Quantum Physics Division (JILA)

Overview

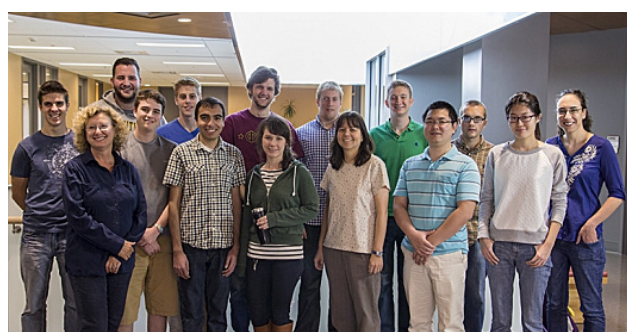
The Quantum Physics Division is the NIST part of JILA*, a joint research, training, and technology innovation institute between NIST and the University of Colorado, Boulder (CU). Founded in 1962, JILA is the nation's first full university-government partnership, where Federal employee scientists and university scientists are physically co-located and work continuously and collaboratively on research, metrology, training, and technology development. JILA is physically located on the CU campus about 1 km from the NIST Boulder Laboratories.

JILA facilities on the CU campus

The scientific work at JILA is led by 25 JILA Fellows, each of whom has a research group that closely collaborate across JILA, with NIST, across CU and with external partners. 11 of the JILA Fellows are currently NIST employees or CU research faculty completely supported by NIST, and the remainder are CU faculty members. All JILA Fellows, whether NIST employees or CU faculty, have CU faculty appointments in one or more of four CU academic departments: Physics; Chemistry and Biochemistry; Molecular, Cellular, and Developmental Biology; and Astrophysics and Planetary Sciences. (No NIST JILA Fellows in this department.)

NIST employees have adjoint faculty appointments. They have all the responsibilities and privileges of CU research faculty, including conducting independent research, teaching formal classes, supervising graduate student theses, mentoring postdocs, serving on university committees, etc. NIST adjoint faculty receive no financial compensation from the university.

Each JILA Fellow, whether a NIST or CU employee, leads a research group averaging about 10 people, mostly CU graduate students and postdocs, with some CU employee technical staff and visiting scientists from across the world. Approximately 250 people work at JILA, including about 150 CU graduate students and postdocs, and about 70 CU administrative and technical support staff. There are currently nine NIST employee JILA Fellows and two CU employees fully supported by NIST and a small handful of NIST administrative staff.



The Debbie Jin research group

One of the great strengths of JILA is that a casual observer would find it impossible to distinguish NIST JILA Fellows from CU JILA Fellows, in that they all participate in the same research, training, and innovation activities, and closely collaborate with one another continuously. Thus examining only the NIST "part" of JILA, as required here, cannot provide a complete picture of the organization's scope, value, and impact.

For example, JILA (and thereby the Quantum Physics Division) is widely recognized as one of the world's premier research and training organizations in atomic/molecular/optical (AMO) physics and closely related areas. JILA has been ranked as the nation's top AMO graduate program for decades. JILA scientists are responsible for a long list of breakthroughs in AMO physics such as the world's first Bose-Einstein Condensate, first Fermi condensate, first self-referenced laser frequency comb, first evaporative cooling of molecules, first quantum degenerate gas of polar molecules, first cooling to the quantum ground state of a macroscopic object, and many other accomplishments.

JILA scientists include three Physics Nobel Laureates, three MacArthur Foundation Fellows ("Genius grant" winners), eight members of the National Academy of Sciences, and many other winners of the most prestigious awards – and these are among the 25 JILA Fellows.

While JILA is best known for its AMO research and innovation, in recent years the Quantum Physics Division has intentionally expanded into areas of biophysics and nanoscience, where existing JILA AMO expertise can help address key research and measurement problems.

Mission and Alignment with NIST Goals

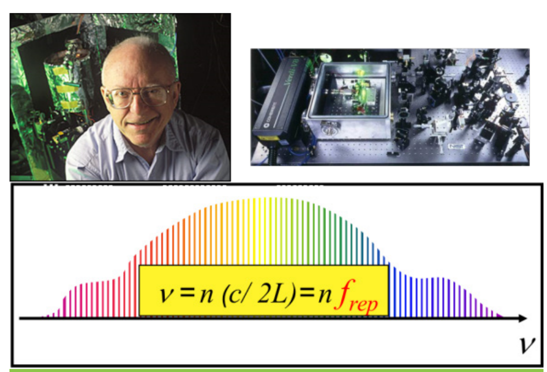
Any objective analysis of the outcomes from JILA and the Quantum Physics Division would conclude that JILA has been very successful in research. But NIST and PML have the mission to use measurements and technology to strengthen the U.S. economy and advance U.S. national interests. One way to view the value of the Quantum Physics Division (as part of JILA) in the context of the NIST/PML mission is by its contributions to three areas:

- *Measurement science innovation*
- *Unique training in measurement science and innovation*
- *Innovations and training in areas that advance national interests*

Measurement Science Innovation:

The Division is an innovation engine, producing high-impact measurement tools and technologies used across PML, across NIST, across industry, and across the world.

