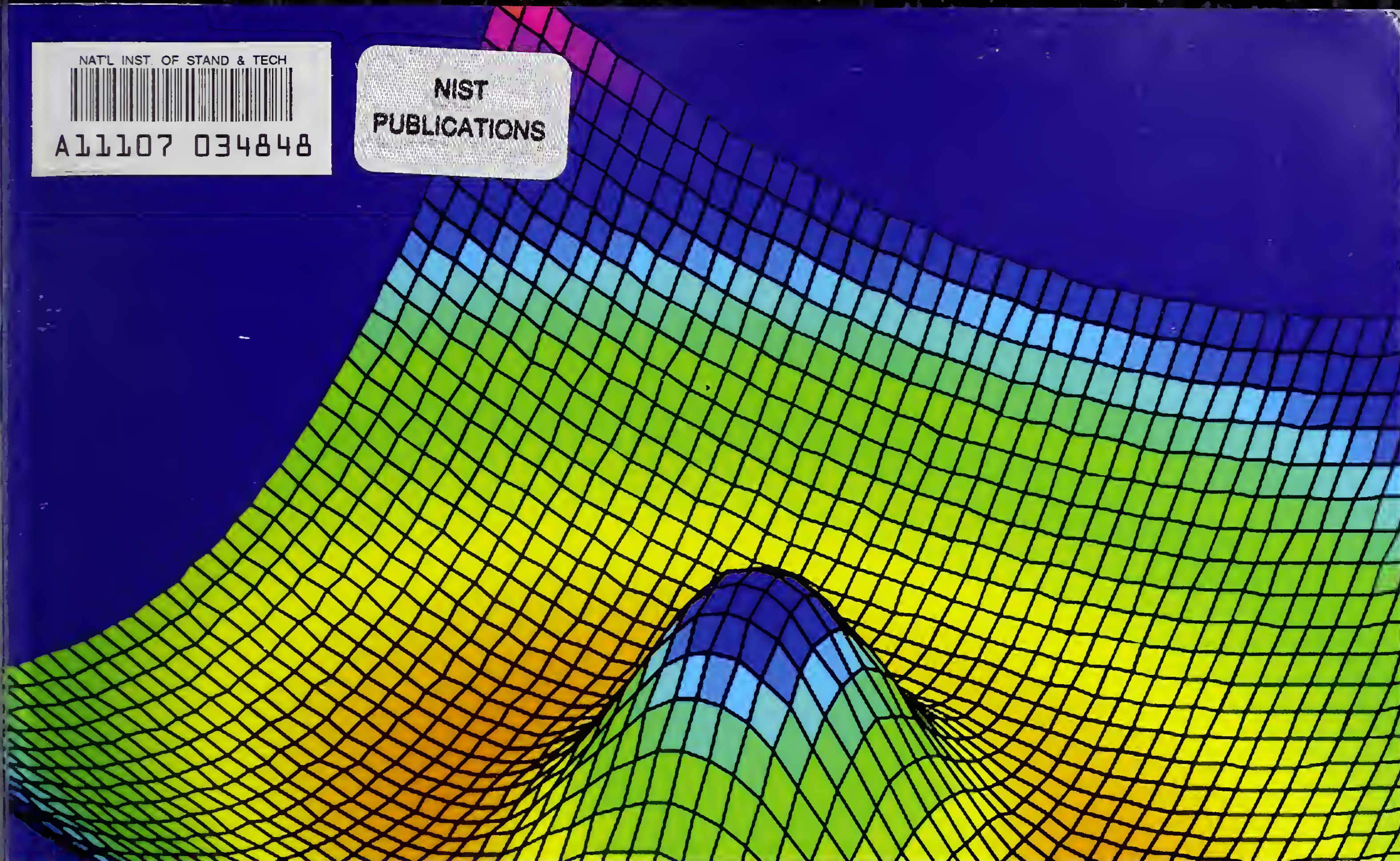

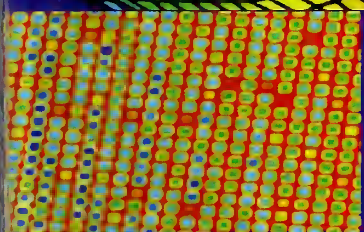

Physics Laboratory

SUPPORTING U.S. INDUSTRY, GOVERNMENT, AND THE SCIENTIFIC COMMUNITY BY PROVIDING MEASUREMENT SERVICES AND RESEARCH FOR ELECTRONIC, OPTICAL, AND RADIATION TECHNOLOGY.

PHYSICS LABORATORY AT A GLANCE

PL Vision

Preeminent performance in measurement science, technology, and services.

PL Mission

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. The Laboratory provides the foundation for metrology of optical and ionizing radiation, time and frequency, and fundamental quantum processes.

PL Divisions

Physics Laboratory is organized into six divisions that are vertically integrated, with projects ranging from basic and applied research to measurement services. Division scientists collaborate with one another, with other organizations within NIST, and with partners outside of NIST in interdisciplinary activities related to health care quality assurance, nanotechnology, homeland security, defense preparedness, information technology, and environmental and energy applications.

Electron and Optical Physics Division: to support emerging electronic, optical, and nanoscale technologies.

Atomic Physics Division: to determine atomic properties and investigate fundamental quantum interactions.

Optical Technology Division: to provide the foundation for optical radiation measurements for our Nation.

Ionizing Radiation Division: to provide the foundation of ionizing radiation measurements for our Nation.

Time and Frequency Division: to provide the foundation of frequency measurements and civil timekeeping for our Nation.

Quantum Physics Division: to make transformational advances at the frontiers of science, in partnership with the University of Colorado at JILA.

Office of Electronic Commerce in Scientific and Engineering Data: to coordinate and facilitate the electronic dissemination of information via the Internet.

PL Resources

185 full-time staff (152 scientific) with expertise in:

- Atomic, molecular, and optical physics
- Computational physics
- Condensed matter physics
- Health physics
- Medical physics
- Nuclear physics
- Biophysics
- Chemistry
- Metrology and precision measurement

$75 million annual budget

Unique facilities, including:

- Bidirectional Optical Scattering Facility
- Center for High-Accuracy Retroreflection Measurements (CHARM)
- Electron Beam Ion Trap (EBIT)
- Electron Paramagnetic Resonance Facility
- EUV Optics Fabrication and Characterization Facility
- High-Illuminance Standards and Calibration Facility
- High-Resolution UV and Optical Spectroscopy Facility
- W.M. Keck Optical Measurement Laboratory
- Low-Background Infrared Radiation Facility (LBIR)
- Magnetic Microstructure Measurement Facility
- Mammographic X-Ray Instrument Calibration Range
- Medical-Industrial Radiation Facility (MIRF)
- Neutron Imaging Facility
- Neutron Interferometer and Optics Facility (NIOF)
- Primary Optical Watt Radiometer (POWR)
- Radiation Detector Test Facility
- Radiopharmaceutical Standardization Laboratory
- Spectral Irradiance and Radiance Calibrations with Uniform Sources Facility (SIRCUS)
- Synchrotron Ultraviolet Radiation Facility (SURF III)

Standard time dissemination services:

- Radio stations WWV, WWVH, and WWVB
- Automated Computer Time Service (ACTS)
- Internet Time Service (ITS)
- Time Measurement and Analysis Service (TMAS)

Measurement and calibration services for:

- Color and color temperature
- Dosimetry of x rays, gamma rays, and charged particles
- Neutron sources and neutron dosimetry
- Optical properties of materials
- Optical wavelength
- Oscillator frequency
- Phase and amplitude noise
- Photodiode spectral responsivity
- Photometry (e.g., luminous intensity, luminous flux, illuminance)
- Radiance temperature
- Radiation detectors
- Radioactivity sources
- Spectral radiance and irradiance
- Spectral transmittance and reflectance

PL Website

http://physics.nist.gov/

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Director's Message

This report is intended to provide not only an overview of the NIST Physics Laboratory's programs, but also a sense of the range, excitement, and relevance of the measurement science pursued in the Divisions.

In keeping with the mission of NIST, the Laboratory supports industry, government, and the scientific community with measurement research and services in electronic, optical, and ionizing radiation technologies. Our great strength—and what distinguishes us from an academic or industrial laboratory—is that we are vertically integrated with a balanced portfolio of programs that span the full range from those that address the immediate needs of industry to the more fundamental research that anticipates the future needs of industry, government, and the scientific community.

The Laboratory addresses the fundamental triad of standards, measurements, and data in a climate of vigorous and competitive research. Just as the breadth, vigor, and excellence of our research programs provide credibility for our services, so the increasing demands for our services provide a strong and crucial focus for our research programs. The Physics Laboratory has ably demonstrated that mission-oriented research can be just as challenging, creative, and significant as "curiosity driven," academic research.

For example, our Time and Frequency Division's seven different T&F services are supported by major efforts in the development of optical frequency standards, chip-scale atomic clocks, and next-generation cesium fountain atomic clocks, which are in turn supported by fundamental research on trapped ions and neutral atoms. And just as our work on trapped ion clocks led to our program in quantum information, so our ability to make quantum logic gates led to the development of the quantum logic clock. Similarly, the Optical Technology Division's work on next-generation light detectors led to the creation of single pairs of photons on demand, which is now an integral part of our program on quantum information. Likewise, the Ionizing Radiation Division is developing highly sensitive neutron detectors for homeland security at the same time that it is using ultracold neutrons to investigate symmetries and parameters of the nuclear weak interaction.

Among our many responsibilities is the maintenance of the U.S. national standards for the Système International (SI) base units of time (the second), light (the candela), and noncontact thermometry (the kelvin, especially above 1200 K). We provide the basis for such SI derived units as the hertz (frequency), the becquerel (radioactivity), and the optical watt and the lumen (light output). At the same time, scientists in the Physics Laboratory work with industry to develop new measurement technologies that can be applied to such fields as communications, microelectronics, nanomagnetics, photonics, industrial radiation processing, the environment, health care, transportation, space, energy, security, and defense.

Our partners are many and our outreach extensive. JILA, our joint institute with the University of Colorado, is now in its 46th year and still gaining stature with three recent Nobel Laureates. Modeled loosely on JILA, our new Joint Quantum Institute (JQI) with the University of Maryland held its Inaugural Symposium on 27 March 2007, an event notable for its high concentration of both talent and enthusiasm. Following in the same footsteps, our nascent Joint Biophysics Institute with the University of Maryland Biotechnology Institute is even now formulating a Memorandum of Understanding. At the same time, the Physics Laboratory was honored by the former NIST Director's selection of its Electron Physics Group, led by Robert Celotta, to form the core of a new organizational unit, the Center for Nanoscale Science and Technology.

The Laboratory places great importance on determining, and focusing on, its highest priority programs. For optical radiation measurements, we rely heavily on the Council for Optical Radiation Measurements (CORM), formed to help define pressing problems and projected national needs in radiometry and photometry. Its aim is to establish a consensus on industrial and academic requirements for physical standards, calibration services, and interlaboratory collaborative programs in the fields of ultraviolet, visible, and infrared measurements. Similarly, the Council on Ionizing Radiation Measurements and Standards (CIRMS) helps to advance and disseminate the physical standards needed for the safe and effective application of ionizing radiation, including x rays, gamma rays, and energetic particles such as electrons, protons, and neutrons. For time and frequency, where the constituency is less well defined, we use decadal surveys and contacts with manufacturers of WWVB clocks and GPS receivers. When we can assist in an important area of measurement or research, we form Cooperative Research and Development Agreements with industry. Laboratory scientists serve with distinction in standards-development committees and readily give of their time to assist the public.

Our talent is focused on meeting today's challenges—in biosystems and health care, quantum technologies, and nanoscale metrology, to name but a few. For health care, the Physics Laboratory conducts research on standards to enable hospitals to use nuclear medicine more effectively. We develop ways to image single biomolecules and to use terahertz radiation for measuring biomolecular processes. The Physics Laboratory is at the forefront of the nascent field of quantum information processing—computing and communications—challenging preconceived notions of computational complexity and communications security. Similarly, the Physics Laboratory has been a leading center for metrology at the nanoscale, even before "nanotechnology" gained prominence. We pioneered electron-spin microscopy, which images magnetic materials, and our unique EUV optics facility supports the electronic industry in its drive to develop advanced lithographic systems for producing ever smaller chips.

Over the years, the Physics Laboratory's contributions have been recognized by awards from industry, government, and the scientific community, including 3 Nobel Prizes, 5 members of the National Academy of Sciences, 1 MacArthur Fellow, and 47 Fellows of the American Physical Society. Some of our recent awards and honors are listed in this report.

As you browse this summary of the Physics Laboratory, we expect you will want to learn more. We invite you to visit our website, http://physics.nist.gov/, and we invite your inquiries and interest in measurement services and collaborations.

Katharine Gebbie

Electron and Optical Physics Division

GOAL

To support emerging electronic, optical, and nanoscale technologies

The strategy for meeting this goal is to improve measurement science and to develop the measurements and standards needed by emerging science and technology-intensive industries.

The first strategic focus is the development of metrology for extreme ultraviolet (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.

EXTREME ULTRAVIOLET RADIATION METROLOGY

INTENDED OUTCOME AND BACKGROUND

The intended outcomes of this program are: maintenance and continuous improvement of the national primary measurement standards for extreme ultraviolet radiation (EUV: wavelengths between 4 nm and 250 nm, i.e., from soft x rays to vacuum ultraviolet), development of techniques for fabricating and characterizing EUV optical systems, and the development of a synchrotron-based, national primary standard for source-based optical radiometry.

The Division has longstanding responsibility for the national primary radiometric standards in the EUV region of the spectrum. EUV radiation is an important tool for determining the electronic structure of materials, diagnosing plasmas, measuring dynamics of the upper atmosphere, and probing the structure and dynamics of astrophysical objects.

One of the top candidates for next-generation semiconductor manufacturing technology is an EUV micropatterning tool, since operation at this short a wavelength (13 nm vs. 193 nm for present, production ultraviolet lithography) enables diffraction-limited imaging of features with smaller critical dimensions. We are working actively with the semiconductor industry to develop new metrology and testing capabilities as needs arise in their effort to commercialize this next-generation lithography.

The Division's key tool for EUV metrology is the NIST Synchrotron Ultraviolet Radiation Facility (SURF III). SURF III, the successor to the world's first dedicated source of synchrotron radiation, is a low-energy (< 400 MeV), high beam-current (above 1 A), perfectly circular electron storage ring. Its operational characteristics are ideal for EUV metrology. It does not produce the hard x-ray radiation of higher energy sources, and it can be operated over a wide range of beam energies to match the spectral response of systems of interest. As a calculable source of radiation from the far infrared through EUV spectral regions, SURF is also used as a primary standard for source-based radiometry throughout the optical spectrum.

ACCOMPLISHMENTS

Calibration of the EUV Variability Experiment for NASA's Solar Dynamics Observatory Mission

The SURF III facility has calibrated every extreme ultraviolet (EUV) spectrometer flown on NASA missions since the 1970s. In 2008, the first mission of NASA's Living With a Star program is scheduled for launch: the Solar Dynamics Observatory (SDO). The SDO mission will provide measurements and models of the solar radiation and dynamics that can disturb Earth's space weather environment.

Figure 1. The EVE package in the course of a SURF III calibration run. Here it is being loaded into a large vacuum chamber on SURF III beamline 2, which is enclosed in a clean room environment.

SDO contains three instrument packages, one of which is the EUV Variability Experiment (EVE), built by the Laboratory for Atmospheric and Space Physics (LASP) of the University of Colorado. EVE measures solar EUV irradiance with unprecedented spectral resolution, temporal cadence, accuracy, and precision. The EVE investigation program incorporates physics-based models of the solar EUV irradiance to advance the understanding of the solar EUV irradiance variations based on the activity of the solar magnetic features. Such variations have been found to have major effects on satellite drag and radio propagation in the ionosphere, due to the complete absorption of EUV radiation in the earth's upper atmosphere.

The EVE package was calibrated at SURF III before its transfer to NASA for incorporation into SDO. Such calibration is essential for integrating EVE results into the historical record of solar EUV variability, and SURF III is presently the only facility in the world that can provide this service.

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Electron Emission Properties of Graphene and Carbon Nanotube Devices

Carbon nanotubes and nanosheets (graphene) are promising candidates for low-field, cold-electron emission devices, such as efficient electron sources and displays. Low threshold fields are required to initiate electron emission in these systems, on the order of 1 mV/nm to 10 mV/nm.

This field strength is roughly the same as that used in photoemission electron microscopy, so we investigated the field-emission and photoemission properties of carbon nanotubes and nanosheets, with emphasis on the threshold field and the uniformity of emission. Typical nonimaging characterization focuses on the total emitted current. However, to optimize device performance, the entire emitter structure must be active.

This motivated our spatially resolved photoelectron emission microscopy (PEEM) studies of prototype devices produced by Prof. Brian Holloway at the College of William and Mary. These studies were carried out in collaboration with Prof. Martin Kordesch of Ohio University, while he was on sabbatical leave at NIST. Devices prepared for photoelectron emission imaging and field emission microscopy were observed in both imaging modes with submicron spatial resolution.

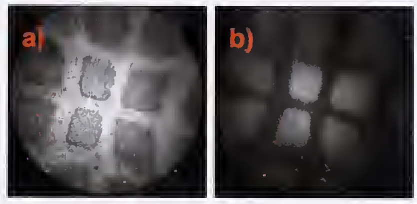

Figure 2. (a) PEEM and (b) field-emission micrographs of a carbon nanotube electron emission device.

It was found that low-current emission was uniform and correlated with the photoelectron (PEEM) image. Hot spots were observed on some specimens that could be imaged simultaneously in PEEM and field emission microscopy. Metallized graphene sheets were found to be very good emitters, and the nature of their emission enhancement is currently under study.

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Record Beam Currents, Autonomous Operation, and Royal Visit at SURF III

In late 2006, it became possible for the first time to inject currents in excess of an ampere into the SURF III electron storage ring. When SURF II first came on line in the mid-1970s, its maximum injection currents were 10 mA. These were increased to about 300 mA by the time of the conversion to SURF III in 1997, but the maximum currents then could not be generated reproducibly. A wide range of improvements in the injection and RF control systems, carried out over the past five years, have led to deterministic injection conditions, which generate initial currents that are as large as those used in any other synchrotron radiation source.

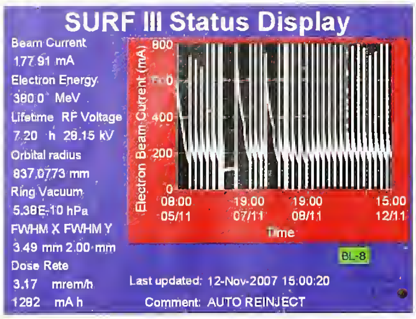

Figure 3. SURF III beam current as a function of time, showing re-injections during the night in the autonomous mode of operation.

Furthermore, in 2007 we were able to institute regular autonomous operation of the facility, whereby it automatically re-injects itself when the beam current decays to a predetermined target level. (Such decay occurs due to electrons being lost from the beam due to collisions.) This allows for round-the-clock operation, which has been necessary to accommodate growing user demand, particularly that associated with lifetime testing of EUV optical components, which is discussed below.

Figure 4. HRH Princess Sumaya of Jordan receives a certificate of proficiency in synchrotron facility operation from Dr. Katharine Gebbie.

The synchrotron radiation research community is tight-knit, and members of the SURF III staff frequently interact with their counterparts at other synchrotron facilities worldwide. In May 2007 an unusual engagement of this type occurred in the form of a visit by a royal personage, HRH Princess Sumaya of Jordan. The Princess is the head of the Royal Scientific Society of Jordan, which contains the Jordanian counterpart of NIST, and is also the sponsoring organization of a synchrotron radiation facility, SESAME, which is under construction there. During her tour of SURF III, Princess Sumaya was offered the opportunity to inject a beam, and carried out the procedure quite successfully.

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Predicting the Lifetime of Extreme Ultraviolet Optics

To help the semiconductor industry meet its goal of achieving extreme-ultraviolet lithography (EUVL) production by 2010, we have established a dedicated beamline at SURF III for durability testing of multilayer mirrors, an essential underlying technology. The new beamline is devoted to accelerated testing, and we have added a second branch to a preexisting beamline to provide broadband illumination (wavelengths of approximately 11 nm to 50 nm) onto a single spot at approximately 100 times the intensity attainable before.

To determine how damage scales with various parameters, we recently exposed EUVL mirrors (provided by SEMATECH from work it co-funded) to varying levels of light intensity, water, and hydrocarbon concentrations. Contrary to expectations, we found that increasing amounts of water vapor caused less mirror damage, which may be due to a simultaneous increase in the ambient hydrocarbon levels. Subsequent experiments have shown that deliberately introducing trace amounts of a simple hydrocarbon like methanol can mitigate significantly the water-induced damage.

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Nanoscale Chemical Imaging with Electron Beam Tomography

Tomography became an important field about 40 years ago with the application of x rays to medical imaging. The practice quickly spread to electron microscopy. The principal contrast mechanism in x-ray scattering is absorption which follows Beer's Law, i.e., the rule of exponential attenuation. Although it was necessary to develop radically different algorithms for tomography using magnetic resonance imaging or ultrasound, the electron microscopy community imported the assumption of a probe traveling in a straight line through a sample with exponential attenuation.

This assumption is valid for thin samples, but for thick samples multiple electron scattering renders it invalid. Our theoretical analysis found that near the onset of multiple scattering (as the sample thickness under consideration increases), there is a regime in which the projective assumption remained valid, but the transmission as a function of thickness deviated significantly from Beer's Law. Extensive numerical simulations confirmed this, attaining excellent reconstructions of an 8 μm square sample of a photonic band gap material using the multiple scattering transmission function.

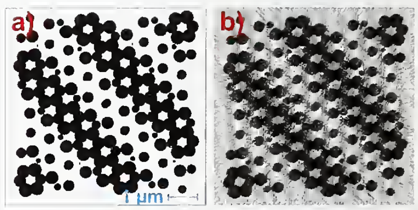

Figure 5. (a) A synthetic photonic band gap structure, and (b) its reconstruction using Bayesian tomography in the multiple scattering regime.

We used a Bayesian approach known as the generalized Gaussian Markov random field, and extended it to treat systems with multiple scattering. The principal features of this formalism are a prior distribution based on correlations of neighboring pixels (or voxels in 3D) in which the smoothness of the reconstruction may be adapted to the sample, and a quadratic approximation to the log of the likelihood derived from Poisson statistics. In its original formulation, Beer's Law was also assumed. We made a more general assumption: that the transmission is any known function, with sufficient differentiability, of a linear combination of the material parameters of the sample. This has enabled us to get highly satisfactory reconstructions of three-dimensional materials structure from limited angular sampling data.

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The second strategic focus is metrology for coherent matter-wave and quantum information processing devices.

COHERENT MATTER-WAVE AND QUANTUM INFORMATION PROCESSING METROLOGY

INTENDED OUTCOME AND BACKGROUND

This program provides measurements and data to enable the development of ultracold atom technology, in particular the use of coherent matter waves in sensors, atom interferometers, and quantum information processing devices.

The Division maintains two efforts in this area, one theoretical and two experimental. The theoretical program is focused on quantitative modeling of degenerate quantum gases, with particular attention to the dynamics of Bose-Einstein condensates subject to external forces, e.g., manipulation of condensates confined in an optical lattice. This program is an outgrowth of extensive collaborations with experimental groups at NIST, JILA, and elsewhere, begun in the mid-1990s.

The experimental programs are concerned with the application of light storage in and retrieval from atomic systems as a technique for quantum information processing, and the development of high-speed quantum cryptography.

ACCOMPLISHMENTS

Quantum Key Distribution System Operating at a Sifted-Key Rate Over 4 Mbit/s

We have collaborated with NIST's Advanced Network Technologies Division in developing a complete fiber-based, polarization-encoded quantum key distribution (QKD) system based on the Bennett-Brassard protocol (BB84). The system operates at a clock rate of 1.25 GHz, and is capable of producing key bits from quantum-channel transmissions (sifted key) at rates above 4 Mbit/s over 1 km of optical fiber. This output can be processed to produce unconditionally secure cryptographic key for encrypting messages.

Our results represent a new record in the operational output rate of a QKD system based on single-photon transmission. They are made possible by the integration of quantum cryptography protocols with classical high-speed telecommunications techniques. The quantum channel uses 850 nm photons from attenuated high-speed vertical cavity surface-emitting lasers (VCSELs), and the classical channel uses 1550 nm light from normal commercial coarse wavelength division multiplexing devices. A polarization auto-compensation module has been developed and utilized to recover the polarization state and to compensate for temporal drift. An automatic timing alignment device has also been developed to quickly handle the initial configuration of quantum channels so that detection events fall into the correct timing window. These automated functions make the system more practical for integration into existing optical local area networks.

We are developing a free-space optical QKD system operating at the Balmer alpha wavelength of 656 nm, where light from the sun is attenuated by 7 dB in a narrow interval, which is advantageous for daylight operation of free-space QKD systems. We are also developing semiconductor optical waveguides as a source of correlated photon pairs, in collaboration with the Laboratory for Physical Sciences of the University of Maryland.

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'March Madness' Effects Observed in Ultracold Gases

We have discovered new quantum phases in ultracold gases that reveal the competition between two major mechanisms of electrical resistance in solids: crystalline disorder, and the interactions between electrons. In "March Madness" terms, basketball fans who arrive early to an empty stadium can move relatively quickly down any row unless they encounter a railing, wall, or other barrier (analogous to crystal disorder). But once the game begins, a fan's movements are constrained along rows by other fans already occupying seats (analogous to electron blocking). Even though

Phillip Anderson and Sir Neville Mott won Nobel Prizes in 1977 for the theory of these phenomena in metals, it has been difficult to observe their effects in real materials.

Quantum phases of hard-core bosons confined in a one-dimensional quasiperiodic potential were studied within the theoretical framework of intensity interferometry (Hanbury Brown-Twiss interferometry). The quasiperiodic potential induces a cascade of Mott-like band-insulator phases, in addition to the more familiar Mott insulator, Bose glass, and superfluid phases. The new phases are incompressible and have zero superfluid fraction. At critical filling factors, the appearance of these insulating phases is heralded by a peak to dip transition in the interferogram, which reflects the fermionic aspect of hard core bosons. In the localized phase, the interference pattern exhibits a hierarchy of peaks at the reciprocal lattice vectors of the system. Our study demonstrates that, in contrast to measurements of the momentum distribution, intensity interferometry provides an effective method to distinguish Mott and glassy phases.

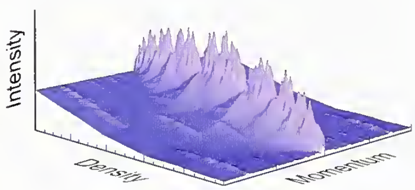

Figure 6. Representation of the interference of wave patterns created by atoms that have been released from an optical lattice with disorder. The complex shape of peaks and valleys is an example of a natural fractal pattern, a pattern that continues to reveal new details no matter how many times it is magnified.

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The third strategic focus is to develop techniques for fabricating nanostructures and measuring their electronic and magnetic properties.

NANOSCALE ELECTRONICS AND MAGNETICS

INTENDED OUTCOME AND BACKGROUND

The intended outcome of this work is the continuous improvement of methods for fabricating and characterizing nanometer-scale electronic and magnetic structures, as required to meet current and future needs of the semiconductor and data storage industries.

