a standing wave of light. The trapped atoms are being explored as a possible route to quantum computation and for the quantum simulation of problems of interest in condensed matter. This work is among the best in its field.

Atomic Spectroscopy

The evaluation of fundamental constants, accomplished with considerable international collaboration and consultation, considers all experiments that bear on these constants and is the accepted source for the best values of the fundamental constants. Likewise, the atomic data evaluated and compiled by the Atomic Spectroscopy Data Center are the primary source of atomic data.

Quantum Processes and Metrology

Optical lithography is reducing the limit on feature size for large-scale integrated circuits to permit even greater densities. The work being carried out by the Quantum Processes and Metrology Group in materials and precision measurements is unique and is much appreciated by the community of users such as Intel Corporation and ASML. Fundamental research involving materials for optics is being undertaken, in particular to find a composite material with as small a birefringence as possible. The most accurate diffraction measurement capability exists in this group; this capability is essential for developing optics at the level needed. In collaboration with the NIST Electronics and Electrical Engineering Laboratory, a new approach is being taken to develop an absolute standard of electrical current. It is based on using a single electron transistor to count the number of electrons per second. The development of such new standards is a highly relevant project for NIST.

Adequacy of Infrastructure

Laser Cooling and Trapping

The recently completed new laboratory facilities supporting the work of the Laser Cooling and Trapping Group provide a research environment that is far superior to that of the previous laboratory facilities. One benefit is that complex laser systems and associated optical components that previously needed considerable adjustment in the morning and a readjusting at midday now operate for weeklong timescales without readjustment. This change frees up to several hours per day for productive work and allows more complicated experimental setups to be constructed, allowing more advanced research programs. Also, some of the noisy pumps and machinery associated with the experiments are now in the service corridor behind the laboratories, which reduces the vibration and stress on experiments as well as on the scientists working on them.

The permanent personnel in the Laser Cooling and Trapping Group are among the best in their field. This group's attractiveness is attested to by the six NRC and other fellows who elected to join the group.

Atomic Spectroscopy and Quantum Processes and Metrology

The facilities for the Atomic Spectroscopy Group and the Quantum Processes and Metrology Group are between adequate and state of the art.

Achievement of Objectives and Impact

Laser Cooling and Trapping

In the area of laser cooling and trapping, the intense correlated photon source is likely to be particularly important in the short run because of its high rate of production for correlated pairs of photons.

Atomic Spectroscopy

The Atomic Spectroscopy Group maintains the premier database of atomic data: the group's fundamental constants work and its atomic data are the world standard.

Quantum Processes and Metrology

The Quantum Processes and Metrology Group is successful in understanding interactions between light and solids and, for example, in using this knowledge to design new materials and techniques for new lithographic processes that are reducing the feature sizes of integrated circuits to ever-smaller dimensions in order to allow faster and more capable semiconductor devices. Light-atom interactions are also used to characterize materials precisely and for the precision measurement of micro-movements of nanostructures. Obtained precision is currently approaching the size of an atom.

CONCLUSIONS

The technical merit of all three groups in the Atomic Physics Division continues at a very high level compared with the current state of the art. The Laser Cooling and Trapping Group is a leader in the coherent control of atoms, which may quite possibly constitute a technological revolution. The Quantum Processes and Metrology Group is performing state-of-the-art work in optical lithography including the precision measurements of materials. The Atomic Spectroscopy Group maintains a unique source of atomic data and fundamental constants, with a critical compilation of new data and the determination of specific measurements for high-priority needs in the industry, in the fusion energy community, and in the astrophysical community.

The facilities, equipment, and human resources of all three groups are good to excellent. The Advanced Measurements Laboratory building provides excellent laboratory space, and much of the equipment is state of the art. The Atomic Spectroscopy Group is currently highly leveraged in personnel through the use of retired employees, contractors, and visitors; their contribution is currently effective, but must be allocated with care and cannot be counted on for the future. All the groups are achieving their stated objectives.

In 2007 NIST received about $6 million for quantum information science under America COMPETES Act funding. One-third (about $2 million) was combined with funding from the University of Maryland and the National Security Agency to support the new Joint Quantum Institute. Quantum information and quantum computers are intrinsically cross-disciplinary, involving physics, mathematics, materials science, and computer science and engineering. Canada and Europe have quantum information centers, and the NIST center is needed to keep up U.S. competitiveness in this potentially revolutionary area of science and technology.

Overall the funds allocated to the Physics Laboratory for atomic physics are a wise investment of U.S. research dollars in an area of technology that is witnessing rapid advances and competition from abroad. The panel strongly encourages the continuation of funding for the new Joint Quantum Institute.

The Atomic Physics Division appears to be in excellent condition in all areas: technical merit; adequacy of facilities, equipment, and human resources; and the progress toward stated objectives. The division has seen the initiation of new projects, most notably the Joint Quantum Institute, and the steady maintenance of important existing projects such as the Atomic Data Center, which continues to serve a large customer base, and the optical lithography effort, which is leading the way on several technological fronts. Over the past 3 years this division has seen small but important growth in its staff, successfully completing three new hires. It has used funding from the America COMPETES Act to support the position of the United States in the emerging field of quantum computing with the establishment of an interdisciplinary institute in coherent quantum control. This area could become an innovator of technology important to national security. Except for the areas mentioned in the recommendations below, morale and productivity in the division are high.

This division should aggressively protect the work environment of the laboratory in order to enhance the productivity of the scientists and to maintain and foster the culture that has built outstanding scientists, many of whom are Fellows in the American Physical Society and recipients of many prestigious outside awards, including a Nobel Prize (1997). The division's reorganization of the groups in response to changing technical and scientific opportunities and efforts and its involvement in the cross-laboratory Quantum Information Program and in the formation of the Joint Quantum Institute have kept both productivity and morale high.

The following recommendations are made in the interest of improving the working environment of the division:

- The security-related background checks of new employees and visitors to the Physics Laboratory should be expedited as much as possible. The scientists at NIST work on complex experiments that often involve measurements being made after regular business hours when vibrations and temperature fluctuations in the building are minimized. Therefore, it is a serious impediment to both progress and a collaborative spirit that new employees, and particularly foreign visitors and employees, often face 5 to 14 months for background checks by an agency outside of NIST before being allowed to run their experiments after hours (when the best data are usually taken). Addressing this issue would be in line with the American Competitiveness Initiative goal of increasing the ability of the United States to compete and retain the most highly skilled workers from around the world.

- The security rules for computers mandated through the Office of Management and Budget should be examined to address the specific needs of the laboratory.

Electron and Optical Physics Division

DESCRIPTION OF THE DIVISION

Mission

The general mission of the Electron and Optical Physics Division is to support emerging electronic, optical, and nanoscale technologies, particularly precision optical measurements in the EUV radiation range through the NIST Synchrotron Ultraviolet Radiation Facility (SURF III). A number of very interesting supplementary research efforts are also pursued, as described below. The departure of the Nanoscale Electronics and Magnetics Group because of reorganization seems to present a strategic opportunity for revisiting, clarifying, and/or redefining the division's goals for the future.

Scope

With the movement of the Nanoscale Electronics and Magnetics Program to the new NIST Center for Nanoscale Science and Technology, there remain two primary research foci within the scope of the Electron and Optical Physics Division. First is the development of metrology for EUV optics, the maintenance of national primary standards for radiometry in the EUV and adjoining spectral regions, and the operation of national user facilities for EUV science and applications. The second focus provides measurements and data to enable the development of atom and photon technology in sensors, atom interferometers, and quantum information-processing devices.

Projects

Several current and future projects in this division that illuminate its core competencies, its connections inside and outside NIST, and its participation in various funding mechanisms are highlighted below.

A major focus of the division concerns optical and source metrologies associated with the nation's effort to develop photolithography in the EUV regime at the 13 nm wavelength. This approach is likely to be the future for extending Moore's law (that the number of transistors on integrated circuits doubles about every 2 years) to enable faster computing through higher-resolution lithography. The division is heavily involved in characterizing the critical large-area, large numerical aperture (NA), aspherical, multilayer-coated EUV optics. The capabilities of the division in this area are unique and crucially important to the EUV program, as evidenced by its work with several customers of such optics (e.g., Intel Corporation and SEMATECH). This effort is important because EUV production facilities will use plasma sources having a broad angular distribution, and these require large-area and large NA collection optics. This work cannot at present be done elsewhere in the United States; it is made possible by recent upgrades to the SURF III facility, coupled to new instruments developed with funding under the America COMPETES Act of 2007. The implementation of autonomous operation of the accelerator with about 1 A of circulating current, also a unique capability, has allowed the division to test radiation damage to EUV optical surfaces under conditions that will be typical in future production facilities; the recent results from the division's work in these areas already have important ramifications for such facilities.

A key remaining barrier to the broad implementation of EUV technology involves developing new EUV photoresists, the generally polymeric materials into which a pattern is written when one is making small electronic devices. As yet, no photoresist offers the required combination of radiation sensitivity, spatial resolution, and low line-edge roughness. The division is developing a grating-based EUV interferometer that can employ sources of limited spatial coherence to pattern lines with widths on the order of 10 nm. This instrument will be used to test photoresists, but it also will serve as a useful testbed for similar measurements using laboratory-based EUV sources being developed for production facilities. It is not yet clear how strongly connected the division is to photoresist vendors; such connections might need to be pursued aggressively. Collaboration with the Polymers Division in the Materials Science and Engineering Laboratory at NIST would possibly be helpful on this project.

EUV technology cuts across many different disciplines and laboratories, including plasma physics, optics, materials science, and several areas of chemistry. The SURF III-based EUV program is a common ingredient of significant utility in all of these disciplines, and it increasingly acts as a focal point for EUV activities at NIST. The division should continue active pursuit of more collaborations and connections to the growing industrial base focused on EUV lithography and a NIST EUV effort, to couple existing expertise in all of these areas. If NIST is to be a major contributor in this area, there is a need for the development of a clear view and possibly a plan for central oversight of this entire NIST EUV program.

The unique capabilities of SURF III have facilitated long-standing efforts in detector calibration. Strong collaborations with the National Aeronautics and Space Administration (NASA) over several decades have been essential in many different missions; the division has brought key enabling capabilities to this collaboration. For example, recent activity will support the NASA European Venus Explorer probe, which will monitor solar weather and its impact on Earth's climate. Also, the division has invested resources to improve its capabilities in EUV detector calibration. The implementation of a cryogenic radiometry capability has improved the accuracy of these calibrations by nearly an order of magnitude. Future improvements extending this methodology to shorter wavelengths will be of much value.

The Electron and Optical Physics Division has spearheaded a recent, very exciting development of a new kind of neutron detector based on the production of Lyman-α radiation following the $n + {}^{3}He \rightarrow {}^{1}H + {}^{3}H$ nuclear reaction. By producing multiple photons per neutron, a very high detection efficiency is possible (only one or two of these photons needs to be detected). In addition to high quantum efficiency, this potentially transforming detector has much lower noise and much higher bandwidth as compared with existing neutron detectors. This development should be of interest in a variety of applications (including ones of relevance to health physics and homeland security) and to several agencies and vendors. The division should be encouraged to pursue this project and its numerous potential spin-offs.