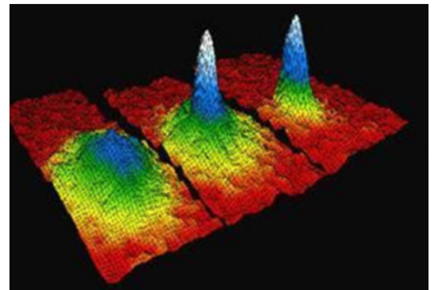
In just one example, Quantum Physics Division scientists, in collaboration with CU JILA students and postdocs, invented the self-referenced femtosecond laser frequency comb. While initially pursued as a tool to improve optical frequency standards (atomic clocks), laser frequency combs have become one of the most powerful and versatile research and precision metrology tools since the 1960 invention of the laser. Laser frequency combs are routinely used in nearly all NIST Laboratories for research and metrology in such areas as telecommunications, remote sensing, chemical analysis and quantification, generation of precision radiofrequency and microwave signals, medical diagnostics, length standards, atomic clocks, and references for exoplanet identification and characterization – with new applications appearing continuously.



Jan Hall, self-referenced laser frequency comb

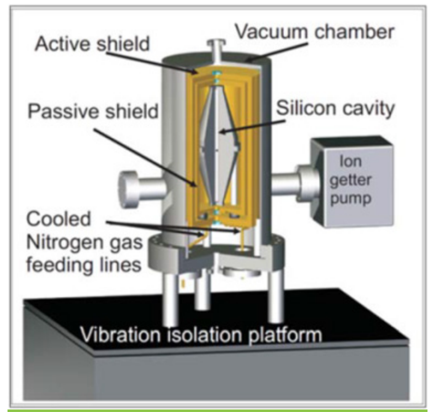
Frequency combs are also ubiquitous in research labs in universities, national labs, industry and many other areas, with new commercial frequency comb products available regularly. Arguably, the impact on NIST alone of just this one innovation exceeds the entire integrated NIST investment in JILA – but there are many, many more Quantum Physics Division innovations.

Other Quantum Physics Division innovations with broad impacts include (only a partial list):



First quantum degenerate gas, BEC

- *Quantum degenerate gases*, including BEC, Fermi condensates, molecular gases, etc. In addition to providing a unique laboratory for fundamental physics, scientists across NIST use quantum degenerate gases for quantum information processing research, quantum simulation, ultrahigh vacuum standards, with new applications continually evolving.
- *Quantum state engineering of macroscopic objects.* Division scientists led the first cooling to the quantum ground state of a macroscopic object – a microresonator in a superconducting circuit. These advances are being used to make "perfect" transducers where quantum information can be shuttled back and forth between optical, electrical and mechanical signals with no loss of quantum state information; ultra-precision quantum-based measurements of force and photon flux; and many other applications.
- *Development of technologies* to probe real-time dynamics and kinetics of large single biological molecules such as proteins, enzymes, and nucleic acids, to better understand normal physiology and disease processes.
- *Unique ultra-stable laser technologies*, including the world's most stable laser based on a laser cavity comprising a monolithic silicon crystal with unique end mirrors; and the world's first demonstration of super-radiant the optical cavity, reducing sensitivity to cavity perturbations by a factor of 10,000 or more.

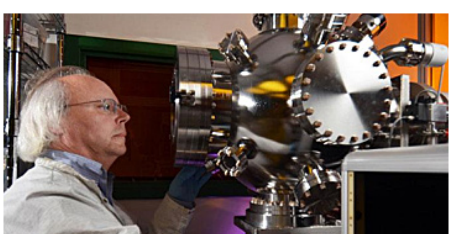


Ultrastable laser cavity

- *The world's most stable atomic force microscope* (AFM), perfected for biophysical applications, and able to make measurements in the warm, wet environment 100 to 1,000 times better than previous best AFMs operating in ultrahigh vacuum at cryogenic temperatures. The Division's AFM technology is currently focused on measuring the complex behavior of proteins and nucleic acids in real-world biological systems, but is also available for a broad range of physical measurements.
- *The world's fastest system* for measuring and separating individual living cells with unique properties revealed by ultra-fast optical studies, demonstrated for such activities as quickly identifying algal cells with highest biofuel production, and rapidly identifying optimal fluorescent proteins used to monitor real-time processes in living cells.

Unique Training in Measurement Science and Innovation

The Division provides unique training to future generations of innovators who become leading NIST scientists and metrologists, start high-tech companies, work in industry and national research labs, and become research faculty at universities.



JILA instrument maker

JILA students, postdocs and visitors are immersed in the unique JILA culture with world-class instrument shops, electronics support, and information technology support. The JILA technical support staff – instrument makers, electronics engineers, IT specialists – are skilled and experienced designers and collaborators, not merely device makers. JILA trainees thus participate directly in the vision, design, fabrication and testing of new instruments, electronics systems, and IT systems. That environment strongly stimulates deep knowledge of the experiments, creative thinking, and an attitude of "if it doesn't exist, we can design and make it" – qualities that encourage innovation.