Our main tools for pursuing this program are scanning electron microscopy with polarization analysis (SEMPA) and the scanning tunneling microscope (STM). The Electron Physics Group in the Division has been a leading innovator in both of these methods, which are outgrowths of work begun at NIST in the 1970s. SEMPA enables us to use conventional scanning electron microscopy (SEM) to image nanometer-scale magnetic structure, through spin-polarization analysis of secondary electrons ejected from the sample. It has several unique capabilities that distinguish it from other magnetic imaging techniques: it is a highly sensitive, nonperturbative method, and thus is especially well suited for *in situ* studies of surface and nanostructure magnetization; it provides a direct measurement of the magnetization of a material region, rather than of a magnetic field; it has the high spatial resolution (about 10 nm), long working distance, and large depth-of-field characteristic of SEM; and it facilitates simultaneous measurements of the magnetization and the topography. SEMPA studies have led to a number of breakthroughs in understanding the basic mechanisms of magnetism on the micro- and nanoscale, and have also addressed near-term measurement issues faced by the magnetic data storage industry.

Our STM program is focused on understanding the electronic and magnetic properties of nanostructures on surfaces. In recent years the STM program has been particularly concerned with the magnetic multilayer materials that have been investigated by SEMPA. The complementarities of SEMPA and STM measurements have elucidated many connections between conditions of layer growth and magnetic device performance.

The main, current direction of the STM program is the course of research made possible by the recently completed Nanoscale Physics Laboratory. This laboratory permits us to measure quantum electronic structures with atomic-scale imaging resolution and high electron-energy resolution. Samples grown *in situ* can be measured in an ultra-high vacuum environment with magnetic fields of up to 10 T at temperatures down to 2.3 K. Additionally, a program in Autonomous Atom Assembly is underway that allows us to fabricate highly complex and perfect nanostructures on demand.

The work reported below was performed by the Electron Physics Group. In 2006, the NIST Director selected the Electron Physics Group to serve as the nucleus for a new NIST Center for Nanoscale Science and Technology (CNST), which would have primary responsibility for activities associated with the new nanofabrication facility in the NIST Advanced Measurement Laboratory complex. In May 2007, CNST was formally established as a NIST operating unit, at the same level as the Physics Laboratory and separate from it. We are proud to see the Electron Physics Group's fine work recognized at this level. Subsequent reports on their activities will be issued by CNST.

ACCOMPLISHMENTS

Changing the Rings: A Key Finding for Magnetics Design

We have made the first theoretical determination of the dominant damping mechanism that settles down excited magnetic states—"ringing" in physics parlance—in some key metals. These results point to more efficient methods to predict the dynamics of magnetic materials and to improve the design of key materials for magnetic devices.

The ability to control the dynamics of magnetic materials is critical to high-performance electronic devices such as magnetic field sensors and magnetic recording media. In a computer's magnetic storage—like a hard disk—a logical bit is represented by a group of atoms whose electron "spins" all are oriented in a particular direction, creating a minute magnetic field. To change the bit from, say, a one to a zero, the drive's write head imposes a field in a different direction at that point, causing the electrons to become magnetically excited. Their magnetic poles begin precessing—the same motion seen in a child's spinning top when it's tilted to one side and begins rotating around a vertical axis. Damping is what siphons off this energy, allowing the electron spins to settle into a new orientation. For fast write speeds—magnetization reversals in a nanosecond or faster—a hard disk wants strong damping.

On the other hand, damping is associated with noise and loss of signal in the same drive's read heads—and other magnetic field sensors—so they need materials with very weak damping. The design of improved magnetic devices, particularly at the nanoscale, requires a palette of materials with tailored damping rates, but unfortunately the damping mechanism is not well understood. Important damping mechanisms have not been identified, particularly for the so-called intrinsic damping seen in pure ferromagnetic materials, and no quantitative calculations of the damping rate have been done. So, the search for improved materials must be largely by trial and error.

To address this, we calculated the expected damping parameters for three commonly used ferromagnetic elements, iron, cobalt, and nickel, based on proposed models that link precession damping in a complex fashion with the creation of electron-hole pairs in the metal that ultimately dissipate the magnetic excitation energy as vibration energy in the crystal structure. The calculation is extremely complex, both because of the intrinsic difficulty of accounting for the mutual interactions of large numbers of electrons in a solid, and because the phenomenon is inherently complex, with at least two different and competing mechanisms. Damping rises with temperature in all three metals, for example, but in cobalt and nickel it also rises with decreasing temperature at low temperatures.

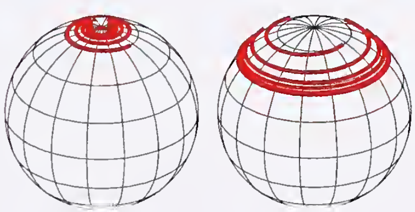

Figure 7. Damped precessional motion of the magnetization represented on the surface of a sphere. The red curve shows the direction of the magnetization precessing around its equilibrium direction. On the left, the amplitude of the precession steadily decreases due to the presence of magnetic damping. On the right, a steady state precession amplitude is reached due to the presence of an alternating applied magnetic field balancing the damping.

By comparing the calculated damping effects with experimental measurements, we were able to identify the dominant mechanisms behind intrinsic damping in the three metals, which at room temperature and above is tied to electron energy transitions. The results point to materials design techniques that could be used to optimize damping in new magnetic alloys.

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Speed Bumps Less Important Than Potholes for Graphene

For electrical charges racing through an atom-thick sheet of graphene, occasional hills and valleys are no big deal, but the potholes—single-atom defects in the crystal—are killers. This conclusion comes from detailed maps of electron interference patterns in graphene that show how defects in the two-dimensional carbon crystal affect charge flow through the material. The results have implications for the design of graphene-based nanoelectronics.

A single layer of carbon atoms tightly arranged in a honeycomb pattern, graphene was long thought to be an interesting theoretical concept that was impossible in practice—it would be too unstable, and crumple into some other configuration. The discovery, in 2004, that graphene actually could exist touched off a rush of experimentation to explore its properties.

Graphene has been described as a carbon nanotube unrolled, and shares some of the unique properties of nanotubes. In particular, it's a so-called ballistic conductor, meaning that electrons flow through it at high speed, like photons through a vacuum, with virtually no collisions with the atoms in the crystal.

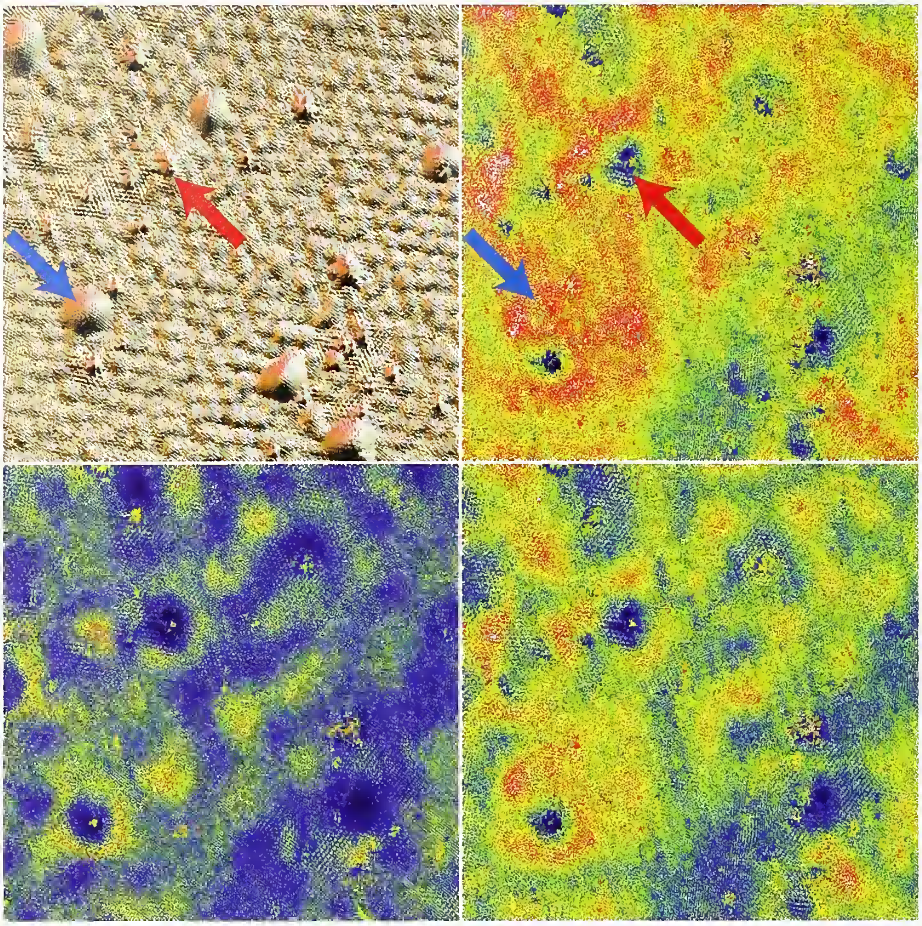

Figure 8. Comparison of an STM topographic image of a section of graphene sheet (top left) with spectroscopy images of electron interference at three different energies. Strong interference patterns are generated by atomic scale defects in the graphene crystal (red arrows) but only modest disturbances are caused by larger scale bumps in the sheet (blue arrows.) Analysis of the ripples shows that the electron energy in graphene is inversely proportional to its wavelength, just like light waves. The area imaged is approximately 40 nm square.

This makes it a potentially outstanding conductor for wires and other elements in nanoscale electronics. Defects or irregularities in the graphene crystal, however, can cause the electrons to bounce back or scatter, the equivalent of electrical resistance. So one key issue is just what sort of defects cause scattering, and by how much?

To answer this, we grew layers of graphene on wafers of silicon carbide crystals and mapped the sheets with a custom-built scanning tunneling microscope (STM) that can measure both physical surface features and the interference patterns caused by electrons scattering in the crystal. (Graphene on silicon carbide is a leading candidate for graphene-based nanoelectronics.)

The results are counter-intuitive. Irregularities in the underlying silicon carbide cause bumps and dips in the graphene sheet that lies over it rather like a blanket on a lumpy bed, but these relatively large bumps have only a minor effect on the electron's passage. In contrast, missing carbon atoms in the crystal lattice cause strong scattering, the interference patterns rippling around them like waves hitting the piles of a pier. From a detailed analysis of these interference patterns, the team verified that electrons in the graphene sheet behave like photons, even at the nanometer scale.

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'Atomic Switch' Experiments Expand Nanoscale Toolkit

We have used a beam of electrons to move a single atom in a small molecule back and forth between two positions on a crystal surface, a significant step toward learning how to build an "atomic switch" that turns electrical signals on and off in nanoscale devices.

A custom-built, cryogenic scanning tunneling microscope (STM) was used to perform several different types of atomic scale measurements and manipulations. A molecular chain of one cobalt atom and several copper atoms was constructed, atom by atom, on a surface of copper atoms using the STM to move the atoms. Then the STM was used to shoot electrons at the molecular chain, and its effect on the switching motion of the cobalt atom was measured. Theoretical calculations of the atoms' electronic structure confirmed the experimental results.

We used a new technique called "tunneling noise spectroscopy"—based on our 2004 discovery that an atom emits a characteristic scratching sound when an STM is used to move the atom—to determine how long the atom stays in one place. We found that a single electron boosts the molecule above a critical energy level, allowing a key bond to break so the cobalt atom can switch positions. The cobalt atom was less likely to switch as the molecular chain was extended in length from two to five copper atoms, demonstrating that the atom switching dynamics can be tuned through changes in the molecular architecture.

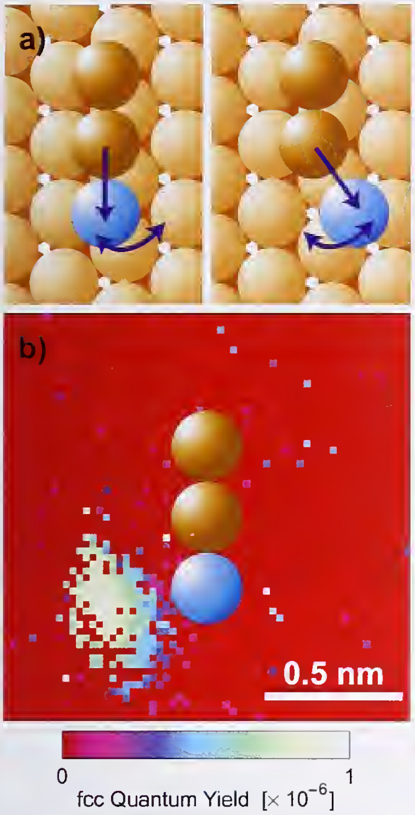

Figure 9. (a) An STM moves a single cobalt atom (blue sphere) in a small molecule back and forth between two positions on a crystal surface. (b) Switching is most likely when the STM tip is positioned to the left of the cobalt atom (blue and white speckled area).

We also found that the position of the STM tip is critical—switching is most likely when the STM tip is positioned to the left of the cobalt atom. This insight raises the possibility that molecular orbital analysis may be used to guide the design and control of single atom manipulation in nanostructures.

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Laser Trapping of Erbium May Lead to Novel Devices

We have used lasers to cool and trap erbium atoms, a "rare earth" heavy metal with unusual optical, electronic, and magnetic properties. The element has such a complex energy structure that it was previously considered too wild to trap. This demonstration might lead to the development of novel nanoscale devices for telecommunications, quantum computing, or fine-tuning the properties of semiconductors.

Laser cooling and trapping involves hitting atoms with laser beams of just the right color and configuration to cause the atoms to absorb and emit light in a way that leads to controlled loss of momentum and heat, ultimately producing a stable, nearly motionless state. Until now, the process has been possible only with atoms that switch easily between two energy levels without any possible stops in between. Erbium has over 110 energy levels between the two used in laser cooling, and thus has many ways to get "lost" in the process. We discovered that these lost atoms actually get recycled, so trapping is possible after all.

Erbium atoms were produced by an oven at 1300 °C. Magnetic fields and six counter-propagating purple laser beams were then used to cool and trap over a million atoms in a space about 100 μm in diameter. As the atoms spend time in the trap, they fall into one or more of the 110 energy levels, stop responding to the lasers, and begin to diffuse out of the trap. Recycling occurs, though, because the atoms are sufficiently magnetic to be held in the vicinity by the trap's magnetic field. Eventually, many of the lurking atoms fall back to the lowest energy level that resonates with the laser light and are recaptured in the trap.

Figure 10. A purple laser beam slows erbium atoms (the purple beam traveling right to left) emerging from an oven at 1300 °C, in preparation for trapping and cooling.

The erbium atoms can be trapped at a density that is high enough to be a good starting point for making a Bose-Einstein condensate, an unusual, very uniform state of matter used in NIST research on quantum computing. Cold trapped erbium also might be useful for producing single photons at wavelengths used in telecommunications. In addition, trapped erbium atoms might be used for "doping" semiconductors with small amounts of impurities to tailor their properties. Erbium—which, like other rare earth metals, retains its unique optical characteristics even when mixed with other materials—is already used in lasers, amplifiers, and glazes for glasses and ceramics. Erbium salts, for example, emit pastel pink light.

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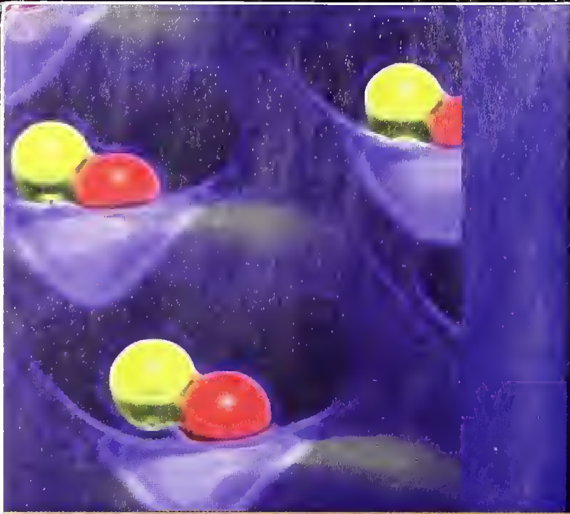

Atomic Physics Division

GOAL
To determine atomic properties and investigate fundamental quantum interactions

The strategy of the Atomic Physics Division is to develop and apply atomic physics research methods, including 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.

The first strategic element is to advance the physics of electromagnetic-matter interactions, to explore new applications for laser cooled and trapped atoms, to study exotic states of matter, and to study and control many-body quantum systems.

LIGHT-MATTER INTERACTIONS AND ATOM OPTICS

INTENDED OUTCOME AND BACKGROUND

This strategic element focuses on the physics and applications of laser cooling and electromagnetic trapping of neutral particles, the manipulation of Bose-Einstein condensates (BECs), and the use of optical dipole forces as a new tool for analyzing microscopic objects in biochemistry. It includes both fundamental studies, like the investigation of superfluidity and applied studies, such as quantum information processing and measurement techniques for biomolecular systems. A strong theoretical-experimental collaboration is aimed at interpreting experimental results and providing guidance for new experiments.

The development of laser cooling and trapping techniques, much of which was done at NIST, allows exquisite control over the motion of atoms. Such control has been exploited to build more precise atomic clocks and other precision measurement devices at NIST and elsewhere. These techniques also enable the study and manipulation of atoms and molecules under conditions in which their quantum or wave behavior dominates. This research has revolutionized the field of matter-wave optics.

Theoretically and experimentally, our programs aims to understand and exploit: Bose-Einstein condensation of neutral atoms; matter-wave optics; optical and magnetic control of trapped, ultracold atom collisions; advanced laser cooling and collision studies for atomic clocks; the quantum behavior of atoms in optical lattices, including studies in one-, two-, and three-dimensional systems, and simulation of condensed matter models with cold atoms; quantum information processing; quantum computing architectures; and optical characterization and manipulation of single molecules, biomolecules, and biomembranes.

The Atomic Physics Division is at the center of the newly established Joint Quantum Institute between the NIST Physics Laboratory, the Physics Department of the University of Maryland, and the Laboratory of Physical Sciences of the National Security Agency. The Chief of the Atomic Physics Division also coordinates NIST's program in quantum information science, which includes activities in the Physics Laboratory, the Electronic and Electrical Engineering Laboratory, and the Information Technology Laboratory.

ACCOMPLISHMENTS

Quantum SWAP Operation with Neutral Atoms as Qubits

Two outstanding problems in neutral atom quantum computing have been the ability to address atoms in an optical lattice and the demonstration of controlled two-atom interactions. We have used a novel, two-period lattice to demonstrate both processes.

In one experiment, published in *Physical Review Letters*, we used the state-dependent, two-period "double well" lattice to selectively address the spins (acting as qubits) in only one of the sublattices, despite the wells being only 400 nm from each other. In another experiment, published in *Nature*, we used the double well to isolate and control pairs of atoms, forcing them to interact in a state-dependent manner (making use of quantum exchange symmetry) that gives rise to the entanglement needed for quantum computing. These experiments were both the first of their kind, and represent a significant step forward for neutral atom quantum computing.

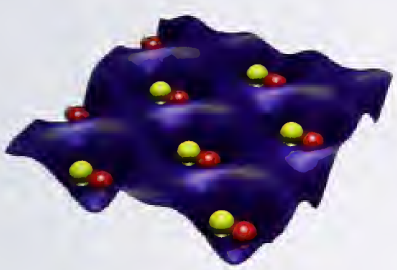

Figure 1. Artist's conception of pairs of opposite-spin atoms (qubits) brought together in an optical lattice to be entangled by their atom-atom interactions.

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Control of Cold Quantum Gases

Many recent atomic physics experiments have used magnetic-field control of scattering resonances to modify the properties and dynamics of ultracold, atomic quantum gases such as Bose-Einstein condensates or mixtures of fermions. These resonances occur when the energy of a bound state of two atoms is tuned to the same energy as that of two separated cold atoms. Such resonances can be used to make cold molecules and molecular Bose-Einstein condensates, to strongly modify the nature of superfluid atom pairing, and to modify the properties of atoms trapped in optical lattices. Such phenomena are relevant to fundamental physics, condensed matter (solid state) physics, atomic clocks, and quantum information.

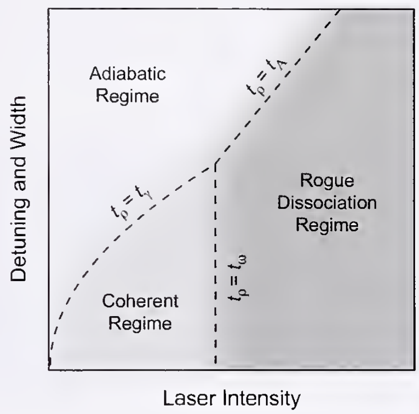

Figure 2. The different regimes for cold-collision photoassociation. Here t_ρ is the time scale on which the overall density of the gas evolves when the light is turned on, t_ω is the time scale for coherent oscillations between atomic and molecular populations, t_A is time scale over which the transient response to the turning on of the light is completed, and t_γ is the time scale for spontaneous emission of light by the excited molecules.

We have quantitatively characterized such resonances for a number of ultracold gases and developed simple physical models for understanding them. Recent work has characterized optically induced scattering resonances for laser control of quantum gases of alkaline earth species such as Sr or Yb, which are of great interest for next-generation atomic clocks. One specific application has been to the temporal dynamics of an atomic Bose-Einstein condensate when pairs of atoms are converted into molecules by photoassociation. We identify three main photoassociation regimes that can be understood on the basis of time-dependent two-body theory. In particular, the so-called rogue dissociation regime, which has a density-dependent limit on the photoassociation rate, is identified with a transient regime of the two-atom dynamics. We have determined how the various regimes could be explored by photoassociating condensates of alkaline-earth atoms.

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Coherent Optical Generation of Vortices in a Bose-Einstein Condensate

Vortices (micrometer-size whirlpools) in a quantum superfluid carry angular momentum, quantized in units of $\hbar$. The first vortices in Bose-Einstein condensates (BECs) were created at NIST-Boulder, and they are now routinely made by mechanically stirring the atomic gas.

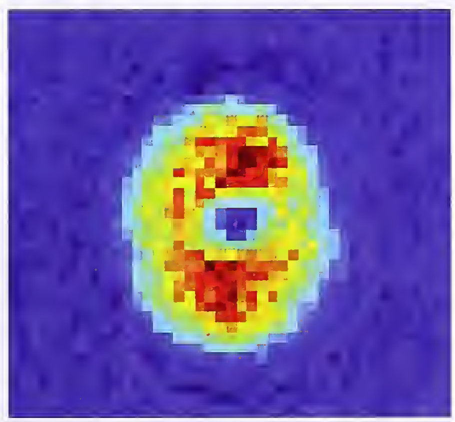

Figure 3. Absorption image of a Na BEC vortex state, taken along the axis of the LG beam, generated by transferring $\hbar$ of optical orbital angular momentum to each BEC atom.

We have developed a new, well-controlled, coherent method of vortex creation. Light can carry both "spin" angular momentum, associated with its polarization and "orbital" angular momentum (OAM) associated with its stial mode. In particular, Laguerre-Gauss (LG, donut) modes of laser beams carry OAM per photon quantized in units of $\hbar$.

In work published in *Physical Review Letters* we used a two-photon Raman process to induce BEC atoms to coherently absorb the OAM of an LG beam, creating a vortex. We verified the coherence of the process by creating and interfering superpositions of different vortex states, showing that the relative phase between the states is determined by the relative phase of the optical fields. We also created vortices of higher angular momentum by transferring to each atom the orbital angular momentum of two photons.

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A Quantum Phase Transition with Cold Atoms

The Mott insulator is a remarkable phase of matter, where the interactions between atoms in an optical lattice lead to a state with an exact number of atoms per lattice site (e.g., one). This state is central to our quantum information program where the Mott state is the initial state. Any deviation from one atom per site will decrease the fidelity of subsequent quantum gates.

To extend our understanding of Mott-insulator physics we recently undertook a detailed study of the insulating phase in a 2-D system. (A 1-D optical lattice divides the system into an array of 2-D subsystems, and a second 2-D lattice provides a corrugated potential in each subsystem.) This work, published in *Physical Review Letters*, focused on the momentum distribution of the atoms, finding that in the insulating phase the distribution agreed *quantitatively* with theory. In addition, we probed the size of the insulating region by measuring correlations in the noise of atom cloud images.

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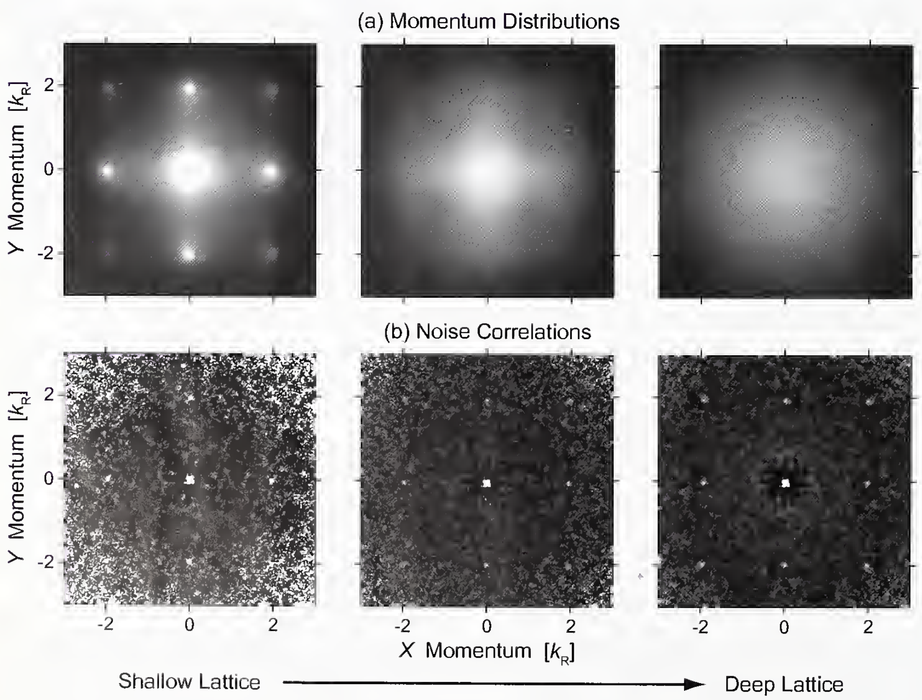

Figure 4. Momentum (a) and noise correlations (b) in a 2-D Mott insulating system, in units of single-photon recoil momentum.

Relative-Intensity-Squeezed Light for Measurement and Quantum Applications

We have discovered a nonlinear optical scheme (nondegenerate four-wave mixing) that robustly generates strongly squeezed light in a simple Rb vapor cell. This technique represents an important advance over the best previous atomic vapor results (-2.2 dB for vacuum quadrature squeezing), and presents new opportunities both in purely optical experiments (e.g., quantum optics, interferometry for precision measurements) and in light-atom interactions (e.g., quantum atom optics, and precision spectroscopy).

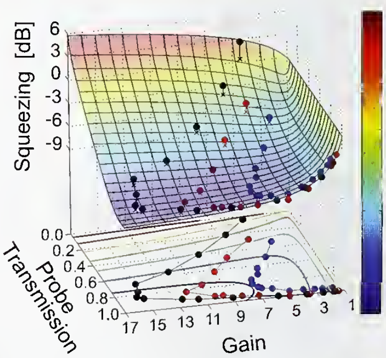

Figure 5. Squeezing versus transmission and gain. The solid spheres show the squeezing measured at 1 MHz, for different cell temperatures, 109 °C (blue), 112 °C (red), and 114 °C (black), as the detuning of the pump laser is scanned. The projection onto the *x-y* plane shows contour lines of the theoretical squeezing at 2 dB intervals from +4 to −8 dB, and the projections of the data points.

We create two light beams whose intensity difference is squeezed by -8 dB (noise ≈ 15 % of the usual shot noise). We have demonstrated low (detection) frequency squeezing down to below 5 kHz, a remarkable feat considering that OPO technology took about 15 years to demonstrate this. The light is narrowband and nearly resonant with the Rb atomic transition.