In the past several years, the division has assembled a small but state-of-the-art quantum telecommunications effort. The team performing this work has developed an ultrahigh-bandwidth detector that offers world-record speed for transmitting a quantum encryption key. The team members are now moving toward developing entangled and correlated photon sources for use with this system, a critical step toward reliable quantum communication. This program, which was developed in part with resources provided under the America COMPETES Act, appears to be well coupled to quantum physics groups across the Physics Laboratory, and as the NIST quantum information effort matures, this program should be a valuable component. The extent to which the quantum telecommunications team is connected to research outside of NIST is of concern; that is, at the moment its quantum communication testbed seems to be used almost exclusively for internal NIST research (in rather sharp distinction with most of the other activities of the division). The division should consider ways in which the quantum telecommunications laboratory can better serve the greater research community outside of NIST.

The division supports a small but active program in x-ray tomography. This effort is well connected to other groups inside and outside NIST. A recent project to develop a LEGO phantom (model) for tomography was well conceived and appears to provide a precise length standard for medical imaging. Such a standard could enable much more precise quantitative evaluations, for example of tumor growth.

Staffing

The division currently supports just under 20 full-time-equivalent of scientific staff, about half of whom are involved with SURF III operations and EUV technology development. This appears to fit the current research scope reasonably well.

Since the implementation of third-generation synchrotron radiation facilities by the DOE, the SURF III facility has redirected its scientific program and has become an important ingredient of the nation's effort to develop EUV technologies. With the right coordination and direction, the impact of SURF III and its associated EUV program could be even greater in the future. The former SURF III director, who retired several years ago, has not been replaced. Although the current arrangement with the division director's assuming this responsibility works, the situation merits some review. The existing EUV-related activities at SURF III are individually strong and useful, but the overall program might benefit from focused direction and coordination. Such coordinated leadership of the SURF III EUV program will likely be essential if a compact x-ray source is purchased and operated by this division.

Major Equipment, Facilities, Ancillary Support, and Resources

The Electron and Optical Physics Division supports a state-of-the-art quantum telecommunications laboratory, as discussed above. The speed records of the system here are impressive; the division's current move to develop sources of entangled and correlated photons for future studies is appropriate. Ongoing or planned connection of this effort to such source development elsewhere at NIST (e.g., the Optical Technology Division) is encouraged.

The SURF III facility supports a variety of beam lines devoted to detector and instrument calibration as well as EUV optics testing, as discussed above. Several of these beam lines provide unique and important capabilities. The division operates the SURF III facility, as discussed above. Twenty years ago, this facility was used extensively for vacuum ultraviolet spectroscopy. In the early 1990s, however, many of those programs migrated to newer facilities around the country, leaving SURF III with a mission focused primarily on the core activity of detector and instrument calibration. The emergent role of EUV radiation in next-generation lithography has offered the facility a new mission of national prominence. This area should continue to be a major focus of this division.

The division is also investigating the possibility of developing an x-ray facility using a compact source based on inverse Compton scattering. Such a source could provide a relatively narrow spectral width of the emitted x-rays, whose energy can therefore be optimized for particular applications. A commercial vendor exists that promises a product with performance comparable to a good bend-magnet line at a synchrotron radiation facility. Motivations for developing such a facility include developing metrology for an emerging tool that might have broad application, particularly in medical diagnostics and therapies; developing in-house x-ray microscopy and tomography capability; and spearheading a service to a broad spectrum of users around the NIST laboratories. The proposal has some merit but needs significant further development, for several reasons:

1. At present the vendor seems a little idiosyncratic, offering little detailed information about the source performance or characteristics. This is cause for concern.
2. The source is fairly expensive to purchase and to maintain, on the scale of common instruments at NIST. The division estimates that to purchase the source and to develop a single x-ray beam line would cost about $10 million. Annual operating costs would be about $3 million, or half of the division's current budget. Some careful planning will be required for this single division to purchase and maintain this instrument and associated facilities.
3. The division, as well the rest of the laboratory, needs to undertake a cost-benefit analysis of developing and operating this facility compared with developing beam lines at an existing synchrotron radiation facility. A synchrotron bend-magnet beam line will cost perhaps $1.5 million to $2 million and will have significantly lower operating costs. Some of what the division wants to do could be done, perhaps better, at a synchrotron radiation facility, and the operating costs (to NIST) would be lower. Some of the metrologies associated with such an instrument that the division wants to pursue might not be easily done at a facility. Also, if compact sources such as the one under consideration achieve widespread use, for example in hospitals, there would be a clear advantage for NIST to research using that same approach.
4. The division should earnestly engage the biomedical community to determine how useful the planned instrument is likely to be in medical therapies. For example, to reach tumors deep inside the body, many cancer radiation therapies require x-ray energies well in excess of 1 MeV. It is not clear whether the commercial device will provide such high-energy photons.
5. The expense of developing and operating this facility suggests the need for sharing the responsibility with other NIST laboratories. The division should investigate this possibility, which it reports that it is doing. However, the

currently available instrument serves as a single source. Serving too broad a community with a single source is known to cause problems at synchrotron radiation facilities. The many trade-offs between local control of a focused program and a broad program with a large user base need careful consideration.

If the proposal is thought to be viable, a more focused review by a diverse panel of experts in x-ray, accelerator, medical, and material physics should be undertaken.

ASSESSMENT OF THE DIVISION

Following is the summary of the panel's assessment of the overall quality of the Electron and Optical Physics Division (including opportunities for improvement) in terms of the charges from the Director of NIST.

Technical Merit Relative to State of the Art

The unique and state-of-the-art capabilities of the division include the following:

- The precision reflectometry of large-area and large NA multilayer-coated EUV optics for at-wavelength testing and characterization;
- The provision of transfer standard EUV photodiodes and the development of cryogenic radiometric capability, which improved calibration accuracy by an order of magnitude;
- The primary national standard for source-based optical radiometry in the EUV regime;
- The integration of EUV optical measurements with surface analytical capabilities; and
- The high-rate testbed for secure quantum encryption key distribution (in free space).

Adequacy of Infrastructure

Supported by funding under the America COMPETES Act, the SURF III upgrades have been very successful and useful, and the development of the quantum telecommunications laboratory has been very productive. The building is old and lacks optimal environmental controls; although this is probably not a large impediment to most existing programs, it clearly affects program efficiency and, to a lesser extent, the morale of personnel.

Achievement of Objectives and Impact

The division supports an active and very useful service activity, combined with several application-driven research programs that will prove useful in facilitating future developments. The service activities amount to about 30 percent of the aggregate effort. Each year, about 40 external users use the SURF III mostly for instrument calibration, about 30 photodiode calibrations are performed, the reflectivities of between 100 and 200 EUV optics are measured, and the radiation damage testing of EUV optics is done for about 2,000 hours per year. The last three of these activities are performed on a cost-recovery basis and are supported by vendors, mostly in the developing EUV sector—which offers good evidence of the value of the SURF III EUV programs. These service activities appear to be valued within the division. The division has a robust record of publication and presentations. Several workshops in the EUV technology area have been organized.

Programs Funded Under the America COMPETES Act

The Electron and Optical Physics Division participated in two projects, discussed above, that received funding under the America COMPETES Act. The SURF III upgrade and EUV activities benefited from $475,000 of funding; the results have been positive. The quantum telecommunications project received $100,000, which has been very useful in continuing the development of this laboratory.

CONCLUSIONS

The Electron and Optical Physics Division integrates a valuable—in several cases essential—service component with cutting-edge, application-driven research and development (R&D). Funds under the America COMPETES Act have been put to good use, assisting in high-value service and R&D activities.

The transfer of division staff to the newly formed NIST Center for Nanoscale Science and Technology resulted in a narrowed research portfolio for the division, which is probably good. Even after the reorganization, there remains a fairly diverse and seemingly somewhat disconnected research portfolio. There is a need for strategic planning. The division should consider what it wants to look like in 5 and 10 years and should address the following issues:

- There will probably be increased EUV activity in the near term, but what happens as the technology is deployed? Does it make sense to complement the division's EUV activities and expertise with laboratory-based sources like extreme ultraviolet (XUV) lasers and/or plasma sources? How does the division move from what is now a very valuable but largely support role in the EUV community into a role of intellectual leadership?
- Is there broad support for a compact x-ray source at NIST, and would the division want to operate this as a user facility? If not, does the division have the resources and research program to run such a source independently? In the face of a multitude of x-ray beam lines in the United States and around the world, what would be the unique intellectual focus inside the division if such a facility were developed? How would these programs compare with others around the country and the world? How important are the coherence properties of a compact x-ray source to the proposed activities? Are there competing compact x-ray technologies on the horizon that need to be considered and evaluated?

- What role will the division play in the coming convergence of quantum communications and cryptography? Will the division house the primary resource in experimental quantum optics at NIST? How can the quantum telecommunications laboratory serve the greater research community beyond NIST?

Ionizing Radiation Division

DESCRIPTION OF THE DIVISION

The mission of the Ionizing Radiation Division is to develop, maintain, and disseminate the national standards for ionizing radiation and radioactivity in order to meet the needs related to health care and the environment and those of academia, U.S. industry, and homeland security, and to conduct underlying basic research in these areas. The division maintains the national measurement standards for the Système International (SI) derived units for radiation dosimetry (the gray) and activity (the becquerel). This division is composed of three groups—Radiation Interactions and Dosimetry, Radioactivity, and Neutron Interactions and Dosimetry.

Radiation Interactions and Dosimetry Group

The mission of the Radiation Interactions and Dosimetry Group is to advance the accurate and significant measurement of dosimetric quantities important in the radiological sciences through programs in the dosimetry of x-rays, gamma rays, electrons, and other charged particles.

The projects in the group are classified in five areas: theoretical dosimetry, quantum metrology, medical dosimetry, homeland security applications, industrial applications, and protection and accident dosimetry. A special focus on homeland security continued in FY 2007. Experimental and calculational support was provided for the performance standards and the testing and evaluation protocols developed for explosives and nuclear detection used for homeland security. This work included participation in several working groups writing American National Standards Institute (ANSI) standards. Significant progress, including the following, was made in a number of the group's measurement standards and calibration services:

- Progress in developing a unique type of signal analysis related to water calorimetry;
- Reference dosimetry calibrations for photon-emitting ^{125}I, ^{103}Pd, and ^{141}Cs radioactive seeds used for prostrate cancer treatment;
- The use of the group's clinical electron accelerator to develop a second-generation water calorimeter to serve as a standard for accelerator-produced high-energy x-ray beams used in cancer treatment;
- The completion of the software for the first Internet-based e-certification service for radiation processing dosimetry; and
- Prototype testing of equipment for detecting radiation sources in cargo containers.