Nearly all JILA research, especially led by Quantum Physics Division Fellows, strongly focuses on precision measurement, and attention to the seemingly endless details that cause uncertainties. JILA trainees thus are indoctrinated in the importance of precision measurement as a key part of research.

Just a few of the highly trained JILA innovators

There are currently approximately 400 scientists and metrologists working at NIST who were trained at JILA in some capacity: Graduate student, postdoc, scientific visitor, etc. These JILA alumni work at the NIST Gaithersburg and Boulder campuses, in nearly all NIST Laboratories. This number includes both NIST employees and NIST associates. Many of these JILA alumni represent top scientific leaders at NIST, leading their own measurement science innovations.

JILA alumni have started about a dozen high-tech companies in such areas as optical components, medical diagnostics, gravity meters, and other areas. These companies provide innovation technologies and good jobs, commensurate with the NIST mission to facilitate economic growth and new technologies.

Small sample of JILA spin-off companies

JILA alumni are key scientific and innovation leaders in industry labs, in universities, in national labs (beyond NIST). They contribute broadly to US economic growth and technology development, and they expand the active network of collaborators for NIST.

Innovations and Training in Areas That Advance National Interests:

The Division's research has broad impacts and directly supports key NIST, PML and national priority areas. These include

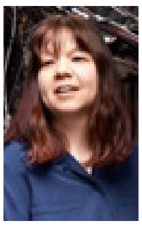
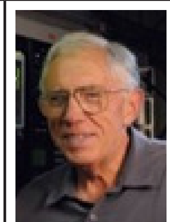
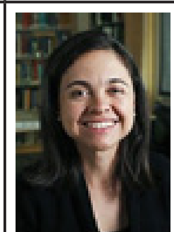
- *Advanced manufacturing:* The very complex and noisy factory-floor environment can interfere with precision measurements needed for high-performance products. Such advances as super-radiant lasing technology holds the promise for future precision measurements largely free from laser cavity perturbations due to vibration, temperature changes, etc.
- *Advanced manufacturing:* Division advanced optical measurements can quickly and nondestructively characterize the chemical composition and physical properties of nanostructure, nanomaterials, and nanocoatings enabling new products and manufacturing processes.
- *Biomedical science:* Division unique AFM measurements of the coiling and uncoiling of integrated membrane proteins elucidates how these "gatekeeper" molecules function in real time, in real biological environments. Integrated membrane proteins control 80% of the material that enters/leaves cells across the membrane, and are the target for at least 50% of new drugs.
- *Energy:* Division fastest-in-the-world sorting cell cytometer nearly instantly determines which individual living algal cells are the most efficient biofuel producers (highest lipid production), and collects only those desired cells, at the rate of thousands of cells per second. This process is many orders of magnitude faster than the standard mass culture technique.
- *Materials science:* Research and measurements on new materials, including biomaterials, benefits from studies in the extreme ultraviolet (XUV), which has generally required use of multibillion dollar synchrotron facilities. Division programs in XUV frequency combs generate XUV light about one million times brighter than synchrotron sources from a tabletop system costing less than $1 million.

- *Quantum information:* The Division's demonstration of "perfect" transduction of quantum states between optical, mechanical, and electrical systems is a big step toward practical quantum repeaters to enable global quantum communication systems.

(The technologies outlined above typically have many other practical and research uses beyond the brief examples used.)

Specific Division Research and Metrology Programs

The best descriptions of the Division's research programs are on the individual web pages of the Division JILA Fellows. Links are provided below.

 John Bohn (Theory). Quantum degenerate gases. Quantum many-body phenomena. Website	 Eric Cornell (Experiment). Quantum degenerate gases. Precision measurements. Ultrafast phenomena. Website	 Ralph Jimenez (Experiment). Biophysics. Ultrafast phenomena. Chemical physics. Microfluidics. Website
 Debbie Jin (Experiment). Quantum degenerate gases. Website	 Konrad Lehnert (Experiment). Nanoscience. Quantum nanomechanics. Quantum information. Mesoscopic physics. Website	 Judah Levine (Experiment). Precision measurement. Website (Joint appointment with Time and Frequency Division)
 David Nesbitt (Experiment). Biophysics. Ultrafast phenomena. Chemical physics. Website	 Tom Perkins (Experiment). Biophysics. Precision measurements. Website	 Ana Maria Rey (Theory). Quantum degenerate gases. Precision measurements. Quantum many-body phenomena. Quantum information. Website
 James Thompson (Experiment). Quantum degenerate gases. Precision measurements. Quantum many-body theory. Ultra-stable lasers. Website	 Jun Ye (Experiment). Quantum degenerate gases. Precision measurements. Ultrafast phenomena. Quantum many-body phenomena. Ultra-stable lasers. Website	

Quantum Physics Division Focus Areas

Another way to examine the Division activities and impacts is in terms of five high-level focus areas:

- Quantum degenerate gases: Cold atoms and molecules.
- Ultrafast phenomena.
- Precision measurements.
- Biophysics.
- Nanoscience.