This light should be particularly useful in "quantum atom optics" experiments where we will interact nonclassical light with atoms to produce nonclassical matter-wave beams. We also foresee applications to atomic "quantum memory" applications for quantum information processing.

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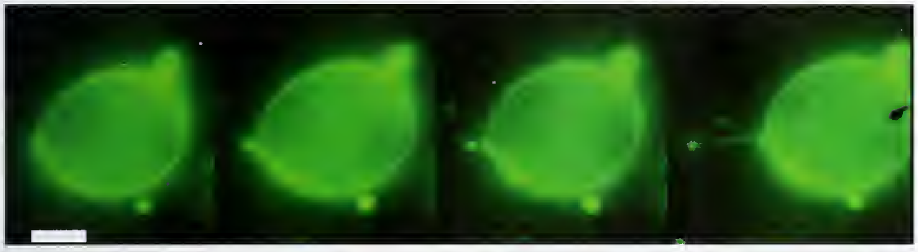

Figure 6. From left to right, an optical tweezer pulls a nanotube from the left side of a polymersome at ~10 μm/s. The white scale bar at left indicates 10 μm.

Optically Directed Formation of Robust Polymer Nanotubes

Nanotubes, like the carbon tubes used in high-strength materials, are among the most promising structures in nanotechnology. Naturally occurring phospholipid and protein nanotubes can transport genetic material between cells, viruses, and bacteria. Transport of biological molecules through nanotubes is a particularly exciting prospect for biotechnology applications.

We have created robust, biocompatible nanotubes by directed self-assembly. Starting with a polymer vesicle (polymersome) having a hydrophilic/hydrophobic bilayer membrane, we use optical tweezers (a focused laser beam that grabs dielectric material) to pull on the membrane. Polymer molecules in the distorted membrane rearrange to form long polymer nanotubes, which we stabilize by chemical cross-linking.

The nanotubes have a water-filled core approximately 80 nm in diameter and are up to 1 cm long. Optical tweezers manipulation creates networks of nanotubes and vesicles, systems that hold promise for nanofluidics and other biotech applications. The results were published in the *Proceedings of the National Academy of Sciences.*

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The second strategic element is to advance measurement science at the atomic and nanometer scale, focusing on precision optical metrology, the quantum optics of nanoscale systems, quantum devices, nanoscale plasmas, and nanooptical systems.

NANOSCALE AND QUANTUM METROLOGY

INTENDED OUTCOME AND BACKGROUND

This 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 with nanoscale features induced on surfaces by highly charged ions. Such systems arise in advanced 193 nm and 157 nm lithography, plasma etching of semiconductor wafers, nanolasers, detectors, biomarkers and sensors, nanomaterials, quantum devices and quantum information, and atomic clocks.

Our research combines theory and experiment. Theory is used to extend the fundamental understanding of systems at the atomic/nanoscale interface as necessary to interpret experiment, to explore new applications in nanoscale and quantum technologies, and to motivate new and enhanced precision metrology. We are developing the theoretical understanding needed to create nanooptics structures that will be needed in emerging quantum and nanoscale technologies.

Experiment is used to develop new precision measurement tools for this regime, to collect precise data essential for the applications mentioned, and to further the understanding of these systems. We are now expanding our expertise by beginning to probe the transport, optical, and mechanical properties of nanoscale and quantum-coherent systems. We are developing the precision metrology needed to make accurate optical measurements of individual quantum nanosystems. We have made the precise measurements of the refractive index of high index fluids needed by the semiconductor industry to develop immersion lithography for sub-100 nm optical lithography.

ACCOMPLISHMENTS

Designing the Nanoworld: Nanostructures, Nanodevices, and Nanooptics

Developing and exploiting precision metrology for quantum and nanotechnology requires nanoscale modeling of ultrasmall structures, devices, their dynamical operation, and their response to probes.

Atomic-scale simulations of the electronic and optical properties of complex nanosystems at the nano/molecular interface are being carried out. These systems include nanocrystals, self-assembled dots, nanodot arrays and solids, and bio/nanohybrids. These simulations provide benchmarks for precise experimental tests of the atomic-scale sensitivity of nanosystems. The work is providing the foundation needed to build design tools for engineering nanolasers, detectors, biomarkers and sensors, quantum devices, and nanomaterials. For example, recent work has demonstrated the critical importance of strain, even in the smallest nanocrystals, for understanding the optical properties of these systems.

Nanoscale simulations of optical fields near nanosystems are also being carried out. Results are being used to design nanoprobes and nanocavities, for use in precision nanooptics metrology. Results are also being used to design and model the nanooptics highway, that is, a collection of nanoparticles used to generate, transport, and collect photons on the nanoscale, well below the diffraction limit that governs the classical transport of photons. Nanooptics highways will be critical for the quantum transport of excitations in quantum devices and in the metrology of these devices. Theory is being developed to quantify and optimize this quantum transport.

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Selectable Resistance Magnetic Tunnel Junctions by Highly Charged Ion Modification

Within a broad program to explore methods to fabricate structures with novel electronic properties at the nanometer scale, we are using highly charged ions (HCIs) to produce ensembles of nano-features within magnetic tunnel junctions (MTJs). MTJs are widely recognized as probable long-term solutions to the magnetic recording industry's need for ultrasensitive magnetic sensors for use as new hard drive "read" heads.

The leading technical challenge is producing MTJs whose resistance-area (RA) product (two dimensional resistivity) falls in a range that allows for both high signal-to-noise and large bandwidths. Contemporary approaches have focused on producing MTJ layer structures with uniform RA products, whereas our approach is to produce a layer structure that is a superposition of high and low RA product regions, whose average RA product is determined by the relative density of each region.

Our strategy is to irradiate high quality oxides with very dilute doses of HCIs, thereby introducing local regions of reduced or ablated oxide at each ion's impact site. The HCI impact sites result in a very low RA product compared to the high RA product of the regions that were not struck by ions. The RA product of the HCI modified oxide is selected by the dose of HCIs. For example, 100 HCIs per square micrometer have been found to reduce the RA product by a factor of 100.

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Laser Cooling of Nanomechanical Systems

Using conventional cryogenic techniques, it is possible to cool nanoscale mechanical resonators to the point that their mechanical modes are near the quantum ground state. To actually reach the ground state, and to be able to measure and control the motion, we use a quantum dot embedded in the mechanical resonator to couple its mechanical energy to optical radiation. The mechanical motion of the resonator modifies the energy spectrum of the quantum dot in a manner analogous to that in which the optical spectrum of a trapped ion is modified by its motion about its equilibrium position. By detuning an incident laser beam to the red-shifted motional sideband, trapped ions can be laser cooled to the quantum ground state of the trap. A similar result is predicted for the system comprised of the nanomechanical resonator with an embedded quantum dot. In both cases, the final temperature is determined by spectroscopic measurement of the fluorescence.

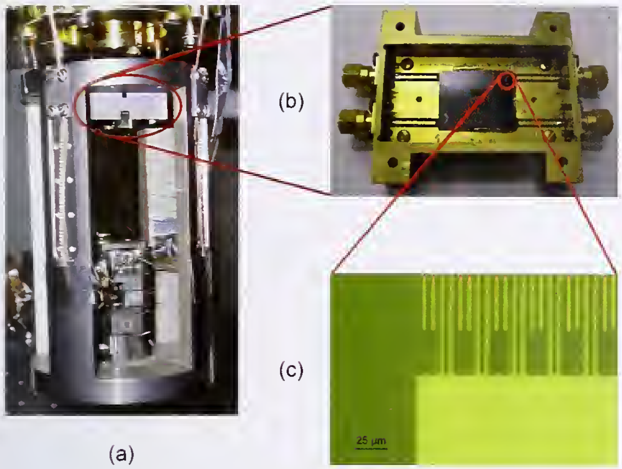

Figure 7.
(a) Monolithic titanium cylinder housing sample and collection optics;
(b) Sample package containing wafer with quantum dots;
(c) Electrodes fabricated to generate surface acoustic wave.

We are implementing this cooling process. The first step is to study the optomechanical coupling of a high-frequency acoustic wave to a quantum dot. We have fabricated a device, as shown in Fig. 7, which creates a surface acoustic wave on a sample containing many quantum dots; one individual dot will be isolated spectroscopically. We have constructed a microscope to capture the dot fluorescence with an optical fiber. The entire microscope is cooled to below 4 K in high vacuum in a closed-cycle cryostat.

The spectroscopy is demanding; the signal is weak (a single quantum emitter) and the resolution required is more than an order of magnitude higher than that provided by grating spectrometers conventionally used in quantum dot spectroscopy. We have built a Fabry-Perot cavity with a resolution of 50 MHz and a throughput of better than 90 %. The cavity transmission is collected by a single-photon counting module. We use the cavity in tandem with a grating monochromator to unambiguously see the emission of a single quantum dot.

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A Few Quantum Dot, Ultralow-Threshold Laser

Stimulated emission and lasing are by nature cooperative phenomena and typically involves large number of emitters. A single-state laser not only represents an interesting limit to the number of contributing states, it also offers a way to probe the system's characteristics as it moves from a continuous distribution of states, to a discrete distribution, to finally a single state. There are also technological motivations to this endeavor, as more efficient lasers requiring smaller numbers of emitters will have an impact in a variety of technologies.

A single-state laser has been recently observed in atomic systems, but requires the preparation of an ensemble of atoms in the same state. This has not been observed in solids. We have shown lasing in solids in which only a few states contribute to the lasing action. We use semiconductor quantum dots (QDs) placed in a high quality factor (Q) optical microcavity. The cavity is a microdisk structure with a diameter of 1.8 µm, and supports whispering-gallery modes in the vicinity of disk perimeter. The Q exceeds 15,000. The microdisk and simulation of the cavity mode is shown in Fig. 8.

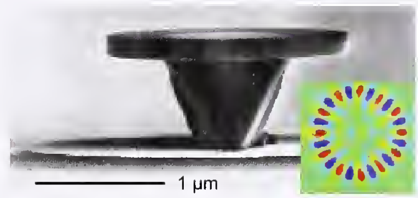

Figure 8. SEM image of 1.8 µm diameter microdisk cavity. Insert: Top-view simulation showing whispering gallery cavity modes.

We observe discrete QD states in the photoluminescence and we control the position of the QD states with respect to the cavity mode by adjusting the sample temperature. Even when the cavity mode is positioned where no apparent state is aligned we observe lasing. Our model indicates this is due to the coupling of tails of the emitter with the very high Q cavity. However, when the cavity mode is aligned with an emitter state, the lasing threshold drops by a factor of about 3–4. Because of off-resonance coupling of the cavity mode and emitter tails, even when a single discrete QD state is aligned with the cavity mode and lases we do not have a purely single state laser. However, this does represent the first time the alignment of such a single QD state produces such a dramatic reduction in laser threshold.

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The third strategic element is to produce reference data on atomic structure, to critically compile reference data for scientific and technological applications, and to develop techniques to apply the data to further the understanding of important plasma devices.

CRITICALLY EVALUATED ATOMIC DATA

INTENDED OUTCOME AND BACKGROUND

The objective of this strategic element is to critically compile fundamental constants and spectroscopic data for atoms from the far infrared to the x-ray spectral regions. We disseminate reference data on the Physics Laboratory website and produce high-quality data for urgent scientific or technological needs. When reliable data do not exist for high-priority needs, specific measurements or calculations are undertaken to produce them.

The NIST databases for atomic spectra and fundamental constants are recognized throughout the world. We regularly add new material to our flagship database, the Atomic Spectra Database, which now contains data for 141,000 spectral lines and 77,000 energy levels. It experiences over 55,000 requests for data each month. To assist in the diagnostics of a variety of plasmas, we added two new databases that contain benchmark data on plasma population kinetics, i.e., properties of ionized gases. These databases provide researchers with the best available data on numerous plasma parameters, such as mean ion charge state for a plasma under specific conditions. An online computational system for collisional-radiative modeling of hot plasmas under diverse conditions was also added, developed with Lawrence Livermore National Laboratory.

ACCOMPLISHMENTS

Precision Wavelengths for New Telescopes

The Very Large Telescope No.1 is one of the largest of a new class of modern telescopes for ground-based astronomy. It is located at the European Southern Observatory in Chile. One of its important missions is to observe spectra of stars and interstellar media at infrared wavelengths, 950 nm to 5500 nm. To do this it uses a major new infrared spectrometer, the Cryogenic High-Resolution Echelle Spectrograph (CRIRES).

The wavelength scale of this spectrometer is established by spectral lines from a thorium/argon hollow cathode lamp, similar to the platinum/neon lamp used to calibrate spectrometers on the Hubble Space Telescope (HST). Unfortunately, the spectrum of the Th/Ar lamp has not been well studied in the infrared and not enough accurate calibration lines are available.

To remedy this problem, we made precision measurements of Th/Ar lamps with our 2 m Fourier transform spectrometer. The wavelengths are accurate to about 0.00004 nm. With these new measurements, CRIRES will be able to achieve its astronomical goals.

In related work for the Hubble Space Telescope, we made observations of Pt/Ne lamps similar to those to be used to calibrate a new spectrograph to be installed on HST in 2008, the Cosmic Origins Spectrograph (COS). Since the lamps will be used much more intensively on COS than on earlier space spectrographs, there was concern as to whether they would last for the whole mission.

We performed accelerated aging tests on lamps from the same production run as the COS lamps by running them on an interval timer to simulate their use in space. After each three hundred hours of aging, we used our 10 m vacuum ultraviolet spectrometer to quantitatively measure the spectral output of each lamp. Each lamp was run until it failed (about 1000 h). Although the aging is continuing for some lamps, results to date indicate that the lamps will perform as needed for COS.

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Critical Data for Fusion Energy Science: Ionization Energies for Tungsten

Construction of the International Thermonuclear Experimental Reactor (ITER) will soon start in France. ITER is expected to generate fusion power for periods up to 1000 s. It will be the most expensive science project ever undertaken. An important part of ITER is the divertor, a region of the vessel that exhausts the flow of energy from charged particles and removes helium and other impurities. Tiles of the divertor will be made of tungsten, a material with very high melting point.

Although the tungsten tiles are able to withstand the high temperatures in ITER, atoms of tungsten will be sputtered into the active gases. To understand the complex processes taking place in these gases, it is important to determine the populations of the various ions of tungsten in the gas. For this it is necessary to have reliable values for the ionization energies of tungsten ions. The ionization energy is the amount of energy required to eject an electron from a given ion so that it is transformed to the next higher ion.

Previously, only values for the ionization energies of tungsten from rough theoretical calculations were available. We developed a method to determine accurate values for all tungsten ions—from neutral tungsten through almost fully stripped tungsten, W^{73+}. The method is based on scaling results of theoretical calculations according to experimental data. Uncertainties vary from 1.7 % for W^{2+} to 0.0008 % for W^{73+}, with typical values about 0.1 %. The results are published in *Atomic Data and Nuclear Data Tables.*

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Critical Data for Fusion Energy Science: Spectra of Highly Ionized Tungsten

In order to help meet the need for spectral data of wall materials in the divertor region of ITER, we excited spectra of tungsten ions with our Electron Beam Ion Trap (EBIT). Spectra in the x-ray region were measured with a microcalorimeter, a new type of spectrometer that detects single photons and measures the rise in temperature to deduce the energy deposited—and hence the wavelength. At longer wavelengths, a grazing-incidence spectrometer was used.

A number of new spectral lines were identified. The observed spectra were interpreted by means of collisional-radiative modeling of the ionized gas in EBIT. Excellent agreement with the observed spectra was obtained. Fig. 9 shows a spectrum from the microcalorimeter together with a spectrum predicted by modeling calculations.

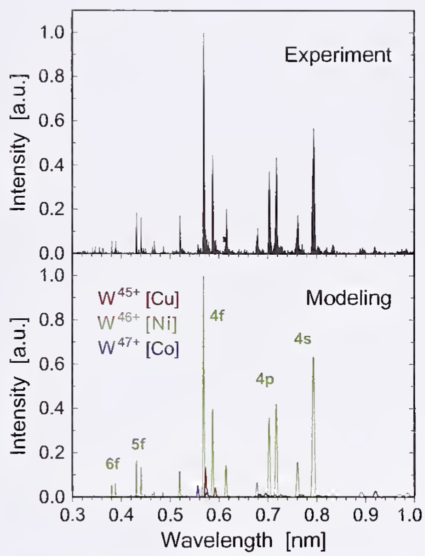

Figure 9. Observed spectrum and theoretical modeling of x-ray spectra of tungsten. The labels Cu, Ni, and Co refer to the isoelectronic sequences of the stages of ionization of the lines (Cu: W^{45+}; Ni: W^{46+}; Co: W^{47+}). The letters 6f, 5f, etc. refer to upper electronic configurations of W^{46+}. The line at 0.79 nm is blend of two transitions forbidden to electric-dipole radiation; one is an electric-quadrupole transition, the other a magnetic-octopole transition.

According to the calculations, an important strong line at 0.79 nm is actually a blend of two forbidden-type transitions. We showed that electron densities in plasma devices like ITER could be determined by measuring the ratio of the intensities of these two lines. The results are reported in *Physical Review A* and the *Journal of Physics B.*

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Redefinition of the International System of Units (SI)

In an effort to improve the International System of Units (SI) to overcome deficiencies, the Fundamental Constants Data Center has published a number of articles describing potential new definitions of the kilogram, ampere, kelvin, and mole, pointing out the merits of these definitions based on prescribed values of the Planck constant, the elementary charge, the Boltzmann constant, and the Avogadro constant.

The possible new definitions would have advantages including providing a stable, precise, and universal measurement system. With fundamental constant-based definitions of the SI units in place, the values of many of the fundamental physical constants, which are presently determined by experiment and theory, would have exact values, and the uncertainties of many other fundamental constants would be significantly reduced.

The Fundamental Constants Data Center has worked with relevant organizations to promote the changes in the SI. This includes the Consultative Committee for Units (CCU), the Committee on Data for Science and Technology (CODATA), and the International Union of Pure and Applied Physics (IUPAP).

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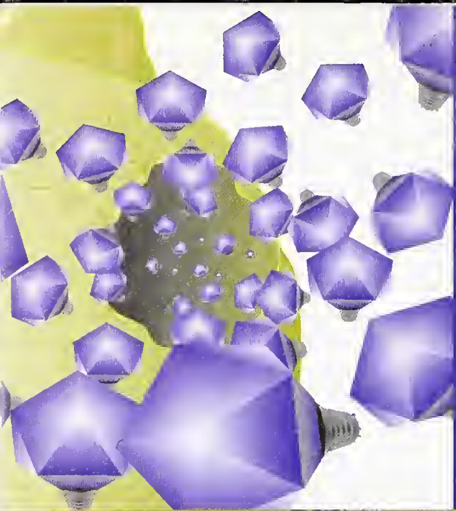

Optical Technology Division

GOAL
To provide the foundation for optical radiation measurements for our Nation

The strategy for meeting this goal is to develop and provide national measurement standards and services to advance optical technologies spanning the microwave through the infrared, visible, and ultraviolet spectral regions.

The first strategic element is to develop and provide optical radiation standards based on the SI units.

OPTICAL RADIATION STANDARDS

INTENDED OUTCOME AND BACKGROUND

The Optical Technology Division provides the optical radiation measurement science and standards to aid the advancement and application of optical technology. In particular, the Division advances, maintains, and disseminates standards for the candela and kelvin base SI units, and associated photometric, colorimetric, pyrometric, and spectral radiometric quantities. These standards benefit industries from aerospace to lighting, by ensuring the accuracy and consistency of measurements between and within organizations.

The Division helps maintain the quality and international comparability of our Nation's optical radiation measurements and standards by participating in international measurement comparisons with other national metrology institutes (NMIs). These comparisons are organized through the Consultative Committees on Temperature (CCT) and on Photometry and Radiometry (CCPR) under the auspices of the International Committee of Weights and Measures (CIPM).

ACCOMPLISHMENTS

New Spectral Irradiance Standards from the NIST Synchrotron Ultraviolet Radiation Facility, SURF III

To reduce uncertainties in the ultraviolet spectral irradiance scale, to meet the increasingly stringent demands of the climate remote sensing, semiconductor manufacturing, and health and safety communities, the Division in collaboration with Electron and Optical Physics Division has developed a highly accurate method for calibrating deuterium lamps. The lamps are now calibrated in air from 200 nm to 400 nm using synchrotron radiation from the NIST Synchrotron Ultraviolet Radiation Facility, SURF III.

The absolute spectral irradiances are calculated from the Schwinger equation using experimental knowledge of the SURF III electron beam current and beam energy and accurate measurements of the area of the aperture used in the specification of the irradiance geometry. The storage ring is operated at low flux levels to minimize radiation damage to optical components. The total expanded uncertainty of the spectral irradiance from 200 nm to 400 nm is 1.3 % ($k = 2$).

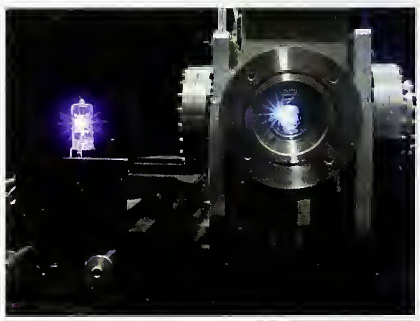

Figure 1. The spectral irradiances of NIST disseminated deuterium lamp standards, such as the one on the left, are measured at the Synchrotron Ultraviolet Radiation Facility (SURF III), which creates the light seen on the right.

A comparison of the SURF III–based calibrations with past NIST calibrations shows agreement within the combined uncertainties. The availability of a new type of deuterium lamp with relighting reproducibility of better than 0.1 % allows dissemination of a UV spectral irradiance scale with lower uncertainties, approximately 1.5 %.

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Total Spectral Radiant Flux Standards Developed

In response to a request from the Council for Optical Radiation Measurements (CORM), the Division has developed a new calibration service to disseminate standards for Total Spectral Radiant Flux, an important fundamental attribute of light sources. A Total Spectral Radiant Flux standard allows industry to improve their measurements of the efficacy of non-incandescent light sources, such as solid-state light sources now under development, for which the amount of output radiation varies significantly with wavelength.

We have realized the scale of total spectral radiant flux (W/nm) in the 360 nm to 800 nm region by using a specialized reference goniospectroradiometer to map the lamp output over the full sphere, as shown in Fig. 2.

The use of a spectroradiometer reduces the typically dominant measurement error associated with the imperfect matching of the spectral response of a photometer to the standard visual response of the eye. The use of a goniometer for mapping the angular output of the sources provides higher measurement accuracy and increased information about the angular dependence of the lamp output not available if an integrating sphere is used instead, as standard within the lighting industry.

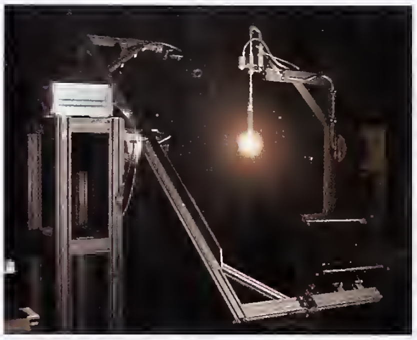

Figure 2. The NIST goniospectroradiometer measuring the total spectral radiant flux scale of a lamp. The optical fiber input of an array spectroradiometer is positioned at one end of the rotating arm. To cover the full range of angles, the lamp is also rotated around its vertical axis.

The NIST Total Spectral Radiant Flux scale is tied to the NIST spectral irradiance scale for the relative spectral distribution and to the NIST total luminous flux unit or lumen for the absolute spectral photometric output. Two types of lamps standards have been made available: 75 W and 60 W quartz-halogen lamps. Higher (200 W) and lower (20 W) power lamps will be offered in the near future. Customer-provided lamps can also be calibrated. This new service provides national traceability for total luminous flux, as well as for color quantities of light sources measured by integrating-sphere-based spectroradiometer systems. The uncertainty in total luminous flux is approximately 0.5 % (k = 2), and the uncertainty in total spectral radiant flux ranges from 1.5 % at 360 nm to 0.7 % at 550 nm.

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LBIR Facility Improves the Accuracy of Missile Defense Sensors

The Division continues to collaborate with the Missile Defense Agency (MDA) to ensure that infrared sensors used in missile defense, such as for the Exo-atmospheric Kill Vehicle or EKV, have the accuracy necessary to discriminate the infrared signature of an incoming missile from space thermal background or from thermally emitting decoys intentionally released by or with the missile during its trajectory.

This work utilizes the Division's state-of-the-art Low Background Infrared (LBIR) Facility, which offers a low-temperature thermal background that mimics the 3 K thermal background of space. The LBIR facility is used to directly calibrate MDA and NIST infrared source and detector standards against the LBIR Absolute Cryogenic Radiometer (ACR). The NIST source and detector standards are deployed to MDA for calibrating test facilities.

The primary NIST detector standard deployed to MDA facilities is the BXR. Recently, the calibration uncertainty of the BXR was lowered by a factor of two to 3 % (k = 1). This reduction was achieved through the use of a specially fabricated and calibrated silver chloride filter to effectively eliminate out-of-band filter infrared radiation leakage affecting the accuracy of the calibration transfer from the ACR to the BXR.

Figure 3. A blackbody standard being calibrated by the NIST BXR in the Exo-atmospheric Kill Vehicle (EKV) missile sensor cryogenic test chamber.

The reduced uncertainty helped resolve a 5 % discrepancy between NIST measurements and MDA test chamber optical models. The discrepancy was shown to be dominated by inaccurate measurement of the reflectivity of a mirror in the test chamber and incomplete modeling of the effects of diffraction in the optical system. Improved mirror reflectance measurements and more accurate diffraction modeling reduced the discrepancy to 2 %, in line with the overall measurement uncertainty. This level of agreement satisfies present EKV program needs, and will help ensure reliable warhead discrimination in the presence of sophisticated decoys.

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The second strategic element is to develop novel optical measurement methods for solving problems in critical and emerging technology areas.

OPTICAL MEASUREMENT METHODS

INTENDED OUTCOME AND BACKGROUND

The Division strives to improve the accuracy, quality, and utility of optical measurements in burgeoning technology areas, such as nanotechnology, biological and medical physics, climate change, quantum information, and national and homeland security.

In the area of nanotechnology, metal and magnetic nanoparticles, quantum dots, and nanoshells are being developed for use as quantitative probes to interrogate and manipulate chemical, physical, and biological phenomena within complex biological systems. Raman spectroscopy is being applied to the determination of the size homogeneity of carbon nanotubes separated using advanced chromographic methods. Such well characterized pure samples have the potential to serve as standards for researchers exploring applications of carbon nanotubes which have size-specific chemical and physical properties.

The Division has a strong biophysics program targeting the development of the critical measurement science infrastructure for systems biology. Spectroscopy, microscopy, and other optical technologies are being developed to characterize and control interactions between biomolecules. Such technologies include single-molecule microscopy, fluorescence resonance energy transfer (FRET), optically trapped hydrosomes containing single biological molecules, and THz spectroscopy. The THz spectroscopic measurements provide benchmark quantitative measurements of the large-amplitude vibrational modes in biomolecules important for folding and function. These benchmark measurements are compared against state-of-the-art molecular models widely used within the chemical, biotechnology, and pharmaceutical industries. Complementing these molecular and cellular-scale technologies, hyperspectral imaging and optical scatterometry are being developed for macroscopic imaging of tissue to improve cancer diagnosis, guide surgical procedures, and improve surgical outcomes.

Climate-change research places some of the most stringent demands on optical radiation measurement due to the need to quantify extremely small changes in the average incident solar radiation, reflected solar radiation, and outgoing infrared radiation over a decadal time scale. In response to these measurement demands, the Division has developed expertise in space sensor calibration and standards in support of the satellite programs of NASA, NOAA, and USGS. The Division also works with land- and sea-based sensor programs to help ensure measurement accuracy and quality.