The overall staffing level of the group is acceptable for accomplishing current projects. Several members of the staff are approaching retirement age, but a succession plan is in place. The group relies on guest researchers, students, and contractors to do a significant portion of the work. This use of outside personnel seems to be acceptable, but there is a concern if funding for these outside employees decreases.

Most of the major equipment used by the group is old and in need of replacement. A serious problem arises from the fact that newer equipment would have to be housed in heavily radiation shielded bunkers, whereas the group is housed in an older building whose shielded facilities do not meet current needs. This is a major issue which may require that a new building be constructed.

Radioactivity Group

The mission of the Radioactivity Group is to develop new technologies for the accurate measurement of radioactivity for various applications. This mission includes the development of standards for research, for the determination of very low levels of radioactivity, and for biological medical applications. The group develops methodology for all the applications given in the mission statement and the application of these techniques to service projects in which the NIST staff coordinate with the scientific community.

The range of projects is very broad and includes the development of accurate counting techniques (an automated ion chamber, an anti-coincident system, a gamma spectroscopy system, and various low-level counting techniques). Cutting-edge techniques for radionuclide metrology are being developed and applied to the quantification of standard reference materials. A final area is in the field of nuclear medicine. In this rapidly expanding field, various applications particularly applied to positron emission tomography (PET) and positron emission tomography/computed tomography (PET/CT) are being developed.

A significant fraction of the effort of this group is working with outside users in a service mode.

In several areas, extra staffing is required because several key scientists are approaching retirement age. Extra staffing is needed particularly in the nuclear medicine area.

In order for the Radioactivity Group to work at the forefront of the various areas, leading-edge equipment, including a PET/CT facility, should be available. Future research might be done using an animal scanner, although justifications and protocols should be reviewed and approved by the appropriate committees before the acquisition of such a system is initiated.

Neutron Interactions and Dosimetry Group

The mission of the Neutron Interactions and Dosimetry Group includes both fundamental research and service activities. The research is anchored in precision measurements with neutrons of fundamental physical constants and data that address issues such as the neutron lifetime, the strength of underlying weak couplings, and tests of symmetry violation such as parity and time reversal. The applications range from neutron tomography and imaging to neutron calibrations. The balance between fundamental research and service activities is approximately equal. While the research makes use of a variety of NIST instruments, the key facility used is the seven neutron beam lines that the group operates at the NIST Center for Neutron Research (NCNR) reactor, which is a leading center for neutron research in the United States. It is a successful users' facility, drawing researchers from commerce, universities, industry, and various national laboratories.

The fundamental science program includes some very challenging projects with high potential payoffs. Examples include the following:

- *Measurements of the neutron lifetime and beta decay correlations that, in the context of the standard model, will determine the strengths of the vector and axial-vector coupling constants.* These measurements also place important bounds on beyond-the-standard model interactions. One of the group's lifetime measurements employed ultracold neutrons confined by a three-dimensional magnetic trap.
- *Measurements of the spin precession of polarized cold neutrons passing through ^{4}He, an effect arising from parity violation associated with the hadronic weak interaction.* (The parity violation allows one to separate tiny weak effects from the dominant strong interaction.) This experiment is important to a 30-year effort to understand the isospin structure of the weak interaction between nucleons.
- *Measurements of fundamental properties on the neutron, including the neutron charge radius and the n-^{3}He scattering length.* The neutron charge radius measurement exploits an interferometer developed by the group, an instrument important to both fundamental research and service activities. The neutron, while electrically neutral, has nonzero charge radius, through which it can interact electromagnetically with charged particles. This interaction in turn produces a phase shift as a neutron beam passes through a silicon crystal, near the Bragg angle. Such a measurement would complement nuclear physics measurements made at flagship nuclear physics facilities such as the Thomas Jefferson National Accelerator Facility. The n-^{3}He measurements are possible because of dramatic improvements in the lifetime of cells containing highly polarized ^{3}He—a major technical achievement by the group.

Some of the important applications include the following:

- *The construction of the advanced Neutron Imaging Facility and its use in probing the performance of hydrogen fuel cells.* This method of radiographic imaging of the water production and movement within the fuel cell, not possible previously, is very effective because of the large neutron capture cross section on protons in the water. The neutron imaging program has achieved unprecedented resolution and provided unique and invaluable data to industry.
- *The development of techniques for high-efficiency neutron detection in liquid scintillator.* The long-term goal is inexpensive, fast-neutron detection that can operate in real time to identify fissile material in cargo or other shipping containers. The group is also involved with the development of performance standards from neutron detectors designed for homeland security applications.
- *The calibration of neutron sources for clients such as DOE laboratories.* The

workhorse facility for this calibration is a manganese sulfate bath system that uses a long-lived (and therefore stable) calibration source to normalize measurements.

- *The development of more precise tools for measuring neutron fluxes.* Two methods under development are based on (n,α) on boron, in which a gamma ray from the final ^{7}Li nucleus is also detected; and on detecting repeated Lyman α transitions produced as the recoil ion, generated in ^{3}He(n,p)^{3}H, passes through the gas. These tools will, in turn, help the group to improve its neutron lifetime and other fundamental measurements.

The Neutron Interactions and Dosimetry Group has just nine staff members and is thus remarkably lean, given the variety of fundamental and service work being done and its task of maintaining and operating seven beam lines. The group's successes derive in part from the successful collaborations established with external users. Two of the group's beam lines are now operated as a user facility, with an informal external advisory/review committee providing advice on priorities and scheduling.

A major upgrade of the reactor facility will take place between now and 2010, providing the group with four new beam lines. This development is potentially of great significance: with modern focusing, it is expected that the flux available in fundamental experiments could increase by a factor of 10, making the NIST facility comparable to the world's best, Grenoble's Institut Laue-Langevin. While this is a very positive step forward, it will also require the group to shoulder major new responsibilities. It will be important to increase the level of staffing in the group substantially, both to exploit new capabilities and to manage the heavier load of users that would be expected.

There appears to be no funding currently in place to instrument the new beam lines, although apparently some may become available. It is important that the Physics Laboratory address this need. The group has some outside support (from NSF and DOE), but the levels are low. It is not clear whether to expect success in increasing the level of outside support: the Spallation Neutron Source (SNS), a major new DOE facility for pulsed neutrons, has begun operations at the Oak Ridge National Laboratory. For many applications, NIST, with its continuous flux, will remain the best facility. However, DOE users might be expected to focus their research at the DOE facility. The Physics Laboratory should explore interagency agreements that would provide neutron experimenters with the broadest choice of facilities while lowering barriers to interagency funding and cooperation. This is scientifically sensible: some experiments developed at NIST may, as second-generation efforts, migrate to the SNS.

ASSESSMENT OF THE DIVISION

The following is a partial list of recently completed and ongoing major projects of the Ionizing Radiation Division:

- Dosimetric support for a local company developing a malaria vaccine,
- The establishment of a dose assurance program for the irradiation of mangos in India,

- X-ray spectral measurements,
- High-energy computed tomography (CT) for homeland security,
- Neutron tomography and imaging,
- Wide-angle polarization analysis,
- Therapeutic alpha emitters,
- Radionuclidic metrology,
- Quantitative imaging, and
- The development of a transportable, personal PET phantom for patients.

Examples of the significant accomplishments of this division include the following:

- Substantial progress has been made in the development of high-energy CT as a result of a collaboration with the Savannah River National Laboratory;
- The first observation was made of the irradiative decay mode of the neutron; and
- The NIST triple-to-double coincidence ratio spectrometer has been rebuilt and improved.

The Ionizing Radiation Division is actively participating in a new NIST initiative in biomedical imaging; $380,000 of new funding has been allocated to the division for this purpose. Collaborative projects related to PET and PET/CT have been initiated with other NIST divisions and laboratories and a university.

With respect to resources, the division is currently staffed with 52 permanent NIST employees and a number of postdoctoral fellows, guest researchers, and summer undergraduate research fellowship students, bringing the total staff number to 98. Funding for FY 2007 was approximately $10 million, with over 50 percent coming from the Department of Homeland Security (DHS) and other outside organizations. This high dependence of funding on one outside customer is of concern.

The quality and direction of the projects in the Ionizing Radiation Division are in line with expectations for superior returns on the investment being made. There are issues with respect to facilities and funding. The issues with respect to facilities include the condition of the physical plant that houses the Radiation Interactions and Dosimetry Group and the Radioactivity Group and the need for modernizing or replacing much of the radiation-producing equipment used by the division. Extension of the Experimental Hall coupled with the development of new beam lines at the NCNR will result in the Neutron Interactions and Dosimetry Group's obtaining four new beam lines. It is essential that funding for the experimental equipment and staff needed to use these new beam lines efficiently be made available.

Technical Merit Relative to State of the Art

The Ionizing Radiation Division's programs are, overall, as good as or better than those in other national and international standards laboratories. Examples include brachytherapy seed and mammography equipment calibrations and fundamental neutron research.

Adequacy of Infrastructure

The division's aging Building 245 needs a major upgrade or replacement; in particular, new radiation-shielded facilities are required to house new accelerator equipment, high-dose-rate brachytherapy calibrations, and a medical imaging facility. Some equipment needs upgrading or replacement, including the instrumentation for a new neutron beam line, the aging accelerator and a need for spare parts, and the new nuclear imaging equipment. Funding is adequate but very heavily dependent on the Department of Homeland Security. Several retirements are expected in the next few years in the division, but succession planning is in place. The work of the division relies heavily on postdoctoral fellows and students.

Achievement of Objectives and Impact

The projects being carried out support the division's mission. The division works collaboratively with other divisions in the Physics Laboratory, with other NIST laboratory divisions, and with numerous other organizations. The technology development and scientific research are at a very high level of technical merit. The objectives of the Ionizing Radiation Division are to develop, maintain, and disseminate the national standards for ionizing radiation and radioactivity in order to meet the needs related to health care and the environment, and those of academia, industry, and homeland security, and to conduct underlying basic research in these areas. The Ionizing Radiation Division develops dosimetric standards based on the SI unit gray; develops neutron standards; develops and provides standards for radioactivity based on the SI unit, the becquerel; and works through strategic alliances, external funding (largely from the DHS), and links with other national and international metrology institutions.

CONCLUSIONS

The vast majority of the projects in the Ionizing Radiation Division are well thought out and relevant to the mission of the division and to the needs of those who use the calibrations, standards, and research results produced. There are three major areas of concern: the heavy dependence of the division on DHS funding, the condition of the physical plant that houses the Radiation Interactions and Dosimetry Group and the Radioactivity Group, and the need for modernizing and replacing much of the radiation-producing equipment used by the division.

The extension of the Experimental Hall coupled with the development of new beam lines at the NCNR will result in the Neutron Interactions and Dosimetry Group's obtaining four new beam lines. It is essential that funding be made available for the experimental equipment, its operation, and staff needed to use these new beam lines efficiently.