The first three areas (quantum degenerate gases, ultra-fast phenomena, precision measurements) represent long-standing traditional strengths of the Division. Biophysics and nanoscience represent newer parts of the Division research portfolio, as the Division continually strives to evolve, innovate, and identify areas of potential impact on national priorities. Biophysics and nanoscience represent huge, enormously diverse areas, with many billions of dollars of national investment. The tiny Quantum Physics Division – 11 JILA Fellows total – strives to determine particular challenging measurement and research problems in these areas where leveraging traditional Division strengths can have significant impacts.

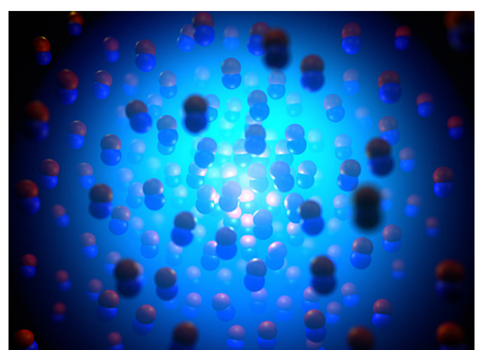
These five areas represent a somewhat arbitrary classification. And there are clearly strong overlaps among them. For example, Division biophysics programs certainly depend on precision measurements and ultra-fast phenomena, etc. This classification approach should be considered as one convenient way to describe the Division programs, but not the only way. Another way some Division members think about the programs is “Ultra-science and metrology: Ultra-cold, Ultra-Precise, Ultra-fast, Ultra-small.”

The Division programs represent particularly strong coupling between experiment and theory. Division experimental and theory groups hold regular joint meetings, and the theorists thrive on delving into the details of what can and cannot be accomplished experimentally. The members of the Division (including the CU Fellows fully supported by NIST) currently comprise 9 experimental Fellows and two theory Fellows. Of course, all Division JILA Fellows closely collaborate with experimentalists and theorists across JILA and NIST, and in many external organizations.

Most Division research (experimental and theoretical) has leveraged what could be considered single-body or few-body quantum physics. For more than 100 years, science and technology have made enormous advances considering simply the quantum interactions between two particles. Such approaches resulted in the transistor, laser, atomic clocks, quantum degenerate gases, and countless other disruptive advances. While continuing this single-body quantum physics research, the Division is moving strongly in quantum many-body phenomena. This enormously challenging area represents a new frontier for quantum physics, a second quantum century. A couple of examples of “simple” quantum many-body phenomena include quantum magnetism, superconductivity, complex materials, and large-scale quantum simulation and computation. There are clear practical potential benefits to such research (better computing and data storage, better energy efficiency, new materials, etc.). But the biggest impacts are likely to come from as yet undiscovered phenomena and measurements. The Division strives to be at the forefront of this second quantum century. This section is intended only to provide some broad highlights to provide an overview of Division research and metrology programs. Please see the links to specific projects above for more detailed information.

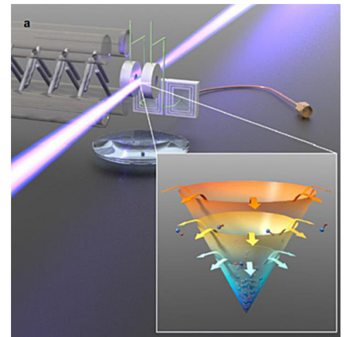
Quantum Degenerate Gases

The Division/JILA has long been a leading center for research and measurements on cold atoms and molecules. The Division’s programs represent a particularly close connection between experiment and theory groups in the Division, and outside of JILA. There has been a continuing and highly successful positive feedback system where initial experimental results stimulate new theories which suggest new experiments, which corroborate the new theories but provide additional insights, etc.


Quantum chemistry in ultracold polar molecules

The Division/JILA is of course well known for producing the first Bose-Einstein Condensate (BEC), and the first Fermi condensate. The Division has continued to explore the fundamental physics of these atomic quantum degenerate gases, and of mixtures of BEC and Fermi condensates.

The Division extended the research to quantum degenerate gases of molecules, producing ultracold gases with 10,000 times greater phase space density (combination of temperature and number density) than other teams, demonstrating the world’s first quantum control of cold molecular reactions – the first time humans have completed controlled chemical reactions rather than rely on nature to perform chemistry on substances put in proximity – and many other firsts.



First evaporative cooling of a molecule (OH radical)

The Division demonstrated the world's first evaporative cooling of molecules (OH radical), a big step towards molecular BEC.

Division scientists made the first observation of Tan's contact in bosons, a measure of the strength of interactions among atoms in a condensate.

Division scientists harnessed the quantum Zeno effect to reduce the loss of ultracold molecules held in an optical lattice.

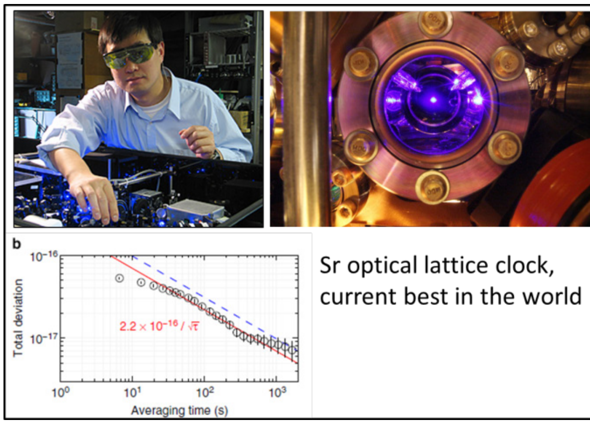
A strong experiment/theory collaboration led to the first measurement of spin exchange among ultracold molecules in a lattice, demonstrating the potential for this system to be a powerful quantum simulator.

