Speech Production Parameters for Automatic Speech Recognition

What we hear as speech is produced by the continuous movement of the speech articulators, such as the tongue, lips, and larynx. These articulators modulate air flow in such a way that speech sounds reach our ear. Do we in any way perceive the movements of those articulators as part of our perception of human speech? One of the mysteries of speech production and perception is the transformation between the discrete units of linguistics and the continuous nature of speech production. For instance, the three distinct sounds, or phones, in the word cop are blended together in a continuous waveform, which is created by the continuous movement of the speech articulators. The human listener is able to decompose the continuous sound stream and thereby recall the component sounds of the word. In this process, does the listener do this strictly with the acoustic signal without reference to how the articulators move or is that movement an object of perception?

A similar problem with decomposition exists in automatic speech recognition (ASR) by machine, where a continuous signal must be decoded into a string of discrete units. Would it help statistical automatic speech recognition algorithms to incorporate constraints that are inherent in the speech production process, which would at least partly characterize the sending channel? Furthermore, there appears to be a similarity between the difficulty in answering the question of whether humans perceive speech directly as gestures of the tongue and lips and in deciding how to include articulatory constraints in the statistical models used in ASR.

Most of the progress towards incorporating articulatory representations into ASR has been enabled by experiments that measure and model speech articulatory movement and coordination. The task-dynamic model, for example, describes the coordinated movement of the speech articulators in terms of control parameters of dynamic systems. The model can provide for a bridge from the discrete phone units to the continuous movement of articulators. The sequence of these parameters is then used to produce a word that can be expressed in the form of a list called a gestural score. Something akin to gestural scores may provide part of the abstract representation of articulatory movement that several researchers are considering.

Recent work at The Ohio State University (OSU) has shown how gestural scores can be derived from data on tongue and lip movement. The articulatory movement data was obtained using the x-ray microbeam machine at the University of Wisconsin, which produces x-ray images of tongue and lip movement using very low dosages of x rays. The OSU group was further able to train a neural network to convert the x-ray images to a string of gestural scores in the sense of recognizing the words of a spoken message from the gestural scores that they derived. To do ASR with gestural scores in the sense of recognizing the words of a spoken message from the acoustic waveform will require that gestural scores be derived from the waveform. Researchers at Haskins Laboratories are experimenting with recovering gestural scores from the speech waveform in computer simulation experiments. In addition, Li Deng of the University of Waterloo has been incorporating gestural scores into speech recognition systems. Further progress in this area can be expected.

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Before last year, only one solar system was known: our own. Now several extraterrestrial planetary systems have been detected through a method that looks for a slight change in the star's spectrum owing to the presence of a nearby planet. The figure shows the planet's masses (in comparison to the mass of Jupiter) and the size of their orbits (scaled to Earth's orbit). See the associated article in the astrophysics chapter. (Adapted from Leigh Anne McConnaughey by Malcolm Tarrton.)

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**Acoustics**

**Speech Production Parameters for Automatic Speech Recognition**

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**Notes:**
Acoustic Waveguides as Tools in Fundamental Nonlinear Physics

Imagine a beam of intense green light guided by an optical fiber. If the light is made to alternate between bright and dim at the source, there will be periodic locations down the fiber where you will see light alternating between red and blue. Moving further along, you will again see green light alternating between bright and dim. Providing that the fiber is long, and one does not subject to energy losses along the fiber, this periodic variation in the color will repeat indefinitely. This mechanism thus allows the possibility of providing tunable coherent light from a single-frequency source.

We have recently probed this concept in acoustics by using a long pipe as a way of guiding high intensity sound waves.1 This “AM–FM conversion” effect (so named because of the way in which the wave alternates between amplitude and frequency modulation) occurs only when a wave interacts with itself, which is normally negligible unless the amplitude is sufficiently high. AM–FM conversion is thus an example of a nonlinear effect.

Since the days of Lord Rayleigh, acoustic waveguides such as the one employed above have played a major role in the advancement of fundamental physics as well as technology. In low as well as high intensity sound investigations, waveguides are frequently useful in restricting the propagation to one dimension. The linear propagation of sound frequency below that of the “transverse modes” in which the wave front bounces along the walls of the waveguide. In one-dimensional propagation in acoustic media, sound waves at all frequencies typically move with the same speed. A wave packet, which is the superposition of waves at many frequencies, will therefore not spread but will retain its shape as it propagates. The medium is thus referred to as nondispersive. By contrast, transverse modes in a waveguide are dispersive, and for that reason waveguides are frequently employed especially for introducing dispersion.

In particular, waveguides have been used to further our understanding of solitons and their nonlinear behavior. A soliton is a “shape” that is of a constant shape that behaves like particles. Acting alone, nonlinearity causes points of greater amplitude in a wave to move faster, so that the wave will eventually “break” in the case of water waves or “shock” in the case of acoustic waves.

Dispersion, on the other hand, acts to spread a wave. Solitons result from a stable balance between nonlinearity and dispersion. Discovered in 1834 by John Scott Russell, these waves have attracted interest in many fields of physics and in biology, and are dramatic examples of inherently nonlinear behavior. Envelope solitons, which are among the most well-known types, result from an instability in which an amplitude modulation of a wave initially grows and eventually self-locates to a small number of transverse modes in space. These unstable modes might support these solitons, leading to novel effects. For example, because nonlinearities may cause a greater temperature increase in a compression compared to the temperature decrease in a rarefaction, it may be possible to employ acoustic solitons to transport localized “heat patches” in heat pumps.

Another recent application of waveguides is in the determination of the relationship between stress and strain in rocks. Nonlinearity must be at work since the stress and strain deformations are made to alternate between bright and dim at the source, there will be periodic variations in the color will repeat indefinitely.

A Plethora of Extrasolar Planets

The 12 months from October 1995 to the time of writing witnessed a revolution in the understanding of planetary systems other than our own. In the fall of 1995, when Michel Mayor and Didier Queloz of the Geneva Observatory announced the discovery of a Jupiter-sized planet orbiting the star 51 Pegasi,1 observer expected that recognizing the telltale wobble of stars caused by planets would take many years, since the orbital periods of the largest planets, Jupiter and those beyond, are five years or more. Marcy and Butler had been making high-resolution velocity measurements of a sample of over 100 nearby sunlike stars since the late 1980s, but had not analyzed the data fully. Their sense of urgency took a quantum leap, however, with Mayor and Queloz’s discovery. The planet around 51 Pegasi, though about half the mass of Jupiter, orbited every 4.2 days in a circular orbit with a radius of about 5 million miles. Scrutinizing their collected measurements, Marcy and Butler confirmed the Geneva discovery, and announced two new planets, orbiting 47 Ursa Majoris and 70 Virginis, at the January 1996 meeting of the American Astronomical Society. The planet around 47 Ursa Majoris, nearly three times the mass of Jupiter, moved in an almost circular orbit, slightly larger than the orbit of Mars, with a period of 2.96 years. This is the sort of orbit expected for a giant planet in our solar system. The planet around 70 Virginis, in contrast, moved in a quite different fashion. Its 116-day orbit was highly eccentric, bringing it briefly closer to its star than the planet Mercury is to the sun, then swinging out again to the distance of Venus. This resounding success has brought additional discoveries, as researchers analyzed their data and made new observations. A number of additional planets like 51 Pegasi were discovered, as massive as Jupiter, but in circular orbits of short period. These included planets around 55 Cancri (14.7-day period), Upsilon Andromedae (4.6-day period), and Tau Bootis (3.3-day period), all discovered by Marcy and Butler. In October they, along with Cochran and Hatzes, announced the discovery of another planet, orbiting 16 Cygni every 2.2 years in a highly elliptical orbit like the one around 70 Virginis. An additional planetary candidate was contributed by George Gatewood of Allegheny Observatory, who detected a telltale astrometric wobble in the star Lalande 21185 by a long series of precise measurements of its position relative to nearby stars, deducing the presence of a Jupiter-like planet with a period of 5.8 years, along with a second possible planet with a period of 30 years.

To the initial consternation and eventual delight of theorists, none of these planets met our reasonable expectations. According to current understanding, planets arise in the flattened disk of gas and dust surrounding a forming star by a process called accretion. In the accretion process solid particles begin to condense and collide, forming larger chunks which can then gravitationally attract even more matter. In the inner solar system, y-trend toward bodies smaller than the new sun’s heat chases any remaining gas and dust. In the outer solar system, however, where the temperature is cooler, rocky planetary cores can continue to grow for a much longer time, producing a “gas giant” that may eventually become a Jupiter-like planet. In our solar system, the original rock and ice core is surrounded by tens or hundreds of kilometers of gas. In the inner solar system, the presence of gas is such that a large number of rocky planets (a tenth the mass of Jupiter) within a few hundred million miles of a star, with gas giants out at a half billion miles or more. In addition, the averaging effects of collisions during the accretion process would ensure that all planetary orbits were circular.
nels permit estimates of spectral energy distributions that may tell how far away fainter than the normal limit of the unaided human eye) and a handful of faint range from the violet to the far red. Superposed, they yield a stunning color image observed. Exposures were made in each of four wavelength bands, spanning the with the orbiting 2.4-m Hubble, and the black sky of space against which it was public now.”

Laurence A. Marschall Gettysburg College


Denzies of the Hubble Deep Field

There is an enlarged reproduction of the Hubble deep field (HDF) on a wall at the Waimea, Hawaii headquarters of the W. M. Keck Observatory on which there is a transparent overlay. On the overlay, next to each of many distant galaxies in the HDF, there are numbers marked that represent the redshifts of these galaxies, as obtained with the 10-m Keck telescope. The galaxies are so faint that, near the detection limit, one photon per week would be received by a collecting area equal to that of the human eye and located above the Earth’s atmosphere, from a whole galaxy of hundreds of billions of stars. To an astronomer knowledgeable in the ways of the profession, the fact that these data represent the efforts of eight different science teams, each granted precious observing time on the world’s largest telescope for what is substantially a common cause, can only underline the high esteem in which our profession holds the HDF, a product of ten consecutive different science teams, each granted precious observing time on the world’s largest telescope for what is substantially a common cause, can only underline the high esteem in which our profession holds the HDF, a product of ten consecutive years of observations in other wavelength bands, including the infrared and visible, before the last word, or possibly even the first definitive word, will be spoken.

The HDF is so much more revealing than comparable images from ground-based telescopes because of the high spatial resolution (about 0.1 arcsec) attained with the orbiting 2.4-m Hubble, and the black sky of space against which it was observed. Exposures were made in each of four wavelength bands, spanning the range from the violet to the far red. Superposed, they yield a stunning color image of more than 1600 galaxies (some as faint as 30th magnitude or 4 billion times fainter than the normal limit of the unaided human eye) and a handful of faint stars, all within a tiny area of Ursa Major, 5.3 square arcminutes (see Fig. 1). Considered separately and intercompared, the images made in different color channels permit precise measurement of spatial energy distributions that may tell how far away the galaxies are (for the great majority of objects for which Keck has not yet obtained a redshift and for which there may be beyond its reach; the “photometric redshifts” derived from these energy distributions are controversial and not very reliable statistically).

The energy distributions, properly interpreted (and different groups may do so differently) reveal whether the galaxies are in the throes of massive early star formation or other evolutionary stages with strong consequences for the collective light of a galaxy. Likewise, the HDF images are fertile ground for investigators’ efforts to classify the total types of substructures of different distance and corresponding eras of time since the Big Bang, to see how these building blocks of the universe have undergone dramatic changes (and how some of them have not). There is great ferment nowadays in observational cosmology in general and in immediate space. Not only is the orbiting Hubble Space Telescope shedding light on distant galaxies but also the fast development of the Planck satellite, a comprehensive survey of the local universe. (February, 1996).


FIGURE 1. The target for the Hubble Deep Field was a carefully selected piece of sky near the handle of Big Dipper (part of the northern circumpolar constellation Ursa Major—the Great Bear). The field is far from any plane of our galaxy and so is “unclouded” of nearby objects, such as foreground stars. The target field is, by necessity, in the continuous viewing zone (CZ) of this orbit, a special region where Hubble can view the sky without being blocked by Earth’s shadow. (NASA Sun and Moon.)


Various kinds of less numerous objects in the HDF have been identified and catalogued, including quasars and active galactic nuclei, previously unrecognized strongly gravitationally lensed distant galaxies, faint faint stars, including that might be associated with the so-called dark-matter halo of our own Galaxy.10 The results, if not compromised fatally by small sample statistics, may constrain models of the halo’s stellar composition, as well as models of the relative numbers of nearby faint stars that belong to different populations.

The data in the Hubble Deep Field, carefully selected and supported by follow-up observations with other telescopes and with two new instruments that (at the time of writing) were scheduled to be installed onboard Hubble in February 1997, should be capable of telling us how galaxies have evolved in form and content over the aeons and when during that process were there great episodes of star formation or other evolutionary stages with strong consequences for the collective light of a galaxy. Likewise, the HDF images are fertile ground for investigators’ efforts to classify the total types of substructures of different distance and corresponding eras of time since the Big Bang, to see how these building blocks of the universe have undergone dramatic changes (and how some of them have not). There is great ferment nowadays in observational cosmology in general and in immediate space. Not only is the orbiting Hubble Space Telescope shedding light on distant galaxies but also the fast development of the Planck satellite, a comprehensive survey of the local universe. (February, 1996).
Light is an electromagnetic wave, similar to a radio wave or the electrical sig- nals in a computer circuit, but at a much higher oscillation frequency. The time for two successive crests of a light wave to pass through a point is only a few femtoseconds (1 fs = 10⁻¹⁵ s = a quadrillionth of a second). This time scale also represents the fundamental “clock speed” for the basic processes (such as chemi- cal reactions) underlying the world we live in. As a result, femtosecond pulses are often used as an ultrasensitive camera shutter, to “freeze” the motion of chemical reac- tions in time, so that we can understand their basic mechanisms. Femtosecond time scales are profoundly short; the geometric mean of 10 fs and the age of the universe (obtained by multiplying the two numbers and taking the square root) is a time of only one minute. In the 1990s, there has been a revolution in the technol- ogy of laser sources, resulting in the ability to simply and reliably produce pulses as short as 30 optical cycles in duration, both in the visible and x-ray regions of the spectrum. More recently, powerful new techniques to obtain accurate pic- tures of the exact shape of these ultrashort light pulses have been developed, which are revolutionizing the way we think about and use light.