The overall quality of the Radioactivity Group's work is among the best in its field. Major input on potential projects comes from the Council on Ionizing Radiation

Measurements and Standards, which generates a list of recommended projects; however, CIRMS does not prioritize the items on that list. An external advisory committee should be appointed to help the Radioactivity Group select and prioritize both new research projects and the specific areas of service collaboration.

Funding for a major renovation to the existing building or, preferably, a new building, should be established for the Ionizing Radiation Division. Shielded radiation cells should be constructed to house the needed modern radiation equipment and high-dose-rate calibration equipment required for industrial-scale dosimetry and medical imaging and calibrations. Careful attention should be given to the current sources of funding for the division. The heavy dependence on DHS funds may lead to a future problem when this funding goes away. An external advisory committee should be established to assist in prioritizing research and service-related projects. Staff and funding in the Neutron Interactions and Dosimetry Group should be increased to allow the efficient use of the new facilities at the NCNR, and staffing in the Radioactivity Group should be increased to meet the growing needs in medical imaging and nuclear medicine.

Optical Technology Division

DESCRIPTION OF THE DIVISION

Mission

The Optical Technology Division's mission is to provide the foundation for optical radiation measurements for the nation. In particular, this division is charged with maintaining two primary standards: the candela, and the kelvin above 1234.96 K, the freezing point of silver. The division's strategy is to develop and disseminate national measurement standards and services to advance optical technologies spanning the terahertz through the ultraviolet (UV) spectral regions. The division's approach to implementing this strategy has three main elements. The first is to develop and provide optical radiation standards based on the Système International (SI units). The second is to develop novel measurement methods for solving problems in critical and emerging technology areas. The third is to disseminate optical radiation measurements and standards to commerce, industry, government, and academia.

Scope

The division activities fall into three main categories—the development and refinement of optical radiation standards, optical measurement methods, and optical measurement services.

The division provides the optical radiation measurement science and standards to aid the advancement and application of optical technology. Its accomplishments include new spectral irradiance standards from the SURF III facility; the development of total spectral radiant flux standards; and the development of the Low Background Infrared (LBIR) Facility for missile defense sensors.

The division strives to improve the accuracy, quality, and utility of optical measurements in burgeoning technology areas. Its accomplishments include spectral and spatial stray light correction in optical systems, satellite instrument calibration, bacteria identification with a variation of the quantum dot method, assembling magnetic nanoparticles into long chains, and construction of an efficient two-photon source. The delivery and refinement of core radiometric calibrations to external customers, including other government agencies, have been ongoing accomplishments.

The division builds and maintains state-of-the-art optical radiation measurement facilities to meet the continued need for standards and specialized measurements by government and industry. Its accomplishments include the development of a hyperspectral image projector for the calibration of remote sensing instruments; research in the area of tackling translucence and other color challenges with the goniospectrometer, an instrument for precisely measuring the intensity of light reflected from the surface of a sample; and the study of perceived and measured colors of retroreflective materials in traffic signs.

Projects

The Optical Thermometry and Spectral Methods Group maintains, improves, and disseminates the national scales for the spectroradiometric measurement of radiation sources and temperatures. This group is also engaged in basic research aimed at applying new techniques in quantum optics to revolutionize future radiometry standards.

The Optical Properties and Infrared Technology Group establishes and disseminates primary measurement scales for the transmittance and reflectance of materials in the infrared (IR) spectral region; studies optical properties of materials in the near-, mid-, and far-infrared spectral regions; provides blackbody calibrations; performs research and development work to achieve accurate, high-precision radiometric measurements at low and ambient thermal background environments; and develops and calibrates transfer standard radiometers to be used for on-site NIST-traceable measurements of missile defense sensor test chambers.

The Optical Sensor Group establishes the national measurement scale for the SI unit the candela and provides measurements of the absolute spectral responsivity of optical detectors in the spectral region from 200 nm through the IR using a high-accuracy absolute cryogenic radiometer.

The Laser Applications Group advances laser and synchrotron radiation technology for applications in optical radiation and measurements of optical properties of materials.

The Biophysics Group develops advanced spectroscopic and microscopic measurement methods, nano-optical probes, and imaging technologies and associated theoretical models to solve important science problems in biophysics and bionanotechnology.

Staffing

The division has 35 permanent technical staff members and 6 permanent support staff members across its groups—the Optical Thermometry and Spectral Methods Group, the Optical Properties and Infrared Technology Group, the Optical Sensor Group, the Laser Applications Group, and the Biophysics Group.

Major Equipment, Facilities, Ancillary Support, and Resources

The facilities of the Optical Technology Division associated with maintaining national standards include the following:

- The National Standard for Optical Power: the Primary Optical Watt Radiometer (POWR) provides the optical power standard to 0.01 percent;
- The LBIR Facility maintains the NIST infrared radiometric standard for instruments that need to be calibrated in background environments that are 20 K and below;
- SIRCUS (Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources) is a tunable laser-based facility for the absolute calibration of optical instruments; the companion Traveling SIRCUS is used at external

sites;

- FASCAL 2 (Facility for Automated Spectroradiometric Calibrations) provides the NIST spectral irradiance scale, covering the 200 nm to 2,500 nm wavelength range;
- The Spectral Tri-function Automated Reference Reflectometer Facility maintains the national scale of reflectance, including bidirectional reflectance distribution function; and
- SURF III is used for detector power response calibration, and for irradiance calibration from 130 nm to 600 nm applications in materials characterization and semiconductor physics and technology.

These facilities are at the core of the division's mission. At present these are mature facilities, although incremental improvements continue to be made. Research on new methods is also being carried out, with the possibility that new approaches (e.g., single-photon source and photon-counting detection) may supplement or substitute for certain of the current facilities.

ASSESSMENT OF THE DIVISION

The mission of the Optical Technology Division is to provide the foundation for optical radiation measurements for the United States. Its approach is to develop and disseminate national measurement standards and services to advance optical technologies spanning the terahertz through the infrared, visible, and ultraviolet spectral regions. The division's main responsibility is to advance, maintain, and disseminate standards for the candela and kelvin base SI units and related radiometric quantities. Its core competency in this area is evident through its execution of several high-profile projects, including SIRCUS, Traveling SIRCUS, SURF III, and the LBIR Facility. The Optical Technology Division's major accomplishment is the continued refinement of core radiometric calibrations at the LBIR Facility and SIRCUS and their delivery to external customers, including other government sponsors through the Missile Defense Agency program.

The division's highly qualified and productive staff executes a diverse program of applied research and calibration services. The facilities and equipment are of the highest caliber and appear to be well maintained. The division appears to be delivering on its stated mission as witnessed by its external sponsor base, which includes other U.S. government agencies, foreign national metrology organizations, and prestigious U.S. industry and academic institutions. Additionally, the division's leadership and participation in international standards organizations and conferences, its capture of a relatively large number of competed NRC postdoctoral fellows, and its overall publication record also indicate the high quality of its delivered products, services, and research accomplishments.

The calibration and sensor facilities and expertise of the division have two or three peers worldwide and clearly no domestic equivalents. Their advanced research effort in the area of quantum information science is also of high quality, comparable to major academic programs throughout the country, and their research into the radiometric applications of correlated photon states is unique.

Concerns include the level to which the division relies on nonpermanent staff to achieve its core mission, the apparent divergence of the new (and very impressive) Biophysics Group from the division's core mission, the future prospects for the terahertz research effort, the distraction of staff effort in order to address administrative issues (namely, the IT burden and other unfunded mandates), and the potential disruption in service that will potentially accompany the planned laboratory relocations.

Technical Merit Relative to State of the Art

The Optical Technology Division maintains a long-term core commitment to high-accuracy measurements in radiometry, photometry, and spectroradiometry. The division continues its successful efforts to develop new approaches to calibration over a wide spectral range, from the far infrared through the UV. The division has invested significant resources in these areas and justifiably places emphasis on maintaining the laboratory investments as well as careful measurement methodologies as tools for external customers in the private and government sectors.

The division has the institutional responsibility for maintaining two base SI units: the unit of temperature, the kelvin, above 1234.96 K, and the unit of luminous intensity, the candela. The division also maintains the national scales for other optical radiation measurements and ensures their relationship to the SI units. These measurement responsibilities include derived photometric and radiometric units, the radiance temperature scale, spectral source and detector scales, and optical properties of materials such as reflectance and transmittance.

A core activity of the division is the development of technical standards for industries relying on optical technologies. The division also has research programs for developing optical and spectroscopic tools for the improved understanding of processes required to support evolving technologies in, for example, the semiconductor, solid-state lighting, and biotechnology and health science industries.

Within the area of optical standards, the activities within the division are clearly distinctive within the United States. The facilities for maintaining standards that have been developed within the division do not exist elsewhere in the nation. The natural technical point of comparison for the optical standards lies in the research carried out in national laboratories in Europe. The staff in the division is well aware of comparable research and engages in international comparisons and cross calibration. Many of the other activities in optical technology, while not involving specific international optical standards, rely on highly refined measurement capabilities. Here the uniqueness of the division's activities results from the choice of the problems addressed as well as from the distinctiveness of the measurement capabilities themselves. The division's overall activities constitute forefront research in areas that are relevant to the NIST mission.

Adequacy of Infrastructure

Laboratory space has been much improved. Five years ago, some of the division's laboratories were severely cramped to the point of being borderline dangerous—that is, laboratory safety was an issue in laboratories that housed major radiometric instrumentation resources. Now several laboratories are in new locations in the AML, and in general the overall increase in floor space offers much more flexibility and a much improved environment for the researchers to work in with their equipment. Unfortunately the occupants of the AML, many of whom are in the new Biophysics Group, will have to move in order to create space for a new NIST Center for Nanoscale Science and Technology. Laboratory moves are always disruptive. Although the affected staff is facing this with a positive attitude, it will slow the progress of their research for a time. It is important that a plan be in place to prepare their destination laboratories adequately prior to the move and to minimize the disruption.

The equipment and instrumentation of the division are of high quality. There is evidence of healthy equipment spending over the past few years. The equipment budget appears to be adequate, and the staff appears to be making insightful decisions in the vendor selection process.

The permanent staff is capable, experienced, and motivated. Their results attest to their commitment to high-quality research and products. The percentage of the researchers who are permanent staff is low—less than 50 percent. This percentage is uneven from group to group, with one notable group having only four permanent staff and more than a dozen short-term or contract personnel. The permanent staff are the leaders of the division. There are many tasks and responsibilities of an institutional nature that they alone are capable of assuming. They also direct and mentor the other technical staff. Obviously the smaller the number of permanent staff, the greater the proportion of time required to fulfill these responsibilities. The risk is high that in the event of the loss of one or two permanent staff, a multiple-month disruption in progress will occur in related research. Most groups depend on external customers for a portion of their funding support, with deliverables to these customers being a central aspect of these task plans. Customer satisfaction would likely be put at risk in the event of a staff loss because of the shallow bench strength. It takes continuity and flexibility to maintain a laboratory of outstanding quality and to be able to respond to new needs and new opportunities. Both capabilities are threatened by the staffing trends of the past few years.