The Division has a long history of supporting our Nation's national defense by working with the Calibration Coordination Group of the Department of Defense to ensure that the standards needs of the military are met in the area of optical radiation measurement. We have developed specialized calibration chambers to mimic the cold thermal background of space to ensure the comparability and accuracy of the sensor measurements of the Missile Defense Agency and its aerospace contractors. Correlated-photon sources are being developed to absolutely calibrate photon-counting detectors with applications to quantum communication and quantum cryptography. Such technology may eventually allow all of the Division's fundamental radiation measurements to be tied to quantum-based standards.

ACCOMPLISHMENTS

A Practical Method for Spectral and Spatial Stray-Light Correction in Optical Measurement Systems

The Division has developed a simple and effective method to correct array spectroradiometers for spectral stray-light errors. Such spectroradiometers are increasingly used in remote sensing, photometry, colorimetry, and radiometry due to their low cost, compact size, and high measurement speed. However, their measurement accuracy is often less than conventional monochromator-based systems due to the presence of significant spectral stray light. Such stray light increases the detected light intensity at wavelengths where the relative output radiation from the viewed source is low, leading to significant measurement error.

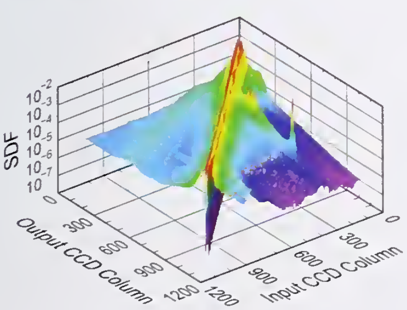

Figure 4. The stray-light distribution function (SDF) of a typical CCD-based spectroradiometer.

To implement the NIST stray-light correction method, the spectroradiometer first measures several spectrally narrow laser lines distributed over the wavelength range of the instrument. Due to stray-light effects, the spectroradiometer will detect light not only at the wavelength corresponding to the laser wavelength, but also weakly in channels corresponding to other wavelengths. Typical data are shown in Fig. 4.

From these data we derive a correction matrix, which is used to reduce measurement error. This method has been shown to reduce the effect of stray light in commercial array spectroradiometers by as much as two orders of magnitude, leading to a dramatic improvement in measurement accuracy.

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Follow-on Satellite Instrument Calibration Conference

NIST, through its U.S. Measurement System Initiative, has cosponsored a follow-on conference to the highly successful "Satellite Instrument Calibration for Measuring Global Climate Change" conference held at the University of Maryland in November of 2002. The first conference discussed the requirements for achieving satellite measurements with sufficient accuracy and long-term precision to monitor climate change. The report has been widely disseminated as NISTIR 7047.

The follow-on conference, "Achieving Satellite Instrument Calibration for Climate Change" or $ASIC^3$ held in May 2006, was organized by the Space Dynamics Laboratory of the Utah State University with additional cosponsorship by the National Oceanic and Atmospheric Administration (NOAA) and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) office. The primary goal of the conference was to develop a calibration science strategy to achieve the measurement requirements determined in the first conference. Breakout groups addressed the following areas: Infrared Sensors; Ultraviolet, Visible, and Near Infrared Sensors; Microwave Sensors; Active Sensors; Broadband Sensors; Sensor Intercalibration; and a National Roadmap for Satellite Calibration.

The second report has two overarching recommendations. The first recommendation is that satellite benchmark missions be initiated to measure Earth's radiation budget, including Earth's spectral emission, its reflectance, and total solar irradiance. The second recommendation is for NIST, NOAA, and NASA to establish a National Calibration Center to ensure climate-quality measurements in operational and research satellite missions.

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Quantum Dot Method Rapidly Identifies Bacteria

A rapid method for detecting and identifying very small numbers of diverse bacteria, from anthrax to E. coli, has been developed in collaboration with scientists from the National Cancer Institute (NCI). The work, described in *Proceedings of the National Academy of Sciences*, could lead to the development of handheld devices for the rapid identification of biological weapons and antibiotic-resistant or virulent strains of bacteria.

Traditional ways of identifying infectious bacteria are time consuming and laborious, requiring the isolation and growth of a bacterial culture over hours to days. The new method speeds up the process by using fast-replicating viruses (called bacteriophages or phages) that infect specific bacteria of interest and are genetically engineered to bind to "quantum dots." Quantum dots are nanoscale semiconductor particles that provide an intense fluorescent signal and are less prone to deterioration than conventional molecular tags when illuminated.

The phages were genetically engineered to produce a specific protein on their surface. When these phages infect bacteria and reproduce, the bacteria burst and release many phage progeny attached to biotin which is present in all living cells. The biotin-capped phages selectively attract specially treated quantum dots, which absorb light efficiently over a wide frequency range and re-emit it in a single color that depends on particle size. The resulting phage-quantum dot complexes can be detected and counted using microscopy, spectroscopy, or flow cytometry, and the results used to identify the bacteria.

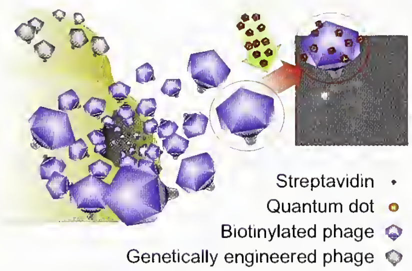

Figure 5. Summary of the new method. A bacterium bursts following infection with a phage. The phages have been genetically engineered to express biotin on their surface. The biotinylated phages have an affinity for quantum dots labeled with streptavidin. The quantum dots fluoresce when illuminated as shown by the bright white spot in the square image.

The new method, summarized graphically in Fig. 5, can detect and identify as few as ten target bacterial cells per milliliter of sample in less than an hour. It is more sensitive than conventional optical methods, and it can count how many viruses are infecting a single bacteria cell or how many quantum dots are attached to a single virus.

The method could be extended to identify multiple bacterial strains simultaneously by pairing different phages with quantum dots that have different emission colors.

A provisional patent application was filed through NIST, and more recently a nonprovisional patent application was filed through the National Institutes of Health. The NIST contributions to the work include experimental design and fluorescence imaging. The non-NIST collaborators are from NCI, NIH, SAIC, and the National Cancer Institute. This research spun off multiple new collaborations with agencies outside NIST, including the Navy Medical Research Center (a novel, fieldable method to detect biowarfare agents) and the Nanotechnology Characterization Laboratory of the National Cancer Institute (flow cytometry standards).

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Magnetic Nanoparticles Assembled into Long Chains

Division scientists have controllably assembled and disassembled chains of magnetic nanoparticles suspended in a solution. The chains were composed of millions of 12 nm diameter cobalt nanoparticles. Such particles and their chain structures may have applications in medical imaging, hyperthermia treatment for cancer, and information storage, provided that techniques are available to manipulate and control their physical and chemical properties and to assemble them into structures. The NIST work is the first to demonstrate the formation and control of centimeter-long chains of magnetic nanoparticles of a consistent size and quality in a solution.

The nanoparticles were induced to form linear chains by subjecting them to a weak magnetic field—about the same strength as a refrigerator magnet. The particles line up because the nanoparticles act like tiny bar magnets, all facing the same direction as the applied field. Once this alignment occurs, the attraction between particles is so strong that reversing the direction of the applied magnetic field causes the whole chain to rotate 180 degrees. When the magnetic field is turned off, the chains fold into three-dimensional coils. When the solution is lightly shaken, the chains fall apart into small rings. The chains were characterized by optical and transmission electron microscopy (TEM). A TEM image is shown in Fig. 6.

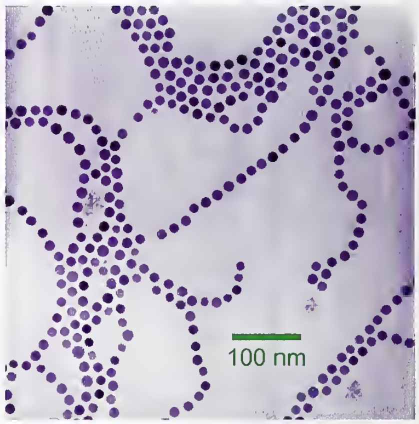

Figure 6. Tunneling electron microscope (TEM) image of 12 nm diameter surfactant-coated cobalt nanoparticles ordered by magnet dipole-dipole couplings.

Magnetic particles have already been used in medical imaging and information storage, and nano-sized particles may offer unique or improved properties. For example, magnetic nanoparticle dyes may improve contrast between healthy and diseased tissue in magnetic resonance imaging (MRI), a possibility under study by a different NIST research group. Research is ongoing to improve the biocompatibility of these magnetic nanoparticles.

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A Highly Efficient Two-Photon Source

Division scientists have developed an approach to efficiently create pairs of photons over a wide range of energy, while minimizing the production of extraneous photons. The approach promises to benefit applications in physics and technology such as quantum information and telecommunications.

Paired photons can be generated from a monochromatic light source—albeit very inefficiently—in standard optical media such as glass optical fibers. Most photons normally travel through glass independently, without interacting. Occasionally, two of the input photons will interact, producing an output photon pair with one higher in energy than the original photons and the other lower in energy by the same amount.

Because the vast majority of photons go through the fiber unchanged, the relative intensity of these pairs is low. Since the fiber generates the pairs randomly with a range of possible energies, selecting those photons with some specific energy further reduces the number of useful photon pairs. Typically, the photon pairs in the system must be detected against the photon noise in the system due primarily to Raman scattering. In Raman scattering individual photons interact nonlinearly with the phonon modes of the glass to change their energies. Such scattering produces undesirable photons with properties that mimic one of the photons of a photon pair.

To increase the efficiency of photon pair production while minimizing noise from the extraneous Raman photons, the NIST two-photon source relies on a microstructured optical fiber. The fiber has a slender glass core at the center of an array of hollow channels, giving a cross-section that resembles a honeycomb. The geometrical structure of the fiber affects the optical modes of the fiber, leading to an increase in the intensity of light in the thin central core with a concomitant enhancement of the photon pair production.

This greater pair-production efficiency reduces the length of optical fiber required, from hundreds of meters to a couple of meters. Moreover, optimization of the size of the channels in the microstructured fiber allows reduction of the amount of Raman scattering relative to the desired two-photon light production. The result is a source that produces significantly more pairs of photons over a wide frequency range, with greatly reduced contamination by spurious Raman photons. A picture of the source is shown in Fig. 7.

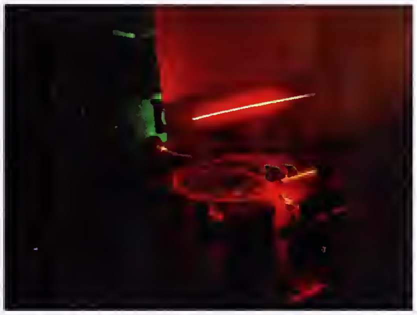

Figure 7. A microstructured optical fiber in NIST's new correlated-photon source delivers high numbers of photon pairs over a broad spectral bandwidth with low noise in a compact device for quantum communication applications.

Photon pairs from the new source are being applied to studies of quantum entanglement and quantum cryptography. These studies take advantage of the quantum properties of these photon pairs by which measurements on one of a pair of photons specifies the measurement result on the other member of the pair.

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The third strategic element is to disseminate optical radiation measurements and standards to industry, government, and academia.

OPTICAL MEASUREMENT SERVICES

INTENDED OUTCOME AND BACKGROUND

The Division builds and maintains world-class optical radiation measurement facilities to meet the continued and emerging needs for standards and specialized measurements by government and industry. These facilities are available to government and industry customers through formal calibration services, special tests, and standard reference materials available from NIST Technology Services or through collaborative research efforts.

The Division maintains facilities for measuring optical properties such as reflectance, retroreflectance, transmittance, color, and gloss; for photometric measurements such as luminous intensity and color temperature; and for radiometric measurements such as spectral radiance, spectral irradiance, spectral power, detector responsivity, and radiance temperature. The Division has highly specialized facilities for performing low-background radiometric measurements, for characterizing remote sensing instruments, for measuring the area of precision radiometric apertures, and for determining the absolute optical power, radiance, and irradiance spectral responsivities of instruments. New measurement facilities have been developed for measuring the emittance and retroreflectance of materials and for providing standards for ultraviolet spectral irradiance.

ACCOMPLISHMENTS

Hyperspectral Image Projector for the Calibration of Earth Remote-Sensing Instruments

Present approaches for calibrating multispectral and hyperspectral imagers and sounders, such as those used in climate-change research and weather forecasting, use spatially uniform and temporally constant optical radiation sources, such as lamp-illuminated integrating spheres, to fill the full aperture of the light-collecting telescope in front of the sensor. Consequently, many systems are not tested prior to deployment with optical signals that mimic the spectrally, spatially, and temporally varying signals expected during operation. The lack of such testing is of particular concern for satellite imagers due to their high cost, difficult operating environment, and inability to be retrieved.

A Hyperspectral Image Projector (HIP) is being developed to enable the realistic test, evaluation, and calibration of ground and space-based optical radiation sensors. The HIP is based on digital micromirror devices (DMDs) commonly found in commercial high definition televisions and projectors. DMDs consist of 768 × 1024 individually addressable, 15 μm square mirrors.

One DMD is illuminated by a prism or a grating, which disperses broadband light into a spectrum focused onto the DMD. The DMD allows 1024 narrow spectral bands to be modulated in intensity, thus creating a user-specified spectral distribution of light. A programmable source with such a high spectral fidelity is essential for realistically reproducing the spectral content of solar radiation reflected off of the Earth's surface or of the thermal emission of a chemical-agent cloud. DMDs used for video displays have color-filter wheels to generate visual images. However, the HIP generates a spectral match, not just a color match.

A second DMD, optically in series with the first, projects any combination of these arbitrarily programmable spectra into the pixels of a (768 × 1024) element spatial image, thereby producing temporally integrated images having spectrally mixed pixels. Calibration of the resulting image using an absolute spectroradiometer provides the absolute values of the radiance as a function of wavelength, spatial coordinate, and time. This calibrated scene, chosen, for instance, to mimic the view of the ocean by a satellite in a geostationary orbit, is then directed into the sensor under test.

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Tool Tackles Translucence and Other Color Challenges

Special effect paints and coatings, such as some automobile paints, look different depending on illumination or viewing angles, or both, subtleties that cannot be accounted for by traditional color measurement instruments. To address this deficiency in measurement capabilities, NIST has developed a goniospectrometer that automatically measures the color of light reflected from a surface as a function of illumination and viewing angles.

The new goniospectrometer provides more complete data on the reflection of light from a color surface, and will be used for calibrating similar instruments and for research on exotic-appearing materials and coatings. A database of measurements of different materials that could be used for modeling surfaces that have complex visual effects will be developed using this new capability. The work is part of a NIST effort to develop accurate measurement methods for reproduction and quality control of appearance attributes, including color matching, by determining the optimal subset of illumination and viewing geometries needed to accurately characterize the perceived color.

The goniospectrometer, housed in a clean room, illuminates a sample with a range of wavelengths of visible light, every 5 nm from 360 nm to 780 nm, i.e. from the near ultraviolet/deep blue to red/infrared. The sample and detector are rotated around three axes, allowing illumination and viewing in any direction within a hemisphere around the sample. The intensity of the reflected beam is measured at several hundred locations on a sample surface, as shown in Figure 8.

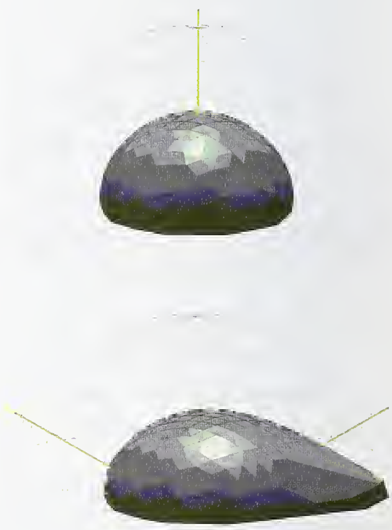

Figure 8. The NIST goniospectrometer measures the intensity of light reflected from the surface of a sample at 332 points. A plot of these measurements results in a different shape depending on whether the illumination comes from above (top) or at a 60-degree angle (bottom).

Based on these measurements, computer software assigns a numerical value to the color of the reflected light at each illumination-viewing geometry.

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Perceived and Measured Colors of Retroreflective Materials used in Traffic Signs

In collaboration with the Federal Highway Administration (FHWA), Division scientists performed a pilot study to compare measured colors with perceived colors for roadway signs. The study was initiated in response to anecdotal observations that instrument-measured daytime chromaticities of retroreflective materials do not correspond well with perceived chromaticities.

(c) Robert Rathe

Figure 9. Cameron Miller mounts a STOP sign on the goniometer at the NIST Center for High-Accuracy Retroreflection Measurements (CHARM).

In the pilot study, instrument measured appearances were directly compared with visually perceived appearances. A hue scaling method was used to measure the colors perceived by the human subjects for six different types of retroreflective materials, as well as for a diffuse reference material. The test samples had chromaticities within the range allowed by U.S. Federal regulations for yellow and white traffic signs.

The results of this pilot study were presented at the Quadrennial Session of the International Illumination Commission (CIE) held in China in July 2007. Overall, instrument measured chromaticities of retroreflective materials corresponded well with observer reported chromaticities. Both the instrument measurements and a majority of observer data showed a marked decrease in chromatic saturation (colorfulness) for yellow and orange retroreflective samples, compared to the yellow and orange diffuse reference material. To confirm and expand these findings, a larger study involving more colors is under development at the FHWA laboratories.

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Implementation of "Once is Enough" at NIST

To help improve the quality and control the costs of its measurement services, the Division has implemented a "Once is Enough" measurement strategy to eliminate unnecessary repeat measurements in calibrations. Spectral Irradiance Lamps and Spectral Transmittance Filters are two of the Division's measurement services in which "Once is Enough" is being applied.

To help Measurement Service customers understand this transition and to aid calibration laboratories in implementing a similar approach in their own facilities, the Division has documented the "Once is Enough" process for the Spectral Irradiance Lamp example in an article in the *Journal of Research of the National Institute of Standards and Technology.* The implementation strategy has five critical components: automation, uncertainty budget, measurement process controls, quality system, and peer review, described in detail in the article. Careful attention to each of these components provides the calibration scientist with the necessary control over the entire process to confidently eliminate repeat measurements.

The implementation of "Once is Enough" by calibration laboratories will help lower costs through reduction in instrument wear, artifact deterioration, and facility and staff time associated with each calibration.

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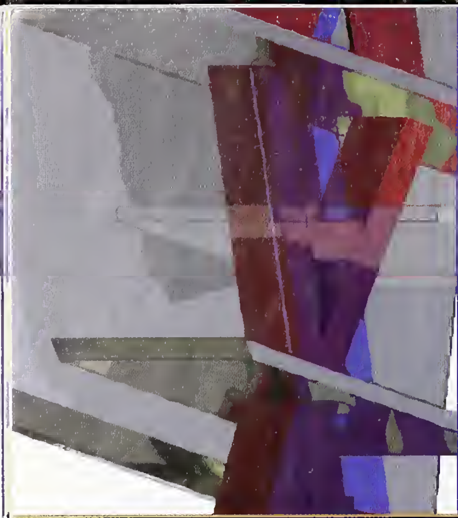

Ionizing Radiation Division

GOAL
To provide the foundation of ionizing radiation measurements for our Nation

The strategy for meeting this goal is to develop, maintain, and disseminate the national standards for ionizing radiation and radioactivity to meet national needs for health care, the environment, U.S. industry, and homeland security.

The first strategic element is to develop dosimetric standards for x rays, gamma rays, and electrons based on the SI unit, the gray, for homeland security, medical, radiation processing, and radiation protection applications.

RADIATION DOSIMETRY STANDARDS

INTENDED OUTCOME AND BACKGROUND

The Radiation Interactions and Dosimetry Group advances the measurement of quantities important in the radiological sciences through programs in the dosimetry of x rays, gamma rays, electrons, and other charged particles. Its mission is to develop, maintain, and disseminate the national measurement standards for these radiations, and to engage in research on radiation interactions and effects to meet requirements for new standards and to address the needs of industry, medicine, and government.

We maintain the national standards for the gray (Gy), the Système International (SI) unit for radiation dosimetry, and develop, maintain, and disseminate high-quality data on fundamental radiation interactions. These data are used extensively in radiation transport calculations and simulations, with algorithms and codes often developed by our staff, to solve a wide range of problems in radiation science and applications.

Standards are disseminated both directly to the customer and through networks of secondary calibration laboratories. We work closely with such networks to maintain measurement-quality assurance and traceability, by means of calibrations and proficiency testing services.

Our staff continues to make important contributions to the work of national and international standards and scientific organizations, and we are central to measurement-quality assurance of dosimetry in the many application areas of ionizing radiation. For example, the radiation doses in cancer treatment, radiosurgery, diagnostic radiology, and public or worker exposures in the U.S. are traceable to our standards and programs. Our focus on homeland security continues, while significant progress was made in our more traditional radiation-dosimetry programs.

ACCOMPLISHMENTS

Accelerator Facilities

The Division's accelerator facilities continue to support research efforts in industrial and medical dosimetry, homeland security, and radiation-hardness and materials-effects studies. Substantial progress has been made in the development of the High-Energy Computed Tomography (HECT) facility. A number of hardware and software improvements were made as a result of collaboration with engineers from Savannah River National Laboratory, including the installation of an object manipulation system consisting of a rotating turntable and a two-dimensional linear stage. A number of test objects are being assembled, which should allow us to evaluate the performance of the HECT imaging hardware and gain expertise in the use of tomographic reconstruction tools.

Figure 1. Angular "slice" of HECT test object obtained using 19 MV x rays from the MIRF accelerator. A drill bit is clearly observed on the left side of the image; aluminum support hardware and mounting holes are apparent in the center portion of the image.

Quality-assurance testing continues on the Clinac 2100C medical accelerator, typical of those used in cancer therapy. Using a recently acquired radiation scanner, depth-dose measurements in water were conducted in order to validate machine performance. Software controls have been implemented to allow the beam to be cycled on and off for a fixed period of time and a preset number of cycles. This technique will allow frequency-domain analysis of the response of a second-generation Domen-type water calorimeter, which will become the primary standard for high-energy absorbed dose-to-water. Plans are to make use of the Clinac in a high-energy calibration laboratory based on this primary dosimetry standard.

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X-Ray Calibration Range Measurements

The calibration and irradiation of instruments that measure x rays are performed in the NIST x-ray calibration facilities in terms of the physical quantity air kerma. Calibrations are performed by comparing the instrument to a NIST primary standard, which includes four free air chambers.

Figure 2. 320 kV replacement x-ray tube.

Air-kerma-measurement comparisons with the BIPM and other primary standards laboratories are conducted for quality assurance. One important comparison began in 2006. The comparison involved a series of measurements at PTB in Germany and at NIST using the air-kerma standards and two NIST reference-class transfer ionization chamber standards. Tungsten and molybdenum reference beam qualities in the range from 10 kV to 50 kV (low energy) were used. This comparison with PTB will be the third comparison for mammography energies, but the first for NIST using the recently developed BIPM/CCRI reference beam qualities. Prior to the next direct BIPM comparison, the results of the CCRI beam comparison will verify the new correction factors as applied to the NIST standard for these beam qualities.

In addition to participating in measurement comparisons, the NIST x-ray facilities are used to conduct proficiency tests for various customers. These include secondary calibration facilities, chamber manufacturers, the nuclear industry, the Department of Energy, the Department of Defense, private calibration facilities, medical facilities, and the Food and Drug Administration. Calibrations are provided in terms of gray/coulomb for various reference-quality ionization chambers to achieve traceability to NIST. Updates made to our website (http://physics.nist.gov/Divisions/Div846/Gp2/gp2.html) explain the proficiency test policy.

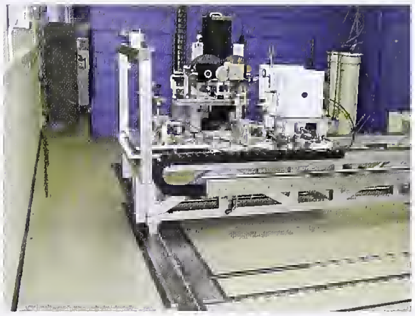

Figure 3. NIST 300 kV calibration range, showing the Wyckoff-Attix free-air chamber (white assembly), the national standard for medium-energy x-ray beam air kerma.

A new free-air ionization chamber has been designed to realize air kerma for x-ray beams of 50 kV to 300 kV, replacing the Wyckoff-Attix chamber used at NIST as a primary x-ray standard (medium energy) for more than fifty years. The dimensions and the parallel-plate design of the new chamber are identical to the Wyckoff-Attix chamber, but the materials are different. The chamber incorporates a unique guard bar and insulator design, and precision slides facilitate alignment and the direct measurement of the air-attenuation correction. Once the new standard is constructed, it will be fully evaluated in a parallel measurement arrangement until the correction factors are established and tested.

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X-Ray Security-Screening Standards for Homeland Security

With support from the Department of Homeland Security (DHS), we have been developing technical-performance standards for four classes of x-ray security screening systems: checkpoint cabinet, computed tomography, cargo and vehicle, and human subject. Four ANSI working groups have been organized to develop national standards for technical performance, focusing particularly on image quality.

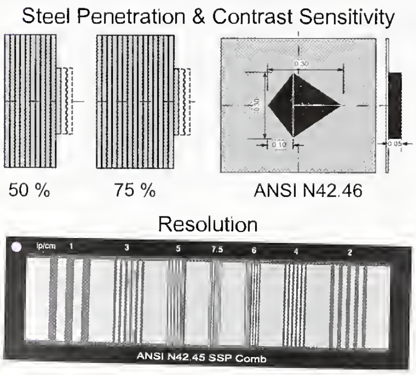

Figure 4. Objects being considered to test penetration, contrast sensitivity, and resolution for standards being developed for x-ray and gamma-ray noninvasive inspection systems for cargo containers and vehicles.

Each standard will include both test methods and x-ray phantoms appropriate for the application. Examples of artifacts that are being designed and tested are shown in Fig. 4. In the upper portion, to test penetration and contrast sensitivity of high-energy inspection systems used to inspect cargo, the orientation of an arrow must be determined through increasing thicknesses of steel. The lower portion of the figure is a test piece proposed to test the spatial resolution of CT imaging systems.

In related work, we have established a testbed for assessing the image quality of portable x-ray and imaging systems used by bomb squads for explosives and ordinance detection and disarmament. The results of testing will be used to establish minimum image-quality standards and to update a National Institute of Justice standard covering these systems.

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Testing a Method for Establishing e-Traceability to NIST High-Dose Measurement Standards

To meet rapid turn-around time needs, yet maintain high accuracy and minimal uncertainties, an Internet-based dosimetry calibration system is being developed for remotely certifying the calibration of industrial radiation sources. Using alanine dosimeters and a Bruker *e-scan* electron paramagnetic resonance (EPR) spectrometer, subscribers' dosimetry systems will be calibrated to the NIST reference dosimetry system. A computational method for determining the measurement conversion factor (MCF) relating the NIST reference system to the remote customer system has been established. The uncertainty in applying the MCF to the dosimeter response has been evaluated and used to establish an overall uncertainty budget.

The Internet-based system promises to deliver immediate certification results to customers, on-demand at lower cost. A working alpha version was assembled on lab computers and a server within the Division. Recently, several system design changes were required to adapt to changes in security requirements, changes that actually led to a simpler and more user-friendly system. The next stage will be to transfer the software to Bruker to begin beta testing the system.

Figure 5. Alanine dosimeters used in radiation processing allow for accurate transfer dosimetry.