The technology of femtosecond lasers began in the 1980s, and as early as 1986 resulted in the generation of 6-fs pulses by researchers at Bell Labs.1 However, the technology remained very difficult until the discovery by Wilson Sibbett at the University of St. Andrews in 1990 of a way to make a simple and reliable, crystal- based laser which spontaneously emits short pulses.2 Work by our group and that of the Technical University of Vienna made it possible to routinely generate light pulses shorter than 10 fs using such a laser.3,4 The stability, reliability, and average power of these pulses is vastly superior to femtosecond pulses generated previ- ously. These improvements made it possible to develop new ways of looking at and using this light. For example, the work of Rick Trebino and coworkers at Sandia Labs now makes it possible to take the “snapshot” of the exact shape of an ultrashort pulse in time, using a combination of new experimental techniques and calculational algorithms similar to those used in medical CAT-scan images.5 This technique is referred to as frequency-resolved optical gating (FROG).6

In very recent work of our group, we applied FROG to pulses as short as 10 fs, allowing our students, Greg Taft and Andy Rundquist, to make the fastest electr- omagnetic wave form measurement ever.7 The FROG output, shown in Fig. 1, is equiva- lent to an “optical oscilloscope,” but with a speed thousands of times faster than even the fastest conventional oscilloscope. Furthermore, techniques have been developed which make it possible to manipulate the shape of these ultrashort pulses.8 The result of all of this work is that in the past year, it has become possible to produce, measure, and manipulate light pulses as electromagnetic wave forms, rather than simply as bursts of energy. This revolution in thinking has im- plications for our study of dynamic processes in nature, our ability to generate light from the far infrared to the x-ray regions of the spectrum, and on the possibil- ity for communications networks with terabit/s (1 terabit/s = 10¹² bits/s) data rates. In very recent work, we generated high-power versions of these ultrashort optical- pulses, which can generate focussable intensities greater than that which would be obtained by focusing the entire solar flux incident onto the earth into a pin- head.9 Because the size of a laser depends primarily on its pulse energy, it is only by reducing the duration of a pulse in time that we can achieve such immense

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**FIGURE 1.** Measured electric field waveform of a light pulse only 10 fs (quadrillionths of a second) in duration.
power densities using relatively small lasers. High intensity light pulses allow us to access previously unexplored extreme states of matter—for example to generate very short pulses of light at new wavelengths. Although atoms within such a focused laser are very quickly torn apart, all recent work has demonstrated that this does not occur instantly, but takes a few femtoseconds. We have thus used this fact to our advantage to generate the shortest x-ray pulses ever, only a few femtoseconds in duration. Using a technique for converting optical frequency light into x-rays, we found that by using very short laser pulses we could generate higher-energy x-rays than previously possible, with greater tunability, and with an unprecedented short duration. These x-rays, by virtue of x-rays ability to more directly observe atomic structure, will make it possible to study with unprecedented clarity the most basic processes which occur in our natural world—for example, the motion of atoms in chemical reactions and in material phase transitions. This new, table-top sized x-ray apparatus will allow all of the types of experiments previously performed using synchrotron facilities, to now be performed with an added dimension: ultrashort time-resolution.

Many other potential applications of very short optical pulses exist. Ongoing research by others may mean that extremely short duration optical pulses will be used to perform on-site characterization of silicon surfaces during chip manufacture, and to take 3-D pictures of living cells. The applications are becoming a reality because ultrashort pulses combine two seemingly contradictory characteristics: extremely high peak power (which makes it possible to access nonlinear processes such as how molecules jump to a higher-energy state by simultaneously absorbing two photons instead of a single photon) with very low average power (which makes the laser small and the disturbance caused by it relatively noninvasive). Very short duration ultrashort-power optical pulses have the potential to efficiently drive future laser-based particle accelerators, and to perform more accurate micro machining and laser surgery. The potential is enormous.

A number of students and scientists contributed to this work—Stirling Backus, Zengu Chiang, Ivan Christov, Charles Durfee, Kim Maginnis, Greg Taft, Kendall Read, Andy Rundquist, Haiwen Wang, Erik Zeek, and Jingping Zhou. We gratefully acknowledge support by the National Science Foundation, the Air Force Office of Scientific Research, and the U.S. Department of Energy. M. Murnane and H. Kapteyn acknowledge Sloan Foundation Fellowships.

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References


A New “Momentum Microscope” Views Atomic Collision Dynamics

A new “microscope” is providing spectacular views of the correlated motion of the fragments of atomic breakup processes. Whereas ordinary microscopes reveal the spatial structure of an object, this new approach provides multidimensional “pictures” of momentum distributions for all particles produced in fundamental atomic reactions such as ionization of an atom by charged particles or by photons. The technique, termed “cold target recoil ion momentum spectroscopy” (COLDTRIMS), allows the measurement of previously undetectable small momenta of ions emerging from atomic reactions. Furthermore, this is done with high-resolution, large-3-D slices of the collision volume, and often includes measurement of the momenta of electrons produced in the reaction.

In 10 years of development, researchers have progressed from making the first successful measurements of such ion momenta to creating today’s high-resolution reaction “microscopes.” This effort was pushed by groups at the University of Frankfurt and at Kansas State University. Today additional systems are in use at CIRIL/GANIL (France), Riken (Japan), and the Lawrence Berkeley National Laboratory and are being installed at University of Missouri at Rolla and at Argonne National Laboratory. The COLDTRIMS technique detects the low-energy collision products (a recoil ion and electrons) in a weak, uniform electric field which projects their 3-D motions onto 2-D position-sensitive ion and electron detectors. Combined with measurement of the time-of-flight to the detectors, the 3-D momentum distributions can be determined. The result is similar to that obtained from nuclear or high-energy particle collision experiments, i.e., an event-by-event accounting of the momentum components of the reaction products. To gain the highest precision measurements of final momenta, a cold, supersonic helium jet target is used. In the case of atomic reactions, the relevant particle energies are truly tiny, only fractions of an electron volt; whereas in nuclear collisions, the low-energy particle collision products have energies millions or (billions) of times higher.

In many cases, images of the momentum distributions of the ions and electrons from atomic reactions directly “display” the processes responsible for the breakup of the atom. Thus some longstanding puzzles in atomic collision physics were solved recently using this new approach and many new questions and challenges to theory were raised.

For example, Lutz Spielerber (U. Frankfurt) and coworkers have recently separated different mechanisms of photoionization—in which light removes electrons from atoms or molecules to produce ions—by measurement of the final ion momentum. If a photon completely surrenders all its energy to the atom, it breaks into two fragments (a positive ion and an electron) of equal momenta, while for Compton scattering (in which the photon loses only part of its energy) the photon makes a billiard-ball-like collision with one target electron without direct momentum transfer to the atom’s nucleus (see Fig. 2). This allowed for the first time the study of how the helium atom’s second electron responds to these different interactions with the first electron. The new measurements provided a long-needed conclusive experimental answer to intense controversy among theorists about the ratio of the probability for Compton-scattered light to remove two helium electrons to that for single ionization.

In another application of this new approach, Robert Moshhammer (GSI-Darmstadt) and coworkers have demonstrated that the impact of a fast, highly charged projectile ion (moving 16 times faster than the mean velocity of electrons within the target atom) acts like a high-intensity light pulse, causing the atom to break into an ionic core and one or more electrons. The recoil of the ionic core is so large that it almost compensates the total momentum of the electrons. The measured momentum distributions of the freed electrons carry information on their correlated movement inside the atom on a time scale of 10^-17 seconds (a billionth of a second).

In low-energy collisions, with proton projectiles moving slower than the electrons in the target helium atoms, Reinhard Dörner (U. Frankfurt) and coworkers and Scott Kravis (Kansas State Univ.) and coworkers were able to see that electrons appear to be “left stranded” on the saddle point between the two recoiling “heavy partners” (in this case, the daughter nucleus and the helium ion). This effect was predicted by Ron Olson (U. Missouri, Rolla) in 1983 and has since been a subject of intense theoretical and experimental research. The new momentum spectroscopy results have provided a definitive observation of this phenomena.

A collaboration led by Kansas State University and the University of Frankfurt, which has employed this new technique to investigate photon-induced breakup of a helium ion into its three constituents (nucleus and two electrons) using light from the Lawrence Berkeley National Laboratory Advanced Light Source. The photons used were chosen near-threshold for the process, that is, they had barely enough energy to achieve double ionization. The results show how the mutual forces between the three charged fragments yield simple momentum configurations in the final state which follow from basic arguments proposed by Wannier in 1953. Owing to the long-range nature of the Coulomb potential, the behavior of as few as three particles in the continuum is hard to treat by first-principles quantum mechanical calculations and successful theoretical approaches have only recently been developed.

Although this new technique has already brought a rich harvest in ion-atom, electron–atom, and photon–atom collision physics, its use is just beginning to flow. Future applications can extend to fields like molecular physics or to tests of quantum electrodynamics (the theory that unifies quantum mechanics, special relativity, and classical electromagnetism) in collisions between heavy ions traveling near light speeds. Another exciting application is in the study of the radioactive process known as beta decay. With this new technique, one can expect precise measurements of the angular correlations between the decay products (the daughter nucleus, a positron or electron, and a neutrino). One may even imagine a high-resolution neutrino mass measurement for each beta decay event. Such a measurement, which would provide coveted information on whether neutrinos have mass, could employ an accurately determined neutrino momentum value deduced from measuring the momentum values of the daughter nucleus and the emitted electron or positron.

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Precision Molecular Spectroscopy with Cold Trapped Atoms

By using light to combine two colliding, cold trapped atoms into a molecule, a new kind of high precision molecular spectroscopy is probing the long-range forces between the atoms. This approach of “photoassociation spectroscopy” has been used to make the most precise measurements yet of the lifetimes of the first excited state of the Na and Li atoms, and to observe the sensitivity of retardation corrections to the long-range force between one ground-state and one excited-state atom. Retardation refers to the ultrashort, but finite, time for light to cross the molecule—in seconds, roughly the fraction 10 divided by a billion times a second. Since particles interact electromagnetically through the exchange of photons, the finite speed of light affects the long-range forces between the atoms. In any atomic or molecular system, absorption of light often occurs at a set of unique narrow frequencies. A plot of the response of the system, which can be observed in many ways, against the frequency of the light is the “spectrum” of that system. The spectrum displays unique “lines” because they were first observed as lines on photographic plates. Each of the spectral lines has a width, that is, a narrow but finite range of frequencies where the light is absorbed. A part of this width arises from the spread of velocities of the moving atoms, by the familiar Doppler effect: the shift in frequency caused by a moving source. The Doppler shift minus what is an example of this effect for sound waves.) For the case of a collection of atoms moving at different velocities, one has a superposition of many different Doppler shifts which contribute to the total spread seen in the absorption line. If one can arrange to have all the atoms moving with the same velocity, the Doppler spread is nearly zero. One does not, however, reach zero width because (even for motionless atoms or molecules) there is an irreducible width—the natural linewidth—which is determined by the lifetime of the excited state.

To measure the lifetimes of the atoms’ excited states, a laser of variable frequency is shone on the cloud of the gas, which creates an interference pattern between an excited state of the diatomic molecule formed from the atom pair, and the ground state of the colliding atoms. The formation of the excited molecular state is observed either by ionizing it with a second photon and detecting the ions or by detecting the loss of trapped atoms due to decay of the excited state. The frequency of the laser is scanned in excitation experiments, which is an experiment in photoassociation spectroscopy (the photoassociation spectrum) for production of the molecular excited states. The spectral line shapes are very sharp, rivaling those seen with conventional methods of high-resolution laser spectroscopy. This is because the kinetic energy of the cold ground-state atoms is sharply defined; the very small kinetic energy of the cold atoms yields a Doppler spread less than a natural linewidth of the atom line used to laser cool the atoms. A careful consideration of the actual spectral line shapes is necessary for the most precise use of these spectra, since they are strongly influenced by the quantum nature of the cold colliding atoms.

A combined theoretical and experimental effort at NIST has concentrated on a very special excited state of the sodium diatomic molecule. This state is a “pure long-range state” which correlates at large separations of the atom pairs, to the combination of one atom in the ground state and one in its first excited state. The long-range form of the force between two atoms of the same species, one in the ground state and one excited, is similar to that between two between two bar magnets; it vanishes as the inverse cube of the separation between them and is proportional to the product of their dipole strengths. (The dipole strength is a quantity which determines how strongly an atom absorbs light.) Here, the dipole strength product is proportional to the energy level of the excited-state atom, that is, to the inverse of the atomic lifetime. The potential energy of this state, plotted against the interatomic separation, has a very shallow minimum about 55 GHz deep (1 GHz = 1 billion cycles/ s; spectrosocists often express energies as frequencies, omitting the conversion factor of Planck’s constant. Visible light photons have energies equivalent to ~1/2 million GHz.) This minimum occurs at a separation near 71 Å (1 Å is the radius of the hydrogen atom, is ~50 trillionths of a meter) and a repulsive wall that never lets the atoms get closer than about 55 Å. (In contrast the common diatomic molecule formed from two oxygen atoms, O2, the atoms are separated by about 2.4 Å.)

The long-range molecular state is entirely determined by the properties of the separated atoms. However unlike a single atom, a diatomic molecule can absorb light at frequencies which excite vibrational motion (that is, motion of the two atoms toward or away from each other) or rotational motion (where the two atoms spin as if at the ends of a twirling baton). Because the molecule is a quantum system, these motions occur at sets of discrete vibrational or rotational energies. Careful measurement of the photoassociation spectrum of the long-range state, along with theoretical modeling of the line shapes, determines the positions of the rotational lines of the lowest seven vibrational levels to ~5 MHz (1 MHz = 1 million cycle/second). By adjusting the dipole strength used to match these molecular spectra, the NIST researchers determined the Na excited state lifetime to an accuracy of 0.1%. The vast majority of atomic lifetime measurements have uncertainties at least 10 times larger. In addition, the 121 MHz shift in binding energy of the ground vibrational level due to the retardation corrections to the interatomic force is evident from the measurements.

A group at Rice University, led by Randall Hulet, has recently reported a Li atomic lifetime with 0.03% accuracy measured using photoassociation spectroscopy of trapped Li atoms. These researchers did not use a “pure long-range state” of Li2, molecules that experience chemical bonding at short range. The improved accuracy follows from the wider range of lines surveyed, supplemented by conventional spectoscopic data. The Rice group also detected the effect of retardation corrections to the long-range force. The atomic lifetimes determined from these molecular spectra are the most accurate to date for Li and Na. Although these measurements are much more accurate, they agree (within error limits) with other recent determinations, thus essentially setting to rest longstanding questions and discrepancies about the lifetimes of these simple excited atoms. Photoassociation spectroscopy has also determined an atomic Rb lifetime at the 1% level, and work is in progress on K. In addition, conventional molecular spectroscopy on long-range excited states of the Na molecule has also been used to determine the atomic Na lifetime with 0.3% accuracy. In the study of excited-state lifetimes, researchers have therefore made dramatic progress not only in opening new avenues but also in enhancing traditional routes.