Visiting researchers are major contributors to the quality of a laboratory, bringing in new ideas, establishing close working relationships that continue after the individuals have returned to their own institutions, and filling gaps in expertise in particular projects. There is an impressively large number of NRC postdoctoral fellows in this division. This is evidence of the attractiveness of the division's activities to early-career scientists, as well as of the commitment of the division's staff in making the effort to attract and mentor these young scientists.

The relatively low permanent staff population appears to be partially related to the NIST overhead structure, which places the preponderant portion of the overhead on the permanent staff with little or no overhead being attached to the other technical personnel or the office or laboratory space usage. A NIST committee is addressing the NIST overhead structure. The panel looks forward to seeing that committee's report. Another related factor appears to be the extent to which support depends on external funding sources, which can create a mood of conservatism regarding hiring. The Optical Technology Division and the Physics Laboratory should be more aggressive in hiring early-career talent.

Achievement of Objectives and Impact

The research program in the Optical Technology Division reflects careful technical strategic planning aimed at responding to NIST and to national priorities. The existence of a vibrant and dynamic technical strategic planning process can be seen in the realignment of many of the activities that were in the Laser Applications Group. Whereas several years ago there was no work related to biological sciences, staff and projects are now in place (with extensive external collaborations) to address this strategic thrust. Also, in a related vein, the frontier of optical spectroscopy of nano- and molecular-scale objects has been impressively extended.

The issue of customer focus is particularly relevant within the standards area. In this respect, a special role is filled by the Council for Optical Radiation Measurements, which periodically evaluates national needs in optical metrology and provides feedback on the services and standards supplied by the division. CORM is a body originally instituted by NIST to provide guidance and prioritization on technical needs in industry and research. The laboratory's colorimetry facility, for example, was developed in response to CORM recommendations. The impressive level of customer satisfaction with the division can be gauged by the high level of other-agency research support. A continued high level of such external support is the ultimate test of attention to the customer.

The Optical Technology Division makes use of a variety of effective means for delivering its technical output. For long-term research, the means are primarily the traditional methods of publication in the technical literature and presentations at conferences. For standards work, the division's output takes the form of calibrations of customer sources and detectors and making available transfer standards. Several additional forms of disseminating the technical capabilities of the division have also been implemented. Notable among these are holding specialized courses and tutorials and making available specialized software. The latter has been implemented very effectively with respect to the analysis of optical scattering data. A flexible analysis program developed in the division has been very popular, with more than 1,000 downloads. The division evidently places a healthy emphasis on publicizing and disseminating much of its technical output.

The division has an excellent balance with respect to meeting immediate needs and at the same time developing new long-term programs. This approach will keep the division at the technical forefront and will ensure significant long-term impact. The standards work has an impact through a widespread chain of technology, since calibration is essential for a wide spectrum of applications. Similarly, fundamental advances in the optical characterization of materials have broad impact beyond the immediate field of optical science.

NIST has identified biosciences as a strategic area of emphasis. Excellent work in this field is already underway in a number of NIST's laboratories, including the Physics Laboratory, where the new, impressive Biophysics Group has been formed in this division. Although currently small in number, the research personnel are a very capable group, enthusiastic about their research. The overall group objectives appear to be in line with the NIST mission. The bioscience thrust in the division relies heavily on multidisciplinary and interdisciplinary research. The collaborations with the National

Institutes of Health and the appointments of several NIST personnel as participants at the Center for Advanced Research in Biotechnology (CARB) are consistent with strategic goals.[8] As pointed out in the previous NRC assessment, there is an increasing need for interdisciplinary approaches in the biosciences.[9]

Although this group fits into the Optical Technology Division (which seems appropriate), several other divisions include the activities of this group in their portfolios. This brings up questions about the present and future ownership of this promising group. It would be helpful to address this issue and articulate the understanding of the extent of the sharing of the objectives and products of this group among the various divisions. Addressing this issue would help to alleviate the perception of a lack of coordination of efforts in this research area. The level of coordination or overlap among these divisions should be clarified. The Physics Laboratory has the potential to play an increasingly important role in collaborating with other external organizations to exploit the new technologies and methods in many facets of the biosciences. However, it will be necessary for the Physics Laboratory to elucidate a comprehensive plan for organizing and staffing its expanded role in this area if it is to optimize its effectiveness.

The division has outstanding measurement capabilities in the terahertz spectral region, originally based on traditional Fourier-transform techniques, and more recently it has been developing forefront capabilities for measurements using laser sources including both frequency-domain and time-domain approaches. The suite of measurement capabilities is outstanding. A significant investment has been made in the terahertz laser source technology resident in this division, and it is attracting a number of outstanding postdoctoral fellows.

The terahertz research appears, however, to be at a crossroads. There are questions about the future applications: Who are the customers of the future? What biological problems do the principals on the permanent staff who are now associated with the new Biophysics Group plan to address in the future? The problem associated with the application of terahertz tools to biological research is the very strong water absorption throughout the terahertz region of the spectrum. It is timely for the terahertz technical leads and the division management to enunciate applications areas for their unusual capabilities in which they will have desirable impact. Particularly interesting would be the application of such a tunable terahertz source to microscopic apertures. High pressure physics is one such area. The small aperture associated with the highest pressure diamond anvil cells could make tunable terahertz the ideal probe for exploring the appearance of pressure-induced insulator-metal transitions in front-line materials like solid hydrogen. There is an effort in the division to explore such new applications areas.

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[8] CARB is located at the University of Maryland Shady Grove campus near NIST. CARB was initially a joint collaboration of the NIST Biochemical Science Division, within the NIST Chemical Science and Technology Laboratory, and the University of Maryland Biotechnology Institute.

[9] National Research Council, 2005, *An Assessment of the National Institute of Standards and Technology Measurements and Standards Laboratories: Fiscal Years 2004-2005,* Washington, D.C.: The National Academies Press.

CONCLUSIONS

The Optical Technology Division is successfully maintaining its long-term core commitment to high-accuracy measurements in radiometry, photometry, and spectroradiometry. This commitment is in line with the NIST mission. Core facilities continue to be operational, and new methods and techniques are continuing to be developed. The division has engaged in strategic planning that involves new areas of emphasis. One notable example is biophysics. A new Biophysics Group has been formed, collaborations with external organizations have been put in place, and the future looks bright. The staff are capable and motivated; however, the mix between permanent staff and temporary and contract personnel appears suboptimal for long-term health and consistency in meeting strategic objectives.

The Optical Technology Division and the Physics Laboratory should be more aggressive in hiring early-career talent. The Physics Laboratory should elucidate a comprehensive plan for organizing and staffing its expanded role in the biophysics area if it is to optimize its effectiveness. The terahertz technical leads and the division management should enunciate the applications areas for the unusual capabilities of terahertz tools in which they will have desirable impact. The Optical Technology Division should adequately prepare the destination laboratories prior to the move of the Biophysics Group personnel and minimize the disruption from the move.

Quantum Physics Division

DESCRIPTION OF THE DIVISION

Mission

As stated in the NIST *Physics Laboratory* report for 2008, the mission of the Quantum Physics Division is as follows : "[The division's goal is] to make transformational advances at the frontiers of science, in partnership with the University of Colorado at JILA. . . . The strategy of the Quantum Physics Division is to help produce the next generation of scientists and to investigate new ways of precisely directing and controlling light, atoms and molecules; measuring electronic, chemical and biological processes at the nanoscale; and manipulating ultrashort light pulses."[10]

Scope

The strategic elements of this division are as follows:

- To develop measurement science tools and their applications to technology;
- To exploit Bose-Einstein condensation, quantum degenerate Fermi gases, and cold molecules for metrology and ultralow-temperature physics;
- To advance ultrafast science and apply it to physics and biophysics;
- To apply cutting-edge measurement science to biological systems;
- To apply laser spectroscopy to important problems in chemical physics and biophysics; and
- To educate a supply of top-quality scientists for NIST and elsewhere.

Projects

JILA excels in the area of neutral atom cooling and trapping, and the Nobel Prize for physics was shared by two JILA Fellows and an MIT professor for realizing Bose-Einstein condensation in 2001. Work continues at the frontier of fundamental understanding of the condensed state as well as in applications of BEC. One example is the study of fundamental elementary excitations of BEC such as vortices. By confining ultracold atoms in an optical lattice, a phase-coherent quasi-two-dimensional array of Bose-Einstein condensed atoms has been produced. In two dimensions, an exotic phase transition known as the Berezinskii-Kosterlitz-Thouless (BKT) transition is expected, and this has been observed for the first time in BEC as vortex excitations appear with increasing temperature. Another example is the use of a BEC of rubidium atoms for a new sensitive measure of the Casimir-Polder force due to quantum interactions between the condensed atoms and a nearby surface of fused silica.

Ultracold clouds of Fermi atoms are also studied. In this system correlated pairs of atoms form, and the pairs could Bose condense similar to the formation of Cooper

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[10] National Institute of Standards and Technology Physics Laboratory, 2008, *Physics Laboratory,* Gaithersburg, Maryland: National Institute of Standards and Technology, p. 44.

pairs in a superconductor. The interactions between pairs are mediated by the so-called Feshbach resonance, in which the relative translational motion of the pairs is strongly coupled to a bound state with a different total spin. Because of the difference in spin, the strength of this interaction can be tuned with an external magnetic field, while the cold atoms are held in an optical dipole trap. The ability to tune the pair interaction has led to a wealth of phenomena. In one experiment, a sudden pulse of magnetic field puts pairs of atoms into a novel quantum superposition that oscillates in time between bound and unbound states.

Another study explores the variation from the BEC regime, where localized pairs could form a Bose condensate to the Bardeen-Cooper-Schrieffer (BCS) regime, where pair formation is mediated by the surrounding condensate atoms and the size of the pair could become very large. This BEC-BCS crossover is important theoretically, and its understanding could impact the theory of High-T_c superconductivity. This work has been enabled by novel techniques developed for extracting information on the pair correlations from noise in absorption images of the cold atomic cloud.

A third line of experimentation seeks to convert the highly interacting pair states into real bound states by removing the appropriate energy from the pairs with an optical Raman process. This has recently succeeded in producing bound diatomic molecules (though still highly excited relative to the molecular ground state) from these interacting cold Fermi pairs.

Techniques for cooling small molecules are also being developed, with the goal of placing the molecules into a single chosen quantum state in order to study the fundamental quantum physics of cold molecules and their chemical interactions in single quantum states. To this end, OH molecules have been cooled with a novel Stark deceleration method and trapped in a magnetic trap.

