



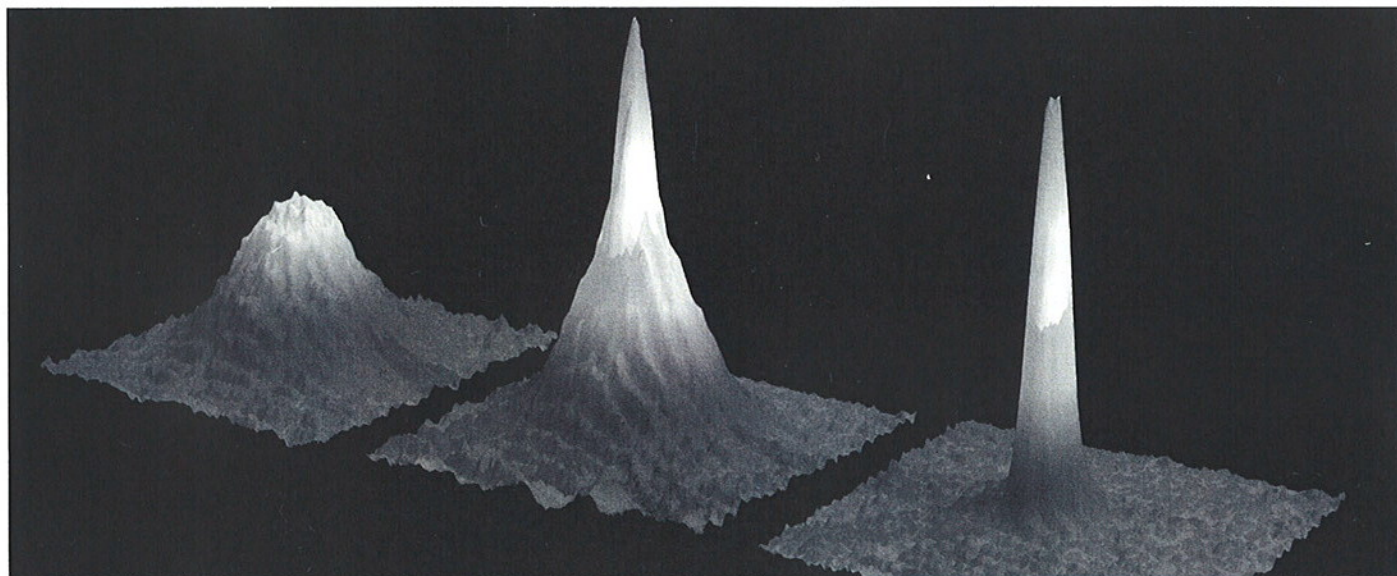
RLE

currents

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The Research Laboratory of Electronics at the Massachusetts Institute of Technology

FRONTIERS OF ATOMIC PHYSICS AT RLE



Absorption shadows of sodium atoms in ultracold clouds show evidence for Bose-Einstein condensation as the clouds are cooled to lower temperatures (from left): above the condensation point, just after condensation begins, and the remaining, essentially pure condensate. BEC of atomic gases presents new possibilities for applied and fundamental research. For the first time, it provides scientists

with macroscopic samples of atoms in a single quantum state, implying ultimate control over the motion of atoms. Several applications are foreseen in nanotechnology (high-resolution atom deposition), precision measurements (new atomic clocks and the determination of fundamental constants), and atom optics (atom interferometers that hold promise as ultraprecise gyroscopes).

The quantum world is remote from the familiar, everyday experience of most people. In the quantum world, waves can act like particles and particles can act like waves. However, to atomic physicists, the quantum world is a friendly and familiar place. Today, with the assistance of powerful experimental tools—some old and honored (such as spectroscopy), and others hardly dreamt of a decade ago (such as atom trapping)—and the beautiful mathematical apparatus of quantum theory, atomic

physicists are exploring a world of breathtaking discoveries.

The focus for this issue of *RLE currents* is research on fundamental atomic physics in RLE's Atomic, Molecular, and Optical (AMO) Physics group. Traditionally, atomic physics is concerned with the structure of atoms and how they interact with each other, with other particles, and with light. Much of the field continues to be occupied with these studies, and the fruits of this research are

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Director's Message

I want to thank everyone for helping to make the RLE 50th anniversary celebration such a grand success. We have received lots of very appreciative feedback, some of which is included in this issue. It's clear that the entire set of events reaffirmed the strength of RLE and that we are poised for a highly successful future. I enjoyed meeting many RLE alumni, including some who were here in 1946. The intellectual excitement combined with a good time socially was tremendously exhilarating. So a hearty thanks to everyone who made it happen.

For many years, RLE has been the MIT home for fundamental studies in atomic, molecular, and optical physics. This research continues to provide a great test bed for demonstrating and utilizing basic quantum-mechanical phenomena. Recently, new techniques have been developed to isolate individual atoms and ions in low-temperature magnetic traps, and to facilitate the demon-



Jonathan Allen, Director,
Research Laboratory of Electronics

stration of the Bose-Einstein condensate, which is a configuration of atoms all in a single quantum-mechanical state. This significant accomplishment opens up many new possibilities, such as an "atom laser." Certainly the ability to manipulate individual atoms in controlled environments makes this an exciting era for atomic physics, and we are pleased to highlight it in this issue.

ATOMIC PHYSICS AT RLE (continued)

eagerly consumed by other scientific disciplines, including molecular physics, astronomy, astrophysics, plasma physics, and atmospheric science. Beyond these pursuits, however, atomic physics has a tradition of crucial experiments that provide critical tests for new and established theories. These experiments also lead to the development of refined methods for precise observation. This tradition has animated atomic physics research at RLE since the laboratory's earliest days, and it is very much alive in RLE today.

EARLY ATOMIC PHYSICS RESEARCH IN RLE

Dr. Jerrold R. Zacharias, one of RLE's early investigators, pursued research in atomic physics in the 1950s and the 1960s. Dr. Zacharias was a pioneer in

the development of molecular-beam magnetic resonance under the direction of Nobel laureate I.I. Rabi. While applying the new resonance techniques to the study of atomic structure and nuclear properties, Dr. Zacharias became preoccupied with measuring the effect of gravity on time—the *gravitational red shift*. For this, he proposed to use the frequency of a microwave transition in cesium to control the frequency of an oscillator, creating what is known as an *atomic clock*. Although he was not alone in realizing this possibility, he had the unique vision to conceive of the device as a practical clock, rather than as a complex laboratory apparatus. Under his direction, a portable clock was built in MIT's Building 20. The result of this work was the first practical atomic clock, the Atomichron, which was built under Dr. Zacharias' supervision at the National Company in Malden, Massachusetts.

Since 1967 the International Commission on Weights and Measures

has defined the second in terms of the frequency of the hyperfine transition in cesium—the transition employed by Dr. Zacharias. Today, the cesium clock is used as the primary time standard in laboratories around the world. The latest version of the clock, housed at the National Institute of Standards and Technology in Gaithersburg, Maryland, has a stability that corresponds to approximately one second in a hundred million years.

In order to measure the gravitational red shift, Dr. Zacharias proposed a new type of atomic clock. It employed an *atomic fountain*, so named because the atoms shot up several meters in a vacuum and fell back under Earth's gravity. Although his fountain clock was not a success, a new generation of atomic clocks is now being constructed using his original principle. These new clocks use ultracold atoms and have fountains only a few centimeters high. Dr. Zacharias' goal to measure the gravitational red shift with an atomic clock was realized in 1979, when a hydrogen maser clock was carried aboard a NASA spacecraft.



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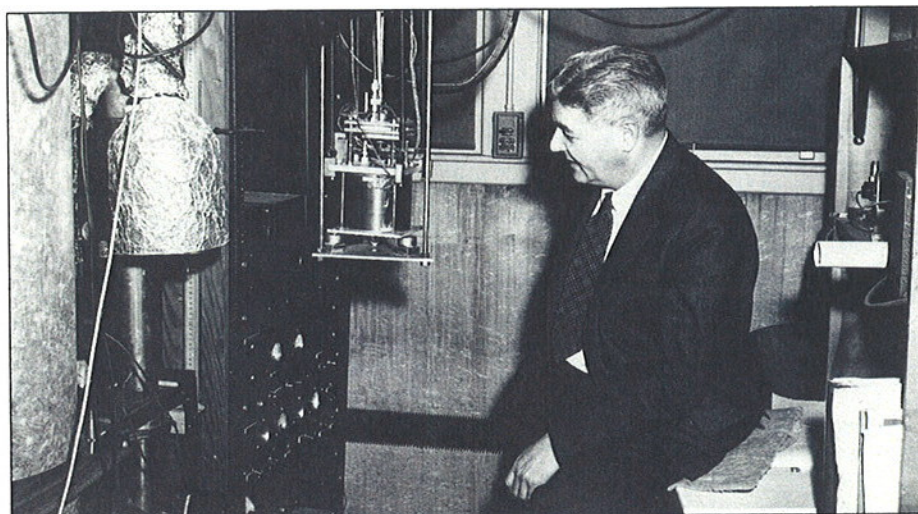
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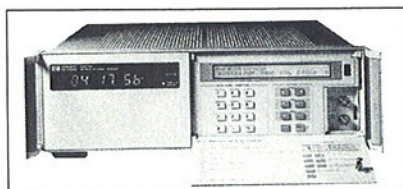
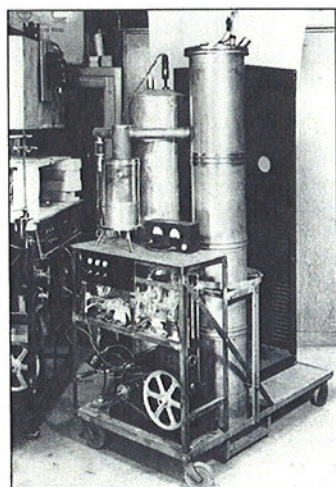
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When I.I. Rabi invented magnetic resonance at Columbia University in the late 1930s, important paths were opened to new science and to new technology. One application of magnetic resonance was the atomic clock, since the ability to measure the natural frequencies of atoms to very high precision made it possible to use these frequencies to control the clock's rate.



Dr. Jerrold R. Zacharias, who had participated with Rabi in his magnetic resonance experiments, set up an atomic beam laboratory at MIT shortly after RLE was started in 1946 and took the first steps towards making a practical atomic clock. He employed the separated oscillatory field technique invented by Norman F. Ramsey of Harvard University, who also had worked with Rabi. The National Company of Malden, Massachusetts, produced the first commercial atomic clock, the Atomichron, based on Dr. Zacharias' design. His clock is the progenitor of today's clocks, and the hyperfine transition of the cesium atom that he employed in the mid-1950s is used in today's primary time standards.



Counterclockwise from top: Dr. Zacharias checks the operation of an early experimental cesium clock; the portable atomic clock constructed by Dr. Zacharias in MIT's Building 20; and today's version of a cesium atomic clock, Hewlett-Packard's model HP5071A. Primary frequency and time standard devices like the HP5071A are used in observatories and research laboratories, in satellite tracking and communications, and in global positioning systems. (Photos courtesy MIT Museum and the Hewlett-Packard Company)

ATOMIC PHYSICS RESEARCH AT RLE TODAY

The World of Giant Atoms

Dr. Daniel Kleppner received his PhD from Harvard University where, in 1960, he co-invented the hydrogen maser with Dr. Norman F. Ramsey. In 1966, he became a member of RLE and MIT's Physics Department. His early RLE research included the determination of fundamental constants, tests of the relativistic theory of hydrogen, and atomic scattering, which included early experiments on the differential scattering of excited atoms. In the mid-1970s, he undertook pioneering experiments on *Rydberg atoms*, a principal theme that continues in his research today.

The Rydberg atom is named in honor of the Swedish spectroscopist Johannes Robert Rydberg (1854-1919), who found a formula for the spectral series of single-electron atoms. A Rydberg atom is any single-electron atom in a very high quantum state. The principal quantum number can be 100 or more. Since the diameter of the atom scale is the square of the number, a Rydberg atom is thousands of times larger than an ordinary atom. Rydberg atoms were discovered by radio astronomers in the mid-1960s. In astrophysical environments, they are formed when free electrons recombine with protons to form hydrogen atoms. As the atoms radiatively cascade from state to state, they emit the microwave radiation by which they were first identified.

With the development of laser techniques, it became possible to create these atoms in the laboratory. By shining light from two or more lasers on an atom, often an alkali metal atom such as sodium or cesium, the atom is excited to an intermediate state and then to the Rydberg state. Rydberg atoms can be ionized in an applied field and be detected with almost 100 percent efficiency. The atoms are detected by ionizing them in an electric field and then detecting individual charged particles. The method is so sensitive that experiments can be done with single atoms.

New research that has emerged from Rydberg atom studies includes: atom-field interactions, the dynamics of ionization, radiation phenomena, quantum optics (including the field now called *cavity quantum electrodynamics*), atomic and molecular scattering, electron correlation and other structural effects, the connections between classical and

Atomic physicists often pioneer experimental techniques so novel that their applications simply cannot be predicted. Dr. Zacharias' pursuit of general relativity (arguably one of the most fundamental but least practical of all pursuits) not only produced new techniques for precision measurements, but it also helped to create a burgeoning technology that was totally unforeseen. In the early days of the atomic clock, no one

could have guessed that it would become the heart of today's global positioning system. This new technology, which is playing a pivotal role in applications for navigation, tracking, surveying, and geodesy, is already a multibillion-dollar venture. Today in RLE, other new technologies continue to be developed. Experience has shown, as with the atomic clock, that it would be rash to predict their eventual applications.

TOOLS OF THE TRADE

Some experimental techniques used in atomic physics are descendants from the early years of modern physics. Others are so novel that they were hardly dreamt of a few short years ago. Here, we describe several of these tools, some old, some new.