A testbed consisting of two separate *e-scan* spectrometers at NIST is being used to test the MCF calculation method. Calibrated alanine dosimeters are assembled into a "customer" *e-scan* dosimeter insert set, as would be used for an actual calibration event, and the results are used to test the MCF computation. Testing the electronic certification process is conducted by measuring a series of unknown/test dosimeters, applying the MCF, and calculating dose from the NIST standard reference curve. These tests will be performed for all of the commercially available inserts and will serve as guidelines for the operational aspects of this future service.

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The second strategic element is to develop and provide neutron standards and measurements needed for worker protection, nuclear power, homeland security, and fundamental applications.

NEUTRON STANDARDS AND MEASUREMENTS

INTENDED OUTCOME AND BACKGROUND

The Neutron Interactions and Dosimetry Group maintains and supports the nation's premier fundamental neutron physics user facilities, including a weak interactions neutron physics station, the Neutron Interferometry and Optics Facility (NIOF), the Ultra Cold Neutron Facility (UCNF), an Advanced Monochromatic Neutron Test Facility, and the nation's only high-resolution Neutron Imaging Facility (NIF) for fuel-cell research. We maintain and disseminate measurement standards for neutron dosimeters, neutron survey instruments, and neutron sources, and improve neutron cross-section standards through both evaluation and experimental work.

The Group is at the forefront of basic research with neutrons. Experiments involve precision measurements of symmetries and parameters of the "weak" nuclear interaction, including measuring the neutron lifetime using both thermal and ultracold techniques, setting a limit on an important time-reversal-violating asymmetry coefficient, and characterizing the radiative decay mode of the neutron. These data address fundamental issues that are important in the understanding of theories of evolution of the cosmos. It is an internationally renowned program that maintains an extensive level of cooperation with premier national and international academic and research institutions.

The neutron interferometry program provides the world's most accurate measurements of neutron coherent scattering lengths, which are important to materials science research and modeling of the nuclear potentials. We recently carried out new interferometry experiments to determine the charge distribution of the neutron and for reciprocal space imaging. We are developing and promoting the applications of efficient neutron spin filters based on laser-polarized ^{3}He, and are pursuing applications for these filters at NIST as well as at neutron research centers throughout the U.S.

To support neutron standards for national security needs, we are developing key technical infrastructure. Advanced liquid scintillation neutron spectrometry techniques will lead to characterization of neutron fields and detection of concealed neutron sources with low false-positive rates. We are planning to organize and lead a Consultative Committee for Ionizing Radiation (CCRI) comparison of thermal neutron fluence rate measurements, characterizing four different beam qualities at the NCNR, and to carry out comparisons of NIST standard neutron sources. The Group is leading an effort that will result in a new international evaluation of neutron cross-section standards.

ACCOMPLISHMENTS

Active Interrogation Standards

Active interrogation involves directing nuclear radiation into a closed container and measuring secondary radiations to gain information about the contents of the container. Typically, but not always, neutrons are used as the impinging radiation. Active interrogation has the potential for detecting smaller quantities of special nuclear materials than is possible by using passive detectors. It also holds the promise of detecting nonnuclear materials, hazardous chemicals, and explosives.

NIST organized a drafting committee and held four meetings to prepare a new ANSI Standard, N42.41, Minimum Performance Criteria for Active Interrogation Systems used for Homeland Security, which is being published by the IEEE. A cargo-container testbed with three massive cargo regions, as needed for testing under ANSI N42.41, has been set up for use at NIST. It is capable of mobility to other locations.

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First Observation of the Radiative Decay Mode of the Neutron

Beta decay of the neutron into a proton, electron, and electron antineutrino is occasionally accompanied by the emission of a photon. An experiment to study the radiative beta-decay of the neutron was completed at the NG-6 fundamental physics end station. The experiment employed the magnet previously used for the NIST proton trap neutron lifetime apparatus, with the addition of a detector for photons with energies above 15 keV. A photon detector that operates efficiently in the high magnetic field, low temperature environment of the magnet was developed. This apparatus allowed half of the available electrons and all of the available protons from neutron beta-decay to be detected, which provided a high-rate, background-rejecting trigger for the observation of radiative decay photons. In this first-generation experiment, the photon detector consisted of a single 12 mm by 12 mm by 200 mm scintillating crystal coupled to an avalanche photodiode.

We observed electron-proton-photon coincidences that were unambiguously due to the radiative decay of the neutron. We reported the first observation of the radiative decay mode, and a manuscript detailing the measurement was published in the journal *Nature*.

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Seeing Inside an Operating PEM Fuel Cell

We are applying neutron-imaging methods for industrial research on water transport in fuel cells and on hydrogen distribution in hydrogen storage devices. This facility has provided critical services to major automotive and fuel cell companies during the last few years. This is a high demand and high profile, nationally recognized program.

Recent advances in neutron imaging detector technology, based on microchannel plates (MCPs) have resulted in an order-of-magnitude improvement in the achievable neutron image spatial resolution. This enhanced resolution of 25 µm allows the fuel cell researcher to directly measure the through-plane water distribution in the gas diffusion layer (GDL) and distinguish the water in the anode from that in the cathode in the membrane electrode assembly (MEA). This was not possible with scintillator-based neutron detection. Measuring the through-plane water distribution gives insight into the water transport mechanisms in the GDL and MEA. Ongoing developments of neutron MCP detectors should reach an ultimate resolution of about 10 µm, which will enable the study of commercially viable membranes that are from 25 µm to 50 µm thick.

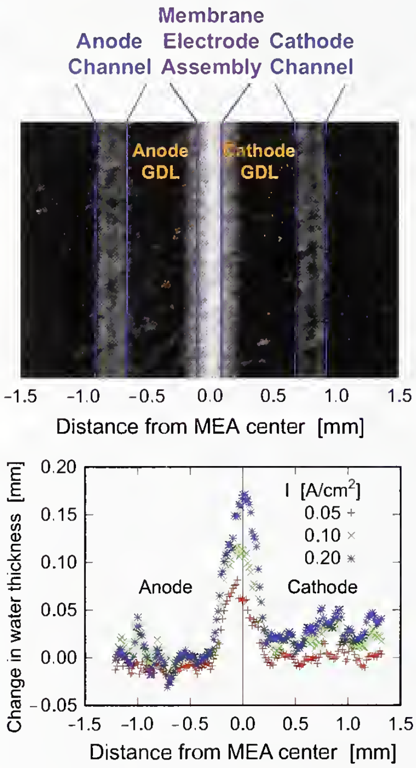

Figure 6. An image of water content in a representative section of an operating PEM fuel cell, in the "through-plane" dimension. Corresponding water content is shown in the graph.

The initial effort at visualizing the *in situ* through-plane water distribution of a proton exchange membrane (PEM) fuel cell was recently published, using an MCP detector at the thermal neutron imaging facility at the NIST Center for Neutron Research, as shown in Fig. 6. The visualization of the through-plane water distribution with a spatial resolution of 30 µm with neutron imaging was demonstrated. The analysis suffered from the inability to resolve the membrane swelling. Future work will focus on mitigating this problem. For instance, thinner membranes will have a smaller total volume change, reducing the problem. Additionally, rather than being directly coupled to the detector, the cell will be mounted from the bottom, providing a reference surface for determining the location of cell components.

Future work with the enhanced resolution will focus on measuring the GDL porous media properties and their interplay with the dynamic fuel cell operation. Also, using thick membranes, we will measure the proton conductivity as a function of membrane hydration in an operating fuel cell.

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Measurements of the Neutron Vertical Coherence

We have measured the vertical coherence function of a single crystal neutron interferometer for different vertical beam distributions. We carried out the measurements by introducing a vertical path separation via a pair of prisms placed in the two beam paths of a single crystal neutron interferometer and measured the loss in fringe visibility (contrast) as this separation is increased. This loss of contrast is directly related to the vertical coherence of the neutron beam. We showed that the measured coherence length is consistent with the experimental distribution of the incoming neutron beam momentums in the vertical direction. We also demonstrated that the loss in contrast with beam displacement in one leg of the interferometer could be recovered by introducing a corresponding displacement in the second leg of the interferometer.

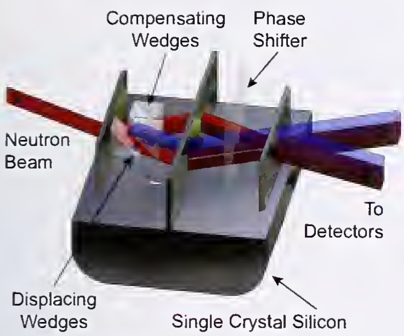

Figure 7. Schematic diagram of the coherence length experiment. The neutron is coherently split and recombined after traveling two paths.

Results from this experiment raise intriguing possibilities for the development of Fourier Spectroscopy to enable very precise direct measurement of vertical momentum distribution of beams reflected from surfaces and hence allow characterization of various surface properties (as done in normal reflectivity measurements) of a sample. Having a single crystal neutron interferometer with a long coherence length also provides studies coherence scattering over scales that are not easily accessible by other approaches.

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The third strategic element is to develop and provide standards for radioactivity based on the SI unit, the becquerel, for homeland security, environmental, medical, and radiation protection applications.

RADIOACTIVITY STANDARDS

INTENDED OUTCOME AND BACKGROUND

The Radioactivity Group develops and improves the metrological techniques used for the standardization of radionuclides. Our mission is to develop, maintain, and disseminate radioactivity standards, develop and apply radioactivity measurement techniques, and engage in research to meet the requirements for new standards. We carry out a wide range of programs in low-level standards for environmental measurements and monitoring, nuclear medicine, and radiological instrumentation used for security.

We continue to lead the national effort, in collaboration with the Department of Homeland Security (DHS), to develop standards and protocols for radiation instrumentation for early and emergency responders. We are spearheading the development of ANSI standards and testing protocols for spectroscopic portal monitors, neutron detectors, x-ray and high energy gamma-ray interrogation methods, x-ray imaging, data formats for instrumentation data output, and training standards for responders. The Group has been heavily involved in the testing and data analysis of advanced spectroscopic portal monitors (with DHS/DNDO) at the Nevada Test Site, and is involved with the testing of large-area NaI crystals to be used in these spectroscopic portal monitors.

The Group continues to lead an internationally recognized program for standards in nuclear medicine, providing the national standards for radionuclides used in 13 million diagnostic procedures and 200,000 therapeutic nuclear medicine procedures annually in the U.S. Work is currently being carried out on the standardization of two alpha-emitting radionuclides, ^{211}At and ^{223}Ra, that are being investigated for use in targeted radiotherapy against two different forms of cancer. A new initiative, aimed at establishing standards and measurement support to improve accuracy and consistency in quantitative Positron Emission Tomography/X-ray Computed Tomography (PET/CT) and Single-Photon Emission Computed Tomography (SPECT) imaging, has also been started.

The Group's environmental program leads the community in low-level and natural matrix material measurements and standardization, and continues to be heavily involved in the worldwide measurement of environmental-level radionuclide dispersal and contamination through a large number of international intercomparisons, traceability programs, and SRMs. A Radioanalytical Emergency Procedures Manual Database has been developed to assist organizations preparing for emergency response.

ACCOMPLISHMENTS

New Approaches in Radionuclide Metrology

The NIST Triple-to-Double Coincidence Ratio (TDCR) spectrometer has been rebuilt and, as part of the testing phase, standard solutions of ^{3}H were measured to assess its performance. An agreement of 0.3 % between the TDCR and certified massic activities (activity per unit mass) was obtained without any attempt to optimize the value of the ionization quench factor. As a second test, the TDCR was used in experiments leading to the standardization of ^{63}Ni. Part of this study involved a direct comparison with Le Laboratoire National Henri Becquerel (LNHB) using the same solution. The NIST TDCR result for the massic activity was in excellent (0.3 %) agreement with the value reported by LNHB, which used three different TDCR spectrometers to obtain their result.

A short study involving measurements of the electron capture nuclide ^{55}Fe was somewhat less satisfying, with the NIST TDCR and CIEMAT/NIST results agreeing only to within 4 %, although no effort was made during these experiments to optimize the ionization quench factor. Despite the lack of agreement in the experimental results for ^{55}Fe, a comparison of calculated efficiencies as a function of the coincidence ratio using NIST-developed software and a program written at LNHB agreed to within 0.01 %.

Figure 8. NIST TDCR system, open view showing the photomultiplier tubes.

Due to the complexity of the efficiency calculation arising from the need to account for atomic rearrangements and competition between x-ray and Auger electron emission, a separate program needs to be developed for each electron emitter being studied. Programs are under development to analyze data from the decay of the ^{223}Ra decay chain, $^{68}Ge/^{68}Ga$ (mixed electron capture, positron annihilation), and the ^{210}Pb decay chain (beta, conversion electron, alpha). Experiments are currently underway to standardize $^{90}Sr/^{90}Y$ using the TDCR spectrometer. Initial results indicate excellent agreement between the TDCR and CIEMAT/NIST.

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Primary Standardization for a New SRM and International Measurement Comparisons

A primary standardization of ^{55}Fe by isothermal microcalorimetry, initiated in 2004, was completed in 2006. Determinations of the activity for nuclides that decay by pure, low-Z (atomic number) electron capture (EC) to the ground state of their daughters are amongst the most difficult within the realm of radionuclidic standardization. The present work on this difficult-to-measure nuclide is a return by NIST to the use of calorimetry for primary radionuclidic standardizations. While calorimetry was a classical radionuclidic measurement method used by the NIST Radioactivity Group from the early 1950s through 1975 for primary standardizations, it was not used for the past 30 years or so. In the past 5 years, calorimetry was used by NIST to perform calibrations of brachytherapy sources of ^{32}P, ^{90}Sr, and ^{103}Pd.

A solid 30 GBq source of ^{55}Fe was prepared and gravimetrically linked to a ^{55}Fe master solution. The source was used to obtain an accurately determined power measurement using the NIST dual-cell isothermal calorimeter. The power measurement was converted into a ^{55}Fe activity through the use of a conventional average energy per decay estimate. This activity was linked to the master solution, which had an assigned (k = 1) uncertainty of 0.39 %.

This standardization was used as the basis for calibrating a new ^{55}Fe solution standard (SRM 4929F) as well as for measurements of a BIPM-distributed ^{55}Fe solution that was part of an international measurement comparison. Although the results on the international intercomparison are not yet compiled and released by the BIPM, the NIST results are in very good agreement with several other national metrology laboratories.

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Standards for Medical Imaging

NIST has established a satellite facility at Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, to promote measurement accuracy for nuclear medicine imaging. NIST scientists will use the NIST/ORNL Nuclear Medicine Calibration Laboratory to prepare and measure radioactivity standards used for Positron Emission Tomography (PET), a noninvasive technique that helps doctors diagnose diseases (such as cancer), plan medical treatment, and measure the efficacy of therapies. An estimated one million PET procedures were performed in 2004, a number expected to reach three million annually by 2010.

The NIST program needs to be carried out regionally because the short half-lives of most PET radiopharmaceuticals prevent shipment of standard test samples over long distances. Radioactive ^{18}F, for example, decays to half its total radioactivity in about two hours. Therefore, NIST is locating its satellite laboratories at key sites near manufacturers' distribution networks. The sites are selected based on location, capability, and reputation.

ORNL has extensive expertise in radiation measurements, already operates a measurement traceability and testing program with NIST, and is licensed and capable of accepting, handling, and shipping radioactive materials. Initial calibrations of a ^{18}F-FDG solution performed in May 2006 led to the determination of a calibration factor for dose calibrators as are used in the clinical setting. An intercomparison exercise is planned for the near future.

Figure 9. Typical phantom used in clinical quality assurance testing. The red sphere inside the phantom is a NIST prototype demonstrating how calibrated radioactive inserts can be prepared.

Our close collaboration with the user community will lead to the development of improved national standards to evaluate the accuracy and precision of critical and increasingly used medical diagnostic procedures. For example, we are developing realistic and well-characterized phantoms (models) of specific organs and other body parts for the evaluation and calibration of whole body imaging technologies, particularly those relying on the distribution of radioactivity (such as PET). Our work in developing a calibration for ^{68}Ge, which can be used as a longer lived radionuclide for PET instrument calibrations, also contributes towards this goal. Such developments will assure clinical reproducibility, the comparability of clinical results from different sites, and the correlation of measurements with biological parameters.

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Emergency Preparedness for Radiological Incidents

A survey of the national radionuclide metrology community indicated a serious need for performance testing exercises to assess the capability of laboratories to respond quickly to an unexpected release of radioactivity into the environment. Radiological emergency response capabilities had previously focused on *gross* alpha and beta screening and gamma-ray measurements. However, as the 2006 ^{210}Po poisoning incident in the UK had shown, having the capabilities to conduct radioanalytical measurements for *specific* alpha- (and beta-) particle emitting radionuclides is also crucial.

The NRIP'06 emergency preparedness exercise resulted in radioanalytical measurement results reported within eight hours of sample receipt for ^{90}Sr, ^{230}Th, ^{234}U, ^{238}U, ^{238}Pu, ^{239}Pu, and ^{241}Am in urine, soil, and water. Agreement of reported radiochemical results with NIST certified values ranged from 1.4 % to 180 %. While the results varied from laboratory to laboratory and among radionuclides, the information obtained by the participating laboratories will be helpful for method improvement and improved preparedness for radiological emergency incidences.

The Group is also developing a Radioanalytical Emergency Procedures Manual Database (REPMD) to assist organizations preparing for emergency response. This will collect existing procedures from reliable sources into a guide to be accessed and searched by laboratories seeking appropriate methods for sampling, screening, surveying, and making rapid radioanalytical measurements of food, biological, and environmental materials. A first-stage prototype, demonstrating the ability to handle PDF documents describing radioanalytical methods and to simplify the method-collection process, has already been delivered.

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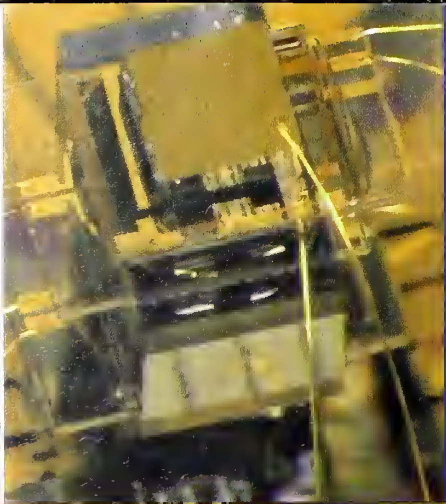

Time and Frequency Division

GOAL

To provide the foundation of frequency measurements and civil timekeeping for our Nation

The strategy of the Time and Frequency Division is to advance measurement science and to provide time and frequency standards and measurement services to commerce, industry, and the public.

The first strategic focus is to develop the standards that serve as reference for time and frequency services and to research advanced measurement systems.

TIME AND FREQUENCY STANDARDS

INTENDED OUTCOME AND BACKGROUND

The Time and Frequency Division maintains 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 coordination of international time and frequency standards, including realization of the SI second.

NIST time and frequency standards are based on the NIST time scale and the NIST primary frequency standard, NIST-F1. The time scale is an ensemble of five hydrogen masers and eight cesium-beam clocks. The stability of the time scale is approximately 0.2 fs/s for thirty days of averaging, with a long-term frequency drift of less than 3 (fHz/Hz)/year. The frequency of the time scale is calibrated by periodic comparisons to the NIST-F1 laser-cooled cesium primary frequency standard (9.2 GHz microwave frequency), with a fractional frequency uncertainty $\Delta f/f$ approaching 4×10^{-16} (0.4 fHz/Hz, as of October 2007).

The NIST time scale is the basis of NIST's realization of Coordinated Universal Time (UTC), the international time scale. NIST is one of about 60 timing laboratories across the world continuously contributing to the realization of UTC. Through improvements to the NIST time scale, NIST's realization of UTC rarely differs from the international average by more than 10 nanoseconds. In addition, NIST is one of only seven laboratories worldwide (as of late 2007) operating the highest accuracy primary frequency standards to determine the frequency (rate) of UTC.

The extraordinarily stable NIST time scale, coupled with world-leading performance of the NIST primary frequency standard (as of late 2007), provides U.S. industry and science with a unique resource for the most demanding applications of accurate time and frequency. However, commercial and scientific needs for even more accurate and stable time and frequency standards drive a vigorous NIST research program to improve microwave frequency standards and to develop new, optical frequency standards.

Since the first atomic clock was invented at the National Bureau of Standards (NIST's predecessor) in 1949, the performance of primary frequency standards has consistently improved by about a factor of ten each decade—driven by, and enabling, advances such as telecommunications synchronization and the Global Positioning System (GPS). NIST research on microwave and optical frequency standards strives to at least maintain this rate of performance improvement.

ACCOMPLISHMENTS

Primary Frequency Standards

The NIST-F1 laser-cooled, cesium fountain primary frequency standard (Fig. 1) is the U.S. national standard for frequency and the realization of the SI second. Since the first formal report of NIST-F1 frequency to the International Bureau of Weights and Measures (BIPM) in 1999, the NIST-F1 uncertainty has been reduced by about a factor of four.

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Figure 1. The NIST-F1 cesium-fountain primary frequency standard, the Nation's standard for frequency and the SI second.

NIST-F1 frequency evaluations reported to BIPM in 2007 included an "in-house" fractional frequency uncertainty of approximately 4×10^{-16} (0.4 fHz/Hz), increasing to about 8×10^{-16} (0.8 fHz/Hz) as received at BIPM due to uncertainties in the satellite-transfer process. Both of these results were the best ever reported to BIPM. NIST-F1 has for several years been the world's best performing primary frequency standard, continuing to lead as the performance of both NIST-F1 and other standards across the world improves.

While continuing to optimize NIST-F1, the Division is actively developing the next-generation primary frequency standard, NIST-F2. The ultimate goal for NIST-F2 is to approach an "in-house" fractional frequency uncertainty of 1×10^{-16} in the next few years. NIST-F2 will use a multi-toss, multiple-velocity system, in which about ten low-density atom balls will be launched to different heights in rapid succession, all coalescing in the detection zone without having crossed paths in the Ramsey interrogation region. This approach will minimize spin-exchange shifts while still providing sufficient atom numbers at detection for good stability.

The second major improvement in NIST-F2 will be to cool the drift tube and interrogation regions to cryogenic temperatures, vastly reducing the blackbody shift. Use of different cryogens, and/or pumping on the cryogens, will also enable accurate measurement of the blackbody shift, the value of which has been the subject of intense debate.

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Research on Optical Frequency Standards

The ultimate accuracy limit of cesium microwave standards, which operate near 10^{10} Hz, is expected to be on the order of 10^{-16} Hz/Hz (their fractional frequency uncertainty). Optical frequency standards, operating on the order of 10^{15} Hz, have the potential for substantially greater stability and accuracy. Optical frequency standards also have a potential for dissemination through optical fiber, which may be advantageous in many applications. As of late 2007, several Division optical frequency standards are performing with fractional frequency uncertainties on a scale of 10^{-17} Hz/Hz, with rapid progress continuing toward the expected achievement of fractional frequency uncertainties in the 10^{-18} Hz/Hz range.

The Division conducts a vigorous research program on prospective optical frequency standards, simultaneously pursuing several different approaches. These include cold, trapped single ions; cold, neutral atom clouds; and "logic clocks," using techniques of quantum information processing. A crucial part of optical clock research is optical frequency synthesis using femtosecond laser frequency combs, described in a later section.

There are several reasons for studying multiple systems. It is too soon to predict which optical standard will have the lowest overall uncertainty during a period of particular rapid progress; having multiple standards using different species and techniques enables intercomparisons that reveal unforeseen uncertainties; different standards show promise for different applications such as higher stability or lower ultimate uncertainty, just as hydrogen masers display greatest stability and cesium fountains lowest uncertainty among current microwave standards; and comparing different frequency standards is a sensitive probe of fundamental physics, such as possible time variation in fundamental constants.

Mercury-Ion Optical Frequency Standard

A frequency standard based on optical transitions (282 nm, 1064.7 THz) in a single, laser-cooled, trapped mercury ion has potential for better accuracy than cesium fountain standards by a factor of 100 or more. With a Q factor > 10^{14} and a transition that is relatively insensitive to environmental factors, the potential fractional frequency uncertainty $\Delta f/f$ for a mercury ion standard is as small as 10^{-18} Hz/Hz.

As of late 2007, continuing improvements in the mercury ion standard have reduced the fractional frequency uncertainty to 1.6×10^{-17} Hz/Hz—the world's best result so far for any frequency standard. This result is about 25 times better than the current NIST-F1 performance. However, frequency is defined by a microwave transition in cesium, so no standard based on another oscillator can have a smaller absolute frequency uncertainty. (As further improvements are developed, there may ultimately be an international redefinition of frequency.)

For several years, NIST has been conducting intercomparisons between NIST-F1, the mercury-ion clock, and other optical frequency standards. Measurements are referenced to NIST-F1 through a hydrogen maser, using a femtosecond-laser frequency comb to compare optical and microwave frequencies. Such experiments demonstrate the frequency stability of the optical standards. They also set a limit on possible variations of fundamental constants related to the fine-structure constant α, in particular the possible temporal variation of the quantity $g_{Cs}\ (m_e / m_p)\ \alpha^6$.

Assuming any variation is due to α only, the most recent NIST result (early 2007) sets an upper bound for the fractional change in the fine-structure constant as no greater than 1.3×10^{-16} per year. It is a tighter bound by about a factor of 300 than astronomical observations that suggested variations in the fine-structure constant over periods comparable to the age of the universe, and better by a factor of 20 compared to previous measurements based on frequency standards.

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"Logic Clock" Optical Frequency Standard

A new type of optical frequency standard uses quantum-information (QI) techniques to exploit previously inaccessible clock transitions. The aluminum ion has a very narrow, doubly forbidden transition at 267 nm that is highly promising for a precise optical frequency standard. However, the aluminum-ion laser-cooling transition at 167 nm is not accessible with current laser technology. The logic clock navigates around this barrier by using a beryllium ion and an aluminum ion in tandem. Laser operations on the beryllium ion—the workhorse of the trapped-ion QI program—cool and interrogate the aluminum ion.

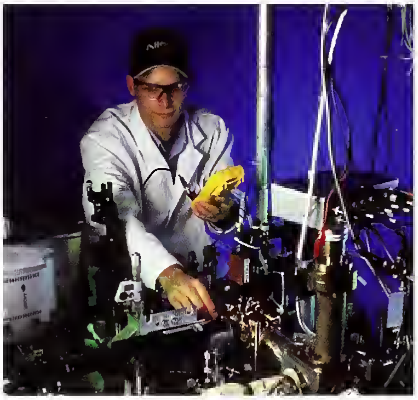

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Figure 2. Till Rosenband adjusts the "logic clock," an optical frequency standard based on quantum information processing techniques.

Even in early-stage development, the aluminum-ion logic clock has relative uncertainties approaching 2×10^{-17} Hz/Hz, with significant improvement likely. This approach can be applied to nearly any ion, opening up a wide range of potential frequency standards that were previously unavailable.

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Neutral Atom Optical Frequency Standards

The Division develops optical frequency standards based on clouds of cold neutral calcium atoms and lattices of cold ytterbium atoms. The calcium optical standard, based on a 657 nm (456 THz) transition, is particularly robust and well suited as a frequency reference ("flywheel") for intercomparisons of optical standards.

Division scientists have constructed a simple, robust, and potentially transportable version of the calcium optical standard, requiring less than 15 minutes warm-up time and remaining locked with no intervention for 10 or more hours. The calcium standard achieves a short-term fractional frequency stability of 2×10^{-15} Hz/Hz with one second of averaging and 3×10^{-16} Hz/Hz for 200 seconds.

