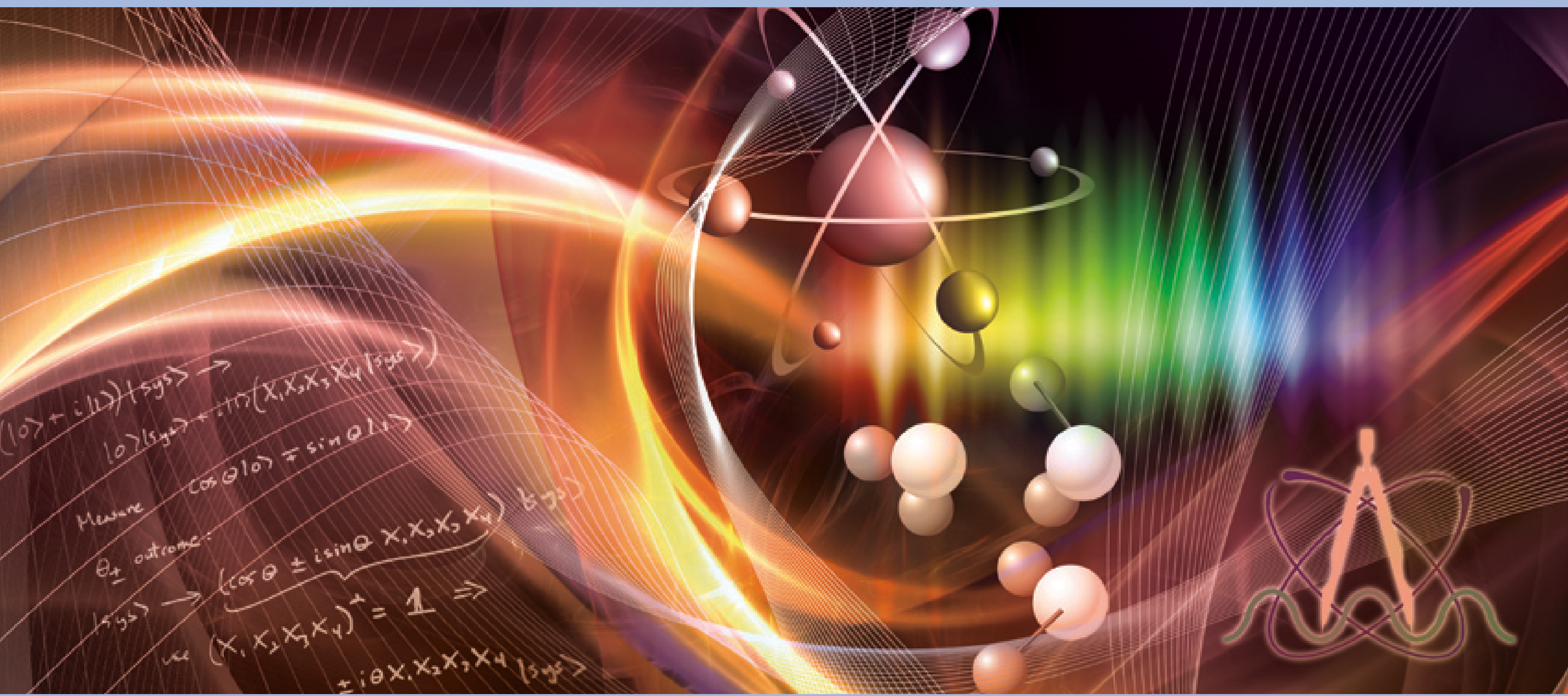
Physics Laboratory



Supporting U.S. Industry, Government,

and the Scientific Community by Providing

Measurement Services and Research for

Electronic, Optical, and Radiation Technology

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

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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 investigate and exploit the quantum behavior and interactions of atomic matter and radiation

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

227 full-time staff (182 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

$81.6 million annual budget

Unique facilities, including:

- Ambient Infrared Radiometry and Imaging Laboratory
- 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
- Facility for Automated Spectroradiometric Calibrations
- Geometric Aperture-Area Measurement Facility
- High-Resolution UV and Optical Spectroscopy Facility
- W.M. Keck Optical Measurement Laboratory
- Low-Background Infrared Facility (LBIR)
- Low Dose Rate Brachytherapy Calibration 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)
- Spectral Tri-function Automated Reference Reflectometer (STARR)
- Synchrotron Ultraviolet Radiation Facility (SURF III)
- Vision Science Laboratory

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)
- *http://www.time.gov/*

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/

Director's Message

Twenty years ago the NIST Physics Laboratory was formed by NIST Director John Lyons specifically to support industry, government, and the scientific community with measurement research and services in electronic, optical, and ionizing radiation technologies.

Since then the Physics Laboratory has redirected its resources to address the increasing demands on precision measurement in areas such as homeland security, health care, the environment, and information technology. Remaining constant has been our commitment to excellence and service, demonstrating all the while that mission-oriented research can be just as challenging, creative and significant as "curiosity-driven," academic research.

Our achievements during the last two decades include:

- Pioneering research on laser cooling and trapping of atoms, Bose-Einstein condensation, ultracold Fermi gases, and ultrafast laser frequency combs;

- Significant "firsts" in quantum computing and a world-leading program in quantum information science;

- Three Nobel Prizes for core research in support of NIST's mission to advance measurement science;

- The world's most sensitive neutron interferometer, used for studies ranging from fundamental problems in quantum mechanics to the determination of hydrogen content in materials;

- The NIST Synchrotron Ultraviolet Radiation Facility (SURF-III) upgrade, which provides increased service to users like NASA and Intel who require improved accuracy, bandwidth, and access to beamlines with unique measurement capabilities (radiometry and reflectometry);

- A Medical-Industrial Radiation Facility (MIRF) and a CLINAC medical radiation facility to provide increased service for the radiation processing industry and for the healthcare community;

- New, national dosimetry standards for brachytherapy, used to treat prostate cancer and other internal lesions, and for mammography, to ensure the safety and effectiveness of clinical x rays;

- Critically needed dosimetry standards for radiation sterilization of mail exposed to anthrax in 2001, and expanded measurement support for testing of personnel and cargo sensors used to ensure homeland security;

- Three generations of atomic frequency standards: NIST-7, in its time the most accurate cesium-beam frequency standard in the world (5×10^{-15}); NIST-F1, the most accurate cesium fountain frequency standard in the world (3×10^{-16}); and the mercury ion clock and the aluminum ion "logic clock," the most precise frequency standards in the world by a significant margin (1×10^{-17}, 1 second in 3 billion years, and rapidly improving);

- Chip-scale atomic clocks, magnetometers, and sensors for specialized applications ranging from navigation and defense to healthcare and basic research;

- A revolution in the measurement of optical radiation with the development of the cryogenic radiometer as a detector-based standard and SIRCUS (Spectral Irradiance and Radiance Calibrations with Uniform Sources), the most accurate optical calibration facility of its kind in the world;

- A suite of new, detector-based measurement services in the infrared spectral region, including the Low Background Infrared (LBIR) user facility, in response to measurement needs of the remote sensing community;

- The first internet accessible databases at NIST for critically evaluated reference data, currently providing more than 1 million downloads per month to users worldwide; and an internet time service providing 3 ½ billion updates per day to computer clocks;

- Creation of the Joint Quantum Institute, a cooperative effort between NIST, the University of Maryland, and the Laboratory for Physical Sciences of the National Security Agency;

■ NIST's new, independent Center for Nanoscale Science and Technology, created by the NIST Director from the Electron and Optical Physics Division's Electron Physics Group, which pioneers in scanning probe microscopies and nanoscience research.

These and other highlights from the last 20 years are serving today to provide inspiration for a new generation of scientists who will continue to advance the frontiers of measurement science. 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.

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.

For example, our Time and Frequency Division's seven services are supported by major efforts in the development of optical frequency standards, chip-scale atomic clocks and related devices, 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 while 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.

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 much broader, 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 measurement challenges—in particular in quantum information science, in biosystems and health care, in nanoscale metrology, in sensors for homeland security applications, and in greenhouse gases and climate change. For example, for improved health care, the Physics Laboratory conducts research on standards to enable hospitals to use nuclear medicine and medical imaging technology more effectively. And in the nascent fields of quantum information processing, computing, and communications, the Laboratory is at the forefront, challenging preconceived notions of computational complexity and communications security.

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

Katharine Gebbie
Director, Physics Laboratory

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 element 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

Determining the Sensitivity of EUVL Photoresists

Extreme ultraviolet lithography (EUVL), a patterning technique using 13.5 nm radiation, is a leading contender for next-generation lithography, for fabricating microelectronics. One of the key research challenges for EUVL is the development of a photoresist that has a high sensitivity, low line-edge roughness, and high resolution.

Until recently, the sensitivity of a photoresist was measured relative to a "standard" photoresist, whose sensitivity had been measured over a decade ago (and not at 13.5 nm). Late in 2007, scientists at the Advanced Light Source in Berkeley, CA, used a Division-calibrated EUV photodetector to determine the validity of this resist-based method. The detector-based measurements indicated that the sensitivity of a modern photoresist was about twice that determined by the old method.

These surprising results resulted in an urgent request for us to independently measure the sensitivity of several candidate EUV photoresists. Together with staff from NIST's Center for Nanoscale Science and Technology, we used SURF III for EUV exposure and pre- and post-processing of the photoresists.

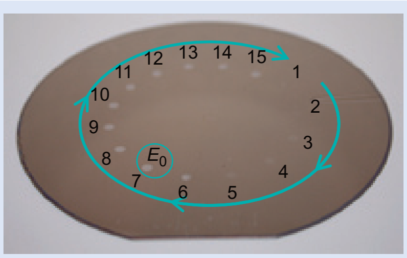

Figure 1. 300 mm silicon wafer with incrementally increasing doses of extreme ultraviolet (EUV) radiation at 15 spots. The seventh exposure was the minimum dose required to fully remove the photoresist.

The results confirmed and extended those made in Berkeley. This has resulted in increased industry appreciation for accurate dose metrology and for the use of traceable standards in their evaluation of source and tool performance.

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High-Accuracy Reflectivity Map of EUVL Mirror

EUVL differs from conventional lithography in two important ways: all the optics must be reflective, and the radiation source is not a laser but rather a plasma created by either a discharge or a laser. In order for EUVL to be commercially viable, the source must be capable of delivering at least 120 W of in-band power to the entrance aperture of the illumination optics. Generation of EUV radiation is inefficient and expensive, so large and complex collection optics are required.

We characterized a new EUV condenser designed for use with a laser-produced plasma source. This optic is 32 cm in diameter, and it is polished to a surface roughness of about 0.1 nm. The optic is then coated with a multilayer structure with a period of about 7 nm.

We developed a unique measurement scheme to provide reflectivity measurements to better than 0.35 % absolute, at wavelengths specified to better than 0.005 nm. The reflectivity was measured in a 2 nm band about 13.5 nm as a function of position across two diameters, to investigate reflectivity and wavelength uniformity.

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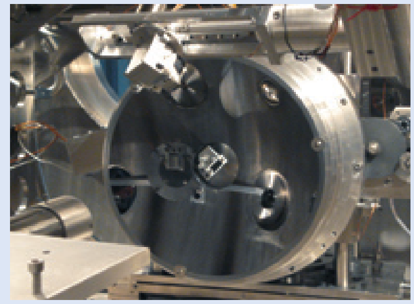

Figure 2. Multilayer mirror for 13.5 nm radiation. This 32 cm optic is a key element in the EUV lithographic process.

Optics Durability for EUVL

A major obstacle to the introduction of EUVL is the deterioration of optics caused by long-term exposure to the 13.5 nm radiation in a non-bakable vacuum environment. In order to meet the throughput requirements for high-volume commercial production, the reflectivity of the projection optics must not drop more than a few percent over the entire 30,000 hour lifetime of the tool. To achieve this, in situ methods are being explored to ameliorate the carbonization and oxidation processes induced by EUV irradiation of the organic molecules and water that adsorb on the optic surfaces from the ambient vacuum.

Key to advancing this effort is a better understanding of both the thermally driven adsorption processes and the photon-induced reactions that contribute to EUV-optics contamination. Such knowledge would lead to predictive models to estimate optics lifetime in the production environment, as well as more effective mitigation techniques. Central to formulating a reliable predictive model is finding the relationship between the partial pressure of a contaminant and the coverage of contaminant molecules on the surfaces in equilibrium with the gas phase, the so-called adsorption isotherm.

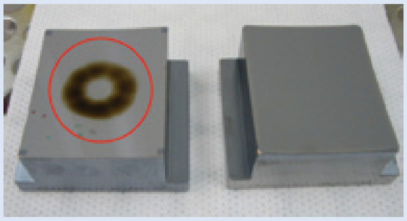

Figure 3. EUV optics carbonization on an EUV mirror used in a lithographic patterning tool.

Recent results from the Division have shown that simple models based on ideal surfaces and basic Langmuir adsorption physics (i.e., reversible adsorption on a finite density of identical sites) would dramatically underestimate the coverage and therefore the real-world contamination rates of most concern to end users. At the low partial pressures of contaminant vapors expected in a production tool, these simple models would predict a linear scaling of contamination with pressure. However, direct EUV-induced contamination rates measured at SURF III have demonstrated a highly sub-linear (approximately logarithmic) pressure dependence of the contamination rates over three to four decades of pressure for every contamination species tested. Our results are consistent with direct measurements of equilibrium coverage at Rutgers University that also show adsorption isotherms with logarithmic pressure dependence.

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Lyman Alpha Neutron Detector

We have developed an ultrasensitive, high-bandwidth neutron detector, in collaboration with Ionizing Radiation Division and the University of Maryland. Neutron detectors are important in a variety of applications, ranging from fundamental physics experiments to materials science, oil well logging, monitoring of special nuclear materials, and personal protective equipment for first responders.

Most neutron detectors use proportional counters, in which high-voltage electrical discharges are initiated by neutron absorption in a gas cell. Our Lyman-alpha neutron detector (LAND), on the other hand, detects neutrons by sensing radiation at 122 nm following neutron absorption by helium-3 gas.

The LAND technique offers significant advantages over proportional counters. For example, optical emissions are faster than electrical discharges, yielding a detector with intrinsically higher bandwidth. LAND demonstrates single-neutron sensitivity, which has not been possible with proportional counters. In addition, LAND seems less susceptible to spurious neutron reports triggered by gamma rays.

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Figure 4. Lyman alpha radiation detector, shown here in prototype, could dramatically improve performance in key applications.

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

Live Conference Demonstrations of Broadband Quantum Encryption and Random Number Generation

In 2008, NIST's quantum communication testbed traveled to the Black Hat Briefings and DEFCON, the world's largest hacker convention, to present live demonstrations of high-speed quantum encryption. A subset of the larger field of quantum communication, quantum cryptography is a technique for distributing cryptographic keys over potentially insecure channels. It exploits the properties of quantum mechanics to detect eavesdropping.

Communications channels operating in the quantum regime are uniquely vulnerable to noise and losses, both of which can significantly reduce their throughput and practical utility. NIST's approach, developed with support from the Defense Advanced Research Projects Agency, adapts telecommunication clock-recovery techniques and specially modified single-photon detectors to realize transmission rates exceeding 1 GHz. The system operates in free-space and is capable of producing usable cryptographic key at rates over 1 Mb/s.

As an illustration of the system's capabilities, the live demonstration included continuous one-time-pad encryption of a streaming video signal captured from a camera in the conference hall. Attendees were invited to act as eavesdroppers by inserting linear polarizers into the link, resulting in a detectable disturbance to the quantum signals and halting key production.

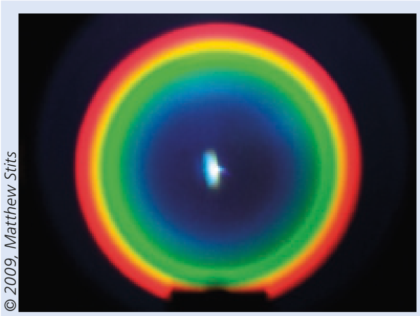

Figure 5. Correlated photon emission from spontaneous parametric down-conversion, as photographed at DEFCON 2009.

In 2009 we returned to DEFCON with live demonstrations of entanglement and quantum random-number generation (qRNG). For cryptographic applications, random number generators need not only be random, but also unknown. One way to generate verifiably unknown random bits is by using quantum states that can be shown to violate the Bell inequalities. Such states can be generated from spontaneous parametric downconversion, a process attendees could witness with unaided eyes by observing the spectral rings of correlated emission from a KDP crystal pumped at 405 nm.

As part of a collaborative effort with the University of Illinois, another demonstration of qRNG used NIST's high-speed time-tagging electronics to generate random numbers from the arrival-time intervals of photons from a laser. This system is one of the highest-speed qRNG ever demonstrated, and is a simple example of technologies being developed from the intersection of information science and quantum mechanics.

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Ultracold Atoms Could Replicate the Electron "Jitterbug"

Ultracold atoms moving through a carefully designed arrangement of laser beams will jiggle slightly as they go, according to theoretical studies made in the Division. If observed, this never-before-seen "jitterbug" motion would shed light on a little-known oddity of quantum mechanics arising from Paul Dirac's 80-year-old theory of the electron.

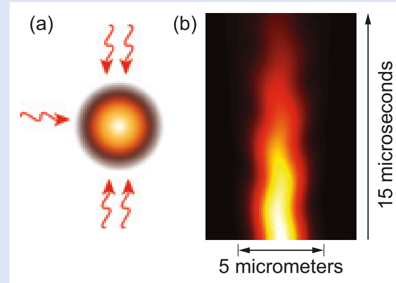

Figure 6. (a) Optical lattice of five laser beams trapping an atomic cloud. Color scale indicates cloud density; black is low, white high. (b) Jittering motion of the atomic cloud in the optical lattice. The horizontal axis shows the spatial distribution of the cloud in one direction; the vertical axis shows the variation of cloud density with time.

Dirac's theory, which successfully married the principles of Einstein's relativity to the quantum property of electrons known as spin, famously predicted that the electron must have an antiparticle, subsequently discovered and named the positron. More enigmatically, the Dirac theory indicates that an isolated electron moving through empty space will vibrate back and forth. But this shaking—named Zitterbewegung from the German for "trembling motion"—is so rapid and so tiny in amplitude that it has never been directly observed.

Division scientists devised an experimental arrangement in which atoms are made to precisely mimic the behavior of electrons in Dirac's theory. The atoms will show Zitterbewegung—but with vibrations that are slow enough and large enough to be detected. In Autumn 2009, a group at the University of Innsbruck, Austria, reported the observation of Zitterbewegung in an ion trap, using a similar scheme.

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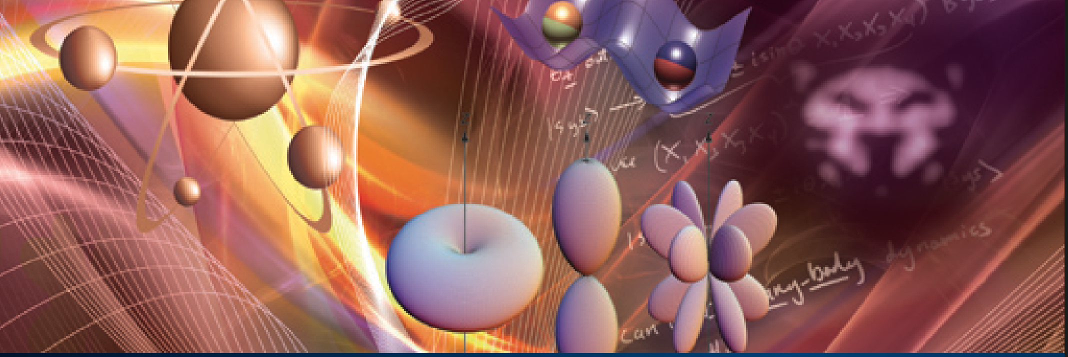

Atomic Physics Division

GOAL

to investigate and exploit the quantum behavior and interactions of atomic matter and radiation

The strategy of the Atomic Physics Division is to develop and apply atomic-physics and condensed-matter research methods, particularly those making novel use of electromagnetic fields, to achieve fundamental advances in measurement science—including measurement at and beyond the standard quantum limit.

The first strategic element is to advance the understanding and applications of cold atomic matter, including the study of many-body quantum systems, exotic states of matter, atomic analogs of condensed-matter systems, metrology of and with cold atoms, and quantum information.

COLD ATOMIC MATTER

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 ultracold atoms and Bose-Einstein condensates (BECs), and the creation of exotic states of matter through control of ultracold atoms. It includes both fundamental studies, like the investigation of superfluidity, and applied studies, such as quantum information processing and the engineering of synthetic charge along with synthetic electric and magnetic fields for *neutral* atoms.

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, given rise to the field of quantum simulation, and now allows the simulation of the behavior of *charged* particles using *neutral* atoms.

The Atomic Physics Division is the principal NIST participant in the Joint Quantum Institute (JQI)[1], a cooperative venture of Physics Laboratory and the University of Maryland, with the support and participation of the Laboratory for Physical Sciences of the National Security Agency. The JQI is a strategic partnership that allows NIST to increase its activity in the study of quantum phenomena—including their coherent interaction with electromagnetic fields—in both atomic and condensed matter systems and to expose academic researchers to the fundamental measurement challenges of NIST. The goals and objectives of the JQI align strongly with the first three strategic elements in this chapter.

A strong theoretical-experimental collaboration within NIST, and now extending to new colleagues within the JQI, helps interpret experimental results

[1] *http://www.jqi.umd.edu*

and provides guidance for new experiments. Theoretically and experimentally, our program goals are to understand and exploit: neutral atom BECs; 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; the simulation of condensed matter models with cold atoms; quantum information processing; and quantum computing architectures.

The Chief of Atomic Physics Division also coordinates NIST's program in quantum information science and quantum based measurements, which includes activities in nine Divisions within Physics Laboratory, the Electronic and Electrical Engineering Laboratory, and the Information Technology Laboratory. This multi-laboratory program provides support to both the JQI and many of the activities that are represented by the first three strategic elements.

ACCOMPLISHMENTS

Ultracold Polar Molecules

Scientists at JILA have produced a dense sample of ultracold, 300 nK $^{40}K^{87}Rb$ polar molecules in their ground state of vibrational and rotational motion. Theory developed in the Division and the JQI guided these experiments by calculating the molecular properties needed to understand and control the formation of these molecules from ultracold atoms.

Figure 1 schematically illustrates the steps: (1) association of a ^{40}K atom and a ^{87}Rb atom to make a very weakly bound molecular state of the $^{40}K^{87}Rb$ molecule (green), then (2) coherent optical transfer (blue) of this state to the ground vibrational and rotational state of the $^{40}K^{87}Rb$ molecule (red).

