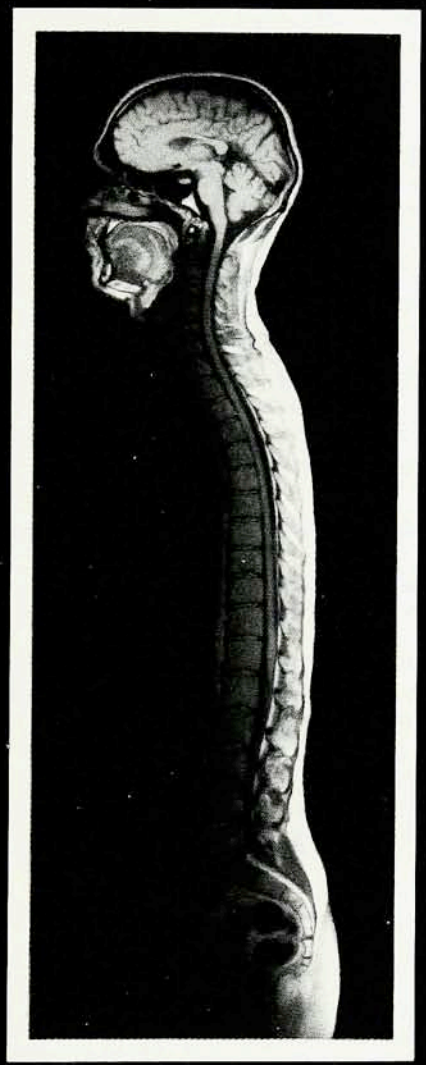
PHYSICS NEWS IN 1986



An American Institute of Physics
Special Report

Phillip F. Schewe, Editor

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Preface

Physics News in 1986, prepared by the Public Information Division of the American Institute of Physics (AIP), is the 18th in a series of annual reviews of physics news. In past years *Physics News* was published in booklet form and was distributed to reporters, students, libraries, teachers, scientists, and to the general public. More recently *Physics News* has been published as a supplementary report in the January issue of *Physics Today*, beginning with the January 1984 issue. The articles in *Physics News in 1986* were selected and prepared by the AIP Member Societies. The following individuals helped to organize the chapters and in some cases to write articles:

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1 December 1986 Phillip F. Schewe

COVER:

A composite sagittal (midline) nuclear magnetic resonance image of the head and spinal cord. Surface coils provide improved resolution and contrast of the cervical, lumbar, and thoracic spine. (Courtesy of Philips Medical Systems.)

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Physics News in 1986
An AIP Special Report

ASTROPHYSICS

Astrophysics, the investigation of the universe beyond the Earth, made great strides in 1986 despite the terrible loss of the *Challenger* and its crew. As the Challenger tragedy unfolded, Voyager 2 was charting the remarkable moons, dark rings, and tilted magnetic field of Uranus, the third giant planet to be explored by this remotely-controlled spacecraft, now *en route* to Neptune. Less than two months later, a fleet of five interplanetary probes, VEGA 1, VEGA 2, Sakigake, Suisei, and Giotto, flew near or through Comet Halley in a single week, and shortly thereafter the International Cometary Explorer, veteran of an earlier comet mission, encountered waves and particles from Halley in the solar wind, tens of millions of kilometers upstream of the comet.

Also in 1986 the first detailed scientific results were published from the balloon payloads that VEGA 1 and VEGA 2 deposited at Venus as they flew past in June 1985 on their way to Halley. Tracked by twenty radio telescopes around the world, the VEGA balloons explored the hot, turbulent middle cloud layer of our twin planet where vertical drafts as strong as those in earthly storms are commonplace. The technique of Very Long Baseline Interferometry (VLBI) was critical to precision determination of the balloons' trajectories, as it was to a new determination of the distance to the center of our galaxy, the Milky Way. The center of the Milky Way, close to the radio source Sagittarius B2, was found to be about 7.1 kiloparsecs from Earth, versus 8.5 kpc for the previous best estimate.

Most distances in astrophysics beyond the solar system are expressed in parsecs (pc) and their multiples. One parsec, the distance at which the angle subtended by the semimajor axis of the Earth's orbit would be one second of arc, is about 3.26 light years, or 3.09×10^{13} kilometers. Kiloparsecs—thousands of parsecs—are good enough to measure distances across the galaxy, but megaparsecs (Mpc—millions of parsecs) are the units of choice when the vast distances between external galaxies and clusters of galaxies are investigated. Although VLBI now offers the prospect of direct distance determinations for nearby external galaxies, the distance scale over megaparsecs is still uncertain by about a factor of two. Thus, the survey of a slice through the universe, which revealed that galaxies may be located predominantly on the surfaces of thin-shelled spherical bubble structures, extended to 100 Mpc for galaxies of typical brightness, assuming a particular value (100 km/s/Mpc) for the Hubble constant, a measure of the expansion of the universe. However, in fact, the survey objects may be twice as far away, if the Hubble constant is twice as small.

New kinds of stars and star systems also made news in 1986. White dwarfs, typically as large as the Earth but with about two-thirds the mass of the sun, were found to include some objects with immense magnetic fields, around 500 megagauss, some with exceptionally high temperatures, to 350 000 K by one estimate, and at least one with the lowest luminosity yet observed for a star. The European Space Agency's satellite EXOSAT made pioneering studies of a new type of stellar phenomenon, the QPOs or quasi-periodic oscillators. EXOSAT operated for over 1000 days, from May 1983 through May 1986 in a high orbit (initial apogee, 200 000 kilometers; period 99 hours), considered ideal for monitoring variability in x-ray sources.

An old, well-known star, the sun, still excites the greatest scientific interest. Astrophysicists still seek an explanation for the discrepancy between the observed flux of solar neutrinos at the Earth and the predictions of solar interior models. If the theory of the solar interior cannot withstand experimental verification, what hope is there for the vast corpus of stellar interior and evolution models? Fortunately, two new explanations for the observed neutrino flux seem to deserve the most serious consideration. There may be a resonance in neutrino scattering within the sun, or weakly interacting massive particles may lower the temperature in the solar core. Either process would reduce the neutrino flux at the Earth.

Stephen P. Maran, NASA-Goddard Space Flight Center

Voyager at Uranus

The durable and venerable Voyager 2 spacecraft (launched August 1977), swept by Uranus on January 24, 1986. Four days later, the space shuttle *Challenger* blew up. The reaction to the shuttle tragedy meant that almost everyone would overlook Voyager at Uranus, no matter what it found. But this planetary encounter was, if anything, more surprising than the earlier visits to Jupiter and Saturn. Planetary scientists expected something strange, because Uranus is remarkable in having its rotational axis tilted 98 degrees from the perpendicular to its orbital plane. The orbits of the Uranus satellites and rings share this unusual orientation, suggesting perhaps that some event tilted the Uranus system on its side just as the planet was forming. Uranus's rotational axis pointed almost directly towards the sun at the time of encounter, and so half of the planet had been experiencing night for 42 Earth years. The variety of terrain on the coal-black satellites was unexpected, as were the bizarre tilt of Uranus's newly discovered magnetic field and the complex geometry of its rings.[1,2]

The discovery of active volcanoes on Jupiter's moon Io by Voyager 1 in March 1979 dispelled any notion that the satellites of the major planets would prove to have cratered surfaces resembling that of the Earth's moon. Saturn too has strange satellites with geologically young, grooved surfaces. Voyager 2 discovered ten small moons of Uranus and obtained close-up images of the five large moons discovered many years ago. They are all considerably darker than the satellites of Saturn. The bright areas on their surfaces are probably water ice, but the dark areas have an albedo of 0.1 or less, as dark as carbon black, and among the darkest stuff in the solar system. The Uranian rings are even darker. The nature of the dark matter in the Uranus satellite system is a major mystery.

Broadly speaking, the large Uranian satellites are divided into two major groups. The outer three have relatively old surfaces, with many impact craters. This indicates that little internal activity has altered these three moons since formation, although the details of the formation process may have been affected by events in the formation of Uranus itself. The inner two large moons (Ariel and Miranda) are the strange ones. Tiny Miranda, innermost, has many deep, globe-girdling grooves and enormous scarps. Planetary scientists speculate that the event which tipped Uranus on its side disrupted Ariel and Miranda. Miranda, some suspect, may even have been disrupted and reaggregated five times. The small numbers of craters in parts of the Ariel and Miranda surfaces suggest that violent events continue to occur. Perhaps water in their interiors is spiked with an ammonia antifreeze that keeps it liquid. Then, flows of the ammonia-water mixture might fill in craters on the surface and produce a young-looking terrain. Another possible explanation for the young surfaces of Ariel and Miranda is that these moons may contain more rocky matter than the outer Uranus satellites, making radioactive decay a more significant source of internal heat.

The rings of Uranus were discovered in March 1977 from the Kuiper Airborne Observatory when they occulted the light from a background star. Voyager 2's photography of this ring system revealed new rings and ringlets. A carefully planned sequence of pointings imaged the rings that contain very small dust particles; these particles scatter light strongly in the forward direction but are much harder to see in the backscattered light visible from the Earth. The dusty rings are distinct from those composed of larger particles. Any small particles near Uranus will spiral into the planet in about 2000 years, so these measurements suggest that the Uranian ring system is young and quite dynamic.

Uranus itself is generally a featureless greenish disk seen through ground-based telescopes, and the raw images from Voyager 2 were similarly uninteresting. But sophisticated image processing brought out patterns in the atmosphere. Uranus proved to look surprisingly like Jupiter and Saturn, despite the unusual orientation of its polar axis. The planet is girdled by bright and dark zones aligned along parallels of latitude. Although the present dark hemisphere has not experienced sunlight in 42 years, it is as warm as the sunlit hemisphere.

Another Uranus surprise was the strange magnetic field. The very existence of a field was surprising, since Uranus has no internal heat source (unlike Jupiter and Saturn). But stranger still was the field's orientation. The Earth and all other magnetized planets have magnetic axes that are reasonably close to parallelism with their rotation axes, with fields roughly like that of a dipole. In the other planets, then, it's much as though a giant bar magnet were buried in the interior. However, Uranus's magnetic field is tilted 60 degrees from the rotation axis. An offset dipole, in which the center of the planet is not at the planet's center, is a good initial model, but there are probably complex components to the field. The nature and origin of Uranus's field raise questions; Ness and co-workers speculate that Uranus may be undergoing a field reversal like those which, geological evidence suggests, have occured in the past on Earth.[3]

Harry L. Shipman, University of Delaware

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2. J. K. Beatty, Sky and Telescope **71**, 333 (1986) and A. Chaikin, *ibid.*, 338 (1986).
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Encounters with Comet Halley

1986 will go down in astronomical history as the year of Comet Halley, and will be particularly remembered for the studies made by five remote-controlled spacecraft which encountered the comet between March 6 and 14. An international cooperative effort of remarkable proportions yielded the first direct images of a comet nucleus and its dust jets, as well as information on the parent molecules of the gases observed, the dust emissions, the solar wind and many other phenomena.[1-3]

Although Comet Halley was a visual disappointment to much of the public, who saw it only with difficulty or not at all, the success of the spacecraft encounters made it an exciting object to the many scientific teams. Planning for the missions had begun as long ago as the late 1970's. The Japanese Institute of Space and Astronautical Sciences (ISAS) developed two vehicles, Suisei and Sakigake, which were launched in January and August of 1985. These craft were designed primarily for studies at fairly large distances of the solar wind and the comet's hydrogen halo. The Soviet Union's Space Research Institute also sent two missions, VEGA 1 and VEGA 2, in December of 1984; these studied the planet Venus before being rerouted to Comet Halley. (See the following article.) Their intent was to observe the

nucleus, if possible, and to study the processes going on in the coma and the composition of the gas and dust.

The European Space Agency's Giotto spacecraft was launched by an Ariane rocket in July 1985. It was designed to fly closest to the comet (ideally about 500 km away) and to obtain images of the nucleus, as well as information on the inner coma, neutral gas and ion composition and distribution, dust particles and dust jets, and magnetic fields. All five missions achieved their primary goals, despite the dangers from possible collisions with dust particles.

The most spectacular results were the first direct observations of a comet nucleus, obtained both by VEGAS 1 and 2 from distances of 8000–9000 km, and by Giotto from about 600 km. These offered support for Whipple's icy conglomerate model of comet nuclei.[4] Halley's nucleus is nonspherical, rather like a potato, about 15 km long by 10 km wide. Its surface is extraordinarily dark: the albedo is less than 4%, suggesting a thick layer of nonvolatile material coating the nucleus. The surface is irregular and rough, probably with pits and hills on the order of 100 meters in size. Two large dust jets and some smaller ones projected from the sunward side of the nucleus, evidently from relatively localized areas of the surface, covering in all perhaps 10% of the total surface area. A large part of the surface must consist of a thick dark crust that insulates the ice within, since the observed rate of gas and dust release was lower than expected. This insulation is also suggested by the VEGA probes' measurements of the temperature of the nucleus as 300-400 K, hotter than that which would cause water ice to sublime. The irregular shape of the nucleus further suggests that sublimation of ice below the crust does not occur uniformly, so the nucleus is not homogeneous.

Both Giotto and the VEGA probes also looked at the gas emissions in the coma near the nucleus. Water seems to be the most abundant parent molecule, with CO_2 next; among other neutral molecules detected were OH, C_2, CH, CN, and NH. Ions observed included H^+, C^+, H_2O^+, O^+, He^+, and others; C^+ was unexpectedly abundant, and may have come from the dust grains or from carbon atoms released at the surface.

The VEGAs first detected dust particles while still over 3×10^5 km away from the comet, but the number density increased rapidly within 1.5×10^5 km. These grains ranged in mass from the smallest detectable (about 10^{-16} g) to 10^{-6} g, the largest encountered by the VEGAs. Giotto recorded some 12 000 dust particle encounters, the largest being 1.4×10^{-4} g. The dust particles appear to be rich in H, C, N, and O. The dust production rate was estimated by Giotto experimenters at 3.1×10^6 g/sec; dust activity is much higher close to the nucleus, and heavier particles are also more abundant there.

Interactions of cometary ions with the solar wind were detected at distances of 10^7 km. The Japanese vehicles monitored the solar wind's behavior for about a year, especially near the closest approach times of the other spacecraft. The comet/solar wind interactions are fairly complex; Giotto detected a bow shock, a turbulent magnetic region, and various other regions including a zone near the nucleus with almost no magnetic field. Suisei observed the comet's hydrogen corona in November 1985, at a distance of about 2.5×10^8 km. Its brightness changed regularly in a 2.2 day cycle, suggesting a rotation of the nucleus with that period. The hydrogen corona changed with time in non-periodic ways also, and brightened appreciably in early March of 1986.

Further analysis of the many experiments is still in progress; but it can already be said that our knowledge of comet nuclei and structure has been vastly enriched by these five encounters with Comet Halley. It is to be hoped that the success of this international adventure will lead to further cooperation in the future on other projects.

Katherine Bracher, Whitman College

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2. K. Hirao and T. Itoh, *ibid.*, 294 (1986) and accompanying papers.
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Afloat in the Clouds of Venus

The first balloon exploration of planetary meteorology beyond the Earth was accomplished in June 1985.[1] The Soviet agency Intercosmos delivered two balloons to the middle cloud layer of Venus through release from the VEGA 1 and 2 spacecraft, which also deposited lander probes and flew on to encounter Comet Halley. French and U.S. investigators also played major roles in the mission. (For an article on the geology of Venus, see the chapter on geophysics.)

The helium-inflated, 3.5-m diameter, superpressure Teflon balloons each supported a 6.9-kg instrumented gondola,[2] coated to withstand sulfuric acid in the hot (305 K) clouds. Released, respectively, at latitudes 7.3 deg N and 6.6 deg S near the midnight meridian, the balloons were caught up in the retrograde (east to west) zonal wind and tracked by six Soviet antennas and by a worldwide network coordinated by CNES, the French space agency. These included the three 64-m reflectors of NASA's Deep Space Network, and eleven radio astronomy observatories. Instrument data were telemetered, while each payload was tracked by differential Very Long Baseline Interferometry on the signals from each balloon and the on-flying spacecraft that released it.[3] Tracking of each balloon extended for over 46 hours, until the lithium batteries in the gondola were exhausted.

The surface of Venus is hidden from view by thick clouds. However, this near-twin of the Earth (the two planets have similar size and mass) has been explored by many Soviet landers, by the U.S.'s Pioneer Venus descent probes and Or-

biter, and by radar astronomy from the Earth's surface. Conditions within the clouds have been measured during brief intervals as the probes and landers fell through them. The VEGA balloons represented, in contrast, the first extended survey of conditions within the cloud layer.

Each gondola was equipped to measure temperature, pressure, ambient light level, cloud particle backscatter, and frequency of lightning. Three-dimensional wind data, derived with the aid of the tracking network, support investigations of atmospheric dynamics, including vertical and horizontal heat and momentum transport, and the presence and origin of large-scale eddies and waves. Some previous work has suggested, amidst dispute, that lightning is prevalent over putative volcanic mountains on Venus, a result that, if sustained, would support other indications, also controversial, that there is active volcanism on the planet. No lightning flashes were observed from the VEGA gondolas, nor were obvious breaks in the clouds detected.

The balloons were initially deployed at 50 km altitude (900 mbar) and rose to an equilibrium float altitude of 53.6 km (535 mbar). They were blown westward into the sunlit hemisphere by the prevailing 70 m/s horizontal winds, but were subjected to intermittent gusts of vertical wind larger in amplitude than many investigators had expected. The observed predominance of downward vertical winds may be a consequence of horizontal convergence that biases the location of free-floating balloons to regions where such winds are present. The vertical winds were frequently larger than 0.5 m/s and reached 3.5 m/s; sometimes one balloon or the other was subject to such winds for a few hours at a time.[4] A strong and consistent vertical temperature and pressure gradient prevails in the cloud layer. Thus, the vertical gusts allowed the balloon instruments to explore a greater range in the atmosphere than anticipated, from about 535 to 880 mbar. The horizontal range of the observations was about 11 000 km, or roughly one-third of the way around Venus.

A consistent 6.5 K temperature difference between readings taken at the same atmospheric pressure by the balloons to the north and south of the Venus equator was observed, perhaps an indication of long-lived, large-scale eddies that propagate in the zonal (east–west) direction. Tracking data suggest that some eddy motions are either fixed in relation to the sun direction or fixed with respect to the planetary surface. The VEGA-2 balloon experienced severe downdrafts near the end of its observed float, when it passed over the high mountainous region Aphrodite. This may be attributable to a mountain or lee wave, familiar phenomena on Earth.[5]

The success of the VEGA balloon experiments suggests that balloons deployed from spacecraft may have further utility in the future exploration of Venus and perhaps other planets.

Stephen P. Maran, NASA-Goddard Space Flight Center

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New Determination of the Distance to the Galactic Center

The distance to the center of our Milky Way Galaxy, R_0, when combined with measurements of the 21-cm wavelength radio emission line from neutral hydrogen atoms is an important parameter for understanding the mass distribution in the Galaxy. The most recent standard value, $R_0 = 8.5$ kpc, was adopted by the International Astronomical Union in order to insure that different investigators can intercompare results based on standard calibrated distance scales. Classically, the determination of R_0 has relied heavily on observations of the density maximum in the distribution of RR Lyrae stars in directions close to the galactic center. Uncertainties in our knowledge of the intrinsic luminosity of these "standard candles" and in the amount of interstellar absorption, however, have historically influenced the value of R_0. The 8.5-kpc value, for example, was a downward revision from the "round number" of 10 kpc previously adopted in 1964.

Recently, a geometric technique making use of the precise sub-milliarcsecond accuracy of Very Long Baseline Interferometry has been employed to determine a new value of R_0. The method depends on the existence of moving H_2O maser spots in Sagittarius B2 (Sgr B2), a young star-forming region very close to the galactic center. In this technique VLBI images of the maser spots were repeatedly obtained over the course of about one year. Individual moving maser spots were identified and measured, and Doppler velocities were also obtained for each spot. For a large assemblage of emitting sources, statistically, the conversion between angular motion across the plane of the sky and velocity components toward the observer determines the distance to the emitting region.

Previously, the power of the VLBI technique was demonstrated through monitoring the motions of many H_2O maser clumps associated with star-forming regions throughout the Galaxy; the most prominent one is Orion A, less than 500 pc distant from the sun. For Sgr B2, however, independent considerations place it within 300 pc of the galactic center, and its distance was an important reference value to establish.

An international team led by Mark J. Reid at the Harvard-Smithsonian Center for Astrophysics analyzed the VLBI data.[1] They estimated the distance to Sgr B3 at 7.1 ± 1.2 kpc. This constitutes a new determination of the distance to the galactic center. At the same time, the VLBI technique will provide an additional check on the value of R_0, once the distance of another strategically located source, W49, is determined. Final improvements in R_0 are also dependent on a thorough understanding of the systematic error in the distance to both sources.

Beyond the immediate importance of geometrically determining the distance scale of the Galaxy, the VLBI technique

shows promise for determining extragalactic distances. H_2O maser sources also exist in the young star-formation regions of nearby galaxies, where careful monitoring should provide valuable independent calibrations of the extragalactic distance scale.

Robert J. Havlen, National Radio Astronomy Observatory

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Bubble Structure in the Universe

A recent survey of a slice through the universe indicates that galaxies are distributed on the surfaces of thin spherical shells.[1] This conclusion has strong potential implications for crucial issues in cosmology, including the formation of galaxies,[2] the origin of clustering and superclustering,[3] the nature and prevalence of dark matter in intergalactic space,[4] and the interpretation[5] of an equally recent discovery, that galaxies in a vast region that includes the Milky Way and its Local Group of Galaxies share a common directed motion.[6]

The survey slice through the universe measures six degrees wide and 117 degrees long on the sky (see Fig. 1). It is centered near the north galactic pole and passes through the Coma cluster of galaxies. Since the survey was magnitude limited, the distances to which galaxies were observed depend on their intrinsic brightnesses; brighter galaxies are detected at greater ranges. Galaxies of average intrinsic brightness were observed to depths in the slice of about 100 Mpc (about 330 000 000 light years), assuming that the Hubble constant H_0 equals 100 km/s/Mpc. For smaller values of H_0 favored by some astrophysicists, the distance surveyed and the scales of structures identified may be as much as twice as great.