Spectroscopy

In the late 19th century, the wavelengths of the spectral lines absorbed and emitted by atoms were cataloged with little understanding of their origin. Theoretical interpretation of the spectra became possible with the development of quantum mechanics, and scientists can now relate the spectra to the detailed structure of atoms. Spectroscopy has always been a high-precision art; even in its early days, wavelengths could be measured to one part in ten thousand. The creation of the laser led to new spectroscopic techniques with extremely high precision. One part in ten million is now routine, and one part per billion is possible with a little more work. The frontier of spectroscopy is currently at one part in a trillion, and a thousand-fold increase is within sight.

Interferometry

Interferometry is a specialized spectroscopic technique that can reveal

the structure of complex spectral lines or can be used to measure small changes in the optical properties of matter. Probably the best known interferometer is the Michelson interferometer. It was invented in the 1880s by physicist Alan A. Michelson in his attempt to detect the Earth's motion through the *ether*; the hypothetical medium then believed to carry electromagnetic waves. His failure to uncover this mystery is explained by Einstein's special theory of relativity. Michelson's experiment was hardly a failure, however, for it showed how to measure length with the precision of a fraction of a wavelength of light. This technique was approximately a thousand times better than any other available means at that time. Among the fruits of this work was the commercial production of precise Jo blocks, which are essential for mass production machining.

Today, a new type of interferometry is being developed that uses matter waves instead of light waves. It can provide detailed information about interactions between atoms and can be used to study some of the most fundamental aspects of quantum behavior. Although the resolution of a matter-wave interferometer is much higher than that of an optical interferometer, it can only be used in

highly specialized situations. In future applications, the matter-wave interferometer may find use as a highly sensitive gyroscope.

Atom Cooling and Trapping

Thermal motion in atoms is an impediment to precise observation. To abate this problem, an apparatus is sometimes cooled to the liquid-helium temperature regime, which is a few degrees above absolute zero. However, techniques have been developed recently for cooling atoms to a few millionths of a degree above absolute zero, and even colder, by using light from lasers. These low-temperature atoms can be confined with various combinations of optical and magnetic fields in devices known as *atom traps*, and can be studied with phenomenal precision. This has opened the way to new types of ultraprecise measurement and to the study of matter in a new energy regime where many familiar properties are transformed. Among the most spectacular developments realized from these techniques is the recent achievement of Bose-Einstein condensation in an atomic gas (see article on page 7).

by Dorothy A. Fleischer and
Daniel Kleppner

quantum behavior (called *quantum chaos*), and the determination of fundamental constants.

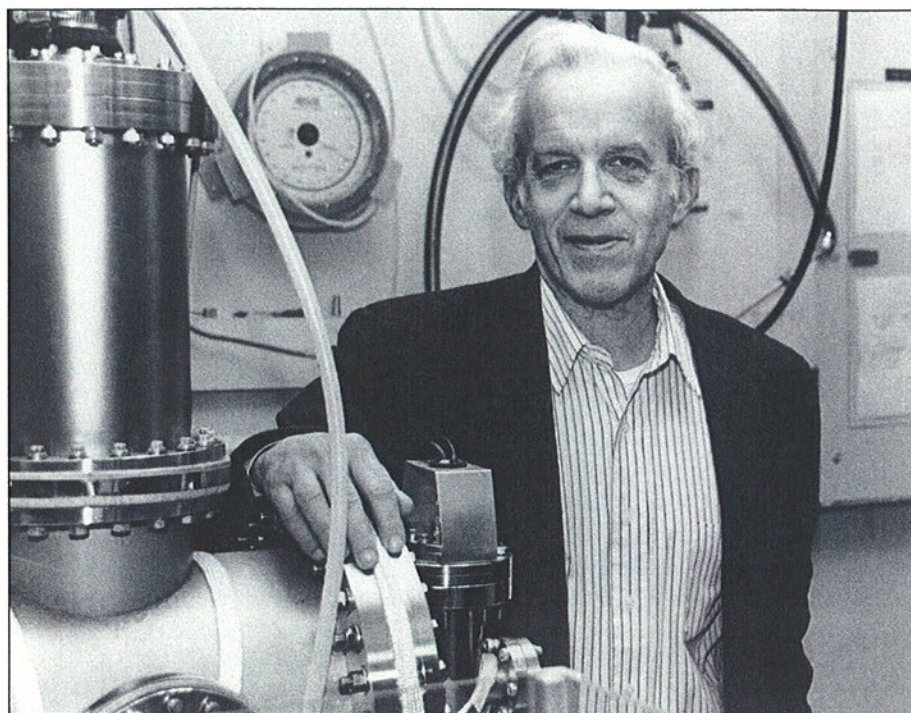
Early research by Professor Kleppner and his group involved studies of Rydberg atom structure in electric and magnetic fields, as well as the atom's ionization properties. This basic knowledge is required for essentially all Rydberg atom experiments. One outcome of their work was a novel quantum optics experiment. All excited atoms, including Rydberg atoms, eventually radiate their energy and fall into the ground state. This process, called *spontaneous emission*, was considered to be a fundamental property of atoms. It is important not only because it is the mechanism by which nearly all radiation

in the universe is generated, but also because it is the ultimate source of noise in quantum devices. With Rydberg atoms, however, it is possible to turn off spontaneous emission by putting the atoms in a cavity-like structure. By demonstrating the suppression of spontaneous emission, Professor Kleppner's group carried out one of the seminal experiments in cavity quantum electrodynamics.

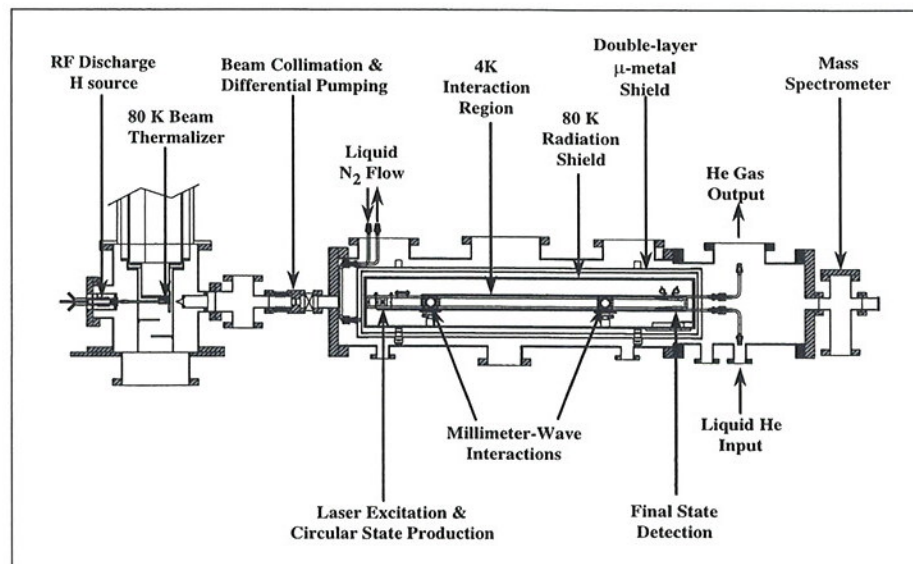
A typical problem for students of quantum mechanics is to find the effect of an electric field on a hydrogen atom. This is one of the few problems in quantum physics with an exact solution. In contrast, the effect of a *magnetic* field on hydrogen not only lacks an exact solution, but is unexpectedly complicated.

The approximation methods used to solve similar quantum-mechanical problems do not work. Experimental studies of this problem, however, revealed a complex structure in which there appeared to be underlying regularities. Stimulated by these observations, several theoretical groups developed new methods to calculate the spectra, and these have proven useful in other scenarios. It was also recognized that the classical motion of an electron around a proton in a magnetic field could display a transition to chaos. This introduced a new direction in Rydberg atom research: spectroscopic studies of quantum chaos.

According to Bohr's correspondence principle, which states that quantum mechanics has a classical limit equivalent



Dr. Daniel Kleppner, Lester Wolfe Professor of Physics and RLE's Associate Director, studies atomic structure, light-matter interactions, and quantum optics. His current research includes the structures of atoms in strong fields, the connections between quantum mechanics and nonlinear dynamics, ultrahigh-resolution laser spectroscopy, and the measurement of fundamental constants. (Photo by John F. Cook)



Professor Daniel Kleppner's group has brought into operation a new generation of apparatus for measuring the Rydberg frequency, one of the fundamental constants. Using millimeter-wave spectroscopy between Rydberg states of hydrogen, this technique differs from previous methods because no optical measurements are involved and the frequency is measured directly in terms of an atomic clock. Because it employs circular states, the measurement is free from uncertainties due to relativistic effects and quantum electrodynamic energy shifts. The apparatus includes: a low-temperature atomic hydrogen source, a laser system for creating the Rydberg atoms, a circularizer, a millimeter-wave source, a cryogenically cooled and magnetically shielded interaction region, a selective field ionization atom detector, and a data acquisition system.

to that of classical mechanics, classical-like behavior can be observed in the quantum properties of a system in the regimes of very large quantum numbers. Rydberg atoms, which exist in this regime, are a natural testing ground for the connections between quantum and classical mechanics. However, the connections are elusive when the classical motion is chaotic. Rydberg atom spectroscopy has deepened the understanding of this problem. For example, it is now possible to detect the onset of classical chaos by studying the quantum spectrum, to observe the existence of periodic orbits, and to witness the growth of new periodic orbits as the system's energy is varied.

Another topic pursued by Professor Kleppner and his students is the determination of the *Rydberg constant*. This fundamental constant relates the natural atomic unit of length with the unit of length used for laboratory measurements. In addition, it is used to interpret many other fundamental constants. Traditionally, the Rydberg constant has been determined by optical and ultraviolet spectroscopy on atomic hydrogen. At RLE, it is being measured by millimeter-wave spectroscopy between Rydberg states of hydrogen. (See illustration at left.) This method of measurement is fundamentally different from previous measurements because the frequency is compared directly with that of an atomic clock. Furthermore, since Professor Kleppner's experiment employs *circular* states (in which an electron behaves like a particle moving in a circle, rather than in an elliptical path passing close to the nucleus), the measurement is free from uncertainties due to relativistic effects and quantum electrodynamic energy shifts. Because the transition's frequency is measured directly in terms of an atomic frequency standard, it provides an absolute frequency calibration for the entire hydrogen spectrum.

Precision Instrumentation

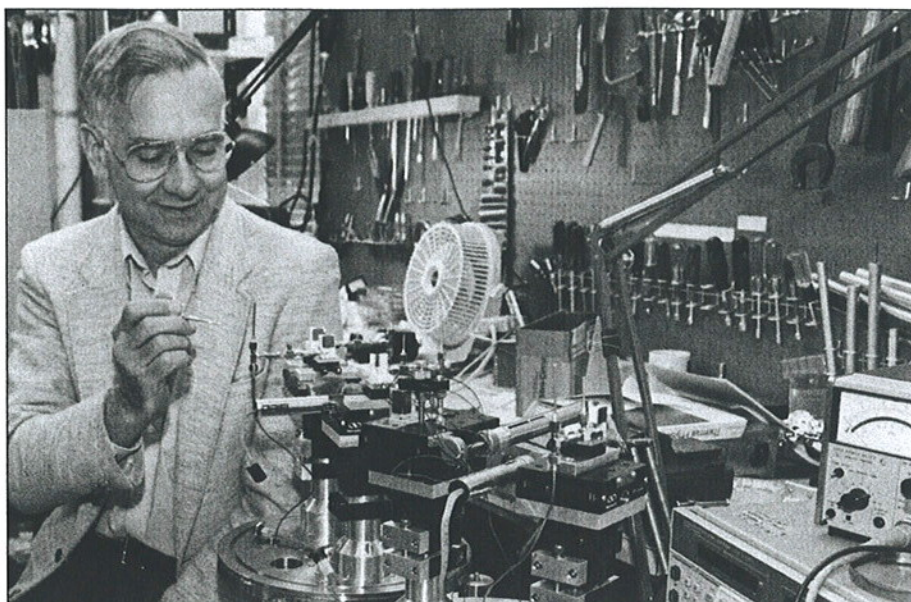
Dr. David E. Pritchard joined RLE as a postdoctoral fellow in 1968 and was appointed to the MIT physics faculty in 1970. His broad range of research includes atom-molecule collisions, matter-wave diffraction, the trapping and cooling of atoms, and ultraprecise mass spectroscopy. He has discovered and explained various scaling laws for energy transfer collisions in molecules. In addition, he has invented two traps,

including the magneto-optical trap, that have become workhorses of the cold-atom community. Recently, he has developed an atom interferometer that is being applied to numerous scientific problems (see illustration below). In advancing fundamental *metrology* (the science of measurement) and physics, he has also performed super-accurate mass measurements on a single trapped ion.

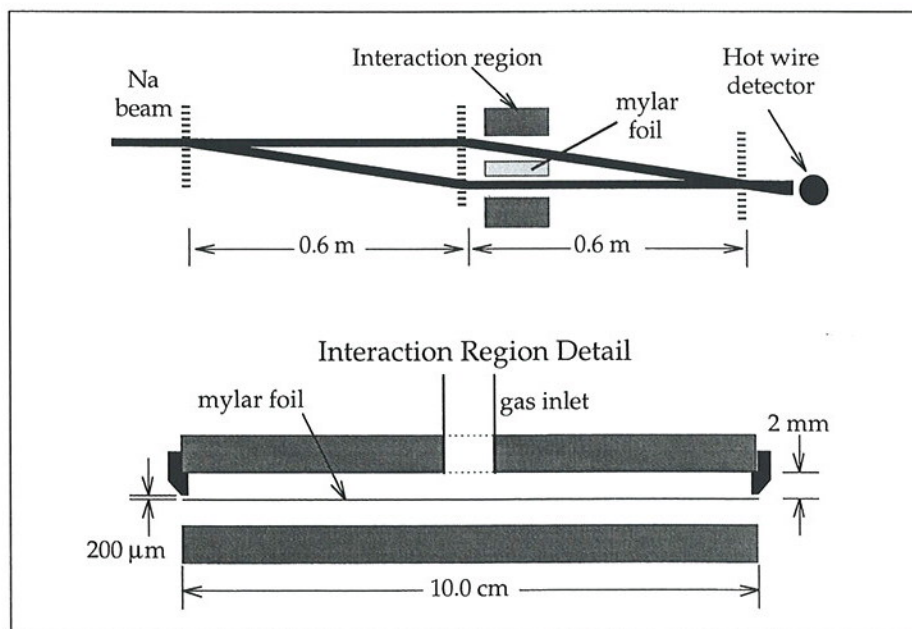
Professor Pritchard and his colleagues pioneered the field of *atom optics* in the mid-1980s, demonstrating diffraction gratings based on the wave-like nature of atoms. His group exploited the quantum duality between light and matter by passing atoms through a standing wave of light (which they called a *light grating*), and demonstrated that these functioned like the *phase gratings* used in optics. These light gratings had slits 100 nanometers wide—so small and tightly spaced that each atom wave passed through several slits simultaneously and diffracted in several discrete directions. In 1988, they demonstrated that the gold transmission gratings made in RLE's Submicron Structures Laboratory by Professor Henry I. Smith and Dr. Mark L. Schattenburg functioned like amplitude gratings in optics, which also diffracted the atom waves in several discrete directions.