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Experimental Realizations of Quantum Thought Experiments

Physicists traditionally construct imaginary experiments, termed “thought experiments,” to explain the strange behavior of physical systems to which quantum or relativity theories (or both) must be applied. These thought experiments “run” only on paper because they are generally technically impossible to realize with hardware in the laboratory. However, a class of thought experiments—in which single atoms, photons, and other quantum systems are precisely manipulated and observed—have recently become possible to realize in real experiments in quantum optics laboratories. Some of the most intriguing experiments involve investigations of the behavior of quantum parts of a total quantum system. These new studies have provided fundamental insights into the quantum nature of the electromagnetic field. Physicists traditionally construct imaginary experiments, terms “thought experiments,” to explain the strange behavior of physical systems to which quantum or relativity theories (or both) must be applied. These thought experiments “run” only on paper because they are generally technically impossible to realize with hardware in the laboratory. However, a class of thought experiments—in which single atoms, photons, and other quantum systems are precisely manipulated and observed—have recently become possible to realize in real experiments in quantum optics laboratories. Some of the most intriguing experiments involve investigations of the behavior of quantum parts of a total quantum system. These new studies have provided fundamental insights into the quantum nature of the electromagnetic field. Physicists traditionally construct imaginary experiments, termed “thought experiments,” to explain the strange behavior of physical systems to which quantum or relativity theories (or both) must be applied. These thought experiments “run” only on paper because they are generally technically impossible to realize with hardware in the laboratory. However, a class of thought experiments—in which single atoms, photons, and other quantum systems are precisely manipulated and observed—have recently become possible to realize in real experiments in quantum optics laboratories. Some of the most intriguing experiments involve investigations of the behavior of quantum parts of a total quantum system. These new studies have provided fundamental insights into the quantum nature of the electromagnetic field.
field, the “spooky” (in the words of Einstein) entanglement between a pair of quantum systems, and the way in which the dissipation of energy in a system can destroy its quantum-mechanical properties. Central to these experiments is the Jaynes–Cummings model, a long-time favorite of theorists. It describes the behavior of a composite system consisting of a two-level quantum system (one with two possible energy levels, such as an electron in a magnetic field) coupled to a quantum-mechanical system that is a simple harmonic oscillator (a system with many equally spaced energy levels, such as a tiny weight attached to a spring). Two groups working independently have now realized good approximations of this ideal model and performed complementary experiments which test fundamental aspects of quantum mechanics. One example consists of dramatic experiments performed at the Ecole Normale Supérieure (ENS) in Paris. In these studies, a two-level system interacts with a single quantized harmonic oscillator—namely, a microwave field inside a superconducting cavity, consisting of a pair of closely spaced niobium slabs. Readers given to shower stall arias are familiar with the resonant properties of soundwaves in a small enclosure. In a highly refined miniature version operating with microwave electromagnetic fields. By virtue of its shape and the high conductivity of its walls, it can contain electromagnetic microwave fields only with certain discrete frequencies and localized spatial properties. Classical, nonquantum physics describes a sinusoidal cycling of energy between the atom and the cavity’s microwave field. Quantum mechanics, however, dictates that the microwave field may take up energy only in discrete steps. These steps manifest themselves as individual packets of energy known as photons. Until this work, the discrete nature of the coherent exchange of energy between an atom and the quantized electromagnetic field had not been clearly demonstrated. The ENS has provided the first experiment explicitly demonstrating the effect of field quantization on the interchange of energy between field and atom. In the experiment, the physicists first cooled the cavity to the zero point, the minimum-energy quantum field state corresponding to the presence of zero photons in the cavity. Quantum theory says that every harmonic oscillator has a zero point state with a minimum, but nonzero, energy. For the electromagnetic field this energy is half that of a single photon. But our strange quantum world actually permits an undisturbed, unmeasured quantum system to “exist” in many quantum states simultaneously. When the ENS team added microwave energy to the cavity, the cavity’s electromagnetic field simultaneously entered into a superposition of states which is sent through a cavity containing the microwave field and entangled, classically valid positions of the atom play the role of the living or dead. The ENS counterpart of this Schrödinger cat state is a superposition of two microwave fields with different phases (different relative positions of the wave’s crests and valleys) simultaneously present in the cavity. A single atom in a superposition of states is sent through a cavity containing the microwave field and entanglement ensues between the electronic state of the atom and the cavity field state, which depends on the phase. The field state superposition can then be analyzed by observing interference effects in the energy state of a subsequent atom crossing the cavity. The investigation of such “cat states” opens the way to the study of the much debated quantum decoherence phenomenon, in which the dissipation of energy can lead to a breakdown of a system’s quantum properties. As shown by the Paris group, another relativistic approach, the relativistic exchange of a photon between the atom and the cavity field is sensitive to the unavoidable exchange of energy between the entire system and its environment as the separation between the atom and cavity is increased. By varying the number of photons in the cavity and monitoring the rate at which the quantum interference effects disappear, physicists now can study quantitatively how quantum interference phenomena vanish in the macroscopic world.

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The following items are meant to provide a brief summary of new particle beam developments over the past year at a number of accelerators around the country.

Thomas Jefferson National Accelerator Facility
Formerly called the Continuous Electron Beam Accelerator Facility, this $600M construction project was completed on schedule and within budget. It was officially dedicated on May 24, 1996 and renamed the Thomas Jefferson National Accelerator Facility (Jefferson Lab). The performance of the accelerator has been excellent, delivering in the last 10 months over 3200 h of beam time for physics. Superconducting accelerator cavities have performed so well at a nominal energy of 4 GeV that a 5 GeV run is planned for early 1997, while 6 GeV is expected in early 1998. Initial data show that the accelerator is stable enough for serious parity-violation experiments. In one of the experimental areas, Hall C, the equipment is installed and fully functioning for users. Five experiments have run, with two more expected to be complete by the end of the calendar year. The first beam has been sent to Hall A, and Hall B is on track for completion with all six calorimeters installed and a first commissioning run scheduled for after Thanksgiving 1996. (See the related article in the Nuclear Physics chapter.)

Stanford Linear Accelerator Center
SLAC’s newest accelerator, the Next Linear Collider Test Accelerator (NLCTA) reached a major milestone in August with the first electron beam accelerated to 65
MeV with an acceleration gradient of 50 MeV/m. The NLCTA is part of SLAC’s on-going development of accelerator and microwave power technology for a future electron–positron linear collider, dubbed the “Next Linear Collider” (NLC). The NLCTA operates at a radio frequency of 11.4 GHz, four times the SLAC frequency and with a gradient more than double that of the SLAC linac.

Snowmass Meeting on the Future of Accelerator-Based Physics in the U.S.

Nearly 500 physicists attended a three-week-long workshop at Snowmass, Colorado to contemplate the future of accelerator-based physics in the U.S. The meeting this year marked a turning point in the collective recovery from the cancellation of the SSC, which itself grew out of a discussion at the 1982 Snowmass meeting. The participants considered a first-time move to support a large project over seas, the Large Hadron Collider (LHC) at CERN. They also considered the Next Linear Collider (NLC) electron–positron collider based on the presentation of the extensive Zeroth-Order Design Report for the NLC. The participants discussed various advanced acceleration techniques, possible upgrade plans at the Fermilab Tevatron, ideas for a muon collider, and concepts for a large hadron collider.

Los Alamos National Laboratory

The Accelerator Production of Tritium (APT) Facility plans call for an accelerator with an average beam power of over 150 MW. The APT would produce tritium in sufficient quantities to replace the amount that decays owing to the 12.3-year half-life. The APT design is based on a 1700 MeV, 100 mA cw beam of protons produced by a linear accelerator. The beam strikes a tungsten target producing neutrons that are moderated in a surrounding blanket and then captured in helium-3 to make tritium. The assembly and testing of the 20 MeV Low Energy Demonstration Accelerator (LEDIA) has started at LANL. The proton injector for LEDIA routinely provides 120 mA at 75 keV with the required beam quality. The project is headed by LANL and includes LLNL, BNL, and Westinghouse Savannah. The DOE has selected Burns and Roe Enterprises, Inc. as the prime contractor.

Sandia National Laboratory, Particle Beam Fusion Accelerator

The PBFA-Z achieved a milestone by generating 1.6 MJ of soft x rays by operating in the z pinch mode. A plasma pinch is created by passing the stored energy of the PBFA through an array of tiny wires. The pulse of current in the axial, or Z, direction causes the plasma to implode, releasing over half of the stored energy in an x-ray pulse. In the PBFA-Z experiment, the peak x-ray power was about 110 TW, and the x-ray pulse width was about 8 ns full width at half-maximum. X-ray data were taken using x-ray diodes, resistive bolometers, time-integrated and time-resolved spectrometers, and phasemetering detectors. The x-ray pinhole consisted of 120 tungsten wires, 10 µm in diameter, configured in a cylindrical array at a diameter of 4 cm and a length of 2 cm. The design goal for PBFA-Z is 1.5 MJ and 150 TW of x-ray energy and power. This energetic, intense source of soft x rays will be used in experiments at high energy density for studying intrinsically confined fusion (ICF), weapons physics, and weapons effects applications.

Fermilab

On February 25, 1996 the 1994–96 Tevatron collider run ended and the reconstruction of the Tevatron (where protons and antiprotons are collided head on) in support of fixed target operations began. The success of this extremely long running period can be measured partly in terms of luminosity, the parameter (in units of inverse “barns,” equivalent to a cross section of 10⁻²⁴ cm²) which describes the intensity of the proton and antiproton beams that are brought to bear in the interaction areas. In this case the integrated luminosity of about 150 inverse picobarns was delivered to each of the two detectors (CDF and DØ), while the peak luminosity was 2.5 × 10³⁹ cm⁻²·sec⁻¹—25 times the initial Tevatron performance specification. Data collected during this run led to the long-sought discovery of the top quark (see Physics News in 1995, p. 55).

Significant progress has been made on the Main Injector project at Fermilab. The project is approximately 70% complete with commissioning expected to commence in Spring 1998. The goal is to improve by a factor of 5 the collider luminosity. In addition, a design has been completed for a new antiproton storage ring, the “Recycler,” which would reside in the existing main injector enclosure and boost luminosity performance by an additional factor of 2. This project is currently under review by the Department of Energy. Longer term efforts at Fermilab include R&D into electron cooling, muon colliders, and plasma beat-wave acceleration.

Biological Physics

Stochastic Resonance Moves Toward Medical Science. The phenomenon of “stochastic resonance” describes how introducing a certain amount of noise into a system can actually increase the transmission or detection of a signal so as to maximize the signal-to-noise ratio. First explored in climate studies and then in laser science, stochastic resonance has turned, in the past few years, towards understanding how biological organisms may use noise to enhance the transmission of weak signals through nervous systems. Frank Moss of the University of Missouri at St. Louis and William Ditto of Georgia Tech describe new experimental results in which researchers have used stochastic resonance to boost the transmission of a weak signal in rat brain tissue. Moss and Ditto also describe a study in which noise increased the distinguishability of electrical signals in a frog nervous system having similar structural and electrical characteristics to those of the human auditory nerve.

Peptide and Receptor Protein Signature Matches. A protein binds into its final three-dimensional shape from a one-dimensional sequence of building blocks called amino acids. In efforts to identify the proteins that bind to specific receptors in the body, researchers have come up with a tool for computing characteristic signatures for proteins and receptors based on their one-dimensional amino acid sequence. Each of the 20 different amino acids from which all proteins are composed is assigned a value of hydrophobicity, that is, the degree to which it repels water. One then constructs a sequence of hydrophobicity values from which distinctive signatures can be determined. Viewing proteins in terms of their hydrophobicity is a reasonable approach, because proteins naturally exist in a water-based environment and many of their properties depend on how they interact with the water that surrounds them. In their article Arnold Mandell and Karen Selz of the Emory University School of Medicine, and Michael Shlesinger of the Office of Naval Research report that this powerful new method has uncovered intriguing new details about the binding of certain hormones and neurotransmitters in the brain, such as those which transport dopamine.

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AIP

Stochastic Resonance Moves Toward Medical Science.

Stochastic resonance (SR) is the phenomenon whereby information about a weak, nontriggering signal is detected or transmitted through a system by the action of random processes, or noise. Since single neurons are, in the simplest view, detectors triggered by incoming signals exceeding a certain threshold, they are ideal systems in which to demonstrate SR. But can this process operate in networks of neurons, for example, as an aid to the processing of information? An answer to this question was provided by the work of Paul Moss and his colleagues at the University of Mississippi.

In the first, SR has been demonstrated for the first time in mammalian brain tissue. A weak electric field, comprising both signal and noise, was imposed on a slice of rat hippocampus, a brain region essential for memory and other tasks. The slice was cut parallel to the plane where the neurons convert incoming signals into electrical nerve impulses. In this way, a weak signal can be applied via the field to all neurons in the network, a configuration which had been studied previously only in simulations. Recording from a cell body within the network revealed SR as the noise intensity was increased, as shown by (a) in Fig. 1. In the second, SR has been shown to increase the distinguishability of the electrical signals recorded by a simple nervous system that is similar to the human auditory nerve. The signals had a range of characteristic frequencies, called the “tonic” frequencies, corresponding to those of spoken vowels. The experiment was performed on the sciatic nerve of the toad *Xenopus*, this well-understood system has structural and electrical similarities to the human auditory nerve. The sciatic nerve was stimulated by an external source, and the combined neural response of many of its nerve fibers was recorded.

In this process, as well, the tissue sample consists of many active elements connected in parallel, all subject to the same weak signal. Noise was added to signals which mimic electrical stimuli applied by cochlear implants to

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the auditory nerves of profoundly deaf patients. SR was observed in the response of the nerve as shown in (b) of Fig. 1. This experiment suggests that SR may be only a few steps away from a practical application of importance to hearing-impaired people.

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Peptide and Receptor Protein Signature Matches

Proteins are the workhorses of the body, carrying out myriad biological functions. Each protein is composed of a relatively short linear chain of amino acids, which range in length from the 18–140 amino acid peptide messengers (which include hormones) to the generally 200–2500 amino acid membrane receptors. For a peptide messenger to initiate or terminate an action, it must bind to a receptor protein. Peptides with a specific sequence can be made in the laboratory. Whether a given peptide will bind a given receptor has traditionally been resolvable only through trial-and-error experiments. Generating peptides to act on a known receptor has usually been approached through random permutation followed by tests to see if and how well they bind to that receptor. Taking an alternative approach, we have had success in addressing the question of binding by computing characteristic signatures for each peptide and receptor based on their one-dimensional amino acid sequence.

Specifically, we look at each amino acid’s hydrophobicity, a value that reflects its local water-repelling characteristics, and use the series of these values which correspond to the amino acid sequence to make a hydrophobic representation of the peptide or receptor protein. Each of the 20 amino acids from which all proteins are composed can be assigned an estimated real value between 0 and 3.77. Through a cascade of linear transformations, we use this hydrophobic sequence to compute a hydrophobic signature for each peptide or receptor protein. When these values are relatively similar the peptide messenger and receptor bind; when they are disparate they do not.

We have used these signatures to successfully match peptide messengers with transmembrane brain opioid receptors (the binding sites for opiate-like substances such as endorphins), and in other systems to uncover testable, previously unknown binding relationships. As an example, our analysis (see Fig. 2) finds a signature match between corticotropin releasing factor (CRF, a hormone that acts on the brain’s hypothalamus) and its receptor. There is a mismatch, however, between CRF and a mutant CRF receptor (found in patients with a pituitary-adrenal glandular disorder) known not to bind to CRF.

Additionally, this analysis may have clarified a mystery. The gastrointestinal peptide CCK is known to affect brain levels of the neurotransmitter dopamine, but our analysis showed a mismatch between the CCK and dopamine receptor signatures. We did find a signature match between CCK and DAT, a dopamine-transport peptide. This suggested to us that it might be fruitful to examine dopamine binding to DAT alone and with CCK present. These experiments are being carried out in collaboration with Mike Owens and Charles Nemeroff at the Emory University School of Medicine. Preliminary evidence suggests that CCK may reduce dopamine binding to DAT by as much as 50%.

Knowledge that a peptide binds to a receptor does not address what the effect of this binding is, but it is a necessary first step. We are now completing the development of algorithms such that we can use the signature of a known receptor to generate a small set of new peptides (amino acid sequences) that will bind to the receptor, some of which should initiate or terminate biological functions.

In the past year, chemical physics has seen great advances in understanding the forces that molecules experience in complex condensed-matter environments. The three examples featured below each provide new perspectives and challenge existing concepts of molecular dynamics.