As in all studies of large scale structure in the universe, distances were not measured directly but were determined from the redshifts of the 1100 galaxies in the study, which were attributed exclusively to the expansion of the universe. Many of the redshifts were measured with a 1.5-meter telescope at Mount Hopkins, near Amado, Arizona. Presumably each galaxy has a so-called peculiar velocity, due to its motion with respect to nearby mass concentrations such as galaxy clusters. The effects of the peculiar velocity components were ignored, a circumstance that may require further analysis.

The galaxies in the slice surveyed appear to be located on the surfaces of shells, the "bubbles," with typical diameters of 25 Mpc; there is a pronounced dearth of detectable galaxies in the interiors of the bubbles, which range up to 50 Mpc in size. The data encourage advocates of the explosive galaxy formation theory, since blast waves predicted by that theory might explain the thinness of the shell walls. However, existing versions of the theory cannot readily account for the great diameter of a typical bubble. The pancake theory for the formation of large-scale structure (such as superclustering) in the universe leads naturally to the prediction of filamentary structure in the universe, which some observations seem to reveal. However, provable filamentary structure is lacking in the slice of the universe surveyed in the recent work. Clusters of galaxies, from the recent survey, seem to be located at or near where adjacent bubbles meet. Velocity dispersions for galaxies on the outskirts of clusters may need to be reinterpreted, or interpreted with extreme care, in the light of this observation. Such velocity dispersions are often used to support claims that there is a very high mass-to-light ratio in clusters, presumably due to dark matter of uncertain nature.

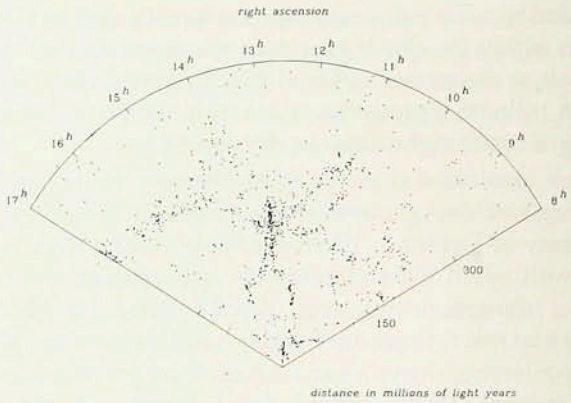

FIG. 1. This two-dimensional representation of the 3-D map prepared by Margaret Geller, John Huchra, and Valérie de Lapparent of the Harvard-Smithsonian Center for Astrophysics shows galaxies (represented by dots) distributed on the surfaces of giant bubble-like structures. The torso of the "human figure" at the center of the map is a cluster of galaxies in the constellation Coma.

Stephen P. Maran, NASA-Goddard Space Flight Center

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Some Record-Breaking White-Dwarf Stars

White dwarf stars are tiny balls, the size of the Earth, in which several tons of starstuff are packed into a volume the size of a thimble. They are dying cinders, the final remnants of low mass stars like our sun. White dwarf matter, with its high density, is weird enough, but other extreme values of stellar properties are found among the white dwarf stars. During the past year, several different groups have established a number of extremes in the properties of these objects: the highest temperatures, the strongest magnetic fields, and possibly the lowest luminosities among all ordinary single stars.

A few percent of white dwarf stars have extremely high magnetic fields, which range from a few to a few hundred megagauss (for comparison, the magnetic field at the surface of the Earth is 0.3 gauss). In these stars the magnetic field disturbs the energy levels of the atoms in the stellar surface, altering the star's spectrum and making interpretation difficult. On the basis of calculations of the behavior of the common element hydrogen in high magnetic fields,[1] two groups estimated that the first magnetic white dwarf star ever discovered (a star called Greenwich + 70° 8247) had a 300 megagauss field.[2] Gary Schmidt and collaborators at the University of Arizona identified the object PG1031 + 234 as a magnetic white dwarf with a still higher field, exceeding 500 megagauss.[3] The rotation periods of magnetic white dwarfs can sometimes be determined, since the spectrum and polarization pattern change as the star's rotation brings different regions with different field strengths into view. A curious difference between these two magnetic stars is that PG1031 + 234 rotates reasonably rapidly, turning once in 3 hours and 24 minutes, while Grw + 70° 8247 takes at least two centuries to spin once (its spectrum has remained unchanged for 50 years). These magnetic fields are far stronger than those known in any other type of more or less ordinary star. The only known stronger fields are those of the pulsars (10^{12} gauss).

Two determinations of the highest well-established temperatures among ordinary single stars appeared during the year. The star called H1504 + 65 was first discovered as the seventh brightest source in the soft x-ray sky by the HEAO-1 all-sky x-ray survey, and follow-up work identified it as a very blue, faint star, with a very peculiar spectrum that rises steeply from the visible through the ultraviolet. For such a faint star to be so bright in x rays, it must have a temperature of 160 000 K, making it the hottest white dwarf star known.[4] But its chief peculiarity may be its composition. Most stars contain hydrogen and helium, but this star contains no sign of either of these two astronomically common chemical elements. It could be a very hot helium-rich star, so hot that the helium lines don't show up. More likely, it is a unique carbon-oxygen star, the remnant of a red giant star which has shed its envelope, exposing its nuclear burning core.

An even more extreme temperature was established for an object about to become a white dwarf star, the central star of the planetary nebula NGC 2440. In at least some, if not all cases, stars which are about to become white dwarf stars are surrounded by a cloud of glowing gas, the last remains of the outer envelope of the dying star. This cloud of gas is called a "planetary nebula" because it can resemble a planet when seen through a telescope. The nebula itself can be used to determine how many high energy photons are emitted by the central star, because these photons cause the nebula to emit light by fluorescence. Atherton, Reay, and Pottasch were able, for the first time, to measure the visual brightness of the central star of NGC 2440 by using a charge-coupled device (CCD) camera at the focus of the Anglo-Australian Telescope.[5] The central star is very faint, only six times brighter than the faintest objects visible on large scale sky surveys. If such a faint object is to produce a visible nebula, it must be very hot indeed: in this case about 350 000 K.

To complement this set of record high temperatures, a white dwarf star which is one of the coolest and dimmest, if not *the* coolest, known was discovered in the course of a supernova search program at the University of Chile. Ruiz, Maza, Wischnejwsky, and Gonzalez recognized this object, called ER 8, as peculiar because it moves very rapidly across the sky and is quite faint.[6] Its spectrum is generally similar to the spectra of two other very cool white dwarfs, which have temperatures of around 4000 K. Its faintness and high proper motion suggest (but do not prove conclusively) that it may be cooler, which would make it the least luminous star known. Very cool white dwarfs like ER 8 are not the coolest stars, but because of their small size, they are the stars of lowest known luminosity.

The discoveries of these weird inhabitants of what has been called the "astrophysical zoo" raise questions about the origin and evolution of the strangely different types of white dwarf stars. The extreme characteristics of some white dwarfs suggest that you don't need to discover fundamentally new classes of objects in order to face new puzzles.

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Quasi-Periodic Oscillations in Galactic X-ray Sources

The brightest galactic x-ray sources were discovered over twenty years ago, but in many respects they are still mysterious. Astronomers have developed an acceptable general scenario in which a companion star dumps mass onto a neutron star (or in some cases a black hole), producing the x rays. But progressing beyond this general picture has been difficult because the neutron star itself is unobservable directly, hidden beneath a complex, turbulent, and possibly magnetized accretion disk. In the past year and a half a number of teams have discovered that the x-ray intensity of several galactic x-ray sources, as measured by the European EXOSAT, varies semiregularly. Reanalysis of earlier data from the EINSTEIN satellite provided confirmation. This phenomenon may prove to be a valuable observational tool which will allow us to probe the complexities of accretion disks surrounding neutron stars.[1]

The teams were looking for periodic x-ray emission produced by the rotation of the neutron star, similar to the well-defined, regular pulses seen in pulsars. While such pulses were not seen, the persistent searches paid off with the discovery of quasi-periodic oscillations (or QPO's) in many sources. There are now ten known QPO's. These QPO's show up as a broad peak in the power spectrum, quite different from the sharp peak which would be expected from a spinning neutron star. The first

reported detection[2] of a QPO was in the bright source GX5-1, and this was quickly followed by similar reports of a number of other sources.[3,4]

Any newly discovered phenomenon immediately stimulates efforts to interpret it. Models published so far suggest that the oscillations arise from the interaction of a rapidly spinning neutron star with material at the inner part of an accretion disk. Material binaries being dumped from one star to another in an interacting binary system forms a disk around the accreting star, and velocities in the disk increase as you go closer to the accreting star. The temperature of the disk becomes higher, and the magnetic field (if any) of the accreting star becomes stronger, producing complex interactions.

Alpar and Shaham[5] interpreted the periodicity of the QPO's as arising from the difference between the frequency at which material at the inner edge of the accretion disk orbits the neutron star and the frequency at which the neutron star spins on its axis—as a beat frequency. In a later elaboration of this model, Lamb, Shibazaki, Alpar, and Shaham[6] introduced the idea that clumps of material at the inner edge of the disk could make the beat frequency observable. In this scenario, a clump of gas encounters magnetic fields of different strength and geometries as it orbits the neutron star. Each time it reaches the same longitude, relative to the spinning neutron star, material is stripped off of the clump, falls to the neutron star surface, and emits a more intense burst of x rays.

This model can predict a relation between the frequency of the quasi-periodic oscillations and the intensity of the x-ray source. The rate at which material is being dumped onto the neutron star varies in these sources; in general, a higher accretion rate produces a denser disk, which extends closer to the surface of the neutron star, and higher x-ray emission. A reasonable choice of model parameters fit the data for the first reported QPO, GX 5-1, very well, where higher frequency oscillations occurred when the source was more intense (see Fig. 2).

However, the intensity-frequency relationship is quite different in different sources, and in some cases it can be quite complex. In the brightest galactic x-ray source (Sco X-1), the frequency goes down slightly, not up, with increasing source intensity, as long as the source is not too bright.[3] But when conditions in the source change, the energy as well as the intensity of the x rays can change too. A drop in the x-ray intensity at a particular energy observed by some satellite instrument does not necessarily mean that the total x-ray flux has gone down, and so the interpretation of intensity–frequency relationships can be quite complex.

Other models for the QPO's have been proposed. All models (including the one described above) are basically similar in that interaction between a spinning neutron star and the environment immediately surrounding it, in the inner part of the disk, produces oscillations. In one scenario, x rays produced directly by the central neutron star are scattered from hot gas located above the accretion disk,[7] and it is the periodic rotation of blobs of hot gas around the neutron star which produces the quasi-regular bursts of x rays. In a second scenario, the complex interaction of magnetic fields and hot gas in the inner part of the disk channels material to the surface of the neutron star, producing

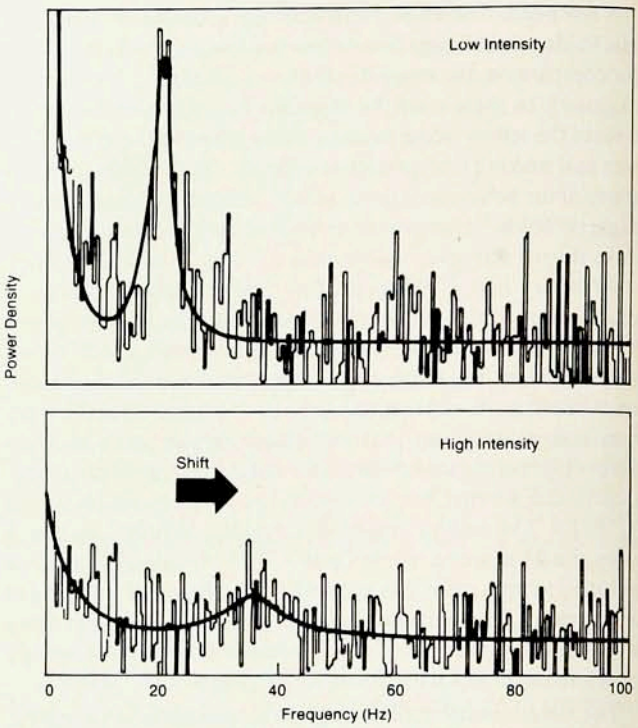

FIG. 2. Power density spectra of quasi-periodic oscillations in x-ray emission from GX 5-1. When the source is at low intensity, the oscillations correspond to the broad peak near frequency 20 Hz, while at high intensity, the peak appears near 36 Hz. (Illustration from William C. Priedhorsky, Los Alamos National Laboratory.)

bright spots which appear randomly on the neutron star surface and persist for a few rotation periods.[8] Gas accreting onto a neutron star must produce a torque on the spinning neutron star or the disk of matter surrounding it, and Priedhorsky has argued that changes in this torque could explain a number of observed phenomena including the QPO behavior of Sco X-1.[9] Still more schemes may be published in the coming months. A common theme of many of these scenarios is that similar, much slower QPO's are seen in cataclysmic variables, binary systems in which a white dwarf rather than a neutron star is at the center of the accretion disk. Instabilities in the Earth's magnetosphere have also been used to guide theoretical interpretations.

The QPO phenomenon is rather complex. Work in future years will show whether these (or other) models can explain the data. It may be that QPO's will be a very good observational probe of x-ray binaries, since the frequency with which an astronomical object oscillates is often fundamentally related to that object's structure. But it is also possible that the cause of this phenomenon may remain as an intriguing puzzle in high-energy galactic astronomy for some time.

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Solutions to the Solar Neutrino Problem?

Do we understand how the sun shines? Do we know how neutrinos propagate? These questions have plagued astronomers and physicists for almost two decades. An experiment by R. Davis and his collaborators using 100 000 gallons of perchlorethylene in the bottom of the Homestake Gold Mine in South Dakota has yielded a puzzling result: observation differs markedly from calculation. The measured value is about a factor of three lower than the theoretical expectation based upon the standard theory of how the sun shines.[1] This persistent discrepancy has spawned many imaginative solutions, some based upon the idea that conventional astronomical theory is wrong and some based upon speculative ideas in physics. Two new suggestions from the arena of fundamental physics have stimulated investigators around the world to reexamine the properties of weakly interacting particles.[2]

Soviet cosmic-ray physicists Mikheyev and Smirnov,[3] following up earlier work of L. Wolfenstein,[4] have shown that electron neutrinos may be converted to muon neutrinos by resonantly scattering off electrons that the neutrinos encounter on their way out from the core of the sun to the Earth. The asymmetry between electron and muon neutrinos is caused by the extra (charged-current) interaction that exists between electrons and electron-neutrinos. This process, now called the MSW effect, after its inventors, is the most conventional solution yet proposed for the solar neutrino problem since it requires only that: (1) neutrinos produced in radioactive decays are a mixture of neutrino states; (2) the difference of neutrino masses be somewhere in the range between 10^{-2} and 10^{-4} eV; and (3) the electron neutrino be lighter in vacuum than the muon neutrino.

Two groups of American astrophysicists[5,6] have proposed, instead, the existence of weakly interacting massive particles (WIMPS) that would simultaneously solve two fundamental problems: the missing matter problem and the solar neutrino problem. The abundance of these massive (typically several GeV or heavier) particles produced in the Big Bang would be just sufficient to account for the unseen matter discovered astronomically, provided they also have the right cross sections to be captured by the sun and transport a significant amount of energy from its core outward to larger radii. The captured WIMPS could lower the central temperature calculated for the sun and, in turn, the important neutrino flux, because they add to the efficiency with which photons transport energy. Parameters can be postulated for the WIMPS that are consistent with a single solution of both the missing-matter and the solar neutrino problems. There remain important questions as to why the WIMPS do not annihilate efficiently or reveal themselves by their mutual destruction.

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CHEMICAL PHYSICS

Alignment and Orientation Effects in Collision Dynamics

Investigation of new aspects of atomic and molecular alignment and orientation effects on collision dynamics using polarized laser radiation is emerging as a stimulating field of research.[1,2] Intriguing new experiments use the weak van der Waals interaction between atoms and molecules to orient molecules in clustered species for state-to-state dynamical studies.

The early classic example of the effect of molecular alignment on reaction dynamics uses a hexapole magnetic field to orient molecules of CH_3I in a crossed beam reaction with an atom such as Rb.[3] The scattering is found to have a large reactive asymmetry and the reaction probability is significantly attenuated when the Rb approaches the CH^3 end of the molecule.

Thorough studies of orientation effects in the $NO + O_3$ system demonstrated that the NO molecule can approach and react with either the central O atom or an O atom on the end of the ozone molecule.[4]

More recently, laser excitation schemes have been used to align electronically excited orbitals of Ca and Na atoms in studies of reactions and energy transfer of these atoms.[5–7]

The reaction of a Ca P state with Cl_2 shows a dramatic dependence on the yield of the CaCl(A) excited state with the direction of the orbital alignment in the collision. The reaction has a marked preference for perpendicular alignment of the p orbital with the incoming reaction partner. Energy transfer induced by rare gas collisions from the Ca 5^1P state to the near-resonant 5^3P states shows a 50% effect on the cross section with varying direction of the $5P$ orbital alignment. The results have been successfully explained in terms of the differing potential energy surfaces for the perpendicular and parallel approaches in the collision. Crossed beam studies with good angular resolution and intricate laser state preparation find the favored alignment for reaction of an Na($4d$) orbital with HCl when the orbital points along the direction of approach.

For molecular reagents, a high degree of alignment can be achieved by selective photodissociation with a high-powered laser of effectively all the molecules except those along one axis. In this way, the plane of rotation of IBr can be selected, and one finds that the reaction of IBr with excited Xe atoms is enhanced when the molecular plane is parallel to the reagent approach.[8] Information about the alignment of molecular orbitals involved in the transition states of chemical reactions is obtained by analysis of the "lambda doublet" spectroscopic components of the products. In the reaction of translationally fast H atoms with O_2, for example, one lambda doublet component, in which the lone p-orbital electron is left in the plane of rotation of the product OH molecule, is strongly favored.[9]

Weak van der Waals cluster formation is used to prepare selective geometries for reaction with subsequent laser excitation or photofragmentation. In this way, the axial and perpendicular electronic configurations of the metal atom p orbital are excited to produce an internal reaction of the Hg–H_2 van der Waals complex; the resulting product states of HgH are detected and show dramatically different dynamical behaviors for the two alignments.[10] A complex of CO_2–HBr is formed and reacted internally by photodissociation of the HBr to produce OH products.[11] The OH rotational populations differ considerably in this geometry-fixed case compared to the reaction in the bulk, in which all impact parameters and orientations are sampled.

These novel experiments are providing conceptually new ways to understand the dynamics of reactive and energy transfer collisions and the geometrical effects of orbital alignment on electron transformations.

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Molecular Recognition

Much of chemistry, biochemistry, and pharmacology depends on the specific formation of noncovalent complexes between molecules in solution.[1–3] The ability to bind certain molecules and not others is essential to the activity of many chelating agents, catalysts, enzymes, antibodies, drugs, and other types of molecules. Although the physical principles responsible for selectivity in binding have been fairly well understood for some time, it has only recently become possible to predict and quantitatively interpret such recognition phenomena in a systematic fashion.

These recent developments reflect advances both in fundamental theory and in the power and availability of computers. The specificity of molecular activity can often be expressed in terms of differences in free energy, which can be calculated using perturbation methods.[2–4] Consider, for example, the binding of two different ligands L and M to a receptor molecule R in some solvent. The ligand that binds with the greatest decrease in the appropriate free energy will bind most strongly to R. In principle, the free energy of binding for each ligand can be computed by forcing each ligand–receptor pair to associate (or dissociate) during a molecular dynamics or Monte Carlo computer simulation. In practice, it is usually much easier to simulate the "transmutation" or perturbation of L to M because this involves relatively localized changes in the system. By reference to a thermodynamic cycle, the difference in free energies of binding is seen to be equal to the difference in free energies of "transmutation" of the uncomplexed and complexed ligands.[2–10]

The thermodynamic cycle-perturbation method has been used successfully to compute the relative free energies of binding different halide anions to an organic receptor,[3] different inhibitors to an enzyme,[4] and a given inhibitor to genetically engineered enzymes.[4] The method can be applied to other types of molecular activity as well. Reaction rates can be studied by computing relative free energies of activation. The simulations can also be analyzed to provide physical interpretations of the computed properties. For example, the relatively weak affinity of one inhibitor for an enzyme was shown to be due to the difficulty of desolvating the inhibitor rather than to a poor fit to the enzyme.[4]

In the case of diffusion-controlled processes, molecular recognition may occur as a kinetic property and may reflect long range interactions. For example, the rates of diffusion-controlled reaction between charged or polar molecules will be increased if electrostatic interactions tend to steer the diffusing reactants toward productive collision geometries.[2] The rate constants for such diffusion-controlled reactions can be computed by analyzing reactant trajectories generated by Brownian dynamics simulations.[11,12] Such calculations have been used to show that the reaction of superoxide anion catalyzed by the enzyme superoxide dismutase is accelerated by electrostatic steering of the anions toward the active sites of the enzyme.[12]

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Vibrational Energy Exchange in Molecular Collisions with Solid Surfaces

Although vibrational energy exchange between gas-phase molecules and solid surfaces plays an important role in such practical areas as thermal transport, plasma confinement, and corrosion, it is only in recent years that our understanding of the microscopic dynamics of this process has made rapid advances. New molecular beam and laser techniques have provided detailed measurements that awe the experimentalist and challenge the theorist.