The Division recently demonstrated an optical standard based on neutral ytterbium atoms confined to a lattice, produced by the electromagnetic potential wells of standing laser beams. The lattice confines ultracold atoms to small spatial areas, enabling high signal-to-noise ratios while suppressing motion-related effects such as Doppler shifts and cold collisions. The ytterbium lattice is the first example of using even-numbered nuclei (^{174}Yb) with a strictly forbidden $^1S_0 - {}^3P_0$ clock transition. A small, external magnetic field provides enough dipole mixing to enable the transition, one insensitive to AC Stark shifts.

The ^{174}Yb lattice standard demonstrates a fractional frequency stability of order 10^{-16} Hz/Hz in early testing, with substantial improvements expected in the near future.

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The second strategic focus is to develop and operate the frequency and time services essential for synchronizing important industrial/commercial operations and supporting trade and commerce.

TIME AND FREQUENCY SERVICES

INTENDED OUTCOME AND BACKGROUND

The Division provides continuous, reliable, time and frequency signals in a wide variety of formats and accuracies to meet diverse needs of U.S. industry, trade, science, and the general public. NIST time and frequency information is distributed over the Internet, by radio broadcasts, over telephone lines, and through satellites to serve customers in finance, telecommunications, science, transportation, radio/TV broadcasting, and other businesses—and as a reliable and convenient source of official U.S. time for the general public.

NIST radio stations WWV in Ft. Collins, Colorado and WWVH in Kauai, Hawaii broadcast shortwave radio signals containing a rich variety of time and frequency information, in the form of verbal announcements, tones, and digital time codes. NIST radio station WWVB in Ft. Collins, Colorado broadcasts a low-frequency (60 kHz) digital time code that automatically sets consumer timepieces to official U.S. time and date, automatically correcting for daylight saving time, leap years, and leap seconds.

NIST's most heavily used service is the Internet Time Service (ITS), automatically setting clocks in computers and networked devices to NIST time. The Division also provides the modem-based Automated Computer Time Service (ACTS) to set computer and network device time. Many ACTS customers need the security of a direct connection to NIST to ensure that the time is legally traceable to NIST and is auditable. For example, the National Association of Securities Dealers (NASD) requires its 600,000 members to time-stamp many billions of dollars of electronic transactions each business day against NIST time.

The Frequency Measurement and Analysis Service (FMAS) and the Time Measurement and Analysis Service (TMAS) serve industrial and research customers who need tight traceability to NIST time and frequency standards. These customers receive continuous, real-time NIST traceability through a highly automated system remotely monitored by NIST, receiving NIST standards by comparison to GPS broadcasts. The Division has developed similar technology to enable coordination of time scales among nine national timing laboratories in North America, Central America, and South America, with additional laboratories scheduled to join the network in future years. The low-cost, user-friendly systems allow laboratories with limited technical and financial resources to synchronize their time scales to low uncertainties previously available only to the most advanced timing centers.

To enhance U.S. expertise in this field, the Division offers a variety of training courses. A four-day metrology seminar with more than 20 expert instructors is offered annually, a new three-day seminar has been initiated for entry-level time and frequency metrologists, and we cosponsor an annual workshop on synchronization in telecommunications systems. NIST staff members also teach about 20 courses per year on special topics in time and frequency measurement at conferences and on-site at NIST.

ACCOMPLISHMENTS

NIST Internet Time Service (ITS)

Fourteen ITS servers at eleven locations across the Nation respond to more than two billion requests per day (as of late 2007) for setting computer and network clocks to NIST time, automatically. (See Fig. 3.) The Division website provides free client software, complete source code, and complete instructions (about 100,000 downloads per month). Automatic synchronization to ITS is now a capability of the most popular computer operating systems, including the latest versions of Windows, Mac OS, and many commercial versions of Linux.

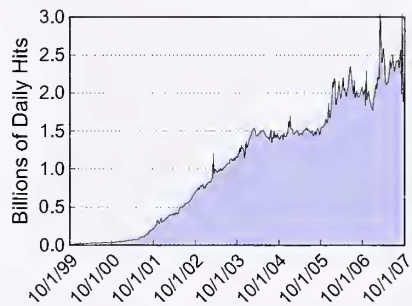

Figure 3. Growth in use of the NIST Internet Time Service.

The Division continually updates the servers, software, and network infrastructure, working with the NIST networking group, to ensure continued provision of ITS in light of increasing demands.

A number of companies have partnered with NIST to add traceability and auditability to ITS for timestamping electronic documents and financial transactions. These applications are in rather limited use now, but are growing rapidly.

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NIST Radio Stations WWV, WWVH, and WWVB

The Division continues to upgrade the radio stations as part of a long-term modernization plan. Progress includes continuing improvements to WWV and WWVB transmitters and broadcast systems, including systems to ensure automatic recovery from power failures or loss of primary transmitters, replacement of WWVH (Hawaii) metal antenna towers with fiberglass towers to eliminate corrosion damage, and upgrading insulators in the guy wires supporting the eight 122 m (400 ft) towers for the WWVB antennas (Fig. 4).

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Figure 4. An aerial view of the WWVB antenna systems.

More than 50 manufacturers produce WWVB-controlled timepieces, with several million new units sold each year. With growing sales, both manufacturers and consumers want to know that WWVB signal strength is sufficiently strong across the Nation to ensure good reception. We designed monitors to measure power from WWVB broadcasts, which we plan to place at strategic locations around the U.S. Each will continuously report the WWVB signal strength to the Division through the Internet. The results will be displayed on a publicly available website, along with archives of all signal strength records. These data will help manufacturers set performance specifications for real-world signal strengths.

We have been actively consulting with WWVB-controlled timepiece manufacturers to improve their product performance. Based on experiments conducted with manufacturers, we modified the modulation depth of the time code broadcasts to provide more reliable performance for radio-controlled timepieces in noisy environments. Also, the Division published *Recommended Practices for Manufacturers and Consumers of WWVB Radio Controlled Clocks* after consultation with manufacturers and enthusiast user groups. It has been downloaded more than 200,000 times in the past two years.

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The third strategic focus is to develop new measurement systems and methods in support of emerging technologies.

NEW MEASUREMENT SYSTEMS AND METHODS

INTENDED OUTCOME AND BACKGROUND

In addition to meeting current customer needs, the Division prepares for the future of time and frequency measurements and calibrations. Through interactions and discussions with constituents, we identify important emerging requirements and technologies. We strive to apply our expertise and creativity to those applications with the potential for greatest impact on U.S. industry, science, and the general public.

Synthesis and measurement of optical frequencies is crucial to the future of Division programs, and time and frequency metrology in general. Division expertise in developing and applying frequency combs based on femtosecond lasers has led to measurement of frequencies with relative uncertainties approaching 10^{-19} (0.1 aHz/Hz), orders of magnitude better than previously possible, and to direct comparison of microwave and optical frequency standards, bridging five decades in frequency. We are working on techniques for amplification, noise reduction, and applications across different frequency ranges, such as the important near-infrared telecommunications range.

A second key thrust is development of new tools to better measure close-to-carrier noise in oscillators and other electronic components. Such measurements are crucial to development of new oscillators, microwave and optical, used in advanced radars, telecommunications, high-speed digital circuits, and many other applications. Much of this work is conducted with significant support from DARPA, involving NIST, industry, and research organizations.

A third major program is the development of ultra-miniature atomic frequency standards and related devices, to dramatically improve the performance of small electronic devices such as GPS receivers, portable magnetometers, and gyroscopes. Such chip-scale atomic devices need not be as accurate or stable as large laboratory standards, but they will bring atomically precise measurement and frequency control to small, battery-powered electronic devices.

DARPA and other funding agencies support the Division's participation in government-industry-university collaborations, recognizing that our core expertise in research and metrology accelerates the development of commercial and military products and services with strategic national economic and security impacts. This support is one important way the Division ensures that programs are well aligned with high-priority industrial and national needs.

ACCOMPLISHMENTS

Improvements in Frequency Combs

A key application of frequency combs based on femtosecond lasers is to generate an arbitrary optical or microwave frequency output given an optical frequency reference input. This remarkable capability is crucial to the development and dissemination of useful optical frequency standards. As mentioned, the Division uses optical frequency combs to directly compare a wide range of microwave and optical frequency standards, including NIST F-1 (9.2 GHz), the calcium atom standard (456 THz), the mercury ion standard (doubled 532 THz), the aluminum ion "logic clock" (doubled 562 THz), the ytterbium lattice clock (519 THz), and the strontium atom clock at JILA (430 THz).

The Division has been continually improving the performance and versatility of frequency combs by exploring new ways to broaden the femtosecond laser output without use of microstructured optical fibers, which are susceptible to damage. The Division also collaborates with the NIST Electronics and Electrical Engineering Laboratory to develop near-infrared femtosecond lasers for improved wavelength and frequency references, such as in the important 1.4 μm to 1.6 μm optical telecommunications band.

The Division led an intercomparison of four different femtosecond-laser frequency combs from three different laboratories, using two fundamentally different comb-generation techniques: broadband operation and nonlinear microstructure fiber. The frequency differences, determined by optical heterodyne techniques, were measured to a relative uncertainty of 1.4×10^{-19} Hz/Hz, with the uncertainty arising primarily from mechanical and thermal effects and limits on integration time. The results suggest optical frequency combs can be reliably used for frequency comparisons and synthesis to at least a fractional uncertainty of 10^{-19} Hz/Hz, and likely better when technical noise (mechanical and thermal fluctuations) are better controlled and longer integration times are used.

Recent Division advances in frequency comb development and applications include techniques for high-resolution, two-dimensional dispersion of the modes of the comb, into a "frequency brush." (See Fig. 5.) This enables rapid, high-resolution spectral fingerprinting—high-resolution absorption spectroscopy of iodine vapor spanning 6 THz can be collected in a few milliseconds. This technique is promising for high-resolution quantum coherent quantum control and arbitrary optical waveform synthesis, areas the Division is actively pursuing.

The Division also demonstrated the use of frequency combs for ultraprecise time and frequency transfer over fiber optic networks, including a "real world" demonstration of time transfer over 30 km of optical fiber in an urban environment with a timing jitter better than 10^{-17} Hz/Hz at 1 second of integration. Such exquisite performance will enable the power of future optical frequency standards to be efficiently transferred and applied.

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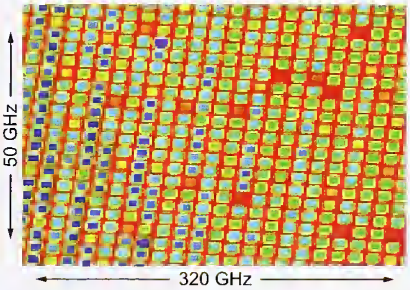

Figure 5. Tara Fortier adjusts an optical frequency comb, and a "frequency brush," dispersed modes of the frequency comb used for massively parallel absorption spectroscopy of iodine.

Figure 6. Scott Diddams with a femtosecond-laser-based optical frequency synthesizer system.

Chip-Scale Atomic Devices

The Division has become a world leader in research, metrology, and development of chip-scale atomic devices (CSADs), bringing atomically precise measurements to portable electronic applications, such as timekeeping and frequency control, measurement of magnetic fields, and inertial navigation (gyroscopes).

The program began with development of a miniature, all-optical atomic clock, based on coherent population trapping. This stimulated DARPA interest in further developing a chip-scale atomic clock (CSAC) to bring atomically precise timing and frequency control to portable electronic devices, such as enhanced GPS receivers and more secure communications devices. The goal is to develop a CSAC of 1 cm^3 total volume, consuming no more than 30 mW of power with a fractional frequency stability of about 1×10^{-11} Hz/Hz over one hour. This has now moved into a commercialization phase in which NIST assists with evaluations.

The Division has expanded the basic chip-scale atomic technology into other types of instruments. Atomic magnetometers, for example, have been developed with physics packages of similar size to the CSACs. Measurements indicate that the sensitivity of these instruments can be as good as 70 $fT/Hz^{1/2}$, which compares favorably with magnetometers based on high-T_c superconducting quantum interference devices (SQUIDs)—but without the need for cryogenic cooling, large electronics packages, and the power they require.

Highly sensitive gyroscopes are under development with the same power and size goals as the clocks and magnetometers. These inertial sensors are based on polarized atomic nuclei that define a direction in space as a reference for precision measure of rotation.

The Division has collaborated with the NIST Electronics and Electrical Engineering Laboratory to use standard MEMS fabrication techniques in making the CSAD physics packages, suggesting that chip-scale atomic devices based on the Division model could be mass-produced at relatively low cost using wafer-level assembly techniques. Such a process would enable the extremely broad application of CSADs. The Division continues to actively partner with companies and research organizations to help commercialize CSADs and to develop new applications.

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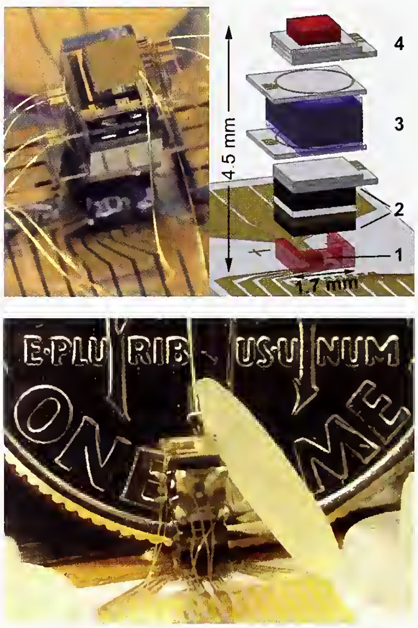

Figure 7. Photomicrograph of the physics package of a NIST chip-scale atomic magnetometer (CSAM), with a schematic diagram. (1) Laser. (2) Optics. (3) Vapor cell with rubidium atoms. (4) Detector. For scale, a CSAM is shown next to a dime and rice grain.

The fourth strategic focus is to develop quantum-logic components and quantum information systems based on trapped ions, in support of new atomic frequency standards and a national program aimed at advancing computation and communication.

QUANTUM INFORMATION PROCESSING USING TRAPPED IONS

INTENDED OUTCOME AND BACKGROUND

We conduct research on the development and properties of prototype quantum-logic devices consisting of small numbers of electromagnetically trapped and laser-cooled ions serving as quantum bits (qubits). This research comprises quantum computing, quantum measurement (including noise reduction in frequency standards), and development of new classes of quantum-logic-based frequency standards.

This project arose as part of a long-term research program on ion-based frequency standards. In particular, the goal of reducing fundamental quantum projection noise suggested the possibility of using similar approaches for quantum computing and quantum metrology. Division researchers soon became leaders in quantum computing research, and NIST-wide programs in quantum computing and quantum communications rapidly developed and demonstrated significant success.

Our focus on quantum computing meets two primary needs. First, quantum computing research is a national priority to ensure economic and physical security, with substantial investment by both defense and civilian funding agencies. Our unique expertise in quanrum state engineering has made the trapped-ion quantum computing program a world-leading effort.

Second, Division work on quantum state engineering serves our time and frequency merrology mission. The "logic clock" optical frequency standard described earlier is an excellent example of quantum information processing techniques being applied to develop a new type of atomic clock, which is already performing comparably to the world's best optical frequency standards. It can, in principle, be adapted to other species that hold potenrial for even better performance. The Division has also demonstrated Heisenberg-limited spectroscopy with three entangled ions, in a scheme that could be scaled to an arbitrary number of ions or atoms. In principle, this could dramatically reduce the averaging time required for a frequency standard to reach its statistical uncertainty limit, substantially improving the performance, and broadening the applications, of atomic clocks.

ACCOMPLISHMENTS

Progress in Quantum State Manipulation for Quantum Computing and Quantum Measurement

The Division's quantum computing and quantum measurement program continues ro make strong progress. We have now demonstrated all the so-called DiVincenzo criteria for a practical, scalable quantum computer, although of course much additional research and development is required before a practical quantum computer is realized.

In the past several years, Division scientists have demonstrated for the first time deterministic teleportation of quantum information on atomic (ionic) qubits—paving the way for efficient transfer of information in a complex quantum computer—and robust quantum error correction schemes necessary for practical, scalable quantum computers. Division scientists achieved a world record of entangling six beryllium ions in a Schrödinger cat state—general considered the most useful and most highly entangled state for quantum information processing.

More recently, the Division has demonstrated semi-classical quantum Fourier transform operations on an array of three trapped beryllium ions. Performing Fourier rransform operations is a key step towards realizing Shor's algorithm in a scalable quantum computer, a method to quickly factor large integers for quantum cryptography.

The Division has demonstrated world-leading coherence times of greater than 10 seconds for single physical qubit states, orders of magnitude greater than previous experiments, and orders of magnitude greater than the typical microsecond-order operation times. In principle this enables many thousands of operations to be performed without loss of coherence. And the Division demonstrated the first successful experimental purification of two-ion entangled states, overcoming the effects of decoherence when one qubit in an entangled pair is physically transported to another location.

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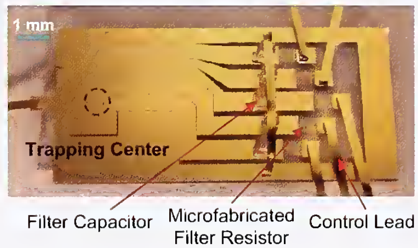

Figure 8. David Wineland adjusting one of the systems used for studying quantum-logic gates, and a new planar electrode ion trap for scalable quantum computing research.

A major challenge for developing a large-scale quantum computer based on trapped ions is to develop an architecture that can simultaneously handle a large number of ion qubits, including laser cooling, quantum processing operations, storage and transport of qubits throughout the computer, and other operations. Recently, the Division has demonstrated a planar geometry for ion traps, where the previous three-dimensional array of electrodes has been "unfolded" into a planar array that still generates an electromagnetic potential well to trap and move the ion qubits. This new planar geometry is highly promising for a practical, scalable solution.

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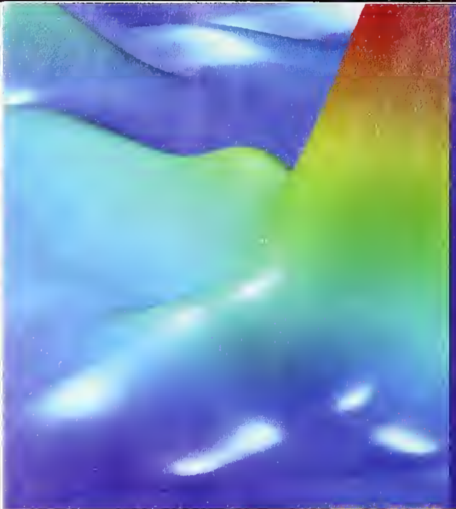

Quantum Physics Division

GOAL

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.

The first strategic element is to develop measurement science tools and applications.

MEASUREMENT SCIENCE

INTENDED OUTCOME AND BACKGROUND

Measurement science is used for many industrial and scientific purposes and is central to many NIST activities. Applications range from providing the length scale for mechanical measurements to providing a direct connection between optical and radio frequencies. The Quantum Physics Division continues a leadership role in developing new precision-measurement techniques and applications.

The highly stabilized laser is the workhorse in precision measurement. Traditionally, this meant continuous wave (CW) lasers that generate light with a very precise and stable single frequency. Recently, the Division became an international leader in adapting CW techniques to the stabilization of mode-locked lasers, which generate a broad comb composed of sharp lines, each of which has a very precise and stable frequency. Such a stable frequency comb not only simplifies measurement at any given optical frequency, but also facilitates establishing a direct connection between optical and radio frequencies. This connection, in turn, enables optical atomic clocks and absolute optical frequency metrology. The importance of femtosecond (10^{-15} s) comb techniques, and the Division's contributions to them, was recognized by the 2005 Nobel Prize in Physics, shared by long-time Division member and JILA pioneer John L. Hall.

Applying precision optical spectroscopic techniques to help improve our understanding of molecular interactions is also proving fruitful. They can also be used for addressing fundamental physical problems, such as determining the electron electric dipole moment.

These developments continue JILA's tradition of developing laser stabilization and associated precision measurement methods used today by NIST, the international standards community, and leading universities worldwide. Our strong position in this new field assures NIST's continued leadership in standards and measurement.

ACCOMPLISHMENTS

Electron Electric Dipole Measurement

The so-called Standard Model of particle physics is enormously successful in predicting the behavior of the zoo of subatomic particles that make up the world around us. However, it can be shown mathematically that this model cannot explain what happens to particles that collide at very high energies, nor can it describe the high-temperature conditions that must have been present at the very earliest moments after the big bang. It is not possible to build an accelerator big enough to reconstruct those conditions, but theorists point out that the speculative models they construct to explain the highest energy physics also make predictions about the properties of everyday, room temperature particles, predictions that can be tested in a precision measurement lab.

One such prediction is that the electron should have a nonzero electric dipole moment (EDM). The assertion is that the electron possesses a tiny asymmetry such that its center-of-mass and its center-of-charge will be offset from one another. If the current experimental limit on this offset could be improved by a factor of 100, a large class of proposed extensions to the Standard Model could be either disproved or else provided with their first experimental support.

The experiment is daunting: the current experimental limit says the offset is smaller than 10^{-14} femtometers. Put another way, if you were to scale the electron up to the size of the earth, its asymmetry would be smaller than a wavelength of light.

To go another two orders of magnitude further, Division scientists are making use of cold, trapped molecular ions to serve as high-electric-field laboratories for studying electrons. They are probing the electron-in-a-molecule system with a combination of frequency-comb-enabled optical spectroscopy and atomic-clock-driven radio-frequency spectroscopy.

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Figure 1. The Quantum Physics Division's newest hire, James Thompson.

Optical Atomic Clocks

An optical atomic clock uses an optical frequency transition as its quantum reference, giving it better frequency stability than a clock using the standard microwave-frequency transition. An optical clock produces a phase-coherent RF signal from the optical standard by using an optical frequency comb that is precisely phase stabilized to the optical standard.

An optical atomic clock based on ultracold strontium atoms confined in an optical lattice has demonstrated a world-record spectral resolution, reaching a resonance quality factor of 2.4×10^{14}. The fractional frequency instability has already reached 3 fHz/Hz at 1 s. We have characterized the systematic uncertainty in fractional frequency to 0.15 fHz/Hz, which has surpassed the current best evaluations of the NIST cesium primary fountain standard. Future progress on this atomic clock is expected to be as fruitful as in the past. We expect to push this system to an accuracy level reaching 0.01 fHz/Hz and instability lower than 1 fHz/Hz at 1 s.

The stability of such a clock can be evaluated only through comparison to another high-stability optical clock. Ideally, comparison to a third clock is needed to determine the performance of all of the clocks involved. The need for comparison has hindered atomic clock development because the timing/frequency signals are degraded by transmission. Recent efforts at JILA and NIST have demonstrated coherent optical phase transfer over a 32 km optical fiber with fractional frequency instability of 0.01 fHz/Hz at 1 s.

This work constitutes a major advance in the ability to distribute extremely precise and accurate frequency and timing signals over long distances through fiber networks. In fact, we have recently taken advantage of this capability to remotely compare the Sr lattice clock at JILA against the Ca optical clock in the Time and Frequency Division at NIST. The short-term stability of the Ca clock permitted the evaluation of the overall systematic uncertainty of the Sr clock at the level of 0.15 fHz/Hz.

These fiber stabilization results are a two-orders-of-magnitude improvement in the stability of frequency distribution, and demonstrate the lowest level of timing jitter and phase noise for a tens of kilometer long-distance timing distribution system. This technology will be extremely valuable for particle accelerator facilities, synchronized radio or optical telescope arrays, remote calibration of length standards, and long-distance interferometry.

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Fundamental Limits to Femtosecond Combs

Femtosecond optical frequency combs generated by mode-locked lasers have revolutionized optical frequency metrology and enabled optical atomic clocks. Measurements have shown that the intrinsic stability of femtosecond combs is remarkable, better than 10^{-18} Hz/Hz.

At some level, quantum fluctuations will set a lower limit for the stability, in a manner analogous to the well-known Schawlow-Townes linewidth of a CW laser. Just as for the Schawlow-Townes linewidth, some photons spontaneously emitted by the gain medium will be incorporated into the lasing mode, but they will have the wrong phase, timing, and wavelength. A mode-locked laser is intrinsically a nonlinear system, thus the analysis is much more complex than for a CW laser, although there are similarities to noise processes in an amplified fiber optic telecommunications system.

Accurate calculation of the effect of quantum fluctuations on a mode-locked laser requires a good understanding of the laser's dynamic response to a small perturbation. We have experimentally characterized the dynamics by recording how the pulse energy, center frequency, phase, and timing respond to small changes in pump power. The measurements showed that gain dynamics, which had been neglected previously, must also be included. The full characterization is now being used to predict the phase fluctuations driven by spontaneously emitted photons.

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The second strategic element is to exploit Bose-Einstein condensation, quantum degenerate Fermi gases, and cold molecules for metrology and ultralow-temperature physics.

ULTRACOLD ATOMS AND MOLECULES

INTENDED OUTCOME AND BACKGROUND

The Quantum Physics Division and JILA are world renown for studies of Bose-Einstein condensates and quantum degenerate Fermi gases. The exemplary JILA collaboration between NIST and the University of Colorado (CU) led to the achievement of the first Bose-Einstein condensate by Eric Cornell (NIST) and Carl Wieman (CU), who together received the 2001 Nobel Prize in Physics. This achievement, coupled with the creation of the first quantum degenerate Fermi gas and the first Fermi condensate by MacArthur Fellow Deborah Jin (NIST), places the Quantum Physics Division and JILA at the forefront of studies of macroscopic quantum mechanical systems.

A better understanding of these systems is critical as the miniaturization of electronic components pushes into the size region where quantum mechanical effects play a significant role in their operation. Additionally, these systems provide unique opportunities for metrology and for gaining insights into analogous transitions in technologically important solid-state systems. We plan to continue to explore the new quantum mechanical systems that these discoveries have made accessible and to maintain our leadership position. The development of techniques to produce ultracold molecules also promises important advances in chemical physics.

ACCOMPLISHMENTS

Casimir-Polder Forces

When two solid objects are brought very close together but not quite into physical contact, they experience a mutual attraction called the Casimir force. While this force is very small by most measures, it has technological significance because in nanoscale mechanical devices, the force can dominate the behavior. Generated by quantum mechanical fluctuations in the vacuum separating the two objects, the Casimir force has long been predicted to depend on temperature, although this dependence has never been conclusively demonstrated.

Division scientists have been studying an effect that is simpler than, but related to, the Casimir force—the Casmir-Polder force. This force between a solid surface and a nearby atom is so small that it is most readily studied using an ultracold sample of atoms, a Bose-Einstein condensate (BEC).

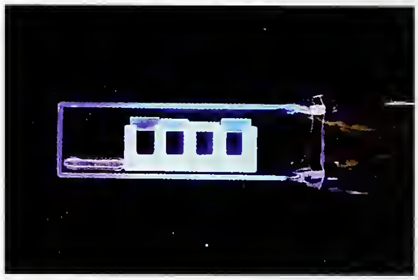

Figure 2. The ultrahigh vacuum chamber used for Casimir force measurements.

Division scientists have recently succeeded in observing for the first time the temperature dependence of a Casimir-type force. A BEC of rubidium atoms was suspended magnetically about 6 μm above a surface of fused quartz. Then, as the surface temperature was increased from 300 K to 570 K, the attractive pull on the BEC was seen to more than double.

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Kosterlitz-Thouless Transition on a Lattice

The nature of a phase transition (such as melting, ferromagnetism, superconductivity, or superfluidity) can be strongly affected by the dimensionality of the system. For instance, it's widely believed that high-T_c superconductivity is at least in part a consequence of the two-dimensional nature of the layered structure of copper oxide crystals. In gases of ultracold atoms, the now familiar Bose-Einstein phase transition (between a normal and a superfluid gas) that occurs in three dimensions is predicted to be suppressed in two dimensions in favor of a more exotic transition known as the Berezinskii-Kosterlitz-Thouless (BKT) transition.