**Vibration Echoes.** A novel experimental technique, known as picosecond echo spectroscopy, is providing new insights into the vibrational properties of molecules. Earlier echo experiments, first developed in the 1970s, probed small gaseous molecules like CHF using microscopic pulses of infrared radiation to excite the vibrations. However, Michael D. Fayer of Stanford University has recently extended these methods to complex condensed-matter systems where changes in vibrational properties can occur millions of times faster than those in gases. His research is providing a unique window into the nature of the energy fluctuations in liquids, gases, and proteins. Dissecting the vibrational-energy spectrum of a condensed-matter system over a wide range of temperatures represents a significant advance in vibrational spectroscopy.

**Fast Protein Folding.** Just a few years ago, investigations of protein folding were confined to the arena of classical biochemistry and the “ultrafast” steps in folding were those faster than a millisecond. As a result of a combination of theoretical and experimental advances, these questions have sharpened. Studying the forces which change a protein’s complex shape has become an exciting part of chemical physics in which the time range has been extended to the picosecond regime and quantitative macroscopic and atomic-level descriptions are now expected. Experimental challenges include the design of methods whereby the folding or unfolding process can be triggered, and the refinement of spectroscopic techniques that are able to detect time-dependent changes in structure. In a fast-folding experiment of William A. Eaton and his coworkers at the National Institutes of Health, a laser pulse starts the folding process by dissociating the carbon monoxide that maintains the unfolded protein structure. The folding steps were studied by measuring the electronic spectra of the protein.

**Snapshots of Electrons at Interfaces.** Chemical reactions that occur on metal surfaces are greatly dependent upon the exchange of electrons between the metal and adsorbed atoms and molecules on the surface. Therefore it is of great importance to determine the properties of electrons on the surface, particularly as these may be modified by the presence of adsorbates. Charles B. Harris and his colleagues at the University of California at Berkeley and Lawrence Berkeley National Laboratory have greatly advanced our understanding of surface electronic states by devising techniques whereby electron localization and the vibrational properties of the metals are studied in real-time with fs pulses.
The vibrational echo experiment involves a two-pulse excitation sequence. The first pulse puts each solute molecule’s vibration into a superposition state, which is a mixture of the lowest-energy vibrational level and the next higher-energy level. The vibrational echo experiment reveals homogeneous energy fluctuations in spite of a broad inhomogeneous distribution of vibrational energies, because the technic of the vibrational echo experiment involves the addition of another laser pulse (the second pulse) at a variable offset from the first laser pulse (the echo). The second pulse, entering the sample at a time $t_2$ after the first pulse had exited the sample, produces a peak or “line” in the spectrum. Vibrational spectra of even large molecules reveal beautiful structure, a large number of lines that can be assigned to the various types of modes that occur in a molecule. The position of a peak associated with a particular mode gives the energy of the vibration. In a molecule isolated from its surroundings, vibrations have energies that do not change with time. In a solvent, the vibrational energies are shifted, and they reflect an average influence of the solvent on the molecule that does not change with time. But there is an additional factor in a real-world condensed-matter system. At a given temperature above absolute zero, the system gains heat. These excited molecules are continually moving. Since interactions between molecules depend on the distance between them and their orientations, the interactions inherently change over time. Thus the vibrational energies, which reflect the molecular structure, are time dependent; they are constantly fluctuating. These fluctuations are intrinsically involved in chemical processes, and they can also provide information on the solvent and how it interacts with dissolved species.

Even a well-resolved vibrational spectroscopic line generally does not provide information on dynamics (how motions of a solvent or protein influence the molecule). A vibrational absorption peak is usually extremely narrow. A vibrational absorption peak will absorb infrared light over a range of wavelengths, giving the vibrational line a width and shape. In principle, dynamical information is contained in a spectroscopic line shape. However, the line shape is also caused by the essentially static structural perturbations associated with the distribution of arrangements of solvent molecules or parts of a protein that surround and interact with the molecule of interest (inhomogeneous broadening). For example, carbon monoxide (CO) binds to the active site of myoglobin, a protein found in muscle tissue. The vibrational lineshape of CO, measured in an absorption spectrum, is wide because CO (CO) binds to the active site of myoglobin, a protein found in muscle tissue.

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FIGURE 2. Measuring the rate \( k_{D+} \) for two regions of an unfolded protein to come in contact by diffusion (adapted from Ref. 10). A laser pulse dissociates carbon monoxide (not shown) from an iron-containing molecule known as a “heme” (ellipsoid) which is covalently connected to a chain on the protein. (Upper) In the “unimolecular” experiment (involving chemical interactions within a single molecule) the amino acid methionine (sphere) separated by about 50 amino acids along the protein chain can now bind at the site vacated by the carbon monoxide. (Lower) The equivalent “bimolecular” experiment (involving interactions between two separate molecules) can be carried out with free methionine and a heme (ellipsoid) attached to a small amino acid chain cut from the protein. Since the rate of chemical bond formation \( k_{R} \) (and of chemical bond dissociation \( k_{D-} \)) is presumed to be the same in the two experiments, the unimolecular diffusion-limited rate \( k_{D+} = k_{D-} \) (3 × 10^5 s^-1) can be calculated from the observed overall unimolecular and bimolecular binding rates (using well-established theory to calculate the missing quantities).

Snaphots of Electrons at Interfaces

Whether by chance or design, the boundary or interface where two substances meet often dominates the performance of technologically important materials.

For example, interfaces between metals and the semiconductor silicon not only abound in computer microchips but control the operation of the myriad tiny transistors comprising the chip. The all-important role of interfaces arises because of the abrupt change in structure (where the atoms are and how they are bonded to one another) at these locations. These changes invariably affect the behavior of electrons at the interfaces and these in turn affect overall properties such as chemical reactivity, electrical conductivity, and magnetism.

To understand the fundamentals of how electrons behave at interfaces and, in particular, to investigate how electronic behavior changes with time (electron dynamics), researchers at the University of California at Berkeley and the Lawrence Berkeley National Laboratory led by Charles Harris have been studying electrons at interfaces using lasers whose wavelength can be adjusted (tunable lasers) while emitting ultrashort pulses of light lasting only a few femtoseconds (fs). After each pulse of laser light, they record the spectrum of kinetic energies of electrons escaping from the sample as the result of absorbing the laser light, a process known as photoelectron spectroscopy. By measuring photoelectron spectra at different times after the laser pulse, they were able to study the dynamics of electrons at interfaces at intervals as short as 30 fs. Additional information comes from measuring the electron emission angle as well.

Except for those electrons tightly bound to atomic nuclei, electrons in metals are normally free to roam throughout the material and are said to be “delocalized” because the quantum-mechanical wavefunctions that describe these electrons extend throughout the metal. One important thing that happens near an interface (including a surface, which is the special case of an interface between a solid and a gas or vacuum) is that the delocalized electrons can become confined (they become localized) in one or more directions. To take one example, an extra electron near a metal interface results in the buildup of a separation of positive and negative electrical charge perpendicular to the interface. This separation or polarization gives rise to new quantum states called image states. Electrons in image states are held close to the interface but can move relatively freely parallel to it.

Electrons from the image states are sensitive indicators of changes at the interface, so it is the electrons emitted from these states that are studied with the laser-photoelectron spectroscopy technique (schematically illustrated in Fig. 3). Specifically, the special small group investigated the case of a metal covered with a thin layer, consisting of a metal covered by a dielectric overlayer (dielectric vacuum) while the sample was in a vacuum. The overlayer tends to attract or repel electrons—a property called the electron affinity that depends on its composition and associated electrical properties.

When the affinity is negative, the resulting repulsive potential tends to push the electrons in image states away from the metal towards the vacuum. When the affinity is positive, the resulting attractive potential pulls the electrons in image states toward the metal.

The Berkeley experiments have demonstrated that the localization occurs by means of small shifts in the positions of the positively charged atomic nuclei around the negatively charged electron (a local deformation of the crystal lattice). The experiments also measure the lattice reorganization dynamics as they occur in real time.

In contrast, for positive-affinity interfaces, the resulting attractive potential associated with the overlayer forms potential wells that are bounded by the metal on one side and the image potential in the vacuum on the other (Fig. 3b). From

measurements of the angular distribution of the photoemission for a series of different overlayer thicknesses, the Berkeley group was able to completely determine the electron quantum states in the overlayer region and determine how the electron states in the interfacial region changed as the interface was made thicker or thinner on an atomic scale. They were also able to model the results of measurements of the electron dynamics in these states (femtosecond lifetime measurements) in terms of the electron quantum states at the interface (interfacial conduction band structure) and the overlap of the electron’s wave function with the metal.

These measurements, while of a fundamental nature, are directly related to the properties and performance of many new devices, some with potentially large economic impacts. For example, many laboratories are actively investigating structures comprising two metal layers separated by an insulating polymer for use in large, multicolor displays, such as the long-sought flat-screen television. Making long-lived, efficient light emitters depends on understanding what controls the performance of many new devices, some with potentially large economic impacts. These measurements, while of a fundamental nature, are directly related to the properties and performance of many new devices, some with potentially large economic impacts. For example, many laboratories are actively investigating structures comprising two metal layers separated by an insulating polymer for use in large, multicolor displays, such as the long-sought flat-screen television. Making long-lived, efficient light emitters depends on understanding what controls the

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CONDENSED-MATTER PHYSICS

Normal-State Properties of High-Temperature Superconductors at Low Temperatures

To better understand superconductivity in copper oxide materials, it is desirable to study how charge carriers move under normal-state (i.e., nonsuperconducting) conditions. Above the transition temperature this is no problem, but at low temperatures a way must be found to suppress the superconductivity that would otherwise develop. The answer is the use of high magnetic fields. Gregory Boebinger describes new experiments in which the unusual normal-state conduction properties of superconductors are revealed at low temperatures.

**Spin Ladders.** The magnetic properties of arrays of atoms in one-dimensional chains and two-dimensional planes are very different. To understand the crossover from one- to two-dimensional systems, physicists have devised low-dimensional materials from “ladders” of copper–oxide chains. The magnetic interactions among the atoms (arising from the atoms’ magnetic moments, or spins) in various configurations can be quite complicated. Martin Green reviews on theoretical, experimental, and numerical studies of such spin ladders.

**Revealing the Low-Temperature Normal State of High-Temperature Superconductors**

At temperatures above the superconducting transition temperature, superconductors exhibit a so-called “normal state,” in which the motion of charge carriers is accompanied by electron dissipation, which leads to the finite resistivity observed in ordinary metals. In high-temperature superconductors, the normal state is two-dimensional: charge carriers travel easily within those parallel planes of the crystal which consist of copper and oxygen atoms, while motion between different copper–oxygen planes is difficult. The two-dimensional normal state of the high-temperature superconductors is highly unusual, characterized by optical, magnetic, and transport properties unlike anything previously studied. These normal-state properties are sufficiently strange that many physicists believe they hold the key to eventually understanding the physical mechanism for high-temperature superconductivity. One example is the normal-state resistivity; as the crystal is cooled, the “in-plane” resistivity decreases linearly with temperature, while the “out-of-plane,” or “c-axis,” resistivity, increases rapidly with decreasing temperatures. This contrasting behavior between the “metallic” in-plane resistivity and “insulating” c-axis resistivity persists down to the superconducting transition temperature Tc. Below Tc, the behavior of the normal-state resistivities is hidden by the presence of superconductivity. A recent series of experiments1 has utilized an intense magnetic field exceeding 60 T (600,000 G, or 1.5 million times the Earth’s magnetic field) to destroy the superconductivity and reveal the low-temperature behavior of the unusual normal-state resistivities in the high-temperature superconductors.

As shown in Fig. 1, the superconducting transition temperature can be optimized by tuning the concentration of charge carriers. Charge carriers can be either electrons or holes, their less commonly known positively charged analogs. In most of the high-temperature superconductors, the charge carriers are actual holes (i.e., a varying the hole concentration is accomplished in the case of La2-xSrxCuO4 (LSCO) by varying the Sr content x. Figure 1 shows that the maximum Tc (40 K) in LSCO is achieved for x = 0.16 (arrow), which is thus called “optimum doping.” If the carrier concentration is reduced below the optimum doping, Tc is reduced and superconductivity is eventually destroyed. Compounds in this region are non-superconductors (“INSUL.,” in Fig. 1), that is, the resistivities increase with decreasing temperature and extrapolate to an infinite resistivity (no current flow) in the limit of zero-temperature limit. In this regime, the compounds exhibit “variable range hopping,” a well-known type of conduction in which charge carriers are mostly localized near individual impurities and hop between impurities in response to an applied electric field. Near the transition between insulator and superconductor, both variable range hopping and an unusual logarithmic dependence of the in-plane resistivity6 have been reported.

Increasing the carrier concentration above optimum doping also decreases Tc until the destruction of the superconducting state reveals a metallic phase (“METAL” in Fig. 1), which shares some of the properties of a conventional metal, but retains some evidence of the unusual linear temperature dependence of the in-plane resistivity that is evident in samples near optimum doping. One would like to study the insulator-to-metal crossover in the normal state; however, once again the superconducting phase (“SUPERCONDUCTING” in Fig. 1) gets in the way—unless an intense magnetic field is applied.

**Intense magnetic fields provide a relatively gentle way to destroy superconductivity.** However, in high-temperature superconductivity the unusually large energies involved in forming the superconducting phase require a high temperature or magnetic field to destroy the superconductivity. When a field of 60 T is applied to LSCO, superconductivity is completely destroyed and new features of the normal state are revealed. Figure 2 shows the most obvious new finding, that the insulating phase extends up to optimum doping and that the crossover between insulator and metal occurs very near the same hole concentration which leads to optimum superconductivity, a coincidence which seems difficult to ascribe to mere chance. Furthermore, while the insulating phase in compounds without strong superconductivity (x less than 0.06) exhibits conventional variable-range hopping, the insulating phase in the shaded region of Fig. 2 is revealed to be quite unusual in that both the in-plane and c-axis resistivities diverge as the logarithm of the temperature.

Future high-magnetic field experiments will seek to determine which of the strange new normal-state behaviors revealed in LSCO are common to other high-temperature superconductors. Many of the high-magnetic field properties of such large Tc’s (e.g., near or above 100 K) that still more intense magnetic fields would be required to perform these experiments, but the puzzle of high-temperature superconductivity provides strong incentive to build still stronger magnets.7

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1. For example, see P. W. Anderson, Science 266, 1526 (1992).
Spin Ladders

Low-dimensional magnets, materials in which magnetism arises from a configuration (such as a chain or plane) of atoms with a dimensionality less than three, exhibit fascinating collective properties at low temperatures, largely owing to the increased importance of quantum mechanical effects. Research in this area is bringing new insights to the study of magnetism and may also lead to the development of new materials, known as superconductors.

In the 1930s, Bethe studied what could be considered one-dimensional (1D) magnetism. He looked at the Heisenberg-type interactions of atoms in a simple 1D antiferromagnetic chain. That is, the spins of neighboring atoms (each with a value of $S = 1/2$) prefer to orient themselves in opposite directions. He found that because of quantum fluctuations (the propensity of spins to spontaneously flip occasionally) the correlation of spins along the chain would slowly decay with increasing distance, even at a temperature of absolute zero.