The process of vibrational *excitation* has been examined as a function of translational energy, scattering angle, and surface temperature in collisions of NO with Ag(111), where the (111) denotes the planar orientation of the Ag surface.[1] NO was prepared with high translational energies by supersonic expansion, while the vibrational excitation was monitored by laser-induced fluorescence. The fraction of NO molecules vibrationally excited by their collision with the surface was found to increase weakly with the incident kinetic energy and strongly with the surface temperature, reaching 7% at 120 kJ/mole and 760 K. Angular distributions for the vibrationally excited molecules were quasispecular (that is, the angles of incidence and scattering were nearly equal). Although other investigators have observed vibrational excitation following trapping at the surface,[2–4] this is the first report of direct excitation during a single collisional encounter.

Vibrational *deactivation* has been investigated for collisions of the first vibrational state of NO, denoted as NO($v = 1$), with Ag(111), Ag(110), and LiF(100) surfaces.[5,6] A pulsed infrared laser was used to excite a fraction of the incident molecular beam to a single rotational level of $v = 1$, and the subsequent relaxation was monitored by resonantly enhanced multiphoton ionization using a second, ultraviolet laser. On all three surfaces studied, the surviving NO($v = 1$) was found to be scattered roughly into the specular direction with a broad rotational distribution and with a 30% loss of the original translational energy. Survival probabilities for the vibrational excitation were found to be about 0.9 for all three surfaces. Survival probabilities of 0.7, 0.8, and 0.3 have also been measured for CO($v = 2$), CO_2(001), and CO_2(101) on polycrystalline silver using a laser-induced fluorescence technique.[7]

The detailed results from these experiments suggest that an electronic mechanism, probably one involving electron–hole pairs[8] or molecular ion formation,[9] is responsible for the vibrational excitation and deactivation. Calculations of vibrational relaxation at metal surfaces seem to require such a mechanism, although the agreement for insulating surfaces is adequate without the inclusion of electronic processes.[10]

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High-Resolution Optical Spectra of Large Organic Molecules

It has traditionally not been possible to apply the techniques of rotationally resolved spectroscopy (that is, the study of the rotational quantum states of a molecule) to electronic transitions in large molecules with energy level densities sufficient to permit rapid occurrence of singlet–triplet interconversion processes, intramolecular vibrational relaxation processes, isomerizations, and other chemically interesting phenomena. In fact, there are chemists who would state that if a molecule is small enough to permit a complete rotational analysis of its spectrum, then it is probably too uninteresting chemically to merit study.

However, this historical point of view is no longer as true as it once was. The ground-breaking work of Levy, Wharton, Smalley and collaborators at the University of Chicago about a decade ago,[1,2] as well as numerous later studies, have shown that the three techniques of high-resolution tunable dye laser excitation, fluorescence detection, and molecular cooling in supersonic beams can be utilized simultaneously for remarkably successful high-resolution studies on large organic molecules containing a visible chromophore.

A particularly important class of problems which can be studied with this technique concerns the behavior of a single, discrete rotation–vibration energy level of a given electronic state when this level is imbedded in a higher density manifold (or even a "quasi-continuum") of rotation–vibration levels belonging to one or more lower electronic states.

One example of the tremendous potential of the latest technology applied to such problems is illustrated by a study[3] of rotation vibration–electronic eigenstates in the vicinity of the $v = 0$ (vibrational) level of the $^1B_{3u}$ electronic state of the pyrazine molecule ($C_4H_4N_2$). Pyrazine exhibits a complicated fluorescence decay[4] from this $^1B_{3u}$ state. Although the density of states of the manifold into which the excited state decays is high, it is still sufficiently sparse that only a limited number of molecular eigenstates are contained within the coherence width of the exciting source. The observed decay then depends on the width of the exciting source, which accounts for the greatly varying reports on decay behavior and quantum beat patterns in the literature.

A second example of high-resolution information on states imbedded in a continuum is the work of Riedle and Neusser[5] on the homogeneous linewidths of single rotational lines in the "channel three" region of benzene (C_6H_6). Using Doppler-free, two-photon, dye-laser spectroscopy, with instrumental linewidths of about 5 MHz, they have accurately measured the rotational and vibrational dependence of molecular linewidths in the 10–150 MHz range. Such data leads directly to information on the extent of participation of rotational and vibrational motions in the intramolecular relaxation processes.

Theoretical models for intramolecular relaxation and decay processes have often been forced in the past to rely rather heavily on a variety of partially tested assumptions. High-quality energy-domain measurements like those described above, especially when combined with more traditional time-domain decay measurements, can be expected to lead to significant quantitative tests and dramatic qualitative improvements in our understanding of intramolecular energy flow. As a bonus result, we may also hope for a speedy reduction in some of the semantic (and perhaps even scientific) confusion which arises when workers in the time domain and energy domain attempt to discuss related observations on the same molecule.

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CONDENSED MATTER PHYSICS

Condensed matter physics is a broad field with ill-defined boundaries, as one might expect. It encompasses properties of matter and indeed, some phenomena that can be independent of material properties. Technological advances often follow from knowledge gained in the pursuit of fundamental physics in condensed matter research. Advances in this field result from theory, experiment and the development of new tools. In addition to the articles in this chapter, two other articles describing condensed matter research, those on ballistic transport and on electronic conduction in silicon dioxide, appear in the chapter on physics applied to industry.

The discussion by Lee of the universal conductance fluctuations illustrates one aspect of small samples, namely the concept of an ensemble averaging that does not lead to a correct description as it does for large systems. There is a signature of a small system that is different from that for another "identical" small system. With relation to some parameter, these systems have fluctuations that are universal in

their behavior, as well as in how they differ from each other.

That fluctuations produce noise in dynamical systems is well known. It is not surprising, therefore, that the observation that it is possible to reduce the noise in the electromagnetic field has generated a great deal of interest. Kimble and Levenson discuss "squeezed states," a phenomenon in which the granularity of the quantum nature of light is explored. Although the generation of squeezed states is expected to be independent of the media in which it is observed, it should modify decay rates and hence become a new tool in the study of the properties of matter.

The study of nonequilibrium phenomena is as important as those of equilibrium. Convection is of interest not only as a fundamental physical phenomenon but from many technological points of view as well. Hohenberg describes studies of convection in fluid mixtures. A new dimension is added, as diffusion may play an important role in studies of chaos and other such phenomena. Of particular interest is the study at the polycritical point.

Friedan, Shenker, and Qiu discuss a fluid and a gas in their introduction to a description of phenomena near the critical point where there is no characteristic length. Such studies also seek universal behavior, that is, the appearance of certain critical exponents for several classes of phenomena.

The scanning tunneling microscope (STM) continues to expand, at a fantastic rate, the horizons of what may be explored. The ability to discover what the three-dimensional geometry of a surface is by studies in ultra-high vacuum continues to be important in surface physics. Now the energy of surface states can be determined, and the directions of the wave functions in real space as well. The ability to carry on studies in air, liquid nitrogen, and water illustrates the power of this relatively new tool. (In addition to the description here by Hansma, articles on STM can also be found in the chapters on industrial physics and vacuum physics and in the article on the 1986 Nobel prize for physics.)

Finally, Narayanamurti describes how the development of additional new tools allows studies of lattice dynamics in the picosecond time domain. One of the critical parameters in lattice dynamics is the lifetime of individual photons. The use of picosecond and femtosecond laser pulses has allowed realtime studies on very short time scales for the first time. Thus, the development of techniques hitherto unavailable, extends considerably the range in which experiment and theory can be compared.

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Squeezed States

In the past year a great deal of excitement has been generated in the community of optical physicists by the observation of squeezed states of light in several laboratories.[1-5] Although the prospect of "squeezing light" may conjure up a variety of images regarding the "elasticity" of the electromagnetic field, what has in fact been observed are quantum states that directly display the intrinsic granularity associated with the quantum nature of light.

Any measurement of the amplitude or phase of a light wave must have some uncertainty, if only that required by quantum mechanics. Even the vacuum state—which has zero average amplitude—shows quantum-mechanical zero-point motion around its average value. Modern theories of quantum optics attribute the uncertainty in measurements of highly coherent laser beams to interferences between the laser and these quantum-mechanical fluctuations of the vacuum. Experiments in four laboratories have now shown that the vacuum fluctuations do not pose an intrinsic limit to the precision of optical measurements. Rather, it is possible to "squeeze" the fluctuations in such a way that those that interfere with the laser beam to produce noise have magnitudes below the vacuum level, while those that are out of phase with the laser are above it.[6] Such squeezed light may ultimately be useful for gravity wave detection, optical data storage, communications, and spectroscopy.

The squeezing of the vacuum fluctuations is accomplished by nonlinear optical interactions. In a nonlinear medium, light waves shifted equally above and below a pump frequency are coupled together in such a way that changes in the amplitude or phase of one wave cause changes in phase or amplitude of the other. Correlations are thus created even among the vacuum fluctuations. When waves that have been subject to such a nonlinear interaction are incident on a detector along with a coherent beam of the correct phase, the correlated fluctuations interfere destructively with one another, resulting in a detected intensity more stable than for a coherent beam alone. The noise in such a squeezed state of light is said to be below the standard quantum limit. If the phase of the coherent beam were changed by 90 degrees, the enhanced fluctuations required by the uncertainty principle would appear.

The first experimental demonstration of this squeezing phenomenon was in late 1985 at AT&T Bell Laboratories.[1] A 7% reduction in quantum noise was observed when light that had interacted with a sodium atomic beam in an optical cavity was mixed with a laser beam on a detector. When the nonlinearly generated light was blocked, the noise increased. Later experiments on sodium increased the noise reduction to 17%, still far short of the 90% reduction necessary to be technically useful.

In 1986 a second program, at IBM, reported a noise level 13% below the standard quantum limit for light that had propagated through an optical fiber cooled below 4.2 K.[2] While still small, the noise reduction appeared over two wide bands of frequency rather than only at the resonant modes of an optical cavity. Both of these experiments employed nondegenerate four wave mixing as the nonlinear optical inter-

action. At MIT, meanwhile, a 4% reduction for four wave mixing in sodium vapor was obtained.[3]

A group at the University of Texas, Austin, employed a completely different approach to the problem of squeezed state generation that proved enormously successful: they used subharmonic conversion; a photon at frequency ω_2 splits into two photons at frequencies near $\omega_1 = \omega_2/2$.[4] A net noise reduction of greater than 50% relative to the vacuum level was observed for infrared radiaton at a wavelength of 1.06 μm when a lithium niobate crystal (also in a cavity) was pumped at 0.53 μm. The large noise reduction resulted from the immunity of the subharmonic conversion process to noise from scattered pump light. Further efforts in parametric down conversion are expected to result in quantum noise reductions of 90% or more.

In addition to the intrinsic interest in the nonclassical nature of squeezed states of the electromagnetic field, there are as well a number of exciting applications in measurement science and in optical communication associated with sensitivity beyond the standard quantum limit, which is determined by the vacuum fluctuations of the field. Squeezed state technology is especially important when small forces must be measured, as in gravity wave detection. Squeezed states of light injected into an interferometric gravity wave detector would perturb the system less than coherent light, permitting repeated measurements without adding uncertainty. Such effects do not violate the uncertainty principle as fluctuations are being added to the system, but in a way that the extra noise does not affect the quantity being measured.

Harry J. Kimble, University of Texas and
Marc D. Levenson, IBM Almaden Research Center

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Universal Conductance Fluctuations

In condensed matter physics, conventional wisdom says that physical measurements are well represented by ensemble averages. In the past few years, this belief has been challenged by work on small samples at low temperatures. One of the most striking discoveries was that the conductance of a metallic sample at sufficiently low temperature exhibits fluctuations as a function of magnetic field, chemical potential, or impurity configuration with a root-mean-square (rms) equal to the ratio e^2/h, where e is the charge of the electron and h is Planck's constant. This effect, called universal conductance fluctuation, is due to the fact that the fluctuation amplitude is independent of sample size and the numerical coefficient in front of e^2/h depends weakly on dimensionality and the amount of disorder, as long as the sample is metallic and the temperature sufficiently low.

The original impetus for this discovery came from experiment. Along their way to observing Bohm–Aharonov effect in normal metallic rings (see *Physics News in 1985*, p.19, for a review of this interesting story, which will not be repeated here), Umbach *et al.* found that the conductance of a wire of approximate dimension $(400\ \text{Å})^2 \times 7000\ \text{Å}$ exhibited aperiodic fluctuations as a function of a perpendicular magnetic field.[1] The fluctuations are not time-dependent noise, but are reproducible for a given sample upon cycling through magnetic field or temperature. The magnetoconductance curve is, in effect, a signature of a given sample. The physical origin of this effect has to do with quantum interference of the electron wave function and the fact that the magnetic field changes the phase of the wave function. Stone performed numerical simulation on a two-dimensional lattice of tight binding model with random site energies, and produced fluctuations in the conductance very similar to the experiment.[2] However, the key question remained: how can numerical results on a few thousand sites be extrapolated to a wire with 10^8 atoms? The answer was provided by Lee and Stone, who showed analytically that the rms conductance fluctuation should be approximately e^2/h, and this result is consistent with both the numerical simulation and the experiment.[3] Essentially the same result was obtained independently by Altshuler in the Soviet Union.

The requirement for universal conductance fluctuation is that the temperature must be sufficiently low so that the inelastic length—that is, the length that an electron can diffuse in between inelastic scattering—exceed the sample size. In this case the conductance must be understood as quantum mechanical transmission through a disordered region. In a disordered medium, the motion of an electron is diffusive and its quantum mechanical description leads to conductance fluctuations which are much larger than what is expected classically. If the low temperature is not met, one can simply divide the sample into regions of size given by the inelastic length and add their contributions as classical series-parallel resistance fluctuations. In practice, for metallic wires several thousand angstrom in length, the low temperature limit is reached at a few tens of millikelvin. Owing to the much longer deBroglie wavelength of the electron in a silicon inversion layer, the low temperature limit can be reached at 4.2 K in a structure of a comparable size.[5] The inversion layer has the additional advantage that it is possi-

ble to observe the conductance fluctuation by tuning the chemical potential as well as the magnetic field.[5,6] By making very small structures, Skocpol *et al.* were able to test the predictions of the universal conductance fluctuation in great detail.[5]

The unexpectedly large fluctuations which are specific to a given sample (or a given impurity configuration) leads naturally to the following question: how sensitive are the conductance fluctuations to a small change in the impurity configuration, and in the extreme limit, to the motion of a single atom? The result, obtained independently by Altshuler and Spivak[7] and by Feng, Lee, and Stone,[8] is that in one and two dimensions, moving a single atom by a distance on the order of the deBroglie wavelength, the conductance changes by an amount which is independent of sample size, and equals e^2/h when the disorder is strong. In three dimensions the effect is somewhat weakened, but still much larger than what is expected classically. This surprising result can be understood by recognizing that the Feynman paths of an electron in a disordered medium can be thought of as random walk. In two dimensions, a random walker which crosses the sample basically visits a finite fraction of all the sites, so that the alteration of a single site affects a finite fraction of all the Feynman paths. In the strong disorder limit, changing a single impurity is then the same as changing the entire configuration and leads to a conductance change of e^2/h. It should be possible to observe this effect directly by experiments, and indeed discrete changes in the magnetoconductance curves are observed in the inversion layer and are attributed to the change of a single scattering center.[5] Very recently, time-dependent jumps in the conductivity have been observed in small bismuth wires and films and interpreted in terms of defect motion.[9]

While the initial discovery of sample specific fluctuations was made at low temperatures, it has become clear that quantum mechanical coherence plays an important role as long as the inelastic scattering length greatly exceeds the mean free path, a condition which is satisfied even at room temperature if the metal is sufficiently disordered. For example, Feng *et al.*[8] have pointed out that the sensitivity to impurity configurations provides an estimate of the magnitude of $1/f$ noise due to defect motion in highly disordered metals. At the same time, it is likely that insights gained from the studies of electron wavefunctions will deepen our understanding of the propagation of classical waves such as electromagnetic or sound waves through a random medium.

P. A. Lee, Massachusetts Institute of Technology

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Convection in Fluid Mixtures

Many of the most striking examples of nonequilibrium pattern formation and chaos have been observed and studied in Rayleigh–Benard convection. This is the flow of a thin fluid layer contained between horizontal, thermally conducting plates held at different temperatures. This research has been extended now from the study of pure fluids to fluid mixtures; these are particularly interesting because the additional diffusion mode allows for the possibility of two different types of convective threshold, an instability to steady convection as in pure fluids, and an oscillatory instability to a time-periodic state.[1] This additional degree of freedom offers the hope of observing interesting dynamic phenomena (such as chaos, intermittency, etc.) immediately above threshold, and thus of developing a quantitative "first principles" theory of chaos based only on the hydrodynamic equation.

A phenomenon of particular interest is the polycritical point where the oscillatory and steady instability thresholds coincide. Interesting dynamic behavior was predicted by Brand, Hohenberg, and Steinberg[2] in the vicinity of this point, and some, but not all, of the qualitative predictions of their theory were confirmed in experiments by Rehberg and Ahlers[3] on cryogenic ^{3}He–^{4}He mixtures in a porous medium.

An important advance came from flow visualization experiments by Walden, Kolodner, Passner, and Surko on alcohol-water mixtures, which showed that the oscillatory state above threshold was in the form of traveling waves.[4] Indeed, it was argued theoretically[5,6] that the standing waves previously assumed[2] were unstable to traveling waves in this system. Surprisingly, however, even traveling waves did not occur as stable oscillations immediately above threshold,[4b,7] but were only visible as transient growing waves. The propagation of these waves and their reflection from the sidewalls of the container were studied experimentally by the Bell Labs group,[4b] and understood theoretically on the basis of a linear theory by Cross (Caltech).[8] When the amplitude of the waves grows beyond a certain range, the system makes a large transition to a nonlinear state of slowly traveling waves which has also been studied experimentally by Moses and Steinberg,[7] but whose nature is at present only imperfectly understood.[6,8]

Although this system has complicated behavior and has shown many features unanticipated by theory,[9] it is reasonable

to hope that further fruitful interaction between experimentalists and theorists will help us to identify rich dynamics[10] and interesting pattern forming behavior.[4,7]

P.C. Hohenberg, AT&T Bell Laboratories

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Lattice Dynamics in the Picosecond Time Domain

A direct determination of the lifetimes of both acoustic and optic phonons as a function of frequency and temperature is of fundamental interest to a variety of problems in solid state physics. The determination of acoustic phonon lifetimes, for example, is crucial to understanding the thermal transport properties of insulators, semiconductors, and amorphous materials. The kinetics of the decay of optic phonons, and their coupling to other excitations in the condensed phase, is of importance for such diverse problems as hot electron transport in semiconductors and the generation of nonequilibrium high frequency acoustic phonons in insulators. The lifetimes of acoustic phonon excitations in short mean-free-path materials or at elevated temperatures are often in the picosecond time regime. Optic phonons have typical frequencies (5–10 THz) which correspond to the femtosecond time domain. Using picosecond and femtosecond laser pulses, several researchers have made considerable progress in the last two years in studying (in real time) phonon excitations at very short time scales. In this article I shall discuss this recent progress.

Acoustic Phonons. Over the last fifteen years, much work has been done using heat pulse techniques to study acoustic phonon propagation in solids at liquid helium temperatures.[1] At low temperatures and moderately high frequencies (hundreds of gigahertz) acoustic phonon lifetimes in dielectric solids and semiconductors is often in the 10^{-7} to 10^{-6} sec range, and time-of-flight techniques can be readily applied using conventional electronics. As noted above, at higher temperatures one has to be prepared to study phonons with very short lifetimes and short mean free paths. In one experiment[2] a "pump" light pulse (duration 0.2 ps) is focused on a suitable absorbing transducer film (typically 100 Å thick). The heating of this layer sets up a thermal stress which in turn results in the generation of a strain wave (phonon pulse) which propagates into the sample film behind. The transducer film also serves as a detector through measurements of the change in reflectivity due to the acoustic strain using a "probe" pulse whose time delay can be varied with respect to the pump.

At phonon energies of about 2 eV, Maris *et al.* have found strong detector responses in a-As_2Te_3, InSb, and Al, among several materials. They have performed measurements at frequencies as high as 400 GHz and have studied the attenuation in *a*-SiO_2 films of thickness 600 Å at room temperature. The method shows considerable promise to measure acoustic phonon attenuation over a wide frequency and temperature range and should help in elucidating, for example, the nature of heat transport in amorphous materials, particularly in the region of the thermal conductivity "plateau." [1]

Optic Phonons. Even though linear spectroscopy in the far infrared and nonlinear optical and Raman spectroscopy have provided a wealth of information on optical phonon decay processes, until recently the time resolution was insufficient to measure the individual oscillations of an optical phonon. In some beautiful recent experiments, Auston *et al.* have shown that the propagation of femtosecond optical pulses in electro-optic materials is observed to produce a Cherenkov cone of pulsed far IR radiation in the terahertz spectral range.[3,4]

The above technique has led to the first[4] coherent excitation and detection of traverse optic (TO) phonons in $LiTaO_3$. Two femtosecond pulses were used: one to generate the radiation field and the other to detect it. The distance between generator and detector was as small as 7 μm. This was essential to minimize the influence of the strong frequency-dependent absorption near the lattice resonance. The damping time (380 fs) of the lowest TO phonon at 6 THz has been measured directly through the decay rate of the oscillations.

The method should be applicable to all noncentrosymmetric crystals. Through the use of more intense optical pulses, the effects of nonlinear processes may possibly be observed directly for the first time.

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Scanning Tunneling Microscopy

There have been many exciting new developments in the study of scanning tunneling microscopy[1] since it was first described in *Physics News* three years ago (*Physics News in 1983*, p. 16). Within the past 18 months atomic resolution images have been published for surfaces in air,[2] in liquid nitrogen,[3,4] and even in water.[5] The ability to operate in new environments makes possible opportunities for research on technologically important processes.