Division scientists have been studying BKT physics in a system of ultracold rubidium atoms confined in a two-

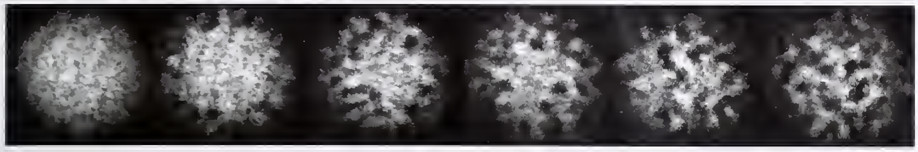

Figure 3. Top view of a quasi-2D Bose-Einstein condensate as the effective temperature gradually increases from left to right. The randomly ordered dots that appear at higher temperature are the cores of thermally generated vortices and are the signature of a Berezinskii-Kosterlitz-Thouless transition.

dimensional optical lattice. Atoms can move from one well of the lattice only by tunneling; atoms within each well make up a conventional, if small, 3-D BEC, with a well-defined quantum phase. Initially, the phases in all the wells are the same; the phase coherence of the system extends across the entire sample. As the temperature is increased, thermally driven phase fluctuations increase and eventually pairs of vortices are spawned and wander randomly through the sample, destroying the phase coherent state. The sudden appearance of vortices is the microscopic mechanism for the BKT transition. While the BKT transition has been studied in other condensed-matter systems, this is the first time the appearance of vortices has been quantitatively documented.

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Ultracold Fermions and Superfluidity

Several studies of the behavior of Fermi condensates in the region of the BCS-BEC crossover have been completed. Working with condensed matter theorists with expertise in high-T_c superconductivity, the measured phase diagram for Fermi superfluidity was compared with a BCS-BEC crossover theory. While the good qualitative agreement seen in this comparison is very encouraging, quantitative differences reveal the need for more advanced theoretical understanding of the crossover.

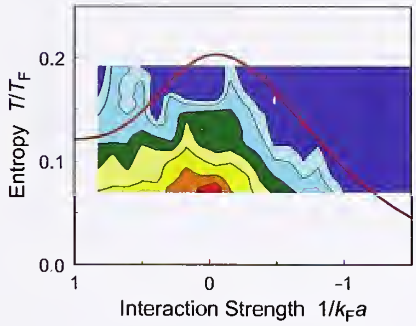

Figure 4. Measured Fermi superfluid phase diagram compared with BCS-BEC crossover theory (red line).

We have also quantitatively studied the thermodynamics of the Fermi gas in the region of the BCS-BEC crossover. We measured the momentum distribution of the Fermi gas, which shows dramatic effects due to the pairing of atoms. We also measured the energy of the gas at unitarity (strongest possible interactions). This measurement demonstrated that ultracold Fermi gases are in the regime of "universality," where the physics does not depend on the details of the interatomic potentials.

In related work, a new experimental probe of the gas was introduced by demonstrating that information can be extracted from noise in absorption images of the ultracold cloud. In particular, by looking for correlations in the noise we were able to detect atom-pair correlations, including both spatial correlation and momentum correlations. In the future, this new technique could be used to detect the pairing of atoms in a Fermi superfluid.

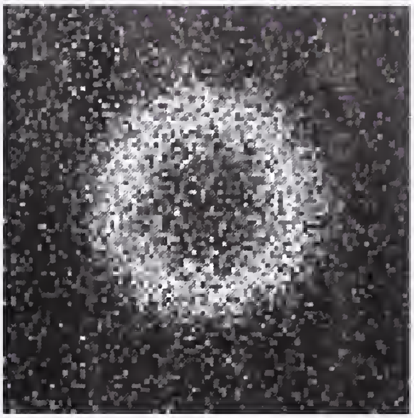

Figure 5. *P*-wave molecules, seen after dissociation.

Another exciting direction for future work is exploring the possibility of creating new types of Fermi superfluidity. To this end, we have explored the possibility of creating a new type of atom pairs using a *p*-wave Feshbach resonance in the ultracold Fermi gas. We successfully created and detected *p*-wave molecules, as well as *p*-wave quasi-bound states. We measured both the energy of these pairs and their lifetime as a function of magnetic field. Unfortunately, the measured lifetime of the molecules is relatively short and appears to be limited by molecule-atom collisions.

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Cold Molecules

We have performed the first experimental and theoretical investigations of ground state polar molecules confined within a potential surface defined by combined electric and magnetic fields. This type of trap is novel as the molecule has both electric dipole and magnetic dipole moments, causing complex dynamics within the spatially inhomogeneous electric and magnetic fields. Unlike previous work where ground state polar molecules were trapped inside an electric trap, the new trap configuration gives the freedom to apply an external electric field to control dipole-dipole interactions while keeping the molecules trapped in an inhomogeneous magnetic field.

This capability will be important for precision measurements and for study of dipolar gas physics and cold dipolar collisions and reactions. We have already used this trap to determine the collision cross section between cold molecules and hot background gas. In addition, we made clear observations of single particle dynamics inside the trap that are in excellent agreement with theory.

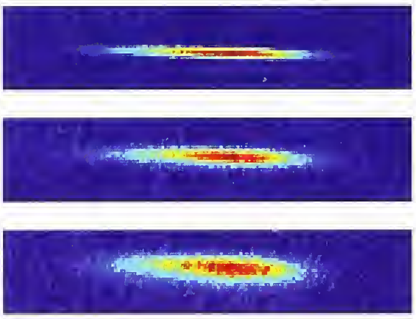

Figure 6. Absorption images of a gas of ultracold heteronuclear molecules expanding after release from the trap. Elapsed time on top frame is 1 ms, middle 3 ms, and bottom 6 ms.

We see a possibility of producing ultracold polar molecules from ultracold gases, using Feshbach resonances and optical transitions. For this experiment we have built an apparatus that is capable of producing ultracold-atom gas mixtures and accessing magnetic-field Feshbach resonances.

Rapid progress has been made in this experiment. Using an interspecies Feshbach resonance, we have created and detected heteronuclear Feshbach molecules, measured their binding energy as a function of magnetic field, and studied various molecule-atom collisions that limit the molecule lifetime. These results are very promising in that we have been able to realize relatively long lifetimes for ultracold, trapped molecules.

With these molecules we have begun optical spectroscopic measurements, exploring transitions to electronically excited molecule states. We have seen a dramatic enhancement in these excitation rates when starting with Feshbach molecules, compared to photoassociation of ultracold atoms. Future work will employ multiple optical frequencies, referenced to an optical frequency comb, to drive these weakly bound molecules to more deeply bound states.

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The third strategic element is to advance ultrafast science.

ULTRAFAST SCIENCE

INTENDED OUTCOME AND BACKGROUND

Ultrafast science has traditionally exploited ultrashort optical pulses with durations as short as a few femtoseconds. These pulses provide precise time resolution and/or high peak powers. Because they are produced by mode-locked lasers, their frequency comb spectra can be controlled with the techniques described in the first strategic element. In ultrafast science, the control of the comb spectrum corresponds to control of the electric field of the pulses in the time domain. Control of the electric field of the pulses enables the observation of unique physical phenomena and the ability to coherently synthesize new pulse shapes.

Traditional ultrafast techniques are used in the Division to study the interactions of excitons in semiconductors, collision dynamics in atomic vapors, and the motion of biomolecules, providing technologically important information for both optoelectronics and biotechnology. We use phase stabilization to improve measurement techniques and develop radical new ultrafast technologies such as “gainless” amplification of femtosecond pulses in a build-up cavity.

ACCOMPLISHMENTS

Femtosecond Enhancement Cavities

The use of femtosecond enhancement cavities continues to push the frontiers on wide-bandwidth molecular detections and VUV frequency comb generation. Optical frequency comb-based cavity-ringdown spectroscopy has recently enabled high sensitivity absorption detection of molecules over a broad spectral range.

We have demonstrated an improved system based on a mode-locked erbium-doped fiber laser source centered at 1.5 μm, resulting in a spectrometer that is inexpensive, simple, and robust. It provides a very large spectral bandwidth (1.45 μm to 1.65 μm) for investigation of a wide variety of molecular absorption features. Strong molecular absorption at 1.5 μm allows for detection at sensitivities approaching the level of 1 nL/L. We have performed measurements of the rovibrational spectra for CO, NH_3, H_2O, and C_2H_2 with an absorption sensitivity of 10^{-8} $cm^{-1}Hz^{-1/2}$ per detection channel. Spectral resolution has been dramatically improved to less than 100 MHz, easily useful for isotope identification.

Femtosecond enhancement cavities can also be used to reach high intensities, which are usually achieved by using low repetition rate, expensive optical amplifiers. High-harmonic generation at 136 MHz repetition rate has been produced with a cavity enhanced, Yb-fiber frequency-comb laser. The intracavity field peak intensity reaches above 3×10^{14} W/cm^2, corresponding to a record high 3.5 kW average power. We have demonstrated laser-induced plasmas and high-harmonic generation in Xe, Kr, and Ar. High-harmonic signals after an Al filter have been observed, thus it is clear that we are now reaching shorter wavelengths in comb generations than ever before.

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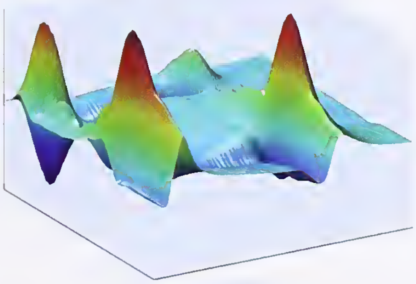
Optical Two-Dimensional Fourier Transform Spectroscopy

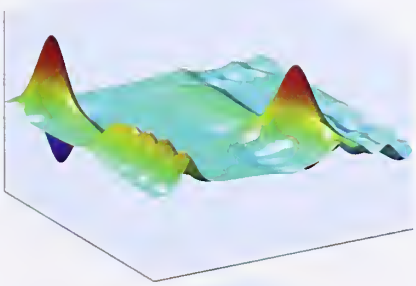
An optical two-dimensional Fourier transform spectrometer has been developed and is being used to study many-body effects in semiconductors. Multidimensional Fourier-transform spectroscopy was originally developed in nuclear magnetic resonance using radio frequencies. Recently there has been significant work to bring these techniques to infrared and optical frequencies. Achieving the necessary phase control and stability is a challenge. We have achieved it by using actively stabilized delay lines.

Many-body effects in semiconductors were extensively studied using traditional ultrafast spectroscopic techniques. While the experimental results proved the nonlinear signals are dominated by many-body effects, they were unable to disentangle the various terms. Optical two-dimensional Fourier transform spectroscopy excels at separating the various contributions to the signals. The separation is in part due to the spreading of the signals in two dimensions and also because full phase information can be obtained. The experimentally obtained spectra have been compared to calculations and show good agreement, but only when terms beyond the standard Hartree-Fock approximation are included.

a)



b)



c)

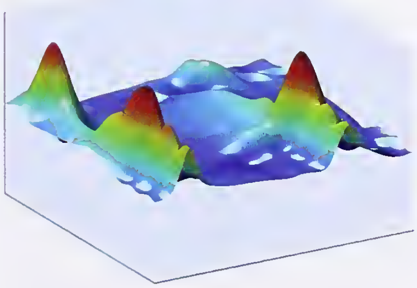


Figure 7. Two-dimensional Fourier Transform spectra of exciton resonances in a GaAs heterostructure. (a) is experimental data, (b) is theory within a Hartree-Fock approximation, and (c) is a full theory including terms beyond Hartree-Fock.

A second-generation spectrometer is under development. It will allow all excitation pulses to be phase locked, not just two, as is the case for the current spectrometer. The new spectrometer will be used for continuing studies on semiconductors and for studies of atomic vapors and proteins.

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Grism-Based, Scalable-Repetition-Rate Ti:Sapphire Amplifier

Working with academia and industry, Division scientists have developed efficient reflection grisms (gratings in contact with prisms) for pulse compression in femtosecond Ti:sapphire laser amplifiers. These components simplify and miniaturize the optics required for commonly used femtosecond amplifier systems. A simple and efficient grism-based femtosecond amplifier system that produces 36 fs, 300 μJ pulses at 5 kHz to 15 kHz repetition rates was demonstrated using the down-chirped pulse amplification technique.

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The fourth strategic element is to apply cutting edge measurement science to biological systems.

BIOPHYSICS

INTENDED OUTCOME AND BACKGROUND

The Quantum Physics Division investigates important biological systems at the single molecule level, thus leveraging our measurement expertise and experience with atomic and quantum systems. Accordingly, we are evolving a part of our research program in this direction to help NIST contribute to the scientific revolution taking place in the biosciences.

The Division's strengths are the foundation for our efforts to contribute to groundbreaking research on biological systems. These strengths include our ability to build institutional bridges to renowned university departments, a superlative infrastructure, experience in manipulating and measuring atomic and quantum mechanical systems, and a reputation that allows us to attract and hire the best and brightest of today's young scientists. Our new biophysics program is being implemented in close collaboration with the Department of Molecular, Cellular, and Developmental Biology and the Biochemistry Division of the Chemistry Department at the University of Colorado. We expect that bringing additional departments into JILA will enhance the very productive interdisciplinary character of the institute. Most importantly, because of our existing expertise, NIST's bioscience program should rapidly acquire the high stature achieved by our other programs.

ACCOMPLISHMENTS

Subnanometer Optical Tweezers Measurements of DNA Molecular Motor

Single molecule experiments are revolutionizing biophysics. Optical traps, also known as optical tweezers, can hold micrometer-sized beads in three dimensions, apply calibrated piconewton-scale forces, and measure displacement with atomic precision.

Atomic-scale sensitivity is most useful for biology if it can be maintained over periods sufficient to average Brownian motion, and thus reveal the underlying protein motion. The most widely used single molecule experiments are anchored to surfaces, but drift of this surface prevents them from being atomically precise. To address this shortcoming, the Division has developed an actively stabilized, optical-trapping microscope based upon improved laser stability and the introduction of a fiducial mark firmly attached to a cover slip.

To demonstrate the capabilities of this microscope, measurements were made on a DNA helicase. DNA helicases are molecular motors that unwind DNA, which is critical to the replication and repair of the genome. As they hydrolyze adenosine-triphosphate (ATP), they unwind the DNA duplex.

Pioneering work on a super-family one (SF1) helicase provided the first direct evidence for the step size of a helicase. These single-turnover biochemical unwinding experiments showed a rate limiting step every 4 to 5 base pairs (bp). This large "kinetic" step size has been seen in other SF1 helicases for unwinding double stranded DNA (dsDNA). In contrast, recent crystallographic studies of SF1 helicases bound to DNA, in different nucleotide states, suggested one base pair motion per ATP. Fluorescent ATPase assays also show 1 ATP/bp. Thus, the mechanism and step size of SF1 helicases (if a single step size is even correct) remains unresolved.

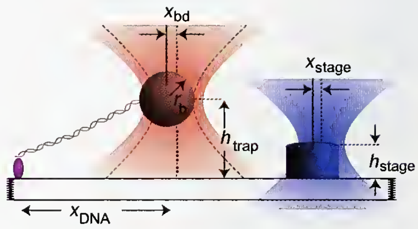

Figure 8. An optical trap stretches a DNA molecule. One detector laser measures the trapped bead position, while the other one measures the sample drift. This drift is then actively suppressed by moving a piezoelectric stage in three dimensions.

To address this ongoing uncertainty, we directly measured the physical step size of a SF1 helicase (RecBCD) along DNA using a single-molecule, optical-trapping assay with atomic-scale resolution. With this enhanced resolution, we note three significant results. First, RecBCD takes distinct steps of variable size (2 bp to 7 bp, occasionally larger). Second, the average observed step size is 4.1 bp, which agrees with the previously determined kinetic step size (3.9 bp). Third, we see an unexpected backward motion of a few base pairs at moderate force and low ATP levels, consistent with a kinetic competition between reannealing of the unwound DNA and forward helicase activity.

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Femtosecond Spectroscopy of Heme-proteins

Heme proteins fulfill diverse roles, important in both human health and in biotechnology. In the former, they serve as carriers and storage molecules for oxygen and other small molecules in tissues, as electron transfer mediators in mitochondrial respiration, and as drug metabolizers in the liver. In technological applications, heme proteins are being employed in toxic waste remediation and in hybrid bio-nano-electronics systems.

Research on the function of heme proteins has largely focused on structure. However, paralleling the growth in structural data, a large body of evidence has accumulated showing that proteins are flexible molecules, continuously undergoing structural fluctuations on timescales ranging from femtoseconds to seconds or longer. Since protein motions are critical to their kinetics (e.g. the access of molecules to their interiors) and thermodynamics (e.g. entropy), there is a compelling need to quantify the relation between structure, dynamics, and function.

We have performed photon echo spectroscopy on heme proteins, and have used a combination of experiments and theory to demonstrate that, with an understanding of the symmetry properties of the heme, this popular measurement technique can be used to provide information on protein motions. The development of this method sets the stage for detailed studies of physiologically and industrially relevant heme proteins.

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Real Time Folding Kinetics of Single RNA Molecules

The ability to image fluorescence from single biomolecules represents one of the major scientific achievements of the last decade. In combination with time-correlated single photon counting, these methods now offer an unprecedented window into kinetics and dynamics of single biomolecules. They completely avoid the "blurring" that unavoidably occurs in any collection of molecules due to ensemble averaging.

The biomolecules are labeled with donor and acceptor dyes, where the efficiency of fluorescence resonance energy transfer (FRET) from initially excited donor to acceptor is a strong function of the biomolecular conformation. For donor/acceptor dye pairs bound to a folding biopolymer, the FRET efficiency (i.e., $I_{red}/(I_{red}+I_{green})$) and polarization anisotropy information are monitored in real time and used to provide conformational information from the well known distance and alignment dependence for dipole-dipole energy transfer.

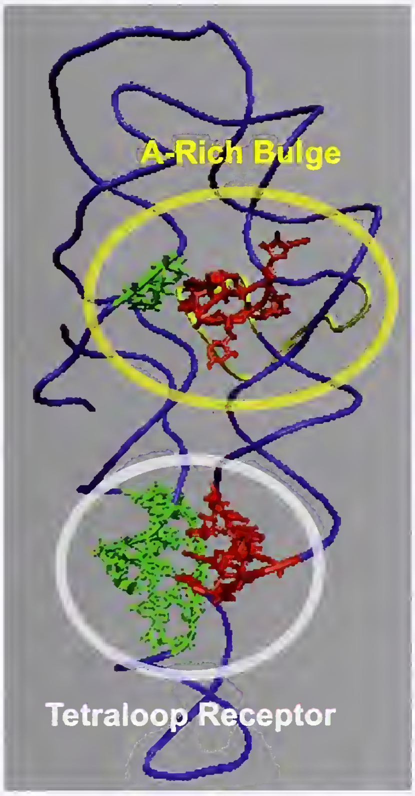

Figure 9. The P4-P6 domain of the Tetrahymena thermophyla group 1 Intron. The "tetraloop/tetraloop receptor" and "A-rich bulge" are ubiquitously present in ribozymal RNA.

Work in the Division has focused on real time folding dynamics of small RNA sequences, using single molecule FRET methods to explore tertiary "loop-loop" interactions responsible for making larger ribozymal RNA fold into biochemically active conformation. The specific system of interest is the P4-P6 domain of the Tetrahymena thermophyla group 1 Intron, in particular the presence of two classic tertiary binding motifs (the "tetraloop/tetraloop receptor" and "A-rich bulge") ubiquitously present in ribozymal RNA. This system is an interesting target from a biophysical perspective because we know the exact RNA sequence, and therefore can successfully design relatively simple constructs that recapitulate a specific tertiary motif in isolation.

Recently, we have focused on developing new experimental "burst" capabilities for studying single RNA constructs freely diffusing in solution, which permit a rigorous control for ruling out possible surface tethering effects on the kinetics. Data reveal "bursts" of fluorescence as single RNA molecules diffuse into and out of the focused laser excitation volume (≈0.1 fL). Analysis of the "red" vs. "green" photon arrival statistics permits us to infer the FRET value and therefore the folded vs. unfolded conformation of an individual RNA as a function of external stimulus (e.g., $[Mg^{+2}]$).

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Office of Electronic Commerce in Scientific and Engineering Data

GOAL

To coordinate and facilitate the electronic dissemination of information via the Internet

The strategy for meeting this goal is to publish Physics Laboratory information on the World Wide Web, to develop web-accessible databases of physical reference data, and to evolve protocols to ensure interoperability in the exchange of scientific and engineering data.

WWW DISSEMINATION OF INFORMATION

INTENDED OUTCOME AND BACKGROUND

The Office of Electronic Commerce in Scientific and Engineering Data (ECSED) is responsible for the Physics Laboratory (PL) World Wide Web pages at **http://physics.nist.gov.**

We produce material for Web publication, encourage and support the production of material by others, and ensure the high quality of disseminated information. We are also engaged with PL Divisions and the Measurement Services Division of Technology Services in developing physical reference databases for Web dissemination. We design and develop effective Web database interfaces to facilitate access to the data, providing data in multiple formats suitable for customer needs.

Since June 1994, we have provided a wide array of information ranging from physical reference data, technical activities, research and calibration facilities, technical contacts, publication lists, general interest, and news items. For the most recent six months, there was an average of nearly 2 million requests for web pages per month from the Gaithersburg server, over half coming from about 30 online databases containing physical reference data. A complete list of our databases is available at http://physics.nist.gov/data.

Recent work includes the development of new (1–4) and updated (5–11) Web databases:

1. Atomic Energy Levels and Wavelengths Bibliographic Database
2. NLTE4 Plasma Population Kinetics Database
3. SAHA Plasma Population Kinetics Database
4. FLYCHK Collisional-Radiative Code
5. Fundamental Physical Constants
6. Searchable Bibliography on the Constants
7. Atomic Spectra Database
8. Energy Levels of Hydrogen and Deuterium
9. Atomic Transition Probabilities Bibliographic Database
10. Atomic Spectral Line Broadening Bibliographic Database
11. X-ray Transition Energies

ACCOMPLISHMENTS

Units Markup Language

We have continued to develop an XML (eXtensible Markup Language) schema for encoding scientific measurement units. This includes initiating an OASIS (Organization for the Advancement of Structured Information Standards) UnitsML Technical Committee to finalize the development of the UnitsML schema. Adoption as a standard will allow for the unambiguous exchange of numerical data over the Internet.

To complement the UnitsML schema, we are in the process of developing a database (UnitsDB) containing detailed information on both SI and non-SI scientific units. We anticipate UnitsDB will be used by our customers to download industry-specific dictionaries of scientific units, using a Web Services interface.

We are also planning to develop a general ontology to describe the relationship between measurement quantities independent of any specific system of units. These activities are supported in part by the NIST Systems Integration for Manufacturing Applications (SIMA) program.

Support for Publication of the DLMF

Abramowitz and Stegun's *Handbook of Mathematical Functions (with Formulas, Graphs, and Mathematical Tables)* was first published by the National Bureau of Standards in 1964. It remains a technical bestseller and is among the most widely cited of all math reference compendia. But the *Handbook* is increasingly out of date, especially its numerical tables which account for over half its length. It also lacks many recent developments in the theory and computation of functions that find essential use in physics and other sciences.

A project is underway at NIST to develop a replacement that will become a major resource of math reference data for special functions and their applications. The new *Digital Library of Mathematical Functions (DLMF)* will appear in a hardcover edition and as a free electronic publication on the Web, at http://dlmf.nist.gov/. The completed hardcover edition will be over 1000 pages in length and is scheduled to be printed in 2008.

We provided support to the development of the *DLMF*. This assignment entailed electronic editing of existing chapters with extensive handwritten corrections, and adding new sections from handwritten text. We began working on the *DLMF* in August 2003 (providing up to 40 % of one staff person per year) and ultimately contributed to all 37 of its chapters.

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NIST Atomic Spectra Bibliographic Databases

New Capabilities for On-Line Databases

Atomic Transition Probability Bibliographic Database

The NIST Atomic Transition Probability Bibliographic Database (http://physics.nist.gov/fvalbib) has been available on-line since 1994, and was one of Physics Laboratory's first physical reference databases available on the Web. This database contains references to publications that include numerical data, comments, and reviews on atomic transition probabilities (oscillator strengths, line strengths, or radiative lifetimes). The initial database contained approximately 2300 references. The current database now contains 7465 references, dating from 1914 through 2007.

Atomic Energy Levels and Spectra Bibliographic Database

We recently collaborated with Physics Laboratory's Atomic Spectroscopy Data Center to release an on-line version of the NIST Atomic Energy Levels and Spectra Bibliographic Database (http://physics.nist.gov/elevbib). Its references pertain to atomic structure and spectra that arise from interactions or excitations involving electrons in the outer shells of free atoms and atomic ions, or from inner shell excitations corresponding to frequencies up to the soft x-ray range. This interactive database allows access to references on atomic energy levels and wavelengths. Preference is given to experimental papers. The database contains approximately 10880 references, dating from 1892 through 2007.

Atomic Spectral Line Broadening Bibliographic Database

The NIST Atomic Spectroscopy Data Center also maintains an additional bibliographic database that contains references to publications that include numerical data, general information, comments, and reviews on atomic line broadening and shifts (http://physics.nist.gov/linebrbib). The NIST Atomic Spectral Line Broadening Bibliographic Database, on-line since 1998, has been updated to contain 3666 references, dating from 1961 through 2007.

These bibliographic databases have a wide customer base including major corporations, government laboratories, and universities. The users of these databases include scientific researchers working in atomic physics, laser physics, lighting, semiconductor fabrication, material processing, biophysics, thermonuclear fusion, astrophysics, and chemistry.

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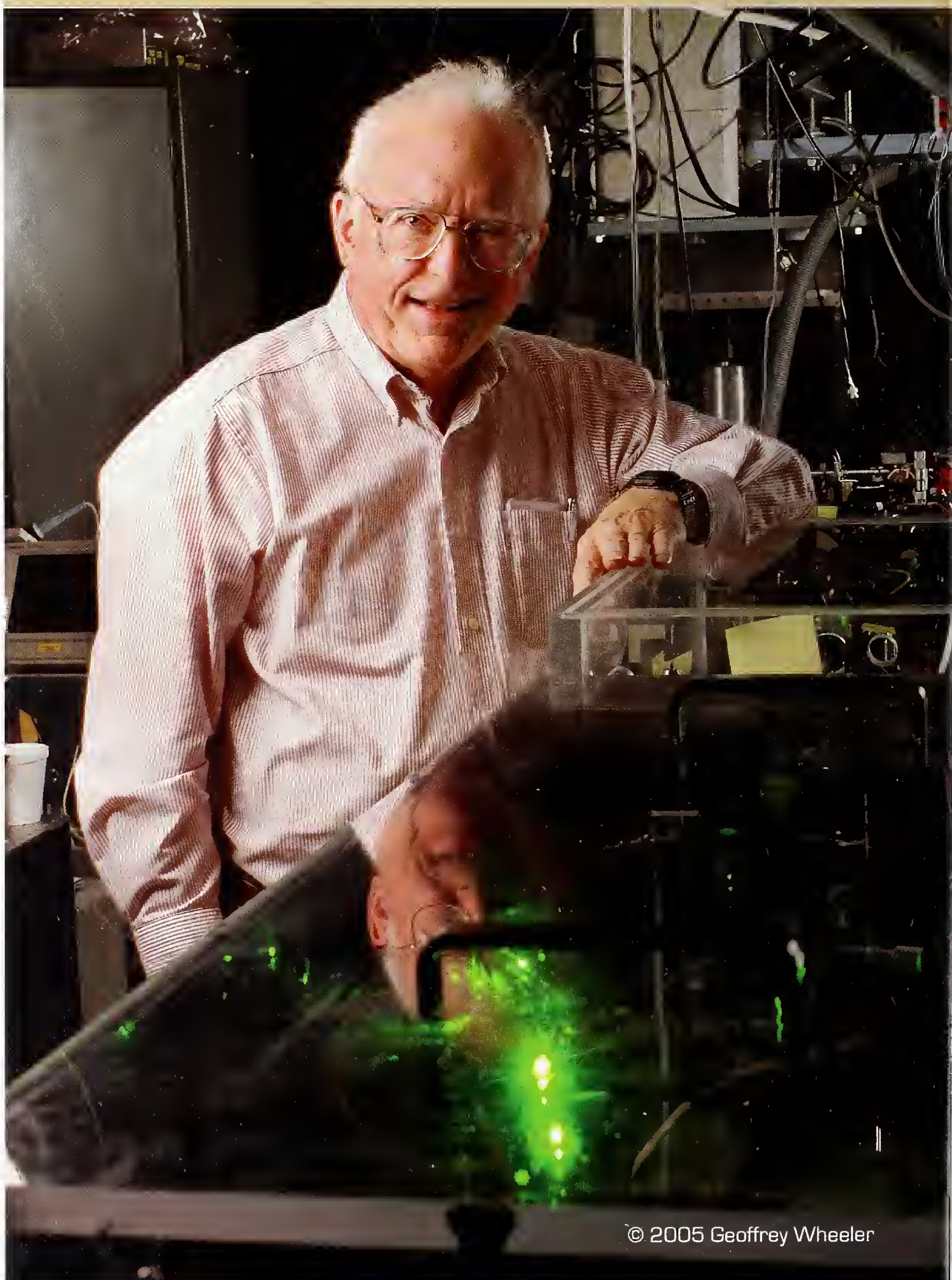
Awards and Honors

NOBEL PRIZE IN PHYSICS

John ("Jan") L. Hall, Scientist Emeritus in Quantum Physics Division and a Fellow of JILA, a joint research institution of NIST and the University of Colorado in Boulder, Colorado. Dr. Hall shared the 2005 Nobel Prize in Physics with Theodor W. Hänsch of the Max-Planck-Institute for Quantum Optics (Garching, Gemany) and Ludwig-Maximilians-Universität (Munich, Germany) and Roy J. Glauber of Harvard University. Hall and Hänsch were cited, "for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique."