In 1991, his group made the first *atom interferometer* by passing atom waves through three equally spaced matter gratings. These were arranged so that two diffracted beams from the first grating were then diffracted by the second grating and came back together at the site of the third grating. These two components of the atom's wave combined to create an interference pattern similar to interfering light waves. Alternating bands of intensity called *interference fringes* were produced where the atom waves either canceled or reinforced each other. Subsequent improvements of the gratings (now made of silicon nitride membranes at Cornell University's National Nanofabrication Laboratory) were needed to produce an atom interferometer in which metal foil separated the two halves of the atom wave.

In 1995, Professor Pritchard's group measured the shift of interference patterns that resulted when a sodium wave on one side of the interferometer passed through an electric field. This measurement led to an order of magnitude improvement in the value for sodium's polarizability. In a subsequent experi-



Dr. David E. Pritchard, Professor of Physics and principal investigator in RLE's Atomic, Molecular, and Optical Physics group, points out unique features on the atom interferometer designed by his group for neutral atoms. It uses nanofabricated gratings to split, redirect, and recombine atom waves in order to produce interference fringes upon recombination. (Photo by John F. Cook)



A series of three diffraction gratings is used to split and recombine atoms in the sodium atom interferometer developed by Professor David E. Pritchard and his colleagues. The vertical dashed lines in the schematic represent 200-nanometer period diffraction gratings. The first grating splits the incident de Broglie wave into two wave components. The middle grating then redirects the two separated components to a point on the third grating, where they are recombined to form interference fringes. The sinusoidal position of the fringe intensity is measured by repositioning the third grating parallel to the grating. A movable hot wire detector maps the fringe pattern of the atoms. The detail of the interaction region shows the 10-micron mylar foil suspended between the side plates. Using their atom interferometer to exploit the wave nature of atoms, Professor Pritchard's group has measured the susceptibility of sodium atoms to electric fields and the degree to which atom waves are refracted as they pass through another gas.

ment, the atom wave on one side passed through a cell filled with various gases, thus enabling the first measurement of the index of a gas's refraction for matter waves.

More recently, a *Gedanken experiment* (a hypothetical experiment) proposed more than thirty years ago by physicist Richard P. Feynman to explore the wave-particle duality was demonstrated by Professor Pritchard's group. A single photon of laser light was scattered from each atom passing through the interferometer. In principle, this could be used to determine the position of the atom passing through the interferometer. Simultaneously, the amount of *interference structure*, which is an indi-

cator of the atom's wave-like behavior, was monitored. As Feynman had predicted, interference fringes were observed when the atom's two possible paths were separated by a distance less than half the photon's wavelength. In this situation, the position measurement lacked the resolution needed to determine which path the atom took through the interferometer. The interference pattern disappeared when the path separation exceeded half the laser's wavelength. Surprisingly, it partially reappeared at several locations when the separation exceeded half the wavelength. These reappearances were attributed to diffraction rings that arose in imaging the atom and caused uncertainty in identifying the

atom's path. Thus the *principle of complementarity* was confirmed: it is impossible to simultaneously observe particle-like behavior (the path taken) and wave-like behavior. Extending these ideas, it was demonstrated that the lost interference pattern could be regained by observing only atoms that scattered light in a particular direction.

Professor Pritchard and his colleagues recently suspended an atom interferometer from a wire and used it to measure rotations as slow as a quarter of a degree per hour. When an atom interferometer is rotated, one atom beam's path is shortened while the other is lengthened. The resulting phase difference observed in the interference pattern

BOSE-EINSTEIN CONDENSATE: WHAT DOES IT MATTER?

In 1924, after having his paper on blackbody radiation rejected for publication, Indian physicist Satyendra Nath Bose mailed it to Albert Einstein. In his paper, Bose no longer assumed statistical independence of particles, as in classical statistics. Instead, he put the particles into cells and proposed the statistical independence of the cells. Einstein recognized the importance of Bose's work and arranged to have the paper published.

At that time, it was known that when a gas is cooled and the velocity of its atoms decreased, the position of the atoms becomes less certain due to Heisenberg's Uncertainty Principle. Quantum mechanics describes atoms as wave packets and, at low temperatures, the wave packets expand. Einstein combined the quantum-mechanical description of atoms with Bose's statistical treatment. The theory had a surprising result: below a certain temperature (when the wave packets of the atoms overlap), a macroscopic fraction of the atoms would condense into the lowest quantum state where the atoms are virtually motionless. Almost all the atoms would form one big entity—a giant matter wave—now called a *Bose-Einstein condensate*.

Bose-Einstein condensation (BEC) is possible for all particles for which there is no restriction on the

number of particles that may exist in the same state simultaneously. British physicist Paul Dirac coined the term "boson" (in honor of S.N. Bose) to describe such particles. Bosons are particles having integer spin. These include photons, pi mesons, and all nuclei that have an even number of neutrons and protons. They obey Bose-Einstein statistics. In contrast, fermions, which are the other class of particles known to exist in nature, have half-integer spin. They are governed by Fermi-Dirac statistics and follow the Pauli exclusion principle, which states that no two fermions of the same kind can occupy the same quantum state.

The realization of BEC in a dilute atomic gas became an elusive scientific search in the decades since its prediction, and was sometimes called the Holy Grail of atomic physics. In 1995, after the development of methods to cool atomic gases below a one-millionth of a degree above absolute zero, BEC was finally demonstrated. To date, three systems of bosonic alkali atoms have been cooled into this new state of matter—rubidium, lithium, and sodium. In June 1995, Eric A. Cornell (PhD '90), Carl E. Wieman (SB '73), and coworkers at the National Institute of Standards and Technology and the University of Colorado created the first BEC in a

dilute gas of rubidium atoms. In September 1995, Wolfgang Ketterle and his colleagues at RLE succeeded by using sodium atoms. Randall G. Hulet (PhD '84) and his group at Rice University cooled lithium atoms to the BEC transition in July 1995, and observed BEC the following year. An interesting footnote to all these BEC successes is that physicists Cornell, Wieman, and Hulet are MIT alumni and were students in RLE's Atomic, Molecular, and Optical Physics group.

Recently, Professor Ketterle's research group in RLE extracted a beam of atoms from the BEC and showed their coherence. This wavelike atom beam has properties similar to an optical laser beam, and it was dubbed an atom laser. Efforts are underway to develop a more powerful and practical coherent source of atoms.

Continuing studies of BEC attempt to identify the further remarkable properties of this degenerate quantum gas, including superfluidity. Already having served as the stepping stone to the atom laser, BEC promises to be an important tool for science. In the future, BEC may have an impact on the development of ultrasensitive measuring devices, more precise atomic clocks and global positioning navigation systems, atom nanolithography, and quantum computation.
by Dorothy A. Fleischer

indicates how much the interferometer has been rotated as the atoms pass through it. This type of rotation shift occurs in all interferometers. It is the scientific basis for fiber and laser gyroscopes, which are essentially rotating interferometers that use light. Measuring such small rotations has given the atom interferometer one of its first promising commercial applications as a replacement for optical interferometers used in highly accurate inertial navigation systems.

The group has also built the world's most accurate mass spectrometer. This advance was made possible by the development of a current sensor composed of superconducting electronics and a *superconducting quantum interference device* (SQUID) so sensitive that the current from a single trapped ion can be measured. Not only does single-ion sensitivity represent three orders of mag-

nitude improvement in the state of the art, but it also eliminates the errors in the mass that result from perturbation by other ions in the trap. This allows accuracies of one part in ten billion to be achieved. The group's recent measurements open the way for the artifact kilogram mass standard to be replaced by another standard based on a perfect silicon crystal with a definition of Avogadro's number (the number of molecules in the gram-molecular weight of a substance). Another result was the improvement of the gamma-ray wavelength standard. This was achieved by measuring the mass difference in a nuclear reaction and applying $E=mc^2$ in order to determine the gamma-ray energy. Further developments may allow the binding energy of ionic molecules to be determined by measuring the mass difference between the molecule and its constituents.

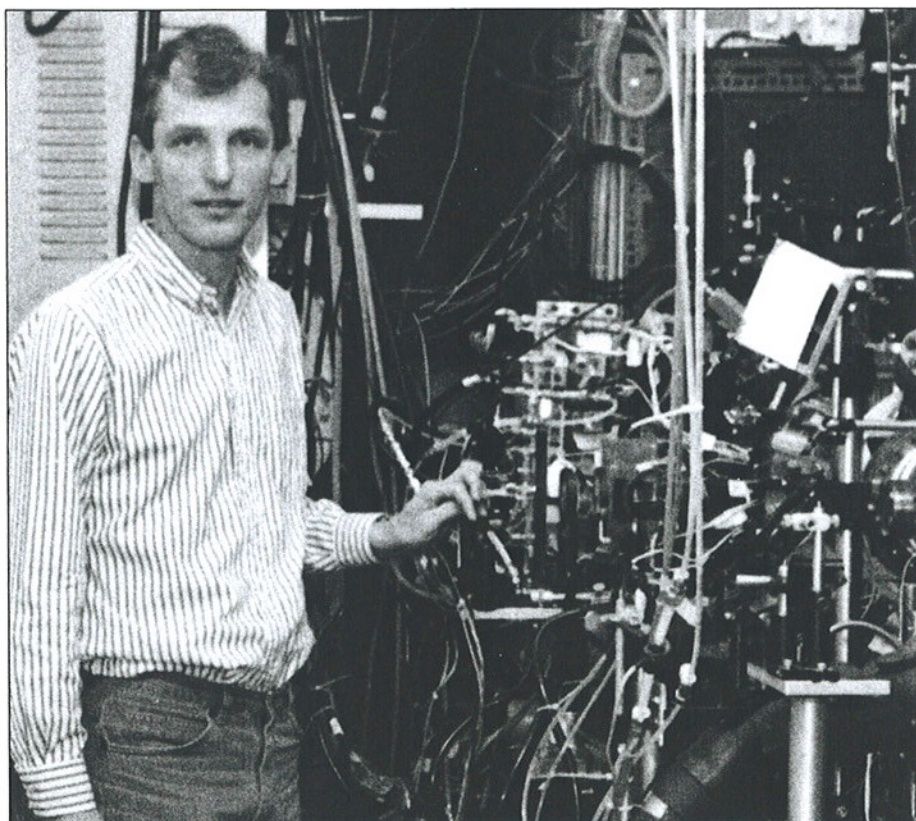
Ultracold Atoms

Dr. Wolfgang Ketterle came to RLE in 1990 to work with Professor David Pritchard on cold atom sources. With Professor Pritchard, he developed a new type of atom trap called the *dark SPOT* (spontaneous optical trap), which provided higher densities than previously possible. Dr. Ketterle joined MIT's Department of Physics in 1993 and, building on his work with Professor Pritchard, has gone on to study the novel properties of ultracold neutral atoms at high densities.

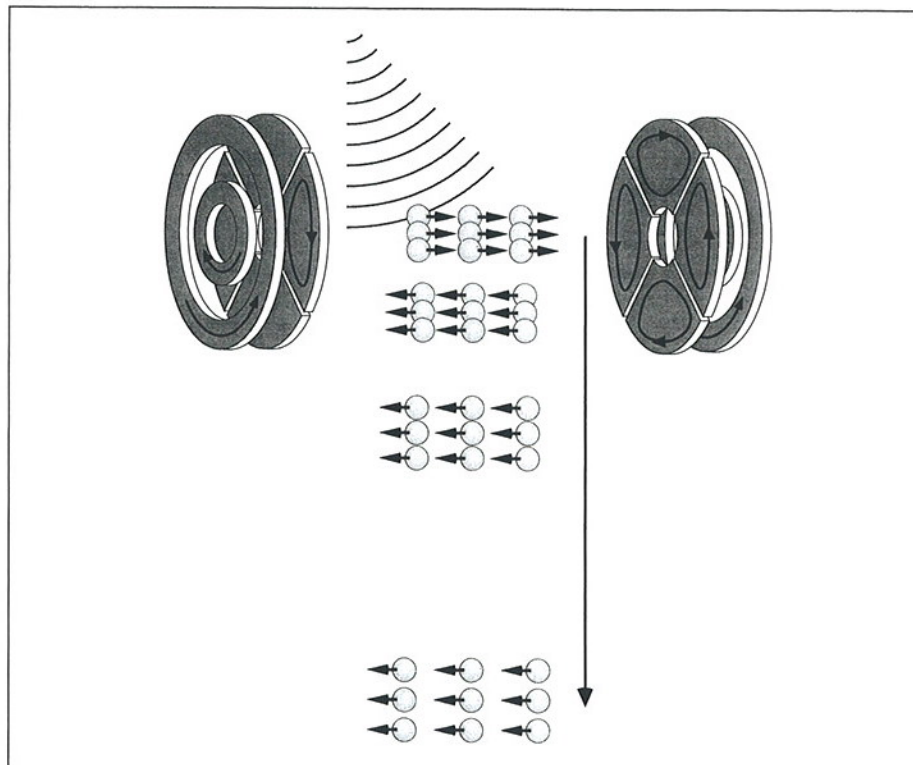
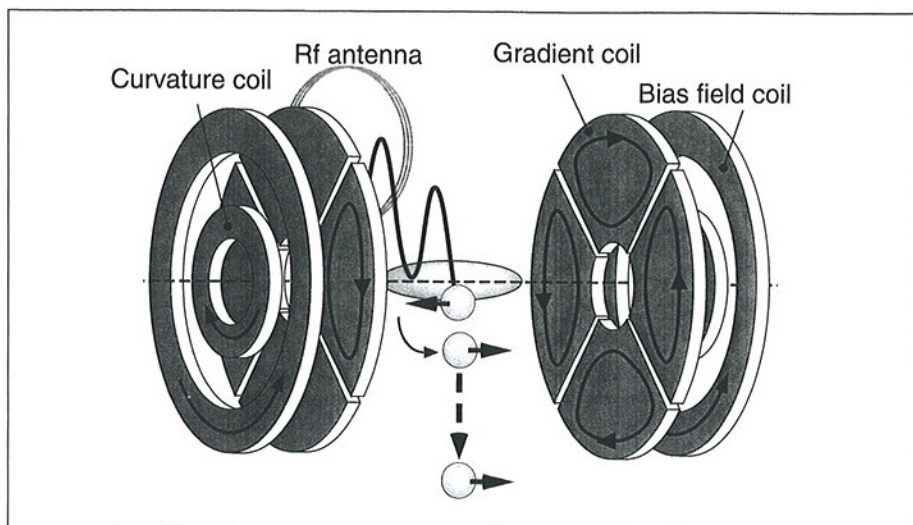
Professor Ketterle's group is particularly interested in quantum-statistical effects such as Bose-Einstein condensation (see article on page 7). Among the first groups to observe BEC in September 1995, Professor Ketterle and his colleagues have used their Bose-condensed samples to create a source of coherent matter waves and demonstrated the first atom laser in 1996. They now employ several different techniques to obtain the dense atom samples needed for their experiments: slow atomic beams, laser cooling, evaporative cooling, and magnetic and spontaneous light-force traps. The group's achievement of record sample sizes for Bose condensates and their development of novel imaging methods allow them to study and manipulate this phenomenon with extraordinary facility.