For example, Sonnenfeld and Schardt[6] were able to obtain atomic resolution images of a graphite surface immersed in a 0.05 M $HgClO_4$ solution before they electroplated the surface with silver, between islands of plated silver, and after stripping the silver from the surface. Their images of the plated surface were consistent with an island film growth mechanism. Their pioneering study demonstrates that atomic-scale studies of electrochemical processes occurring in electrodes in solution are now possible without ever removing the elctrode from the solution.

At an international conference in Spain[7] last summer, other exciting work included a report of molecular vibration spectra obtained in liquid helium, images of a DNA-protein complex that clearly showed the protein spiraling around the DNA and many improved designs for scanning tunneling microscopes.

Thus the future looks bright for scanning tunneling microscopy.[8] We can expect not only topographic, but also spatially resolved spectroscopic images for a variety of environments. These images may contribute to our understanding of technologically important devices and processes.

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Conformal Invariance and Critical Exponents in Two Dimensions

As water is heated through its boiling point it suddenly changes from liquid to gas. When the pressure is raised, this phase transition becomes less and less abrupt, until at a certain critical pressure it becomes continuous. At this critical point the density fluctuations in the fluid have a remarkable property. Under normal conditions the fluctuations are coherent only over lengths on the order of the space between water molecules, but at the critical point fluctuations occur at all length scales. The system has no characteristic length, so it is invariant under change of scale. Because of these large fluctuations, thermodynamic quantities (e.g., the specific heat) develop power-law singularities at critical points. The numerical powers are called critical exponents.

Scale invariant critical points occur in a wide range of materials, but physical systems which are quite different under normal conditions have exactly the same critical exponents. This is the remarkable phenomenon of universality. Only the most basic properties, like spatial dimensionality, determine the universality class, making the problem of determining the possible universality classes a fundamental one. The renormalization group has provided a satisfying conceptual framework for understanding the phenomenon of universality, but it provides no effective general procedure for determining the possible universality classes.

Most physical systems have the important property of locality—the interactions between degrees of freedom are short ranged. Local systems at their critical points should respond in a simple way to local scale transformations, called conformal transformations.[2] Conformal transformations preserve angles but not scale lengths at different points. Two dimensions is an especially promising place to study conformal invariance because the set of conformal transformations in two dimensions is enormous. Any analytic mapping of the complex plane is conformal. This very large symmetry group is a powerful tool to study critical phenomena in two dimensions.[3] In a certain domain it allows us to determine all possible values of critical exponents.[4]

The algebra of two-dimensional conformal transformations is called the "Virasoro algebra" and was first studied in the rather different context of string theory.[5] This is a branch of high energy physics (see the article on strings in the chapter on elementary particle physics) originally developed to explain the behavior of the strong interactions and currently showing great promise as a unified, self-consistent description of all forces.

Two-dimensional scale invariant systems are representations of the Virasoro algebra. The mathematical properties of these representations are crucial to understanding the allowed forms of critical phenomena. The representations which can occur in the kinds of systems most often encountered—genuine thermal phase transitions with spatial isotropy—have the mathematical property of unitarity. As in quantum mechanics, unitarity means that the states of the representation cannot have a negative metric. Unitarity puts severe constraints on the possible values of critical exponents.[4] The constraints are rather similar to those that arise from rotational symmetry in quantum mechanics. There the z component of angular momentum is constrained to have integer or half-integer values. In the case of conformal symmetry, the critical exponents are constrained to have certain rational values. This explains the occurrence of rational critical exponents in many known two-dimensional systems—the most famous case being the Ising model.

To be more precise, the realization of conformal symmetry is described by a parameter c which measures the response of the system to distortion of the substrate[6] and describes the leading finite size correction to scaling.[7] For c less than 1 only a certain infinite set of rational values of c is allowed, the discrete series.

At each of these values a finite set of rational critical exponents are possible.[4,8] For c greater than or equal to 1, all positive critical exponents are permitted.

This still leaves unanswered the question of which combination of these representations can occur in a critical system. The first constraint is that consistent correlation functions must exist.[3] In the discrete series, correlation functions are miraculously simple—they obey linear differential equations—so this condition can be checked.[3,9] A second constraint is that a consistent partition function must exist. This condition has been effectively implemented for systems in the discrete series on a torus.[10] Recently, an exhaustive list of solutions to this constraint has been conjectured.[11] A complete classification of the university classes for c less than 1 is close at hand.

Physical realizations of the discrete series are known.[12] These include familiar systems such as the Ising model and certain other generic multi-critical systems. Recently, models realizing the additional members of the conjectured exhaustive list have been constructed.[13]

Conformal symmetry can be extended to include supersymmetry, a symmetry relating fermions and bosons. The two-dimensional version of this, first studied in string theory, was the original example of supersymmetry. The possible physical representations of supersymmetric conformal algebras have been classified, with results similar to the ordinary conformal case.[4,14] A laboratory system has been identified that displays this exotic structure[4,14]—helium adsorbed on krypton-plated graphite, a realization of the Ising model with annealed vacancies.[15] This is the first realization of a supersymmetric field theory in nature.

Recently an even more comprehensive and abstract description of two-dimensional critical phenomena has been given, as analytic geometry on the space of all surfaces of arbitrary topology.[16] This will perhaps provide the framework for a complete classification of all two-dimensional critical phenomena. It also provides the basis for a new approach to string theory.[17]

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CRYSTALLOGRAPHY

Small-Angle Scattering

The scattering of x rays or neutrons at small angles has been used to address several key questions in the areas of materials and polymer science. Availability of intense sources, such as either synchrotron radiation facilities or rotating anode sources, has advanced the use of time-resolving scattering techniques to probe kinetic processes in these disciplines, providing key pieces of information on several outstanding questions. The enhanced flux from storage ring facilities has permitted substantial increases in the resolution limits of small-angle x-ray scattering, producing a bridge between light scattering and x-ray scattering methods. This has been of tantamount importance in the area of fractal structures. In addition, the brilliance of the beam from synchrotron sources has made possible the simultaneous measurement of x-ray scattering with other characterization techniques, such as, for example, differential scanning calorimetry. The combination of these methods yields information on phase transitions that was hitherto impossible to obtain. The following articles examine recent progress in small-angle scattering research.

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Fractals and Small-Angle Scattering

Although disordered materials are ubiquitous in nature, the characterization and modeling of such structures have eluded physicists for decades. The recent application of fractal geometry to the interpretation of scattering data, however, has substantially changed this situation.

Fractal geometry is important in disordered systems because most simple models of random growth lead to self-similar, or fractal, objects. Such objects look the same under different degrees of magnification and show power-law spatial correlations. Typically, one measures the fractal dimensions D from the power-law slope of scattering profiles. Recent scattering experiments showed fractal behavior in branched polymers,[1] colloidal aggregates,[2–4] porous materials[5–8] and rough colloidal particles.[9]

Fractal structures are typically observed on length scales exceeding 10 Å, so small-angle x-ray and neutron scattering, as well as light scattering, are the techniques of choice for characterizing fractals. In fact, the desire to study fractal materials prompted an Exxon group[4] to develop a synchrotron-based instrument capable of resolving structures between 10 and 10 000 Å.

Substantial progress was made in 1986 in the understanding of the origin of random structures in terms of chemical and physical growth processes. The polymerization of silica is a prime example where, depending on catalytic conditions, either branched polymers, smooth colloidal particles, or rough colloidal particles can be prepared.[1,9] Based on simple rules, silica polymerization can be mapped on to computer-simulated fractal growth models.[9,10] Catalytic conditions control growth by determining whether growth occurs by monomer addition or cluster-cluster growth.

For suspended colloidal aggregates, the essential factors which control growth are less clear. Several groups find structures consistent with reaction-limited cluster–cluster growth.[2–4] In the case of diffusion-limited aggregation, however, the extreme rapidity of aggregation coupled with restructuring,[11] precludes definitive experiments.

Fractal aggregates can also be grown in the gas phase—fused silica[12] and carbon black[13] being two commercially important examples. Studies of commercial powders generally reveal D's which fall between the diffusion-limited and the reaction-limited regimes. Recent studies on the *in-situ* growth in flames, on the other hand, show very small D's, suggesting that growth is modified by electrostatic interactions.[14]

Fractal structures have been found in numerous porous materials, both natural[5,7,8] and synthetic.[6] In the case of the synthetic porous silicates, the catalytic factors described above for solution growth, ultimately determine the structure of the dry porous material.[6,9] For natural materials, however, the origin of fractal porosity is not yet understood.

Fractal geometry is not a necessary concept to interpret all power-law scattering curves. The Debye function, for example, represents a complete structure factor for an ideal linear polymer. The fact that such polymers are fractal with $D = 2$ represents no new information.

The real value of fractal concepts is the ability to characterize complex structures and thereby clarify the essential chemistry and physics which control structure. Physics often advances on simple unifying concepts. The burst of activity in 1986 on the structure of disordered materials suggests that fractal geometry falls in this category.

Dale W. Schaefer, Sandia National Laboratory

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Time-Resolved X-Ray Scattering

The measurement of real-time x-ray scattering has been used in the past to study deformation,[1] crystal annealing,[2] and phase separation[3] in high molecular weight polymers. Recently, Keller and co-workers,[4,5] using synchrotron radiation, performed an important set of measurements resolving a discrepancy between solution and bulk crystallization processes in polymers. Theoretical arguments predict that for both bulk and solution crystallization the primary crystal thickness should vary inversely with the difference between the melting and crystallization temperatures. This had been found to be true in solution crystallization but not in the bulk. Via a combination of Raman and time-resolved x-ray scattering measurements, these workers found that the primary crystal thickness was nearly a factor of two smaller than that measured by static scattering methods, and varied in a manner similar to that of solution crystallized material, thereby resolving this outstanding discrepancy. The discrepancy between the time-resolved and static measurements was due to a rapid crystal thickening. The ability to measure the scattering at the very early stages of crystallization was made possible by the enhanced flux of the storage ring facilities.

The combination of time-resolved, small-angle x-ray scattering (TRSAXS) measurements with differential scanning calorimetry (DSC) has also been developed recently.[6] While the full potential of these combined measurements has not been realized, it is clearly evident that an understanding of complex thermal behavior in materials can be attained. Of particular note is a recent study on the multiple endothermic response (a reaction in which heat is absorbed) exhibited by polyurethane block copolymers.[7] Typically, these materials exhibit three endotherms when they are heated from ambient temperatures to temperatures above the melting point. Combination of TRSAXS and DSC has clearly shown that these materials undergo a melting of shorter length crystallites followed by a mixing with the amorphous soft segment phase. At somewhat higher temperatures, a melting of the larger crystallites is observed. It is essentially impossible to unravel such complex thermal behavior without the use of these combined techniques. Further advances are also in progress to couple these techniques with wide-angle diffraction methods, thus providing structural information for a range of size scales from several to thousands of angstroms, along with the corresponding calorimetric data.[8]

Thomas P. Russell, IBM Almaden Research Center

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High-Resolution Small-Angle X-Ray Scattering

A high-resolution small-angle x-ray scattering (SAXS) instrument, designed to exploit the characteristics of synchrotron radiation, has recently been developed by a group at the Exxon Research and Engineering Company and installed at the Stanford Synchrotron Radiation Laboratory. This instrument extends the SAXS technique into areas and applications hitherto accessible to conventional x-ray sources only with great difficulty. These research areas include: (a) measurements of SAXS diffraction patterns over a wave vector (the inverse of the wavelength) range from 3×10^{-4} to 0.1 Å^{-1}; (b) resonant SAXS studies, that is, SAXS measurements with the incident radiation tuned alternately close to, and then away from an absorption edge of one atomic component in the system under study, thus providing an additional means of contrast variation; and (c) real-time SAXS measurements to study the relaxation and growth processes is subjected to strong initial perturbation.

Charles Glinka, National Bureau of Standards

Colloidal Dispersion Structures Analyzed by Small-Angle Neutron Scattering

Colloidal particles, which are defined as having at least one spatial dimension between 1 and 1000 nm, exhibit a variety of fascinating phenomena when dispersed in aqueous or oil-based solvents. Typical examples are polymer-based thixotropic paints, which tend to spread when sheared by a brush and then immediately re-thicken to prevent dripping, or oils

which have been modified to become magnetic, viscoelastic, or micro-emulsified. A multitude of industrial processes rely upon at least a phenomenological understanding of such behavior, but the complexity of many colloidal dispersions has until recently inhibited the development of a more detailed description at the fundamental level.

Dispersion structures may be classified in three broad categories: isotropic dispersions of particles which interact isotropically (e.g., spherical polymer lattices), isotropic dispersions of particles which interact anisotropically (e.g., magnetic colloids or ferrofluids), and anisotropic structures which may be formed from particles which interact through either isotropic or anisotropic potentials (e.g., colloidal crystals). Understanding the way in which particles relate to each other at the microscopic level in such systems is complicated by the fact that many of the most interesting particles, especially bio-colloids, self-assemble from molecules in the dispersion and have no separate existence; we must simultaneously and unambiguously determine the structures of both the dispersion and the particles from which it is formed.

Small-angle neutron scattering (SANS) has proved to be an ideal tool for such studies for several reasons: light-atom structures may be studied in light-atom solvents with good contrast, selection rules for magnetic scattering allow model-free separation of magnetic contributions, and isotopic substitution permits wide variation of the refractive index of sub-assemblies to allow specific sites to be studied. In the first class of studies, on strongly interacting charged spherical colloids, a major breakthrough was achieved by appropriate use of modern liquid theory to develop a quantitative description of the scattering in fully analytic form.[1] Such studies are now routinely used, for example, to measure the size and charge of small colloids *in situ* in a concentrated dispersion.[2] Ferrofluids provided a second class of colloids, a major practical as well as theoretical interest, in which a quantitative analysis of SANS studies was made possible by advances in magnetic liquid theory.[3,4]

The most recent breakthrough has been in the field of dispersions of anisotropic colloidal particles, such as, for example, the rodlike micelles which form in many amphiphilic molecular solutions. In these systems, analytic liquid theory is rendered intractable by its ability to predict the probability of the relative orientation of two such particles at a given distance. In this case, a new experimental technique has been developed in which all particles are given the same orientation by subjecting the dispersion to a viscous shear flow, thus side-stepping the theoretical difficulty completely.[5,6] A further advantage of this method is that the SANS scattering patterns show directly the symmetry of the colloidal particle. As a result of these and other developments, SANS has become routinely used in colloidal studies in recent years. An interesting spin-off is that many colloidal systems are now sufficiently well understood to be used as controllable model systems for the study of other physical processes, such as shear melting.[7]

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ELECTRON AND ATOMIC PHYSICS

Quantum Jumps in a Single Atom

Quantum mechanics seeks to describe the dynamical process of spontaneous emission, whereby an excited atom emits a photon during de-excitation. Dramatic quantum effects, which are normally washed out in the emission from a collection of many atomic emitters, can be seen in the fluorescence from a single atom. The sudden switching on and off of the fluorescence as the atom makes "quantum jumps" is a recently observed example of such an effect.

In 1985, Cook and Kimble[1] realized that three atomic energy levels in the "V" configuration (two excited levels which decay to the same ground state), where one excited level decays in a short time and the other remains excited for a much longer time, is a system ideally suited for studying the photon emission and absorption process of atoms. Originally, this system was discussed by Dehmelt[2] as a photon amplification scheme for the detection of a very weak optical transition. If a laser is used to couple the ground state to the "strong" (quickly decaying) upper level, the fluorescence from the strong level appears as a steady intensity when the averaging time is sufficiently long. Ordinarily, when observing the fluorescence from a collection of many atoms, the effect of a second laser, which couples the ground state to the "weak" (slow decaying) upper level, is to reduce the average fluorescence intensity, since, on the average, the population of the strong level is diminished. However, the question of how this reduction in average intensity is manifested for a

single atom has two possible answers: (1) it may diminish to a steady but reduced level as occurs with a collection of many atoms, or (2) it may switch abruptly from "on" to "off" if the atom "quantum jumps" between the ground state and the weakly coupled level.

Many authors have examined the general three level system theoretically in the past year and have calculated the statistical properties of the emitted radiation.[3] They conclude that the quantum jump picture is the correct one. A recent experiment has unambiguously shown that the fluorescence intensity (from the strong transition) from a three-level "V" system is, indeed, two-valued rather than continuous when measured with a time resolution shorter than the lifetime of the weakly coupled level.[4] In this experiment, a single positively charged mercury ion was confined to less than one micron in an electromagnetic ion trap, and simultaneously irradiated by two lasers. Similar experiments, employing a single trapped barium ion, were performed by two other groups.[5,6] A fourth group observed the fluorescence emitted by single barium atoms in a very weak atomic beam, and by measuring correlations in the time interval between detected photons, were able to infer that quantum jump picture is correct.[7] These experiments provide insight into the statistical nature of the atomic emission and absorption process.

Randall G. Hulet, National Bureau of Standards

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Parity Nonconservation in Atoms

One of the great successes of theoretical physics has been the electroweak theory, which describes the weak and electromagnetic forces in a single unified framework. One prediction of this theory is that a small force exists between the electrons and nucleons in atoms which does not conserve the spatial symmetry known as parity. If parity is not conserved, it means that the atom has a "handedness," and therefore appears different from its mirror reflection. The measurement of the amount of this "handedness" or parity nonconservation (PNC) provides a unique test of the electroweak theory. Such measurements are extraordinarily difficult, however, because this "handedness" involves a distortion of the atomic shape which is only about one part in 10^{11}.

In spite of the many difficulties, PNC has now been observed in several different atoms, and the precision of these measurements has steadily improved over the past decade.[1] Recently, PNC in an atom was measured with an accuracy better than 10%.[2] In this experiment a tunable laser was used to excite a transition between two selected states of cesium atoms. Perpendicular electric and magnetic fields were applied to the excitation region. These fields, in combination with the polarization of the laser light, defined a coordinate system or handedness for the excitation process which was thereby sensitive to the handedness of the atom. A small but measurable change in the excitation rate for the atom occurred when the handedness of the excitation was reversed. A reversal was accomplished by changing the sign of either field or the laser polarization. This change in the excitation rate is directly related to the amount of PNC in the atom.

To relate the experimental measurements to the fundamental electron–nucleon force, one must calculate the structure of the atom, particularly in the vicinity of the nucleus. This is a challenging problem in theoretical atomic physics, which several groups around the world are now attacking with a variety of new techniques. Improved calculations for a number of atoms are being carried out, and results obtained to date for cesium have an estimated uncertainty of a few percent.

Combining the results of atomic theory and experiment, one obtains a value for the PNC interaction in cesium which agrees with the predictions of the electroweak theory to within the experimental uncertainty. Atomic PNC measurements complement high energy accelerator tests of this theory; they involve lower energies and are sensitive to different electron–quark couplings. Thus atomic PNC measurements are now providing important constraints on possible alternatives to the standard electroweak theory, such as superstring theories.

Work is under way at a number of laboratories which should lead to substantially more precise measurements of atomic PNC in the near future. These small scale experiments will provide new information on the fundamental forces of nature.

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Uranium Lamb Shift

Quantum electrodynamics (QED), the quantum theory of the interaction of charged particles and light, is the funda-

mental theory of the atom and the basis for theories which explain the interaction of quarks (quantum chromodynamics) and also the weak nuclear force. QED accurately describes the hydrogen atom—a single electron bound to a single proton. But to be a complete theory, it must also describe the uranium atom where the electrons are bound to the much stronger electric field of a charge-92 nucleus. It is difficult to test QED in neutral uranium because the QED effects are swamped by the ordinary interaction of any one electron with the other 91 electrons.

Stripping off most of the electrons can make it easier to interpret the experiments, and an experiment has now been performed using uranium ions from which all but two of the normal 92 electrons were removed.[1] The experiment measured the average time for a spontaneous transition between two atomic levels. This time is very sensitive to the energy difference between these levels, and so to any QED contribution to the energy difference. The shift in the energy levels of an atom due to quantum electrodynamic effects is referred to as the Lamb shift, for Willis Lamb Jr., who first measured the shift in hydrogen. For the energy levels chosen in two-electron uranium, calculations predict that QED effects contribute 20% of the energy difference, and the ordinary interaction between the two electrons contributes most of the remainder. Because only two electrons remain, QED and non-QED effects can be calculated precisely.

Uranium with two electrons is made by passing uranium ions traveling at half the speed of light through a paper-thin metal foil. Uranium and other atoms at relativistic velocities are produced by the Lawrence Berkeley Laboratory Bevalac—the combination of the Super-HILAC, a heavy-ion linear accelerator, operating in tandem with the Bevatron, a synchrotron. The Bevalac is capable of producing uranium, or any other atom, with all of its electrons removed.

The experiment uses foils both to strip electrons and to put two-electron uranium in the desired atomic level. The uranium passes through the foil and the atomic level decays in flight, emitting x rays whose intensity decreases exponentially with distance past the foil. The measured exponential decrease determines the average transition time and hence the energy difference between the levels. The result is a value for the Lamb shift in uranium which is accurate to 12% and which agrees with the predictions of QED. Future experiments with more intense beams may be able to measure the Lamb shift in uranium to 0.1%.

QED provides a complete description of the interaction of charged particles and light. But Newton's Laws also once provided a complete description of gravity, the only unexplained phenomenon being the anomalous advance of the perihelion of Mercury, the planet bound in the strongest gravitational field that could be studied. By studying an electron bound to the strongest electric field available, one may also find unexplained phenomena.

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Atoms in Strong Laser Fields

It has been known[1] for more than 15 years now that any atom exposed to a laser of intensity above 10^{10} W/cm^2 will undergo substantial ionization, losing one of its outer electrons. Around 1982, experiments at Saclay[2] produced evidence of significant multiple ionization (ejection of more than one electron per atom) in the rare gases. Since the wavelength of the lasers employed in those experiments were either in the infrared (1064 nm) or optical (532 nm) range, the absorption of a number of photons (a so-called multiphoton process) was required for the ejection of the first electron; of an even larger number for the ejection of a second electron, and so on.