Ultrafast Phenomena and Precision Measurement

These two areas are closely coupled through the development and application of femtosecond laser frequency combs, and will be considered in combination.

Recent Accomplishments

Frequency Standard



Sr optical lattice clock, current best in the world

The Division holds the current world record for the most accurate and stable optical frequency standard (atomic clock). The Division's strontium lattice optical frequency standard has a fractional frequency uncertainty (Δf/f) of approximately 2 x 10^{-18}, or the equivalent of one second in 15 billion years (longer than the age of the universe). Frequency standards are crucial for modern technology infrastructures such as telecommunications, GPS, utility distribution, remote sensing, and many other applications. At this exquisite level of performance, frequency standards also become excellent sensors of a wide range of parameters which affect atomic transitions. For example, a change in elevation of 2 cm near the surface of the Earth changes the frequency of the Sr standard by 2 x 10^{-18} (its detection limit) through the general relatively red shift. Thus the Sr frequency standard can be a highly sensitive gravimeter. Such ultra-precise frequency standards can also measure magnetic fields, motion, force, temperature, and many other quantities. Ultra-precise frequency standards are broadly enabling measurement technologies, and the Sr optical lattice clock continues to rapidly improve. (Please see the Time and Frequency Division section for further discussion. This work is conducted in close collaboration with the Time and Frequency Division.)

CONTACT: Jun Ye (303-735-3171), JILA

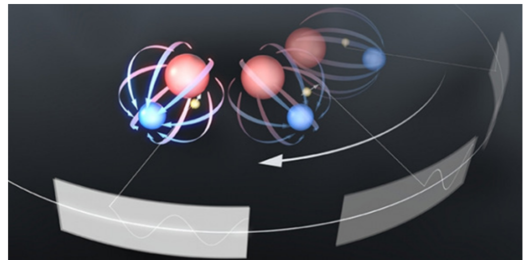
Extending the Range of Frequency Combs

Division scientists develop new frequency comb technologies and continually extend the spectral range of frequency combs, deep into the extreme ultraviolet (XUV) and far into the infrared and eventually to the terahertz range. The Division demonstrated high coherence XUV radiation (greater than one second coherence time) at wavelengths recently as short as about 20 nm, and continually getting shorter. This spectral range is particular valuable for studies of materials and biological systems. The Division's XUV frequency comb is a tabletop system costing about $1 million that is about one million times as bright in this spectral range as multibillion synchrotron facilities.

CONTACT: Jun Ye (303-735-3171), JILA

Electron Electric Dipole Moment

The Division is conducting a tabletop experiment to precisely measure the possible electric dipole moment of the electron (eEDM). The potential for non-point structure of the electron has deep implications for fundamental physics, cosmology, the apparent imbalance between matter and anti-matter, and many other issues. The Division's approach leverages the ultra-strong electric fields in heavy polarized molecules such as HfF^+ combined with ultraprecise spectroscopy to measure tiny deviations. The team has pushed in the 10^{-28} uncertainty range where possible eEDM effects may be just detectable, and is poised to push into the unexplored 10^{-30} range.



eEDM measurement through precision spectrscopy of HfF^+

CONTACT: Eric Cornell (303-492-6281), JILA

Stable Laser Cavity

Division scientists invented the world's most stable laser cavity, comprising a monolithic crystal of silicon, with special end mirrors, specially supported to minimize mechanical strains, and operated at a cryogenic temperature minimizing cavity changes due to temperature variations. The laser has a stability on order of 10^{-16}, about ten times better than the previous record.

CONTACT: Jun Ye (303-735-3171), JILA

Super-Radiant Laser

The Division also demonstrated the world's first super-radiant laser. A "traditional" laser obtains phase stability from an optical cavity, with the stability of the distance between the mirrors determining the phase stability. Even if that mechanical distance could be perfectly stabilized (it can't), there would still be normal thermal fluctuations of the atoms on the mirror surfaces, effectively generating cavity length noise. The super-radiant laser stores the phase information in ultra-narrow atomic transitions in atoms within the cavity, reducing the sensitivity to cavity fluctuations by a factor of 10,000 or more. While a super-radiant laser is limited to a few ultra-narrow atomic transitions, that is not a practical limitation – the super-radiant laser can be used to stabilize a frequency comb to provide ultra-stable laser radiation at any desired wavelength.