The group's first BEC demonstration employed a spherical quadrupole trap to confine the atoms. Since the magnetic field vanishes at the center of this trap, the atoms passing through lose their magnetic alignment, flip their magnetic moments (or spin), and are lost. This process was suppressed by repelling atoms from the center of the trap using a focused, far-off resonant laser beam called an *optical plug*. Another combination of optical and magnetic forces was used to create the condensates in a double-well potential. Following their observation of BEC, a new magnetic trap was designed with an eight-coil cloverleaf design. (See illustration on page 9.) This cloverleaf trap avoids the trap loss problem and has ideal properties for studying and manipulating Bose-Einstein condensates.

The observation of BEC has generated wide theoretical interest in understanding the properties of this unusual system. Among the mysteries being pursued are the superfluid properties of the condensate, the interactions of condensed atoms with light, the role of coherence in this new atomic system,



Dr. Wolfgang Ketterle, Professor of Physics and principal investigator in RLE's Atomic, Molecular, and Optical Physics group, conducts experiments on ultracold neutral atoms at high densities, where novel phenomena in collisions, light scattering, and quantum statistics are studied. Professor Ketterle is flanked by the vacuum chamber used to trap, cool, and Bose-condense sodium atoms. His group's recent observation of Bose-Einstein condensation offers the unique opportunity to explore the properties of coherent atoms and to study macroscopic quantum phenomena that can be described from first principles. (Photo by John F. Cook)



These experimental setups were designed in Professor Wolfgang Ketterle's group to cool atoms to Bose-Einstein condensation and generate a coherent, propagating beam of atomic matter waves.

Top: After being pre-cooled in an optical trap, a cloud of sodium atoms is transferred to a magnetic trap created by six magnetic coils in a cloverleaf configuration. Evaporative cooling, controlled by radio-frequency (RF) radiation from an antenna, is used to further cool the atoms. RF radiation forces the most energetic atoms to flip their spins and puts them in a state not confined by the magnetic fields. As these atoms fall out of the trap, they take energy with them, and the temperature of the remaining atoms is decreased.

Bottom: Using RF radiation, atoms can be coupled out of the magnetic trap in a controlled way. This output coupler for Bose-condensed atoms employs a short burst of radio waves that causes some atoms to flip their spins and leave the trap. By varying the intensity and duration of the RF burst the percentage of atoms coupled out of the condensate can be controlled continuously from 0 to 100 percent.

and interactions between separate condensates.

Dispersive imaging methods were devised by the group to take pictures of the Bose-condensed atoms without disturbing them. These methods enabled real-time observations of the dynamics of a macroscopic quantum system and are now used to study sound propagation and condensate formation. Collective excitations in the Bose condensate, formed by modulating the magnetic trapping potential, have also been studied with these techniques. The characteristic frequencies observed were in good agreement with the values predicted by theory.

Professor Ketterle's group realized an *output coupler* for a Bose condensate that allows the controlled extraction of atom pulses from a magnetically trapped cloud. In this output coupler, radio waves are used to flip the spin of the trapped atoms, which put them into untrapped states. (See illustration at left.)

Matter-wave interference was observed between the outputs of two Bose condensates that were created independently in a double-well potential. The detection of an interference pattern provided the evidence needed to prove that the Bose condensates are coherent.

By using their Bose-condensed samples to create a source of coherent matter waves, Professor Ketterle and his colleagues demonstrated the operation of an atom laser. This device emits atoms with properties closely analogous to the photons emitted from a laser.

There are many potential applications for atom lasers, though they are far from being realized. However, atom laser sources may replace conventional atomic beams in demanding applications such as atom interferometry, precision measurements, new atomic clocks, and the creation of microscopic structures by direct-write lithography.

by Dorothy A. Fleischer and
Daniel Kleppner

Further information on RLE's Atomic, Molecular, and Optical Physics group may be obtained by browsing the following Worldwide Web pages on the Internet:

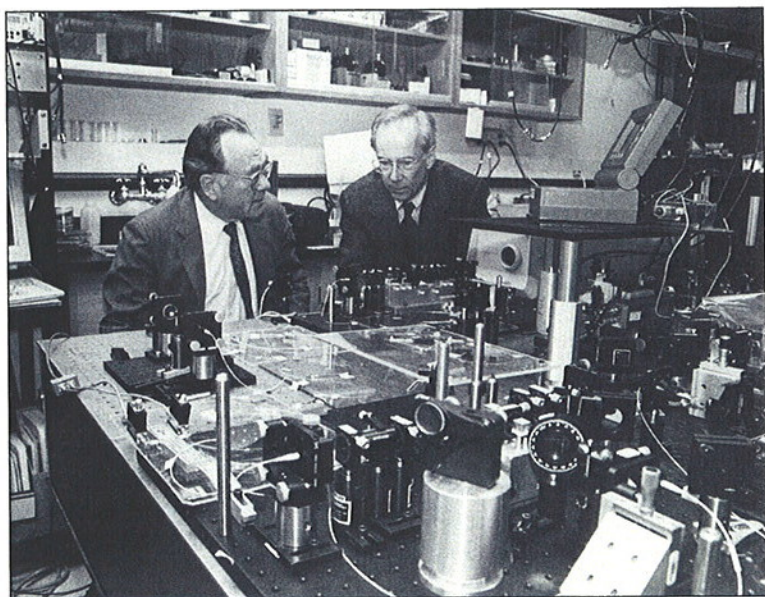
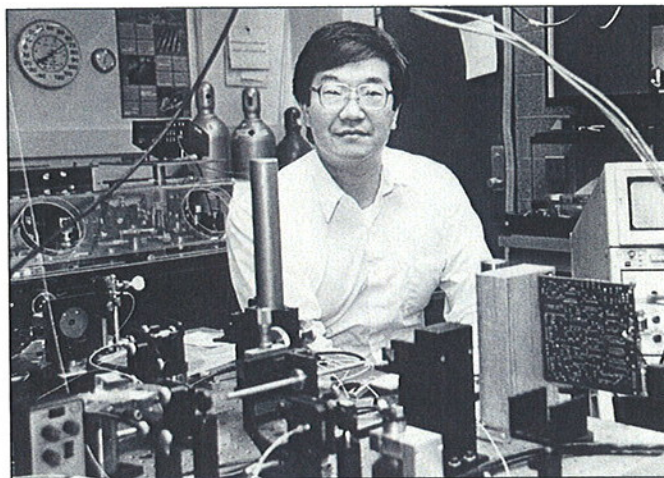
<http://amo.mit.edu>
<http://rleweb.mit.edu/g-AMO.htm>

RLE CONNECTIONS

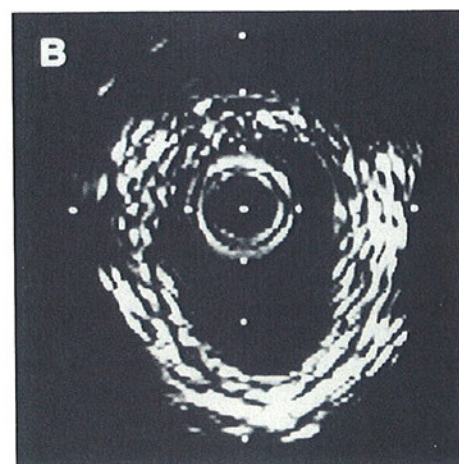
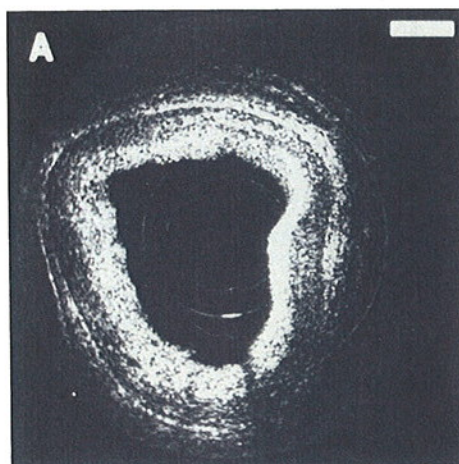
Lasers are an indispensable scientific tool used in virtually every RLE research group. Several groups in RLE not only use lasers and optical techniques in their investigations, but they also design and construct new types of lasers for specific applications.

Professor James G. Fujimoto's group has invented and developed optical coherence tomography (OCT), a new medical imaging technology that allows high-resolution cross-sectional imaging of tissue microstructure. OCT is similar to ultrasound or radar imaging (see below), except it uses light to provide improved micron-scale resolution. Recently, the group has developed an OCT system based on femtosecond lasers to perform high-speed, real-time catheter-endoscope imaging.

(Photo by John F. Cook)



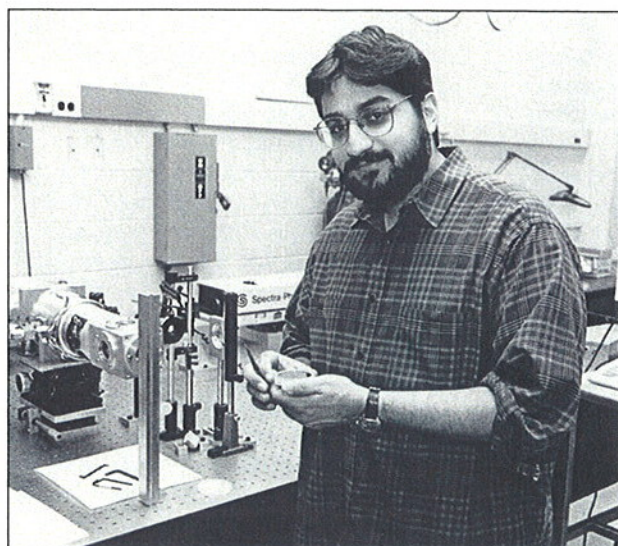
The state-of-the-art femtosecond laser systems developed in Professor Hermann A. Haus' (left) and Professor Erich P. Ippen's groups are used to characterize the next generation of high-speed photonic devices. The ultrashort optical pulses generated by these systems enable the study of ultrafast dynamics in electronic materials, semiconductor nanostructures, and nonlinear optical waveguides. New ultrashort-pulse optical fiber lasers, recently demonstrated in Professors Haus' and Ippen's groups, are being used to investigate optical switching and pulse transmission in ultrahigh-speed fiber networks. (Photo by John F. Cook)



A comparison of imaging performed in vitro by OCT (A) and standard intravascular ultrasound (B) shows intimal hyperplasia in a human coronary artery. The improved resolution achieved by OCT permits clearer imaging of arterial pathology.

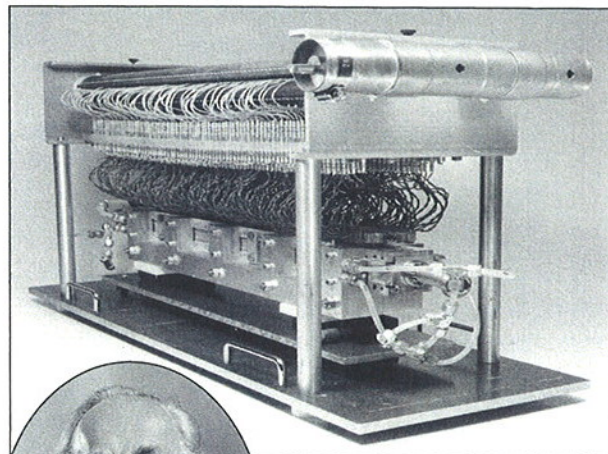


Quantum optics and photonics are the focus of Professor Shaoul Ezekiel's research in RLE's Atomic, Molecular, and Optical Physics group. His experimental setups use laser-induced atom interferometry for nanolithography applications in next-generation microprocessors. From left: Postdoctoral Fellow Dr. Timothy T. Grove, Research Assistant Darren S. Hsiung, Visiting Scientist Dr. Xiao-Wei Xia, Research Scientist Dr. Selim M. Shabriar, and Professor Shaoul Ezekiel. (Photo by John F. Cook)



Professor Rajeev J. Ram of RLE's Optics and Devices group holds a gallium arsenide microcavity laser. The semiconductor microcavity contains polaritons, which are strongly coupled electron-hole pairs and photons. Polaritons are excellent candidates for matter lasers in semiconducting media.