Such multiphoton absorptions have been investigated since the mid-sixties, but the accumulated experience[1] and wisdom appeared to suggest that processes requiring large numbers of photons, more than 10 or so, should be rather unlikely at those intensities. Thus it came as a surprise that processes requiring the absorption of 20 or 30 photons per atom were occurring with great ease at laser intensities of the order of 10^{12} to 10^{14} W/cm^2. In 1983, reports[3] of multiple ionization, with up to 9 electrons ejected, not only of rare gases but of a number of other atoms as well, extended the observation of these phenomena to regions of ultraviolet wavelengths (193 nm) and higher power, up to 10^{16} W/cm^2. Moreover, radiation of wavelength shorter than that of the incident laser was in some cases emitted in the process.

Several important questions with potentially far-reaching implications are posed by these experiments: (a) Why is it so easy to strip electrons from atoms and what is the underlying mechanism? (b) Are they stripped one by one or in groups? (c) If excitation in groups contributes significantly, can it be exploited towards the creation of short-wavelength and especially x-ray lasers? (d) What is the role of above-threshold ionization? (e) What role do the pulse duration and shape play in the overall process?

These and a number of other related questions provoked widespread debate, speculation, and a flurry of activity in the theory of such strong field phenomena.[4] In mid-1985, events took an ironic twist when it was demonstrated[5] that some of the answers were lurking within the existing theoretical

framework. Theoretical analysis and experimental evidence now conclude that under the conditions of the existing experiments, successive stripping of single-electrons is the dominant mechanism. The resulting understanding underscores the importance of the laser pulse duration and shape, and appears to suggest the possibility of novel behavior if the duration and especially the rise time of the pulse become shorter, say 10 fs or less.

At this point, little is known about the role of doubly and multiply excited states in these processes. It is nevertheless possible to speculate on certain possibilities based on the fundamentals of atomic structure as well as some existing data. We can expect that photons of optical and near ultraviolet wavelength will interact mainly with electrons of the outer shell and possibly the subshell just below it. This is in contrast to double excitation by extreme ultraviolet or x-ray photons where one photon excites (or ejects) an electron from an inner shell. It appears, therefore, that multiphoton excitations with powerful lasers of suitably chosen frequency, intensity, and pulse properties may lead to novel atomic states that would be virtually impossible to create otherwise. The $1s^2\ 3p^4$ state of a carbon-like ion would be one such example which must, however, be understood as a state embedded in the strong field. Thus, in addition to possible applications, the next few years are apt to reveal new vistas of atomic structure and its behavior under strong laser fields.

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Discovery of the Soliton Self-Frequency Shift

In recent years, the prediction[1] that soliton pulses could exist and propagate stably in single mode optical fibers has been well verified experimentally.[2,3] Several exciting uses have been found or proposed for these non-dispersive pulses. One is the soliton laser (see *Physics News in 1984*, S·84), a mode-locked color center laser which produces pulses of any desired width, from psec down to a few tens of fsec, as controlled by a fiber in its feedback loop.[4] Another is the possibility of creating an "all optical" communications system—one without electronic repeaters—in which a single fiber could transmit as much as 100 Gbits/s over thousands of kilometers. Such a system would use Raman gain to overcome loss, and the signal pulses would be transmitted as solitons.[5,6]

The development of such applications has created the incentive to better understand the basic physics of fiber solitons. The nonlinear Schrödinger equation—the familiar equation of quantum mechanics, but with different coefficients and the addition of a term to reflect the fiber's index nonlinearity—seems to describe well the propagation of solitons with widths of several picoseconds or greater.

But we have recently discovered a new and unexpected effect, one that is not predicted from the nonlinear Schrödinger equation as normally written.[7,8] We observe a continuous red shift in the optical frequency of the soliton as it travels down the fiber. The effect is caused by a Raman self-pumping of the soliton, by which energy is transferred from the higher to the lower frequency parts of its spectrum.

The effect becomes particularly dramatic in the subpicosecond regime, as it scales inversely as the fourth power of the pulse width. For example, in 400 m of fiber, we see an 8 THz shift out of an optical frequency of 200 THz (at a wavelength of 1.5 μm) for a 500 fs input pulse; similar shifts are obtained in just a few meters as the pulse widths are reduced to about 100 fs. Thus, it may be possible to use this phenomenon to derive femtosecond pulses of different optical frequency from the same laser source (even possibly outside the laser tuning range); this would be of interest for pump-probe experiments.

The soliton self-frequency shift does not render the proposed scheme for soliton-based communications obsolete; for other reasons, the optimal scheme[6] would involve pulses of width greater than 20 ps, but the scaling of the effect with the minus fourth power of the width should make the effect negligible for such pulse widths. Subpicosecond telecommunications schemes would seem to be ruled out, however.

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ELEMENTARY PARTICLE PHYSICS

Superstrings

One of the fundamental goals of theoretical particle physics is the formulation of a unified theory of the various forces of nature: gravity, electromagnetism, the weak nuclear force (which controls the burning of the sun), the strong nuclear force (which binds quarks into protons and neutrons and these into nuclei), and perhaps forces yet to be discovered. Superstring theories (see *Physics News in 1985*, p. 31) are the latest, and by far the most promising, attempt to achieve this goal.

Unification of the weak and electromagnetic forces appears to have been achieved. A parameter in the electroweak theory which determines the relative strength of the electromagnetic and weak forces is correctly predicted by certain "grand unified theories," which incorporate the strong interactions as well, although more direct experimental tests of these theories are so far lacking.

Attempts to incorporate gravity in unified theories have met with less success, owing in part to the lack of a theory of gravity which is consistent with the principles of quantum mechanics. String theories, which are based on generalizing the notion of a point particle to that of a string-like object are rapidly changing this situation. In analogy to a string of piano wire, the lowest note of the string corresponds to massless or very light particles, such as the photon, graviton, or electron; the harmonics or higher modes of the string correspond to very massive particles which modify the theory at high energies in a way that cures the divergences (infinitely large contributions to cross-section calculations) which have plagued quantum theories of gravity in the past. Superstrings also incorporate supersymmetry, a theory which predicts that each particle is accompanied by a superparticle with similar properties, except that the spin must differ by one half unit. Such superparticles are characteristically predicted to be heavier than ordinary particles.

Much of the recent enthusiasm for string theory is due to a flurry of activity which occurred in the fall of 1984. Before that time it was thought that string theories that incorporated forces other than gravity suffered from certain mathematical inconsistencies. In a period of only a few months the absence of these inconsistencies in certain string theories was discovered,[1] a new type of string theory that incorporated both gravity and other forces in a new and fundamental way was invented,[2] and a plausible scenario for obtaining certain grand unified theories from this new string theory was presented.[3] It seemed that the goal of unification was just around the corner. In the last year and a half the difficulty of this undertaking has become more apparent, owing to the highly mathematical nature of string theory and to the fact that, in this case, one is attempting to reformulate the foundations of physics without experimental input. While enthusiasm for string theory remains high and the number of practitioners is growing rapidly, significant new developments may be farther in the future than was originally hoped.

One of the unsatisfactory aspects of string theory is the lack of a simple fundamental principle which would explain many of its marvelous properties. The search for the foundations of string theory has largely concentrated on formulating a field theory of strings in analogy to field theories of point particles. This approach has been more successful for the older "open" strings; a satisfactory field theory for the more popular "closed" string theories (in which the strings close on themselves to form loops) does not yet exist.

Another area of much effort has been the development of techniques for calculating string scattering amplitudes and, in particular, for proving the finiteness of the theory. While no universally accepted proof of finiteness yet exists, many feel that one is likely to appear in the next year or two.

The third major area of string research involves attempts to relate the low-energy structure of string theory to more conventional grand unified theories. Superstring theory requires the existence of nine space dimensions and one time dimension. It is thus necessary to assume that six of the space dimensions form a very small space whose size must be comparable to the Planck length (10^{-33} cm). The structure of this space is strongly constrained in string theory and profoundly influences the particle types and interactions which are observed in our four-dimensional space-time. This approach to obtaining predictions from string theory suggests the possible existence of new weak forces which might one day be detected. Eventually the hope is not only to explain the properties of the known particles, but to predict the properties of particles which have not yet been detected, such as possible further generations of elementary particles or the superpartners of the known particles.

Research in string theory involves many of the frontiers of mathematics, often in seemingly unrelated areas. Thus it is likely that string theory will eventually have a profound influence on mathematics. Given the extremely high energies involved, direct experimental tests will probably involve either dramatic changes in technology or discovery of some completely unexpected aspects of the theory. This fact has caused some theorists to question the wisdom of the particle physics community pursuing string theory *en masse*.[4] Although not a direct test of string theory, the discovery of supersymmetric partners of known particles, one of the main goals of the Superconducting Supercollider, would be an important indication that superstring theorists are on the right path.

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Snowmass 1986

A summer study devoted to the physics of the proposed Superconducting Supercollider (SSC) was held at Snowmass Village, Colorado during the summer of 1986. Successor to similar workshops held in 1982 and 1984, this year's study was organized by Lee Pondrom of the University of Wisconsin under the sponsorship of the Division of Particles and Fields of The American Physical Society, and was attended by over 250 physicists. The principal goal of the 1986 study was the critical evaluation by the high energy physics community of all aspects of the SSC in the light of the recently submitted conceptual design report (CDR)[1] and in view of progress in accelerator technology, collider physics, and instrumentation. To achieve this goal, working groups were established to address four principal study topics: accelerator physics, physics and Monte Carlo studies, instrumentation and detectors, and non-accelerator physics.

The accelerator physics working group concluded that, overall, the SSC conceptual design rated high marks. The primary design goal[2] of the SSC is to achieve 20 TeV proton-on-proton collisions (40 TeV in the center of mass frame) at a luminosity of 10^{33} cm^{-2} s^{-1}. A particular concern has been whether the aperture of the conceptual design would in fact permit obtaining the design luminosity. A detailed examination concluded that a luminosity of 10^{33} is achievable, but that there is little room for error. Considerable effort was devoted to the analysis of methods for compensation of magnet errors, with the aim of (economically) increasing the dynamic aperture. In particular, changes in the magnet lattice design to permit the incorporation of local corrections were suggested.

The accelerator physics group studied the layout of test beams and the key issue of the design of the interaction regions. One important innovation to emerge from the Snowmass study was the proposal of a beam bypass around the interaction regions. Such a bypass would require a small enlargement of the main ring, but would greatly add to the accelerator's flexibility. By permitting the assembly of critical components of large detectors in place, it would make possible future innovation and growth without long interruptions in the physics program. A bypass could also provide long straight sections, permitting the study of certain types of interactions requiring detectors very close to the beam lines.

The other working groups addressed themselves to several related questions. What are the best signatures and relevant background interactions for SSC experiments? What requirements do these physics considerations, and the high design luminosity, impose on detector design? How can non-accelerator physics experiments be expected to complement the SSC program?

The physics and Monte Carlo discussions at Snowmass determined that the long sought-after Higgs boson should be observable at the SSC, unless perhaps its mass lies somewhere between twice the mass of the top quark and twice the mass of the W boson, in which case top-quark decays would dominate in a study of collision events. Other subjects under discussion included heavy-quark physics (see the related article in this chapter), *CP* violation, rare B meson decays, and possible experimental signatures of supersymmetry and superstring gauge theories.

The instrumentation and detector working group reported encouraging progress towards the design of "4π" detectors, detectors affording complete spherical coverage of the interaction area, capable of working at the SSC design luminosity. The prospects for muon detection look very good, and the problems associated with silicon chip microvertex detectors, and with the needed electronics and triggering, look solvable. Electron identification is likely to achieve a pion-to-electron rejection of 10^{-3}, and high quality calorimetry should be feasible using a uranium/lead-plus-liquid-argon combination. Central tracking still poses formidable problems because of high cell occupancy, and considerable further work will be needed to establish the feasibility of solving the pattern recognition problem and reconstructing tracks at design luminosity.

In addition to considering detector components, layout studies were done for two overall detector designs. These studies indicate that the muon system should be built in place, and that strong consideration should be given to building the central detector in the interaction hall, thus eliminating the need for an extensive assembly area underground (which would be possible if there were a bypass, as discussed above). On a cautionary note, nearly all of the advances in instrumentation and detectors reported at Snowmass '86 have come from research and development for detectors for other storage rings or accelerators. Since most of these outside detectors are now past the development phase, and since many of the unresolved problems are specific to TeV energies and high luminosity, funding of an SSC-oriented detector research and development program is essential if one is going to be able to construct proper SSC detectors in time.

While the SSC will be the primary tool for the study of particle physics in the 1990s, nonaccelerator experiments can provide complementary information on the same fundamental questions, and also offer the possibility of studying particle physics beyond the TeV energy regime. The non-accelerator physics working group set itself the task of predicting the contributions of non-accelerator experiments to particle physics in the 1990s in order to assess the needs for new facilities. The mounting evidence that objects like the Cygnus X-3 are the sources of high energy cosmic rays (see *Physics News in 1985*, p. 10) suggests new cosmic-ray experiments. The recent idea that solar matter can amplify neutrino oscillation effects promises to open up a whole new field of neutrino studies.

Neutrino physics may also benefit from promising developments in detectors which utilize quasiparticles and phon-

ons to detect very low energy particles. Such detectors could revolutionize experiments to observe double beta decay, solar neutrinos, and dark matter. Experiments to detect proton decay are continuing to improve in sensitivity, and are now focusing on the kaonic modes, which may dominate in supersymmetric unified theories. The first generation of large proton decay experiments have proved to be versatile instruments for cosmic-ray physics, magnetic monopole searches, and neutrino physics. A new generation of very large and powerful underground experiments, motivated in part by solar neutrino studies, would also provide unprecedented sensitivity to proton decay and other phenomena.

European accelerator plans, described at the final summary session, depend very much on American progress towards construction of the SSC. If the SSC is built on a schedule leading to completion in the mid-1990s, the Europeans will most likely move towards a complementary large electron–positron machine; if the SSC is not built, a favorable European option would instead be a large proton collider (8.5 TeV on 8.5 TeV) in the LEP tunnel at CERN, targeted at essentially the same physics as the SSC. This option would require an extensive development effort to achieve magnets capable of 10 T fields.

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New Issues in Cosmology

The interface of particle physics and cosmology in the early universe has provided much excitement over the past few years. This comes in part from the possibility that observations and experiments in different fields can be used to investigate and constrain theoretical ideas. In this present survey of new developments, two are specifically of this type; (1) the beginning of experimental verification of the cosmological neutrino counting and (2) the new large scale structure observations of "foam," high velocities, and spatial correlations, and their implications for early phase transitions that might have produced the fluctuations which eventually led to the present structure of the universe. The other topic that I shall discuss is still at the theoretical stage but is beginning to lead to observational and experimental results. This is the present status of the inflationary scenario.

Almost ten years ago, it was shown that Big Bang Nucleosynthesis constrains the number of generations of light (masses less than 10 MeV) neutrino types, N, which in turn seems related to the number of quark flavors. Thus cosmology was setting a constraint on one of the most fundamental aspects of nature. Over the years these ideas were refined, until it now seems clear that cosmology requires that N be equal to 3, plus or minus 1. Since three ν's are already known, this is a very powerful constraint. Particle physics theories might be just as happy with much larger values for N. Collider experiments are now beginning to check the cosmological prediction using the decay width (the width of a plot of the mass of the Z as reconstructed from the properties of its decay products) of the intermediate vector boson Z^0 which decays to all ν species. Current results[3] from CERN and the PEP collider at Stanford show that N must be less than or equal to 5, a limit which is coming down towards the cosmological limit. New experiments at the Stanford Linear Collider, Fermilab's Tevatron, and CERN's LEP should refine the limit much further and provide the ultimate test of the theory. This is the first time a cosmological prediction is being checked with a collider experiment. In fact, since determining N and the width of the Z^0 are the bread and butter experiments for SLC and LEP, one might even say these machines are new style telescopes for probing the early universe.

The early universe, where particle physics effects dominate, is opaque to photons and thus invisible to astronomers. Shortly after the universe becomes transparent, structures begin to form in the universe and these structures can be observed by astronomers. The conditions that produce these structures are what were left from the elementary particle epoch. Thus the formation of structure in the universe has become a point of common ground for particle theorists working in cosmology, as well as more traditional cosmological observers using large telescopes, and everyone in between.

Recently our ideas about the very largest structures in the universe have undergone a revolution. Observers have found that galaxies and clusters of galaxies are not randomly distributed on the sky but in fact seem to lie in a foam-like pattern with lots of empty regions and the glowing galaxies lie on the walls of the foam bubbles.[4,5] The scale of the bubbles seems to be several tens of megaparsecs (1 parsec = 3.26 light years). In addition, other observers[6] claim to have demonstrated that similarly large regions are moving *coherently* with velocities of about 600 km/s. It is also becoming increasingly apparent that clusters of galaxies correlate[7] with each other *more* strongly than galaxies correlate. To summarize, there appears to be some very large scale structure superimposed on the universe.

In order to enable the universe to reach its critical density, cosmologists have postulated various forms of dark matter and many experimentalists have begun designing experiments to search for the stuff. These new large-scale structure observations now force an alteration of the assumptions and criteria used to select various dark matter candidates. Dark matter candidates can be divided into two basic categories: (1) hot matter: low mass neutrinos or other particles moving at high velocity just prior to matter dominating over radiation's contribution to the cosmological density, and (2) cold matter: axions, GeV-mass photinos or any other particle which was slow moving at matter domination.

Before these new large scale structure observations occurred, cold matter appeared preferable because it could cluster rapidly on galactic scales and thus enable galaxies to form fast. Cold matter had a problem, however, because it all clustered on these small scales so its total contribution would be measured in cluster dynamics which implied cosmological densities far below critical. Thus, to avoid this constraint, cold matter advocates postulated biased galaxy formation, saying that only the density peaks shine and that there are many clumps of cold matter and accompanying baryons which do not shine and yet which provide the dominant mass for the universe. While this scheme may work for the density problem, it is a disaster for the large scale velocity fields and the large cluster–cluster correlations. The more biased the galaxy formation is, the *smaller* the large scale velocities, since the glowing stuff is then in negligible isolated clumps.

Hot, neutrino-like matter, seems to have the opposite problem: although it naturally yields large scale (40 Mpc) structures owing to its high velocities at the time of matter domination and although the collapsing 40 Mpc structures do produce large velocity fields, low mass neutrinos have fallen into disrepute because they can not rapidly make galaxies. Now that the large scale structure predictions of the neutrinos are beginning to be confirmed, neutrinos are being resurrected to see if some alternative way to make galaxies can be devised.

Two ideas for saving the neutrino picture and possibly even the cold matter scenario are: cosmic strings[8] and explosive galaxy formation.[9] The cosmic string picture (see the article on this subject later in this chapter) has the advantage that it easily produces the cluster-cluster correlations,[10] yielding a scale-free fractal structure from galaxies through rich clusters.[11] The explosive scenario provides small scale structure by explosively moving things about, but requires a sufficiently high density to percolate[12] the explosions if it is to reach large scales. It also requires something to produce the seeds for the explosions, perhaps debris from the quark-hadron transition (strange matter nuggets or planetary mass black holes) or maybe clumps of cold matter or small loops of string.

At present it is not clear if any combination of dark matter and galaxy formation scenarios can consistently satisfy all of the observational claims. However, it does seem clear that whatever the scenario is, it involves some elementary-particle initial conditions. The cosmic strings would be produced in an early phase transition, the explosion seeds may come from the quark-hadron transition, and the bulk of the matter itself may be some as yet undiscovered particle like the photino or at the very least a neutrino would need a finite rest mass.

The inflationary scenario first developed by Alan Guth (see *Physics News in 1982*, S·11) has undergone some remarkable developments as well as demonstrated some glaring problems.[13] If the early universe undergoes a rapid expansion prior to settling down to our current standard expansion, then most of the cosmological initial-condition problems vanish. In particular, the horizon problem, of how the universe got to be so smooth on scales that appear causally disconnected is removed. Also the flatness problem or how did the universe managed to survive 15 billion years without going to zero or infinite density long ago, is solved by the rapid inflationary expansion forcing the universe to be right at its critical density. The inflationary expansion can also remove any magnetic monopole density that might have been produced at the epoch of grand unification. The end of inflation also has the wonderful effect of producing fluctuations in the density which might be responsible for galaxy and structure formation.

The good news is that new developments by A. Linde in the Soviet Union as well as several others show that inflation is not a special phenomenon, but that any scalar field that existed in the early universe will result in a rapidly expanding inflationary epoch. Such an inflation will automatically solve the horizon and flatness problem. Thus we believe that something like inflation probably occurred even if we don't know the details.

The bad news is that all known models tend to produce density fluctuations that are too large, unless some fine tuning is carried out. On the other hand, this is not so bad, since prior to inflation we had no idea how to produce any primordial fluctuations. Now at least we have a plausible mechanism. Unfortunately, they give fluctuations that would have been detected by the microwave anisotropy experiments. They also give a random phase spectrum which does not seem consistent with the large scale structure results (unless perhaps, strings or explosions form later).

The major astronomical test of inflation, determining whether the universe is at the critical density, had, up until recently, appeared a serious failure. As mentioned above, the dynamics of galaxies and clusters imply densities far below critical. In addition, the ages of globular clusters and radioactive dating of the universe implies ages of about 15 billion years. A critical density universe would require a Hubble constant H_0 of 45 km/s/Mpc. While H_0 is traditionally listed as 50 to 100 km/s/Mpc, values as low as 40 are really still allowed, and, in fact, Sandage's and Tammann's best estimate[14] from Type I supernovae gives a value of 42 km/s/Mpc.