Super-radiant laser

CONTACT: James Thompson (303-492-0082), JILA

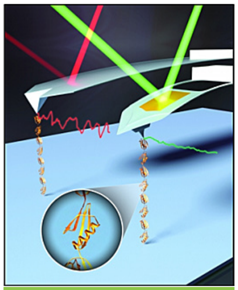
Biophysics

The Division pursues three primary efforts in biophysics:

- Precision force spectroscopy on large biomolecules (proteins, nucleic acids) with ultra-stable atomic force microscopy and laser tweezers.
- Microfluidic/ultrafast laser systems to rapidly analyze biomolecules and cells in real time and sort those molecules/cells with the desired properties.
- Single molecule laser spectroscopy on large biomolecules to elucidate structure/function relationships.

These areas leverage long-standing Division strengths in laser systems and precision measurements.

Recent Accomplishments



Ultrastable AFM

Stable AFM

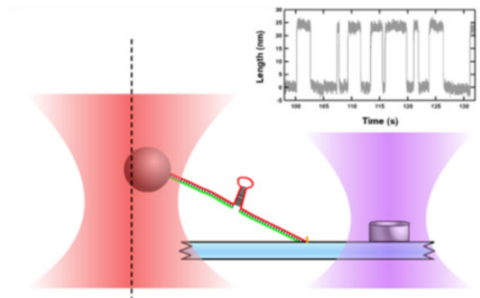
Invention of the world's most stable AFM, optimized to study large biomolecules in the normal warm, wet environment, but achieving 100 times or greater stability compared to previous best AFMs that operated in ultrahigh vacuum and cryogenic temperatures (unsuitable for meaningful studies on biomolecules in normal environments).

CONTACT: Tom Perkins (303-492-5291), JILA

DNA Dynamics

Precision measurement of DNA dynamics (forces required to "unwind" DNA) revealing previous details of DNA dynamics and kinetics that could not be seen with less sensitive AFMs or other approaches.

CONTACT: Tom Perkins (303-492-5291), JILA



Precision DNA stretching force metrology

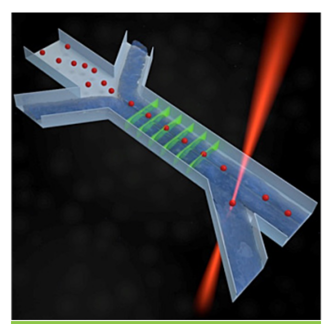
DNA Force Standards

Demonstration of using engineered DNA sequences as force standards at the 10^{-12} Newton level. Such tiny forces are important not only for biological systems, but also for micro/nanofabrication processes, MEMS, etc.

CONTACT: Tom Perkins (303-492-5291), JILA

Microfluidic/Laser Systems

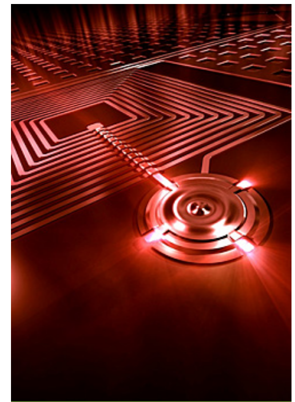
Pioneering of microfluidic/laser systems to rapidly measure the performance of fluorescent proteins, and sort in real time those fluorescent proteins with optimal performance characteristics. Fluorescent proteins are powerful tools to measure chemical and physical processes at the molecular level in living cells. But currently available fluorescent proteins have limitations in spectral range, sensitivity, affinity for the target molecules, stability, etc. Many biological studies would be vastly enhanced by having "designer" fluorescent proteins with ideal characteristics. The Division system is bringing that ideal much closer to reality, speeding up by orders of magnitude the ability to test and select fluorescent proteins with favorable characteristics.



High-speed cell metrology

Similar microfluidic/laser systems are used in the Division to nearly instantly quantify the performance of living cells for certain characteristics, and select the particular desired cells in real time. One example of this technique is to rapidly identify those individual algal cells that are optimized for lipid production – and thus most efficiently produce biofuels – and separate those particular cells at the rate of thousands of individual cell measurements and selections per second. This performance is orders of magnitude faster than previous systems.

CONTACT: Ralph Jimenez (303-492-8439), JILA



Quantum state engineering of macroscopic objects

Nanoscience

As with biophysics, Division programs in nanoscience are designed to leverage existing Division/JILA expertise in precision measurements, lasers, and other areas.

Recent Accomplishments

First cooling to the quantum ground state of a macroscopic object, a microresonator on an integrated superconducting circuit.

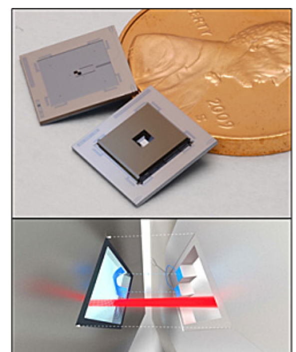
First quantum entanglement of a macroscopic object (microresonator) with a microwave field (photons).

First “perfect” (lossless) coherent state transfer between optical and electrical (microwave) fields, mediated by a mechanical object (microresonator).