(Photo by John F. Cook)



In free-electron lasers, the generation of light using electron beams with moderate energies requires very short-period magnetic wigglers. A novel pulsed "microwiggler" was designed and constructed in RLE's Plasma Physics

group under the direction of the late Professor George Bekefi (inset). Each half-period of the microwiggler is individually adjustable. Through a novel tuning regimen, the world's most uniform periodic field for subcentimeter-period wigglers was implemented, making the MIT Microwiggler a unique tool for free-electron laser research. (Photos by John F. Cook)

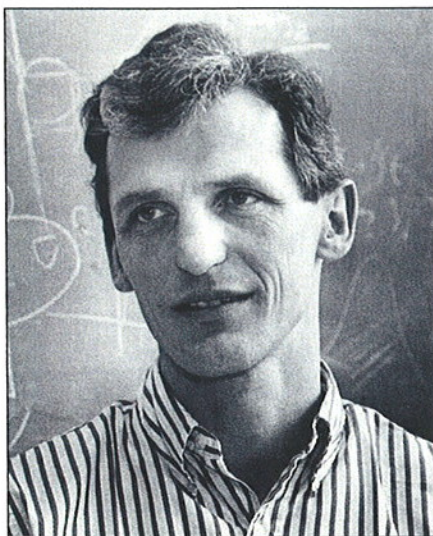
FACULTY PROFILE:

Wolfgang Ketterle

Wolfgang Ketterle received his diploma thesis (master's equivalent) from the Technical University of Munich in 1982, working on theoretical solid-state physics. Under the direction of Professor Herbert Walther at the University of Munich, he received his PhD in 1986, studying experimental molecular spectroscopy. His postdoctoral work included laser spectroscopy of molecules at the Max-Planck Institute for Quantum Optics in Garching and combustion diagnostics in Heidelberg. In 1990, he joined Professor David Pritchard's group in RLE as a postdoctoral associate. Dr. Ketterle was appointed to the MIT faculty in the Department of Physics as an assistant professor in 1993, and his promotion to full professor was recently announced.

The focus of Professor Ketterle's previous research in Germany was the spectroscopy of two small molecules, triatomic hydrogen (H_3) and helium hydride (HeH). He was the first to observe the discrete spectra of HeH , which gave final evidence for the existence of this molecule. At MIT, Professor Ketterle's research has focused on atomic physics and laser spectroscopy. His initial work with Professor David E. Pritchard in RLE's Atomic, Molecular, and Optical Physics group included the first use of isotropic light to slow and cool atoms, and the development of the dark SPOT (spontaneous force optical trap). This new magneto-optical trap greatly improved the density of trapped atoms. It is now a standard technique used in many laboratories and a key to achieving Bose-Einstein condensation (BEC).

Today, Professor Ketterle's group in RLE develops novel methods to slow, cool, and trap atoms in order to investigate the fascinating properties of ultracold atomic matter. The group's observation of the Bose-Einstein condensate in September 1995 was only the second



Professor Wolfgang Ketterle

(Photo by John F. Cook)

demonstration of this quantum phenomenon. As a direct result of this work, they demonstrated the first atom laser in November 1996. The group continues to study the properties of the Bose condensate, and to work towards the development of a practical, more powerful atom laser.

A member of both the American and German physical societies, Professor Ketterle was named corecipient of the 1997 American Physical Society's Rabi Prize. He was cited for achieving Bose-Einstein condensation of an atomic gas, creating techniques to study the Bose condensate, and measuring the physical properties of the weakly interacting atomic Bose gas. Professor Ketterle was also awarded the 1997 German Physical Society's Gustav-Hertz Prize, a 1996 David and Lucile Packard Fellowship, and MIT's 1994 Michael and Philip Platzman Award for emerging leadership in the field of laser cooling and trapping of atoms at high density.

•What attracted you to atomic physics?

Actually, I've changed my field a few times. I started in theoretical physics, working in condensed matter and statistical physics. Then, I was attracted to experimental physics because of the potential to apply experimental techniques to "the real world." I chose laser physics and started out in molecular

spectroscopy. My early work with Professor Walther in Garching used molecular spectroscopy to understand the basic properties of simple molecules, whereas my molecular spectroscopy work in Heidelberg was applied to the study of combustion processes. Our goal there was not to learn about molecules, but to learn about their environment, which were combustion processes. This work fascinated me, and it gave me a special form of satisfaction when I applied my knowledge of fundamental physics to real-world problems. In applied work, you don't need to ask yourself what the work is good for because there's an immediate goal.

I left applied physics because I missed the challenge of working in a freer environment where I could define the goals of my research. In fundamental research, you're at the frontier of your field, and you try to find the point where you can make advances. You don't follow a clear line, and if you find an obstacle, it's best to go around it. However, in applied research, you have a goal that you need to accomplish, and if there are obstacles, you must fight them. So applied and fundamental research are different in terms of their goals and approaches to the work.

When I decided to return to fundamental research, I looked for promising directions. I was already well advanced in my career (I was 32), so I picked an area that overlapped with my expertise in laser physics and spectroscopy. Laser cooling and trapping seemed to be the most fascinating work where I could apply my experience. I then looked around to see who the best people were and where the best places were to enter the field. It was only when I came to RLE in 1990 that I began atomic physics work.

•Could you describe your work when you joined Professor David Pritchard's group in RLE?

In 1990, our main goal was to study cold collisions, which required the careful design of a cold atom source. So we started thinking about schemes to slow and cool atoms. We generated intense slow beams, and developed new methods to trap atoms at higher densities. Of course, we often discussed the limitations associated with slowing, cooling,

and trapping, and we tried to find ways to overcome them.

At that time, our focus was on laser cooling using optical techniques. Of course, evaporative cooling was in our minds because its pioneers, Tom Greytak and Dan Kleppner, were here at MIT. We would have liked to apply evaporative cooling to alkali atoms, but laser cooling did not create samples of atoms that were dense enough to get efficient evaporation. After we developed intense slow beams and the dark SPOT (spontaneous force optical trap), the situation changed. For me, it's still a very memorable discussion that we had when we assessed this situation. The whole group—Dave, the graduate students, and myself—decided not to pursue cold collision work or to continue developing optical traps. We would now use the techniques we had developed (for a rather different purpose) to achieve evaporative cooling in alkali atoms. Evaporative cooling, magnetic trapping, and progress towards BEC were in our minds for a long time; but in the summer of 1992, we decided it would be our sole focus.

•What is the importance of being able to magnetically manipulate atoms?

Optical cooling and trapping have limitations in density and temperature. If you want to go further, you have to avoid resonant light, and the preferred method is to use magnetic forces. Light can do a great job of cooling atoms to microkelvin temperatures. However, below this temperature, the absorption and emission of photons become a heating process. This is the so-called recoil limit of optical cooling. Similarly, when our atom clouds become very dense, light can't do a good job anymore because it's absorbed. So the important aspect of magnetic trapping is that it's a way to confine atoms without light. More specifically, it's a means of magnetic levitation to keep the atoms confined and levitated inside an ultra-high-vacuum chamber. That keeps the atoms away from the hot walls in a room-temperature machine and insulates them from the environment. In that sense, a magnetic trap is similar to a Thermos bottle.

•How significant was your work on the dark SPOT magneto-optical trap?

As we discussed, optical trapping has limitations, and one is due to density. Atoms at very high density absorb the laser light, so it can't do the cooling well. However, atoms can be put into states where they won't absorb light. It was a basic idea, and we discussed several schemes, but they were fairly complicated. We worked on it until we realized a simple way to do it: illuminate the atoms with an extra laser beam while casting a shadow onto the central area where most of the atoms were. In that shadow, the atoms could stay in a dark state. It was a trivial solution to a

By studying Bose condensates we hope to learn more about certain phenomena that are at the root of physics.

fairly complicated problem, and it worked immediately. The dark SPOT was the development that got us into BEC. It provided densities of atoms that were one or two orders of magnitude higher than what had been achieved with conventional optical trapping techniques. We knew immediately that with the dark SPOT we now had a sample of atoms for which evaporative cooling would work. Later, the dark SPOT was also used in Boulder when that group realized BEC.

•What are the implications of studying the properties of a Bose condensate?

Bose condensates are a novel form of quantum matter with unusual properties. They are also a link between the microscopic world and the macroscopic world. In the microscopic world, quantum mechanics reigns; in the macroscopic world, we use classical physics. Macroscopic quantum phenomena that connect the microscopic with the macroscopic world have fascinated

physicists since their discovery. The examples that we know are superfluidity and superconductivity. The Bose condensate is the third of those phenomena that is known, and it is the most basic one. Since superconductivity can be described as BEC of electron pairs, BEC is at the heart of all these macroscopic quantum phenomena. BEC of dilute atomic gases allows us to study these phenomena in their purest form. By studying Bose condensates we hope to learn more about certain phenomena that are at the root of physics.

Currently, we are studying what's going on inside a Bose condensate, how it forms, and how it reacts to light and other perturbations. One of the major goals is to show explicitly that Bose condensates can have superfluid properties. Another important aspect of BEC is that it forms at such low densities (typically eight orders of magnitude smaller than the densities of solids). At these densities, we can observe the matter-wave behavior of atoms undisturbed by strong interactions between atoms or molecules. In liquids or solids, there are strong interactions, and you can't exploit or observe such matter-wave phenomena. Both the Bose condensate and the atom laser rely on the fact that an atom is a wave. If you densely pack atoms, then you have a system that doesn't consist of individual atoms, and you don't have atomic matter waves. These are the systems that are usually found in condensed-matter physics.

•Was the BEC that you created shiny and metallic or transparent?

That question reminds me of the discussions which happened before BEC was observed. People wondered if we were to achieve BEC, would we be able to see it. Maybe it will be transparent to radiation, and we won't see anything. Or maybe it will be fully reflective. Then the laser light won't penetrate it, and we can't probe what's inside. All this talk about the condensate being shiny, or metallic, or pitch-black indicated that people weren't thinking about it carefully enough; experiments were simply too far away from it. Now, the answer is it depends. We've seen pitch-black Bose condensates that absorbed all the light when we used resonant probe light. We've also seen transparent

condensates when we've shone off-resonant laser light onto the condensate. The light passed through, and the only effect of the Bose condensate was that it slightly deflected the light, so it acted like a transparent glass marble or sphere. People could have figured it out by studying it theoretically. That only shows there were lots of discussions, but also quite a bit of ignorance, before the field was eventually created.

Our group used an experimental approach and, for several years, we just said let's advance and monitor our progress. As long as we made progress, we got colder and colder atoms. These were ordinary atoms, however, and our techniques worked well to see those atoms. Eventually, we got colder and colder, and then we saw the Bose condensate with the same techniques we had used before. It was fortuitous that we could use our old techniques.

So far, we've built a pulsed atom laser in which we have been able to extract pulses of coherent matter.

•What temperature and density did your BEC demonstrations achieve?

We typically reached the transition temperature to BEC at temperatures between 1 and 2 microkelvin. However, in working with more dilute samples, we've also seen transitions in the nanokelvin regime—at a few hundred nanokelvin. Typical densities are 10^{14} particles per cubic centimeter. We have goals to push to lower temperatures. After having achieved nanokelvin atoms, we're thinking of picokelvin atoms as the next challenge. We were surprised to find no major technical limitations in the nanokelvin regime, but sooner or later nature will show us the limitations.

•Why are sodium, rubidium, and lithium the atoms of choice in BEC experiments?

If you want to do BEC, you must pick

an atom that's a boson. There are only two classes of particles in nature—bosons or fermions. Fermions have half-integer spins and bosons have [full] integer spins. In a more colloquial way, bosons are gregarious and want to stick together; whereas fermions dislike each other. In fact, the majority of atoms of the common isotopes are bosonic atoms, but there are plenty of choices. We pick our atoms keeping in mind the cooling technologies that we need to apply. We want atoms that can be easily manipulated with laser radiation. So we chose atoms with strong transition lines in the visible or near-infrared part of the spectrum because, in those spectral regions, good lasers are commercially available. Furthermore, since magnetic manipulation and trapping are essential, we must choose an atom with magnetic properties; or more specifically, one with a strong magnetic moment. Alkali atoms such as rubidium, sodium, and lithium are ideal candidates.

•What are your thoughts on the BEC work being done elsewhere?

Atomic physics and, on a narrower scale, laser cooling and trapping, is a wonderful scientific community. There is a lively exchange of information, and I've benefited from many discussions with my colleagues. For me, it's like a big family. In pursuit of BEC, the efforts to develop evaporative cooling techniques in magnetic traps and to apply them to alkali atoms were pushed forward at Boulder and MIT. Every time I met people from Boulder, although we were competitors, we had genuine scientific discussions. Afterwards, each of us was more inspired. Also, both groups worked harder because they knew other groups were thinking about the same problems. I also think very highly of the BEC work done at Rice, Stanford, and more recently, at many other places. Many new ideas have been added, and there's a lot more excitement to come.

•What is needed for continued progress in studying the BEC phenomenon and towards the development of a practical atom laser?

We will study further properties of the Bose condensate. Superfluidity and other remarkable properties haven't

been studied experimentally. It's also important to do accurate quantitative measurements and compare them to theoretical predictions. An improved atom laser is high on our agenda. This involves not only trying to make a more powerful atom laser, but also a laser with improved output characteristics, including better control over the shaping of the pulses. So far, we've built a pulsed atom laser in which we have been able to extract pulses of coherent matter. It would be desirable to have a continuous stream of atoms, but that will require new ideas and techniques, and we're working on it.

Experimental physics is an interactive process; an interplay between developing technology and adding new ideas. In the near future, many studies will simply require careful observation of the Bose condensate. On the other hand, our group is strong in advancing methods. We enjoy doing new things and putting the atoms into new environments. So a large part of our group may be dedicated to more intense sources of Bose-condensed atoms and to put atoms into novel forms of traps. In the end, I believe the advances in technology move the field forward. The fact that we can study BEC now is the result of advances in magnetic trapping and evaporative cooling.