The first observational hints of a critical density universe have begun to appear. Loh and Spiller have found that at very large redshifts, the number density of galaxies is best fit by a flat geometry consistent with a critical density universe.[15] In addition Rowan-Robinson has found that the Infrared Satellite (IRAS) catalogue of galaxies appears to have a high velocity distribution on scales of 200 Mpc, which is best fit if the universe is at or near its critical density on these ultra-large scales. While both of these observations are very preliminary and numerous loopholes can be found, it is comforting that observational astronomy has finally pro-

vided something positive for inflation proponents. Of course, the final results await many more observations, including the space telescope which should confirm or deny a low H_0.

While there are many other developments at the particle-cosmology boundary, including direct probes of the quark-hadron transition through quark matter searches in heavy ion collisions, the three topics mentioned here clearly show that the new field of the boundary of particle physics and cosmology is rapidly developing, and that it is not free from real experimental and observational tests forcing theorists' feet to the hot coals of experimental reality.

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Heavy Quark Physics

In the standard model of elementary particles, there are three quark generations, each having one quark of charge 2/3 and one of charge $-1/3$. The first generation consists of the up and down quarks (u and d), which are the constituents of nucleons. The second generation consists of the charmed and strange quarks (c and s), and the third generation includes the top and bottom quarks (t and b). Heavy quark physics, the study of the c, b, and t quarks, began in 1974 with the discovery of the charmed quark. The spectroscopy of particles containing heavy quarks has been used to measure the strong interaction between quarks at short distances. The decays of mesons containing a heavy quark and a light antiquark have provided a new testing ground for the physics of weak decays. A great deal of experimental information on these weak decays has been reported recently, providing more stringent tests for the theoretical models.

The charmed quark is the lightest of the heavy quarks, and it is therefore the one about which we know most. The charmed particles (particles containing a charmed quark) have lifetimes of 10^{-13} to 10^{-12} s, which is characteristic of weak decays. Originally, it was expected that the charmed quark would decay with no effect from the antiquark, which would serve only as a spectator. This model (the simple spectator model) predicted equal lifetimes for all of the weakly decaying charmed mesons. (These are the D^0, D^+, and F^+, in which the c quark is bound to a u, d, and s antiquark respectively.) First measurement of the D^0 and D^+ lifetime showed that the lifetimes were not equal, thus contradicting the model.

In the past year, precise measurements of charmed particle lifetimes have been made. While earlier experiments had used samples of less than 50 D decays to measure lifetimes, present results are based on many more events.[1] One experiment at Fermilab is analyzing a sample of about 4000 events for each of the D^0 and D^+.[2] The lifetime of the D^+ is measured to be about 1.0 ps, while the D^0 and F^+ live for approximately 0.4 ps. New measurements for the charmed baryon, the Λ_c, indicate a lifetime even shorter than those of the D^0 and F^+. In some models, the differences in charmed meson lifetimes are explained by a relatively high rate for annihilation of the charmed quark and antiquark in the D^0 and F^+, which reduces their lifetimes. In other models, the destructive interference which occurs only in the case of the D^+ increases its lifetime. The increasingly precise lifetimes for all of the weakly decaying charmed particles will help to constrain these models, and to obtain a sharper picture of the underlying quark interactions.

The other experimental data needed to describe charm decay are the branching ratios to various final states. The Mark III group, working at the SPEAR collider at Standard, has published a new analysis of all the major decay modes of the D^0 and D^+.[3] By collecting a large number of events in which both the charmed particle and antiparticle are reconstructed, they were able to make accurate measurements of the absolute branching ratios. The result was a shift upward of all D branching ratios, such that the known decays add up to almost 100%. In addition, three groups reported the observation of a decay mode $D^0 \rightarrow \phi \bar{K}^0$, which is effectively forbidden in the simple spectator model.[4] Intense effort, both experimental and theoretical, continues on the question of whether this is the first clear signal of quark-antiquark annihilation in the D^0 decay.

The dominant weak interaction involves the conversion of one quark to the other quark in the same generation. There is, however, an important interaction with smaller coupling strength between quarks of different generations. Such a coupling is responsible for the weak decays of K mesons, since they are the lightest particles containing second-generation quarks. A similar interaction between generations is responsible for the weak decays of the B mesons, which are bound states of a bottom quark and a light antiquark. In these decays, the bottom quark can be converted to a charmed quark, or less frequently to an up quark. The very weak coupling of the bottom quark to the up quark is of

particular importance, because it determines the scale for *CP* violation in the model which explains *CP* violation in a natural way. Groups at Cornell and the DESY accelerator in Hamburg have been analyzing their β-decay events to search for final states with no charm, which would result from the b-to-u transition. Presently these groups quote upper limits of around 10% on the fraction of bottom quarks decaying in this way.[1] Improving the sensitivity of the search for B mesons decaying into noncharm states will continue to be a central goal of experiments working in the area of bottom quark decay.

Finally, the status of the sixth quark, the top quark, is still unclear. (The original evidence for this quark was discussed in *Physics News in 1983*, p.31, and *Physics News in 1984*, p. 31.) Events compatible with the decay of a top quark of mass 30–50 GeV/c^2 were seen in the UA1 experiment at CERN in 1983 and 1984. With more data and more analysis, the picture has not improved. More experimental work is required before the top quark can be considered to be well established.

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Cosmic Strings

Modern theories of elementary particles suggest that at energies above 10^{15}–10^{16} GeV all fundamental particle interactions (except gravity) have the same strength. Such energies are far beyond the scope of particle accelerators, and the main arena where these ideas can be tested is the early universe shortly after the big bang. As the universe expands and cools down from extremely high temperatures, the symmetry between the particle interactions is spontaneously broken, typically in several steps, so that the strong, weak and electromagnetic forces become distinct.

Cosmological symmetry breaking is similar to phase transitions in familiar solids and liquids, such as boiling of water into vapor or its crystallization into ice. We know that a crystal formed by cooling a liquid is never perfect; it always has defects. Similarly, in cosmological phase transitions the symmetric high-energy phase can be trapped in various kinds of "defects," which can be in the form of surfaces, lines or points. The names for these defects are, respectively, domain walls, strings and monopoles. (Strings, in this case, are not to be confused with the "superstrings" discussed earlier in this chapter.) The type of defect produced depends on the underlying theory of elementary particles.[1] Observations rule out the existence of domain walls in the visible universe and put a very tight upper bound on the number of monopoles. Strings, on the other hand, can have interesting cosmological implications and have attracted much attention recently because of their possible role in galaxy formation.

Strings are forbidden to have ends; they either form closed loops or extend to infinity. Tension in curved strings makes them wiggle violently at a speed close to that of light. In the string scenario of galaxy formation, galaxies condense around oscillating loops of string, while the loops gradually lose their energy by gravitational radiation, shrink, and disappear.[2] The lifetime of a loop is proportional to its mass. Loops responsible for the formation of galaxies have already decayed, but larger loops which served as seeds for rich clusters and superclusters may still be around. Numerical simulations based on this model produce a correlation between clusters of galaxies in agreement with observations.[3]

If light from a distant quasar encounters a string on its way to the Earth, the light rays would be slightly bent by the string's gravity, and we would see two distinct images of the same quasar, one to either side of the string. Other gravitational effects of strings include the gravitational radiation emitted by oscillating loops and a discontinuous change in the microwave background temperature across the string. In some elementary particle models strings can behave as superconducting wires.[4] Such strings interact with magnetized cosmic plasmas and can be detected as sources of radio waves.[5] With so many observational side effects predicted by the string scenario, astronomers should be able to confirm it or to rule it out in the near future.

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Advanced Accelerator Research and Development

When one reaches for higher particle-collision energies, two effects become troublesome. First, at high energies the effective center-of-mass collision energy of a high-speed particle incident on a stationary target increases only as the square root of the incident particle energy. Secondly, in circular orbits the energy loss due to synchrotron radiation becomes excessive. These effects dictate that for extremely high energies, particles must be accelerated in linear accelerators and that high effective collision energies should be attained by colliding two high energy particle beams head-on. Such an arrangement is called a linear collider.

The synchrotron radiation loss is much smaller for the heavier protons compared to electrons. It is, therefore, still

feasible to design a 20-TeV on 20-TeV circular proton–proton collider, the Superconducting Supercollider (SSC), whereas the circular Large Electron Positron collider (LEP) under construction at CERN can reasonably go only up to 100 GeV on 100 GeV. For the SSC, furthermore, the high magnetic field strength and the low electric power consumption are facilitated by the use of superconducting magnet technology. Nevertheless, these colliders are likely to be the highest energy machines of their kinds. LEP is scheduled to begin operation at 50 GeV on 50 GeV in 1989. The conceptual design of the SSC was completed early in 1986 and passed the review by a Department of Energy team with flying colors. With a price tag of about $3 to $4 billion, funding for the SSC is still awaiting authorization by the U.S. Government.

Beyond these machines the future lies in linear colliders. A modified linear collider, the SLC (Stanford Linear Collider), colliding electron and positron bunches accelerated simultaneously in the SLAC linac, is in an advanced stage of construction and is scheduled to go into operation in 1987. The e^+ and e^- bunches that exit from the linac at 50 GeV are transported by magnets in two big arcs and then collide head-on. In its basic configuration a linear collider would have two linacs facing each other and the accelerated particle beams colliding at the midpoint between the linacs. The requirements are clear: the accelerating field strength in a linac must be high so that its overall length is manageable, the power transfer efficiency from power supply to particle beam must be reasonably high, and the beam currents must be high and focusable to extremely small dimensions at the collision point in order to yield useful high luminosity (particle collision rate). As energy goes higher, the collision cross-sections decrease as the square of the energy. In collisions of hadrons, the energy is shared among the constituent quarks and gluons, and the cross-section is, further, a sharply decreasing function of the momentum-transfer relative to the collision energy. Thus, extremely high luminosity or over-energy is needed to obtain the minimum observable rates for interesting violent quark or gluon collisions.

Several rather bold and far-sighted R&D programs are being pursued to meet these requirements for future linear colliders, although only at minimal expenses of money and manpower. Most of the innovations consist of inventions of accelerating structures appropriate for novel power supplies. To obtain high power density—hence high accelerating field—and high electric breakdown limit, one must go to high frequencies or short pulses. Frequencies from tens of GHz (cm and mm microwaves) up to 10^{14} Hz (μm laser waves) are being considered. As an example of a cm-wavelength source, a Berkeley-Livermore group will use the free electron laser. The accelerating structure for this cm-wave is simply a miniature iris-loaded wave guide similar to the SLAC linear structure. The FEL microwave supply of this TBA (Two Beam Accelerator) has already been operated and the whole setup should be ready for study in 1987. Accelerating fields of hundreds of MV/m are expected.

High-power glass lasers, gas lasers, and excimer lasers are all available. Here the principal development required is to obtain the high repetition rate necessary for high colliding beam luminosity. The proposed μm-wavelength accelerating structures are open low-Q resonant structures excited simply by shining the laser beam in the proper orientation. These open structures can take on a variety of shapes: gratings, rows of micro-bumps, streams of micro-droplets, etc. If made of physical material they will evaporate and turn into plasma when heated by the high-power laser, but will keep their integrity for a few transient nanoseconds to yield very high accelerating fields next to the surface. Theoretical estimates give fields on the order of 1–10 GV/m.

Micrometer accelerating structures can also be formed in a plasma. In this case the strong fields in the plasma can be used to accelerate particles. The most promising scheme of this type is the Plasma Beat Wave accelerator being investigated experimentally at UCLA and at INRS in Canada. In this scheme, a plasma wave is resonantly excited by Raman scattering with two incident laser beams of slightly different frequencies such that their beat frequency equals the plasma oscillation frequency. The plasma wave will stay coherent for tens of oscillations before being destroyed by instabilities and non-linear effects. The field in a high density, strongly modulated plasma wave can be several GV/m. Fields as high as 1 GV/m were measured and electrons have been accelerated by about 1.5 MeV in 1.5 mm.

Without any accelerating structure, a plane-wave laser beam can still be used to accelerate particles in a transverse plane while they are going through an undulator. This is an Inverse Free Electron Laser accelerator (IFEL). The acceleration rate is limited, only a few hundred MeV/m, and the maximum energy attainable is a few hundred GeV being limited by the rapidly increasing synchrotron radiation loss of wiggling charged particles.

Yet another source of accelerating field is the wakefield generated by an intense beam bunch propagating either in a wave guide or in a plasma. The arrangement must be so designed as to produce an amplification of the field (transformer ratio) from the power-supplying beam (primary winding) to the accelerated beam (secondary winding). A straightforward theorem states that for a simple arrangement in which both beam bunches are short and travel along the same orbit, the most energy the accelerated beam can gain is only twice the energy of the power-supply beam. A complicated beam-wave guide structure giving a transformer ratio of about ten is being tested by a DESY–Los Alamos collaboration.

These are all long shots, but they are the only hope for the long-range future of high-energy physics.

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References: Details of all these works can be found in the proceedings of the two workshops contained in AIP Conference Proceedings Numbers 91 (1982) and 130 (1985). The proceedings of the third workshop held in August 1986 will be forthcoming shortly.

FLUID DYNAMICS

Fluid dynamics is the study of the flow of gases and liquids. It underlies many areas of science, including astrophysics, geophysics, aeronautics, combustion, and plasma physics. The equations governing fluid motion are derived from the conservation of mass, momentum, and energy that leave or enter a volume of space. The form of these equations is known, but they are notoriously difficult to solve. The recent availability of supercomputers and of new methods in experimental flow visualization have led to a major increase in our ability to understand and predict complex fluid flows. The fluid dynamics articles presented below highlight the use of large-scale numerical computations to solve complex fluid problems.

The Structure of a Propagating Detonation

A detonation wave is supersonic and driven by rapid energy release behind it. It contains a shock wave, followed by an exothermic chemical reaction zone, then a region of fully reacted hot material. Interactions between compressible, supersonic fluid dynamics and energy release lead to complicated shock interactions at the detonation front.

The detonation front itself consists of interacting shock waves.[1] Laboratory and field experiments have shown that a propagating detonation leaves a cellular pattern on the sidewalls of the confining chamber. These patterns also exist in detonations in free space. They are formed by "triple-points" created when three shock waves interact at the front of a detonation. These triple-points move through the systems and trace out the cellular pattern.

Detonation cells may be regular and repeating, but more often they are irregular, sometimes with a number of preferred sizes. The size and regularity of the cell structure of a detonation are functions of the specific material, its dilution, and the nature of its confinement. Understanding this detonation structure and how it varies with geometry and material provides important information on the use and safety of explosive materials.

High-speed supercomputers with adequate computer memory and accurate numerical algorithms for time-dependent compressible flows permit the numerical study of detonation structures.[2] Numerical simulations have been used to study basic mechanisms of detonation cell formation and propagation, the structure of the interacting shocks at and behind the detonation front, detonation structure irregularity, and estimate the size of detonation cells.

One unexpected and important phenomenon found in the experiments and simulations is the formation of unreacted pockets of material behind the detonation front.[3] Experiments showed these first, but the pockets were not explained until they were observed in numerical simulations. Figure 1 is a series of "snapshots" taken during a calculation of a detonation propagating in a mixture of hydrogen and oxygen diluted with argon. The upper figures show the extent of reaction. The detonation propagates to the right into the unreacted gas mixture. The fully reacted gas is on the left-hand side. The various shades in between represent different degrees of reactedness and together comprise the detonation front. In the third frame, we see a detached pocket of unburnt gas behind the detonation front. The bottom figures show the temperature of the gases in the various regions. The figures show a cold, unreacted pocket cut off by interacting shock waves.

The formation of the unburned pockets can be traced directly to the curvature of the transverse shock waves. When two collide or one hits a wall, the interaction can cut off a portion of unreacted, cold material. If the material in the pockets burns slowly enough, the process effectively draws energy out of the detonation and can provide a mechanism for detonation extinction. If the pockets burn rapidly, they can generate new pressure pulses that perturb the system and cause new structures to form at the detonation front. This is one possible mechanism for generating the irregular cellular pattern observed in most gases and liquids.

These findings are curious because they show how an initially homogeneous material can develop an extremely inhomogeneous structure as the shocks move through it. These findings are important because the existence of unreacted pockets and their properties can determine whether a detonation will live or die.

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Triangle-Based Grids in Computational Fluid Dynamics

The last ten years have seen major advances in the numerical algorithms used to solve fluid dynamics problems. These advances have been so substantial that the largest improvements in future calculations may now come from new ways to improve spatial resolution.

The most straightforward way to fill space is with rectangular grids, which fill two-dimensional space with rectangles and three-dimensional space with parallelepipeds. The most innovative methods for improving spatial resolution, however, now use triangular grids for fluid dynamics calcula-

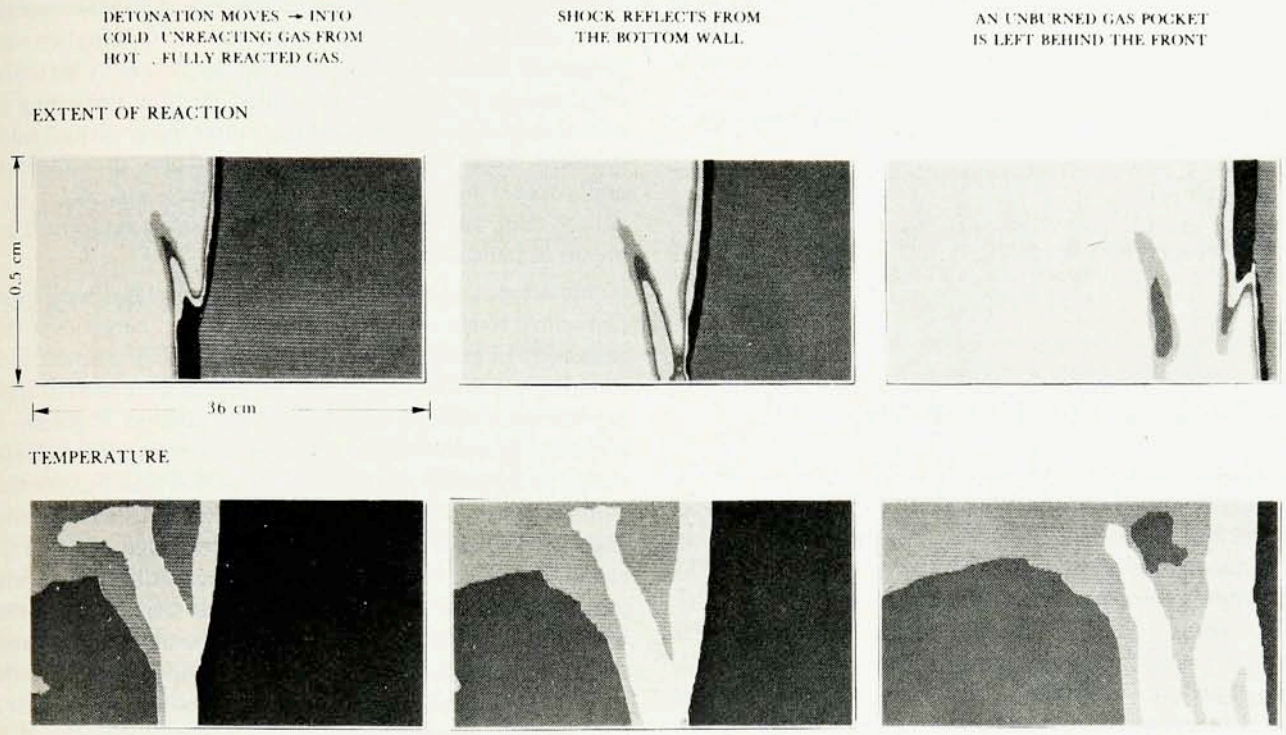

FIG. 1. Extent of reaction and temperature contours showing the formation of an unburned gas pocket during detonation propagation. The detonation is propagating from left to right.

tions: triangles in two dimensions and tetrahedra in three. Figure 1 shows timesteps from calculations that use a triangular grid technique. Triangles are used to give fine resolution throughout large parts of the grid. The triangles are smallest where there is the most structure in the flow.

Figure 2 is a frame from the calculation of a shock wave passing over two irregularly shaped obstacles. The shock is initially planar and vertical. It is then disturbed as it hits the obstacles and a complicated evolving pattern of interacting shocks results. This calculation was done with an algorithm[3] in which the fluid moves through the grid. In this kind of calculation, the grid does not naturally become distorted when the flow structure does, so there is no need to reconnect triangles sides. However, it is still important to change the resolution locally as the flow becomes more complicated. When structures develop in the flow, the resolution is automatically increased by dividing triangles into smaller triangles.[4] As the flow field smoothes out, these small triangles are automatically removed to reproduce the larger triangles. At the time shown in the figure, the initially vertical shock wave has developed into an extremely complicated pattern of interacting shocks in the region of the obstacles.

Triangular grids have been used for some time in finite-element calculations.[5] What is new for computational fluid dynamics is the development of algorithms that combine these grids with accurate numerical methods for time-dependent fluid dynamics problems. The types of calculations

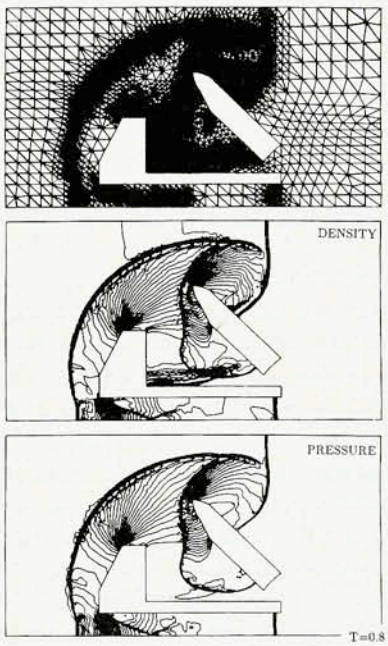

FIG. 2. Resolutions of the complicated pattern of shock interactions that develop as a shock passes two irregularly shaped obstacles.

shown above would be extremely difficult and expensive, if not impossible, with other types of grid system.