CONTACT (for all above): Konrad Lehnert (303-492-8348), JILA

These accomplishments focus on perfecting opto-electro-mechanical transductions for a broad range of applications, including (only a partial list):

- Perfect quantum repeaters to enable global quantum communications with no loss of quantum state information regardless of path length/transmission time. Such devices are crucial to practical use both of secure quantum communications networks, and to disseminating information from quantum computers. They could also play key roles in such things as networks of quantum oscillators to provide ultraprecise timing information across the globe. *CONTACT: Jun Ye (303-735-3171), JILA*
- Development of new categories of chip-scale quantum-based measurement systems. Such devices could provide deployable, accurate measurements of quantities such as force, pressure, photon flux (radiant power), acceleration, motion, and many other quantities. These devices are likely to be key to the “NIST on a Chip” program (see Time and Frequency Division discussion). *CONTACT: Konrad Lehnert (303-492-8248), JILA*



Lossless opto-electro-mechanical transduction

Quantum many-body phenomena

As mentioned above, the Division is moving strongly into research and measurements on quantum many-body phenomena (also called collective quantum phenomena) as the key thrust of the second century of quantum mechanics. Single-body (individual) quantum phenomena have been enormously successful and powerful, and underpin much of our modern technology. While there are some early known quantum many-body phenomena with clear impacts (quantum magnetism, superconductivity, etc.), it is highly likely the biggest impacts will come from phenomena not yet even known or observed. The Division strives to play a leadership role in this new frontier, in both experiment and theory, while still leveraging research and measurements using the many important single-body (individual) quantum phenomena. A couple of examples of recent Division accomplishments in early quantum many-body research and measurements:

Recent Accomplishments

SU(N) Symmetry

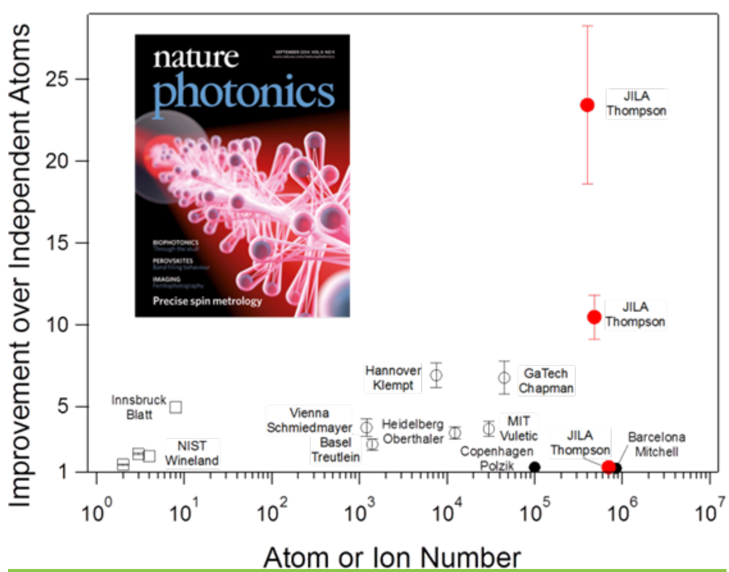
Division scientists made the first observation of SU(N) symmetry in an atomic system (strontium atoms in an optical lattice). Until this observation, SU(N) symmetry was known only in sub-atomic systems as part of the Standard Model. Just as SU(N) symmetry in the Standard Model provides many strange and important effects in the subatomic world, Division scientists are eager to explore how this symmetry might impact the “larger” world of atomic systems. For example, there are potential intriguing applications for quantum magnetism and other phenomena.

Division scientists also studied the quantum many-body spin systems in the strontium lattice optical clock. Because the Sr optical lattice clock can be so exquisitely controlled, this may prove to be a highly valuable laboratory for studying such collective quantum phenomena such as superconductivity.

CONTACT: Ana Maria Rey, arey@jilau1.colorado.edu

Spin Squeezing

Division scientists set the record by an order of magnitude in spin-squeezing measurements, obtaining about 25 times better results than the standard quantum limit in a collection of nearly one million atoms. Spin-squeezing/state-squeezing is a quantum many-body effect that in principle can be used to dramatically improve measurement accuracy and precision beyond the standard quantum limit (at the expense of relinquishing certain other less important information). Spin-squeezing experiments across the world had been showing measurement improvements of a few percent to about a factor of five, usually with only a relative few atoms or ions. Useful measurement improvements require a significant increase beyond the standard quantum limit, and in most cases require such measurements on a large collection of particles. The Division’s research set the record for both number of particles and amount of measurement improvement.



World record spin-squeezing

CONTACT: James Thompson (303-492-0082), JILA

Quantum many-body research and measurement is in the very early stages. It will likely require many years of hard work to reap practical benefits, especially considering the virtuosic mastery of single-particle quantum systems by many teams across the world (including many NIST activities). But the Division will vigorously pursue quantum many-body research and measurement opportunities, while maintaining its focus and leadership in current areas described above.

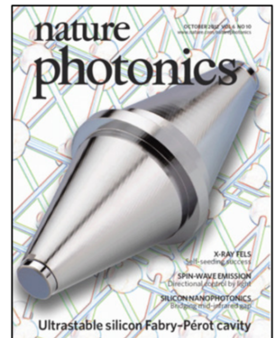
---

* JILA was founded in 1962 as the “Joint Institute for Laboratory Astrophysics,” but over time its mission and research has continually evolved. Today almost no laboratory astrophysics research is performed and the organization’s name is simply JILA (not an acronym).