Work also continues on the development of new systems and techniques in frequency measurement. JILA has long been renowned as a center of excellence for laser frequency stabilization and for the development of methods for precision frequency measurement. One of the most important tools in recent years is the stabilized laser frequency comb, a technique that was brought from conception to fruition at JILA and for which a retired NIST JILA Fellow (now NIST Scientist Emeritus and JILA Fellow Adjoint) shared the Nobel Prize in physics in 2005. The laser frequency comb has produced a revolution in optical frequency measurement and is key to the development of optical atomic clocks. Current work in this division applies the frequency comb technique to a new atomic clock system composed of an optical lattice of laser-cooled strontium atoms. Scientists in this division realized that the energy states of strontium had characteristics that should lead to extremely small systematic frequency uncertainty and thus to potential clock accuracy and repeatability comparable with or better than the best previously identified clock systems. In a tour de force of atom cooling, trapping in an optical lattice and optical clock technology, this novel optical clock features a large number of atoms responding identically, thus providing the precision of a single atom with vastly enhanced signal-to-noise ratio. Fractional frequency instability of 3×10^{-15} has already been achieved, with the expectation that this can be improved by a factor of three. A cooperative effort with the NIST Time and Frequency Division in Boulder has compared the accuracy of this clock with the calcium optical clock at Time and Frequency. This was achieved using the capability for coherent optical phase transfer over a 3 km optical fiber with instability of 10^{-17} in 1 s, which allowed the overall systematic uncertainty of the strontium lattice clock to be evaluated as 1.5×10^{-16} in 1 s.

The ability to transfer a stable optical frequency over considerable distance through optical fiber has broad potential applicability to precision metrology in the context of synchronized telescope arrays and long-distance interferometry, for example. The current performance represents a factor-of-100 improvement over previous techniques at 10s-of-kilometer distances.

Further development of the optical frequency comb and extension of comb techniques to new applications are also underway. These include the Arbitrary Optical Waveform Generator, which is a joint competency program with the Time and Frequency Division, and the use of optical frequency combs for trace molecule detection and molecular fingerprinting.

Another area of endeavor involves approaching quantum-limited nanoscale mechanical and electronic measurement. Studies of novel mesoscopic and nanoelectronic devices aim to explore the ultimate quantum limits of mechanical and microwave electronic measurements. Areas of application include quantum information, noiseless microwave amplification, and high-bandwidth detector arrays. Precision measurements on microfabricated mechanical oscillators explore the onset of quantum behavior as the dimensions approach the nanometer scale and low temperatures remove most of the thermal excitation. A sensitive scheme for the detection of the amplitude of a nanomechanical gold beam uses an atomic point contact and can detect motion at the quantum level as well as the effect on the oscillator of the quantum measurement noise imposed by the measurement of its position.

The quantum limits to microwave measurement, amplification, and interferometry are tested in a series of elegant experiments that use novel microwave interferometers and nonlinear Josephson devices to explore the concept of microwave quantum optics. A microwave Fabry-Perot interferometer has been fabricated containing the microwave equivalent of a nonlinear Kerr medium composed of a metamaterial built from a series of 400 Josephson junctions. This device is a phase-sensitive parametric amplifier, capable of near-noiseless amplification of one quadrature of a microwave signal. It can also be used to generate squeezed states of the microwave field, and as much as 85 percent phase-dependent noise suppression has been observed.

Using related technology, a low-noise superconducting quantum interference device multiplexer has been developed for the readout of arrays of low-temperature astronomical sensors. These have the potential to read out an array of thousands of detectors in a single channel with gigahertz bandwidth and could have application to novel detector arrays used in nuclear and particle physics, materials science, and astronomy.

A group is also studying ultrashort, femtosecond laser pulse interactions with matter. There is significant overlap in work between this group with work on the dynamics of chromophores in proteins. This area is divided into three subareas: interactions between alkali atoms in the gas phase, condensed-matter systems, and spintronics dynamics.

In the gas dynamics work, the effort is primarily on the study of the collision dynamics of potassium atoms. Potassium atoms are illuminated with a sequence of two pulses. The first excites the atom to a specific state, and the second has a frequency that is absorbed only by the excited atoms and thus induces emission, as long as the excited atoms have not lost their energy by collision. The intensity variation as a function of delay provides a measure of collision dynamics.

The condensed-phase work involves cross-correlation two-dimensional near-IR spectroscopy of excitons in semiconductors using three femtosecond, near-IR pulses to generate excitons in semiconductors such as gallium arsenide (GaAs). The correlation between absorption and emission was determined in a plot of wave patterns and frequency. This two-dimensional spectroscopy method is capable of determining the correlated oscillation of two groups in a molecule or lattice. Using this rather new two-dimensional spectroscopic method, the structure of large biological molecules and also the electronic properties of semiconductors may be revealed, phenomena impossible to observe when only the normal one-dimensional spectroscopic methods are used. The knowledge obtained on GaAs and other semiconductors by this method may lead to better electronic devices.

The spintronics work involves developing the capability of maintaining spin direction for several nanoseconds while being transported micron distances; it is of paramount importance for high-capacity storage and other devices. Researchers at JILA have determined that the spin direction is more stable when confined in the defects of semiconductors and that it loses alignment fast when embedded in a perfect single-crystal environment. It was determined that the place of highest spin stability is located in a crossover magic point somewhere between perfect crystal and defect.

This research group confined electrons in quantum wells. An IR light pulse induces spin on the electron while the light of a second polarized pulse reflected by the quantum wells is rotated by the electrons. The magnitude of the rotation gives a measure of the number of electrons with the same spin. With the application of a magnetic field the spins are flipped, and consequently the reflected polarized light oscillates. From these oscillation patterns the spin disorder and spin stability-retardation time are calculated. Spintronic materials, where the spins of electrons can be manipulated, and their properties provide a wealth of basic scientific knowledge in addition to holding the promise of wide use in electronic devices and other areas of industry.

In summation, the femtosecond laser work involves elegant research in several cutting-edge scientific areas that also have strong industrial applications.

Another group is examining laser spectroscopy kinetics and dynamics of organic molecular and nanoparticle systems. As is true of the ultrashort, femtosecond laser pulse interactions with matter, there is a connection with biological physics, which is described below.

This group determines basic chemical-reaction dynamics by means of laser spectroscopy of jet-cooled molecular ions, intermolecular energy surfaces, and low-temperature radical and ion kinetics. In addition, a large effort is made in the study of single-molecule kinetics and microscopy. The systems that have been studied in this area include single quantum dot emission kinetics of cadmium sulfide (CdS) and silver (Ag) nanoparticle lithography.

This group has been very active and successful in the design of new equipment and devices and the improvement of standard equipment for utilization in specific experiments. For example, this group has developed, designed, and built a novel, near-field apertureless scanning optical microscope capable of less than 10 nm resolution that finds use in many areas of physics, chemistry, and biology. This group has sufficient space, equipment, and funding to continue to generate a large quantity of excellent theoretical and experimental research data in diverse, yet very fruitful fields of chemistry, physics, and biology.

Biological physics is a growing area of expertise at JILA, and increasing collaborations are developing among the various groups there. It is very encouraging to see the application of techniques coming out of seemingly esoteric areas such as frequency combs to very applied biological problems. Several groups of this division have some biological projects, but that is not the core of their efforts. There are two primary biological physics principal investigators.

An outstanding example of the cross-fertilization of technologies developed at JILA for the core mission of the development of measurement science tools is the extension of the Nobel Prize-winning work on optical combs to the application of this technology to biomolecule detection. The latter group invented cavity-enhanced direct frequency comb spectroscopy and has shown that it can perform ultrasensitive detection of unknown chemicals. This group has recently developed a more sensitive, smaller, and less costly fiber laser for this system, which can make ultrasensitive and fast detection of organic molecules using a simple charge-coupled device camera, opening the door for using this technique for medical and homeland security applications.

Another group has built on its expertise in single-molecule optical detection to elucidate the conformational kinetics of single ribonucleic acid (RNA) molecules and single deoxyribonucleic acid (DNA) molecules in electrophoresis. This group has used fluorescence energy transfer techniques at the single molecule level to measure distances of 2 to 8 nm between specifically labeled sites on the RNA. This information is crucial to understanding RNA-based enzymes, or ribozymes. In the future, these techniques should make it possible to probe the folding and unfolding of biomolecules in chemically active states.

The two main biological physics groups have quite different areas of expertise and interact with different groups within JILA and at the University of Colorado. One group studies single molecules as does the other, but while one uses fluorescence energy transfer techniques the other is a renowned expert in the use of optical tweezers and lately atomic force microscopes in the incredibly precise measurements of subnanometer motions of biological molecules. This work on the molecular motor RecBCD (also known as Exonuclease V, a protein of the *Escherichia coli* bacterium) is an example of how much there is to learn about how nanomotors move along biological polymers. The questions of the step sizes of these motors, the role of thermal noise, and the basic physics of very small displacement measurements all come into play here.

This group is working to improve the resolution of optical tweezers by increasing sensitivity while reducing system noise, which is clearly connected to the JILA tradition of precision measurements. This group has explored the use of a more stable optical design (with improved laser-pointing stability and reduced microscope-stage drift), active sample stabilization, and the introduction of a grid of nanofabricated fiducial marks.

Some work overlaps with the work on protein dynamics. The researchers here are interested in performing experiments that provide data for the understanding of the motion and thermodynamics of proteins and the influence that motion has in the chemistry of these and other large biological molecules. This group is also exerting an effort to measure accurately the motion of proteins, and from this motion data to calculate several of the important thermodynamic values including entropy. This group employs several cutting-edge techniques and equipment such as femtosecond lasers for the study of ultrafast spectroscopy and kinetics of these molecules, and because the laser pulse duration is much shorter than the protein motion, a sequence of such pulses separated by a pre-selected period of time may freeze motion and thus record snapshots of the protein at a given time. When a train of snapshots is put together in a movie format, a histogram of the protein motion will be obtained, from which the thermodynamic values may be calculated as a function of time and process such as coiling.

A time-resolved extended x-ray absorption fine structure (EXAFS) system that is aimed at revealing the transient structure of proteins in motion is under consideration for being constructed in collaboration with a high-power-laser JILA group. Another active area is microfluidics where chemical concentrations have been mapped in three-dimensional form inside a microfluidic cell. This has been achieved by employing two-photon fluorescence imaging techniques. Some of these projects are still in the development stage; therefore, this group has not yet had the number of publications and impact that other established research groups of the Quantum Physics Division have had. The research, however, is of good quality, and it is expected that the group will grow in size and generate a high research output of excellent quality.

Staffing

The Quantum Physics Division consists of nine principal investigators who are NIST employees, in addition to three administrative staff members. Recent years have seen the retirement of two senior JILA Fellows and the hiring of a new principal investigator in the areas of atom cooling, spin squeezing, measurement science; and theory of ultracold atoms and optical lattices, respectively. The supporting research staff, technicians, postdoctoral fellows, and graduate students are of high quality and are sufficient in numbers.