In the 1980s, Haldane suggested that chains of atoms with integer spin ($S = 1, 2, \ldots$) would behave very differently from those with half-integer spin values ($S = 1/2, 3/2, etc.$). For integer spin values, he predicted that the ordering of spins would decrease much faster—indeed exponentially fast with distance—and that the spins would essentially constitute a quantum mechanical “spin liquid.” These two different types of quantum ground states would lead to fundamentally different thermal properties for integer and half-integer spin chains. There is now much evidence for the correctness of Haldane’s famous conjecture, which initially took a small measure, due to the availability of tunable x-ray sources of high brilliance and weakly diffracting crystals. Tunability is the ability of “dialing in” the wavelengths accepted. High brilliance permits collection of quality data from small crystallography samples in a reasonable time.

The Advanced Photon Source (APS), the first third-generation synchrotron source in the hard x-ray range in America, was dedicated on May 1, 1996. This milestone in the hard x-ray range in America, was dedicated on May 1, 1996. This milestone was the beginning of a bright future for the community of structural investigators in general and in particular for macromolecular crystallographers, scientists devoted to the study of the structure and function of proteins and other large molecules.

Synchrotrons are devices that accelerate charged particles within circular orbits; synchrotron radiation is the electromagnetic radiation given off tangentially from the ring as the particles are confined to their circular orbits. Because the electrons travel around the ring in bunches, the radiation beam itself consists of pulses approximately corresponding to the time it takes for the bunches to complete an orbit. Critical characteristics of synchrotron radiation for macromolecular crystallography are high brilliance, tunability, and the time-resolved structure of the beam. Brilliance is an indication of the intensity (photons/second) of the beam as seen on a unit area, unit of angle, and within a narrow band (0.1%) of wavelengths accepted. High brilliance permits collection of quality data from small and weakly diffracting crystals. Tunability is the ability of “dialing in” the wavelength of the x rays (akin to selecting the color in the visible spectrum) to perturb certain heavy atoms in the atomic structure. This facilitates dramatically the determination of the protein structure by collecting data at different wavelengths and combining the observations by the method of multilength anomalou diffraction (MAD). The time-resolved nature of the beam can be utilized to analyze enzymatic processes typically at the milli-to-micro second time scale.

It is often not realized that the dramatic increase in the number and complexity of the macromolecular structures determined in the last decade or so is, in no small measure, due to the availability of tunable x-ray sources of high brilliance and weakly diffracting crystals. Tunability is the ability of “dialing in” the wavelength of the x rays (akin to selecting the color in the visible spectrum) to perturb certain heavy atoms in the atomic structure. This facilitates dramatically the determination of the protein structure by collecting data at different wavelengths and combining the observations by the method of multilength anomalou diffraction (MAD). The time-resolved nature of the beam can be utilized to analyze enzymatic processes typically at the milli-to-micro second time scale.

A Brilliant Star in the Midwest Illuminates the Future of Macromolecular Crystallography

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FIGURE 1. Analysis of the structures of macromolecules using synchrotron radiation. Proteins or macromolecules of biomedical interest are cloned, expressed, and produced in milligram quantities using DNA recombinant technology. Samples are crystallized (top left), exposed to x-rays and complete diffraction data (bottom left) are collected to determine or “solve” the structure. The availability of tunable x-ray sources of high brilliance such as the APS (top right) dramatically accelerates the process of structure determination of biological macromolecules of various sizes (bottom right). The knowledge of the three-dimensional structures of protein targets is extremely valuable to design more effective drugs and to engineer proteins with specific and novel catalytic properties. (Photos courtesy of Cele Abad-Zapatero, Abbott Laboratories, and Susan Barr, Advanced Photon Source, Argonne National Laboratory.)


Recent Developments in Physics Education Research

Physics education research (PER) focuses on improving instruction by studying how students learn the complex concepts of physics. Although this type of work has been going on for decades, it is only within the past few years that the field has seen substantial growth. An expanding international body of scholars has been driven to employ PER as a recognized subfield of physics. This has been promoted by disseminating findings from many studies which highlight the ineffectiveness of traditional instruction. Upon discovering substantial weaknesses in understanding among even their best students, faculty are usually eager for a scientific approach to addressing the problem. The PER field seeks to understand and develop new methods of teaching. The strong interaction between PER, curriculum development, and teacher education is a hallmark of the field.

There continues to be a deepening examination of student understanding of the topical areas of physics, including mechanics, optics, electricity, thermodynamics, and even relativity and quantum mechanics. 1-3 Teachers at the high school and college levels are probing their students’ knowledge through the use of research-based testing instruments like the Force Concept inventory, the Mechanics Diagnostic test, and the Conceptual Physics Inventory. These tools are designed to determine students’ understanding of the material. In fact, PER studies 4-10 generally indicate that most successful instructional techniques appear to be those that account for preexisting ideas brought into the classroom and that emphasize student activity and involvement with the material.
ing in light of hands-on activities that challenge their intuition.

Several new research-based textbooks1,2 and instructional software packages have been published recently. National meetings of the American Association of Physics Teachers also host a rapid growth in the number of talks, tutorials, and workshops dealing with the findings and classroom applications of PER. Teacher education is expanding at all levels, by virtue of several important efforts for elementary teachers and dozens of projects involving college faculty. One of the most exciting approaches has been the effort to find cost-effective ways of applying PER in classrooms. The first detailed test of this approach has been demonstrated in small classrooms, to large enrollment sections.

The Raleigh Conference on Issues in Physics Education Research, held in October of 1994, was an important milestone for PER. At the meeting, plans were formulated to discuss the establishment of a journal devoted to PER, to develop an electronic network of PER resources, to promote the creation and strengthening of PER groups in physics departments, and to write a position paper on the relation-ship of PER to other subfields of physics. Since then, good progress has been made on all these fronts. Finding ways to improve the learning of physics through scientifically rigorous investigations is proving to be a fruitful and exciting endeavor.

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1. B. Adrian and R. G. Fuller, AAPT Announcer 26, 80 (1996).

NSF Reviews Undergraduate Science Education

On July 11–13, 1996, the National Science Foundation and the National Research Council (NRC) sponsored a conference entitled “Shaping the Future: Strategies for Revitalizing Undergraduate Education” in Washington, DC. The conference was guided by two recently released reports. “From Analysis to Action: Undergraduate Education in Science, Mathematics, Engineering, and Technology” summarized the conclusions of a national convocation organized by NRC and NSF. The April 1995 convocation began the “Year of Dialog,” which ran in parallel with a year-long, nation-wide review of the status of undergraduate education in science, mathematics, engineering, and technology (SME&T), sponsored by NSF.

The review considered all aspects of undergraduate SME&T education including the needs of SME&T majors, nonscience majors, and preservice teachers. Institutions ranging from two-year colleges to research-intensive universities participated, with additional input solicited from government and industry. The resulting report, “Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology,” produced by the Advisory committee to the NSF Directorate for Education and Human Resources, was the first comprehensive review of undergraduate science education in nearly ten years.

Both reports came to similar conclusions, with the primary imperative being that “all students have access to supportive, excellent undergraduate education in SME&T, and that all students learn these subjects by direct experience with the methods and processes of inquiry.” The emphasis is on all students, not just science majors, and a shift in focus from teaching to learning. Both reports agree that significant improvement will require large-scale changes, thus the focus on institution-wide reform. Further information about NSF’s efforts toward undergradu-

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Physics Olympiad

The United States Physics Team consisted of 20 of the most capable high school physics students in the country who have a special interest and ability in physics. Five of these students represented the team and their country in the 27th International Physics Olympiad held in Oslo, Norway in July 1996. The five students represented the U.S. quite effectively, bringing home three gold medals and two bronze medals.

The competition consisted of a five-hour theory exam and a five-hour practical or laboratory exam. The students worked separately and each was graded on his or her own paper. The questions included motion of a charged particle in crossed electric and magnetic fields within a coaxial cable, a calculation of the magnitude of the ocean tidal effect caused by the motion of the earth–moon system, and several shorter questions concerning the electrical resistance of downhill motion of a skier, heat flow due to radiation, heat capacity, and current in conducting wires.

The experimental question involved a physical pendulum, measurement of the acceler-
dation due to gravity, and use of the same apparatus to determine a magnetic field and to measure the magnetic moment of a permanent magnet.

As is true in each year’s Olympiad, the questions were devised and graded by physicists in the host country. The questions and answers are reviewed and ap-
proved by an International Board consisting of 2 delegates from each of the 56 participating nations.

In addition to the physics competition, the program developed by the Norwe-
gian hosts included numerous opportunities to sample Norwegian cuisine and culture and for students of various countries to learn about each other’s cultures and the universality of physics.

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Predicting Supersonic Jet Noise from First Principles

The noise of supersonic jets used in military airplanes is familiar to anyone who has been to an air show. Smaller-sized supersonic gaseous jets are used in many manufacturing and materials processing applications and can be a signifi-
cant source of noise in an industrial plant. It is now possible to calculate, from first principles, the noise that is radiated by a jet (a continuous stream of air or other fluid) that is supersonic (travels faster than sound) and turbulent (exhibits irregu-
lar flow with random variations in space and time). These first-principle calcula-
tions of supersonic jet noise involve numerical simulations based on the basic

mass, momentum, and energy conservation equations describing the gas flow. A combination of accurate numerical algorithms with the power of parallel supercomputers is enabling a new fundamental look into what makes some flows more noisy than others. This understanding will, in the future, allow new strate-
gies to make the flows quieter.

However, to achieve this goal researchers must successfully meet several chal-

FIGURE 1: Simulation of the sound field radiated by a supersonic jet. Black lines mark the regions where fluid elements rub against each other in irregular patterns due to turbu-
lence. The grey scale shows regions in which the fluid volume changes; these regions provide a visualization of the acoustic waves radiated by the jet.
Expected Shock Rocks an “Aseismic” Area. Earthquakes occur over wide regions in the continents, but scientists over the years have identified apparently “aseismic” zones that are seemingly free of earthquakes. For example, there are parts of Greece which have had no evidence of seismicity either from historical records or from 20th-century seismological studies. Western Macedonia in Northern Greece was labelled as one of numerous aseismic zones in the region; yet a magnitude 6.6 earthquake struck the center of this assumed aseismic block in May 1995. Scientists went back to the region and conducted “paleoseismological studies,” investigations in which they attempted to uncover evidence of past earthquakes in the region occurring before seismological studies were available. Stathis Stiros of the Institute of Geology and Mineral Exploration in Athens, Greece explains how paleoseismological studies have shown evidence that earthquakes are not unusual for this area. Stiros and his colleagues have also uncovered other earthquake-prone areas that were previously identified as being part of an aseismic region.

FIGURE 1. Seismicity in Greece (inset) and the wider area, 1961–1988, U.S. Geological Survey data (Ref. 1). Earthquake epicenters are confined to narrow zones along plate margins (for instance, the mid-Atlantic Ridge), but are distributed over wide regions in the continents. Inside some of these wide regions are zones traditionally believed to be “aseismic”—(free of earthquakes and active faulting). The 1995 Grevena earthquake of magnitude 6.6 hit one such aseismic area in Greece; its epicenter is marked by a white star. The area around Istanbul, former Constantinople (marked by C) is totally aseismic in the last decades and centuries, but was very active for at least one millennium. A stands for Aegaeum, T for Thrace. (Adapted from Refs. 1 and 2.)

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Another Grevena-type earthquake, but with much more severe consequences. If scientists and governments fail in doing so, we may face the whole spectrum of paleoseismic data is necessary before reliable maps of seismic aseismic zones in Greece and adjacent regions. The most characteristic example is the area of Grevena was in risk of abandonment, and this made necessary the investment of millions of dollars from the government to cover full cost of reconstruction of private and public buildings.

The major shock, however, from this unexpected earthquake was for the inter-national seismological community: theories about continental tectonics and earthquake risk maps in one of the most seismically active and well-studied regions of the world proved unsuccessful, and need to be revised. Some of the questions that arise are: Was this earthquake really unexpected, or was it a systematically recurring event? In the case of the Greenea earthquake what is its recurrence interval and the expected maximum magnitude? Why has this area appeared seismically for at least one century? Can the knowledge obtained from the seismogenic zones of western Macedonia be extrapolated to other apparently seismogenic zones in Greece and other countries?

In order to answer at least some of these questions, “paleoseismological” studies in this area were made. The aim of such studies is to identify traces of, and study major earthquakes which occurred before the advent of seismographs from their effects on the physical environment (permanent deformation, such as surface faulting, coastal land uplift and subsidence) and on ancient constructions. Some of the latter are found either by seismogenic faults, or bearing traces of ground shaking, and they can hence be regarded as “fossil seismographs.”

The first paleoseismic results summarized in Fig. 2 reveal that seismic coastal uplifts, somewhat analogous to those in Crete1 and Alaska,5 or even seismic disas-ters like those identified in archeological excavations,6 7 are not unusual in the study area. Hence, western Macedonia was seismically dormant for around 100 years, but is certainly far from being aseismic.

Palaoseismic evidence of strong earthquakes exists also for other apparently seismogenic zones in Greece and adjacent regions. The most characteristic example is modern Istanbul, the former Constantinople. In the past this city was affected by destructive earthquakes which left their traces on the Byzantine monuments. The dome of the church of Agia Sophia, for instance, collapsed twice during earthquakes, and buttresses were added to prevent a total collapse of the building. In the last centuries, on the contrary, this city is totally aseismic (Fig. 1); houses and other constructions are built without much care, and the risk of a death toll of unprecedented scale during a forthcoming earthquake is high!

The recent Grevena earthquake was, in this aspect, an alert. Seismic safety regulations must not be based entirely on seismograph recordings—study of a whole spectrum of paleoseismic data is necessary before reliable maps of seismic risk are compiled. If scientists and governments fail in doing so, we may face another Grevena-type earthquake, but with much more severe consequences.

3. S. Stiros and R. Jones, eds., Archæoseismology (The British School of Archaeology, Athens, Greece, 1996); also S. Stiros, Eos 69, 1633 (1988).
7. Y. Iakelidze and E. Syamnet-Sokolarti, National Geographic 149, 204 (February 1981).

Ice Mass "Moves" the Earth

Bering Glacier, the longest and largest glacier in continental North America, is now under study from a unique vantage point: space. A series of satellites that estimate precise positions on Earth from space, the Global Positioning System (GPS), is helping scientists study Earth movements and the movement in Bering Glacier, which has recently undergone a major surge. A surge is a periodic, rapid movement of large quantities of ice within a glacier, alternating with much longer periods of near stagnation or retreat. During a surge, ice velocities may increase by hundreds of times their normal values.

Located in southern Alaska, Bering Glacier has ice thicknesses exceeding 1 km. It has undergone at least six surges this century1 and it surged again in 1993–1995.2 When a surge removes ice from the upper reaches of the glacier, its surface lowers by tens or hundreds of meters and ice is added downstream, where the ice thickens and advances the glacier.3 In three consecutive years, surface lowering of as much as 50 m was observed at locations 60–80 km upstream from the advancing face of the glacier. Although the advance of the face of the glacier of up to 9 km has been well documented, the extent and magnitude of surge-related changes in the upper regions of the glacier is less well known. However, satellite and aerial surveys showed that more than 3000 km2 of the Bering’s 5300 km2 surface displayed fracturing and deep cracks indicative of active surging. The mechanics of the surge process is recognized as one of the outstanding unsolved problems in glaciology. Surges are of wider interest because of the possibilities that surging glaciers may impinge upon works of man and that surging of the Antarctic ice sheet may be a factor in the cyclic variations of sea level.4 The Bering Glacier surge, in fact, increased iceberg production and posed a potential threat to the Gulf of Alaska tanker lanes that exit and enter Prince William Sound, about 100 km to the west.