Herbert P. Broida Prize (American Physical Society)

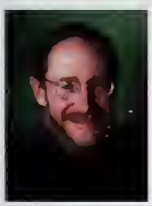
In recognition of an outstanding contribution to the field of atomic and molecular spectroscopy or chemical physics

James Bergquist, Time and Frequency Division, 2007 Prize, "for seminal contributions to ultra-high-resolution laser spectroscopy and the realization of accurate optical frequency standards"

I.I. Rabi Award (IEEE Society for Ultrasonics, Ferroelectricity, and Frequency Control)

To recognize outstanding contributions related to the fields of atomic and molecular frequency standards, and time transfer and dissemination

James Bergquist, 2006 Award, "for seminal contributions to laser spectroscopy and the realization of accurate optical frequency standards"



Leo Hollberg, Time and Frequency Div., 2007 Award, "for seminal contributions to optical frequency metrology with the development of ultra stable optical frequency standards and related femtosecond clockwork"

De Boer Services Gold Pin (International Commission on Illumination (CIE))

Yoshi Ohno, Optical Technology Div., for exceptional administrative and scientific contributions to the physical measurement of light and radiation

William F. Meggers Award (Optical Society of America)

For outstanding work in spectroscopy

Jun Ye, Quantum Physics Division, 2006 Award, "for development of innovative spectroscopic measurement techniques based on femtosecond optical frequency combs"

Carl Zeiss Research Award

Jun Ye, 2007 Award, for his outstanding applications of femtosecond frequency combs

I.I. Rabi Prize in Atomic, Molecular and Optical Physics (American Physical Society)

To recognize and encourage outstanding research in Atomic, Molecular and Optical Physics by investigators who have held a Ph. D. for 10 years or less

Jun Ye, 2007 Prize, for advances in precision measurement, including techniques for stabilizing and measuring optical frequencies, controlling the phase of femtosecond laser pulses, and measuring molecular transitions

Deborah Jin, Quantum Physics Division, 2005 Prize, for her pioneering work in the production of degenerate Fermi gases and exploitation of their novel physical properties

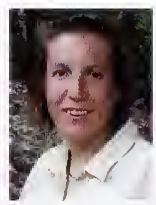
George C. Pimentel Prize for Advances in Matrix Isolation Spectroscopy

Marilyn Jacox, Scientist Emeritus, Optical Technology Division, 2005 Prize, for her many major contributions to matrix isolation spectroscopy, including, most recently, investigations of highly unstable negative ions and negative ion clusters

Doctor of Science (Honoris Causa), University of Waterloo

Marilyn Jacox, 2006 Award, "for her long and distinguished career in physical chemistry"

European Young Scientist Award



Scott Diddams and **Svenja Knappe**, Time and Frequency Division, 2007 Award from the European Frequency and Time Forum, for Diddams' work on femtosecond laser frequency combs, and for Knappe's work on chip-scale atomic devices

The Texas A & M Trotter Prize and Endowed Lecture Series

William Phillips, Atomic Physics Division, 2006 Prize, for pioneering contributions to the understanding of the connections between science and religion and their role in establishing a consistent worldview

Member of the National Academy of Sciences

Deborah Jin, Quantum Physics Division, for her work in the rapidly advancing field of experimental ultracold fermions

Fellowship of the American Association for the Advancement of Science

Deborah Jin, Quantum Physics Division, for advances in the study of quantum gases and the properties of a Fermi degenerate gas

Alfons Weber, Scientist Emeritus, Physics Laboratory, for playing an important role in the development of molecular physics as a researcher and as a manager of Federal programs at NIST and NSF

Fellowship of the American Academy of Arts and Sciences

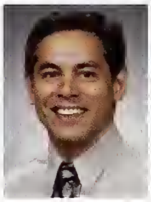
Eric Cornell, Quantum Physics Division, for preeminent contributions to the science of Bose Einstein condensation and to society at large

Deborah Jin, Quantum Physics Division, for preeminent contributions to the science of ultracold, degenerate gases

Fellowship of the American Physical Society

Garnett Bryant, Atomic Physics Division, for seminal contributions to nanooptics and to the theory of semiconductor quantum dots and other complex quantum nanostructures

Steven Cundiff, Quantum Physics Division, for pioneering work in carrier-envelope phase stabilization of mode-locked lasers and its applications to optical frequency metrology and ultrafast technology



Kristian Helmerson, Atomic Physics Division, for pioneering work in cooling, trapping, and coherent manipulation of cold atoms and for the development of seminal techniques for the manipulation and control of objects with optical tweezers

Dietrich Leibfried, Time and Frequency Division, for seminal contributions to the field of quantum information processing using trapped ions, including the demonstration of high fidelity logic gates and the implementation and application of entangled states

William Ott, Deputy Director, Physics Laboratory, for sustained leadership of the research and service programs of the Physics Laboratory of the National Institute of Standards and Technology

Eric Shirley, Optical Technology Division, for important contributions to the computation of the optical properties of solids from the infrared to the x-ray spectral regions

Eite Tiesinga, Atomic Physics Division, for pioneering work on the measurement and control of cold atomic collisions by scattering resonances

Fellowship of the Optical Society of America

Steven Cundiff, Quantum Physics Division, for contributions to ultrafast laser spectroscopy of semiconductors and to carrier-envelope phase stabilization of mode-locked lasers

Jun Ye, Quantum Physics Division, for the application of frequency combs and ultrafast and ultrastable lasers to precision measurements and fundamental science

Fellowship of the Illuminating Engineering Society of North America

Yoshi Ohno, Optical Technology Division, for contributions to the metrology of light through development of measurement methods and metrics and education of the lighting metrology community

Fellowship of the Royal Society of Chemistry

David Nesbitt, Quantum Physics Division, for promoting the advancement of a wider application of chemical science

Fellowship of the Health Physics Soceity

Chris Soares, Ionizing Radiation Division, in recognition of outstanding contributions to the profession of Health Physics

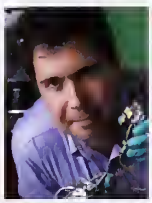
Senior Member of the IEEE

John Curry, Atomic Physics Division, for progress in developing energy-efficient lighting

International LORAN Association, Best Paper Award

Michael Lombardi, Time and Frequency Division, 2006 Award, for the paper "The potential role of enhanced Loran-C in the national time and frequency infrastructure"

IEEE International Solid-State Circuits Conference Jack Raper Award



John Kitching, Time and Frequency Division, with Clark T.C. Nguyen (DARPA, Univ. Michigan), 2005 Award, for the paper "Towards chip-scale atomic clocks"

National Conference of Standards Laboratories International, Best Paper Award

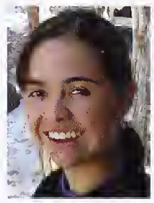
John Kitching, Time and Frequency Division, 2005 Award, for "Chip-scale atomic clocks at NIST"

Young Scholars Competition

Jun Ye, Quantum Physics Division, 2005 Technological Innovation Prize, for his paper "Optical phase control from 10^{-15} seconds to 1 second: precision measurement meets ultrafast science"

American Physical Society, Outstanding Doctoral Thesis Research in Atomic, Molecular and Optical Physics

Cindy Regal, University of Colorado and guest researcher in Quantum Physics Division, 2007 Award for, "Experimental realization of BCS-BEC crossover physics with a Fermi gas of atoms"

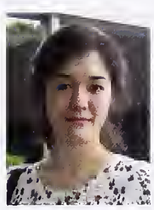


Ana Maria Rey, University of Maryland and guest researcher in Electron and Optical Physics Division, 2005 Award for, "Ultracold bosonic atoms in optical lattices," conducted at NIST

American Physical Society, Best Student Paper (in Experiment)

Chris Langer, U. of Colorado graduate student in Time and Frequency Div., 2006 Award, for "Robust quantum memory using magnetic-field-independent atomic qubits"

Optical Society of America, New Focus / Bookham Student Award

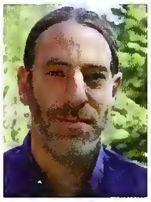


Virginia Lorenz, U. of Colorado graduate student in Quantum Physics Division, 2006 Award, for her presentation "Three-pulse photon echo peak shift measurements in dense potassium vapor"

Arthur S. Flemming Awards

Established in 1948, the Flemming Awards honor outstanding Federal employees with no more than 15 years of government service. About ten winners are selected each year from all areas of the Federal service.

David Jacobson, Ionizing Radiation Division, 2006 Applied Science, for applying neutron metrology techniques to address technical barriers to the development of robust and efficient hydrogen fuel cells



Steven Jefferts, Time and Frequency Division, 2004 Applied Science, for outstanding technical and managerial leadership of NIST-F1, the world's most accurate atomic clock

Keith Lykke, Optical Technology Division, 2004 Applied Science, for the development of novel laser technology for the accurate calibration and characterization of optical instruments used in ground and satellite-based remote sensing, missile defense and targeting, and standards research, development, and dissemination

Yoshi Ohno, Optical Technology Division, 2005 Applied Science, for his innovative research and international leadership in the optical sciences of photometry and colorimetry

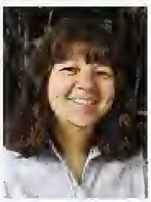
James "Trey" Porto, Atomic Physics Division, 2006 Basic Science, for an experimental program and research team to attack the problem of quantum processing with neutral atoms, establishing NIST's program in neutral atom quantum information as one of the top in the world

Carl Williams, Chief, Atomic Physics Division, 2005 Basic Science, for definitive theories of the physics of ultracold atoms and molecules and their application to precision measurement, atomic clocks, and the new fields of Bose-Einstein and fermionic condensation and quantum computing

Jun Ye, Quantum Physics Division, 2004 Basic Science, for his contributions to the fields of precision measurement, quantum optics, ultrasensitive detection, and cold molecules

Bonfils-Stanton Foundation

Recognizes outstanding Coloradans for significant and unique contributions in the arts and humanities, community service, and science and medicine



Deborah Jin, Quantum Physics Division, 2006 Award for Science and Medicine, for her work in the field of ultracold Fermionic gases

Service to America Medals

Presented by the Partnership for Public Service to celebrate excellence in federal civil service

Konrad Lehnert, Quantum Physics Division, was a 2007 finalist for the Call to Service Medal, for pushing the frontiers of measurement science up against the ultimate limits imposed by the famous uncertainty principle of quantum mechanics

William Phillips, Atomic Physics Division, was awarded the 2006 Career Achievement Medal for service as an ambassador for science and the Federal workforce

Presidential Rank Awards

Recognizes Senior Executives for exceptional long-term accomplishments

Robert Celotta, Electron and Optical Physics Division & CNST, 2006 Award for Distinguished Senior Professional, for pioneering research in nanotechnology

Charles Clark, Chief, Electron and Optical Physics Division, 2007 Award for Distinguished Executive, for establishing SURF III as the Nation's preeminent facility for ultraviolet radiation measurements and for maintaining a vigorous program of personal scientific research

James Faller, Quantum Physics Division, 2006 Award for Meritorious Senior Professional, for a career dedicated to precision measurement science with an emphasis on experimental gravitational physics and tests of fundamental physical laws

Katharine Gebbie, Director, Physics Laboratory, 2006 Award for Distinguished Executive, for sustained, extraordinary leadership and dedication in creating and managing the NIST Physics Laboratory to an unprecedented level of excellence

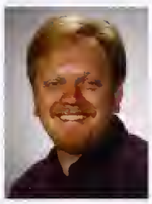
Paul Julienne, Atomic Physics Division, 2007 Award for Meritorious Senior Professional, for being one of the world's preeminent theorists in the fields of photoassociation and ultracold collisions

William Phillips, Atomic Physics Division, 2005 Award for Distinguished Senior Professional, for his leadership in the development of laser cooling and trapping of atoms and its application to atomic clocks and neutral atom quantum computing

Presidential Early Career Award for Scientists and Engineers

Established in 1996, the highest honor bestowed by the U.S. government on scientists and engineers beginning their independent careers

Joshua Bienfang, Electron and Optical Physics Division, 2006 Award, for outstanding research in quantum communications and experimental quantum cryptography



James "Trey" Porto, Atomic Physics Division, 2005 Award for world-class research on neutral-atom quantum computing and novel quantum properties of atoms in one-dimensional systems

Washington Academy of Sciences Physical Science Award

Paul Julienne, Atomic Physics Division, 2005 Award, for pioneering studies of the theory of ultracold atomic collisions and its numerous applications that continue to impact forefront research, from Bose-Einstein condensation to atomic clocks

Albert Parr, Optical Technology Division, 2006 Award, for leadership in developing state-of-the-art optical measurement facilities in support of national programs crucial to the U.S. economy and defense preparedness

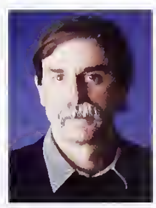
Accenture Government Women's Leadership Award

Katharine Gebbie, Director, Physics Laboratory, 2006 Award in the Government Visionary category. "In her 15 years of leadership at NIST's Physics Lab, Dr. Gebbie has repeatedly proven her dedication to the spirit of scientific discovery and teamwork. Under her direction, scientists from NIST have received three Nobel Prizes, and her leadership has led to improvements in the quality of clinical mammography, port entry radiographic devices, and the irradiation of potentially contaminated mail."

R&D 100 Award

Joshua Bienfang, Electron and Optical Physics Division, 2007 Award, for NIST's high-speed fiber-based quantum key distribution system, able to transmit at gigabits per second and produce megabits per second of secure key, twice as fast as any other existing quantum key system

Scientific American 50



David Wineland, Time and Frequency Division, in 2006, for his research on quantum computing and for fabricating chips capable of storing just a few ions, paving the way for more elaborate chips that can manipulate ions in more serious numbers

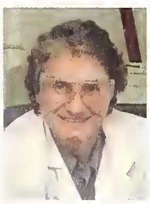
Gold Medal (DoC)

The highest honor conferred by the Department of Commerce, for distinguished performance characterized by extraordinary, notable, or prestigious contributions that reflect favorably on the Department

Lisa Karam, Chief, Ionizing Radiation Division, 2006 Gold Medal, "for her leadership in developing radiation standards and measurement methods needed in the national effort to ensure protection from terrorist attack"

Jabez McClelland, Electron and Optical Physics Division & CNST, 2006 Gold Medal, "for pioneering experiments on the fabrication and replication of permanent nanostructures based on an atom optical control of molecular beam epitaxy"

Thomas Parker and **Judah Levine**, Time and Frequency Division, 2007, for their "leadership of the NIST time scale, the source of all NIST time and frequency measurements used billions of times each day"



Joseph Stroscio, Electron and Optical Physics Division & CNST, 2005 Gold Medal, "for the development of new instruments and methods to measure nanostructure properties and for seminal research in nanoscale science and technology"

Silver Medal (DoC)

For exceptional performance characterized by noteworthy or superlative contributions that have a direct and lasting impact within the Department

Raju Datla, Optical Technology Division, 2005 Silver Medal, "for directing the development of innovative infrared optical measurement technology and standards to support critical national needs in missile defense and climate-change research"

Mitchell Furst, Electron and Optical Physics Division, 2006 Silver Medal, "for outstanding improvements in performance of the NIST SURF III Synchrotron Ultraviolet Radiation Facility"

Leonard Hanssen, Optical Technology Division, 2007 Silver Medal, "for seminal contributions to infrared measurement science and technical standards in support of civilian and defense applications of remote sensing"

Edwin Heilweil, Optical Technology Division, 2007 Silver Medal, "for advancing the state-of-the-art in terahertz technology and data for applications in defense, homeland security, and manufacturing"

Kristian Helmerson, Atomic Physics Division, 2007 Silver Medal, "for pioneering the field of coherent atom optics and persistent atom currents"

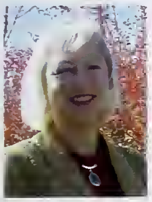
Jeeseong Hwang, Optical Technology Division, 2007 Silver Medal, "for the development of innovative nanotechnology tools for the highly selective and sensitive optical detection of bacterial pathogens"

John Kitching, **Leo Hollberg**, **Hugh Robinson**, and **Peter Schwindt,** Time and Frequency Division, and **John Moreland** and **Li-Anne Liew**, EEEL Electromagnetics Division, 2005 Silver Medal, "for designing, constructing, and operating the world's first ultra-miniature atomic clocks and magnetometers"

Mark Stiles, Electron and Optical Physics Division & CNST, 2005 Silver Medal, "for exceptional contributions to the theory of magnetic phenomena in nanostructures and thereby furthering U.S. competitiveness in the development of a wide array of magnetic sensors and information storage devices"

Bronze Medal (NIST)

For work that has resulted in more effective and efficient management systems, the demonstration of unusual initiative or creative ability, significant contributions on major programs, scientific accomplishment, or superior performance



Julia Bachinski, Quantum Physics Division, 2006 Bronze Medal, "for excellence in administrative support of science at JILA"

Joshua Bienfang, Electron and Optical Physics Divison, and **Barry Hershman**, **Alan Mink**, **Anastase Nakassis**, and **Xiao Tang**, Advanced Network Technologies Division (ITL), 2005 Bronze Medal, "for outstanding performance in advancing quantum cryptography towards commercial application"

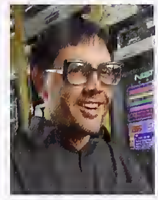
Garnett Bryant, Atomic Physics Division, 2007 Bronze Medal, "for exceptional contributions to the theory of nanomaterials, semiconductor quantum wells, quantum wires, quantum dots, and nanocrystallites"

Karen Olsen, **Robert Dragoset**, and **Gloria Wiersma**, Office of Electronic Commerce in Scientific and Engineering Data, 2005 Bronze Medal, "for pioneering the dissemination of physical reference data on the WWW and for providing outstanding customer service for more than 10 years"

Alex Farrell, Electron and Optical Physics Division, 2005 Bronze Medal, "for outstanding service to customers of the NIST SURF III Synchrotron Ultraviolet Radiation Facility"

Gerald Fraser, Chief, Optical Technology Division, 2007 Bronze Medal, "for leadership in the development of programs, facilities, and partnerships in infrared and optical radiation measurement and standards"

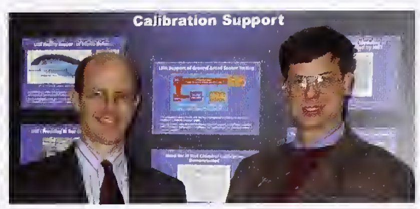
David Jacobson, Ionizing Radiation Division, 2006 Bronze Medal, "for his contribution in developing an advanced neutron imaging facility for fuel cell research"



Michael Lombardi and **Andrew Novick**, Time and Frequency Division, 2007 Bronze Medal, "for development and implementation of the SIM network for precision international time synchronization in North, Central, and South America"

Cameron Miller, Optical Technology Division, 2007 Bronze Medal, "for contributions to the first-ever assessment of the U.S. measurement system's ability to sustain innovation at a world-leading pace"

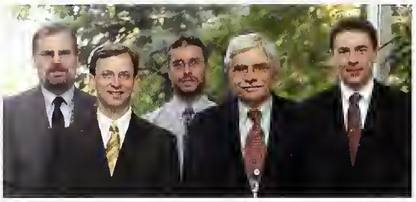
James "Trey" Porto, Atomic Physics Division, 2006 Bronze Medal, "for the creation and leadership of a program in quantum information using neutral atoms as qubits"



Adriaan Carter and **Eric Shirley**, Optical Technology Division, 2005 Bronze Medal, "for developing innovative computational and experimental methods to accurately calibrate infrared sensors used in missile defense"

William P. Slichter Award

For outstanding achievements by NIST staff in building or strengthening ties between NIST and industry

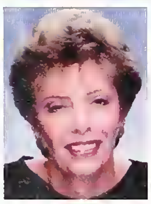


Steven Grantham, **Robert Vest**, **Charles Tarrio**, **Thomas Lucatorto**, and **Shannon Hill**, Electron and Optical Physics Division, 2007 Award, "for establishing a firm measurement foundation for EUV reflectometry, optics lifetime characterization, and pulsed radiometry for EUV lithography"

John Burnett, Atomic Physics Division, 2006 Award, "for his pioneering contributions to the development of immersion microlithography"

Colleagues' Choice Award

Recognizes nonsupervisory employees who, in the eyes of their colleagues, have made significant contributions that broadly advance the NIST mission and strategic goals or contribute to the overall health and effectiveness of NIST



Anita Sweigert, Physics Laboratory, 2006 Award, "for extraordinary dedication to, and administrative support for, the NIST Summer Undergraduate Research Fellowship (SURF) program"

Samuel Wesley Stratton Award

For outstanding scientific or engineering achievements in support of NIST objectives

Jun Ye, Quantum Physics Division, 2006 Award, "for femtosecond comb technology work which merges time- and frequency-domain spectroscopic techniques and is enabling new developments in optical atomic clocks"

Allen V. Astin Measurement Science Award

For outstanding achievement in the advancement of measurement science or in the delivery of measurement services

Howard Yoon and **Charles Gibson**, Optical Technology Division, 2005 Award, "for major advances in the realization and dissemination of the NIST spectral irradiance scale, widely used in climate-change research"

Edward Uhler Condon Award

For distinguished achievement in effective written exposition in science or technology

Michael Lombardi, Time and Frequency Division, 2005 Award, "for publications aimed at informing not only technical experts and manufacturers about NIST time and frequency services, but also the general public"

Eugenne Casson Crittenden Award

Recognizes superior achievement by permanent employees who perform supporting services that have a significant impact on technical programs beyond their own offices

Eyvon Petty, Time and Frequency Division, 2007 Award, "for outstanding support of NIST Boulder programs, including the Boulder SURF Program, Boulder Labs seminars and colloquia, and training Boulder staff"

Jacob Rabinow Applied Research Award

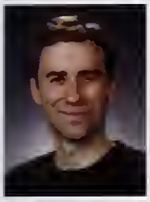
For outstanding achievements in the practical application of the results of scientific engineering research

John Kitching, Time and Frequency Division, 2007 Award, "for outstanding leadership of NIST's world-leading chip-scale atomic device program"

Sigma Xi (NIST Chapter) Outstanding Postdoctoral Presentation Award

Benjamin Brown and **Patricia Lee**, Atomic Physics Division, 2007 Award for their paper, "A two-qubit quantum gate with neutral atoms in an optical lattice"

Sigma Xi (NIST Chapter) Young Scientist Award for Excellence in Scientific Research



Jason Crain, Electron and Optical Physics Division & CNST, 2006 Award, for work leading to the discovery of "end states" in one dimensional atom chains and elucidating electronic effects in the length distributions of one dimensional chains of atoms

Department of Energy Hydrogen Program R&D Award

Muhammad Arif, Ionizing Radiation Division, 2007 Award, for his outstanding achievement in fuel cell research and development

NASA Group Achievement Award

Joseph Reader, **Gillian Nave**, and **Craig Sansonetti** (jointly with staff of the Space Telescope-European Coordinating Facility), Atomic Physics Division, 2006 Award, in recognition of painstaking efforts to provide maximum scientific value to Hubble Space Telescope data using precision laboratory spectral measurements and physical instrument modeling techniques

ORGANIZATIONAL CHART

Physics Laboratory
Katharine Gebbie, Director
William Ott, Deputy Director

- **Electron and Optical Physics Division**
  Charles Clark, Chief
- **Atomic Physics Division**
  Carl Williams, Chief
- **Optical Technology Division**
  Gerald Fraser, Chief
- **Ionizing Radiation Division**
  Lisa Karam, Deputy Chief
- **Time and Frequency Division**
  Thomas O'Brian, Chief
- **Quantum Physics Division**
  Steven Cundiff, Chief

PHYSICS LABORATORY RESOURCES

Key to Table Abbreviations

STRS — Congressionally appropriated funds for NIST's Scientific and Technical Research and Services

ATP — Intramural research funds provided to support the goals of the NIST Advanced Technology Program

OA — Funds provided by other agencies in support of needed research and measurement services

Other — Other sources of funding, including calibration fees

PHYSICS LABORATORY RESOURCES 2003-2007 ($ Millions)

	2003	2004	2005	2006	2007
STRS	43.1	40.3	43.6	48.1	49.2
ATP	2.7	0.6	1.6	0.9	0.9
OA	14.0	20.8	20.4	21.6	20.7
OTHER	5.2	5.2	5.0	4.6	4.7
TOTAL	65.0	66.9	70.6	75.2	75.5

Federal Agencies Supporting Physics Laboratory Research

Department of Agriculture
Department of Commerce
Department of Defense
Department of Energy
Department of Health and Human Services
Department of Homeland Security
Department of Justice
Department of State
Environmental Protection Agency
National Aeronautics and Space Administration
National Science Foundation

Representative Private Sector Collaborators

American Association of Physicists in Medicine
American Chemical Society
American Geophysical Union
American National Standards Institute
American Physical Society
American Society for Testing and Materials
Biophysical Society
Commission Internationale de l'Éclairage
Council for Optical Radiation Measurements
Council on Ionizing Radiation Measurements and Standards
Health Physics Society
Illuminating Engineering Society of North America
Institute of Electrical and Electronics Engineers
International Electrotechnical Commission
International Organization for Standardization
National Council on Radiation Protection and Measurements
NCSL International
Nuclear Energy Institute
Optical Society of America
International SEMATECH
SPIE—The International Society for Optical Engineering

EDITORS:
Jonathan E. Hardis and William R. Ott

Physics Laboratory, National Institute
of Standards and Technology

U.S. Department of Commerce
Carlos M. Gutierrez, Secretary

National Institute of Standards and Technology
James M. Turner, Deputy Director

NIST SP 1075
May 2008

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