Major Equipment, Facilities, Ancillary Support, and Resources

The Quantum Physics Division is housed in the JILA building on the campus of the University of Colorado. Laboratory and office space continues to be insufficient to house current programs adequately. The lack of space is detrimental to productivity, creates potentially unsafe working conditions, and could affect the ability to attract and hire top-class scientists in the future. This should be considered a top-priority item for this division. Funding to build additional space is now in the current proposed federal budget; it is important that this funding be provided so that expansion can proceed in a timely fashion. The Quantum Physics Division has access to a very good pool of graduate students by virtue of its association in JILA with the University of Colorado. The excellence of the scientific work at JILA attracts some of the very best of these students, and a large number of JILA graduates have gone on to employment within NIST. JILA also has top-notch mechanical and electronic shops, and this infrastructure is vital to the productivity and success of the division. The JILA Fellows were uniformly enthusiastic about the excellent quality of the mechanical and electronic shops; it is critical that this valuable resource be maintained at its present level of first-rate quality.

ASSESSMENT OF THE DIVISION

The major accomplishments of the Quantum Physics Division include the following:

- Nobel Prizes in Bose-Einstein condensates and femtosecond laser frequency combs, continued excellence in extending work in ultracold Bose and Fermi atoms and molecules, and applications of optical frequency combs;
- State-of-the-art measurement of piconewton forces at subnanometer length scales with optical tweezers;
- The development of an innovative strontium optical lattice clock with high signal-to-noise ratio;
- Ultrafast two-dimensional Fourier transform spectroscopy that reveals new insight into many-body effects in semiconductor charge and spin dynamics;
- Pioneering work in microwave quantum optics; and
- Conformational dynamics of single RNA and DNA molecules studied with fluorescence resonant energy transfer.

The standard of technical research in the Quantum Physics Division is very high. The research is very productive and explores the frontiers of the areas that are investigated. In areas of its traditional core competencies—that is, laser stabilization, spectroscopy and precision frequency measurement, and trapping of ultracold atoms and molecules—the work of the division ranks among the best. The division has also attracted top applicants in areas identified for expansion such as biophysics and nanoscale physics.

It is critical that funding for the new JILA building be put in place and that the plans for design and construction move forward, both to relieve the space crunch at JILA and to maintain the high morale and productivity that are key in making JILA an attractive place to continue to work for highly talented staff members who are actively recruited by other institutions. The increased emphasis on nanotechnology needs to be supported by upgrades to some instrumentation, especially an improved scanning electron microscope with a state-of-the-art field emission source.

The impact of the Quantum Physics Division is outstanding, as measured against its stated mission of making important advances at the frontiers of science that enable future precision measurement technology and in producing graduates that form a talented pool of scientists who are now spread through the NIST laboratories and elsewhere. Collaborations between the Quantum Physics Division and the nearby Time and Frequency Division are strong, particularly in the further development of frequency combs and their use in high-precision remote frequency comparisons over an optical fiber connecting the two sites. They are also having significant impact through applications of their technology outside NIST, for example in sensitive high-resolution frequency comb spectroscopy for trace detection and molecular fingerprinting, and the development of technology for multiplexed low-temperature detector arrays for astronomy.

The America COMPETES Act of 2007 has provided support ($100,000) to the area of mesoscopic physics, bridging the gap between quantum and classical physics, and electronic measurement work under the umbrella of quantum information. The funding aided in the development of the pioneering field of microwave quantum optics, in particular the noiseless amplification of microwave signals with innovative phase-sensitive amplifiers.

Technical Merit Relative to State of the Art

The standard of technical research in the Quantum Physics Division is very high. Without exception, the research reviewed is very productive and explores the frontiers of the areas that are being investigated. The association of the division with the faculty of the University of Colorado through JILA has resulted in a very collaborative and open environment, leading to a free exchange of ideas and a great deal of cross-fertilization between the research groups. The scientific work at JILA has resulted in many awards, including a sharing of Nobel Prizes in physics for Bose-Einstein condensation of cold neutral atoms in 2001 and for the development of the stabilized laser frequency comb in 2005. Work in both of these areas continues to be advanced and remains among the best. Other work that has earned notable awards includes the production of ultracold degenerate Fermi gases and quantum-limited electromechanical measurements. Four of the 30 NIST Fellows are in this division.

In the areas of their core competencies—laser stabilization, spectroscopy and precision frequency measurement, atom cooling and trapping, and Bose-Einstein condensation—the work of this division is outstanding and ranks with that of the top research groups in the field. When the research scope has been expanded with new hires in biophysics, mesoscopic physics, and nanotechnology, the strong scientific reputation of JILA has attracted top-notch applicants, and these new areas of research have kept pace with the overall level of excellence exhibited by this division as a whole.

Adequacy of Infrastructure

As noted above, it is critical that funding for the new JILA building be provided and that the plans for design and construction move forward, both to relieve the space crunch at JILA and to maintain the high morale and productivity of the highly talented JILA staff members.

The division's very impressive work could have broad applications on astrophysics detection capabilities. JILA would benefit from the hiring of an astrophysicist/instrumentalist to complement the division's ongoing work.

There is a strong emphasis in many of the projects on nanotechnology—for which JILA needs in-house a very high quality scanning electron microscope for the imaging of the nanostructures and to do nanolithography. The present SEM is not state of the art, and a newer-generation, higher-resolution SEM is necessary to support this growing area.

Achievement of Objectives and Impact

The work of the Quantum Physics Division is outstanding, as measured against the strategy that it has put forth. The division has been very successful at educating new generations of measurement scientists who have gone on to find employment within NIST as well as elsewhere and thus have a large impact on the field of precision measurement and metrology. The division's scientific contributions in its traditionally core areas of emphasis continue to have significant impact in the overall physics community. This division has successfully expanded its expertise into new areas identified as being of importance to the future NIST mission. These include nanotechnology, mesoscopic physics, and biophysics.

This division is the NIST part of JILA, a joint institute at the University of Colorado made up of principal investigators (called JILA Fellows) who are NIST staff members or university faculty and who manage groups of graduate students and postdoctoral fellows in an academic environment. They serve a key role in educating graduate students, thus creating a pool of talent in areas of measurement science of importance to NIST. Their stated mission is to do new science that will form the foundation for future advancements in the overall NIST mission, including developing new ways of controlling light, atoms, and molecules and their interactions, measuring nanoscale processes, and manipulating ultrashort light pulses.

The relationship between NIST and the University of Colorado has a history of producing groundbreaking and excellent, high-impact scientific research that is being successfully continued today, resulting in two Nobel Prizes in recent history. Previous difficulties related to the NIST-university relationship appear to have been successfully solved or mitigated; the current relationship appears to be running smoothly. NIST plays a vital role in fostering a NIST-university collaborative environment with a free exchange of ideas; this panel had no opportunity to review or interview research groups in the university half of JILA, and this report reflects a NIST-centric view of this joint institute.

CONCLUSIONS

The research performed by the scientists in the Quantum Physics Division is outstanding. The output is significant in numbers and excellent in quality, and the research topics selected are at the forefront of related science and technology.

The scientific equipment and technical support, such as electronic and machine shops, are sufficient for the high performance that has been demonstrated and is expected from this division. The supporting research staff, technicians, postdoctoral fellows, and graduate students are of high quality and sufficient in numbers. The purchase of a modern, high-resolution scanning electron microscope is needed to support the increasing efforts in nanotechnology.

The interaction with the astrophysics group at the University of Colorado is of some concern; it should be enhanced, and the number of researchers of this group should be increased. Space, which is of concern, is expected to be increased by the construction of the new building, a project that is essential to the continued productivity of the division.

The work of the division is of high caliber. There is a high and collegial spirit among the scientists and staff; productivity is high, and the quality of the basic science and its application to industry are outstanding.

The Quantum Physics Division and JILA are national assets, and every effort should be exerted to sustain and, if possible, increase their support and funding. The most critical items that need to be addressed are funding for the JILA building expansion and funding for improvements in instrumentation relevant to nanotechnology research.

Time and Frequency Division

DESCRIPTION OF THE DIVISION

Mission

The mission of the Time and Frequency Division is to develop the highest-accuracy time and frequency measurements in support of commerce, research, and the general public.

Scope

The NIST 3-year plan (FY 2009-FY 2011) includes the following elements directly applicable to the mission of the Time and Frequency Division:[11]

- Develop an all-optical clock for more precise time and frequency measurement;
- Develop quantum logic clocks capable of providing improved time and frequency for the next generation of the Global Positioning System (GPS) and for tests of fundamental physics theories;
- Improve environmental conditions within NIST's Boulder, Colorado, research laboratories to enable production of the extremely accurate data needed by industry and academia and to support further progress in measurements related to high-frequency electronics, advanced materials characterized at the atomic level, subcellular forces, timing accuracy, and other areas; and
- Make precision frequency measurements above 100 GHz (100 billion cycles per second), which are required for advanced commercial electronics, military systems, and homeland security.

Projects

The Time and Frequency Division is responsible for the realization and dissemination of the SI unit of time in the United States. The division provides a broad range of advanced measurement services and performs research and development for the future generations of time and frequency standards. In addition, the division is a key U.S. resource advancing quantum information processing.

This division has one of the most complete ranges of time and frequency research and metrology tools that can be combined for unique research and metrology. The division operates the following:

- The most accurate primary standard (NIST-F1), the NIST time scale;
- Femtosecond laser frequency comb systems to mediate the comparison across

[11] National Institute of Standards and Technology, 2008, *Three-year Programmatic Plan for the National Institute of Standards and Technology, U.S. Department of Commerce: Fiscal Years 2009-2011*, Gaithersburg, Maryland: National Institute of Standards and Technology.

a factor-of-100,000 frequency range;
- The narrowest linewidth laser for precision frequency measurement;
- The unique mercury ion and logic clocks; and
- The best capability for the phase noise measurement of microwave and millimeter-wave sources.

This range of assets and experiments leads to unique scientific by-products, such as improvements by a factor of 10 in setting limits on the possible time variations in fundamental constants, and the most accurate tests of special and general relativity.

NIST provides an array of services to a very broad user community in the United States: the NIST Internet Time Service is used more than 2.5 billion times every day; NIST radio station WWVB is widely used to synchronize commercial timekeeping devices to NIST time; the NIST Automated Computer Time Service helps industry meet Securities and Exchange Commission requirements to synchronize the time-stamping of hundreds of billions of dollars of electronic financial transactions to NIST time.

The following international projects are noted as excellent examples of building goodwill for the United States:

- The NIST-led project of developing an international network of common-view GPS receivers will enable time and frequency comparisons throughout the Inter-American Metrology System (SIM), which covers North, South, and Central America. Eventually, continuous comparisons will be enabled between the United States, Canada, Mexico, Argentina, Brazil, Costa Rica, Jamaica, Panama, Uruguay, and perhaps several other SIM member nations (already operational for the countries identified). This project was funded by the Department of State.
- The NIST-developed Satellite Time Service for the North African and Middle Eastern region in a joint venture with the National Institute of Standards of Egypt. This project is sponsored by the U.S.-Egypt Joint Board on Scientific and Technological Cooperation.