The dramatic changes in a surging glacier’s extent and thickness cause the solid earth to undergo elastic deformations, temporary distortions which disappear after the load of the glacier is removed. Elastic deformations due to the chang-ing glacier load occur instantly. Glacier changes were not the only source of de-f ormation in this region, however. In southern Alaska, two tectonic plates are slowly but continuously colliding as one is forced into the Earth’s interior (Pacific plate) plate bounds with a second, overriding plate, the North American plate. At shallow depths, above ~30–40 km, the plate interface is commonly locked and slips primarily in the upper regions of the glacier is less well known. However, satellite and aerial surveys showed that more than 3000 km2 of the Bering’s 5300 km2 surface displayed fracturing and deep cracks indicative of active surging. The mechanics of the surge process is recognized as one of the outstanding unsolved problems in glaciology. Surges are of wider interest because of the possibilities that surging glaciers may impinge upon works of man and that surging of the Antarctic ice sheet may be a factor in the cyclic variations of sea level.4 The Bering Glacier surge, in fact, increased iceberg production and posed a potential threat to the Gulf of Alaska tanker lanes that exit and enter Prince William Sound, about 100 km to the west.

The recent Bering Glacier surge was, in this aspect, an alert. Seismic safety regulations must not be based entirely on seismograph recordings—study of a whole spectrum of paleoseismic data is necessary before reliable maps of seismic risk are compiled. If scientists and governments fail in doing so, we may face another Grevena-type earthquake, but with much more severe consequences.

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FIGURE 3. Map of the region af-fected by the Bering Glacier surge and the predicted hori-zontal (a) and vertical (b) deforma-tion of the solid earth caused by the ice redistribution. Triangles indicate the global positioning system occupied in June 1993 and 1995, solid triangles indicate the stations nearest to the Bering Glacier. In (a) thin lines outline the major glaciers. The thick line shows the Gulf of Alaska coast-line.

3. S. Stiros and R. Jones, eds., Archæoseismology (The British School of Archaeology, Athens, Greece, 1996); also S. Stiros, Eos 69, 1633 (1988).
7. Y. Iakelidze and E. Syamnet-Sokolarti, National Geographic 149, 204 (February 1981).

PHYSICS AND GOVERNMENT

The year began and ended under very different circumstances. Bitter disputes between the Congress and the Administration led to a shutdown of significant parts of the federal government early in the year, including the National Science Founda-
AIP offers electronically distributed summaries of science policy developments affecting the physics community. FYI, The American Institute of Physics Bulletin of Science and Public Policy News, is available without charge. To subscribe, send an e-mail message to listserv@aip.org. Leave the subject line blank. In the message space, type add fyi.

Functional Magnetic Resonance Imaging

Functional magnetic resonance imaging (fMRI) is a new tool which uses high-speed versions of magnetic resonance imaging (MRI) techniques to noninvasively map the functioning, intact brain. In contrast to conventional MRI, which provides high-resolution images of brain anatomy, fMRI identifies only those brain structures that are actually performing, controlling, or monitoring specific functions. fMRI is more available, less invasive, easier to apply, and yields sharper, faster snapshots of the working brain than the pictures obtainable by previous functional imaging methods. Prime among these earlier methods is positron emission tomography (PET) which uses a radioactive tracer to map metabolic activity of the brain’s response to a specific task.

The principle of fMRI is that the signal used to construct MR images increases by small amounts (on the order of 1%) in regions of the brain cortex that are activated by appropriate sensory stimuli, mental processes, or even the intake of drugs. With current MRI systems, it is possible to monitor changing regional activation patterns in response to stimuli with temporal resolution on the order of 1s and spatial resolution on the order of 2mm. For monitoring a single-image slice of the brain, fMRI images can be obtained in times as short as 100ms at the spatial resolution of MRI.

An example of an fMRI study is shown in Fig. 1. Image data were acquired as a series of images through the brain cortex, while the subject was presented cyclically with two different sound patterns that alternated in time. The tracing shows how the strength of the MRI signal from the human auditory cortex varies over time in response to the cyclic application of the stimulus.

The signal used to construct a MR image is derived from the net magnetization of hydrogen nuclei within tissue water which results from the polarizing effect of the field of the MRI magnet on the human body. Specifically, the MR signal is produced when the magnetization is manipulated by means of electromagnetic pulses applied at radio frequencies to induce an alternating current in a receiver coil placed near the body part of interest. The rate of decay of the alternating current signal is known to be a function of the uniformity of the magnetic-field strength within the local tissue, i.e., the more uniform the field the longer the duration. fMRI relies on the fact that capillaries and red cells within tissues induce changes (gradients) in the magnetic field on a microscopic scale. These microscopic field gradients shorten the signal duration to a degree that depends on the precise value of the blood’s magnetic susceptibility (a quantity that indicates the net magnetization it will acquire when exposed to a magnetic field) which in turn depends on the local oxygen concentration. Because of this, fMRI is also referred to as BOLD (blood oxygenation level dependent) imaging. Blood containing oxyhemoglobin (hemoglobin with oxygen molecules attached to it) has a susceptibility close to that of tissue water, whereas deoxygenated blood (in which oxygen has been removed) is significantly different. An increase in nerve-cell activity produces a flow increase locally that introduces oxyhemoglobin to such an extent that there is a net decrease in the concentration of deoxyhemoglobin. As a result, the magnetic susceptibility within the blood vessels then more closely matches the surrounding tissue than it does when the vessels contain deoxyhemoglobin, and the MR image intensity increases. As the stimulus is cyclically applied and removed the activated area will show a corresponding pattern of increased and decreased signal intensity. It was the work of Ogawa4 and Tumern2 which demonstrated that deoxygenated blood could serve as a natural MRI contrast agent.

fMRI, building on the use of imaging to study brain function established with PET, promises to have a significant impact on the management of clinical patients by differentiating healthy from pathological brain function. fMRI also promises to extend our fundamental knowledge of the human body by mapping various functional neuroanatomy of distributed processing systems within the brain.

fMRI is now being exploited by centers throughout the world to study basic brain function. It is also being evaluated for numerous potential clinical applications. These include the noninvasive mapping of the functions of different re...
gions of cortex, including the identification of brain language areas and other vital regions in patients who are candidates for brain surgery.\textsuperscript{1,2} identification of seiz-
ure foci in epileptics,\textsuperscript{3} sensory and motor-function evaluation in stroke patients and monitoring of fine-motor function in recovering alcoholics. In addition, a variety of neuropsychiatric disorders, including autism, schizophrenia, and Tourette’s syndrome, as well as learning disabilities, dyslexia, and attention disor-
ders, are being better understood and characterized using fMRI.

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NUCLEAR PHYSICS

CEBAF (TINAF) Comes on Line. An important new nuclear physics facility to watch is the Thomas Jefferson National Accelerator Laboratory (TINAF)—for-
merly known as the Continuous Electron Beam Accelerator Facility, or CEBAF. A facility which can accelerate electrons to energies of 4 GeV—and produce con-
tinuous streams of electrons, rather than short bursts, TINAF, located in Newport News, Virginia, has undergone its first experiments. Some of the first experimen-
tal results show off its impressive capabilities, such as high momentum resolution and a potential to perform important studies of nuclei containing strange quarks. Other experimental results are providing information on the interactions between nucleons (protons and neutrons) as they move through the nucleus and investiga-
tions of how the deuteron (a nucleus consisting of a neutron and a proton) dissoci-
ates into a proton and neutron that show how effects at the quark level are impor-
tant; the data support the picture that the six quarks in the deuteron act in a con-
certed fashion as they exchange the gluons that hold them together. John Dirk Waldecka and his colleagues at TINAF describes the first results from this brand new accelerator facility.

More Evidence for Neutrino Oscillations. Neutrinos are chargeless particles abundantly produced in nuclear reactions such as those that occur in the Sun. Like quarks, which come in six types, neutrinos come in three varieties: the ones pro-
duced in the Sun’s nuclear reactions are known as “electron neutrinos.” Neutrinos are notoriously hard to detect because they interact with other particles only via the weak nuclear force. Even when their hard-to-detect nature is accounted for, the flux of electron neutrinos from the Sun reaching Earth-bound detectors is much less than that predicted by the Standard Model of particle physics and our knowl-
edge of the Sun. To address this problem, theorists proposed in the late 1970s and mid-1980s that neutrinos may transform from one type to another. In 1995, ex-
perimenters at Los Alamos announced that they obtained evidence that neutrinos “oscillate” from one type to another. Gerry Garvey of the Office of Science and Technology Policy and Los Alamos now amassed an additional four months of data—with results that remain consistent with the neutrino oscillation scenario. As Garvey explains, if neutrinos oscillate, then they must have mass; whether or not neutrinos have mass has been a long-
standing question since their discovery earlier in the century. The abundant but hard-to-detect neutrinos may therefore constitute some of the invisible “dark” matter that plays a large role in holding together galaxies and clusters of galaxies in our universe.

Simulating the Cosmic Cauldrons. Nuclear physicists have employed innova-
tive techniques in existing accelerators and have explored new ways of ob-
taining their abilities to produce beams of short-lived nuclei with energies similar to the nuclei found in stars. Experiments at accelerators around the world are creating conditions that simulate the nuclear processes responsible for making medium- and heavy-elements in stars. Such studies may provide insights into the exact chain of nuclear reactions inside stars as they manufacture the elements that appear in the periodic table. As Walter Henning of Argonne National Laboratory explains, researchers are also employing beams of short-lived nuclei to create reactions that may not occur in stars, but may indirectly provide invaluable information on astrophyysical properties. For example, the breakup of the boron-8 nucleus—which can occur through electromagnetic, not nuclear, forces—can provide information on the reverse reaction in which boron-7 combines with a proton to make boron-8. This process can, in turn, provide information on fusion reactions involving protons in our sun and even neutrino oscillations in nuclear reactions.

CEBAF (TINAF) Comes on Line

On Sunday morning, May 26, 1996, at a plenary session of the Particles and
cosmic Cauldrons. Nuclear physicists have employed innovative techniques in
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beams of short-lived nuclei with energies similar to the nuclei found in stars. Experiments at accelerators around the world are creating conditions that simulate the nuclear processes responsible for making medium- and heavy-elements in stars. Such studies may provide insights into the exact chain of nuclear reactions inside stars as they manufacture the elements that appear in the periodic table. As Walter Henning of Argonne National Laboratory explains, researchers are also employing beams of short-lived nuclei to create reactions that may not occur in stars, but may indirectly provide invaluable information on astrophyysical properties. For example, the breakup of the boron-8 nucleus—which can occur through electromagnetic, not nuclear, forces—can provide information on the reverse reaction in which boron-7 combines with a proton to make boron-8. This process can, in turn, provide information on fusion reactions involving protons in our sun and even neutrino oscillations in nuclear reactions.

Ben P. Stein
AIP
Second, during the experiment E91-13, a brief test of the CEBAF Large Acceptance Spectrometer (CLAS) in Hall C collaborated in this experiment an electron collides with a proton, the nucleus of the electron is called a deuteron, and a K meson (a kaon) is detected in coincidence, along with a variety of other particles which are not detected. The short-hand notation for this reaction is \( K^+ e^- \rightarrow \Lambda e^- \). Quarks of positive and negative strangeness are created in pairs in this high energy reaction, with the \( K^+ \) meson being the signature (and the carrier) of the positive strange quark. The missing mass (the collective masses of the unobserved particles) spectrum for this reaction shown in Fig. 4 is indicative of the effectiveness of the system for kaon production studies that provide unique access to this process which implies strangeness (through the presence of strange quarks) into the nucleus. Here the remaining Lambda and Sigma hyperons produced in this reaction, which now carry negative strangeness, are clearly identified.

Third, the results of CEBAF E91-13 on nuclear transparency in the quasifree (e, e' p) reaction, in which the emerging proton is detected in coincidence with the scattered electron, are shown in Fig. 3, together with previous results from SLAC experiment NE18 and from Bates Laboratory. The goal of E91-13 is to understand the motion of nucleons through the nucleus in an energy range—0.3 to 2.0 GeV—where the underlying nucleon-nucleon interaction is changing rapidly. At the lower energies, nuclear many-body effects dramatically influence the propagation of nucleons, while at high energies pion production dominates nucleon-nucleon scattering and dynamical QCD effects may become evident. The experiment performed the first broad range (in terms of the target and energy used) longitudinal-transverse separation (separation in terms of the scattering of the electron by the electromagnetic and magnetic fields emanating from the charge and current densities of the nucleons and mesons comprising the nuclear target) of the nuclear response in the (e, e' p) reaction. Furthermore, the new data also suggest that there is an onset of the scalar component of the deuteron in the photon energy range from approximately 1 to 4 GeV at a reaction angle of 25º in which the light gray areas of the graph show the pairs of mass and angle values that would be consistent with the requirement at 90% confidence level (The dark gray areas are regions of 90% confidence level.) Also shown are limits from the KARMEN experiment at ISIS in the UK, the E77 experiment at Brookhaven National Laboratory, and the BUSSY reactor experiment in France. In the case of the other experiments shown, the values in the area to the right of their boundaries are excluded, and the values to the left are allowed.

More Evidence for Neutrino Oscillations

The Liquid Scintillator Neutrino Detector (LSND) collaboration1 at Los Alamos National Laboratory has presented strong evidence for an excess of electron antineutrinos from neutron production target. Since about 3/4 of the total antineutrino flux at the LSND group has operated their experiment for an additional four months, providing a total of nine months of data that are consistent with neutrinos changing from one type to another, a process which requires that neutrinos have mass. If confirmed by other experiments, massive neutrinos would have an enormous impact on our understanding of the makeup and evolution of the universe. In the Los Alamos experiment, the half-mile-long LAMPF accelerator fires an intense beam of 800 MeV protons into a water target producing pions, short-lived particles whose subsequent radioactive decays produce the neutrinos for study. The processes in the source are such that copious numbers of muon neutrinos and antineutrinos are generated while the number of electron antineutrinos is suppressed by more than a factor of 1000. The LSND researchers observe the neutrinos by the light produced from their interactions in the 170 tons of mineral oil contained in a large detector placed nearby (see Fig. 5). Neutrinos are very difficult to detect because they only interact via the so-called weak interactions, forces between particles that are about one hundred trillion times weaker than the strong interaction that holds together a nucleus. As a result, only about one in every billion billion neutrinos passing through this large detector is detectable. A careful examination of the nine months of data led the LSND experimentalists to conclude that they had conclusive evidence for the presence of electron antineutrinos far in excess of the number expected. An article published in Physical Review C reports 22 events that are consistent with muon antineutrinos that had changed (oscillated) into electron antineutrinos. The expected number of such events from cosmic rays and known sources of electron antineutrinos is only 4.6 with an uncertainty of 0.6 events, making it extremely unlikely (less than one chance in ten million) that the observed excess is due to a statistical fluctuation. If the excess is indeed due to neutrino oscillations, then it would imply that at least one neutrino has a mass greater than 0.2 eV/c². The lightest particle with a known mass is the electron with a mass of 511,000 eV/c². The most likely explanation for these electron antineutrinos is that they were made by the transmutation of muon antineutrinos that are copiously produced at the water-
The creation of nuclei typically occurs under explosive conditions like those found in novae (stars that brighten as a result of receiving nuclear material from an exploding partner), supernovae (massive stars that explode as a result of gravitational collapse), and shortly after the birth of the universe itself. Many of the reactions that proceed along paths which involve very short-lived nuclear species having far-from-stable configurations. Even since the earliest theoretical models of nuclear synthesis (the name for the process of creating nuclei, generally under high-temperature, high-pressure conditions), it has been a challenge to experimentalists to find ways of investigating these processes in the laboratory. This challenge is now being addressed with new and powerful experimental techniques. Major advances have recently been achieved by nuclear physicists who are forming beams of short-lived nuclear species, with energies equal or exceeding those found in stars. Such beams have been generated with several unique experimental techniques, involving innovative uses of existing accelerators and incorporating novel concepts for upgrading their abilities. For example, researchers studied crucial Big Bang reactions \(^1\) with \(^{15}\)Li ions (lifetime of 0.8 s). The short-lived \(^{15}\)Li ions were generated in-flight in a nuclear reaction using beams of stable \(^{15}\)Li from an existing low-energy accelerator at Notre Dame University. At the other end of the energy scale, uranium beams of several tens of GeV at the GSI Laboratory in Darmstadt, Germany, were fragmented in a reaction target. From the fission-product beams (which were “forward focused” by virtue of their high, relatively uniform momentum values in the forward direction) more than a hundred new neutron-rich isotopes were observed for the first time in a region which is near the astrophysical rapid neutron-capture process \((r\) process\). The \(r\) process is responsible for making most of the heavy elements (heavier than iron) and is important during the few seconds of a supernova explosion. These exotic nuclei were observed for the first time, their lifetimes and other properties that are required for making the \(r\) processes remain to be measured.