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The Condensational Instability

The condensational (or thermal) instability results from a delicate imbalance among convection, heating, cooling, and thermal conduction in a radiative, compressible fluid. In order to maintain pressure balance, the portion of the fluid that is cooling also becomes denser. If the radiation rate increases with increasing density, the cooler region radiates more effectively, thus enhancing the instability. In this way, cool, dense regions are formed within a hotter, more rarified medium. Radiation-driven condensational instabilities can occur in an ionized gas, for example, which is optically thin and which cools primarily by means of temperature-dependent and density-dependent radiative losses. The nature of the ambient heating mechanism and the presence or absence of a magnetic field also influence the behavior of this instability.

This mechanism for forming filamentary structures in a complex fluid may operate throughout the solar atmosphere, which exhibits coexisting cool and hot regions over a wide range of spatial scales. Condensational instabilities also have been invoked as possible explanations for a variety of astrophysical phenomena, including interstellar clouds, condensations in planetary nebulae, and even galaxies.[1] Therefore, we would like to know how condensational instabilities are initiated, how they grow in different environments, and under what conditions the condensations stabilize or disappear. In addition, predictions of the spatial and temporal scales associated with the condensations provide a basis for comparison between theory and observation or experiment.

Most theoretical research on this instability has addressed the linear regime.[1–4] As with the well-known Kelvin–Helmholtz and Rayleigh–Taylor instabilities, however, the nonlinear evolution is extremely important because the contributing physical processes are described by highly nonlinear differential equations. At present, numerical simulations are the best method for studying the nonlinear evolution of the condensational instability under a range of initial conditions. In recent years, several nonlinear calculations have been performed which explore the condensational stability of an ionized gas at temperatures and densities typical of the solar transition region and corona.[5,6] Initial one-dimensional simulations[6] showed that the instability led to the development of a stable, bifurcated medium consisting of cool condensations imbedded in a hotter, more rarified environment. Solar phenomena such as spicules, prominences, and coronal mass ejections, all of which are cooler and denser than their surroundings, might thus be formed by means of the condensational instability.

Most recently, multidimensional simulations have been performed to investigate the dynamics and energetics of the instability in greater detail.[7–9] In one series of calculations, random velocity or density perturbations were used to trigger the instability in the gas.[8,9] This method of initiation simulates turbulent effects which exist in many physical systems of interest. As was found in the earlier one-dimensional work, stable cold structures are formed which oscillate only slightly around characteristic temperature and density values. In addition, the multidimensional calculations indicate that the condensational instability can be responsible for the formation of filaments and associated turbulent flows, and that these structures can be stable over long timescales. It was also found that condensations will not form if a velocity perturbation of sufficiently large amplitude is used.

More work is needed to explore the role of condensational instabilities in establishing stable structures in fluids whose energy balance is governed by complex physical processes. For example, an analogous "runaway" situation might occur in chemically reactive fluids through self-enhancing imbalances between endothermic reactions and the ambient energy sources, thus leading to a similar type of instability. Detailed investigation of the applicability of the condensational instability to the astrophysical phenomena mentioned above has barely begun. To understand the behavior of this instability in real physical systems, however, we must establish its nonlinear development under less simplified conditions than have been modelled thus far: for example, in the presence of magnetic fields, continual forcing of the driving perturbations, or initially nonuniform media.

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GEOPHYSICS

In 1986 the American Geophysical Union became the 10th Member Society of the American Institute of Physics. Thus we include here for the first time a chapter on geophysics.

Geology of Venus

Because of the dense clouds that cover the entire planet, the surface of Venus has remained a mystery longer than that of any of the other inner planets. Venus is especially interesting to earth and planetary scientists, because it is our nearest planetary neighbor and is, in size and mass, almost the twin of Earth. The other terrestrial planets are much smaller, with diameters half that of the Earth or less.[1]

They thus have smaller internal "heat engines" (heat generated during planetary formation and from decay of radioactive elements within the planet). Volcanic activity and plate recycling act to bring heat from the interior of a planet to its surface. The Moon, Mercury, and Mars are "one-plate" planets; they never developed plate tectonics as seen on the Earth, in which relatively rigid plates move horizontally, driven by thermal convection currents in the Earth's mantle.[2]

Much of our information about the tectonics of the other terrestrial planets has come from photographs of their surfaces. Photogeologic data provide information on the basic features of a planet's surface (volcanoes, craters, faults, etc.); these data, when combined with information on the planet's size, mass, moments of inertia, and gravitational field, can be used to constrain models for the internal structure and geologic history of a planet. In the case of Venus, scientists must use radar imaging techniques, rather than normal photography, to "see" the surface of the planet through the dense atmosphere. Radar can provide information on topography, surface roughness, and the surface dielectric constant.[3]

The first planet-wide data on the surface topography of Venus came from the Pioneer Venus orbital spacecraft in late 1978.[3] Altimetry data revealed that the surface of Venus has both very high and very low areas, including areas of high elevation comparable in size to Earth's continents. However, the horizontal resolution of the Pioneer Venus topographic data (100–200 km) was not good enough to settle the question of whether Venus is a one-plate or a multi-plate planet.[1]

In 1983 and 1984, the Soviet spacecraft Venera 15 and 16 surveyed the northern polar regions of Venus, producing radar images covering about 25% of the planet's surface with a horizontal resolution as fine as 1–2 km.[4–7] The recently published Soviet images have revealed an astonishing variety and complexity of features on the surface of Venus. The Soviets have also placed seven landers on Venus since 1975, which returned photographs of the surface, data on atmospheric conditions, and chemical analyses of rock samples.[8–11] Current research is focused on the analysis and interpretation of the Venera data.

The Venera images reveal large numbers of circular features, ranging from 100–140 km in diameter down to about 10 km.[7] Many of these features are morphologically similar to impact craters seen on the other terrestrial planets. The density of cratering can be used to estimate the age of a surface; age estimates for the cratered terrain on Venus are in the range 0.5–1.0 billion years.[7] For comparison, plate recycling on our planet is so fast that 60% of the Earth's surface is less than 200 million years old, less than 5% of the age of the planet.[1]

Other circular features seen on the Venera images appear to be related to volcanic rather than impact processes, although the origin of some of these features is still uncertain.[12] For example, Cleopatra Crater is a 100-km-diameter feature located just below the summit of Maxwell Montes, the highest area on Venus; if this feature is a volcanic caldera, then any model for the formation of Maxwell Montes must take into account this evidence for volcanism.[13]

In contrast to the one-plate planets, which are dominated by vertical tectonics related to the emplacement of volcanic loads,[2] Venus appears to have had lateral tectonics, including regions of both extension (rifting) and compression (ridges and mountains).[4,5,14,15] Offsets of lineaments in the Maxwell Montes region may be the result of strike-slip faulting, horizontal motions in the same style as Earth's San Andreas fault.[16] Whether these features indicate true plate recycling is still unknown; one possibility is that the tectonic style of Venus falls somewhere between that of the smaller planets and the full plate recycling found on Earth.[14]

For the foreseeable future, American researchers will continue to depend on data provided by Soviet spacecraft. Launch of the Venus radar mapping mission ("Magellan"), originally scheduled for 1988, will be delayed at least 19 months owing to the *Challenger* disaster.

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Geomagnetic Reversals

The phenomenon of magnetic polarity reversal has surged into the scientific limelight with the suggestion that Uranus may indeed be experiencing such an event just now (see the article on Uranus in the chapter on Astrophysics). For the earth, paleomagnetic observations from rocks indicate that changes in polarity have occurred throughout geologic time. How the dynamo in the Earth's fluid outer core manages to undergo reversal has become a hot topic of geophysical research and, with an influx of quality paleomagnetic recordings spanning actual events, considerable new insight has recently been gained.

What has emerged is a more defined picture of the core process, one which now appears to be neither simple nor continuous, yet sometimes surprisingly reproducible. For example, a recently reported, detailed accounting of chronological "snapshots" of transitional field behavior recorded in lavas shows the reversal mechanism to be highly sporadic with alternating periods of rapid directional changes and relative dynamo inactivity.[1] The suggestion here is that a reversal may be accomplished through a staggered series of events by which magnetic flux is carried along, essentially frozen into the highly conductive core fluid as it undergoes rapid alterations in its convective flow.[2]

Also seen in this record is the occurrence of an initially unsuccessful attempt by the dynamo to secure the opposite polarity, during which time the field "rebounds" to an intermediate direction between the two polarity states before ultimately completing the transition. Data obtained from the southern hemisphere further show that, prior to a successful transition, the geodynamo may undergo a succession of attempts. Interestingly, each attempt appears to involve the same intermediate field geometry, like a steppingstone between the two polarity states.[3] With regard to longer-term repeatability, sediments on Crete indicate that the spatial characteristics of the reversal process can remain virtually invariant over the time spanning a number of polarity intervals.[4] Over this time period, the magnetohydrodynamic mechanism in the core appears to be blind to the initial sign (polarity) of the reversing field.

Paleomagnetic evidence consistently supports the hypothesis that transitional field geometries are not simply dipolar, but far more complex. This observation together with the above-cited studies suggest that, perhaps, only a portion of the core may reverse at any given time, with each such regional reversal occurring over a time far shorter than the complete process. Results of an innovative statistical study of the long-term behavior in the rate of field reversal tend to support this suggestion.[5] Specifically, the analysis suggests that reversals are actually triggered by some physical phenomenon in the core necessarily associated with an energy source *independent* of that which powers the dynamo. The authors' preferred model[5] assumes the geodynamo to be driven by chemical convection derived from freezing at the base of the fluid core. The triggering source? Cold "blobs" produced far away at the outer boundary by way of heat loss into the mantle. Such material descending through the core might be expected to destabilize the local convection pattern, thus initiating a reversal attempt. The number of such attempts and probability of success may then depend on such physical properties as the size, number and free-fall velocity of the blobs.

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Geomagnetic Main Field and Secular Variation

The ultimate aim of studies of the geomagnetic main field and secular variation (the gradual changes in the field with time) is to gain some understanding of the dynamo process in the Earth's core responsible for the regeneration of the field. In recent years the availability of satellite data, culminating in the Magsat mission (1979–1980), has lead to a great upsurge of interest, the results of which are now coming to fruition. The problem of using measurements of the field, which of necessity are made on or just above the earth's surface, to infer the field at the core-mantle boundary some 3000 km below is formidable; however, recent advances in field modelling by two groups (D. Gubbins, K. Whaler, and J. Bloxham in Cambridge, England, and L. Shure, R. Parker, and G. Backus in La Jolla, California) have led to much more detailed maps of the field at the core-mantle boundary.

Bloxham and Gubbins have been able, by using historical

field observations, to extend these maps back in time to the beginning of the 18th century.[1] The results have been surprising: the secular variation at the core-mantle boundary is confined almost entirely to the hemisphere from 90°E to 90°W, and westward drift (the gradual westward movement of the field observed at the Earth's surface) is confined to an even smaller region. The maps also suggest the possibility of coupling between flow in the core and lateral heterogeneities in the lowermost mantle which have recently been mapped by seismologists. Other work, notably by C. Gire and J.-L. LeMouel (Paris, France),[2] by Whaler (now in Leeds, England),[3] and by C. Voorhies (Greenbelt, Maryland),[4] has concentrated on using maps of the secular variation to derive models of the fluid motions at the surface of the core; the results depend strongly on the underlying assumptions, which are currently the subject of some controversy.

The recognition of quite abrupt changes in the secular variation (so-called jerks) by V. Courtillot, J. Ducruix, and J.-L. LeMouel (Paris, France)[5] and by S. Malin, B. Hodder, and D. Barraclough (Edinburgh, Scotland)[6] continues to stimulate much interest and may also lead to new understanding of processes in the Earth's core. The subject is certainly in a period of rapid change and healthy controversy; indeed, it does seem possible that in the next few years we may finally begin to understand the basics of the dynamo, although more satellite data are an urgent requirement if the current pace of activity and rate of advance is to be maintained.

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Rock Magnetism

Two recent discoveries in rock magnetism have added new insights into the origins of stable natural remanent magnetization (NRM) recorded in rock and sediment. The first deals with direct observations of magnetic domain structure in titanium-substituted magnetite (a magnetic mineral found in basaltic lava flows) using the Bitter technique. It has been found that a significant proportion of small multidomain (MD) grains (tens of microns) fail to nucleate domains after removal of a saturating magnetic field and thus remain in a metastable single-domain (SD) state.[1] Domain nucleation will occur only after a reverse field of sufficient magnitude is applied. A model based on a random distribution of nucleation sites was developed to explain the grain size dependence of saturation remanence.

Recently, metastable SD grains were also observed after grains were given a weak-field thermoremanent magnetization.[2] These observations are extremely important and may explain the SD-like intensities and stabilities found in small MD particles. Besides the importance of domain nucleation, the actual domain form in these materials has become a subject of study and controversy.[3] The surface domain structures commonly observed in these materials are exceedingly complex, particularly in Ti-rich compositions, and can vary dramatically within single particles. Because magnetocrystalline anisotropy is low and magnetostriction high in Ti-rich magnetites, stress could play an important role in controlling the domain structure. In this respect, the domain structures found in Ti-rich magnetites are very similar to those found in amorphous metals. Despite these similarities, however, the role of stress in controlling stable NRM remains obscure.

The second discovery comes from the field of biomagnetism. It has been known since 1975 that certain species of aquatic bacteria contain membrane-bound magnetite particles, usually in chains of approximately 10-20 cuboidal particles, each roughly 50 nm in size. The sizes of these particles are within the SD size range for magnetite. Since the initial discovery of magnetotactic bacteria, the question arose as to whether biogenic SD magnetite could contribute to stable NRM found in marine sediments. The answer now appears to be yes, based on two recent reports.[4,5] Biogenic magnetite has been identified in surface sediments at several localities off the coast of California and in deep-sea sediments from the South Atlantic. How general these findings are, however, must await further study. In particular, we do not know how far back in the geologic record magnetotactic bacteria may have existed, and hence it is uncertain whether older marine sediments contain biogenic magnetite.

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Marine Geology

Two-thirds of the surface of the Earth is created along a vast underwater volcanic rift system known as the mid-ocean ridge. Aided by recent technological advances in sea floor mapping, navigation and instrumentation, marine geologists have made important advances over the past decade in understanding the complex and interrelated volcanic, tectonic and hydrothermal processes involved in the formation of new ocean crust.[1] Among the most publicized discoveries to emerge from these studies are the spectacular sea floor hydrothermal vent systems with their unique biological com-

munities and associated sulfide mineral deposits. This hydrothermal activity is thermally driven by the presence of hot, molten rock at relatively shallow levels in the crust in reservoirs known as magma chambers. Although there is general agreement on the importance of crustal magma chambers in the formation of new ocean crust, the shape, longevity and variability of these magma chambers along the rise axis are still the subject of considerable controversy in the geological community.

Over the past few years a general model of the volcanic processes at mid-ocean ridges has emerged from observations of the variations in depth along the rise crest and from laboratory experiments with convecting fluids. The basic idea behind this model, which was initially proposed by Han Schouten and his colleagues at Woods Hole Oceanographic Institution,[2] is that molten rock forming in the underlying mantle rises in localized blobs along the ridge, rather than in a continuous sheet. These upwellings feed melt into a crustal magma chamber, and this melt then flows laterally along the ridge, forming rift eruptions similar to those observed in Iceland. The injection centers are associated with long-wavelength topographic highs that occur with a spacing of about 50–100 km. This appealing model has been tested recently by two important experiments.

The properties of magma chambers at oceanic spreading centers can be inferred indirectly from the composition of the lavas that are erupted at the sea floor. If the model outlined above is correct, then the eruption temperature of the lavas should decrease systematically away from the bathymetric high where the melt is initially injected into the magma chamber. Last year, Charles Langmuir of the Lamont-Doherty Geological Observatory led a team of investigators to the fast-spreading (6 cm/yr) East Pacific Rise off the western coast of Mexico to test this hypothesis.[3] They systematically dredged nearly 1000 km of ridge crest, obtaining a much closer spatial sampling (8 km) than had ever been attempted over this length of ridge. They found that, geochemically, the lavas are surprisingly diverse, with distinct eruptive units occurring on a scale ten times less than the long-wavelength topographic variability along the rise axis. Their results appear to require either multiple regions of supply from below the crust or a magma chamber that is physically discontinuous on a scale much smaller than was previously suspected.

The latter hypothesis was tested at nearly the same time by a novel two-ship, multichannel seismic experiment carried out along this same ridge segment by investigators from Lamont, Scripps Institution of Oceanography, the University of Rhode Island, and the U.S. Geological Survey.[4] Sound travels through the molten lava in a crustal magma chamber at a much lower velocity than in the surrounding rock. As a result, the roof of the magma chamber acts as a strong reflector for seismic energy. Using the same technology developed in the petroleum industry to map subsurface geological structures in sedimentary basins,[5] these investigators mapped the reflections off the top of a crustal magma chamber lying 1–2 km below the sea floor along the East Pacific Rise. They found that the magma chamber is surprisingly narrow (less than 3–4 km wide), but physically continuous along the rise axis over distances of at least 40–50 km, and in one case for more than 90 km. In order to reconcile these observations with the geochemical diversity of the erupting lavas, the molten material within the chamber must be much more incompletely mixed and heterogeneous in its composition than previous magma chamber models had envisioned.

The results from both of these experiments have led to a reexamination of current geological and geophysical models of mid-ocean ridges. Long-term, multidisciplinary investigations of other portions of the mid-ocean ridge system in the central North Atlantic near the Kane Fracture zone, along the Juan de Fuca Ridge off the west coast of North America, and along a very fast spreading portion of the East Pacific Rise north of Easter Island are also under way, and promise, over the next few years, to significantly advance our understanding of the geological processes involved in forming the oceanic crust.

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Oceanography, El Niño, and Chaos

Perhaps one of the most striking events in geophysics in recent years has been the reemergence of "chaos theory" in oceanography and meteorology. "Reemergence," because the modern (post-war) roots of the field are to be found in a paper by Lorenz[1] in the atmospheric science literature of the early 1960s, a paper largely neglected for several years. These ideas subsequently had a very large impact on the mathematical theory of dynamical systems and recently have filtered back into geophysics and fluid dynamics.[2]

It has been known for a long time that many problems are inherently unpredictable (even ignoring quantum effects). The weather is one example—a small error in our observations of the state of the atmosphere at any one time will grow and cause our prediction to be wildly off in a matter of a few days. Chaos theory suggests that this may be an inherent, or generic, property of certain simple nonlinear systems, and that a high degree of complication is simply not needed to produce these effects. Indeed systems with as few as three degrees of freedom can produce such aperiodicity and unpredictability.

Now, many problems in geophysics and astrophysics do display aperiodicity, and seem very hard to predict. El Niño is one outstanding example. This is an event, occurring every few years, but not at regular intervals, in which the water off the coast of Peru becomes anomalously warm, devastating the fishing industry and possibly affecting climate worldwide. Chaos theory tells us that even though the events are aperiodic, we do not need a complicated explanation, or need to invoke some external random forcing. Of course it does not tell us that such explanations are not true, or that some random, small-scale noise is not important. Recently, relatively simple models have been proposed which seek to explain El Niño.[3,4] The simplest one is a conceptual model requiring only three variables. The model is a caricature of the real world, and should obviously not be used for predictive purposes, yet it explains many of the salient features of El Niño in a very direct way.

Are those ideas correct? It's really too early to tell. Only observations and comparison with the theoretical predictions can tell. The observationists who must collect and analyze long-time series of data, and the theoreticians, who must construct more meaningful models, must sit down together and interpret their results in the light of the new theories.

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Stochastic Analysis of the Transport of Contaminants in Groundwater

The occurrence of several widely reported incidents of groundwater contamination has led to the recognition that such incidents pose a significant threat to public health. The political response to this perception has been a recent strengthening of the regulatory climate through the RCRA (Resource Conservation and Recovery Act) and CERCLA (Comprehensive Environmental Response, Compensation and Liability Act) legislation. The requirements of these acts have led to vigorous research activity into the processes of contaminant transport in geologic media and the prediction of migration rates of contaminant plumes in groundwater flow systems. The most common sources of contaminant plumes include hazardous-waste landfills, tailings ponds, waste-injection wells, and buried tanks. Such facilities represent point sources of pollution as opposed to the non-point pollution caused by agricultural use of fertilizers, herbicides, and pesticides. The contaminants of greatest concern include inorganic metals, organic solvents, and radioactive isotopes.

The basic mechanisms of transport of chemical species by flowing groundwater have been recognized for many years.[1] They include advection, diffusion, dispersion, and retardation. Advective transport, the movement of contaminants with flowing groundwater, leads to the displacement of native waters at background concentrations by contaminated waters at concentrations that may exceed acceptable standards. Under conditions of steady-state, saturated groundwater flow, and with a source of constant strength, advective flow leads to a sharp plume front that moves at the velocity of the flowing groundwater. The rate of migration is controlled by the natural hydraulic gradient and by the porosity and hydraulic conductivity of the aquifer.

Hydrodynamic dispersion causes a spreading of the plume front under the influence of heterogeneities in the hydraulic-conductivity field. Such heterogeneities are the rule rather than the exception in stratigraphically complex, unconsolidated geologic deposits of glacial or alluvial origin, which commonly constitute the aquifers of concern.

Retardation is a catch-all term that includes the influences on migration rates of chemical reactions between waters and porous media, and between contaminated and native waters. The most common retardation mechanisms are ion exchange and adsorption on clays and organic matter.

These mechanisms of transport can be embodied in a boundary-value problem based on the advection-dispersion-retardation equation. Such models are usually solved with a finite-element method. They allow prediction of the rates of plume migration, contaminant travel times, and mass fluxes, which can then be used as input to risk analyses for proposed or existing waste-disposal facilities. Such analyses are used in the design of remediation at contaminated sites and in the siting, design, and regulation of new facilities.