Staffing

The division has done an excellent job of anticipating staffing needs by supporting students and postdoctoral researchers to participate in its projects. This approach provides a pool of trained talent, from which a large number of researchers continue employment at NIST. The work in this division is highly specialized, because time and frequency is a niche technology. Thus, specially trained staff are required to carry out the needed research. This need is generally met by a competent staff and a large contingent of visiting researchers, students, and postdoctoral fellows. The latter group typically is a major pool for the future staffing of the division.

There has been notable improvement in the ability of the division to use guest scientists. A highly effective program in Boulder enables both foreign and domestic scientists to work at NIST Boulder on contract through a new scientific services company. Programs through several universities in Colorado enable collaborative work by foreign and domestic scientists with the division.

Major Equipment, Facilities, Ancillary Support, and Resources

The division has developed dedicated laboratories that support the National Time Standard (F1), the Next-Generation Standard (F2), the ion trapping laboratory, which has the special facility to achieve low-line-width lasers, and the phase metrology laboratory.

The division is pursuing an East Coast-based low-frequency broadcast facility to augment the continuously broadcast standard time and frequency coverage of the continental United States. Several potential sites of decommissioned radio stations on the East Coast have been identified as possible sites for a second NIST low-frequency broadcast station, but no decision has been made on the most likely location. The cost of adapting such an existing facility for this project would be on the order of $9 million, compared with a new facility cost of $80 million. This is an excellent example of the intelligent use of a surplus facility to solve an important need at tremendous cost savings (equal to that of the new construction at Boulder).

ASSESSMENT OF THE DIVISION

The division programs focus on four principal thrusts:

- The realization of national and international time and frequency standards with the greatest accuracy and precision;
- The dissemination of time and frequency through a wide variety of measurement services directed to customers at all levels, from industrial and research customers with the most stringent needs to the general public with less exacting needs;
- Research on future time and frequency standards and dissemination methods; and
- Quantum computing with trapped ions, which evolved directly from research on new atomic clocks and which has become a major NIST-wide focus area.

The division has established itself as a leader in these areas, providing a level of organizational performance (e.g., through demonstrated frequency accuracy and stability, scope and quantity of time-dissemination services, publication of scientific results) that exceeds that of any scientific laboratory in its field. The overall quality of the division's work is very high (as demonstrated, for example, by the realization of a logic clock, the realization of the lowest uncertainty in a primary clock, and the demonstrated ability to disseminate time over the Internet on the widest basis); its staff is very talented and its technical approaches are effective. The division's accomplishments, in the context of the criteria requested by the Director of NIST in his charge to the panel, are of high quality and directly relevant. The division's inability to repair and maintain the facility in a timely manner and to an acceptable standard is a significant concern. This facility shortcoming creates gross inefficiencies and has the potential, through staff dissatisfaction and resulting attrition, to erode the present excellence.

Technical Merit Relative to State of the Art

With respect to NIST's realization of the SI second, the division's primary frequency standards have the best accuracy in the world, with a fractional frequency uncertainty of 4×10^{-16}, and its time scale is one of the two best in terms of accuracy and stability as reflected by the NIST time scale contributions to the international time scale.

In the area of measurement services, the division excels in a number of areas. Its remote time and frequency calibrations are the best with respect to accuracy and usability. NIST's network time services are outstanding as well. For example, its Internet Time Service is the most heavily used network time protocol service in the world, logging 2.5 billion hits per day. The NIST radio stations also enjoy heavy use, and their accuracy and stability are the best. In addition, NIST's time measurement and analysis service offers real-time, 15 ns uncertainty. With funding from the Department of State, NIST has expanded to SIM-time scale coordination in North, Central, and South America, generating international goodwill.

In the area of phase noise metrology, NIST has unique capabilities, and its metrology is the leading edge. It is extending capability to 800 GHz, a capability that does not exist today. This extension is driven by advancing civilian and Department of Defense technology requirements.

The division excels in several research and development activities:

- For single-ion optical frequency standards, its mercury-ion standard is at the forefront, with a fractional frequency uncertainty of 1.6×10^{-17}.
- Its aluminum-ion logic clock is the second best, with a fractional frequency uncertainty of 2.4×10^{-17}.
- In the area of cold neutral atomic optical standards, calcium has excellent short-term stability and ytterbium lattice is among the best standards. The division's research includes studies of these optical standards toward providing important high-stability reference clocks for intercomparison of the lowest-uncertainty clocks.
- NIST's femtosecond laser frequency combs have the most precise intercomparisons (1×10^{-19}), and NIST has the top-performing octave-plus spanning combs.
- In addition, NIST has demonstrated numerous firsts for chip-scale atomic sensors, including a chip-scale atomic clock and a chip magnetometer.

In the area of quantum information processing:

- NIST has the sole technology to demonstrate all seven DiVincenzo criteria for scalable quantum computing.
- NIST has demonstrated the first of each of the following: single-atom quantum logic gate, deterministic entanglement, robust error correction, quantum teleportation of massive particles, and quantum Fourier transforms.

Adequacy of Infrastructure

The infrastructure and facilities of the Time and Frequency Division have shown improvement since 2005. A central HVAC facility is being installed to provide improved environmental controls within the existing buildings. A power-conditioning unit is being installed to improve the reliability and quality of the alternating current power to the laboratories onsite. The room in which the new time standard (F2) is being assembled is a significant improvement over what housed the current F1 in 2005.

A new laboratory building to support the entire NIST Boulder facility has been funded, and construction bids have been solicited. There remains, however, the problem of the inability to repair and maintain the facility in a timely manner and to an acceptable standard. This matter affects employee efficiency and morale.

The division's staff and management have noted that an increasingly unhealthy fraction of the time and energy of scientists is consumed with various administrative burdens related to information technology security, procurement, physical security, repeated inventories, required training on obscure administrative issues, and many other distractions. NIST should examine ways to comply with the governing laws, regulations, and mandates while minimizing the distraction of the scientists from their mission and fundamental enterprise and maintaining productivity and morale.

Achievement of Objectives and Impact

The stated objectives of the Time and Frequency Division are as follows:

- Realize the SI second and UTC(NIST)[12] with the greatest possible accuracy and precision as the basis of all division measurement services;
- Provide time and frequency measurement services addressing a broad range of needs, from the most demanding industry and research customers to the general public, based on UTC(NIST);
- Perform research and development for the future generations of time and frequency standards, measurement services, and distribution systems; and
- Perform research on quantum information processing, in support of NIST-wide goals and to improve time and frequency standards.

The division shows a high level of achievement of these objectives, as demonstrated by the following:

- The best realization in the world of the SI second;
- Web clock supporting 2.5 billion hits per day;
- Widely used radio station transmissions and time measurement and analysis services, extended to the international community;
- Unique phase noise measurement capability, extending to 800 GHz;
- Research in ion and cold atomic clocks with unprecedented precision and

[12] UTC(NIST) is Coordinated Universal Time.

stability;
- Research in laser frequency combs; and
- Research in the chip-scale atomic sensor.

CONCLUSIONS

The technical work of the Time and Frequency Division is excellent and serves as a model for other laboratories in the field. The physical facilities in which this work is performed have received modest improvements over the past 3 years, but these facilities need further improvement. Initiatives to construct a new laboratory, appropriate for the work and technology of the division, are laudable; this construction should be completed as planned.

In the meantime, NIST should ensure that projects to repair and improve electric power and other utilities at the NIST Boulder site are effectively prioritized and completed on time and to specification.

The impacts of increasing administrative burdens, poor facilities, and other distractions are severe enough that highly productive and skilled scientists within the division are looking for opportunities outside NIST. The success of the division depends on the ability of the organization to attract and retain the best scientists; such individuals want to work in an environment where administrative issues, IT security, facilities, and other issues are sufficiently minimal distractions so as not to hinder their research and creativity. Repeated reports from staff have indicated that in recent years NIST has become substantially more encumbered by these burdens and distractions. Such reports introduce the significant concern that the long-term scientific leadership and productivity of the division will be compromised by the inability to attract and retain the best scientists, who will seek opportunities where they are not overly encumbered by such administrative issues.

Programs Funded Under the America COMPETES Act

The Physics Laboratory has used its existing resources and expertise to leverage funds provided under the America COMPETES Act of 2007 to rapidly develop programs that address the objectives of the act and of the American Competitiveness Initiative. The funding figures mentioned below were provided under the America COMPETES Act of 2007.

- *Atomic Physics Division:* NIST received about $6 million for quantum information science. One-third (about $2 million) was combined with funding and support from the University of Maryland and the National Security Agency to support the new Joint Quantum Institute. Good progress is being made on advancing plans for a building to house the new center and on experiments to explore cold atoms held in a deformable lattice as a medium for quantum computation. This progress has allowed a new hire in this area.
- *Electron and Optical Physics Division:* This division participated in two projects. The SURF III upgrade and EUV activities benefited from $475,000 in funding; the results have been quite positive. The quantum telecommunications project received $100,000, which have been very useful for the development of this laboratory.
- *Ionizing Radiation Division:* This division is using $380,000 of its funding for a new NIST initiative in biomedical imaging.
- *Quantum Physics Division:* The division received funding of $100,000 in the area of mesoscopic physics, bridging the gap between quantum and classical physics, and electronic measurement work under the umbrella of quantum information. The funding aided in the development of the pioneering field of microwave quantum optics—in particular, the noiseless amplification of microwave signals with innovative phase-sensitive amplifiers.
- *Time and Frequency Division:* The division received funding in the amount of $1,280,000 for three areas in FY 2007: (1) quantum computing; (2) optical clocks, and (3) chip-scale devices. These areas are making excellent progress.

Overall Conclusions

The Physics Laboratory of the National Institute of Standards and Technology is a unique and essential asset within an institute that is also unique and essential. The laboratory provides unduplicated services and technology to business, industry, medicine, academia, and other government agencies in areas of commerce, transportation, communication, defense, science, and research. In parallel with these responsibilities, it carries out a research program, in many instances the only such research in the United States or the world, designed to continually improve and expand its capabilities to maintain the leadership position of the laboratory, NIST, and the nation.

The overall quality and productivity of the laboratory are comparable with or better than that of other peer institutions worldwide, an accomplishment achieved in a environment that is smaller in both size and funding than most national and agency laboratories. The success of the program, its relevance, and the quality of the work are highlighted by the Nobel Prizes in physics awarded to three of its staff during the past decade, an accomplishment not duplicated by much larger and more heavily funded government laboratories or academic research institutions. Such honors should be taken as an affirmation of the importance and success of the overall standards, services, and research being performed within this laboratory and provided nationwide and worldwide, as well as an acknowledgment of the unique and relevant accomplishments of the Nobel laureates themselves. It is worth noting that the research on which the three awards were based is directly related to improvements in measurements and standards.

The Physics Laboratory performed its duties in an outstanding manner at a time when international technologies and industries are becoming more and more competitive. The international climate warrants strong support of the laboratory to rapidly and effectively address major issues with regard to staffing, infrastructure, equipment, and information technology security.