Technology is one aspect, but there is more. There are also nice ideas behind the cooling techniques that we use. It's a combination of knowing how to outsmart nature and finding a way to do it with the available technology. Pure technology would never work, because brute force technology has obvious limitations. Often, if you think harder, you can find a way to get more with less. It still involves technology, but it also involves new concepts and ideas.

•What are the possible applications for the coherent behavior displayed by atom lasers?

The optical laser has shown that we can control photons (light) to the ultimate limit. We can take a single mode of light, amplify it, and have laser radiation limited only by the fundamental equations of physics. Thus a laser beam can be controlled and focused to theoretical limits given by the wave equation. However, there is more than light in the

world. We want to achieve similar control with atoms, and the realization of this idea is the atom laser. In atomic physics, the object of our work is atoms and light, and now we can control both with laser-like precision. The atom laser may advance areas in which atom beams are used for demanding applications. They are already used to precisely measure fundamental constants and forces of nature, and in atomic clocks as well.

One other application may be the deposition of atomic beams on surfaces. Several groups are now applying atom optics for the highly controlled deposition of atoms in extremely fine patterns on surfaces. They have reached about a thirty-nanometer resolution, which is much better than current photolithographic methods used in circuit production. If the people doing patterned atom deposition reach the limits of conventional atom sources, then the atom laser will push those limits even further. Groups are also exploring how to improve communication and computation by going to the quantum level. From the study of Bose condensates, we might learn general things about small quantum systems. More generally, the atom laser is an advanced atom source for the field of

atom optics, where atoms are reflected, focused, and manipulated; things which traditionally have been done with light. Much of this work was pioneered by Dave Pritchard here at MIT.

It's a combination of knowing how to outsmart nature and finding a way to do it with the available technology.

•Is the term "atom laser" a misnomer?

People have tried to give names to the child before it was born. When discussions started about matter-wave amplification and the generation of coherent matter waves, people tried to find a descriptive name for it. I've heard boser, baser, and beamer, but none of these caught on. It seems that if you invent an acronym before you've developed something, the acronym isn't descriptive and nobody knows it. However, atom

laser has a certain meaning and invokes a certain idea. When the maser principle was realized with light, people called it the optical maser until the name laser became accepted. Today, I believe the word laser has lost its original meaning—light amplification by stimulated emission of radiation. Laser is now used to describe any device that generates intense, coherent radiation; no matter if the radiation is light or something else. Now we've realized the laser principle with atoms, so we call it the atom laser. Maybe in a few years, someone will find a better name.

•Did you have a mentor?

My doctoral advisor Professor Herbert Walther was a mentor for my work in Germany. When I joined Dave Pritchard, he became another mentor. After three years as a postdoc here, I applied for other positions and received several offers. MIT's was combined with an unprecedented offer by Dave to take over one of his labs. I realized that continuing our experiments, and not having to start from zero, might give me a chance to play a role in the developments towards BEC. Instead of collaborating with a junior person, Dave stepped aside and said this was now my field; that I should now do the work and get the credit. It was a remarkable part of my career. Two years after I started on the faculty here, we achieved BEC, and I couldn't have done it anywhere else. To a great extent, my success is due to the head start that I got from Dave.

•How would you describe the balance between theory and experiment in your group?

Our group has a strong commitment to experiment. Of course, we read many theoretical papers, but we emphasize the experimental work. Sometimes I see theory as our hobby. To do the theory that accompanies an experiment would be nice, and it could be educational for my group. However, dozens of other groups know how to do theory well, while only a few groups can do the experiments. We have much more of an impact on our field when we focus on the experiment, rather than competing with many other groups on theoretical calculations.



Professor Wolfgang Ketterle (second from right) and his RLE research group (from left): Research Assistant Shin Inouye, Visiting Scientist Hans-Joachim Miesner, Visiting Scientist Dr. Christopher G. Townsend, Research Assistant Michael R. Andrews, Research Assistant Dan M. Kurn, Research Assistant Dallin S. Durfee, Professor Ketterle, and Research Assistant Marc-Oliver Mewes. (Photo courtesy Wolfgang Ketterle)

•*What is the most important issue facing your field of research today?*

It's important for atomic physics to stay active, attract people, create exciting results, and to find new systems. Atomic physics has historically studied atoms and molecules in the world around us. These were the classical days of atomic physics, when many ideas were formulated. Since then, people have proclaimed atomic physics dead several times, but every five or ten years, something new develops. First it was the laser, then quantum optics, and then the supercavities that allowed ultimate control over light. Next we had cooling techniques to study matter at microkelvin temperatures. Now we have BEC. I don't know what we'll be doing in ten years, but every few years over the past several decades, something new was found. That's probably the challenge atomic physics has to face—to always find something new.

•*What is the most challenging aspect of your work?*

Our work has many aspects. You have to raise money, get the right people, and build different components for the experiments. You must focus in order to make it all happen at the same time and be ready to spend twenty, sometimes thirty, hours in the lab until everything works. As we advance our abilities to do experiments faster, we do novel, more complicated things. That's why all good experiments take more than a day and a night to do. So the limit of what you can accomplish is set by the human limits of how long you can stay awake. If you can reach a goal by spending twenty or thirty hours in the lab, you do it. You don't improve the machinery to make it work faster, you just spend a long night and you're done. The challenge is the complexity and making everything work at once.

•*What do you consider to be your most significant achievement?*

The realization of BEC. We started the work and developed the techniques to realize BEC before it became fashionable, before people had the firm belief that it could work. So we pioneered the field, opened it up, and developed the

techniques. We worked several years towards a goal that many people thought was uncertain. Eventually, in 1995, we realized BEC. To have been part of these developments and to have been the second group to observe BEC was our most important contribution. Our second most important achievement is that we could use the Bose condensate to realize the atom laser.

•*What has been the biggest obstacle you've had to overcome?*

You do your work step-by-step, locate your next goal, and then you focus on it. It's as if you're climbing a hill. You do many steps, and then suddenly you realize you've climbed a hill and you see new things. The work itself is much more developmental and evolutionary, but the progress and the results often come in steps. You might not achieve anything for a long time, then suddenly it works, and there's a breakthrough. Using the hill again as a metaphor, the major challenge for a scientist is to make the right decision about which hill to climb. Once you've chosen the hill, it's pretty clear which path to take and how to do the steps. I've never encountered major obstacles; it was simply finding a path and doing all the steps.

•*Is there a secret to your success?*


Success is a combination of hard work and elements of luck. For example, we invested heavily in the sodium atom for BEC. We had the lasers, and we built up the machinery around it, but at that time, nobody knew if sodium would have favorable properties. Fortunately, it did. In pursuit of goals like these, I often feel humble, because we're in the hands of nature. There are so many things we can't control and don't know ahead of time. In hindsight, after we've done something, we can understand it. Then we realize things we hadn't even thought about; but for some reason, we did it right anyway. When the groups at Boulder, Rice, and MIT saw the BEC, they all had elements in their experiments that provided solutions to problems nobody was aware of.

•*Do you have advice for someone considering a career in fundamental physics research?*

Do physics in the way you feel it should be done and don't try to imitate someone else. You should possess your own style of research. Some people do very detailed studies, while others survey a field. If you try to find yourself, then you'll get the best out of yourself. So find out what you want, become excited about it, and get into it. Also, try to work with people who teach you something, and work with groups where there is excitement and progress. Finally, when you're doing fundamental research, ask yourself if you want to do that kind of work. You must be convinced that's what you want to do. If your answer is yes, then you're willing to do major sacrifices and have a full commitment. If you think you'd be happier in a more normal profession, do it because it will be easier, you'll get more direct satisfaction, and you'll have more short-term benefits. However, if you want to dedicate your life to fundamental research, then go for it.

MIT is a place that needs people who are special in a certain sense. This reflects the fact that important contributions in fundamental research are not the usual ones that can be predicted. So we need unusual people, and we must encourage them to follow their personal intuitions.

•*How do you see your research providing a direct benefit to society?*

Learning how to control atoms has a benefit, probably in nanotechnology. It's characteristic of fundamental research that often you don't know what the direct benefit will be. The questions we answer are so fundamental that all the ramifications can't be foreseen. However, our work is so central that I'm confident it will not only improve the understanding of nature, but it will also lead to practical applications. Physics is like art. It's a cultural achievement because we learn about nature. It's also a human endeavor independent of whether or not it helps society directly. However, I don't see my work as the work of an artist who simply wants to do something beautiful. I also want to do something useful, and I think our research qualifies as both. 

RLE's 50th Anniversary Retrospective

POSTER SESSION AND LAB TOURS

Friday, November 1, 1996



"... the whole 50th celebration was a tremendous success... many very good things have come out of the experience, and others will follow. Not the least of which is a revitalization of the connections between groups in the lab... events like this make us stop and reflect broadly on where we've come from and where we're going—something we unfortunately don't find time for often enough in the frenetic pattern of daily life here." —

Gregory W. Wornell (SM '87, PhD '91)



Taking a break from the Friday afternoon open house are (from left): Toshimitsu Musha of Brain Functions Lab, Inc., Kawasaki, Japan; Professor Abraham Bers (SM '55, ScD '59) of RLE's Plasma Physics group; and Charles Freed (SM '54, EE '58) of MIT Lincoln Laboratory.

"I really enjoyed discussing innovative ideas and future directions of technological growth. I also found interacting with alumni gave me an historical perspective of RLE and broadened my thinking about future research."

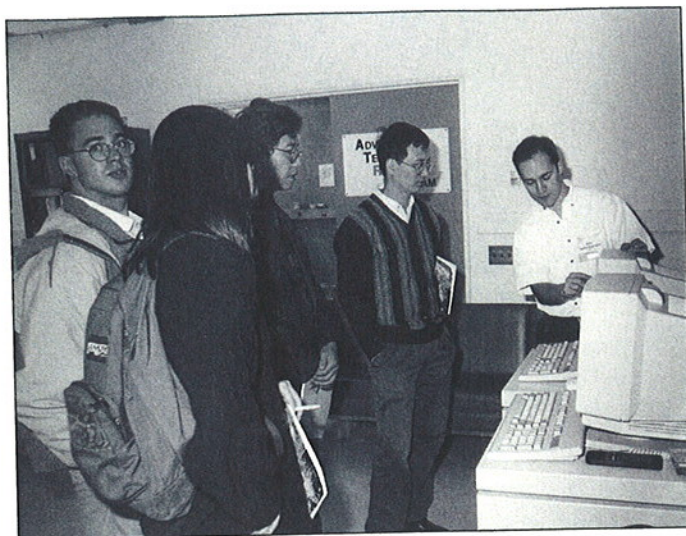
*— Research Assistant Kimberly J. Voss,
RLE Sensory Communication group*



At Friday afternoon's poster session, Research Assistant Kimberly J. Voss of RLE's Sensory Communication group describes work on human and machine haptics in the group's "Touch Lab" to RLE alumnus Dr. Donald H. Steinbrecher (SM '63, PhD '66).

"It was very interesting to learn about some of the diverse research projects performed within RLE. And it was great learning about the history of RLE and the people who helped make it."

— Research Assistant John G. Apostolopoulos,
RLE Advanced Television and
Signal Processing group



In the Advanced Television and Signal Processing group's facilities, Research Assistant John G. Apostolopoulos demonstrates the audio and video compression methods developed in RLE to visitors at the open house.



Research Engineer Dr. Jay N. Damask (right) and Research Affiliate Dr. Patrick N. Everett, both of RLE's Quantum-Effect Devices group, discuss integrated optical devices for all-optical communication systems.

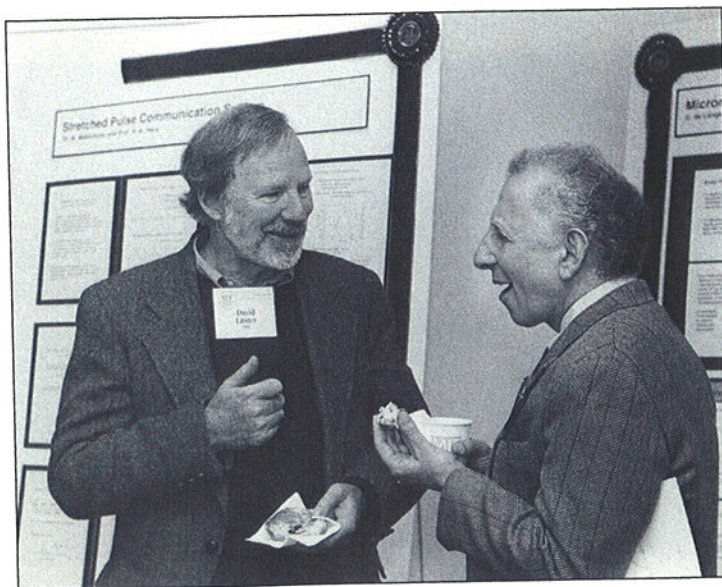
"I liked the fact that people took the time to learn about each other's research... I learned a lot about speech synthesis, an area that I knew very little about... the 50th presented an opportunity for everyone to open new lines of communication."

— Research Engineer Jay N. Damask,
RLE Quantum-Effects Devices group

"The RLE 50th celebration was excellent. It was a tremendous effort and all those involved should be congratulated for a job well done."

— Shaoul Ezekiel (SM '64, ScD '68)

MIT's Vice President of Research Professor J. David Litster (left) engages Professor Shaoul Ezekiel (SM '64, ScD '68) of RLE's Atomic, Molecular, and Optical Physics group in a lively exchange.



**GALA RECEPTION AND
COMPTON GALLERY
EXHIBIT OPENING**

Friday, November 1, 1996

*"You made me feel proud
to have been associated for
43 years with RLE."*

— Abraham Bers (SM '55, ScD '59)



Kicking off the festivities at RLE's Compton Gallery exhibit (from left): Professor Jonathan Allen (PhD '68), MIT's first lady Rebecca M. Vest, MIT President Charles M. Vest, Professor Abraham Bers (SM '55, ScD '59), Nancy Bers, and Dean of Science Robert J. Birgeneau.