At other laboratories beams of short-lived \(^{8}\)N (lifetime 10 min), \(^{19}\)F (lifetime 110 min), and \(^{20}\)Ne (lifetime 17 s) were generated by a different method: by first producing these nuclei with a primary production accelerator and then introducing them into the \(r\) process in a source for acceleration. The fast-neutron accelerator concept is complementary to the in-flight production of radioactive ion beams mentioned before. It has the advantage that the secondary beam is produced with the quality and precise energy necessary to measure the specific cross sections (reaction likelihoods) of astrophysical interest, which often depends sensitively on energy (e.g., because of resonances) or on quantum states for the nucleus (or thresholds) (the minimum energy required for a reaction to occur). In this way, important reactions have recently been studied with beams of \(^{19}\)F and \(^{20}\)Ne that provide the opportunity for a progression beyond the \(r\) cycle in hot stars. The carbon–nitrogen–oxygen \((CNO)\) cycle is the normal path for the conversion of hydrogen into helium and involves slightly more massive than the sun, involving the participation of carbon, nitrogen, and oxygen nuclei. “Breakouts” from the \(CNO\) cycle, in which nuclear reactions proceed to a new stage beyond the production of light elements, are the assumed gateways leading to the generation of elements heavier than oxygen via the rapid proton capture \((r\) process\) mechanism, the mechanism believed to be responsible for generating most of the medium-sized elements, namely those that are heavier than oxygen but have no more than 100 nucleons (neutrons and protons). At Louvain-la-Neuve in Belgium, where much of the two- accelerator technique was pioneered, researchers recently measured \(^{18}\)F\((p,\gamma)\) reactions at the University of Louvain-la-Neuve, Belgium, where much of the two-accelerator technique was pioneered, researchers recently measured. The \(^{18}\)F\((p,\gamma)\) reaction (the parentheses after the nucleus indicate the light particles going into and coming out of the reaction, respectively; \(p\) denotes a proton, and \(\gamma\) indicates a helium nucleus, or alpha particle). This reaction dominates the reaction rate at temperatures present in nova explosions, brightenings of stars believed to be caused by the material falling onto its surface from the explosion of a neighboring partner star (Refs. 5 and 6).

Multiplying The Cosmic Cauldrons

The quest of nuclear astrophysics is to understand how the chemical elements that make up our world are formed in the cosmos. The pioneering work won Nobel prizes for Hans Bethe and William Fowler. They began to unravel the complex cycles and chains of nuclear reactions that they believed would explain how nuclei are created and destroyed in the hot cauldrons inside stars, starting from the lightest and simplest nuclei that were first manufactured in the primordial fireball of the Big Bang. Today’s most advanced observatories such as the Hubble Space Telescope are providing new details on the nuclear composition of the cosmos by making maps that show the abundances of chemical elements in almost primordial gas clouds and the very earliest stars. It is the role of nuclear physics to establish how behavior at the submicroscopic nuclear level leads to effects of large-scale, stellar proportions.

1. The LSDN experiment involves 12 institutions: the University of California campuses at Riverside, Santa Barbara, and San Diego; the University of California Inter campus Institute for Research at Particle Accelerators; Emory-Riddle Aeronautical University; Linfield College; Los Alamos National Laboratory; Louisiana State University; Louisiana Tech University; Southern University; Temple University; and the University of New Mexico. Funding for the experiment came from the Department of Energy’s Office of Energy Research. Other funding sources were the National Science Foundation, Associated Western Universities, and the Mushochi Charitable Trust.
5. Walter F. Henning Argonne National Laboratory (630-252-4004)
Particle Physics is blessed and cursed with a “Standard Model” (SM) of interactions at the very smallest distance scale: blessed in that the SM enables very precise prediction of thousands of experimental quantities, and cursed because the SM rests upon a variety of miraculous accidents of nature, and because so many of the fundamental parameters on which the theory depends, such as the masses of elementary particles, cannot be calculated from first principles.

The Standard Model prescribes how the forces of nature are propagated by the exchange of gauge bosons between matter particles. The term “gauge” refers to the requirement that the force-carrying particles obey the requirements of gauge symmetry, or invariance under local changes of their complex phase. The matter particles are categorized into two classes: the quarks and leptons. Each class has three doublets of particles, with the members of each doublet bearing very closely related properties. For example, the first doublet consists of the up and down quarks, which are the primary constituents of protons and neutrons. The second doublet consists of the strange and charm quarks. The sixth quark, called top, was identified only a year ago in experiments at Fermilab after more than a decade of search. Surprisingly, it weighs some 35 times that of its partner, the bottom quark. Meanwhile, each lepton doublet comprises an electrically charged particle (e.g., the electron) and a companion chargeless neutrino. No clear evidence has been given to date that the neutrinos have mass, although there is no fundamental prohibition to this being the case.

The forces operating in ordinary matter divide into the strong (nuclear) and the electroweak interactions, each arising because the appropriate matter particles possess some characteristic property to which the gauge bosons can connect. Thus the quarks bear a property called color, to which the appropriate gauge boson, the gluon, couples, giving rise to the strong force, as described in the theory of quantum chromodynamics (QCD). This color property is analogous to electric charge, to which the electromagnetic force connects. The strong force (also called the color force) between two quarks actually gets stronger as the quarks are pushed apart (during a high-energy collision). Because of this, isolated (colored) quarks and gluons cannot be liberated and observed in the lab. Instead, excess energy condensed into color-singlet (“colorless”) composite particles (mesons or baryons). These emerge from the collision region as sprays of particles referred to as jets.

Another important ingredient of the Standard Model is the Higgs boson, a particle needed to give mass to the weak force, the so-called weak force in large mass. Because of this the Higgs is also responsible for breaking the symmetry between the weak and electromagnetic forces. It is thought that these two forces are really two different aspects of a single force, the electroweak (EW) force, and between the weak and electromagnetic forces. It is thought that these two forces

Electroweak Interactions

In the past year, much progress has been made in testing the EW model. In these tests, hundreds of quantities are subjected to overall constrained fits for consistency with the SM. The tests require knowledge of a few basic parameter values, such as the electromagnetic coupling constant, the weak decay coupling, the mass of the Z boson, and the mass of the top quark. New determinations of the top quark mass were presented at the biennial international “Rochester” conference (so-named because of the site of the very first meeting) in Warsaw by the Strong Interaction Studies group working at Los Alamos. The result was to bring the charm rates into agreement.

For the most part, these measurements, taken together with the new results from the Tevatron and improved information from neutrino scattering at Fermilab, provide a beautiful confirmation of the SM.

One candidate cure for this problem has been the idea of supersymmetry. According to the supersymmetry model, each known fermion particle would have a boson counterpart, and vice versa. Thus, for every quark (a fermion) there would exist a “squark” (a boson); conversely, bosons such as gluons would possess a fermion counterpart, the “gluino.” It is expected that these new companion particles, if they exist, should be found either at our existing accelerators or in experiments at facilities now under construction, and that such discoveries would fundamentally alter our view of the world. Other alternative theoretical ideas for remedying the SM’s ills would also result in observable new particles, or in deviations of precisely measured quantities from their SM-calculated values.

Strong Interaction Studies

The strong-interaction theory QCD is on relatively firm footing, with few doubting its basic validity. Nevertheless, physicists keep looking for surprises. For example,
great interest arose in 1996 when the CDF experiment announced measurements of quark or gluon jets at large angles with respect to the proton and antiproton beams and with energies approaching half the energy of the incoming beam particles. The data agreed remarkably well over seven orders of magnitude variation in the production rate. But for the largest energy jets the data exhibited an excess of nearly a factor of 2 over prediction. These experiments are a close analog of the Rutherford-alpha-particle scattering experiments of 90 years ago, in that Rutherford was surprised by the number of alpha particles scattered through large angles by his target (gold atoms in a film). This anomaly in Rutherford’s data was later attributed to the existence of constituents (the nucleus) inside atoms. The search for an excess in high energy quark scattering could similarly reveal a new layer of substructure within the quarks. By comparison, the other Tevatron experiment, D0, weighed in with jet data, though agreeing with CDF within their mutual errors, came closer to agreement with the QCD prediction. Subsequent reevaluation (by several groups) of data which concerns the makeup of the proton showed that modification of the fraction of the proton momentum carried by energetic gluons could bring the data and theory into much better agreement, without upsetting the large body of data previously acquired from lower energy experiments of the instance, leptons. As the dust settled, it appeared that the jet data could be adequately understood within the SM. Studies in recent years have shown that the proton does not consist merely of three valence quarks, but is stocked with a myriad of gluons plus virtual particles that momentarily pop into and out of existence. A further modification of this picture occurred last year because of experiments at the HERA electron-proton collider in Germany. They reported that the density of low-momentum gluons in the proton was much larger than expected; indeed, from these results the proton looks much more like a loaded cannon car the structureless elementary particle that we thought of only 30 years ago. With new special detectors installed, the H1 and ZEUS collaborations search for the presence of low-momentum constituents for very small energy probes. What they find is that an excess of gluons persists all the way down to those carrying as little as one-millionth of the proton’s momentum. At some point, this effect must level off so as to satisfy the constraints from the deviation of the proton is viewed as a single unperturbed entity, but the effect is striking and points to an interesting new regime where perturbative treatment must be supplanted with collective effects of multiple-gluon states.

Until recently, the jets of ordinary particles evolving from quark and gluon jets were experimentally indistinguishable. Recent work by the LEP collaborations has been able to isolate quite pure samples of quarks or gluons emerging from Z boson decay. They have been able to show that the jets from gluons are more spread out, and result in more particles of lower momentum than the corresponding quark jets of the same energy. These effects are expected imo from the gluons have not had time to equilibrate with the quarks, and therefore are not a consequence of virtualized gluons. The ability to distinguish quarks and gluons, even imperfectly, could become an important experimental tool in disentangling the decays of particles which decay dominantly into quarks (e.g., the Higgs boson) from the large QCD backgrounds.

Searches for New Particles

As noted above, several recent hints of effects not accounted for by the SM have been observed without the need for new physics. Nevertheless, the continued strong belief that such new phenomena are likely dictates that every possible search be made. The most noteworthy development in the past year also enabled substantial increase in the reach of searches for new particles.

The SM behavior have proved impossible to reconcile with the observed properties of the gauge bosons and leptons, while the Tevatron experiments have placed new limits on possible couplings on the quarks and gluon. An intriguing anomalous concentration of events with four jets in the final state seen by the ALEPH experiment at LEP at 135 GeV did not rematerialize in the early running at 162 GeV; once again, departures from SM behavior have proved impossible to reconcile with the observed properties of the gauge bosons and leptons, while the Tevatron experiments have placed new limits on possible couplings on the quarks and gluon. 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Shear-Stabilized Tokamak Plasmas

Confining a high-temperature, high-pressure plasma presents the scientific challenge of studying the complex ways in which charged particles interact with each other. A plasma is a collection of electrically charged particles, and the interaction between these particles is crucial for maintaining high temperatures and densities. These extreme conditions enable nuclear fusion to occur, but they also present challenges in terms of confinement and energy transfer.

Inertial Fusion Research at the OMEGA Laser Facility

Inertial fusion research focuses on developing techniques to confine plasma and achieve high temperatures and densities. The Princeton Plasma Physics Laboratory describes experimental confirmations of theories predicting how to reduce this turbulence.

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The DIII-D Team

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The TTFR Team

Princeton Plasma Physics Laboratory

Shear-Stabilized Tokamak Plasmas

Shear stabilization is a technique used to improve the confinement of plasma in tokamaks. This is achieved by applying a magnetic field that is not uniform, which in turn causes the plasma to flow. The flow of plasma can help to inhibit small-scale turbulence and improve the confinement of the plasma.

In the past two years, negative magnetic shear experiments have led to greatly improved energy and particle confinement in the DIII-D tokamak (San Diego, CA) and the Tokamak Fusion Test Reactor (Princeton, NJ), and more recently in other devices including JT-60U (Japan), JET (European Community), and Tore Supra (France). A dramatic reduction of turbulence is observed, allowing plasma pressures up to 6 atm at temperatures of 200 to 400 million degrees Kelvin. One reason improved confinement is an increase in velocity shear, leading to further suppression of measured turbulence in good agreement with theory. Thus, surprisingly, the improved confinement can become self-sustaining even if the magnetic field evolves to a positive-shear state. In these experiments the rates of both ion- and energy-loss in tokamaks,
f.

The success of shear stabilization for plasma stability and confinement may point the way to a more compact and economical fusion power plant, the ultimate goal of much research in magnetically confined plasmas. A well-confined, high-pressure plasma is crucial since the fusion power output increases roughly as the square of the plasma pressure. Furthermore, the negative magnetic shear configuration is compatible with the distribution of self-generated electric currents predicted by neoclassical theory, reducing the technological requirements for sustaining the tokamak plasma current. Shear-stabilization techniques have led to record plasma temperatures in several tokamaks, and have tripled the fusion power in DIII-D experiments using deuterium plasmas. The extension to more reactive deuterium-tritium plasmas is being tested at TFTR. A promising theoretical basis exists for understanding the physics of shear-stabilized plasmas, including this regime to steady-state operation in the near future of fusion devices.

Ben P. Stein

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Inertial Fusion Research at the OMEGA Laser Facility

The demonstration of a self-heating nuclear fusion reaction in the laboratory is a major goal of the inertial fusion research program. To create a self-heating fusion reaction, researchers must achieve a condition called ignition, in which the heat produced by the particle-by-products of nuclear fusion exceeds the heat received from the external energy source (either, laser or particle beam) that initiates the reaction.

The demonstration of ignition is a major objective of the National Ignition Facility (NIF)—a 1.8-megajoule laser fusion facility currently being designed by a consortium including Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Sandia National Laboratory (SNL), and the University of Rochester Laboratory for Laser Energetics (LLE). Once the NIF is completed in the early part of the next century, it will be applied to a variety of research and development programs including near-term defense missions and longer-term energy research efforts.