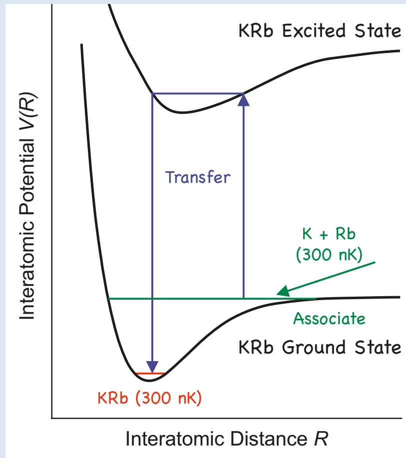

Figure 1. Schematic representation of the molecular potential energy curves *V*(*R*) of the KRb molecule, where *R* is the interatomic separation, indicating the steps used to make ground state molecules.

Additionally, the theory characterized the nuclear spin structure of the ground state molecules, a key element in the precise quantum control of molecular collisions. Polar molecules, which have much longer-range forces than neutral atoms, open new vistas for controlled simulation of many-body phenomena and for studies of strongly correlated condensed matter phases, ultracold chemistry, precision measurement, and quantum information.

This work provided the basis for a successful Multi-University Research Initiative (MURI) recently selected by the Air Force Office of Scientific Research for funding at the JQI. This MURI, entitled "Ultracold polar molecules: new phases of matter for quantum information and quantum control" is a five-year research initiative involving nine research groups at seven different institutions.

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Hybrid System of Superconducting Devices and Ultracold Atoms

We have initiated a theoretical program to investigate the coupling of ultracold atom clouds to superconducting circuits, to explore coherence exchange and provide a new diagnostic of imperfections in superconducting circuits. This effort is a cornerstone of the newly established Physics Frontier Center at the JQI.

In this hybrid system, we hope to improve the performance of both atoms and superconductors as carriers of quantum information. Atoms have long coherence times but slow logic operations. Superconductors, on the other hand, have fast operations but short decoherence times.

This effort will also use the atoms to examine the sources of decoherence in superconducting circuits, uncorrelated with the operation of the devices themselves. Decoherence is believed to be due to so-called two-level fluctuators, caused by defects in oxides separating the superconducting wires. The use of atoms alleviates the need for deposition of sensing devices on the very materials we need to study and, thereby, ensures that we only characterize the circuit of interest.

We plan to bring to bear concepts of quantum optics developed in the atomic

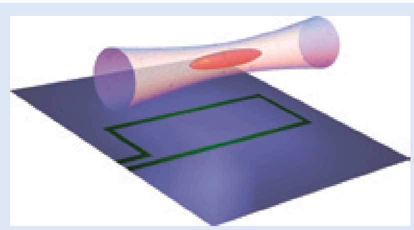

Figure 2. A superconducting SQUID circuit (green) on a substrate surface (blue) with an atom cloud (dark pink) trapped by a tightly focused laser beam (pink).

and optical physics community to describe both coherent evolution and decoherence. Our hybrid device can be described in terms of large numbers of two-level systems coupled to a harmonic oscillator, the quintessential problem of quantum optics. Depending on our point of view, the two-level systems are either the (identical) atoms or the microscopic defects in the circuits. The harmonic oscillator represents the superconducting circuit.

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Superfluid Phase Transition Studies in a Two-Dimensional Atomic Bose Gas

A system can behave quite differently depending on its dimensionality. An example of this is Bose-Einstein condensation (BEC), a low-temperature phase transition in quantum gases. In three dimensions (3D) a gas of Bose particles can undergo a BEC phase transition and exhibit superfluid properties. In uniform 2D and 1D systems a BEC is not possible.

Surprisingly, a uniform, interacting 2D Bose gas can undergo a phase transition to a superfluid state. This 2D superfluid phase transition is known as the Berezinskii-Kosterlitz-Thouless (BKT) transition. It has been observed in superconductors, liquid helium, and most recently in atomic Bose gases.

Recent theoretical calculations, however, predict an intermediate regime between the thermal and superfluid states of the 2D Bose gas. This regime, previously unobserved, corresponds to the appearance of a quasi-condensate, which exhibits a spatial coherence longer than the deBroglie wavelength associated with the thermal cloud, but considerably shorter than the physical size of the system.

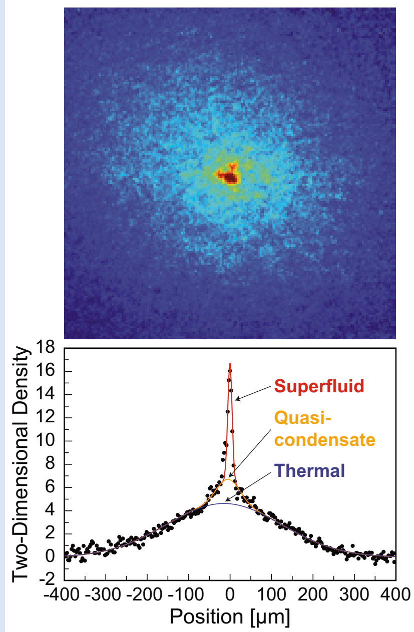

Figure 3. Image of a two-dimensional Bose gas for $T < T_{BKT}$ and its spatial profile along a line through its center. The three components show the simultaneous existence of the three regimes for this spatially inhomogeneous system.

We confined sodium atoms in an optical trap formed by a sheet of light to realize a quasi-2D Bose gas. By evaporatively cooling the 2D Bose gas, we were able to observe the transition from thermal, to quasi-condensate without superfluidity, to a superfluid state. We developed an interferometric method to study the spatial coherence of the gas and observed the expected changes from thermal to quasi-condensate to superfluid, which has a coherence length comparable to the size of the cloud.

The finite size of this system raises new questions about the microscopic picture of the BKT transition, which was formulated for a homogeneous system. Such systems also offer the possibility of a better understanding of the relationship between superfluidity and Bose-Einstein condensation, since the distinctions between the two phenomena are clearer than in 3D.

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Qubit Basis Switching

Prospective quantum computation platforms have competing needs: isolating the quantum system from the environment to prevent decoherence, while coupling the system to particular fields to provide control. For example, pairs of so-called "clock states" in neutral atoms provide nearly ideal qubits because they are magnetic field insensitive and therefore insensitive to field-induced decoherence. On the other hand, these states are also insensitive to control fields that would allow, for example, selective addressing of single qubits using techniques similar to magnetic resonance imaging.

We have developed a technique to simultaneously preserve qubit insensitivity and allow field-sensitive addressing. The trick is to use two pairs of clock states (four states total). Each pair of states is itself insensitive to fields, but the transitions between the pairs of states are field sensitive. This allows field gradients to address selected atoms, while not perturbing unselected atoms.

We demonstrated this approach in a double-well optical lattice, where we first stored the qubit information in field-insensitive "memory" states (Fig. 4, (a)→(b)). We then transferred selected qubits from the memory states to a different pair of "working" states (Fig. 4, (b)→(c)). The selected qubits are addressed with a magnetic-field-like optical field that does not affect atoms in either the memory or workings states, but allows site-specific frequency shifts for transitions between the memory and working states.

This technique should allow for coherent sub-wavelength addressing of atoms in an optical lattice. It may be useful for decreasing crosstalk in any quantum-computing platform with multiple sets of field-insensitive transitions.

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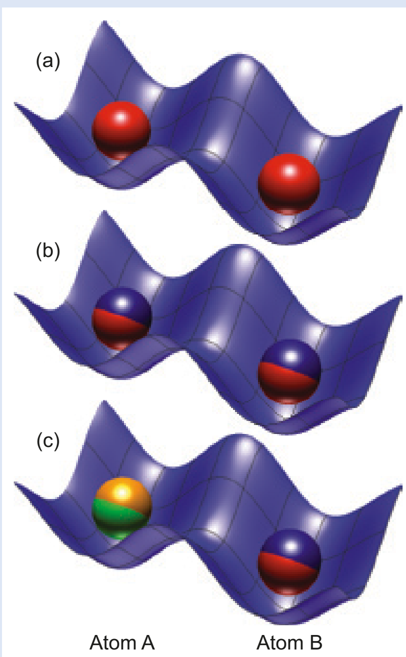

Figure 4. A microwave pulse excites each of two neighboring atoms (a) into a superposition of the |0> and |1> clock states, $\alpha|0> + \beta|1>$ (b). In order to address only Atom A from the pair, we apply a magnetic field gradient that shifts Atom B off resonance. Both atoms' superposition states are insensitive to this field. However, the transitions to another basis set, |0> to |0´> and |1> to |1´>, *are* field sensitive. With the gradient present, a second pulse is applied that affects only Atom A, transferring it to $\alpha|0'> + \beta|1'>$ (c).

A Synthetic Vector Potential for Cold Atoms

Much of the most interesting physics of interacting charged particles occurs in the presence of magnetic fields. Examples include the integer and fractional quantum Hall effects in two-dimensional electron systems. These states of fermions have demonstrated applications in metrology (through the von Klitzing constant) and may potentially be a platform for a robust "topological" quantum computer.

We are working to realize such quantum Hall states in a charge-neutral Bose-Einstein condensate by engineering equations of motion that match those of charged particles in a magnetic field. The first step is to create a synthetic vector potential $\boldsymbol{A}$ that, when given suitable spatial or temporal dependence, will simulate a magnetic field $\boldsymbol{B} = \nabla\times\boldsymbol{A}$ or an electric field $\boldsymbol{E} = -\partial\boldsymbol{A}/\partial t$. We synthesized $\boldsymbol{A}$ and showed that it behaved exactly as expected in our calculations.

We dressed an ^{87}Rb Bose-Einstein condensate with two counterpropagating laser beams that Raman-coupled different atomic spin states, and placed the atoms into the lowest energy dressed state in this configuration. This dressed state has a non-zero synthetic vector potential, the value of which we controlled with an external magnetic field. We proved the existence of this synthetic vector potential by measuring the velocity of the atoms, showing that their final velocity was proportional to the vector potential. Our measurements agreed quantitatively with our theoretical calculations previously published.

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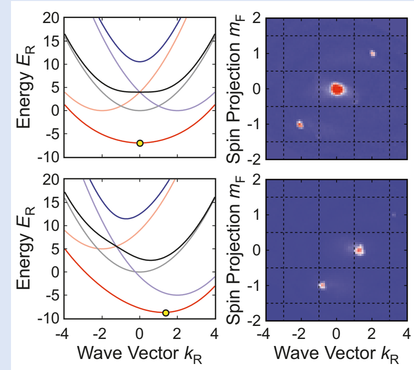

Figure 5. Left panels: Energy-momentum dispersion curves for different Raman detunings (above and below) simulate the Hamiltonian term $(\boldsymbol{p}\text{-}e\boldsymbol{A})^2/2m$ for a charged particle in a vector potential. Pale curves depict the energy-momentum curves without Raman coupling. Yellow circles denote the expected energy and momentum of Bose-condensed atoms. Right panels: The momentum distribution of Bose-Condensed atoms with each spin state resolved separately. The shift to the right of the atoms in the lower panel verifies the simulation of a vector potential.

Dynamics and Phases of a Spinor BEC

A Bose-Einstein condensate (BEC) represents many particles in a single quantum state. In a spinor BEC, the atoms can be in an internal quantum state that is a superposition of spin states. Thus, a BEC of spin-1 particles, like the $F = 1$ ground state of Na atoms, can be thought of as being a single condensate with the atoms in a superposition of the three spin projections, $m_F = -1$, 0, and +1, or equivalently the superposition of three coupled BECs with the same spatial wavefunction, one in each of these spin states.

This many-particle system can be described by a single wavefunction that is a tensor product of the spatial wavefunction and an internal wavefunction that is a mathematical spinor or vector wavefunction describing the amplitudes and phases of the coupled BEC components. The dynamics and steady states of the components of the spinor wavefunction can then be described with a relatively simple set of equations that, in this case, involve only the collisional interactions amongst the different spin states and the quadratic Zeeman, or magnetic field interaction. The system can be described using only a single population and a single phase, exchanging populations through the collisions that convert two $m_F = 0$ atoms into a pair with $m_F = +1$ and $m_F = -1$.

We have studied the dynamics of $F = 1$ Na spinor BECs that are created in non-equilibrium states, and verified the "single spatial mode approximation" theory that has been developed to describe the population oscillations at short times. At long times, the system finds its steady state and can be driven through a quantum phase transition. The system can be either a two-component BEC, with all of the $m_F = 0$ atoms converted to +1/–1 pairs, or a three-component BEC with all of the spin projections populated.

The transition from a two- to three-component condensate is driven by changing either the magnetic field or the net magnetization (excess of $m_F = +1$ over $m_F = -1$ population) of the system. The transition is a quantum phase transition in that it is not driven by thermal fluctuations, but rather by quantum fluctuations. The dissipative dynamics that drive the system from the initial non-equilibrium states to the final steady states are now an active topic of further investigation.

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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, nanoscale devices at the quantum limit, 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, optical microcavities, the quantum optics of nanosystems, 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.

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.

The goals of our experiments are 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 probing the charge and spin 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.

Ultrahigh-precision measurement techniques for the linear and nonlinear optical response of fluids and lens materials have been developed and are being employed. Such measurements are critically needed by the semiconductor industry to develop immersion lithography for sub-100 nm optical nanolithography.

ACCOMPLISHMENTS

Advanced Linear and Nonlinear Optical Metrology in Support of Next-Generation Lithography

We developed a new method for improving the resolution of advanced optical lithography systems, based on high-index, uniaxial-crystal last lens elements (e.g., sapphire) and transverse polarized illumination. We showed that high-order nonlinear spatial dispersion effects, which could compromise the resolution, have high symmetries that allow correction by standard aberration-correction techniques. (See Fig. 6.) Measurements of these effects continue.

We are now investigating these and other types of nonlinear optical effects relevant to advanced 193 nm optical lithography, using a unique pump-and-probe laser system capable of scanning down to 190 nm. One important class of effects is related to high light intensities, which can change the optical properties of materials through changes in the electron band occupancies. We are exploring these effects in oxide nanocrystals as a way to create saturable absorbing materials for potential use as lithography image contrast enhancement layers, and to create nonlinear resists for multiple-exposure lithography.

Another type of nonlinear effect is multiphoton absorption, which causes damage in lens materials, a serious problem in the industry. We are investigating the mechanisms by pump-and-probe measurements, and exploring possible amelioration approaches. A completely uncharacterized class of nonlinear effects we are investigating results from short-wavelength (finite-*k*) combined with high intensities. We anticipate that these effects may impact lithography imaging as laser imaging intensities increase and resolution is extended.

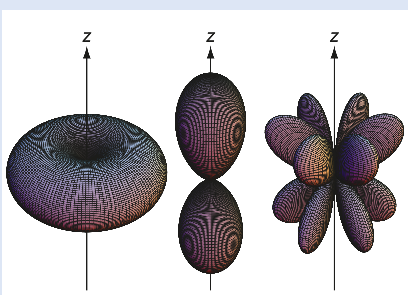

Figure 6. The three calculated photon-momentum-induced anisotropic index distortions in sapphire, with the uniaxial optic axis of the sapphire crystal vertical. The surfaces represent the magnitude of the index deviations in a given direction. Only the third effect causes azimuthal distortions, which can be corrected by lens crystal-axis clocking due to its symmetry.

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Fabrication and Metrology of Novel Magnetic Tunnel Junctions in the Ultra-Thin Barrier Limit

Within a broader program of exploring 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). Technologically, MTJs are a major component of magnetic random access memory (MRAM) architectures, which are widely used in automotive and aviation applications and may eventually replace hard drives. A leading technical challenge is producing MTJs with a resistance-area (RA) product (two dimensional resistivity) that falls in a range that allows for high signal-to-noise, fast write times, and long lifetimes.

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. Our strategy is to irradiate high-quality oxides with very dilute doses of highly charged ions (HCIs), which introduce local regions of thinned oxide at each individual ion's impact site. The HCI impact sites result in ultra-thin (< 1 nm) regions of the tunnel barrier.

Characterization of these ultra-thin barriers has precipitated the development of new measurement and analytical techniques. In the regime where HCI irradiation has reduced the native RA product by many orders of magnitude, a negative resistance error common to all cross-wire devices has been discovered. Modeling and experimental work resulted in high-accuracy correction to these deleterious effects, extended the meaningful range of measurements on crossed-wire devices to extremely small resistances.

The distribution of magnetic domains by coercive and interactive fields is revealed using a first order reversal curve (FORC) technique, providing detailed information about the magnetic switching in patterned, active devices. Shown in Fig. 7 is a FORC diagram that illustrates the fields within one of our MTJ structures. This technique is expected to provide new insight into a wide range of technologically important magnetic devices.

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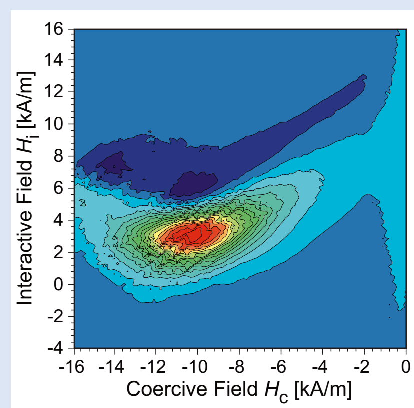

Figure 7. FORC diagram that shows the density of magnetic domain switching as a function of the coercive and interactive magnetic fields.

Reengineering Quantum Dot Optics with Nanomechanical Strain

Developing and exploiting precision metrology for quantum and nanotechnology requires nanoscale modeling of ultrasmall devices, their dynamical operation, and their response to probes. Atomic-scale simulations of the electronic and optical properties of complex nanosystems are being carried out. These systems include nanocrystals, self-assembled dots, nanodot arrays and solids, and nanohybrids. Nanoscale simulations of optical fields near nanosystems are being used to design nanoprobes and nanocavities for precision nanooptics metrology and to model the transport of excitations in quantum devices. This work is providing the foundation needed to engineer nanolasers, detectors, biomarkers and sensors, and quantum devices.

Dynamical control of excitons in quantum dots (QDs) is highly desirable for such applications with QDs as active optical sources and detectors. Applied strain provides a new paradigm for controlling QD optics and for acting as a transducer to couple dot response to mechanical motion and pressure. Applications include QDs as sources in nanolasers; as sources in optomechanical cavities used, for example, for wavelength routing; pressure and motion sensing for ultrasensitive mass detection, electronic skin, mechanical memory and computing; nanomechanical energy harvesting; and as transducers for cooling nanomechanical structures to the quantum limit. We have developed atomistic models for highly strained structures and carried out simulations for structures of 10 million atoms.

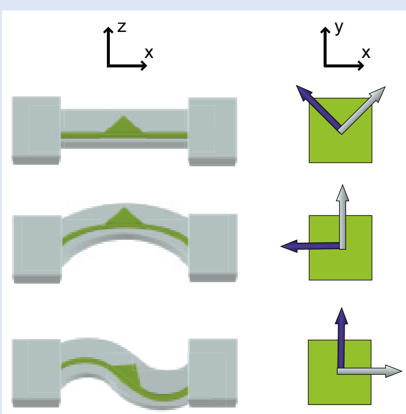

Figure 8. Left: Pyramidal InAs quantum dot in a flat nanomechanical beam, a dot in a beam bent to biaxially deform the dot, and a dot in a beam bent to shear the dot. Right: How the optical polarizations of the lowest bright (optically active) exciton (blue arrow) and the exchange-split exciton (silver arrow) rotate when the beam is bent.

The applied strain makes dramatic changes in the exchange splitting between exciton bright states that modify the exciton fine structure caused by QD asymmetry and atomistic effects, induce crossing between bright states, and rotate the polarized response of bright states through large angles, as shown in Fig. 8. Such control can be exploited in applications of QDs as entangled photon sources, where the elimination of asymmetric exchange splitting is essential, or in cavity-coupled QDs, where tuning the exchange-induced dark and bright states is needed. Manipulation of exciton energies and polarizations via the strain provides a signature for sensing motion or applied pressure.

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Advancing Silicon-Based Charge Qubits

We are pursuing quantum information applications of silicon-based, single electron tunneling (SET) devices, using both charge and spin degrees of freedom. This is a new application that builds upon our extensive experience in using SET devices for metrology requiring precise charge counting.

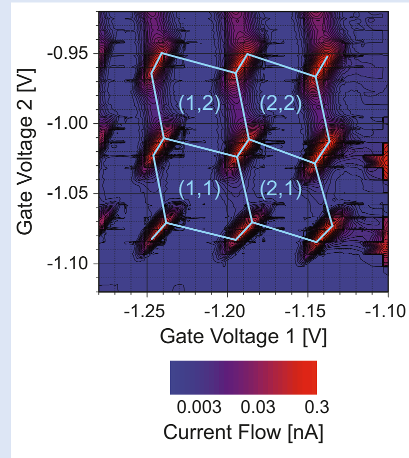

Figure 9. Current flow as a function of voltages on two neighboring gates. The honeycomb diagram demonstrates the ability to control the integral number of electrons on each of two quantum dots (as numbered in white), and to non-coherently transfer electrons between one dot and another.

In the past year, we have completed a thorough analysis of the energetics of these devices to ensure that coherent manipulation will be possible, given what we know of the performance of our devices in the non-coherent regime. A precursor to coherent manipulations in the double quantum dot is the demonstration of charge stability using a "honeycomb" diagram (Fig. 9). We have recently developed this ability.

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The third strategic element is to explore fundamental aspects of the quantum nature of light and its interaction with quantum matter, and to develop applications relating to metrology and other areas of NIST's mission, including measurement at and beyond the standard quantum limits.

QUANTUM BEHAVIOR OF LIGHT AND MATTER

INTENDED OUTCOME AND BACKGROUND

This strategic element focuses on non-classical states of light and analogous states of matter. We study these quantum features in situations that range from the generation of quantum light in atomic vapors and condensed matter systems, to the effect of quantum light on quantum degenerate atomic gases, and to the behavior of mechanical oscillators at the quantum level.

The latter part of the 20th century saw both the recognition and production of radiation that cannot be produced by the motion of classical charges and currents. Squeezed light, single photons, and Fock or number states of light are among the non-classical phenomena that were realized in challenging experiments. Some of these phenomena allowed optical measurement with precision below standard quantum uncertainties such as the shot-noise limit, while others enabled non-intuitive phenomena such as the violation of Bell's inequalities.

Today, NIST is a leader in developing this kind of non-classicality for metrology and other practical applications, and in extending such quantum behavior to new physical platforms. We have developed four-wave-mixing in atomic vapor as a viable technique for creating bright, spatially multi-mode pairs of light beams with high relative intensity squeezing. We have developed quantum dots as reliable sources of single photons, and have developed the tools to entangle the photons from such dots. We are creating micromechanical devices whose mechanical vibration can approach the quantum ground state, opening the way to applying the concepts of non-classicality in a radically new physical system. And we are using atomic-gas Bose-Einstein condensates, the atom-wave analogs of laser light, as a target for imprinting the non-classical character of light onto a macroscopic quantum atomic gas.