*"Congratulations to the
RLE folks who contributed
to a fine celebration.
Students, faculty, and
visitors that I have talked
to all enjoyed it. I did too."*

— William T. Peake
(SB '51, SM '53, ScD '60)

Opening night for RLE's special museum
exhibit at the MIT Compton Gallery.

*"It was a very personal experience
which will stay with me for a long time."*

— Francis F. Lee (SB '50, SM '51, PhD '66)

Professor Emeritus Nelson Y.-S. Kiang (left) shares a moment with Professor Emeritus Francis F. Lee (SB '50, SM '51, PhD '66) and a friend at Friday evening's Compton Gallery reception.



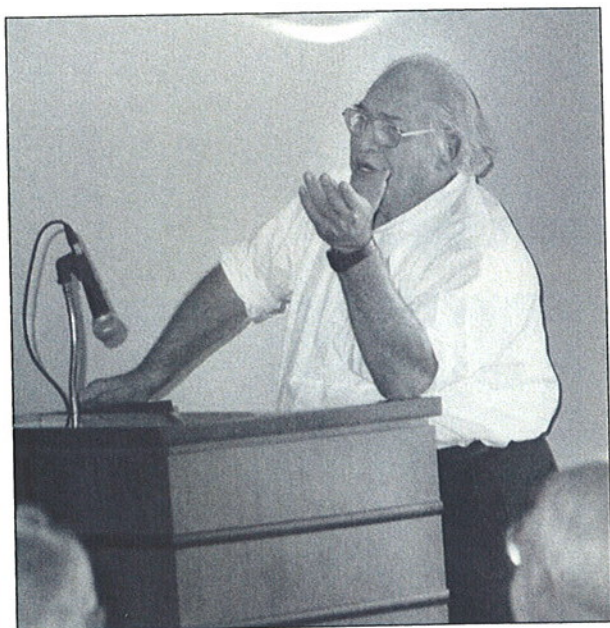
*"Congratulations on the 50th anniversary
of the founding of the
Research Laboratory of Electronics from the
Acoustical Society of America.
I remember some of the early years of the
RLE when I was a graduate student in
physics at MIT... I hope that
your record of outstanding research
continues long into the future."*

*— Stanley L. Ebrlich (SB '48),
President, Acoustical Society of America*



REUNION BREAKFAST

Saturday, November 2, 1996



Saturday morning's breakfast at the MIT Faculty Club featured an enjoyable discourse by Professor Emeritus Jerome Y. Lettvin on the history and culture of RLE.

"... it was amazing to see so many familiar faces from that era when we were all housed in the old wings of Building 20. The Saturday morning breakfast brought back fond memories of the warm 'family traditions' and philosophies of research during the first decades of the laboratory... The gala finale Saturday night was a nostalgic reminder of the elegance of the Assemblies Ball... A special thanks to the current students whose time and energy provided an informative update on the present projects and facilities."

—Phillip M. Jobansen (SB '59)

SYMPOSIUM- TECHNICAL AND PLENARY TALKS

Saturday, November 2, 1996



Professor Wolfgang Ketterle of RLE's Atomic, Molecular, and Optical Physics group describes his group's latest investigations into Bose-Einstein condensation.



Keynote speaker James Burke brings RLE into his ever-widening "connections" fold with RLE Director Professor Jonathan Allen looking on as part of the rapt audience.

"...the people here at the lab were making connections long before I'd ever heard of the word, working innovatively in what one of the lab's great men, Norbert Wiener, once described as the neglected no-man's-land between the various established disciplines..."

— Keynote speaker James Burke

"... from the many people who commented to me, the Jubilee Symposium of RLE was a grand success..."

This was one of those important moments for us to hold a mirror to our past and present selves, remembering what MIT has been and is, and looking to the future we can have—indeed must have."

— Charles M. Vest, MIT President



Saturday's symposium speakers and co-conveners (from left): Professors Wolfgang Ketterle, Dennis M. Freeman, Daniel Kleppner, James G. Fujimoto, Marc A. Kastner, John D. Joannopoulos, Gregory W. Wornell, and Jonathan Allen.

JUBILEE DINNER PARTY

Saturday, November 2, 1996



A bird's-eye view of the jubilee festivities at Walker Memorial.

"... the 50th anniversary of the Research Laboratory of Electronics was awesome... To have been a member of the Laboratory was probably the most important thing I ever did... Thank you for allowing me to be a part of it again—however vicariously and however briefly."

— Ronald W. Cornew
(SB '61, SM '63, EE '65, ScD '67)



Rounding out the celebration on Saturday night at the jubilee dinner dance (clockwise from top): Professor Daniel Kleppner, Ann C. Allen, Professor Charles M. Vest, Beatrice Kleppner, Professor Jonathan Allen, Rebecca M. Vest, Professor J. David Litster, and Cheryl Litster.



RLE alumni reminisce while perusing the lab's scrapbooks from the past 50 years.

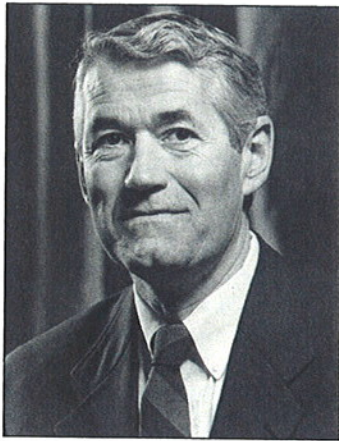


The festivities would not have been complete without enjoying the latest dance craze—Hey, Macarena!

It was a great event, enjoyed by all!

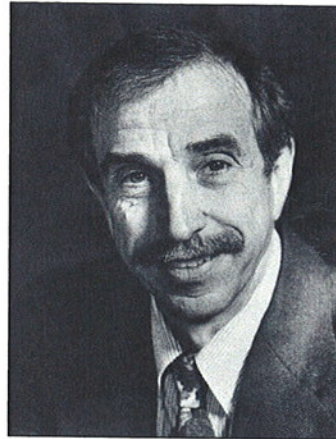
Photos by John F. Cook

----- circuit breakers -----



Dr. Robert J. Birgeneau, Dean of Science and the Cecil and Ida Green Professor of Physics, was awarded the 1997 Magnetism Award from the International Union of Pure and Applied Physics. A faculty member in RLE's Surfaces and Interfaces group, Professor Birgeneau was cited for achievements in the field of magnetism and, in particular, for the identification of model magnetic systems and the exper-

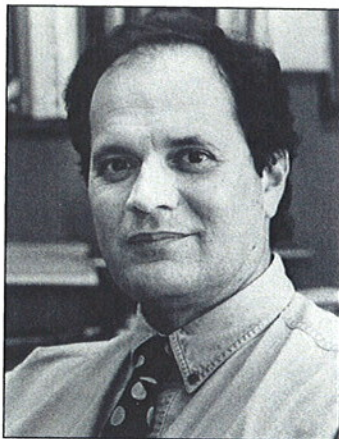
imental elucidation of their behavior by means of scattering techniques. His many important contributions to the field of condensed-matter physics include investigations into the phase-transition behavior of novel states of matter and the microscopic physics of high-temperature superconductors. In collaboration with colleagues at the Brookhaven National Laboratory, Professor Birgeneau has used neutron beams to probe the microscopic structure of matter, and has established the field of synchrotron x-ray scattering for studying magnetic phase changes. The Magnetism Award will be presented in July 1997, at the International Conference on Magnetism in Cairns, Australia. (Photo by John F. Cook)



Dr. Alan V. Oppenheim (SB/SM '61, ScD '64), previously Distinguished Professor of Electrical Engineering, was appointed a Ford Professor in the Department of Electrical Engineering and Computer Science. He was named coholder of the chair along with Professor Barbara H. Liskov. Professor Oppenheim, a faculty member in RLE's Digital Signal Processing group, was also named a 1997 MacVicar

Faculty Fellow. MIT's MacVicar fellow program was established in 1991 in memory of Professor Margaret L.A. MacVicar, MIT's first dean of undergraduate education. The ten-year fellowship provides an annual scholar's allowance to assist fellows in developing ways to enrich the undergraduate learning experience. Professor Oppenheim was cited for three decades of teaching and careful mentoring of MIT students, as well as his worldwide influence on electrical engineering education through his books and other teaching materials. He joins two other MIT faculty members, Professors John M. Essigmann and Lowell E. Lindgren, in receiving the fellowship.

(Photo by John F. Cook)



Dr. John D. Joannopoulos was appointed to the Francis Wright Davis Professorship in the Department of Physics. Professor Joannopoulos, a principal investigator in RLE's Surfaces and Interfaces group, also received the 1997 David Adler Lectureship Award from the American Physical Society (APS) and the 1996 William Buechner Teaching Prize from MIT's Department of Physics. The APS cited

Professor Joannopoulos for pioneering the use of modern computational tools to calculate the properties of amorphous, crystalline, and photonic band-gap materials, and for excellence in lecturing, writing, and training students in this field. A researcher in the field of theoretical condensed-matter physics, Professor Joannopoulos is recognized for developing numerous computational techniques to study complex solid systems. His recently co-authored book *Photonic Crystals: Molding the Flow of Light* addresses the discovery of photonic band-gap materials and their use in controlling the propagation of light.

(Photo by John F. Cook)

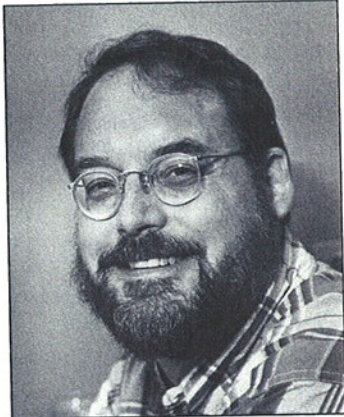


Dr. Rajeev J. Ram, Assistant Professor of Electrical Engineering and Computer Science, joined RLE's Optics and Devices group in January 1997. Professor Ram's research interests are focused on the quantum optics of microcavity lasers and on electron dynamics in quantum structures. A graduate of the California Institute of Technology (SB '91) and the University of California at Santa Barbara (SM/PhD '96),

Professor Ram has conducted a wide range of both theoretical and experimental research, including the quantum statistics of microcavity excitons, electromagnetic models of distributed mirror cavities, process development for long-wavelength vertical cavity lasers, and femtosecond spectroscopy of microcavity polaritons. (Photo by John F. Cook)

KECK FOUNDATION GRANTS \$4.5 MILLION FOR NEURAL PROSTHESIS CENTER

The W.M. Keck Foundation has awarded MIT a three-year \$4.5 million grant to establish the W.M. Keck Foundation Neural Prosthesis Research Center. The grant, announced in December 1996, will enable scientists, engineers, physicians,



Dr. Donald K. Eddington

and students from four Boston area institutions to collaborate on the development of neural prostheses that promise to improve function for deaf, blind, mute, and balance-impaired individuals. MIT, the Charles Stark Draper Laboratory, the Massachusetts Eye and Ear Infirmary, and the Harvard Medical School will work together in a broad area of bioelectronics research to develop shared solutions for new neural prosthetic aids.

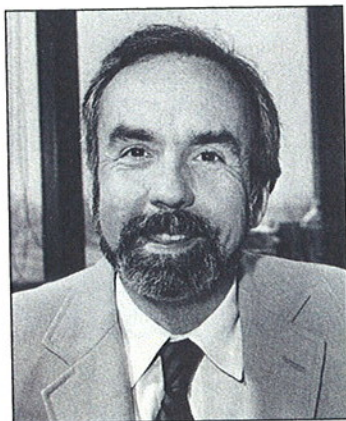
Dr. Donald K. Eddington, principal research scientist in

RLE's Auditory Physiology group, was named director of the new Keck Center. Dr. Eddington is also associate professor in Harvard Medical School's Department of Otology and Laryngology, and director of the Cochlear Implant Research Laboratory at the Massachusetts Eye and Ear Infirmary.

Several investigators and students from various RLE research groups will also participate in four specialized projects:

The Hearing Project will involve the development of a prosthesis that will enable profoundly deaf users to communicate fluently without lipreading. The goal is a wearable neural stimulator to permit better communication for deaf patients who have been implanted with electrodes for auditory nerve stimulation. Dr. Eddington, a recognized pioneer in the field of auditory nerve prostheses, will be the project's principal investigator.

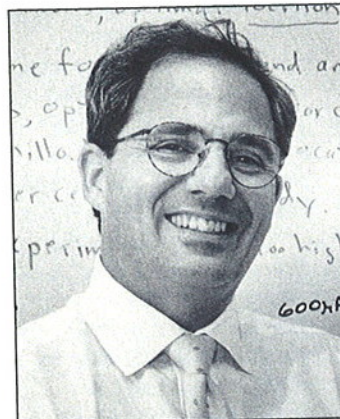
The Vision Project will design a prosthesis to restore vision to patients blinded by retinal diseases. This research seeks to advance previous work with laboratory animals to stimulate the human retina, thus providing visual sensations for blind volunteers. **Professor John L. Wyatt, Jr.**, and **Dr. Joseph F. Rizzo**, both of RLE's Circuits and Systems group, are co-investi-



Professor John L. Wyatt, Jr.

gators on the Retinal Implant Project under the Vision Project.

The Voice Project will develop a prototypical artificial larynx that can supply a natural voice and intelligible speech to individuals with impaired laryngeal function. It is anticipated



Dr. Joseph F. Rizzo

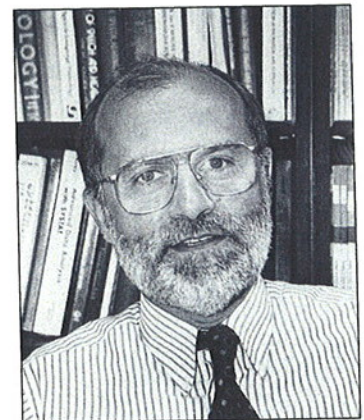
that this prosthesis will provide an improved sound source that more closely approximates normal human voice and speech production. **Dr. Robert E. Hillman**, a research affiliate with RLE's Speech Communication group, is principal investigator on this project.