Two approaches are being investigated for demonstrating ignition at the NIF and for achieving a maximum in the gain, the ratio of the energy released in fusion reactions to the energy deposited in the target. The indirect-drive approach makes use of hohlraums (cylinders made of a heavy element) to convert a significant portion of the laser energy to x-rays that are used to compress and heat the fusion capsule. This is the main-line approach that will be investigated on the NIF. The alternative approach, direct drive, involves the placement of laser energy directly onto the capsule. This approach is potentially more efficient and may lead to ignition (the “match” that starts a self-heating reaction) and burn.(4,5) It is the actual “combustion” that results in large release of energy) with lower laser energy than the indirect-drive approach.

To pursue the direct-drive approach, the OMEGA laser facility was constructed at LLNL and began operations in 1995. OMEGA is a 40-kJ, ultraviolet, 6-beam laser system (see Fig. 2). OMEGA and the companion facility, NOVA, at LLNL are the largest fusion laser facilities in the world. OMEGA is unique in that it is the highest-energy laser possessing the ability to conduct high-quality experiments using both direct-drive as well as indirect-drive targets.

An important goal of experiments to be conducted on OMEGA is to address the key physics issues of hydrodynamic stability for direct-drive capsules. Successful demonstration of direct-drive implosions requires precise control of the irradiation uniformity and the finish of capsule surfaces. OMEGA will be used to test...
Polymer physics

Demixing of Polymer Blends in Ultrathin Films. Polymers are long chain molecules composed of simple molecular building blocks called monomers. Two examples of polymers are polystyrene (used in foam cups) and polyvinyl methyl ether (which is used to make cosmetic creams). While individual polymers may have specific useful properties, mixing them can result in a polymer blend which combines these properties. But such polymer blends are often unstable and the blend films phase-separating similarly to two-dimensional fluids examined in simulations. Computer simulations have shown that phase separation is different in ultrathin polyme blend films, only hundreds or thousands of atoms thick, compared to bulk mixtures. The phase separation process in ultrathin polymer blends involves two-dimensional spatial patterns that are observed on a nanometer scale. These patterns are formed through a process involving two-dimensional breakup in two dimensions occurs through a process involving two-dimensional patterns which lie parallel to the plane of the substrate.

The concentrations of polymers in these phases depend strongly on temperature. At an early stage of phase separation, the concentration of one polymer species over the other becomes enhanced on a local scale, but the material is still uniformly mixed on a larger scale. If the polymers are mixed in roughly equal amounts, a tubular threadlike pattern is formed in the next stage through a self-organization process where the two polymer species form a bicontinuous structure, i.e., intertwined in such a way that each species forms a continuous strand throughout the material (known as a “spindal pattern”; see Fig. 1). During this intermediate stage of phase separation the spindal pattern grows in size and the initially rough interfaces between the different phases become more sharply defined. In Fig. 1 we show a typical optical photograph of a phase-separating polymer blend film at an intermediate stage of phase separation. Numerical model calculations of phase separation give rise to patterns similar to Fig. 1. The fluid nature of the film becomes important in the final late stage of phase separation, where the tubular structures forming the spindal pattern (Fig. 1) break up into droplets as a result of a flow instability. This “capillary instability” superficially resembles the break-up of a water stream into droplets in a hose as it is shut off. But in bulk materials, phase separation occurs uniformly in all directions, whereas the geometry of the material is a film, the phase separation occurs in a different way in the lateral (parallel to the surface of the film) and normal (perpendicular to the surface of the film) directions because of the perturbing influence of the surface. The type of phase separation occurring in bulk films depends on film thickness. In thick films a process similar to the bulk mixture is found while a range of behavior is found in thin films. This thin blend films (on the order of a micron thickness) do not phase-separate laterally because they tend to form stable layered structures which lie parallel to the plane of the substrate.

Our investigation emphasizes ultrathin films, where the layering-type phase separation process is suppressed so that phase separation occurs essentially within the plane of the film. In this case a nearly two-dimensional phase separation process occurs which is similar to bulk fluid (i.e., a bicontinuous spindal structure forms).

A qualitative change in the phase separation process for near two-dimensional films is predicted during the late stage of phase separation where fluid flow becomes appreciable. Basic differences between fluid flow in three and two dimensions make it especially interesting to investigate how the late stage and the transition from intermediate to late stage is affected by the ultrathin character of the film. Unlike thick films, where the spindal structure has a tubular form at intermediate stages of phase separation, the spindal structure attains a highly flattened tubular or ribbonlike form in near-two-dimensional films. Since the capillary instability is only associated with the break up of the tubular fluid filaments, it cannot exist in the ribbonlike structures of ultrathin films, so that these ribbons must break up by some other mechanism. San Miguel et al.3 suggested that this breakup in two dimensions occurs through a process involving two-dimensional diffusion rather than by fluid flow, leading to a qualitatively different late-stage phase separation kinetics than in three dimensions. The verification of this prediction provides a serious challenge for experiment.

Recent two-dimensional numerical simulations indicate that the kinetics of late stage phase separation differs in two- and three-dimensional fluids, as suggested by San Miguel et al., and these findings stimulated us to investigate this transition experimentally. Blend films were prepared having thicknesses of 200, 1000, and 2000 Å and the demixing kinetics was studied in these films. Optical photographs of the phase separation of the 200 and 1000 Å blend films showed the development of phase separation patterns similar to bulk blends and complemented atomic force microscopy measurements (Fig. 2) revealed that the features apparent in the optical micrograph (Fig. 1) arise from undulations of the polymer-air interface. Variations of the interface tension (arising from an overall interaction between the polymer components) within the phase separating layer cause the surface to buckle and the phase separation may then be easily followed by optical microscopy.

An examination of the kinetics of this pattern growth indicated that the thickest ultrathin film (1000 Å) phase-separated...
Similarly to bulk samples, while the kinetics of the 200 Å film is similar to numerical simulations of phase separation in ideally two-dimensional fluid mixtures. These observations are consistent with a transition between three to near two-dimensional phase separation processes in going from thick to thin ultrathin films. The transition to a layering-type phase separation was found in a film whose thickness was expected to be sufficient for this type of phase separation (~2000 Å). This film exhibited no detectable surface pattern formation over an extended period of time.

Anisotropic Phase Separation of Polymers and Liquid Crystals

Under the proper conditions, homogeneously mixed substances can separate into different phases, each having a chemically distinct composition and sharp boundaries. Phase separation processes in polymer science have been the subject of many experimental and theoretical examinations since the beginning of polymer science itself more than a half century ago. Interest stems from the fact that most useful polymer-based products are usually processed not from pure polymer, but from some type of solution or mixture. Examples include inks for advertising and automotive bumpers.

One particular area of interest over the last decade is studying how an initially homogeneous mixture of polymer and liquid crystal (LC) molecules separates into a continuous phase of solid polymer with micron-size regions of LC molecules embedded within. A good analogy of the structure is Swiss cheese wherein the holes correspond to domains of LC molecules, surrounded by the polymer “cheese.” Various techniques can be used to create this Swiss cheese structure from a homogeneous mixture of polymer and LC molecules. In one such technique, researchers begin with a mixture of liquid crystal molecules and light-sensitive monomers (the building blocks of polymers), and then use light to form the polymer phase and subsequently create the Swiss cheese structures. As the monomers grow into polymers, the LC molecules eventually come together to form micron-sized “domains” surrounded by polymer. Such phase-separated materials can posses highly desirable optical properties such as selective reflectivity or refractive index, flat-panel displays, and switchable windows. But to optimize the performance of any of these components, one needs to control the phase separation process and thus the structure of the Swiss cheese (number of holes, size of holes, locations of holes).

Since these films consist of micron-sized domains of liquid crystals randomly dispersed in a polymer, they are termed polymer dispersed liquid crystals (PDLCs). The small LC domains act to scatter light because the host (polymer) and the LC droplets have different refractive indices, a material property which determines the bending angle of light as it passes from one phase to another. But the effective index of refraction for the LC domains can be easily changed owing to the anisotropic shape of the molecules. If the liquid crystal molecules are visualized as cigars, there is an average direction the long axes possess within each domain which differs from domain to domain. However, applying an electric field allows scientists to control the orientation of these cigars within the LC domains (i.e., reorienting the average direction of all domains to point in a single direction) thereby changing the effective refractive index. By proper selection of the polymer and LC, it is possible to match refractive indices thereby allowing transmission (rather than scattering) of light. Films with variable, controllable scattering properties can be formed in this way.

Normal PDLC phase separation processes tend to create the LC domains randomly throughout the polymer host. The properties of the resulting materials are isotropic, or the same in every direction. Adding anisotropy to the phase separation problem was recently demonstrated in a mixture of liquid crystal and photopolymer. Applying two interfering laser beams created bright and dark regions in the monomer mixture. Monomers grow into polymer selectively in the bright regions forcing the liquid crystal molecules to diffuse towards the dark areas. What can result from a carefully controlled anisotropic diffusion process is a structure with regularly repeating bands of nanometer-sized LC domains alternating with polymer bands. Figure 3 shows two examples of these gratings (0.55 μm periodicity), each consisting of different size LC domains. Because the LC domains are smaller than visible light wavelengths in either case, these films do not scatter light. However, the grating spacings are such that incoming light can be bent (diffracted) to change direction in an orderly way. Specifically, they exhibit Bragg diffraction, and as a result, these gratings reflect visible light primarily off by consolidating into droplets which form nanometer-scale domains of LC molecules. The left image (high magnification) reveals liquid crystal bands consisting of very small, nearly spherical LC domains (~100 nm) with little coalescence among the individual droplets. The right image reveals LC bands of larger (200–250 nm) domains. The size and shape of these LC domains have a drastic impact on the electrical and optical properties of the resulting material. Both images reveal that the LC bands are separated by polymer-rich regions with an overall spacing of 0.55 μm.

FIGURE 3. Electron micrographs of materials consisting of polymers and liquid crystals (LCs) separated in a controlled fashion. Liquid crystal molecules start off by consolidating into droplets which form nanometer-scale domains of LC molecules. The left image (high magnification) reveals liquid crystal bands consisting of very small, nearly spherical LC domains (~100 nm) with little coalescence among the individual droplets. The right image reveals LC bands of larger (200–250 nm) domains. The size and shape of these LC domains have a drastic impact on the electrical and optical properties of the resulting material. Both images reveal that the LC bands are separated by polymer-rich regions with an overall spacing of 0.55 μm.

FIGURE 4. Hologram of a half-dollar coin recorded in a one-step process onto a phase-separated polymer/liquid crystal film. (Courtesy of Optics Letters.)
a variety of diffractive optics applications, the area is ripe for both theoretical and experimental studies which fundamentally explore the anisotropic phase separation problem.

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VACUUM MICROELECTRONICS

Vacuum microelectronics deals with submicron- and micron-sized devices and components whose operation involves field emission of electrons from a solid. Electrons tunnel quantum mechanically and then move along electric field lines through a vacuum. The first microelectronic device was demonstrated by Spindt et al. at SRI.1 Since then the impetus for the development of vacuum microelectronics devices has been provided primarily by their applications as matrix-addressable electron sources for field emission flat-panel displays, and as compact and efficient cathodes for microwave power amplifier tubes.4

Field emitters are sharp metal or semiconductor tips surrounded by an integrated gate electrode which is electrically insulated from the electron-emitting material by a dielectric film. As an example, Fig. 1 shows a scanning electron microscope (SEM) picture of a section of a field emission array (FEA) recently fabricated in the Electronic Technologies Division of MCNC, a nonprofit corporation in North Carolina offering advanced electronic and information technologies and services.5 Looking like microscopic strings in underground silos, the tip-on-emitter emitters shown in Fig. 1 are formed in mono-crystalline silicon using silicon etching and oxidation sharpening techniques.6 The metallic gate electrode openings (with radii of less than 1 µm) are self-aligned with the emitter tips. When the gate electrode is biased to a positive potential, typically in the range of 10 to 100 V, a strong electric field is created by the sharp tips causes field emission of electrons from the emitter material.

Cathodes for field emission displays comprise a matrix of FEAs, each array corresponding to one pixel or subpixel of the display. The required electron emission currents are in the modest range of 10–100 µA per pixel, which is readily achievable for gate voltages in the range of 10 to 50 V. On the other hand, cathodes for microwave power amplifier tubes need to exhibit emission currents on the order of 100 mA per pixel, which is a type of microwave amplifier tube.4 This work is being done in collaboration with Litton EDD CPI, SRI, Varian Associates, and Lincoln Laboratories at MIT, with support from ARPA via NRL and NASA.

As fabrication technologies for FEAs mature, with scaling down of device geometries achieving the desired submicron level, more and more effort in the vacuum microelectronics community is being expended on developing a better understanding of phenomena affecting long-term reliability of the devices in environments dictated by specific applications, stability of the emission current, and enhancement of the electron current via modifications of the emitter surface. These phenomena are affected by physical and chemical aspects of the emitting surfaces, such as microscopic structure of the tips and the tip geometry, adsorption and diffusion phenomena, cathode bombardment by ions generated as a result of collisions of electrons with ambient molecules, emission noise, and cathode initiated vacuum breakdown.7 Many of these surface-related issues remain to be investigated and some others probably have yet to be fully identified. The level of research in this area is increasing and is likely to pay off in the increased performance, yield and reliability of vacuum microelectronic devices, some of which are near commercialization.

The 1996 Nobel Prize for physics recognizes the discovery of superfluid helium-3. David Lee and Robert Richardson of Cornell and Douglas Osheroff of Stanford, working at Cornell in the early 1970s, had to chill their helium-3 sample to a temperature of only about 2 mK before it transformed into a superfluid, a special liquid state of matter which can flow without viscosity.

Superfluidity in the two helium isotopes is very different, a fact that stems from the fact that He-4, which consists of two neutrons and a nucleus containing two protons and two neutrons, is a boson while He-3, which consists of two neutrons and a nucleus containing two protons and one neutron, is a fermion.8 In He-4, the superfluid state is essentially a Bose-Einstein condensation of He atoms into a single quantum state. In contrast, the He-3 superfluid state consists of a condensation of pairs of atoms, somewhat analogous to the pairing of electrons in low-temperature superconductivity. The discovery of superfluidity in He-4, at the much warmer of temperature of 2 K, occurred in 1938.9 Furthermore, because its constituents (pairs of atoms) are magnetic and possess an internal structure, the He-3 superfluid is more complex than its He-4 counterpart. Indeed, superfluid He-3 exists in three different forms (or phases) related to different magnetic or temperature conditions. In one of these phases, the A phase, the superfluid is highly anisotropic; that is, it is directional, somewhat like a liquid crystal. To put it another way, this phase of He-3 (unlike He-4) has texture. This property was exploited in a recent experiment10 in which vortices set in motion within a He-3 sample simulated the formation of topological defects (“cosmic strings”) in the early universe.

Another notable experiment in recent years was the verification (by Douglas Osheroff) of the “baked Alaska” model.11 This theory, formulated by Anthony Leggett of the University of Illinois, explains the somewhat piecemeal transition from the A phase of superfluid He-3 into the lower-temperature B phase by supposing that B phase droplets can be nucleated within the supercooled A phase by the ionizing energy of passing cosmic rays.

In 1999 the March and April meetings of the APS will be joined together with several divisional meetings into a joint APS Centennial meeting.

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