Our goals include: evaluating quantum light, atoms, and fabricated micromechanical systems for metrology beyond the standard quantum limits; the development of quantum information transfer between different physical qubit platforms according to which ones are most appropriate for a given function; and the fundamental study of quantum phenomena, such as measurement at the quantum-classical interface.

ACCOMPLISHMENTS

Dressing Entangling Quantum Dot Photons

A near-resonant laser coherently interacting with an atomic-like transition generates hybrid matter-field states. While well established in atomic physics with single atoms and ions, near-resonant coherent interactions have only recently been demonstrated in a nanostructured artificial atom, such as a semiconductor quantum dot (QD).

Nanostructures offer a potentially scalable solution in a number of quantum information applications, and thus coherent control in these systems is particularly desirable. However, the electronic states in QDs are formed from tens of thousands of constituent atoms, and the extent of these interactions is not known.

The photoluminescence spectrum of a single InAs QD was recorded as a secondary resonant laser optically dressed either the vacuum-to-exciton or the exciton-to-biexciton transitions. Polarization-resolved measurements reveal splittings of the linearly polarized fine-structure states that are non-degenerate in an asymmetric QD. These splittings manifest as either triplets or doublets and depend

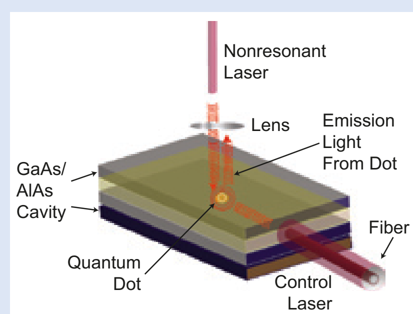

Figure 10. An orthogonal pumping scheme must be used to efficiently couple resonant laser light into quantum dot (QD) samples and to collect light from the QDs at the single photon level. An optical fiber is permanently attached to the side of the sample to inject resonant pump light. Light is collected vertically with high efficiency from a microcavity formed by top and bottom distributed mirrors.

sensitively on laser intensity and detuning. Our approach realizes complete resonant control of a multi-excitonic system in emission, which can be either pulsed or continuous-wave, and offers direct access to the emitted photons.

While QDs maintain remarkable atomic-like, two-level system characteristics, QDs are not identical and ideal symmetries within a QD exist only by chance. Using these techniques we expect to selectively tailored QD states to create a desired symmetry or electronic level structure. For example, working in the far-detuned (AC Stark) regime, we can create discrete photon-pair entanglement from a QD radiative cascade that would otherwise yield only classically correlated photons.

Quantum-state design by coherent optical manipulation would be versatile and deterministic. It would be suitable for a wide variety of QDs and thus could be routinely applied in semiconductor nanostructures.

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Mechanically Induced Sidebands on the Fluorescence of Single InAs Quantum Dots

Mechanical oscillators with dimensions below a micrometer are attractive candidates for observing and controlling quantum phenomena within fabricated systems. Sensing such systems optically, however, is a challenge, as they are smaller than the wavelength of light.

A proposed solution to this difficulty is to embed a self-assembled quantum dot, acting as an "artificial atom," inside the oscillator. Theoretical studies predict that these quantum dots can be fast, sensitive probes of the motion of nanomechanical systems. In addition, an embedded quantum dot should enable a nanomechanical oscillator to be laser-cooled to its quantum ground state.

For laser cooling and quantum control, it is desirable to work in the "resolved sideband" regime, in which high-frequency mechanical motion induces sidebands on the fluorescence spectrum of a quantum dot. These sidebands correspond to the absorption or emission of mechanical quanta.

We have resolved the motional sidebands in quantum dot fluorescence for the first time. For these studies, in order to simulate the motion of a nanomechanical oscillator, we have fabricated thin-film metallic interdigitated transducer (IDT) electrodes on chip using the NIST nanofabrication facility. These electrodes are used to generate surface acoustic waves (SAWs), which "shake" our sample of quantum dots.

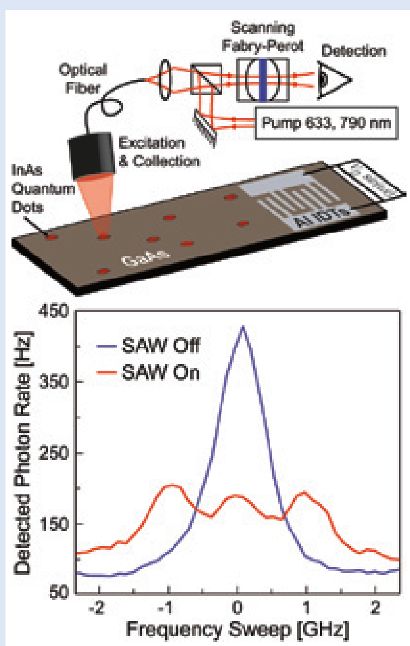

Figure 11. Top: Schematic of apparatus used to "shake" a self-assembled quantum dot and resolve the fluorescence. Bottom: Fluorescence spectrum of quantum dot (blue curve) acquires resolved sidebands (red curve) when "shaken" by surface acoustic wave.

The next phase of this work is to fabricate actual nanomechanical resonators with embedded quantum dots, observe their thermal motion, and attempt laser cooling. Another application of this work that we will pursue is to use the SAW to generate entangled photon pairs from the biexciton fluorescence of individual quantum dots.

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Quantum Entangled Images

We have developed a technique for generating non-classical light by four-wave mixing in atomic vapors. It produces "twin beams" of light that are more closely correlated than for any classical sources.

One particularly useful feature of this technique is that the non-classical light can easily be made in multiple spatial modes. That is, images with quantum correlations can be produced. Pixel-by-pixel, the light in these pairs of images is correlated at levels better than the shot noise for the photon numbers involved.

Light in the corresponding pixels is not just correlated in intensity, but also in phase. The intensity-difference and the phase-sum are quadrature variables displaying quantum entanglement at levels that violate the inequality expressing the Einstein-Podolsky-Rosen paradox. Measurements showing such entanglement have been reported.

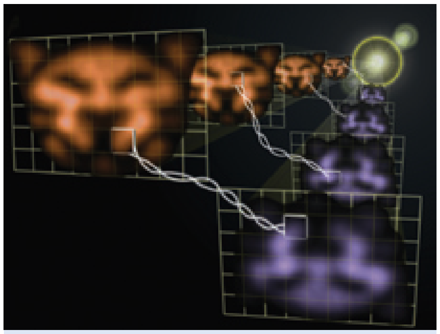

Figure 12. Composite of quantum-correlated images indicating approximate regions of quantum correlations between the "twin" images. The pair of images is created by sending a seed image through an atomic vapor cell, in which the four-wave mixing process amplifies the seed and generates the twin image.

Quantum-correlated and entangled images might be used for faint-object detection. A small absorption or scattering from one of the beams, even at a level below the shot noise, can be detected in the difference between the beams.

Another potential use of such images is in information storage. The parallel storage of quantum information in images has not yet been demonstrated. However, we have taken the first steps in that direction with the "slowing" of quantum images. A vapor cell with a dispersion (change of index with frequency) can display a large group index, which corresponds to a very small pulse velocity in the medium.

We have demonstrated the slowing and delay of continuous beams carrying quantum-correlated images, while preserving the quantum correlations, for times of 20 ns to 30 ns. Future work will pursue stopping, holding, and releasing pulses of light carrying images in a quantum memory configuration.

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Demonstration of a Persistent Current in Superfluid Atomic Gas

One of the most remarkable properties of macroscopic quantum systems is the phenomenon of persistent flow. Current in a loop of superconducting wire will flow essentially forever. In a neutral superfluid, like liquid helium below the lambda point, persistent flow is observed as frictionless circulation in a hollow toroidal container.

A Bose-Einstein condensate (BEC) of an atomic gas also exhibits superfluid behavior. While a number of experiments had confirmed superfluidity, persistent flow, which is regarded as the "gold standard" indicator, had not been observed. The main reason is that persistent flow is most easily observed in a topology such as a ring or toroid, but BEC experiments had been performed primarily in spheroidal traps.

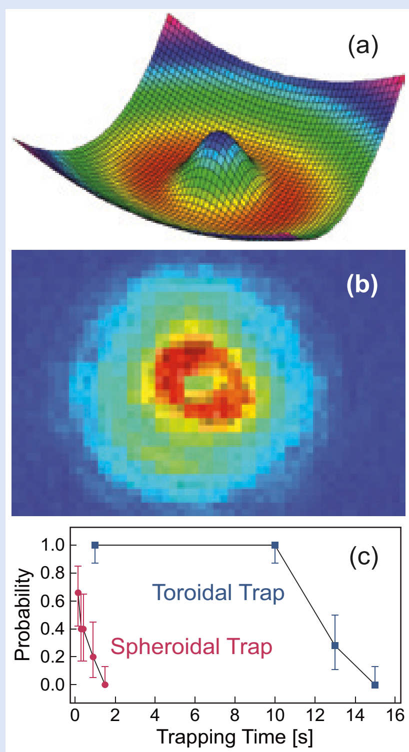

Figure 13. (a) Toroidal potential for the atoms. (b) Time-of-flight image showing the donut shape characteristic of an atomic cloud with quantized rotation. (c) The difference in persistence of flow when the trap is toroidal (with plug) compared to spheroidal (without plug).

Using a combination of magnetic and optical fields, we were able to create an atomic BEC in a toroidal trap. Once the BEC was formed in the toroidal trap filling the entire ring, we coherently transferred orbital angular momentum of light to the atoms (using a technique we had previously demonstrated) to get them to circulate in the trap.

We observed the flow of atoms to persist for a time more than twenty times what was observed for the atoms confined in a spheroidal trap. The flow was observed to persist even when there was a large (80 %) thermal fraction present in the toroidal trap.

These experiments open the possibility of investigating the fundamental role of flow in superfluidity and of realizing the atomic equivalent of superconducting circuits and devices such as SQUIDs.

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The fourth strategic element is to measure, calculate, critically compile, and disseminate reference data on atomic structure and fundamental constants in support of basic research, commercial development, and national priorities.

CRITICALLY EVALUATED ATOMIC DATA

INTENDED OUTCOME AND BACKGROUND

The intended outcome for this strategic element is to maintain NIST as the premier source for atomic data and related fundamental constants.

NIST is recognized for its work in atomic data as the result of three principal efforts. The most prominent of these is the dissemination of critically compiled data through databases on a publicly accessible website. Examples of the most popular databases are the Fundamental Constants database and the Atomic Spectra database, but there are many other similar databases that address specific areas of high impact.

The premier status of the NIST databases arises from the quality of data they contain. Some of this data originates at NIST, but much of it has been gleaned from the open scientific literature. NIST adds considerable value through the process of critical compilation, a process of evaluating all known measurements and calculations for a particular parameter and selecting the best values based on predicted accuracy, as well as consistency with other related parameter values. The result of this effort is a suite of databases that receive more than 300,000 separate requests for data every month.

Second, NIST's reputation for atomic data is also based on a long history of excellent measurements by world-renowned staff using some of the most advanced equipment available. Current work includes measurements of highly charged ions with the NIST Electron Beam Ion Trap (EBIT), development of standard spectral sources for calibration of the next generation of space- and ground-based telescopes, and development of new measurement platforms for improved determination of fundamental constants.

Finally, NIST utilizes state-of-the-art numerical calculations to address needs for atomic data and improve fundamental constants. Work includes atomic structure calculations, studies of fundamental constants, and kinetic modeling of highly charged ions and high-energy-density plasmas.

ACCOMPLISHMENTS

Measurement of Highly Charged Ions Aids International Energy Program

We have used EBIT to produce and study highly charged ions of heavy elements that are relevant to the development of controlled fusion energy. Atoms of the heavy elements hafnium (Hf), tantalum (Ta), tungsten (W), and gold (Au) were stripped of 60 or more electrons and held in the EBIT while their radiative properties and atomic structure were studied. Experimental observations in combination with sophisticated plasma kinetic modeling uncovered combinations of soft-x-ray emission lines that are suitable for use by fusion scientists in analyzing the super-hot plasmas in ITER[2] and other fusion energy devices.

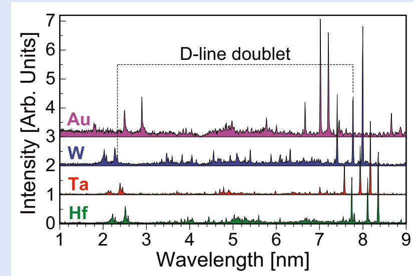

Figure 14. Measured soft-x-ray spectra from highly charged ions of Hf, Ta, W, and Au. Dashed lines indicate the D-line doublet for sodium-like W^{63+}.

Our results are also of significance to fundamental science and the theory of Quantum Electrodynamics (QED). The first simultaneous observation of the sodium D-line doublet in heavy sodium-like ions has enabled accurate measurement of the giant relativistic splitting for several large values of ionic charge. Unlike neutral sodium, where the splitting is one part in a thousand of the mean emission frequency, the relativistic and QED effects for heavy elements become so strong that the line separation is comparable with the mean frequency (Fig. 14). Our measurements of these lines can now serve as essential benchmarks for the most advanced relativistic and QED theories of atomic structure.

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[2] *ITER is the next generation fusion machine being constructed by a multi-billion-dollar international collaboration of the U.S. and other countries. It will be significant step forward in the demonstration of controlled nuclear fusion as a clean, unlimited source of energy.*

Engineered Atoms for Precision Measurement of Fundamental Atomic Constants

In joint work of the Atomic Spectroscopy Group and the Fundamental Constants Data Center, it has been demonstrated, based on quantum electrodynamics (QED) theory, that an ion consisting of a nucleus and a single electron in a so-called circular state can be described more simply than atoms in general. Circular states are weakly bound Rydberg states in which the orbital angular momentum is high. These properties minimize perturbations from the nuclear charge distribution and from interactions with virtual photons. This means that comparisons between measurements and QED calculations are more direct, contain fewer uncertainties, and may lead to superior values of fundamental constants and atomic structure parameters.

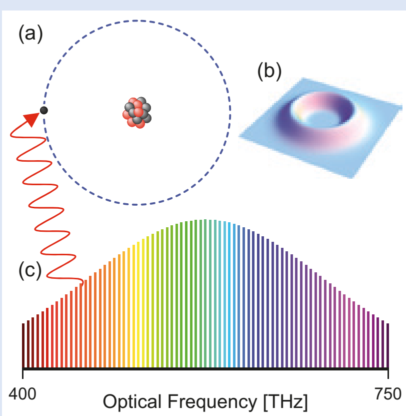

Figure 15. (a) In a circular state, an electron (black dot) orbits far from the nucleus (red and grey core). (b) The electron probability density of such a state. (c) In a highly charged ion, the optical frequency comb can be used to make ultra-precise measurements of Rydberg transition frequencies, which when compared to QED theory determine the value of the Rydberg and fine structure constants.

We plan to develop this approach by uniting three of our competencies. EBIT will be used to create circular states of one-electron ions. There is sufficient energy difference between their Rydberg states that laser techniques may be utilized to cool and trap them, providing the usual advantages. Finally, an optical frequency comb can be employed for precise measurement of transition energies. From these, the values of fundamental constants can be determined.

The initial goal is to obtain an alternative determination of the Rydberg constant with the eventual prospect of improving the precision of both the Rydberg and the fine structure constant.

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New Databases for Atomic Spectra

The Atomic Spectra Database (ASD) has been updated in both presentation and content with the release of version 3.0. This database of critically compiled spectral lines and atomic energy levels is now the world's primary resource for such data. It continues to be very popular with academic, governmental, and industrial researchers, with an average number of data requests per month in excess of 45,000 (Fig. 16). The web interface features several new tools for queries, display, and export to facilitate access to the data.

Version 3.0 has 60 % more wavelength values and 10 % more energy level values than its predecessor, with an emphasis on data that are important for the development of fusion energy. This includes data for all stages of ionization of tungsten,

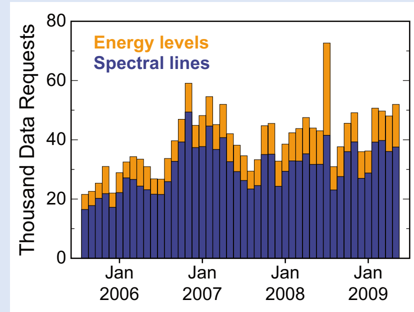

Figure 16. The number of external atomic spectral data requests per month for the last 46 months. Requests for wavelength values are shown in blue, and requests for energy level values are shown in orange.

which will be used as a plasma-facing material in ITER, along with data for iron, neon, argon, krypton, and xenon.

In addition to ASD, new auxiliary databases have been introduced to meet the needs of specific research communities. The Spectrum of Th-Ar Hollow Cathode Lamps, analogous to the earlier Spectrum of Platinum Lamps for Ultraviolet Spectrograph Calibration, is used by astronomers to calibrate new infrared telescopes. The new NLTE4 Plasma Population Kinetics Database is used by computer modelers of high-energy-density plasmas to benchmark their calculations for plasmas that are not in local thermodynamic equilibrium. These include magnetic and inertial confinement fusion plasmas as well as astrophysical plasmas.

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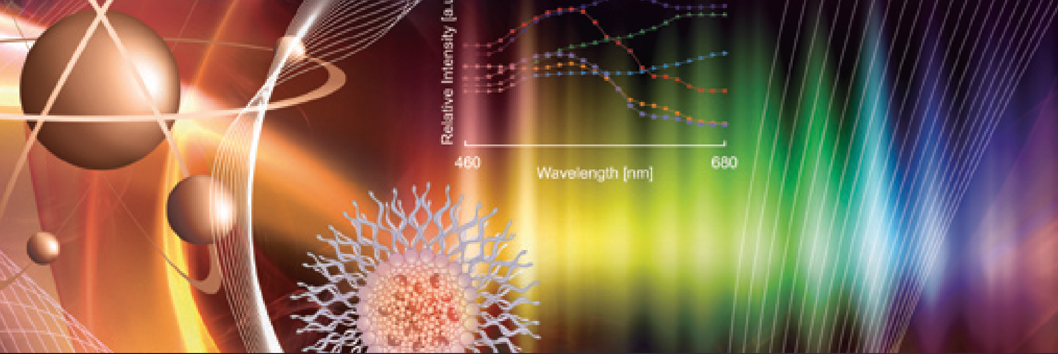

Optical Technology Division

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 terahertz through the infrared, visible, and ultraviolet spectral regions.

The first strategic element is to maintain and advance 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 within organizations and across national boundaries.

Research programs in the Division strive to continually improve the accuracy of our Nation's radiometric and photometric scales to meet the demands of industry, government, and academia. These scales are increasingly being based on stable, low-noise, highly linear detectors, radiometers, and photometers. The absolute responsivities of these instruments are tied to optical power measurements performed using cryogenic radiometry and a state-of-the-art laser facility, SIRCUS (Spectral Irradiance and Radiance Calibrations with Uniform Sources). Cryogenic radiometry provides the highest accuracy optical power measurements by performing a direct comparison of optical and electrical power. The Division's Primary Optical Watt Radiometer (POWR), the Nation's standard for optical power, achieves a relative standard uncertainty of approximately 0.01 %.

The improvements realized by tying the radiometric measurements to cryogenic radiometry are significant. Linking of the Division's spectral irradiance scale, as disseminated by FEL-type lamps, to POWR measurements has enabled the reduction of spectral irradiance uncertainties by a factor of two in the ultraviolet and visible, and even more in the infrared. The spectral radiance and radiance-temperature scales are similarly being tied to cryogenic radiometry. Because of the Division's success in this area, the spectral irradiance scales for many nations are traceable to NIST standards.

These advances in detector-based radiometry are complemented by new research in source-based radiometry, where the spectral output of an emitter is known absolutely. Such sources include correlated-photons produced by optical parametric down conversion in a nonlinear crystal, Planckian black-body sources of radiation tied to phase-transition temperatures of metal-carbon and metal-carbide-carbon eutectics, and synchrotron radiation from the NIST Synchrotron Ultraviolet Radiation Facility (SURF III), maintained by the Electron and Optical Physics Division.

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

Standards to Support Commercialization of Solid-State Lighting

Solid-state lighting is becoming a commercial reality—light emitting diodes (LEDs) are being introduced into more and more products for general purpose and architectural lighting. This is significant because about 22 % of electricity consumption in the U.S. is used for lighting, and white LED lamps are expected to attain at least twice the energy efficiency of fluorescent lamps.

In support of the Department of Energy (DOE), which has set a goal of reducing by half the energy spent on lighting, NIST is developing national and international measurement standards for this emerging technology. We have developed new measurement services for LEDs, a laboratory accreditation program, and are furthering research on photometric and colorimetric aspects of solid-state lighting sources.

In particular, NIST played leadership roles in developing the ANSI (American National Standards Institute) C78.377 chromaticity specifications, and the IESNA (Illuminating Engineering Society of North America) LM-79-08 standard method of photometric measurement for LED products, which have become the key standards used in DOE's Energy Star program.

Figure 1. LEDs are being employed in more and more types of general purpose and architectural lamps, such as these. The Division develops measurement standards that allow buyers to specify and use these new products with confidence.

NIST scientists continue to work towards further, needed LED measurement standards in committees of ANSI, IESNA, and the CIE (International Commission on Illumination). For example, measurements of high-power LEDs have been difficult due to their strong dependence on temperature and due to differences in measurement practice in the semiconductor and lighting industries. We have developed a novel technique to measure high-power LEDs at a set junction temperature, bridging the gap between the two practices. We have also developed a new metric for color rendering of light sources, which solves the problem of applying traditional metrics to white LEDs. It is being proposed as a new international standard.

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New Facility Enables Vision Science Studies

The spectra of LED sources are dissimilar to those of traditional incandescent and discharge lamps, and some traditional lighting standards are insufficient or deficient when applied to LEDs. Thus, it is important to conduct modern vision experiments to better understand the effects of chromaticity, color rendering, and other aspects of spectra on lighting quality.

NIST's new Spectrally Tunable Lighting Facility has been developed to enable this research. The facility consists of two room-size, furnished cubicles in which observers can be completely immersed in a real-life setting. Each cubicle is lit by 1,800 variable-power LEDs under computer control. Organized into 22 wavelength channels, the LEDs span the visible spectral range of 440 nm to 640 nm and can be set to simulate the spectra of various types of light sources. This allows testing and evaluation of prospective lighting systems as people would experience them.

Figure 2. A vision scientist, Wendy Davis, sits in the NIST Spectrally Tunable Lighting Facility, which allows participants to be fully immersed in a real-life setting for color-quality studies in support of solid-state lighting standards.