The Balance Project will develop a wearable device that supplies tactile cues. This prosthesis will enable patients with chronic imbalance problems and inner-ear diseases to stabilize their body position. Miniature

micromechanical inertial instruments will be used to provide essential motion information in order to modulate electrical stimulation of the vestibular nerve, which controls balance.

Dr. Conrad Wall, III, will serve as principal investigator on this project. Dr. Wall is a research affiliate with MIT's Department of Aeronautics and Astronautics, and is on faculty at the Harvard Medical School and at the Harvard-MIT Whitaker College.

The work involved in developing the four different prosthetic aids shares common problems and approaches, including the design, materials, and signal processing techniques used for each device. It is anticipated that progress from one project will carry over into the other projects. For example, the low-power, high-bandwidth neural stimulators developed in the Hearing Project may be used in the other three projects as they progress toward the electrical stimulation of subjects. In addition, the expertise involved in designing and fabricating each complex system may prove valuable to the other projects, since each prosthesis will be developed into a wearable device.

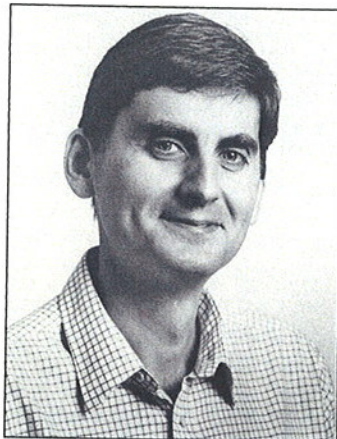


Dr. Robert E. Hillman

(Photos by John F. Cook)

APPOINTMENTS TO FULL PROFESSOR

Effective July 1, 1997, three RLE faculty members received promotions to full professor: Professors Jesús A. del Alamo and Jacob K. White in the Department of Electrical Engineering and Computer Science, and Professor Wolfgang Ketterle in the Department of Physics.



Dr. Jesús A. del Alamo conducts research in RLE's Materials and Fabrication group that involves high-performance heterostructure field-effect transistors for telecommunications and studies of new quantum-effect devices based on one-dimensional heterostructures. A graduate of the Polytechnic University of Madrid ('80) and Stanford University (MS '83, PhD '85), Professor del Alamo joined the MIT faculty in 1988,

after working at the Nippon Telegraph and Telephone Corporation in Japan. He is a former holder of the ITT Career Development Professorship, and a past recipient of the National Science Foundation's Presidential Young Investigator Award, the MIT Baker Award for Excellence in Undergraduate Teaching, and the MIT Edgerton Junior Faculty Achievement Award. (Photo by Mark Ostrow)



Dr. Jacob K. White (SB '80) joined the MIT faculty and RLE's Circuits and Systems group in 1987. He is a former holder of the Analog Devices Career Development Chair and past recipient of the National Science Foundation's Presidential Young Investigator Award. His research focuses on the theoretical and practical aspects of numerical techniques applied to problems in circuit and device simulation, packaging, and micro-

mechanical system design. In addition, his group investigates parallel computation and the interaction between numerical algorithms and computer architecture. Professor White is a graduate of MIT and the University of California at Berkeley (MS '83, PhD '85). (Photo by John F. Cook)



Dr. Wolfgang Ketterle, Assistant Professor of Physics, joined RLE's Atomic, Molecular, and Optical Physics group in 1990 as a postdoctoral associate. His initial research focused on the cooling or slowing of atoms by isotropic light and the development of the dark spontaneous force optical trap (dark SPOT) used to trap cooled atoms. More recently, he has successfully realized a new form of matter, the Bose-

Einstein condensate, and continues to investigate its novel characteristics. (See articles on pages 1 and 12.) Professor Ketterle is a graduate of the University of Heidelberg ('78) and the Technical University of Munich ('82). He received his doctorate in physics from Ludwig-Maximilians University and the Max-Planck Institute for Quantum Optics in 1986. (Photo by John F. Cook)



Professor Emeritus Albert G. Hill, 86, died of pulmonary disease on October 21, 1996, at his home in Needham, Massachusetts. Professor Hill served as RLE's second director from 1949 to 1952.

Born in St. Louis, Missouri, in 1910, Professor Hill received his bachelor's degree from Washington University in 1930. After two years as an engineer at Bell Telephone Laboratories, he returned to Washington University and received his master's degree in 1934. He completed his doctoral studies at the University of Rochester in 1937.

Professor Hill came to MIT as a physics instructor in 1937. He joined the MIT Radiation Laboratory in 1941, and became head of the laboratory's largest technical division. In 1946, he was appointed associate professor in the Department of Physics and associate director of the newly established RLE. He was promoted to professor in 1947, and named as RLE's second director in 1949.

In 1952, Professor Hill became the second director of MIT's Lincoln Laboratory. He was responsible for guiding laboratory personnel in the production of continental air defense systems using modern electronic devices, computers, and radar. These included the Semi-Automatic Ground Environment and Distant Early Warning systems. He also helped establish both the SHAPE (Supreme Headquarters, Allied Powers Europe)

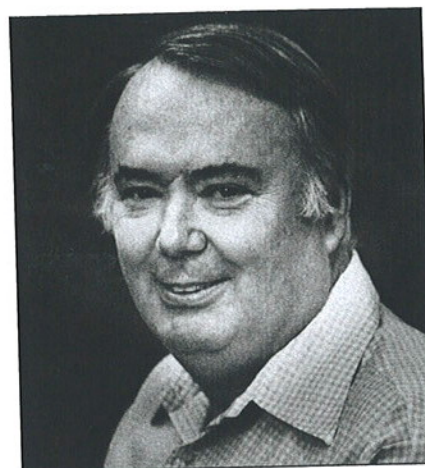
IN MEMORIAM

Technical Center in The Hague and the NATO Communications Line, which stretched from Norway to eastern Turkey.

In 1956, he worked in Washington as director for the Weapons Systems Evaluation Group, and the vice president and director for research of the Institute for Defense Analyses. He resumed teaching at MIT in 1959, and was appointed a lecturer in the Department of Political Science in 1965. In 1970, he was named as MIT's vice president for research and became chairman of the board at Charles Stark Draper Laboratory in May of that year. He served at Draper until 1982.

Throughout his life, Professor Hill served in roles that required both a technical background and administrative experience, and through these positions he contributed to the nation's defense-oriented research and development organizations. He was awarded the Presidential Certificate of Merit (1948), and Distinguished Civilian Service Medals from the Air Force (1955), the American Ordnance Association (1956), and the Secretary of Defense (1959).

Professor Hill is survived by three nieces, a nephew, and nine grandnieces and grandnephews. Remembrances may be sent to the American Lung Association, 1505 Commonwealth Avenue, Boston, MA 02135-3605. (Photo courtesy MIT Museum)



Dr. Charles E. Molnar (ScD '66), died of complications from diabetes on December 13, 1996, at his home in Sunnyvale, California. He was 61. Dr. Molnar was affiliated with RLE's Communications Biophysics group from 1957 to 1965, and collaborated with other researchers at RLE and Lincoln Laboratory on the development of the Laboratory Instrument Computer (LINC) in 1962. The LINC, with its digital logic and stored program, is widely acknowledged to have been the first interactive personal computer. Earlier at RLE, Dr. Molnar also worked on the Average Response Computer (ARC-1), which was used in the late 1950s and early 1960s to average evoked responses of the brain to sensory stimuli.

A graduate of Rutgers University (SB '56, SM '57), Dr. Molnar was recognized for his work in self-timed computer system theory, which is used to design ultrafast computers. His contributions to the field of biomedical and general-purpose computing have also led to innovations in computer graphics, cochlear mechanics, and circuit design.

After leaving MIT, Dr. Molnar joined the faculty of Washington University in St. Louis, where he worked from 1965 until 1995. He held various faculty appointments in the university's medical school and its computer science and electrical engineering departments. In 1984, he established the Institute for Biomedical Computing at Washington University

(continued on page 27)

Publications



The following new RLE technical reports are available from MIT's Document Services Office:

Simple Criteria To Prevent Sustained Oscillations In Nonlinear Fluid Flow Networks, by J.S. Simon, John L. Wyatt, and D. Rowell. RLE TR No. 597. 1996. 27 pp.

Efficient Communication Over Additive White Gaussian Noise and Intersymbol Interference Channels Using Chaotic Sequences, by Brian Chen. RLE TR No. 598. 1996. 103 pp.

Signal Processing and Communication with Solitons, by Andrew C. Singer. RLE TR No. 599. 1996. 142 pp.

Single Unit Recording Following Extracellular Electrical Stimulation of Rabbit Retinal Ganglion Cell Bodies, by Ralph Jenson, Joseph F. Rizzo III, Andrew Grumet, David Edell, and John Wyatt. RLE TR No. 600. 1996. 46 pp.

An Advanced Multiresolution Television Broadcasting System, by William Schreiber. RLE TR No. 601. 1997. 145 pp.

A Circuit Model for Diffusive Breast Imaging and a Numerical Algorithm for its Inverse Problem, by Julie L. Wonos, and John L. Wyatt. RLE TR No. 602. 1996. 99 pp.

The Role of Mechanics in Tactile Sensing of Shape, by K. Dandekar and Mandayam A. Srinivasan. RLE TR No. 604. 1997. 205 pp.

Determination of Mechanical Properties of the Human Fingerprint, in Vivo, Using a Tactile Stimulator, by R.J. Gulati and Mandayam A. Srinivasan. RLE TR No. 605. 1997. 266 pp.

Force Shading for Shape Perception in Haptic Virtual Environments, by H.B. Morgenbesser and Mandayam A. Srinivasan. RLE TR No. 606. 1996. 68 pp.

Sensorimotor Interactions in the Haptic Perception of Virtual Objects, by Gerald L. Beauregard and Mandayam A. Srinivasan. RLE TR No. 607. 1997. 189 pp.

Human Haptic Discrimination of Thickness, by C. Ho and Mandayam A. Srinivasan. RLE TR No. 608. 1997. 97 pp.

Asymmetry and Thermal Effects Due to Parallel Motion of Electrons in Collisionless Magnetic Reconnection, by Motohiko Tanaka. RLE TR No. 609. 1997. 31 pp.

Sensor Data Description for the Infra-red Airborne Radar Program, by Jeffrey K. Bounds. RLE TR No. 610. 1996. 48 pp.

Parameter Estimation for Autoregressive Gaussian-Mixture, by S.M. Verbout, J.M. Ooi, J.T. Ludwig, and A.V. Oppenheim. RLE TR No. 611. 1996. 40 pp.

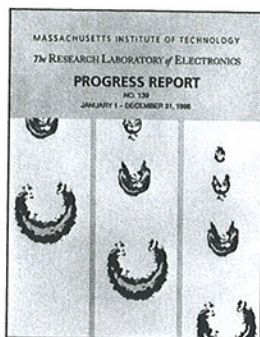
Proceedings of the First Phantom Users Group Workshop, by J. Kenneth Salisbury and Mandayam A. Srinivasan. RLE TR No. 612. 1996. 93 pp.

Fast Iterative Coding Techniques for Feedback Channels, by J.M. Ooi and Gregory W. Wornell. RLE TR No. 613. 1996. 40 pp.

Analysis and Application of Fractal Point Processes and Queues, by Warren Michael Lam. RLE TR No. 614. 1997. 170 pp.

Fast Iterative Coding Techniques for Feedback Channels: Finite-state Channels and Universal Communication, by James M. Ooi and Gregory W. Wornell. RLE TR No. 615. 1997. 48 pp.

Please contact MIT Document Services directly for prices and other information about RLE technical reports (telephone: 617-253-5668; fax: 617-253-1690; email: docs@mit.edu).



RLE Progress Report Number 139 is available from the RLE Communications group at no charge. *Progress Report Number 139* covers the period January through December 1996. It provides detailed information about the research objectives, projects, and publications of RLE's research groups. Faculty, staff, and

students who participated in each project are listed, in addition to current RLE personnel, and funding sources are identified.

RLE welcomes inquiries regarding the laboratory's research. To request *RLE Progress Reports* or theses, or for information on other RLE publications, please contact:

RLE Communications Group
Research Laboratory of Electronics
77 Massachusetts Avenue
Room 36-412
Cambridge, MA 02139-4307
telephone: 617-253-2566
fax: 617-258-7864

Internet users are invited to browse RLE's extensive Worldwide Web pages, which contain previous issues of *RLE currents*. The Uniform Resource Locator for the laboratory's Web page is: <http://rleweb.mit.edu/>.

IN MEMORIAM (continued from page 26)

and served as its director until 1991. Under his direction, the IBC coordinated computing research activities at Washington University's medical school and school of engineering and applied science. Dr. Molnar was a senior research fellow at Sun Microsystems in California at the time of his death, where he was working on advanced computer hardware design.

Dr. Molnar and collaborator Wesley A. Clark (EE'55) received the 1983 Director's Award from the National Institutes of Health for their work on the LINC. Dr. Molnar also received the 1985 NIH Jacob Javits Distinguished Neuroscience Investigator Award.

Dr. Molnar is survived by his wife Donna Addicott Molnar (who worked in RLE from 1960 to 1963), and two sons, Steven and Christopher. An endowed fellowship has been established in Dr. Molnar's memory and will be awarded annually to an entering graduate student in Washington University's Biological and Medical Engineering Program. Contributions may be addressed to: Charles E. Molnar Fellowship, Campus Box 1163, School of Engineering and Applied Science, Washington University, One Brookings Drive, St. Louis, MO 63130-4899.

(Photo courtesy Washington University Photo Services)



Making History Making News

Coverage of RLE's 50th Anniversary Celebration begins on page 17.

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The Hartford Courant
Established 1764

Research lab at
MIT turns 50

The Star-Ledger
MIT research lab
marks 50 creative
years

**COLUMBIA
MISSOURIAN**
Reliving research
MIT celebrates 50 years of lab's scientific
accomplishments

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