Quantum Physics Division (JILA) Supplemental

Division Partnerships and Technology Transfer

The Division transfers the results of its research, measurements and technology development through many means:



Ultrastable laser cavity

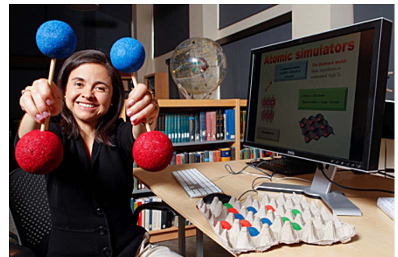
- **Publications:** Over the past 4.5 years, JILA has published about 840 publications, or approximately 180 publications per year. About 25% of those publications were in the most prestigious international journals reflecting JILA's research areas, including 83 *Physical Review Letters*, 45 *Nature* articles, 17 *Science* articles, 35 *Optics Express* or *Optics Letters*, 7 *Applied Physics Letters* and 6 *Journal of Physical Chemistry Letters*. There were also significant numbers of publications in *Biophysical Journal*, *Nano Letters*, *Microfluidics*, and other journals reflecting some of the more specialized Division activities.
- **Training:** Exchange of highly trained people with unique knowledge is probably the most effective form of tech transfer. Over the past approximately 4.5 years, the Division supported 84 graduate students, 59 postdoctoral fellows, and about 30 Visiting Fellows from across the world. As noted earlier, some 400 people work at NIST as employees or associates who were trained at JILA in some capacity: Graduate students, postdocs, visitors, etc. In addition, people trained by the Division go on to start high-tech companies, work in labs in industry or national labs, teach at universities, etc. There is a very large Division/JILA network spanning the globe of scientists with close ties to NIST and JILA. The Division/JILA also operates a vigorous Visiting Fellow program, in which leading scientists from across the world with research programs related to Division/JILA interests are invited and sponsored to work at JILA for a few weeks to many months. This program brings new ideas and skills into the Division/JILA, and further expands the Division/JILA network.
- **Inventions:** Division scientists regularly produce new high-impact technology innovations as describe above: Laser frequency comb technologies, ultra-stable lasers, ultra-stable AFM, microfluidic systems, and much more. When it appears that seeking patent protection will accelerate the development of these inventions, the Division/NIST pursue patents and licensing. In most cases, the inventions are publicly shared, through publications, movement of non-employee inventors to companies, and direct consultations with interested parties. Division scientists have patented (or have pending applications) several technologies in the past few years, but most inventions are publically shared.

Most of the Division's activities are conducted in partnership with industry, other Federal agencies, universities, and international metrology organizations. The Division budget is very roughly equally distributed between NIST funds and funds from other Federal agencies, especially NSF, NIH, and DoD agencies. (Agencies such as NSF and NIH will not pay any part of Federal employee salaries or Federal equipment, but the JILA relationship means that NSF and NIH funds can be used for CU grad students and postdocs who work for NIST employees, CU equipment in NIST labs, etc.).

The Division closely partners with CU's BioFrontiers Institute, a major bioscience research and training institute led by Tom Cech, Nobel Laureate and former Director of the Howard Hughes Medical Institute. Three Quantum Physics Division JILA Fellows are also BioFrontiers Fellows and engage in collaborative research and training. The Division funds activities to strengthen these natural partnerships, including specialized equipment and research infrastructure at BioFrontiers, joint postdocs, and other activities. The Division/BioFrontiers collaboration focuses primarily on quantitative biosciences.

Recognition

One way of measuring the Division's impact is through major scientific awards presented to Division staff. Below is a partial, representative list of awards received by Division staff in the past few years (a full list is available elsewhere). All awards are from external organizations unless specified as a NIST or Department of Commerce (DoC) award.



Ana Maria Rey MacArthur Fellow

- Election to the National Academy of Sciences, bringing the total NAS membership in the Division to four of the 11 Division JILA Fellows.
- MacArthur Fellowship ("Genius Grant"), the second in the Division, and the third at JILA – all to women scientists.
- Isaac Newton Medal of the UK's Institute of Physics, the IOP's highest research award, and the first given to a woman scientist.
- Arthur S. Flemming Award for outstanding accomplishment by early career Federal employees.
- Two Division JILA Fellows named as among the "World's Most Influential Minds," being among the top 144 physicists in terms of citations over the past decade.
- Presidential Early Career Award for Scientists and Engineers (PECASE), the top US early career science recognition.
- L'Oreal/UNESCO "For Women in Science" award, a major international research recognition.
- Presidential Rank Award, recognizing career achievement in the top 1% of all Federal employees (two winners).
- National Academy of Sciences Comstock Prize in Physics.
- American Physical Society Maria Goeppert Mayer Award.
- Two Gold, one Silver, and one Bronze Medals from the Department of Commerce.


Debbie Jin "Women in Science"

Commensurate with the Division's/JILA's commitment to excellence in training, there were also two major awards to graduate students mentored by Division Fellows:

- American Physical Society Best Thesis Award.
- IEEE Best Paper Award.