NIST researchers are using the facility to develop a new color-quality scale, and to investigate optimum spectral compositions of white light to achieve both superior color quality and high energy efficiency. The results of these experiments will lead to new international standards and provide manufacturers with knowledge they need to develop higher quality products.

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Flat-Plate Radiometric Source for Calibrating Satellite Sensors

In partnership with NASA and NOAA, a new radiometric source has been developed for the calibration of satellite optical sensors during the thermal-vacuum stage of testing. During this stage, the conditions on orbit are simulated. Conventional calibration approaches use large lamp-illuminated integrating spheres. However, they would not only require excessively large vacuum chambers for testing, their flux levels and spatial profiles would replicate poorly the radiation field that a satellite sensor would see on orbit.

The interagency team developed a novel, low-profile, vacuum-compatible calibration tool to fit the need. It consists of a flat-plate illuminator fed by xenon arc lamps using optical fibers. Four filter radiometers were used to monitor the spectral radiance of the four quadrants of the flat plate. A diffuser is installed to provide an improved representation of reflected solar radiation, from Earth as seen by the satellite.

The source was demonstrated to have an absolute radiometric uncertainty of 1.9 % (k = 1), sufficient to meet the 2 % requirement of the Visible Infrared Imager Radiometer Suite (VIIRS) sensor being developed for the National Polar-orbiting Operational Environmental Satellite System (NPOESS). Additionally, the team showed that the source could be used at wavelengths as long as 2.4 µm by replacing the xenon lamps with a supercontinuum source. This allows the calibrator to be used throughout the full reflective solar band, from 350 nm to 2.4 µm.

Other applications are being explored, including the calibration of astronomical telescopes, where the space between the entrance aperture of the telescope and the roof of the dome is insufficient for integrating-sphere sources. Additionally, the flat-plate system is scalable to large aperture telescopes, whereas integrating spheres would become prohibitively large and expensive.

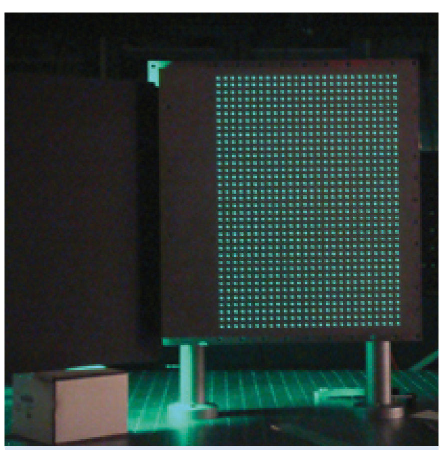

Figure 3. A fiber-fed flat plate for calibrating satellite sensors.

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The second strategic element is to advance optical radiation measurement science to solve problems in critical and emerging technology areas of national importance.

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, quantum dot, nanoshell, metal, and magnetic nanoparticles are being developed for use as quantitative probes to interrogate and manipulate chemical, physical, and biological phenomena within complex chemical and biological systems. Raman spectroscopy is being applied to the characterization of carbon nanostructures, such as nanotubes and graphene. Well-characterized nanomaterial samples have the potential to serve as standards for researchers exploring physical, chemical, and biological applications of nanomaterials and their environmental, health, and safety effects.

The Division is also advancing the measurement science of optical medical imaging for surgical and clinical applications. Optical medical imaging promises to enhance and complement conventional medical imaging modalities that are too expensive for routine use or too complex and slow for surgical applications. The Division's program includes developing advanced digital tissue phantoms to calibrate and compare optical medical imaging systems, particularly hyperspectral imaging systems, and enhancing illumination methods to improve visual and imaging system contrast.

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 decadal and longer time scales. 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 the USGS, such as the NPOESS, GOES-R, LDCM, and CLARREO missions. The Division also works with land- and sea-based sensor programs to help ensure measurement accuracy and quality. A new effort has been initiated to apply this expertise to improve the Nation's multibillion-dollar ground- and space-based astronomical measurements for applications to satellite calibration, atmospheric remote sensing, large-scale sky surveys, dark energy studies, and cosmology research.

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. Specialized calibration chambers have been developed 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.

Expertise in optical radiation standards for defense is being applied to homeland security applications too. Techniques are being developed to improve the detection of improvised explosive devices (IEDs) and the protection of civilian aircraft from shoulder-fired missiles.

Single-photon source and detector metrologies are being advanced for application in quantum communication and quantum cryptography. This may eventually allow all of the Division's fundamental radiation measurements to be tied to quantum-based standards.

ACCOMPLISHMENTS

New Method for Detecting Motions of Aqueous Biomolecules

The ability of biomolecules to flex and bend is important for their function within living cells. Until recently, researchers interested in understanding how biomolecules such as DNAs and proteins function have had to make inferences from "frozen pictures" of pure crystalline samples. Now, using a new technique based on terahertz spectroscopy, Division scientists have taken the first steps toward revealing the hidden machinations of biomolecules in room temperature water.

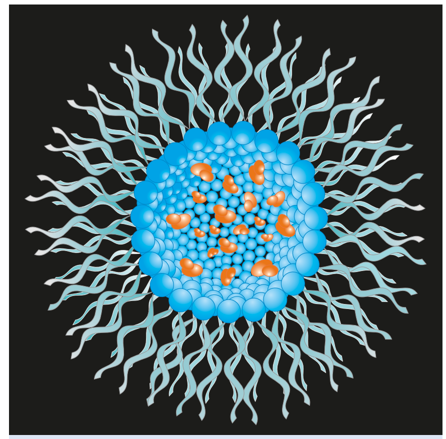

Figure 4. An illustration of L-proline molecules encapsulated within a reverse aqueous micelle formed by anionic surfactant in terahertz-transparent *n*-heptane.

Terahertz radiation, which falls between the infrared and microwave spectral regions, probes concerted and large-scale motions of molecules as well as their interactions with surrounding solvent. Unfortunately, room temperature water, the natural solvent for biological molecules, absorbs nearly all terahertz radiation, limiting the utility of terahertz absorption spectroscopy for probing biomolecular function.

To minimize this problem, we used reverse micelles: nanoscale capsules of water suspended in terahertz-transparent organic solvent surrounded by surfactants. The reverse micelles were filled with a solution of water and, for this test, the amino acid L-proline, a protein building block. Spectral measurements validated the hypothesis that the reverse micelles can provide an aqueous environment that allows the amino acid to flex and bend, with minimal water to absorb the terahertz radiation. The terahertz measurements on this simple biomolecule compared well with other studies, further validating the technique.

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Shape Evolution of Nanoscale Patterns

Division researchers successfully demonstrated the application of scatterometry to monitor, in situ, pattern profiles made by thermal embossing nanoimprint lithography. In addition to obtaining real-time measurement of pattern profiles, researchers also gained new insight into the evolution of patterns imprinted in polymers of different molecular weight.

Thermal embossing nanoimprint lithography uses a mold to stamp a nanoscale pattern into a polymer under heat and pressure. This simple process is a low-cost alternative to photolithography, with high throughput and high resolution. This research studies the process to better understand how the shape of the imprinted pattern evolves during thermal annealing, enabling optimization of the imprint process.

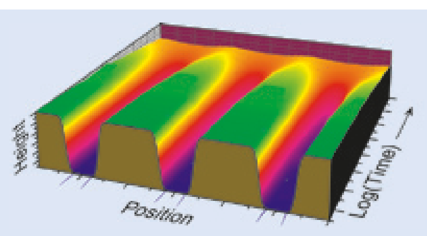

Figure 5. Line profiles of a pattern made by nanoimprint lithography as measured by scatterometry during the annealing process.

Researchers in the Optical Technology, Surface and Microanalysis Science, and Polymer Divisions collaborated to use scatterometry, which combines spectroscopic ellipsometry with rigorous coupled-wave analysis, to extract topographical information from the optical measurement. Scatterometry determines, in situ, the same information about pattern height and shape as the traditional ex situ methods, such as AFM, SEM, and spectral x-ray reflectivity. It also provides a complete record of pattern evolution during annealing of a single sample, whereas ex situ methods require preparation of many samples, annealed for various times, to build up a picture of the pattern decay. Further, scatterometry may provide more sensitive measurements of nanoscale features in the pattern cross-section.

The researchers had expected that patterns imprinted in polymers of high molecular weight to change relatively slowly. However, they observed that the patterns in low molecular weight polymer initially appeared more resistant to change, while the patterns in high molecular weight polymer showed a much faster initial relaxation, consistent with measurements made using ex situ techniques. Furthermore, the scatterometry measurements indicated subtle differences in shape between the annealed high and low molecular weight polymers that were difficult to discern using other methods.

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Advances in Hyperspectral Image Projection

Measuring global climate change with remote sensing instruments requires excellent knowledge of their sensors' performance. For such evaluations, Division scientists have successfully demonstrating the projection capabilities of a Hyperspectral Image Projector (HIP). Using this device, we can generate images in the laboratory with precisely tailored spectra for each pixel, simulating actual scenes in nature without the complications of changing field conditions.

This ability to specify spectra, not just color, is what differentiates the HIP from a common video projector. While the three spectral bands ("red," "green," and "blue") of a video projector are sufficient to create color for the human eye, earth-science cameras need more spectrally detailed test images for their complete calibration.

To demonstrate the HIP's capability, researchers chose a hyperspectral image of a coral reef located off the coast of Puerto Rico and acquired by an airborne hyperspectral sensor. This image, provided by the University of Puerto Rico at Mayagüez, is an ideal subject for emulating a spectrally and spatially complex scene. We recreated the image using the HIP, and recollected the image using a laboratory imaging spectrometer as a proxy for the type of devices used in the field.

This demonstration also revealed the HIP's potential for other applications. A HIP could be used to determine the threshold of detection of changes in scenes. This is a key area of concern for measurement of regional and global climate change. The

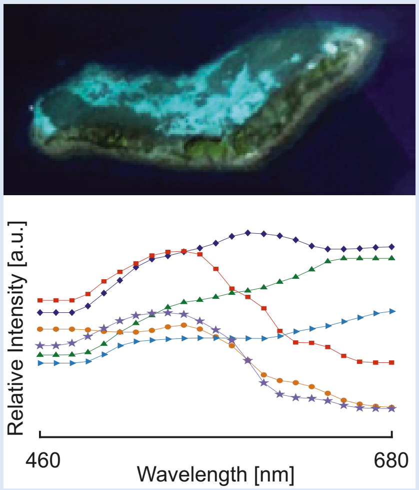

Figure 6. Image of a coral reef projected by the Hyperspectral Image Projector (above), and the basis functions used for the projected image (below).

HIP may also serve as a tool in the development of medical imaging by providing a standard tissue phantom for medical imagers.

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Near-Infrared Reflectance Standards for Satellite Remote Sensing

Accurate reflectance standards in the solar radiation band from the ultraviolet (250 nm) through the short-wave infrared (2500 nm) are important for calibrating satellite measurements of surface albedo, atmospheric aerosols, ocean color, and other environmental variables for weather, climate, and geospatial imagery applications. A new method has been developed to determine the reflectance factor for white polytetrafluoroethylene (PTFE) diffuse reflectance standards from 1100 nm to 2500 nm at the 0°/45° geometry (0° incident and 45° reflected angles).

Diffuse reflectance standards are used, for example, to calibrate the spectral reflectance of solar-illuminated PTFE diffusers deployed on the Moderate-resolution Imaging Spectroradiometer (MODIS) and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite systems, and planned for the future Visible and Infrared Imaging and Radiometry Suite (VIIRS), Advanced Baseline Imager (ABI), and Operational Land Imager (OLI) satellite missions. They are also important for calibrating ground-based measurements of surface reflectance used to validated and calibrate satellite measurements. An example of such a ground-based measurement is presented in Fig. 7.

This work extended the long-wavelength limit of the NIST reflectance factor scale from 1100 nm to 2500 nm, allowing NIST to provide white reflectance standards with low measurement uncertainties over the entire solar band. The uncertainties of the absolute diffuse (non-specular) reflectances are < 1 % from 1100 nm to 2450 nm and 2.5 % at 2500 nm.

The major challenge in measuring diffuse, non-specular reflectance in the short-wave infrared is the low reflected signal. The present effort exploits advances in extended-range indium gallium arsenide detectors and NIST-designed low-noise preamplifiers that together allow noise equivalent powers of approximately 15 fW with a 1 s time constant.

Figure 7. A researcher measures the solar radiance from a calibration plaque reflectance standard prior to measuring the reflectance of the terrain.

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Tuning the Properties of Engineered Cobalt Nanoparticles

Cobalt nanoparticles possess large magnetic moments and unique catalytic properties. Potential applications for these nanomaterials exist in information storage, energy, and medicine.

We have applied a colloidal synthesis route to obtain monodisperse and highly crystalline cobalt nanoparticles. Our results demonstrate that the properties of these engineered cobalt nanoparticles can be tuned by changing the shape of cobalt nanoparticles from spherical to cubic, and by simply aging cobalt colloids in air.

The properties of cobalt nanocubes were compared with their spherical counterparts. One striking difference was their relaxation behavior upon the removal of external magnetic fields. As the strength of the external field is gradually reduced to zero, the magnetization of the spherical nanoparticles also decreases gradually. The magnetization of nanocubes, on the other hand, decreases in a much slower fashion until the formation of vortex states, resulting in a sudden drop in their magnetization.

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The third strategic element is to disseminate optical radiation measurement technology 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. Additionally, 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 facilities are being developed to improve the measurement of the spectral reflectance and transmittance of materials and the measurement of far-infrared to near-infrared radiation for application to satellite remote sensing of weather and climate.

The Division strives to ensure the quality of these programs by publishing our research results and measurement methodologies (as NIST Special Publications and in outside, peer-reviewed archival journals), by participating in measurement comparisons with other laboratories, and by maintaining a measurement quality program. The Division aids good optical radiation measurement practice by developing general approaches to improve quality and reduce measurement time, by publishing training documents, and by offering formal, short courses in photometry, spectroradiometry, spectrophotometry, and radiation temperature measurement.

ACCOMPLISHMENTS

Nationwide Comparison of Infrared Reflectance Measurements

In partnership with the Department of Defense, the Division led a campaign to assess the accuracy and comparability of infrared reflectance measurements routinely performed by government and aerospace industry laboratories. The large number of participating laboratories, 21, reflected the great interest in infrared measurements. They are critical to the interpretation of infrared signatures of ground, air, and space vehicles; to the measurement of temperature using passive, non-contact infrared thermometry; and to the development of calibration targets for ground- and space-based environmental sensors, measuring sea-surface and atmospheric temperatures and cloud heights.

The campaign involved the exchange of sets of five infrared reflectance standards, three diffuse and two specular as shown in Fig. 8. Each of the participating organizations measured a set, with NIST measuring each of the sets both before and afterwards. Measurements covered the 2 μm to 14 μm wavelength range at a spectral resolution of 8 cm^{-1} and with near-normal geometries.

The results demonstrated significant differences among the participants. Although a number of participants had results consistent with their calculated uncertainties, differences in reflectance units up to 0.1 (on a scale of 0 to 1) were not unusual, despite the participants' uncertainty analysis suggesting that they should be much smaller. Participants failed to account for some significant uncertainty components present in the NIST uncertainty budget. A number of participants procured a set of the standards to keep for future calibration purposes. Future work will involve more complicated reflectance measurements, including varying the angle of illumination and characterizing the full bidirectional reflectance distribution function.

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Figure 8. Set of NIST-calibrated infrared reflectance standards (51 mm diameter), as provided to the comparison participants.

A Best Selling Standard Reference Material

Standard Reference Material (SRM) 1921 is a calibration standard for Fourier-transform (FT) infrared spectrometers. Since its release for public sale in 1994, it has sold more than 4000 units to both U.S. and international customers, including infrared instrument manufacturers, chemical companies, pharmaceutical companies, law enforcement and forensics agencies, research institutions, and government agencies.

SRM 1921 consists of a thin film of polystyrene whose infrared transmission spectrum has been well characterized in terms of the absolute positions of the spectral peaks and their uncertainties. Because this standard provides calibration of the wavelength scale that encompasses the fingerprint region of the infrared, it has made a significant impact in its users' ability to accurately identify the chemical signatures of numerous compounds. Thus, it is frequently employed to satisfy the regulatory requirements of the pharmaceutical industry, as well as other standard practice methods. It is also used to validate peak-measurement algorithms.

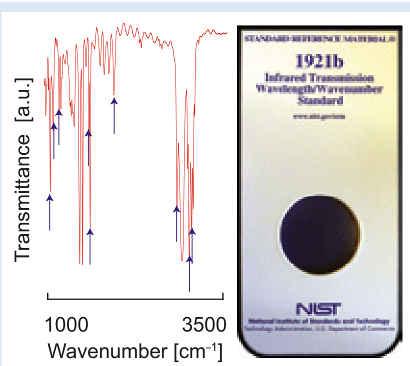

Figure 9. SRM 1921b is used throughout the world to calibrate infrared spectrometers. A portion of the transmittance spectrum is shown with arrows indicating the reference peaks of polystyrene.

This SRM is the best selling SRM from Physics Laboratory, selling three times more than the next best seller. At the close of the 2009 fiscal year, SRM 1921b, the latest issue of SRM 1921, was the 7th best selling SRM at NIST.

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Missile-Defense Transfer Radiometer Ready for First Deployment

In collaboration with the Missile Defense Agency (MDA), the Division has developed a new infrared transfer radiometer for the calibration of sensors and space chambers used in missile defense applications. The radiometer will help ensure that infrared sensors used to support missile defense programs, such as the Exo-atmospheric Kill Vehicle (EKV) and Standard Missile 3 (SM-3), can accurately discriminate the infrared signature of an incoming missile from that of decoys and the natural background of space.

The Missile Defense Transfer Radiometer (MDXR) had been in development for four years at the Division's Low Background Infrared (LBIR) facility. It is an infrared radiometer with full spectral calibration capabilities, and replaces the filter-based transfer radiometer (BXR). The MDXR features numerous improvements, including a cryogenic Fourier-transform spectrometer (Cryo-FTS), an on-board absolute cryogenic radiometer (ACR), an internal blackbody reference, and an integrated collimator.

The Cryo-FTS can be used to measure high-resolution infrared spectra from 4 μm to 20 μm, using a calibrated blocked-impurity-band (BIB) detector. The on-board ACR can be used to calibrate the BIB detector and for absolute measurements of input signals. A set of filter wheels and a polarizer within the MDXR allow for filter-based and polarization-sensitive measurements. The optics of the MDXR enable measurements of both radiance and irradiance, and calibrations of both radiant and collimated sources.

Figure 10. Timothy Jung works on the optical plate of the MDXR, which contains a cryogenic Fourier-transform spectrometer and other instrumentation necessary for absolute spectral calibrations.

The MDXR will be the NIST detector standard deployed to MDA facilities. Its broad functionality will allow a variety of measurements to be performed. First deployment will be at the Arnold Engineering and Development Center in late 2009.

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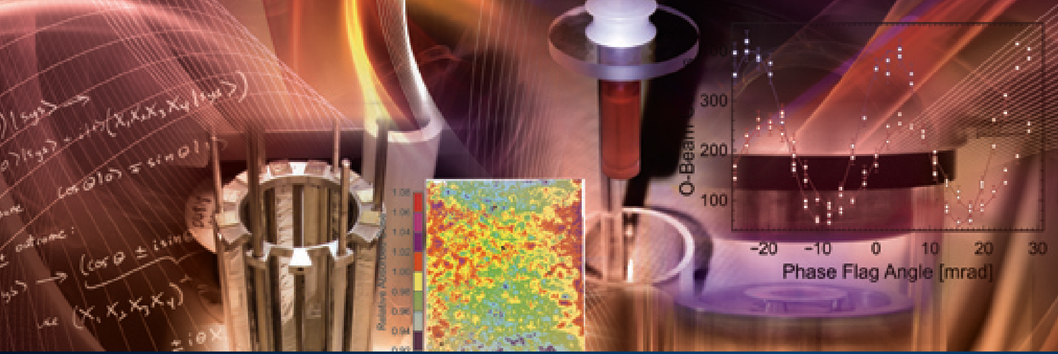

Ionizing Radiation Division

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 art of measurement of quantities important in the radiological sciences, through programs in the dosimetry of x rays, gamma rays, electrons, and other charged particles. Our mission is to develop, maintain, and disseminate the national measurement standards for these radiations. In particular, we maintain standards for the gray, the Système International (SI) unit for radiation dosimetry. We also engage in research to meet requirements for new standards as they arise from industry, medicine, and government.

These standards are disseminated by means of calibrations and proficiency testing services provided to maintain quality assurance and traceability. We work closely with networks of secondary calibration laboratories traceable to us, and we continue to expand our capabilities in a number of measurement areas. Our staff continues to make important contributions to the work of developing national and international standards, and of scientific organizations, and we are central to measurement quality assurance of dosimetry in the many application areas of ionizing radiation.

We also develop, maintain, and disseminate high-quality data on fundamental radiation interactions. These are used extensively in radiation transport calculations and simulations, using algorithms and codes often developed by our staff, to solve a wide range of problems in radiation science and its applications.

We maintain an interest in homeland-security applications, together with more traditional radiation-dosimetry programs. We help develop performance criteria through American National Standards Institute (ANSI) working groups, for x-ray and gamma-ray screening systems used in homeland-security applications, and for radiological protection governing vehicle/cargo inspection systems and personnel body-scanning systems.

Our research in improved water calorimetry to realize absorbed dose continues to move forward. Our clinical electron accelerator has been used extensively in the development of a second-generation water calorimeter to serve as a national standard for accelerator-produced, high-energy x-ray beams used in cancer therapy.

ACCOMPLISHMENTS

Air Kerma Rate Measurements of Small Radioactive Sources Used for Homeland Security Applications

Portal radiation monitors are used at entry ports and land borders to prevent illegal transport of radioactive materials into the country. Recently published air kerma measurements help ensure that they are properly tested and calibrated.

Portal monitors are calibrated in terms of air kerma. The calibration procedure uses small radioactive sources, for which the air kerma rate at a given distance must be well known. These sources are placed at a well-defined distance from the portal monitor so that the reference air kerma rate value and the rate measured by the portal monitor can be compared. However, manufacturers of the radioactive sources do not provide the air kerma rate. Instead they provide the activity of the source, traceable to NIST, which is expressed in units of becquerel (or in older units, curie). It is the user's responsibility to determine the air kerma rate from the activity value.

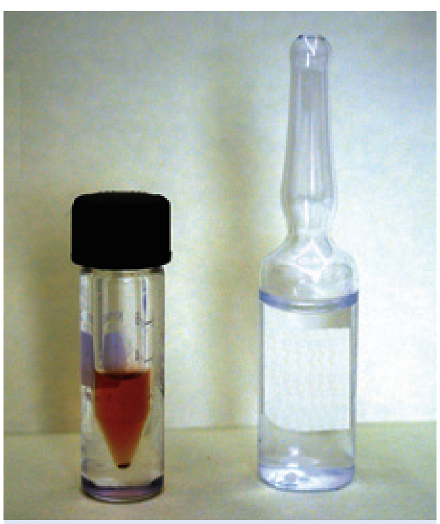

Figure 1. Sample vials of liquid radioactive sources used to study the calibration of portal monitors.

Conventionally, an air kerma rate is estimated from tabulated (calculated) values of the so-called specific gamma-ray constant, which apply to idealized point sources in a vacuum. Our studies took into account self absorption by actual sources and attenuation by the encapsulation and air path. The results showed that these effects could be significant and that portal monitor calibrations should compensate for them.

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TLD Irradiations for the Navy Dosimetry Program

NIST provides radiation measurements to support the Navy's quality-assurance program for testing thermoluminescent dosimeter (TLD) systems. The TLD model DT-526 is a calcium fluoride solid-state dosimeter that has been used by the Navy since 1973. It is used to monitor the exposure of personnel working at shipyards and other sites for the U.S. Naval Nuclear Propulsion Program (NNPP).

In support of this program, NIST provides monthly irradiations of TLDs that are later used to test TLD readers located at the various sites associated with the NNPP. The test is coordinated between NIST and Navy personnel at the Naval Surface Warfare Center in Bethesda, Maryland.

The Naval Dosimetry Center (NDC) in Bethesda monitors radiation exposure of Navy personnel not associated with the NNPP. NIST assists the NDC with measurements to support a quality-assurance program for the newer model DT-702 personnel TLDs. The newer dosimeters provide more accurate readings, better stability, greater energy discrimination, and a lower detection limit.

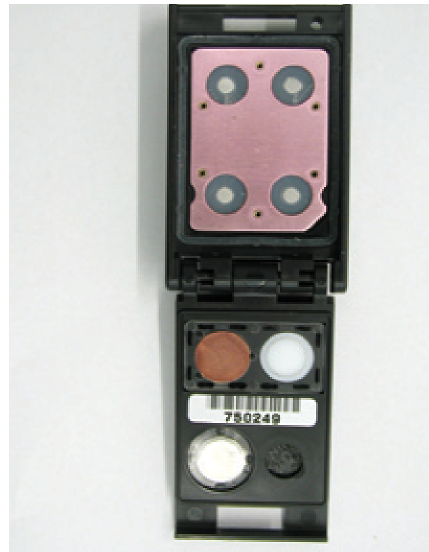

Figure 2. View of the inner structure of the newer, DT-702 TLD system.

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Absorbed-Dose Measurements to Support Biologics Research

We have been working with the biotech firm Sanaria, Inc., which is developing a promising malaria vaccine. (No effective vaccine for malaria yet exists. As of this writing, Sanaria's vaccine is being tested in an early-stage human clinical trial.) A novel aspect of its production process involves irradiating live mosquitoes containing the parasite *Plasmodium falciparum*, the most dangerous species of parasite that causes malaria.

Specifically, we performed measurements to assist Sanaria in assuring a minimum

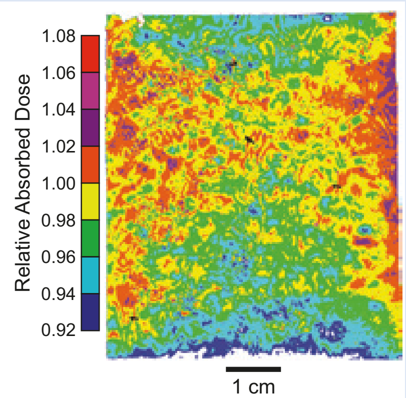

Figure 3. False-color rendition of an absorbed-dose map for the Sanaria irradiator. The relative results are normalized to absolute results from alanine/EPR dosimetry at a reference position.

delivered dose of 150 Gy to all mosquitoes in the Sanaria ^{60}Co irradiator. These measurements support Sanaria's quality-assurance tests that ensure all mosquitoes receive the intended dose of radiation.

Dose-mapping measurements were performed using radiochromic films in vertical sheets. The films were analyzed using a laser scanning densitometer, and the results gave details on the dose uniformity over the entire volume of the irradiation vessel. The film results indicated the regions of minimum and maximum dose inside the chamber.

With these data, we were able to recommend a shift in the vessel position to allow for a more uniform dose. The result was a shorter irradiation cycle that saved time, plus less overdosing, which improved process quality.

A series of experiments was also done to determine the correspondence between dosimeters placed inside and outside of the vessel. Successful determination of this relationship and its statistical uncertainty allows for irradiations to be done with just outside dosimeters. This is critical to the manufacturing process, as there is no option to have dosimeters inside the vessel in the presence of the infected mosquitoes.

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Calibration of Miniature X-Ray Sources for Electronic Brachytherapy

A new laboratory has been established to calibrate, traceable to national, primary air kerma rate standards, miniature x-ray sources developed for the nascent field of electronic brachytherapy, such as those of the Xoft's Axxent system. The Xoft source was designed to provide low-energy x rays (< 50 keV) for prophylactic brachytherapy to treat possible micro-extensions of disease following breast lumpectomies.

Air kerma rate will be realized directly through use of the Lamperti free-air chamber. A high-purity germanium x-ray spectrometer will be used to monitor the energy spectrum of the beam in real time, as well as provide necessary input data for Monte Carlo calculations of correction factors for the free-air chamber. To account for spatial anisotropy of emissions, the free-air chamber and spectrometer will be rotated about the long axis of the x-ray tube during measurements.

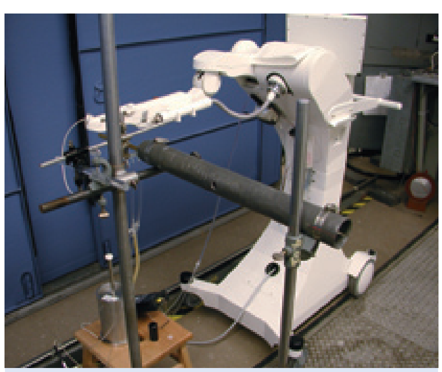

Figure 4. Electronic brachytherapy x-ray source under test.

The response of well-ionization chambers to these x-ray sources will be studied in preparation for the development of a measurement assurance program for the dissemination of the new NIST standard to Accredited Dosimetry Calibration Laboratories. These laboratories are accredited by the American Association of Physicists in Medicine and calibrate radiation-measuring instruments for use in therapy clinics.

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The second 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. Significant programs include low-level standards for environmental measurements and monitoring, standards for nuclear medicine, and standards and testing criteria for radiological instrumentation used for security. Participation in international comparison exercises has kept us abreast of efforts of other laboratories, and has reinforced our own capabilities.

Revitalization of our basic metrology capabilities has involved extensive work. The principle method of primary standardization at NIST is live-timed $4\pi\beta$-γ anticoincidence counting, and we have adapted this method to perform primary measurements on a variety of radionuclides. Since introducing the Triple-to-Double Coincidence Ratio (TDCR) method into routine use at NIST, work is progressing on the construction of a second-generation TDCR system. A new, automated ionization chamber has been developed to measure up to 100 samples with programmable sample queuing, sample handling, and measurement parameters.

We continue to lead the national effort, in collaboration with the Department of Homeland Security, to develop standards and protocols for radiation instrumentation used by front-line inspectors and emergency responders. With the National Voluntary Laboratory Accreditation Program (NVLAP), we have developed an accreditation program for instrument testing. We are also spearheading the development of ANSI standards and testing protocols for spectroscopic portal monitors, neutron detectors, x-ray and high-energy gamma-ray interrogation methods, and x-ray imaging devices. Additional standards cover data formats for instrument output and training for instrument users.

Our leadership is internationally recognized in standards for nuclear medicine, supporting 13 million diagnostic and 200,000 therapeutic procedures annually in the United States. Primary standards of two radionuclides, ^{223}Ra and ^{68}Ge, have been developed recently. A new initiative aimed at improving the accuracy and consistency in quantitative Positron Emission Tomography/X-ray Computed Tomography (PET/CT) and Single-Photon Emission Computed Tomography (SPECT) is well underway.

The Group's environmental program leads the community in low-level and natural matrix material measurements and standardizations. We continue to be heavily involved in the measurement of environmental-level radionuclide concentrations, both natural and due to contamination, through international intercomparisons and traceability programs. A Radioanalytical Emergency Procedures Manual Database has been developed to assist organizations preparing for emergency response.

ACCOMPLISHMENTS

Calibrating Medical PET Scanners

About 2.5 million Positron Emission Tomography (PET) procedures are carried out annually in the U.S. Over 90 % of such scans use [^{18}F]fluorodeoxyglucose (FDG) as the imaging agent. As the technology matures, PET is increasingly being used as a quantitative technique to monitor disease response to treatment, particularly during clinical trials.

The quantification accuracy of PET images depends on both the calibration of the PET scanner and the radioactivity content of the very short-lived (approximately 2 hours) ^{18}F that is injected into the patient. This short half-life precluded a NIST-traceable standard for ^{18}F, which made it difficult to reference activity measurements to a common standard. This is an issue especially for multi-center clinical trials, in which data can be compared well between sites only if all are referenced to a single standard. Even at a single site, it is important to assure that the calibration does not drift during the course of a multi-year trial.

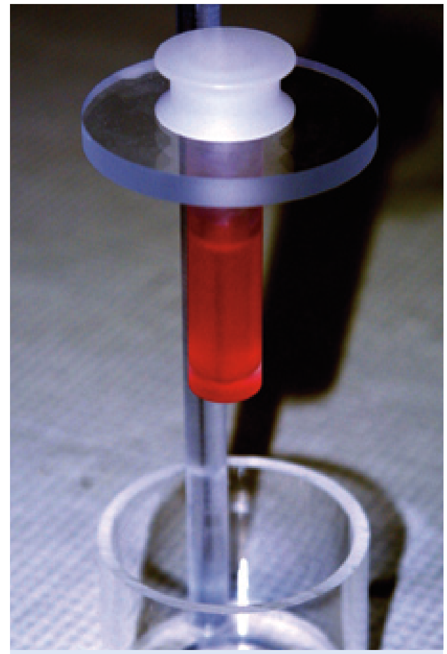

Figure 5. Epoxy-based ^{68}Ge "mock" syringe artifact standard for the calibration of dose calibrators for ^{18}F. The epoxy is colored for show.

Working in collaboration with RadQual, LLC, we have recently developed a calibration methodology for using a long-lived (271 day), ^{68}Ge-based source as an ^{18}F surrogate. This source, designed and marketed by RadQual, is made with the form factor of a syringe for ease of use at the clinic. It was calibrated against the NIST standard for ^{68}Ge with a combined relative standard uncertainty of about 0.5 %. This standard enables the nuclear medicine community to realize the true quantitative potential of PET, thereby enhancing patient care.

In a separate experiment, the relative response factors for ^{18}F and ^{68}Ge were determined for commercially available dose calibrators. This enables measurements of ^{18}F activity with a standard uncertainty of better than 1 %.

As a test, calibrated sources were sent to M. D. Anderson Medical Center, the University of Washington Medical Center, and the University of Oklahoma Medical Center to be measured in their respective dose calibrators. The results showed that, for the most commonly used dose calibrator in the U.S., prior procedure gave measurements for ^{18}F that had been in error by almost 7 %.

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Primary Standardization of Radionuclides by Anticoincidence Counting

The Radioactivity Group uses primary methods to develop its standards and calibration services. These include Standard Reference Materials (SRMs), special calibrations, and proficiency testing. The principle method of primary standardization at NIST is live-timed $4\pi\beta$-γ anticoincidence counting. NIST researchers have adapted this method to perform primary measurements on a variety of radionuclides including alpha, beta, and positron/EC emitters, such as ^{241}Am, ^{57}Co, ^{68}Ge/^{68}Ga, ^{229}Th, and ^{99}Tc.

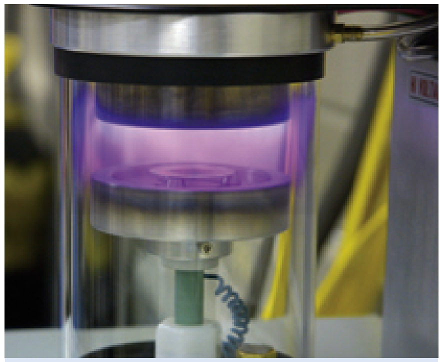

Figure 6. Coating a thin-film source with gold for an anticoincidence measurement.

The anticoincidence system was expanded to detect charged particles using either a liquid scintillation detector or a proportional counter. This upgrade involved developments in source preparation and detector performance. With this new flexibility, NIST will be able to access a wide range of particle energies and source configurations. Work is underway to utilize this capability for the first intercontinental comparison of ^{99}Tc^{m} primary standards.

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Absolute Characterization by NaI(Tl) Detectors of Isotopes with Coincident Emission of Several Gammas

In 1964, Eldridge and Crowther pioneered a coincidence technique to assay ^{125}I. In brief, one leverages the knowledge that ^{125}I emits x rays in pairs to simultaneously determine both the activity of the source and the counting efficiencies of two detectors.

We have extended their method to measure the activity of ^{60}Co using gamma-gamma coincidences. With high probability, ^{60}Co decays with the simultaneous emission of two gamma rays (at 1.17 MeV and 1.33 MeV). Using two NaI(Tl) detectors, a two-dimensional analysis of coincident events allows differentiation of Compton-scattered gammas from the gammas in the photopeak. This additional step enables the absolute determination of ^{60}Co activity through similar logic.

Similar approaches were developed for the more complicated cases of the three coincident gamma emissions in ^{108m}Ag decay, and for positron-gamma coincident emission in ^{22}Na and ^{26}Al decays. Again, a sufficient number of experimentally measured, energy-resolved count rates, both coincidences and not, allow for the absolute determination of both detector efficiencies and source activity.

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International Agreement on ^{210}Pb Radioactivity Standards

Standards of ^{210}Pb are amongst the most important of those needed by the worldwide environmental radioactivity measurement community. Its standardization, however, is exceedingly difficult

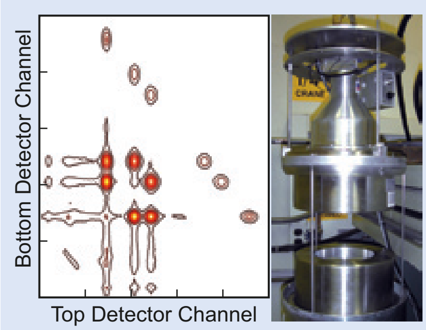

Figure 7. Histogram-contour plot (left) of coincident events in ^{108m}Ag 3γ decay, measured by the NIST 8" NaI(Tl) coincident detector (right), shown open for source loading.

because of its particular decay modes, and it has rarely been attempted by the national metrology institutes (NMIs) of other countries.

The first primary standardization of ^{210}Pb performed by NIST was recently reported and led to the development of Standard Reference Material (SRM) 4337. The standardization was based on $4\pi\alpha\beta$ liquid scintillation (LS) spectrometry with ^{3}H-standard efficiency tracing. Confirmatory measurements were also performed by three other methods. The expanded (k = 2) combined standard uncertainty was conservatively estimated to be 2.4 %, atypically large compared to primary radioactivity standardizations performed by NIST.

This larger-than-usual uncertainty (and to insure the standard's consistency with other NMIs) led us to perform a direct measurement comparison with a UK national standard of ^{210}Pb from the National Physical Laboratory (NPL), which also had links to a primary standardization performed by the Physikalisch-Technische Bundesanstalt (PTB) in Germany. The NIST and NPL solution standards were compared using five measurement methods.

The results by $4\pi\alpha\beta$ LS counting, which was the most precise method, showed agreement within 0.3 %, well within the 1.5 % propagated standard uncertainty assigned to both standards. The other methods gave results in good agreement as well. This suggests that the originally assigned uncertainty on the ^{210}Pb standard may have been overestimated.

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Radionuclide Content of SRM 4355A (Peruvian Soil–I)

Nuclear weapons testing, discharge from manufacturing and reprocessing facilities, and waste dumping by a number of countries have increased the worldwide background level of radioactivity. For more than 20 years, countries and their agencies that monitor the increasing background and potential radiation releases from nuclear facilities relied on NIST SRM 4355, Peruvian Soil reference material, as a calibration standard. Its low fallout contamination made it an ideal "blank" for soil measurements.

While Peruvian soil has minimal radionuclide concentrations, nuclear forensics laboratories have high enough sensitivity to quantitative its isotopic makeup. Consequently, Peruvian soil serves the nuclear forensics community as a calibration, quality control, and testing material needed for methods development, attribution, and legal defensibility. In addition, environmental radioanalytical laboratories use Peruvian soil to assess their laboratory contamination and measurement detection limits.

Presently, SRM 4355 is out of stock. A new batch, Peruvian Soil–I, is under development as future NIST SRM 4355A. Interlaboratory studies to date show an upper limit of its plutonium content to be on the order of 54,000 atoms of ^{239}Pu per gram. Approximately 2100 bottles (100 g each) of pulverized, blended, and bottled soil were radiation-sterilized in preparation for distribution for further interlaboratory analyses, and for future issuance as a natural matrix SRM.

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The third 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, located at the NIST Center for Neutron Research (NCNR), maintains and supports the Nation's premier fundamental neutron physics user facilities. We maintain and disseminate measurement standards for neutron dosimeters, neutron survey instruments, and neutron sources, and we improve neutron cross-section standards through both evaluation and experimental work. The national interests served include industrial research and development, national defense, homeland security, higher education, electric power production, and radiation protection.

We are participating in a Consultative Committee for Ionizing Radiation (CCRI) comparison of thermal neutron fluence rate measurements, characterizing four different beam qualities at the NCNR, and carrying out comparisons of NIST standard neutron sources. We are also leading an effort that will result in a new international evaluation of neutron cross-section standards.

Our resources include a weak interactions neutron physics station, the Neutron Interferometry and Optics Facility (NIOF), the Ultra Cold Neutron Facility (UCNF), a ^{3}He-based neutron polarizer development facility, and the Nation's only high-resolution neutron imaging user facility (NIF) for fuel cell research.

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 the lifetime of neutrons using thermal and ultra-cold neutrons, a limit on the time-reversal asymmetry coefficient, and the radiative decay branching ratio of the neutron.

The neutron interferometry program provides the world's most accurate measurements of neutron coherent scattering lengths, important to materials science research and modeling of the nuclear potentials. Using interferometry we determine the charge distribution of the neutron, and image in reciprocal space.

We are developing the necessary technical infrastructure to support neutron standards for national security needs, such as detection of concealed nuclear materials. In addition, we are developing advanced liquid scintillation neutron spectrometry techniques for characterization of neutron fields and for detection of concealed neutron sources with low false-positive rates.

We are developing and promoting the applications of efficient neutron spin filters based on laser-polarized ^{3}He. Applications for these filters are being pursued at the NCNR, the Spallation Neutron Source at Oak Ridge Natl. Lab., and the Los Alamos Neutron Science Ctr.

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. This is a high demand and high profile, nationally recognized program.

ACCOMPLISHMENTS

Precision Measurement of the Neutron-^{3}He Incoherent Scattering Length

We performed a precision measurement of the spin-dependent *n*-^{3}He incoherent scattering length, b_i, at NIOF. It was the first neutron interferometric experiment to use a polarized gas sample.

Complex, multi-parameter phenomenological models have been developed to tackle the difficult-to-model nucleon-nucleon (NN) interactions. In systems with more than two nucleons, the poorly understood three nucleon (^{3}N) interactions must be included with NN models to match the experimental data on binding energies (which are known to great precision). Neutron scattering lengths, describing a neutron *s*-wave interaction with a target nucleus, are predicted by NN+^{3}N models and provide crucial benchmarks in the testing of various theoretical approaches. Neutron scattering lengths of light nuclei also play an important role in effective field theories (EFTs), since EFTs use low-energy observables to constrain mean-field behavior.

This experiment used a boron-free glass target cell filled with ^{3}He gas placed in one path of the interferometer. Each cylindrical cell (25.4 mm o.d. × 42 mm) was sealed with approximately 200 kPa of ^{3}He gas. The ^{3}He gas was polarized

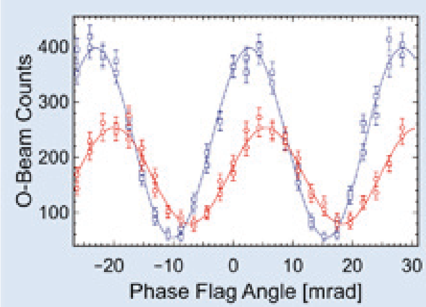

Figure 8. Interferograms with spin flipper on (red) and off (blue), the phase difference of which relates to the incoherent *n*-^{3}He scattering length.

in two days to an initial polarization of P_3 = 65 % using spin exchange optical pumping techniques at a separate facility. The cell was transferred to the interferometer using a portable battery power solenoid with typical transport loss in P_3 of only a few percent. The largest cell lifetime at the interferometer, which had non-ideal magnetic field gradients, was 115 h.

The neutrons were polarized to P_n = 93 % using a transmission-mode supermirror. The neutron spin state could be flipped 180° with a precision coil. The neutron polarization was measured periodically during the experiment by replacing the interferometer with an optically thick ^{3}He cell that provided analyzing powers of up to 99 %. Two different techniques were used to measure P_n and the spin flipper efficiency *s* to 0.04 % relative uncertainty.

We measured b_i = (-2.512 ± 0.012 (statistical ± 0.014 (systematic)) fm, which is in disagreement with the one previous measurement of b_i. This and the previous result are systematically limited by the small but nonzero triplet absorption cross section of ^{3}He, which is known to only 1 %. The result combined with NIST measurement of the spin independent part is in good agreement with the AV18+UIX NN+^{3}N nuclear model.

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Precision Measurement of Radiative Neutron Decay Branching Ratio and Energy Spectrum

Beta decay of the neutron into a proton, electron, and electron antineutrino is occasionally accompanied by the emission of a soft photon. In 2006, we reported the first observation of this radiative decay mode in the journal *Nature*.

Since that time, we have worked to upgrade the apparatus to enable us to make precision measurement (≈1 %) of both the branching ratio and the energy spectrum of the decay photons. The experiment operates by detecting an electron in prompt coincidence with a photon followed by a delayed proton. A beam of cold neutrons passes through the bore of a superconducting solenoid. Decay electrons and protons are guided out of the beam by the magnetic field and detected by a silicon detector.

The primary improvement is increasing the solid angle of photon detection by constructing a 12-element, annular bismuth germanate (BGO) detector that surrounds the decay region of the cold neutron beam (Fig. 9). This allows us to accumulate about 12 times more photon events than before. This detector has been tested and is performing well.

We have also constructed a second detector consisting of bare photodiodes. It should allow us to lower the energy detection threshold to about 200 eV,

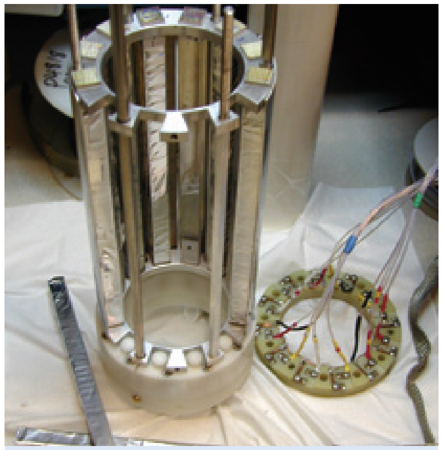

Figure 9. Detector composed of twelve BGO crystals viewed by avalanche photodiodes forming an annular ring around the neutron beam.

significantly lower than the 15 keV from the 2006 experiment. Together, these two new detectors will allow study of the radiative decay mode over nearly four orders of magnitude in photon energy (200 eV to 780 keV).

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Driving Water Transport with Temperature Gradients in Fuel Cells

Removing water from fuel cells is critical when temperatures are below freezing. To do this, energy must be spent in forced-air advection of water from the fuel-cell flow fields. The process can be complicated by the use of hydrophobic parts that resist the transport of water.

To help solve this problem, two temperature-driven mechanisms have been proposed and studied at the NIF by researchers from Pennsylvania State University: thermo-osmosis and phase-change flow (also known as the heat pipe effect). Thermo-osmosis involves colder water being driven by osmosis to a hotter reservoir. However, for the heat pipe effect, transport occurs as hot vapor is transported away to condense on a colder part of the fuel cell.

The researchers showed that the thermo-osmosis effect only contributed weakly to the transport of water when purging fuel cells. Using the 25 micrometer resolution of the NIF, they were able to demonstrate that the phase-change flow is a much more effective means to transport water in the fuel cell.

Neutron imaging proved that the phase-change flow could be used to overcome hydrophobic barriers to water transport in the fuel cell. This means that purging the cell is more effective when colder gases are used to advectively remove water from the cell. These measurements will aid in the design of more energy efficient water purging techniques in automotive fuel cells that will improve durability and lifetime in sub-zero climates.

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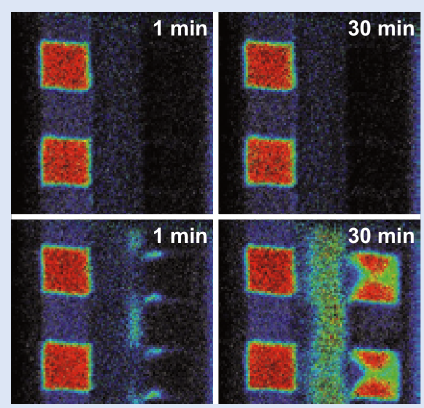

Figure 10. High-resolution images demonstrate the effectiveness of temperature-driven flow to overcome barriers to water transport in fuel cell designs. Top images are side view of fuel cell at a constant temperature of 65 °C. Bottom images show transport of water when the anode is at 60 °C and the cathode is at 70 °C.

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 $\Delta f/f$ approximately 3×10^{-16} (0.3 fHz/Hz, as of 2009).

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 2009) 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 2009), 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.

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 five.

NIST-F1 frequency evaluations reported to BIPM in 2009 included an "in-house" fractional frequency uncertainty of approximately 3×10^{-16} (0.3 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.

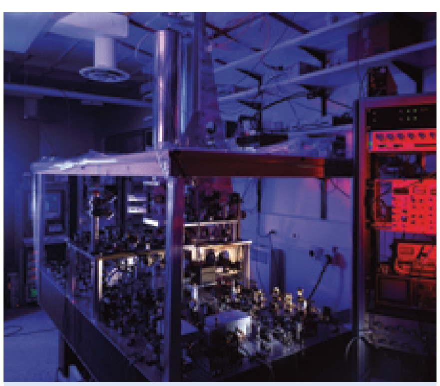

Figure 1. The NIST-F1 cesium-fountain primary frequency standard, the Nation's standard for frequency and the SI second.

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 2009, 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.

"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.

Even in early-stage development, the aluminum-ion logic clock has published relative uncertainties approaching 2×10^{-17} Hz/Hz, and informal, unpublished evaluations demonstrating even better performance. Continued

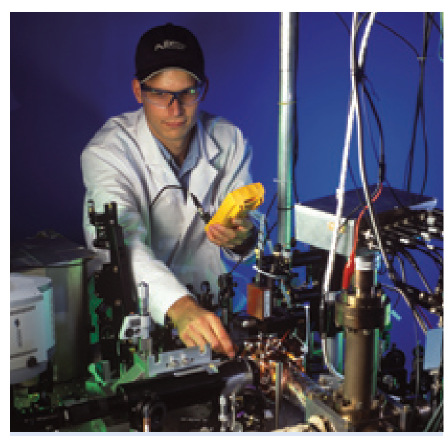

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Figure 2. Till Rosenband adjusts the "logic clock," an optical frequency standard based on quantum information processing techniques.

significant progress is expected. 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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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 2008, continuing improvements in the mercury ion standard have reduced the fractional frequency uncertainty to a formally reported 1.9×10^{-17} Hz/Hz—the world's best result so far for any frequency standard. This result is about 15 times better than the current NIST-F1 performance. Informal internal evaluations (not yet published) demonstrate even better 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 optical frequency standards further improve, it is likely the international definition of the second will be redefined based on an optical transition.

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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 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, 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)

Twenty-two ITS servers at eighteen locations across the Nation respond to more than three billion requests per day (as of 2009) to automatically synchronize clocks in computers and network devices to official NIST time. (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.

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 growing rapidly.

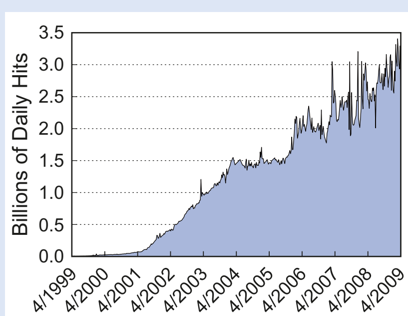

Figure 3. Growth in use of the NIST Internet Time Service.

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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, upgrading insulators in the guy wires supporting the eight 122 meter (400 foot) towers for the WWVB antennas, and completion of a long-term program to replace WWVH (Hawaii) metal antenna towers with fiberglass towers to eliminate corrosion damage (Fig. 4).

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.

Figure 4. Dean Takamatsu and John Lowe assemble new corrosion-resistant antennas for NIST time and frequency radio station WWVH in Kauai, Hawaii.

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 100,000 times each year since initial publication in 2005, and was recently revised to include the latest upgrades to WWVB and radio-controlled timepieces.

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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.

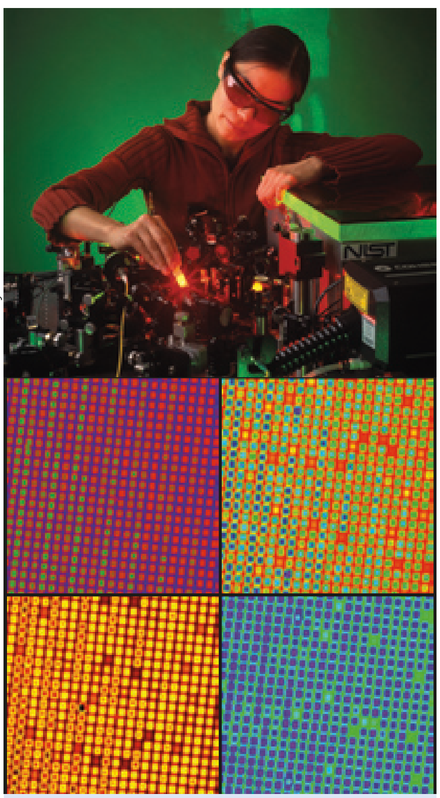

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Figure 5. Tara Fortier adjusts an optical frequency comb, and a "frequency brush," dispersed modes of the frequency comb used for massively parallel absorption spectroscopy of iodine.

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.

Division scientists continue to extend the performance of frequency combs to new spectral regions, increase repetition rates, and develop new applications. For example, Division scientists recently demonstrated a 10 GHz repetition rate comb spanning the spectral range from 400 nm to 1100 nm with the high average power of more than 600 mW. The broad spacing of the comb teeth, determined by the high repetition rate, high power, and spectral range makes it particularly suitable for applications such as measuring the extremely small Doppler shifts of starlight caused by orbiting exoplanets. The new comb is expected to improve the sensitivity of astronomical measurements of such tiny shifts up to 100 times compared to conventional instruments.

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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. Coupled with flux concentrators, these instruments can surpass 10 $fT/Hz^{½}$ measurement sensitivity, 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. Magnetometers developed in the Division have been used in collaborations with biomedical researchers to detect and measure the magnetic fields generated by biological electromagnetic fields, including magnetic fields generated by heart and brain activity in mice.

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 is also initiating a program to use CSAD technologies to develop ultraminiature cold-atom sources for a variety of research and measurement capabilities.

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.

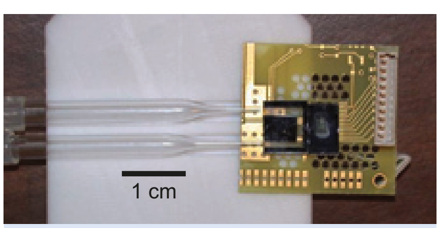

Figure 6. A nuclear magnetic resonance chip combining microfluidics with a chip-scale magnetometer.

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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 quantum 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 metrology 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 is being adapted to other species that hold potential 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 to make strong progress. Division scientists have 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.

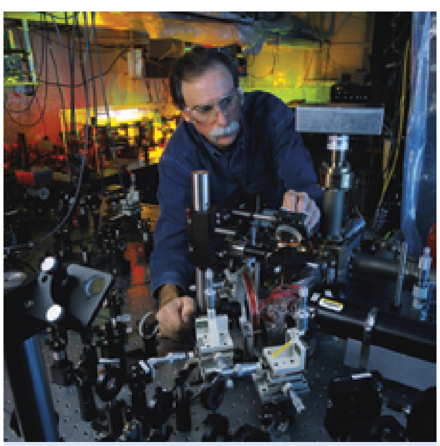

Figure 7. David Wineland adjusting one of the systems used for studying quantum-logic gates.

The Division has demonstrated semi-classical quantum Fourier transform operations on an array of three trapped beryllium ions. Performing Fourier transform 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.

More recently, the Division demonstrated in a single experiment all the components of a scalable quantum computer. Division scientists have also demonstrated new ion trap geometries, including "X junction" and planar traps, providing substantially more capability and flexibility in addressing ions and performing complex operations. The planar geometry is highly promising for a practical, scalable solution. Division scientists have also demonstrated new quantum error suppression techniques, and conducted early demonstrations of using large-scale arrays of ions for quantum simulation. Division scientists extended their research into new trap geometries to demonstrate a stylus trap where a single trapped ion could be used as an exquisite sensor of electromagnetic fields, about one million times more sensitive than an atomic

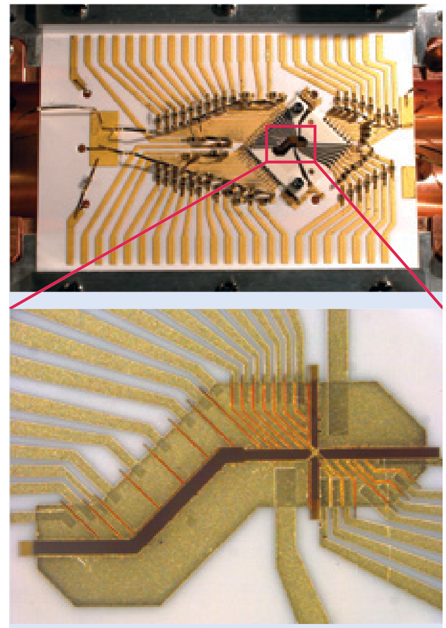

Figure 8. Novel junction ion trap used for research and metrology in transport of qubits.

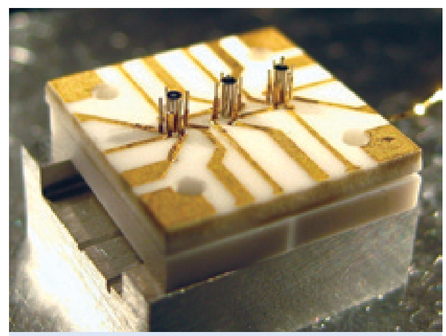

Figure 9. Stylus ion trap used for sensitive measurements of electromagnetic forces on trapped ions.

force microscope using a cantilever tip to measure forces. The new stylus geometry could also be applied to highly efficient transfers of photons between an optical fiber and an ion, a key step in long distance quantum key cryptography.

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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

The Quantum Physics Division continues a leadership role in developing new precision measurement techniques. The Division is perhaps most noted for its achievements in developing lasers as precision measurement tools, in applications ranging from providing length scales for mechanical measurements to generating direct connection between optical and radio frequencies.

Measurement science is central to many NIST activities in support of U.S. research and industry, and the Division responds to the evolving needs. For example, nanoscale objects and devices are increasingly important in industry and science. Their unique properties offer challenges and opportunities in measurement science. Applying concepts from precision optical spectroscopy and laser cooling of atoms, the Division is developing new ways to precisely control and measure at the nanoscale. In addition, the unfolding field of quantum information science provides opportunities for making measurements with an unprecedented low level of noise.

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

ACCOMPLISHMENTS

Understanding Quantum Dot Blinking

Twenty-five years since their discovery, it is now widely appreciated that colloidal semiconductor quantum dots (QDs) have significant potential for use in solar photovoltaic cells and other energy-related applications. In addition, QDs are finding increased application in fluorescent biological assays and as potential light sources for quantum cryptography.

These diverse applications are driven by QDs' unique combination of desirable optical attributes: a continuous absorption spectra, a large absorption cross section, and superior photostability. One can routinely detect emission from a single QD over extremely long time periods (≈ 1000 s).

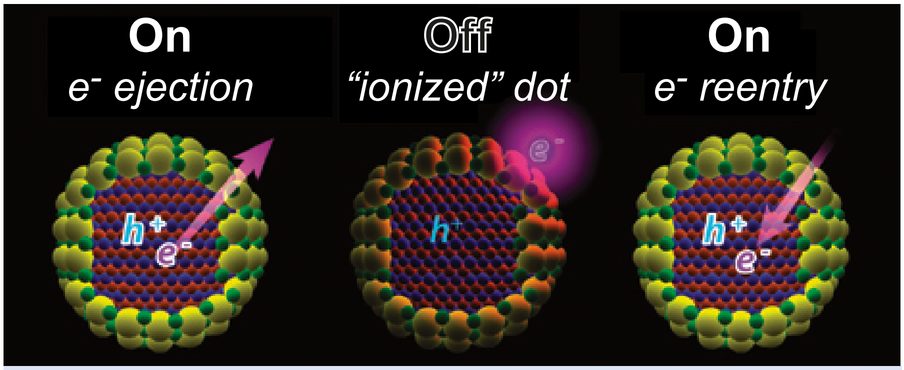

Figure 1. When two electron-hole pairs (biexcitons) are formed inside a quantum dot, one pair can recombine, releasing enough energy to kick the remaining electron onto the surface of the dot. The quantum dot remains dark until the electron trapped on the surface tunnels back into the dot and recombines with its hole.

Despite these advantages, one of QDs' significant limitations is the intermittent cessation of fluorescence known as blinking. In blinking, the QD switches between a fluorescent bright state ("on") and a non-fluorescent dark state ("off"). Even though blinking was initially observed over 10 years ago, the origin of blinking remains an intensely debated subject. It is commonly believed to be the result of an electron (or hole) in an excited electronic state, leaving the core material and residing in a trap state on or near the surface.

The process of blinking is intimately related to photon-induced charge transfer across an interface, a process that has obvious practical significance for capturing solar energy. It is clearly important to understand whether this charge-transfer process requires single excitons or multiple excitons, as well as the statistics of multiple exciton generation.

Division scientists have made significant contributions in this understanding, using single QDs in combination with single photon detection. While the resulting off-time distributions follow an ideal power-law behavior at all wavelengths and intensities, significant deviations from power-law behavior are observed for the on-times. Specifically, a near-exponential fall-off of on-time probability distributions at long times was observed.

Investigation of this fall-off behavior as a function of laser wavelength and power demonstrated that these deviations originate from multiexciton rather than single exciton formation dynamics. The near quadratic dependences observed in the laser power-dependent results indicate the predominant role of biexcitons in the long-time on-to-off blinking dynamics. These data can be further interpreted in terms of probabilities for biexciton induced charge transfer. In conjunction with Poisson modeling of the photon statistics, the data are consistent with QD ionization efficiencies of order 10^{-5}. They highlight a novel role for biexcitons and so-called Auger ionization in the phenomenon of QD blinking.

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Quiet Quantum Collapse

To read out atom-scale sensors, one must perform a measurement of the quantum state of the atoms. The measurement causes each atom to spontaneously and independently collapse into a single quantum state. The randomness in this collapse process is a fundamental source of noise, which already limits the most advanced atomic sensors.

Division scientists are working to push beyond this limit using entanglement. Entanglement allows the noise produced by the collapse of one atom to be offset by the collapse of another atom. To demonstrate the idea, an experiment is underway to trap a million laser-cooled rubidium atoms between two mirrors in a standing wave of light. By bouncing laser light between the mirrors, it should be possible to accurately count the number of atoms in a particular quantum state. But, because the probe light does not carry information about any specific atom, it should be possible to avoid the noisy collapse of individual atoms. Preliminary results of the experiment are highly encouraging.

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Quantum Control of Nanomechanical Motion

Lasers provide the means to control and measure the quantum state of atomic systems. Borrowing ideas developed in laser and atomic physics, Division

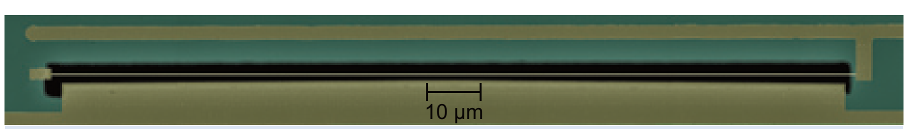

Figure 2. A suspended aluminum wire (150 μm × 150 nm × 160 nm) forms a high quality nanomechanical oscillator.

scientists now use microwaves to control and measure the quantum mechanical properties of macroscopic objects.

For example, lasers have been used to slow and cool the motion of atoms. Using an analogous technique, we have recently demonstrated the use of microwaves to slow and cool the motion of a 150 μm long aluminum wire. We accomplish this by ensuring that the microwave photons are preferentially scattered to higher energy by the wire's motion. By optimizing the technique, we expect to cool the wire to its quantum ground state.

While microwave signals are rarely described using the language of photons, with a sensitive enough amplifier the quantum nature of microwave signals becomes manifest. Division scientists have recently demonstrated a microwave amplifier so sensitive that the dominant source of noise is the quantum fluctuations of the microwave signal itself.

This same amplifier can be used to suppress (or squeeze) the quantum fluctuations in one part of the signal at the expense of increased fluctuations in a conjugate component. This quantum squeezing has been studied in the field of quantum optics, but its realization at microwave frequencies has been challenging because microwave photons carry much less energy.

We are currently investigating these new capabilities for application in the manipulation of quantum information.

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The second strategic element is to exploit quantum degenerate atomic gases and ultracold atoms and 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.

These systems provide unique opportunities for metrology and for gaining insights into analogous transitions in solid-state systems that are technologically important. The development of techniques to produce ultracold molecules also promises important advances in chemical physics. We plan to continue to explore the new quantum mechanical systems that these discoveries have made accessible and to maintain our leadership position.

ACCOMPLISHMENTS

Ultracold Polar Molecules

Division scientists recently created a new kind of ultracold gas—tens of thousands of polar molecules in their lowest energy state. This achievement required expertise in ultracold atoms, ultrafast lasers, and ultrastable lasers, and resulted the creation of a gas that was 3,000 times colder and 10,000 times denser than any previous attempt. Like atomic Bose-Einstein condensates and Fermi gases, these ground-state molecules allow unprecedented explorations of the quantum world.

The JILA team, collaborating with JQI theorists (see page 9), started with a cloud of ^{40}K and ^{87}Rb atoms. We laser-cooled the atoms to less than a millionth of a degree above absolute zero, and coaxed them into forming very loosely bound ^{40}K^{87}Rb molecules. Changing these weakly bound molecules into tightly bound molecules in their lowest energy state required two lasers that

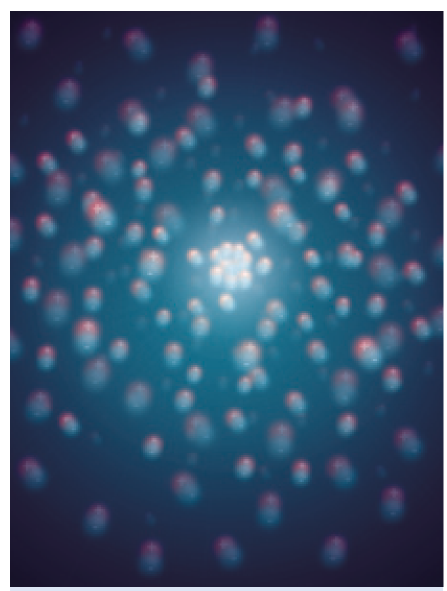

Figure 3. Artist conception of a gas of ultracold polar molecules.

could adiabatically transfer the molecules between states with no residual kinetic energy. To do so, two precisely stabilized lasers with a large difference in wavelength were locked to a frequency comb made from an ultrastable femtosecond laser. The entire process for converting ultracold atoms into ultracold polar molecules was precisely controlled, perfectly coherent, and reversible, resulting in a procedure that caused no heating of the ultracold gas.

Division scientists have recently demonstrated control over the last remaining degree of freedom, namely the nuclear spins inside the molecules. This work demonstrates how one could initialize the molecules for quantum information processing. In addition, the researchers have begun to explore chemical reactions in the ultracold molecule gas. While one might not expect to see chemistry happening at temperatures near absolute zero, the experiments have shown that chemical reactions do occur and that they proceed at surprisingly high rates.

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Optical Atomic Clocks

An optical atomic clock uses a transition occurring in the visible spectrum. Its capabilities have enabled Division scientists to set the strongest limits to date on several fundamental parameters in physics, including the gravitational-coupling coefficients for the fine-structure constant, the electron-proton mass ratio, and the light quark mass (the average mass of up and down quarks).

An optical clock developed at JILA uses a few thousand atoms of strontium held in a column of about 100 pancake-shaped "optical lattice" traps. The lattice is formed by standing waves of intense near-infrared laser light. It constrains atom motion thus reducing systematic errors. After demonstrating state-of-the-art spectral resolution and short-term stability of the strontium clock, the JILA team turned its attention to clock accuracy. We studied physical mechanisms that could perturb the atomic transition frequency and concluded that the overall relative systematic uncertainty of the strontium clock was 1×10^{-16} Hz/Hz, better than that of the primary frequency standard based on cesium.

In the process, we identified a significant source of potential error that had heretofore been unappreciated. Basic quantum mechanics dictates that identical fermions in the same quantum state, such as the strontium atoms in the clock, cannot collide at ultralow temperatures. However, as we improved the performance of the strontium clock, small shifts in frequency due to atomic collisions became apparent. These unexpected collisions came about because, when two atoms in the same well are separated, they are affected differently by spatially varying laser light. As a consequence, the atoms become distinguishable enough to show collision effects.

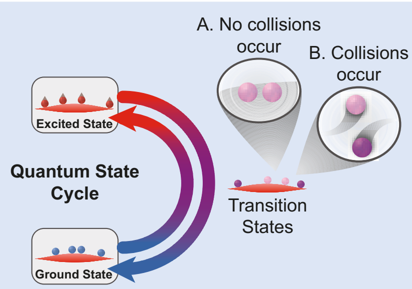

Figure 4. Collisions between identical fermions should not occur. However, in an optical clock, such collisions occurred due to the subtle spatial inhomogeneity in the light necessary to confine the atoms.

We determined that the collision-related frequency shifts could be significantly reduced depending on the fraction of atoms in the excited state. This knowledge enabled reducing or even eliminating the need for a significant correction in the clock output, thereby increasing the clock accuracy. The frequency shift due to atomic collisions has been reduced to the order of 10^{-17} Hz/Hz, and further reductions appear possible.

More generally, many new ideas on quantum optics, precision measurement, and frequency metrology are being developed using this system, including spin squeezing to reach clock stability beyond the atomic shot-noise limit, a new approach for realizing ultrapure optical radiations, and new schemes for efficient and scalable quantum information processing.

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New Tools for Quantum Information Science

The synergy within JILA from expertise in both theoretical and experimental quantum control has resulted in a new thrust to utilize the optical atomic clock architecture (described above) as a novel platform for quantum information science. In experiments, we demonstrated complete control of the electronic and nuclear degrees of freedom of the strontium atoms.

Dr. Ana Maria Ray, a new JILA Fellow, has proposed new schemes for using this

Figure 5. New JILA Fellow Ana Maria Rey confers with Jun Ye.

system for efficient and scalable quantum information processing. They utilize as quantum bits (qubits) the electronic and nuclear degrees of freedom of individual strontium atoms. These atoms can be coupled together to form a scalable quantum network.

In addition, the strontium system may be used as a quantum simulator. We plan to utilize all the degrees of freedom to study spin-orbit physics and to simulate many-body Hamiltonians that describe complex condensed matter systems, such as transition metal oxides and heavy fermion compounds. In the long run, this research may help provide a better understanding of complex phenomena, such as high-temperature superconductivity, colossal magnetoresistance, and spin-liquid phases.

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Probing Strongly Interacting Bose-Einstein Condensates

Of the three most common states of matter (solids, liquids, and gases), liquids remain by far the least understood from the perspective of quantum mechanics. Much of our quantum mechanical understanding of solids and gasses is developed in a perturbative manner: one starts with a macroscopic ground state at essentially zero temperature, and then models all the rich behavior in a solid or a gas as arising from progressively more complicated excitations on this simple state.

For liquids, this approach is problematic because a liquid is by its nature not a zero-temperature object. Cool a liquid down too much and you do not get a cold liquid, but rather a solid that is an entirely different state of matter. During the 20th century, the only known exception was superfluid liquid helium, and much of the research into liquid helium's properties was motivated by its uniqueness.

The vast majority of liquids do not have, even conceptually, a quantum mechanical ground state. This is unfortunate because liquids are extraordinarily important. Most industrial and pharmaceutical chemistry takes place in the liquid phase, and all living processes on earth take place in the liquid environment inside a cell.

Division scientists are developing a new model system for research. Instead of taking a liquid and attempting to cool it to ultralow temperatures while avoiding solidification, we are taking a Bose-condensed atomic gas (an ultracold non-liquid sample) and making it more liquid-like. Using an applied magnetic field to tune the strength of the interactions between the atoms, we have been able to create and make measurements on a gas whose interatomic interactions are very nearly as strong as those in a liquid. The main experimental technique is Bragg scattering, which allows measurement of the dispersion relation of individual quantum excitations above the ground state.

In recent work, we reported on so-called beyond-mean-field (non gas-like) corrections to the dispersion relation in the high-momentum limit. Theorists are attempting to connect these observations to a microscopic theory of our liquid-like gas. In the meantime, the experimentalists have developed a shot-noise-limited photon detector to enable one to probe more deeply into the liquid regime, and to cover the low-momentum (and theoretically more tractable) range of the dispersion relation.

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The third strategic element is to advance ultrafast science.

ULTRAFAST SCIENCE

INTENDED OUTCOME AND BACKGROUND

Ultrafast science has its roots in exploiting light pulses with durations as short as a few femtoseconds. These pulses, generated by mode-locked lasers, provide precise time resolution and/or high peak powers.

The Division has became an international leader in adapting continuous wave (CW) laser techniques to the stabilization of mode-locked lasers, generating a broad comb of sharp spectral lines, each with a very precise and stable frequency. The importance of femtosecond 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.

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. We use phase stabilization to improve measurements, and we develop radical new ultrafast technologies such as "gainless" amplification of femtosecond pulses in a build-up cavity.

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. In addition, the combination of time domain dynamics and frequency domain precision enables new paradigms for spectroscopy.

ACCOMPLISHMENTS

Two-Dimensional Fourier Transform Spectroscopy of Two-Quantum Coherences

Multidimensional Fourier transform spectroscopy (MDFTS) was originally developed in nuclear magnetic resonance. During the last decade, there has been significant work on MDFTS techniques in the infrared through visible portions of the spectrum. MDFTS has the powerful ability to measure and isolate nonradiative coherences, such as multiquantum or Raman coherences.

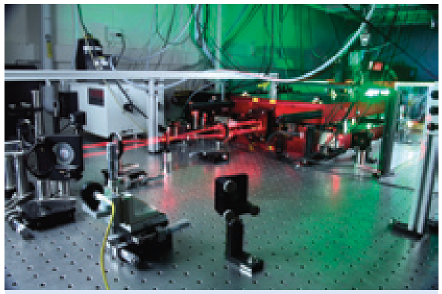

Figure 6. The JILA MONSTR (Multidimensional Optical Nonlinear SpecTRometer) enables precisely controlled two-dimensional Fourier transform spectroscopy.

A second generation MDFT spectrometer provides full phase locking of all excitation beams, which is necessary for measuring two-quantum coherences. Measurements on semiconductor quantum wells show the presence of two-quantum coherences between the ground state and a biexcitonic state. However, two-quantum coherences are also observed between the ground state and many-body states, a possibility that had not previously been considered. In atomic vapors, two-quantum coherences are also observed, even when there is not a resonant state for two-photon excitation. These coherences occur due to interatomic interactions.

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Frequency Comb Spectroscopy: Mid-Infrared to EUV

Cavity-enhanced, direct frequency comb spectroscopy (DFCS) builds upon the Division's pioneering work in optical frequency combs. DFCS was recently extended from the visible to the mid-infrared to cover fundamental absorption bands of many important molecules. The pattern of absorption maps out the chemical environment with remarkable specificity in a non-destructive manner.

Indeed, the infrared spectrum of a molecule is often referred to as its "fingerprint." The ability to detect and unambiguously identify multiple molecular species at the part-per-billion level, in real time, allows fingerprinting of complex chemical mixtures for many practical purposes. This is a technological breakthrough in such potential applications as criminal forensic analysis, pharmaceutical manufacturing quality control, remote sensing of gaseous substances for military and homeland defense, environmental monitoring, and medical diagnostics, as well as fundamental research. Highlights of recent laboratory achievements include human breath analysis and detection of gas impurities deleterious to semiconductor manufacturing.

Visible frequency combs have also been extended to the vacuum ultraviolet (VUV) and extreme ultraviolet (EUV) spectral

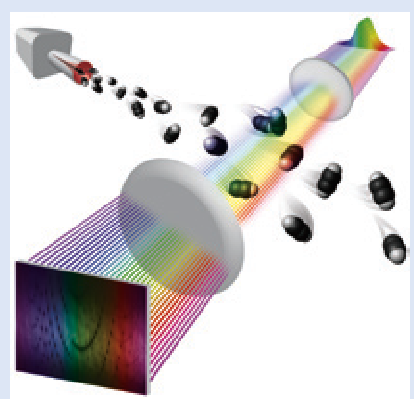

Figure 7. Mid-IR frequency combs enable highly parallel absorption spectroscopy for chemical species detection.

regions. This will allow the future development of DFCS in the far ultraviolet. A key development is the use of a passive, high-quality optical cavity to coherently enhance the visible pulse energy for efficient generation of high harmonics well into the EUV region, while operating at the original high repetition frequency.

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The fourth strategic element is to establish a leadership position in research at the interface of metrology and biology.

BIOPHYSICS

INTENDED OUTCOME AND BACKGROUND

The Quantum Physics Division is evolving its research program to help NIST contribute to the scientific revolution taking place in the biosciences. We are leveraging our expertise and experience with atomic and quantum systems to investigate important biological systems ranging from single molecules to single cells, creating in the process new, state-of-the-art measurement techniques. In turn, we expect to exploit unique properties of biological molecules in NIST's standards mission.

Our initial foray into biophysics has focused on addressing unmet measurement needs in the biological sciences with large payoff potential. Development efforts range from the world's most stable atomic force microscope at biologically useful conditions (in liquid at room temperature) to a microfluidics measurement platform that integrates advanced optical spectroscopy with rapid cell sorting. We will pursue exciting biological and technological application, such as renewable energy, in close collaboration with the Department of Molecular, Cellular, and Developmental Biology and the Biochemistry Division of the Chemistry and Biochemistry Department at the University of Colorado.

In a reciprocal process, Division scientists are also advancing measurement science using biological molecules. Specifically, DNA and DNA-hairpins are being investigated as candidates for SI-traceable force standards based on intrinsic molecular properties.

ACCOMPLISHMENTS

Ultrastable Atomic Force Microscopy

Atomic force microscopes (AFMs) enable visualization and manipulation of the world at nanometer scale. These robust and atomically sensitive tools are being increasingly used at room temperature to study biomolecules, a wide variety of other systems, and to build nanoscale constructs of practical interest.

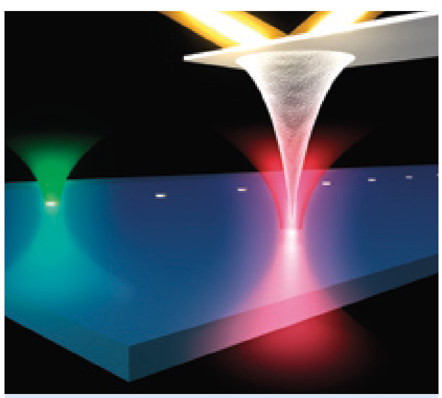

Figure 8. In a laser-stabilized atomic force microscope, one laser beam (red) measures the tip position in three dimensions, while a second laser beam (green) tracks the surface. These lasers complement the traditional measurement of cantilever deflection using a third laser (yellow).

Current-generation room-temperature AFMs cannot return their probe tip to the same individual feature with nanometer-scale precision, nor do they have the stability to hover a tip over an individual protein to measure its conformational dynamics. Until now, precise atomic-scale control has been limited to cryogenic temperatures and ultrahigh vacuum, neither compatible with biomedical applications.

Division scientists leveraged JILA's expertise in precision spectroscopy and optical trapping to develop a novel strategy to directly measure the tip and the sample positions in three dimensions (3D). More specifically, a pair of lasers with excellent differential pointing stability (< 0.03 nm in 3D) establishes a local reference frame. This local detection of tip and sample eliminates the unmeasured, environmentally induced drift that occurs in other instruments, and enables a 100-fold improvement in mechanical stability over current state-of-the-art.

The resulting optically stabilized AFM provides a new measurement tool for structural biology. It has the stability and sensitivity to study protein structure and conformational dynamics in a biologically useful environment—in liquid at room temperature. Additionally, this ultrastable AFM paves the way for new nanomanufacturing techniques.

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Multi-Dimensional Optical Spectroscopy in Microfluidics

The development of fluorescent proteins (FPs) as molecular probes has revolutionized our ability to study cellular processes, providing images with high spatial and temporal resolution. Yet, there are a number of limitations to FPs, including decreased brightness relative to traditional fluorophores, poor photostability, and a tendency to convert to dark states that limit the signal output. Most efforts to produce better FPs have resulted in improvement of one property (e.g., brightness) at the expense of another (e.g., photostability).

Division scientists are collaborating with biochemists from the Univ. of Colorado to generate FPs that dramatically improve ensemble as well as single-molecule imaging in cells. A combinatorial approach will generate targeted libraries of these proteins, express the libraries in mammalian cells, and screen for decreased dark state conversion, increased photostability, and increased brightness using a microfluidic cellular-spectroscopy and optical force-switching instrument recently developed in the Division. This unique selection technology permits high-throughput screening and sorting of mammalian cells based on the measurement of multiple parameters.

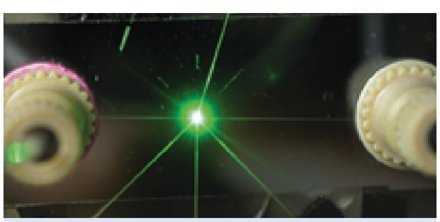

Figure 9. A microfluidics device for high-throughput screening coupled with advanced optical characterization of cells.

We are also applying closely related microfluidics technology to the development of genetically encoded, FRET-based sensors for metal-ion detection. Controlled variation of metal ion concentration is crucial in many biological processes, including signal transduction in nerve cells.

The underlying microfluidics technology is also being applied to the cause of renewable energy. Microalgae-derived lipids are an attractive candidate for a transportation biofuel. However, algae require further development to improve their tolerance to high light levels, and to increase lipid yields.

Division scientists have designed a lab-on-a-chip microfluidic system to accelerate the process of screening genetic libraries of algae and rapidly assessing and optimizing growth conditions. The prototype device measures photosynthetic light use and lipid accumulation on a cell-by-cell basis, increasing both specificity and throughput over previous techniques.

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Biological Force Standards

The forces applied by atomic force microscopes (AFMs) do not have SI traceability over the commonly used range (piconewtons to nanonewtons), even though AFMs are widely used for mechanical characterizations in scientific and industrial applications. Today's best SI traceability relies on a technologically challenging calibration in a NIST-operated electrostatic force balance that provides micronewton forces with nanonewton sensitivity.

Division scientists, as part of a larger NIST project, are studying biological molecules as force-measurement standards. Biological molecules in general, and DNA in particular, exhibit properties that make them excellent candidates. First, DNA undergoes a mechanical phase transition at about 65 pN, where its extension almost doubles in a narrow force range (5 pN). Second, DNA hairpins can flicker between open and closed states at a very specific force (e.g., 12.1 pN). We showed that a 0.1 pN change in force (< 1 %) leads to a > 20 % change in the probability of being open.

These interesting and attractive mechanical attributes are complemented by the ease with which DNA force standards could be distributed. First, unlike AFM cantilevers, the high fidelity of enzymatic replication guarantees a uniform molecule that does not vary in size or composition from batch to batch, even at the atomic level. Second, DNA is made with standard biochemical process, so it is cheap and easy to produce. Third, attaching chemical "handles" is simple and allows quick coupling of the DNA to force probes.

We are currently exploring different DNA hairpins as well as the "over-stretch transition" as potential force standards. In this early work, we are concentrating on improving measurement precision and will focus later effort on making the force measurements more accurate.

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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 published a wide array of information from and about Physics Laboratory. This includes physical reference data as well as news and details of PL's technical activities, research and calibration facilities, technical contacts, and scientific publications. Recently, there have been nearly 2 million requests (on average) for web pages each 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 update of an on-line Periodic Table and handout, and the development of on-line versions of NIST Special Publications 811 and 330, which concern SI units.

ACCOMPLISHMENTS

Units Markup Language

We have continued to develop an XML (eXtensible Markup Language) schema, UnitsML, for unambiguously encoding scientific units of measure in electronic media. UnitsML was designed so that it can be easily incorporated into other markup languages. It is anticipated that it will be broadly implemented. Various communities (e.g., biology, chemistry) initially developed their own methods for representing units of measure in their markup languages. UnitsML, however, is robust enough to encode necessary information for all disciplines.

We have formed an OASIS (Organization for the Advancement of Structured Information Standards) UnitsML Technical Committee to address any needed changes in the schema and to publish a final recommendation. Adoption as a standard will allow for the unambiguous exchange of numerical data over the Internet. Documentation for the UnitsML schema can be found at *http://unitsml.nist.gov*.

To complement the UnitsML schema, we are 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 detailed units and dimensionality information, as well as information on quantities and prefixes.

The database includes information needed to reference units in an XML document, specifically includes unique identifiers, and can include various unit symbols, language-specific unit names and representations in terms of other units (including conversion factors). The database is being designed for both computer-to-computer and human-to-computer interactions. XSLT stylesheets are being developed which can translate XML output into other formats, e.g. HTML.

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New On-Line Database

A new database contains spectral lines in the infrared of a low-current, Th-Ar hollow cathode lamp. The data were obtained with the 2 m Fourier transform spectrometer (FTS) in Atomic Physics Division. It is available at *http://physics.nist.gov/ThAr*.

These measurements establish more than 2400 lines that are suitable for use as wavelength standards in the range 691 nm to 5804 nm. This project was in collaboration with the European Southern Observatory (ESO) to create calibration standards for large telescopes.

This database is used in the calibration pipeline of ESO's Cryogenic High-Resolution Echelle Spectrograph (CRIRES) on the Very Large Telescope in Chile. It is also applicable to other telescopes with similar facilities (e.g., Keck Observatory in Hawaii). Astronomers at the University of Virginia have expressed interest in using the atlas for future studies. More broadly, Th/Ar hollow cathode lamps are potentially useful for calibration of laboratory infrared spectrometers.

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On-Line Database Updates

On-line since 1996, the NIST Recommended Rest Frequencies for Observed Interstellar Molecular Microwave Transitions database has been updated with approximately 2000 new transitions, bringing the total to more than 12000 entries. The update also improved the accuracy of many previously tabulated frequencies. The major users of this database include radio astronomers and molecular spectroscopists. It is available at *http://physics.nist.gov/restfreq*.

Recent work also includes updates of the following Web databases at *http://physics.nist.gov/data*:

1. Elemental Data Index
2. Fundamental Physical Constants
3. Searchable Bibliography on the Constants
4. Atomic Energy Levels and Wavelengths Bibliographic Database
5. Atomic Transition Probabilities Bibliographic Database
6. Atomic Spectral Line Broadening Bibliographic Database
7. SAHA Plasma Population Kinetics Database
8. FLYCHK Collisional-Radiative Code
9. Atomic Spectra Database
10. XCOM: Photon Cross Sections Database
11. Atomic Model Data for Electronic Structure Calculations

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Figure 1. A radiotelescope measuring faint signals from molecules in interstellar space.

Awards and Honors

National Medal of Science

Given to individuals deserving of special recognition by reason of their outstanding contributions to knowledge in the physical, biological, mathematical, or engineering sciences

David Wineland, Time and Frequency Division, 2007 Award, "for his leadership in developing the science of laser cooling and manipulation of ions, with applications in precise measurements and standards, quantum computing, and fundamental tests of quantum mechanics; his major impact on the international scientific community through the training of scientists; and his outstanding publications"

Herbert Walther Award *(Optical Society of America)*

To recognize distinguished contributions in quantum optics and atomic physics as well as leadership in the international scientific community

David Wineland, Time and Frequency Division, 2009 Award (inaugural award), "for his seminal contributions to quantum information physics and metrology, and the development of trapped ion techniques for applications to basic quantum phenomena, plasma physics, and optical clocks"

Member of the National Academy of Sciences

An honorific society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare

James Bergquist, Time and Frequency Division, elected Member in 2009, for his scientific leadership in ultrahigh-resolution laser spectroscopy, with applications to fundamental physics and the world's most precise frequency standards, and for his generous mentoring of young scientists

Arthur L. Schawlow Prize in Laser Science *(American Physical Society)*

To recognize outstanding contributions to basic research which uses lasers to advance our knowledge of the fundamental physical properties of materials and their interaction with light

James Bergquist, Time and Frequency Division, 2008 Prize, "for his contributions to laser science and tests of fundamental physical principles, in particular the application of ultra-stable lasers to tests of quantum measurement theory and the fundamentals of quantum mechanics"

Benjamin Franklin Medal in Physics

For individuals whose great innovation has benefited humanity, advanced science, launched new fields of inquiry, and deepened our understanding of the universe

Deborah Jin, Quantum Physics Division, 2008 Medal, "for her pioneering investigations of the quantum properties of an ultracold gas of fermionic atoms, atoms that cannot occupy the same quantum state, and in particular for the creation of the first quantized gas of fermionic atoms"

William Procter Prize for Scientific Achievement *(Sigma Xi)*

For making an outstanding contribution to scientific research and demonstrating an ability to communicate the significance of this research to scientists in other disciplines

Deborah Jin, Quantum Physics Division, 2009 Prize, for her technical innovations in the field of ultracold fermionic (atomic) gases leading to discoveries that define this new area of physics research

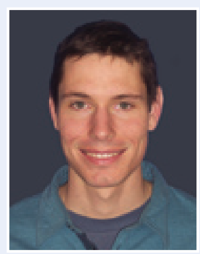
American Physical Society, Outstanding Doctoral Thesis Research in Atomic, Molecular and Optical Physics

To recognize doctoral thesis research of outstanding quality and achievement in atomic, molecular, or optical physics and to encourage effective written and oral presentation of research results

Andrew Ludlow, Time and Frequency Division, 2009 Award, for his University of Colorado thesis research on "The Strontium Optical Lattice Clock: Optical Spectroscopy with Sub-Hertz Accuracy," conducted at JILA in Quantum Physics Division

America Physical Society, Best Student Paper Award in Experimental Quantum Information

For quality of scientific results and quality of the presentation

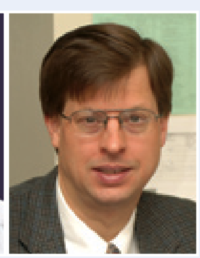


David Hume, Time and Frequency Division, 2008 Award, for thesis work describing use of the "logic clock" apparatus to make extremely high fidelity quantum measurements

American Physical Society Outstanding Referees

To recognize scientists who have been exceptionally helpful in assessing manuscripts for publication in the APS journals



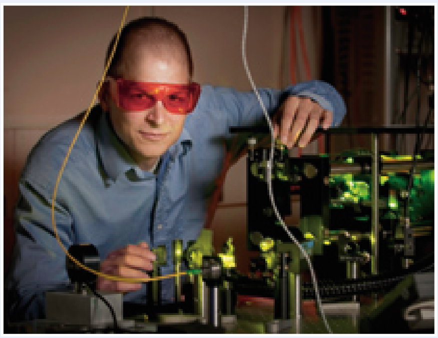


Garnett Bryant, Atomic Physics Division, **William Gadzuk**, Electron and Optical Physics Division, and **Eric Shirley**, Optical Technology Division, 2008 Award (First year of program)


Eric Cornell, Quantum Physics Division, and **Wayne Itano**, Time and Frequency Division, 2009 Award

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



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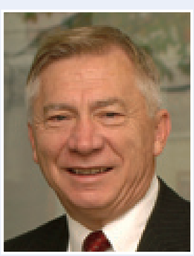
Till Rosenband, Time and Frequency Division, 2009 Award, for his development of the aluminum ion "logic clock," an entirely new type of optical frequency standard using the principles of quantum computing

Presidential Rank Awards

Recognizes Senior Executives and Professionals for exceptional long-term accomplishments



William Ott, Deputy Director, Physics Laboratory, 2008 Award for Meritorious Executive, for his leadership in establishing interdisciplinary technical programs and providing a stimulating intellectual climate for scientific research

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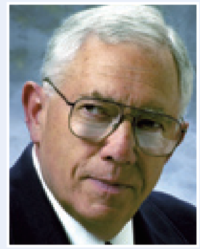
David Nesbitt, Quantum Physics Division, 2009 Award for Meritorious Senior Professional, for world-leading research and measurements on the properties and reactions of molecules for advances in chemistry, biology, and many other fields

Service to America Medals

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



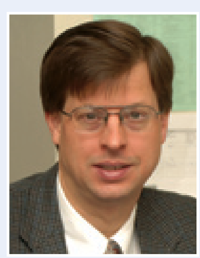
Judah Levine, Time and Frequency Division, was a 2008 finalist for the Career Achievement Medal, for creating a system to synchronize time that is used by financial markets and computer networks, and accessed more than 2.5 billion times each day

Joshua Pomeroy, Atomic Physics Division, was a 2008 finalist for the Call to Service Medal, for using highly charged ion beams to reduce the size of magnetic sensors used to read data on disk drives, promising further miniaturization in data storage

Ian Spielman, Atomic Physics Division, was a 2009 finalist for the Call to Service Medal, for pioneering a new area of research where atomic gases near the absolute zero of temperature simulate models of condensed matter systems

Arthur S. Flemming Awards

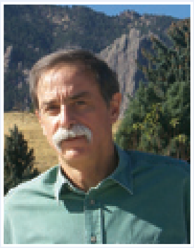
Established in 1948, the Flemming Awards honor outstanding Federal employees with no more than 15 years of government service. About ten winners are selected each year from all areas of the Federal service.



Eric Shirley, Optical Technology Division, 2007 Award, for fundamental advances in the theory and application of the optical properties of materials and light diffraction

Bonfils-Stanton Foundation Award

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



David Wineland, Time and Frequency Division, 2008 Award, for significant, unique, and inspirational research accomplishments in the field of quantum physics

European Frequency and Time Award
(European Frequency and Time Forum)

Awarded since 1993, for recognizing outstanding contributions in all fields covered by the EFTF

Jun Ye, Quantum Physics Division, 2009 Award, "for his pioneering work in establishing a neutral atom optical lattice clock, narrow linewidth lasers, femtosecond spectroscopy, and phase-coherent transmission of frequencies via optical fibers"

Medal of Honor of the University of São Paulo, and Honorary Professor

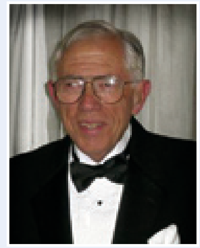
William Phillips, Atomic Physics Division, 2009 Award (inaugural award), in recognition of significant contributions to the Institute of Physics through collaborations or visits that improve scientific understanding

MIT Technology Review: 10 Emerging Technologies

Technology Review presents 10 technologies that we think are most likely to change the way we live

John Kitching, Time and Frequency Division, 2008 Award, for microminiature magnetic sensors using techniques derived from the chip-scale atomic clock

CO-LABS Governor's Award for Research Impact



© 2009 Alice Levine

Judah Levine, Time and Frequency Division, 2009 Award in Information Technology, "for his development of the NIST Internet Time Service, which allows users to synchronize computer clocks via the Internet"

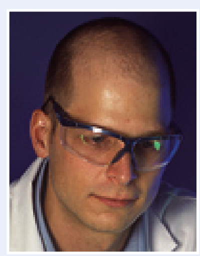
Time Lord Award
(International Telecom Sync Forum)

In recognition of significant contribution to the telecommunication timing community

Judah Levine, Time and Frequency Division, 2009 Award, for his leadership in developing precision timing, synchronization, and time distribution methods to support telecommunications and other technologies

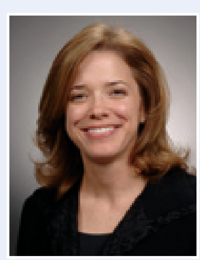
EFTF Young Scientist Award
(European Frequency and Time Forum)

In recognition of a personal contribution that demonstrated a high degree of initiative and creativity and led to already established or easily foreseeable outstanding advances in the field of time and frequency metrology



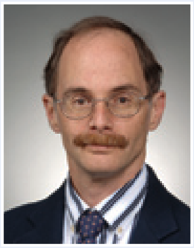
Till Rosenband, Time and Frequency Division, 2008 Award, "for the invention of particularly vibration immune optical resonators and his contributions to today's best optical single ion Al^+ and Hg^+ clocks"

Award of Appreciation
(ASTM Committee E12 on Color and Appearance)



Maria Nadal, Optical Technology Division, 2008 Award, for her outstanding service to the Committee, especially her contributions to standard E2480-07, "Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method with Multi-Valued Measurands"

Fellowship of the American Physical Society



Alan Migdall, Optical Technology Division, for the development of parametric down conversion and correlated-photon generation for metrology, cryptography, communications, and fundamental physics applications

James "Trey" Porto, Atomic Physics Division, for seminal studies of ultracold atoms in optical lattices with applications to quantum information, many-body physics, and condensed matter models, and for the invention of optical lattice techniques including a super-lattice for patterned loading, and a reconfigurable lattice of double wells

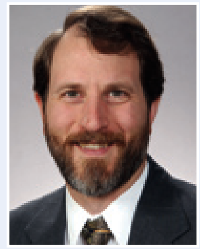
Glenn Solomon, Atomic Physics Division, for extensive contributions to the study of quantum optics with quantum dots

Scott Diddams, Time and Frequency Division, for major contributions to the development of optical frequency comb technology, and particularly for pioneering demonstrations of frequency combs in optical clocks, high-resolution spectroscopy, and tests of basic physics

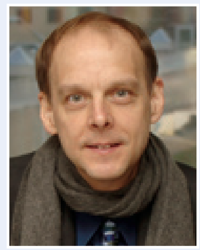
Fellowship of the American Academy of Arts and Sciences

Katharine Gebbie, Director, Physics Laboratory, for her outstanding contributions in scientific administration

Fellowship of the American Association for the Advancement of Science



Paul Lett, Atomic Physics Division, for his work in developing a technique that can be used to measure the forces between atoms cooled very close to absolute zero



Carl Williams, Atomic Physics Division, for distinguished contributions to the theory of cold atom collisions and small molecule spectroscopy, in particular to ultracold photoassociation spectroscopy and dynamics of ultracold gases

Fellowship of the Optical Society of America

Scott Diddams, Time and Frequency Division, for seminal work in the area of precision spectroscopy and optical frequency metrology with femtosecond-laser frequency combs

Edwin Heilweil, Optical Technology Division, for seminal contributions to ultrafast optical studies of vibrational energy transfer and to terahertz spectroscopy

Fellowship of The International Society for Optical Engineering (SPIE)

Thomas Germer, Optical Technology Division, for his achievements in optical scattering measurement and modeling

Fellowship of the American Association of Physicists in Medicine

Stephen Seltzer, Ionizing Radiation Division, for his significant contributions in the field of medical physics

American Association for the Advancement of Science

Charles Clark, Electron and Optical Physics Division, was elected Chair-Elect of the Section on Physics of the American Association for the Advancement of Science (AAAS) for a term of February 2009 through 2012. Clark is a Fellow of AAAS.

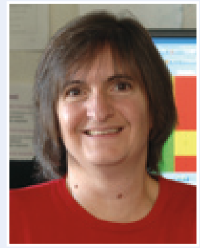
Editor's Choice Award, Best Paper in MEASURE

Mike Lombardi, Time and Frequency Division, 2008 Award, from the Editors of MEASURE published by NCSL International, for his paper "The Use of GPS Disciplined Oscillators as Primary Frequency Standards for Calibration and Metrology Laboratories"

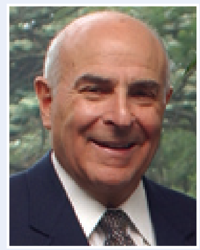
Humboldt Research Award

Steven Cundiff, Quantum Physics Division, 2008 Award, for his exceptional achievements in research and teaching, allowing him to better collaborate with colleagues at the Physikalisch-Technische Bundesanstalt and the Technische Universität in Braunschweig, Germany, which promotes scientific cooperation between our nations

Washington Academy of Sciences Award for Scientific Achievement

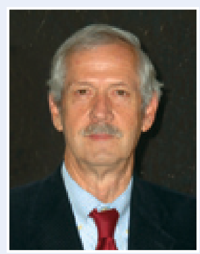


Lisa Karam, Ionizing Radiation Division, 2008 Award for the Physical Sciences, "for leadership in developing radiation standards and measurement methods needed in the national effort to ensure protection from terrorist attack"



Joseph Reader, Atomic Physics Division, 2009 Award for the Physical Sciences, "for providing accurate reference for atomic spectroscopists throughout the world in support of laser research, spectrochemistry, plasma diagnostics, astrophysics, national defense, and remote sensing"

Standards Engineering Society Honorary Life Member



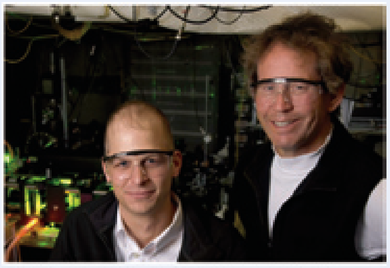
Bert Coursey, Physics Laboratory, for outstanding accomplishment in standardization for environmental radioactivity, nuclear medicine, and radiation dosimetry, and in establishing a national program for standards for homeland security

R&D 100 Award

Michael Coplan (University of Maryland), **Charles Clark**, **Robert Vest** (Electron and Optical Physics Division), **Muhammad Arif**, and **Alan Thompson** (Ionizing Radiation Division), 2008 Award, for the development of an ultrasensitive, high-bandwidth neutron detector

Gold Medal *(Department of Commerce)*

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



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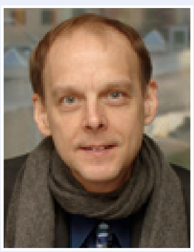
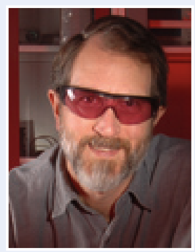
Till Rosenband and **James Bergquist**, Time and Frequency Division, 2008 Gold Medal for Scientific/Engineering Achievement, "for exceptional scientific creativity and accomplishment in developing new types of atomic clocks with best-in-the-world performance"

David Jacobson and **Muhammad Arif**, Ionizing Radiation Division, 2009 Gold Medal for Scientific/Engineering Achievement, "for excellence, innovation, and leadership in developing and implementing neutron imaging to support robust and efficient hydrogen fuel cells"



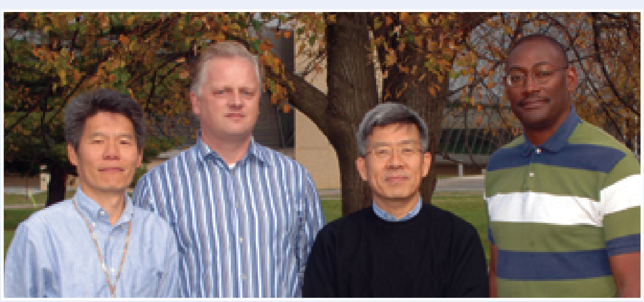
Carl Williams, Atomic Physics Division, 2008 Gold Medal for Scientific/Engineering Achievement, "for contributions to the theory and application of atomic clocks, ultracold atomic physics, and quantum information science"



Paul Lett, Atomic Physics Division, 2009 Gold Medal for Scientific/Engineering Achievement, "for developing new techniques to produce quantum-squeezed light and images, allowing measurement far better than the standard quantum limit"

Silver Medal *(Department of Commerce)*

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



Ping-Shine Shaw, **Howard Yoon**, and **Charles Gibson**, Optical Technology Division, and **Uwe Arp**, Electron and Optical Physics Division (second from left), 2008 Silver Medal for Scientific/Engineering Achievement, "for advancing ultraviolet radiation measurement science for application in materials processing, semiconductor manufacturing, and space sciences"

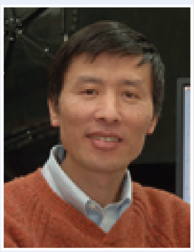
C. Cameron Miller, **Wendy Davis**, and **Yoshihiro Ohno**, Optical Technology Division, 2009 Silver Medal for Scientific/Engineering Achievement, "for developing measurement methods and technical standards to accelerate the commercialization of energy-efficient, solid-state lighting products"

Bronze Medal *(NIST)*

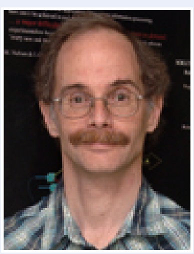
For work that has resulted in more effective and efficient management systems, the demonstration of unusual initiative or creative ability, significant contributions on major programs, scientific accomplishment, or superior performance

Ronald Collé and **Lizbeth Laureano-Perez**, Ionizing Radiation Division, 2008 Bronze Medal, "for the revitalization and expansion of the NIST radioactive SRM program"

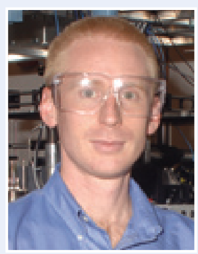
Dean Takamatsu, **Adelamae Ochinang**, **Dean Okayama**, and **John Lowe**, Time and Frequency Division, 2008 Bronze Medal, "for the design and construction of new antennas for time and frequency radio broadcasts that serve millions of customers in the U.S. and the Pacific Rim"



Yuqin Zong, Optical Technology Division, 2008 Bronze Medal, "for innovation in visible light measurement and standards in support of the conventional and burgeoning solid-state lighting industries"

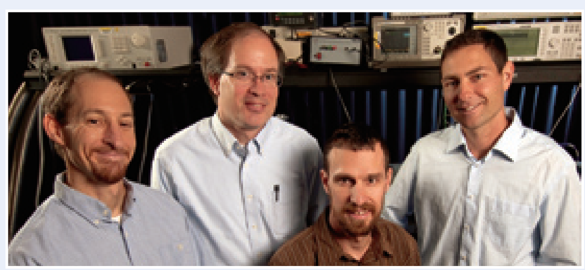


Alan Migdall, Optical Technology Division, 2009 Bronze Medal, "for advancing photon-based metrology for applications in optical radiation measurement, fundamental physics, and quantum information"



Ian Spielman, Atomic Physics Division, 2009 Bronze Medal, "for the development of methods to simulate condensed matter models by creating simple experimental realizations using ultracold atomic gases"

Patrick Hughes, **Alan Thompson**, **Muhammad Arif**, Ionizing Radiation Division, and **Robert Vest** (center), and **Charles Clark**, Electron and Optical Physics Division, 2009 Bronze Medal, "for the development of a new detector of neutrons based on the detection of extreme ultraviolet radiation from excited atoms produced by nuclear reaction"



Steven Cundiff, Quantum Physics Division (second from left) with **Richard Mirin, Martin Stevens**, and **Kevin Silverman**, Optoelectronics Division (EEEL), 2009 Bronze Medal, "for their technical ingenuity in advancing semiconductor quantum dot metrology through ground-breaking absorption studies and practical, world-first devices"

Samuel Wesley Stratton Award

For outstanding scientific or engineering achievements in support of NIST objectives

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Dietrich Leibfried, Time and Frequency Division, 2008 Award, "for the conception and demonstration of a versatile, reliable geometric phase gate, so far the most effective approach to quantum computing research"

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James Bergquist, Time and Frequency Division, 2009 Award, "for leading the research and development of the world's most precise atomic clock, which is based on a single ion of mercury and exquisitely stabilized lasers"

Judson C. French Award

For significant improvement in products delivered directly to industry, including new or improved NIST calibration services, Standard Reference Materials, and Standard Reference Databases

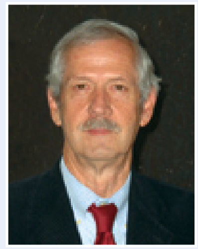
Leonard Hanssen, Optical Technology Division, 2009 Award, "for developing and maintaining a critical Standard Reference Material (SRM 1921) which is used in the wavelength calibration of infrared spectrometers"

Sigma Xi *(NIST Chapter)* Lifetime Service Award

Marilyn Jacox, Optical Technology Division, 2009 Award (inaugural award), for longstanding efforts in support of the Chapter

Edward Bennett Rosa Award

For outstanding achievement in, or contributions to, the development of meaningful and significant engineering, scientific, or documentary standards either within NIST or in cooperation with other government agencies or private groups



Bert Coursey, Physics Laboratory, 2008 Award, "for leadership in developing national standards to qualify chem/bio/rad/nuclear/explosive detectors used to ensure border and transportation security"

Equal Employment Opportunity/Diversity Award

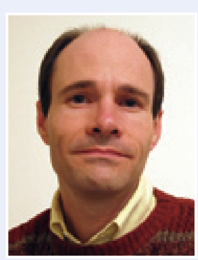
For exceptionally significant accomplishments and contributions to equal employment opportunity/diversity goals

Angela Hight Walker, Optical Technology Division, 2009 Award, "for years of devotion to educational outreach, through compelling science demonstrations to students at NIST events and at local schools"

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

Ian Spielman, Atomic Physics Division, 2009 Award, for innovative research on ultracold, quantum degenerate atoms placed in optical lattices to simulate condensed matter systems of fundamental significance

JARI Enterprise Award



Lawrence Hudson, Ionizing Radiation Division, 2009 Award, "for outstanding progress and future promise in the area of x-ray diffraction spectroscopy of highly charged ions and wavelength standardization, as well as service to the scientific and wider community through editorship and outstanding leadership"

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, Chief
- **Time and Frequency Division**
  Thomas O’Brian, Chief
- **Quantum Physics Division**
  Thomas O’Brian, Chief (Acting)

Physics Laboratory Resources

Physics Laboratory Resources 2005–2009 *($ millions)*					
	2005	**2006**	**2007**	**2008**	**2009**
STRS	43.6	48.1	49.2	49.3	56.1
ATP	1.6	0.9	0.9	0.0	0.0
OA	20.4	21.6	20.7	21.9	20.2
Other	5.0	4.6	4.8	4.9	5.3
TOTAL	**70.6**	**75.2**	**75.6**	**76.1**	**81.6**

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, which ended in 2007*

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

Other *Other sources of funding, including calibration fees*

FEDERAL AGENCIES SUPPORTING PHYSICS LABORATORY RESEARCH

- Department of Commerce
- Department of Defense
- Department of Energy
- Department of Health and Human Services
- Department of Homeland Security
- Department of Justice
- National Aeronautics and Space Administration
- National Science Foundation

REPRESENTATIVE PRIVATE SECTOR COLLABORATORS

- Alliance for Telecommunications Industry Solutions
- American Association of Physicists in Medicine
- American Chemical Society
- American Geophysical Union
- American Institute of Aeronautics and Astronautics
- 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

EDITOR:
Jonathan E. Hardis
Physics Laboratory,
National Institute of Standards and Technology

U.S. Department of Commerce
Gary Locke, Secretary

National Institute of Standards and Technology
Patrick Gallagher, Director

NIST SP 1107
March 2010

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David Allen (Fig. 6, p. 25), Denease Anderson (Various awards photographs, pp. 54–62), Vincent Boyer and Paul Lett (Fig. 12, p. 17), Herbert Breuer / University of Maryland / NIST (Fig. 9, p. 35), Garnett Bryant (Fig. 8, p. 14), John Burnett (Fig. 6, p. 13), Charles Clark (Fig. 4, p. 6), Catherine Cooksey (Fig. 4, p. 23), The DesignPond (Cover and layout), Ryan Fitzgerald (Fig. 6, p. 32), Thomas Gentile (Fig. 8, p. 34), Thomas Germer (Fig. 5, p. 24), Steven Grantham (Fig. 1, p. 5), Leonard Hanssen (Figs. 8–9, pp. 26–27), Jonathan Hardis, Ulrich Jentschura, Peter Mohr, and Joseph Tan (Fig. 15, p. 19), Paul Julienne (Fig. 1, p. 9), Soowhan Kim and Matt Mench / The Pennsylvania State University / NIST (Fig. 10, p. 35), Greg Kuebler / JILA / CU (Figs. 1–8, pp. 45–50), Frank Lovas (Fig. 1, p. 53), Keith Lykee (Fig. 3, p. 22), Michael Metcalfe (Fig. 11, p. 16), Ronaldo Minniti (Figs. 1–2, p. 29), C. Michelle O'Brien (Fig. 4, p. 30), Yoshi Ohno (Figs. 1–2, pp. 21–22), Joshua Pomeroy (Fig. 7, p. 13), Trey Porto (Fig. 4, p. 11), Yuri Ralchenko (Fig. 14, p. 18; Fig. 16, p. 19), Anand Ramanathan and Kris Helmerson (Fig. 3, p. 10; Fig. 13, p. 17), Sanaria, Inc. (Fig. 3, p. 30), Robert Saunders (Fig. 7, p. 25), SEMATECH Inc. (Fig. 3, p. 6), Dawn Shafer / Colorado School of Mines / NIST (Fig. 9, p. 51), Ian Spielman (Fig. 5, p. 11), Curt Suplee / JQI (Fig. 10, p. 15), Charles Tarrio (Fig. 2, p. 5), Eite Tiesinga (Fig. 2, p. 9), Peter Volkovitsky (Fig. 7, p. 32), Solomon Woods (Fig. 10, p. 27), Brian Zimmerman (Fig. 5, p. 31), and Neil Zimmerman (Fig. 9, p. 14)

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