In the past, these boundary-value problems were solved in a deterministic framework. In recent years, however, it has become evident that the heterogeneity in the hydraulic-conductivity fields in real hydrogeologic applications breeds an uncertainty that favors a stochastic approach.[2] Solutions can be obtained either through analytical solutions to the stochastic differential equations using perturbation techniques[3] or through Monte Carlo simulation.[4] The output from such simulations leads to probability density functions (or their first and second moments) for travel times and mass fluxes. Such output is well suited to risk analysis and to risk-based engineering design.[5]

The application of stochastic simulation at field sites is best carried out in a framework[6] in which the estimates of the moments of the probability density function for hydraulic conductivity are updated,[7] and predictive uncertainties in travel times are reduced,[8] through the collection of additional field measurements of hydraulic conductivity at the site.

A recent review paper[9] notes that "the current use of stochastic concepts in subsurface solute transport theory represents an initial attempt to capture field-scale variability in terms of a stochastic convection-dispersion equation." The authors caution, however, that "many of the approximations remain both untested in detailed field experiments and underived from rigorous results in the theory of random processes."

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MEDICAL PHYSICS

Nuclear Magnetic Resonance in Medicine

In recent years, there has been a dramatic acceleration in the application of nuclear magnetic resonance (NMR) techniques within the medical sciences. The potential utilization of NMR in clinical medicine was first demonstrated in 1971 by R. Damadian, who reported that the longer proton relaxation times (T_1 and T_2) exhibited by tumor tissue could provide a basis for differentiation between malignant and normal tissues.[1] In 1973, P.C. Lauterbur described a method using superimposed linear magnetic field gradients to spatially encode the NMR data allowing formation of tomographic cross sectional images. By 1977, initial images of human anatomy were being made,[3–5] with some of the first refined head imaging results being published in 1980.[6] These later advances were pioneered in a large part by physicists at universities. By 1986 the intense academic and industrial research and development efforts had provided the technological capability for efficient, high resolution imaging and spectroscopic analysis of clinically important anatomical and pathological conditions.

There are now more than 450 clinical NMR imaging units (referred to as magnetic resonance imaging, or MRI, by physicians) operating worldwide, including many in community hospitals and private clinics as well as in university medical centers. Depending upon the magnet specifications and siting configuration, the cost of these installations may range from under $500 000 to over $2 000 000. The major components of a clinical, whole-body NMR imaging system are: (a) a large bore magnet with fields on commercial units ranging from a low value of 0.02 T to a high of 2.0 T (for fields above about 0.3 T superconducting magnets are generally used), (b) coils to superimpose the magnetic field gradients required for spatial encoding and slice selection, (c) radiofrequency transmitter and receiver coils, and (d) a computer to control the system and to reconstruct the image from the acquired data using Fourier transform techniques.

Most clinical imaging to date is based on proton resonance. The images thus created can represent the mobile proton density in a thin slice of the body, or the image can be weighted with the proton relaxation times T_1 and T_2 by using various rf pulse sequences including spin echoes. Figure 1 shows a 1-cm thick transverse slice through the eyes obtained using a T_2-weighted, spin-echo technique at a field of 1.5 T. Note that the vitreous humor of the eye, which has a long T_2, appears bright, whereas the more crystalline lens, with a shorter T_2, appears dark. This image was obtained using a circumferential radiofrequency coil which surrounds the head. Recent advances in NMR imaging include the development of surface coils. A significant improvement in signal-to-noise ratio (S/N) can be achieved by using a receiver coil which is placed in close proximity to the region of interest. This increase in S/N can be translated into improved resolution by using smaller pixels. Surface coils have been used for imaging specific anatomical areas such as the eye, the ear, the spine, the knee, and the breast.

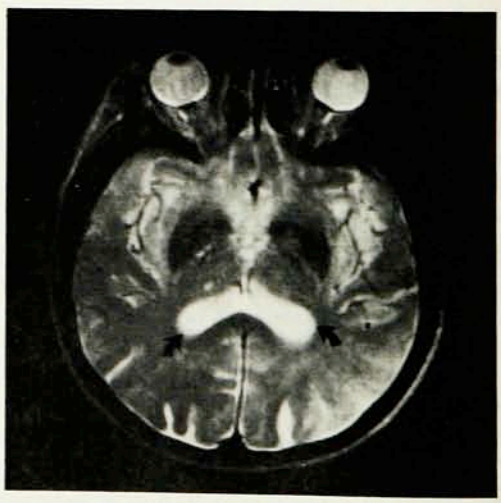

FIG. 1. A transverse NMR image of the normal head at the level of the eyes at 1.5 T. For the T_2-weighted image, the ventricular central spinal fluid appears bright. (Courtesy of Picker International, Inc.)

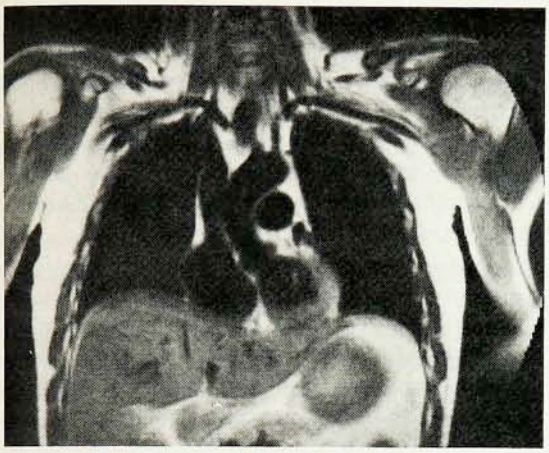

FIG. 2. A gated image showing the chambers of the heart. (Courtesy of Picker International, Inc.)

The image shown on the cover is a composite in which several surface coil images of the spine have been photographically linked with the total head image. As illustrated, unlike x-ray-computed tomography (CT) which is constrained by the mechanical gantry motion, NMR imaging may provide image planes at any orientation (i.e., sagittal, coronal, and oblique, as well as transverse) by means of electronic manipulation of the gradient fields. The images shown demonstrate the spatial resolution (less than 1 mm) and contrast presentation capabilities of clinical NMR imaging. Extension of these basic imaging techniques to small regions is now opening up the new field of NMR microscopy in which spatial resolution down to 10 μm per pixel in the imaging plane has been demonstrated *in vitro*. This has allowed imaging of single cells (frog ova) with clear differentiation between the cell nucleus and various zones within the cytoplasma.[7]

Cardiac research and the associated topic of blood flow imaging have received considerable attention in the past year. EKG signal gating has been utilized as the control for NMR data acquisition. With this technique, it is possible to generate a "stop-action" image of the heart in any given part of the cardiac cycle (see Fig. 2) and to string these images together, thus producing a cine sequence of the beating heart. A number of methods are available which allow visualization of flowing blood. One approach utilizes the spin state phase-dependence of the NMR phenomenon as an informational parameter to characterize the flow of a system. Velocity-dependent phase contrast in conjunction with electrocardiographic gating and imaging subtraction techniques have been used to produce non-invasive NMR angiographic studies.[8,9] Other work involving fast data acquisition techniques has demonstrated the capability for visualizing dynamic flow patterns by real time NMR "movies."[10]

Originally, NMR imaging was considered a relatively slow modality in terms of data acquisition. Even with the conventional multislice NMR imaging today, a typical series of 16 slices requires about 12 minutes, owing to fundamental relaxation time constraints which present a problem in body imaging since the patient moves and breathes. Special fast pulse sequences have been proposed[11] which would enable acquisition of a complete image within the time frame of the T_2 relaxation (40 to 100 ms); however, this method gives coarse spatial resolution and low signal-to-noise. Development and refinement of new fast NMR imaging techniques has represented an area of intense activity over the past two years. A number of different pulse protocol strategies have evolved, generally involving limited rf pulse flip angles and gradient recalled echoes.[12,13] Single slice images exhibiting relatively high S/N characteristics now may be obtained in 2 to 5 seconds while fast, 3-D data acquisition techniques allow formation of a complete multi-slice series (more than 20 images) in four minutes.[14]

Finally, the role of nuclei other than hydrogen and the potential for obtaining diagnostic information through spectroscopic analysis of various biomolecular species within tissue have been of emerging importance within medical NMR. NMR imaging of the natural sodium-23 distribution within human heads has been reported.[15] Fluorine-19, which is present endogenously at extremely low levels, may be introduced *in vivo* in several biocompatible forms (including fluorinated glucose and the "blood substitute" materials) as a high contrast NMR agent. Applications for fluorine-19 NMR are being investigated extensively.[16] Chemical shift phenomena resulting in complex multi-peak NMR spectra for a given nucleus provide a probe for the molecular environment and allow identification of various biochemical species and product metabolites. In fact, chemical shift imaging techniques have been developed which provide the capability for obtaining an image of a selected spectral component. For example, in the case of hydrogen, separate images may be generated for the protons bound in water and for those bound in fat (lipid).[17]

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Dual-Energy Chest Radiography

The concept of utilizing two photon energies to obtain information on tissue characteristics was first suggested by Jacobson in 1953.[1] Dual-photon absorptiometry is currently in widespread use for bone mineral analysis and the idea has also been exploited in a variety of x-ray imaging research projects during the last 15 years.[2-4] Most recently it has been applied to chest radiography, and a prototype unit (designated ESU, for energy subtraction unit) has been under clinical trial at the University of Alabama at Birmingham Medical Center for the past two years.

Dual-energy radiography utilizes both x-ray intensity and spectral information to decompose patient images into water (soft tissue) and bone (mineral) components. By contrast, conventional (single-energy) radiography utilizes only intensity information and is not capable of tissue decomposition. A helpful analogy is to think of conventional radiography as black and white imaging and dual-energy radiography as color imaging. Just as the human visual response may be fully characterized in terms of three primary colors, x-ray attenuation (in biological tissue and in the 20 to 150 keV diagnostic energy range) may be fully characterized in terms of two attenuation processes—Compton scattering and photoelectric absorption or, alternatively, in terms of low atomic number (water) and high atomic number (bone) tissues.[5]

The first step in dual-energy imaging is to generate two simultaneous images of the patient, identical in every respect except that one uses an x-ray spectrum with a relatively high mean energy (approximately 50 keV). These images are then decomposed point by point into water and bone basis (component) images whose intensity values are proportional to the overlying thicknesses of water and bone. A bone-cancelled (soft tissue) image is then generated by adding a small fraction of the bone image to the water image to fill in the voids or "shadows" left by

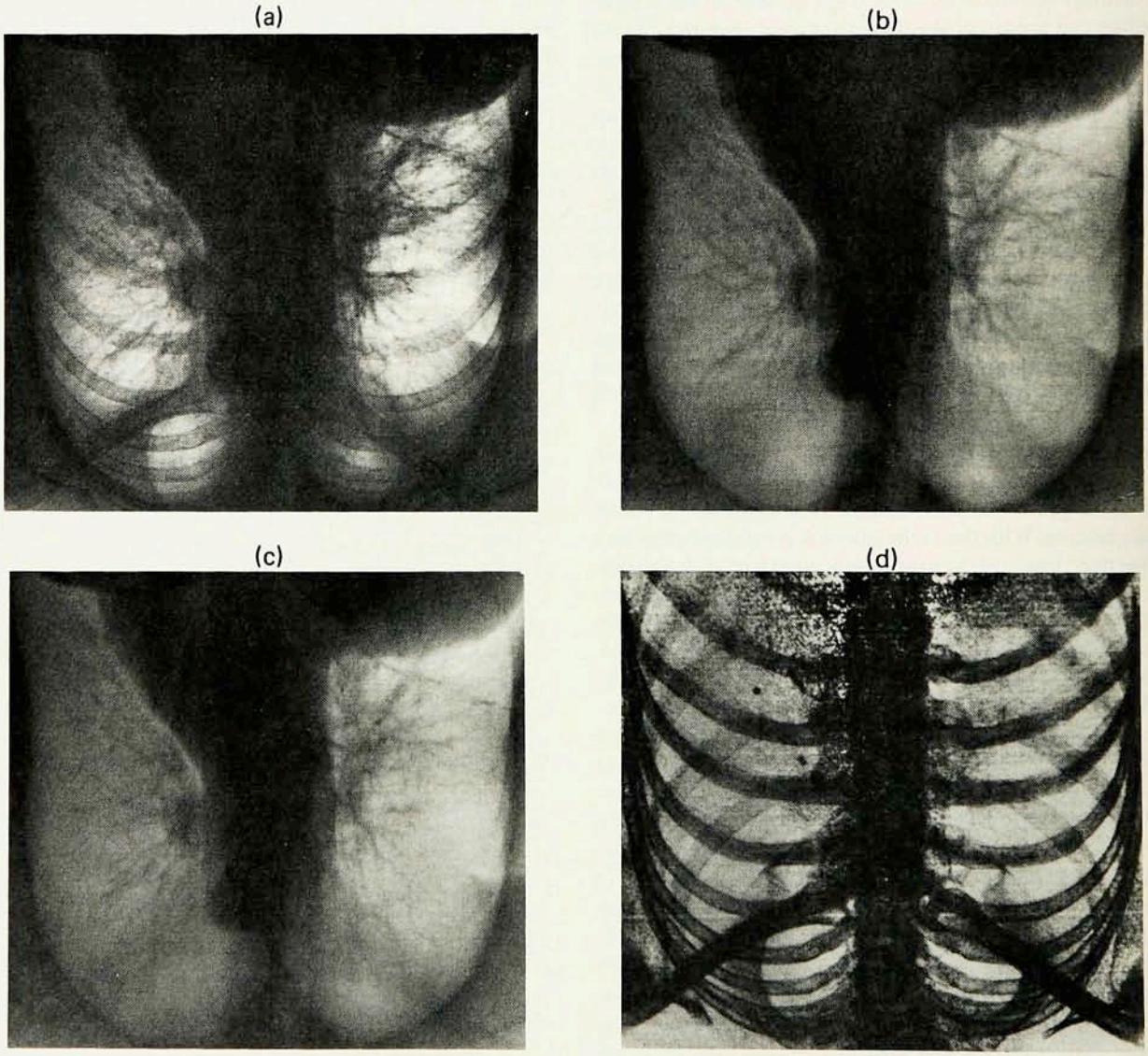

FIG. 3. Dual-energy chest radiography images: (a) soft tissue—lung window, (b) soft tissue—mediastinum window, (c) and bone, (d) images of a patient with calcified nodules in the left lung).

the removal of bone. A final image, analogous to a conventional film and referred to as a normal or single energy image is generated by adding the original low and high energy images together.

In the ESU all these images are generated from a single patient scan at a radiation level comparable to that employed in conventional chest radiography. The normal, bone cancelled, and soft tissue cancelled images (see Fig. 3) are presented to the radiologists simultaneously. Of practical interest is the fact that the bone-cancelled image shows only soft tissue structures; the ribs and spine are completely invisible. The bone image, on the other hand, shows the ribs and spine but on soft tissue structures. Furthermore, the bone image clearly shows the mineral deposits occurring in the calcified lung nodules (see Fig 3d).

The obvious advantage of dual-energy imaging in chest radiography is that it separates the two types of anatomical information present and provides the radiologist with simpler images to view. Thus, a nodule which may be hidden by the ribs of a conventional film is clearly visible on the soft tissue image. Recent results indicate that a dramatic improvement is obtained in nodule detection with the ESU compared with conventional chest films.[6]

To put this improvement in perspective, it should be noted that prior to this, nodule detection rates changed very little over the last 30 years, and as many as one in three nodules was missed which, retrospectively, could have been detected. Furthermore, lung cancer is the leading cause of cancer death in the United States, and its incidence is increasing, especially among women. Early detection and removal of cancerous lung tissue is the most effective treatment, and chest radiography is the primary technique for early detection. Since a relatively large percentage of the U.S. population undergoes chest radiography, this capability offers great promise to decrease the mortality of the disease.

In addition to detecting more nodules than conventional systems, dual-energy chest radiography reveals nodule calcifications with greater sensitivity and accuracy than other noninvasive techniques.[7] This is extremely important, since the presence of calcium is a primary radiographic criterion for benignancy. In many cases, the ESU eliminates the need for nodule biopsy as well as the need to perform more expensive, higher radiation dose examinations. Not only is the calcium more evident with the ESU unit, but it also can be quantified to a high degree of accuracy. However, at this time, the importance of this capability has not been clinically established.

The remarkable performance of the ESU is a result of a synergistic combination of x-ray imaging technologies which matured over the last decade, including scanning fan-beam geometry, linear array solid-state x-ray sensors, laser film writers, and dual-energy x-ray detection techniques.[8] Prior to the dual-energy detector development, the different x-ray photon energy information was obtained by switching the x-ray tube voltage, typically between 85 and 135 kV. Since a time delay occurs between the low and high energy pulses, patient motion and misregistration artifacts can occur. These problems were eliminated by employing a dual-energy x-ray detector and a constant (high) x-ray tube voltage.

In addition to detecting pulmonary nodules and being able to differentiate between benign and malignant nodules, dual-energy radiography holds considerable promise in several other areas of diagnosis. Studies are underway to evaluate its utility in mammography, measurement of bone mineral content (For detection and monitoring of osteoporosis), and evaluation of metastatic calcification of the lungs in kidney disease.

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NUCLEAR PHYSICS

Sharp Positron Peaks

In recent scattering experiments, collisions between such heavy nuclei as uranium, thorium, and curium have resulted in the production of positrons (antimatter counterparts of electrons). Such experiments (see *Physics News in 1985*, p. 50) were motivated in part by the desire to study "vacuum sparking," a phenomenon—predicted by quantum electrodynamics, the theory which describes the electromagnetic force—in which the collision between two heavy nuclei creates for a fleeting moment (10^{-21} s) a nucleus with a charge Z of 173 or more. The electrostatic field of such a "supercritical" nucleus is so strong (10^{20} V/m), that an electron-positron pair ought to be spontaneously created out of the surrounding vacuum. The electron becomes bound to the nucleus, while the positron would presumably be emitted and recorded in detectors surrounding the collision area.

Physicists at the Gesellschaft für Schwerionenforschung (GSI) Laboratory in Darmstadt, West Germany did indeed observe the emission of positrons in the heavy-ion collisions, but were immediately puzzled by the narrowness of the peaks in plots of positron yield versus positron energy.[1-3] That is, for a particular collision combination—say, between uranium and curium, with a combined Z of 188—a plot of the number of positrons observed at different energies exhibited a peak at an energy of 300 keV. The width of this peak was 75 keV, much narrower than one would expect if vacuum sparking were the source of the positrons.

Jack S. Greenberg of Yale University, a leader of one of the GSI experiments, has reported that another surprise was the lack of any Z dependence: different combinations of heavy nuclei, with different composite Z's, were tried, but each time a positron energy peak of 300 keV appeared in the plots.

Still another surprise was the observation of positrons in collisions for which Z was actually below the critical value of 173. Also, in some scattering events, electrons with the same narrow energy peaks were observed.[4] All of these facts suggested to Greenberg and to others that some phenomenon other than (or in addition to) vacuum sparking was at work. The most interesting speculation is that the positrons and electrons are the decay products of a previously unobserved neutral particle with a mass of about three times the electron mass. Such a particle would be of great interest to particle physicists since there would have been an obvious place for it in the generally accepted "standard model" of particle interactions.

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Double Beta Decay and Nuclear Structure Calculations

Properties of neutrinos, unlike those of other elementary particles, are often more conveniently studied at low energies, using the techniques of nuclear physics, rather than at high energy accelerators. Double beta decay is an example of such an approach. Its study gives us indirect but very sensitive information about the mass and interactions of neutrinos.

Neutrinos are perhaps the most elusive of the elementary particles. Their existence was already postulated by Pauli in 1930, but was not experimentally verified until 25 years later. Nowadays, observation of neutrinos is a rather routine matter, but many of their fundamental properties are still unknown. So, we do not know whether neutrinos are massive or massless, or whether neutrinos and their antiparticles (antineutrinos) are distinct or identical. Other particles, such as electrons, are clearly distinct from their antiparticles: they are so-called Dirac particles. Neutrinos might be "ultimately" neutral, that is, identical with their antiparticles, and thus would represent the first realization of a so-called Majorana particle. If we could show that neutrinos are indeed massive, as a so far unverified Soviet experiment of 1980 suggests, then our basic ideas about elementary particles and their interactions would have to be revised; the cosmological consequences would be also profound.

Beta decay is a process in which one of the neutrons bound in a nucleus spontaneously decays into a proton (bound in the final nucleau), an electron, and an antineutrino. Double beta decay is a simultaneous decay of a pair of neutrons into a pair of protons plus a pair of electrons and a pair of antineutrinos. Now, if neutrinos are Majorana particles, another mode of double beta decay is possible. One can imagine that the pair of antineutrinos is equivalent to a neutrino plus its antiparticle which can, therefore, annihilate each other, leaving only a pair of electrons and no neutrinos as the decay products. Observations of such a "neutrinoless" double beta decay would be a proof that neutrinos are indeed Majorana particles. More detailed analysis shows that, moreover, the decay is possible only when neutrinos are massive and that the decay rate is proportional to the square of the neutrino mass. Large experimental efforts are now devoted to the study of both "modes" of the double beta decay.[1] The "neutrinoless" double beta decay has not yet been observed, but one knows that the corresponding halflives are very long; for example, in the case of germanium-76 it is longer than 10^{23} years (for comparison, the universe is about 1.5 times 10^{9} years old).[2]

In order to interpret correctly the results of experiments on double beta decay, one has to solve some important nuclear structure problems. The decay lifetimes depend not only on the neutrino mass, but also on the details of the

structure of the initial and final nuclei (the so-called nuclear matrix elements). The reported work deals with calculation of these matrix elements. As a gauge of our ability to do the job correctly, we calculate the double beta decay mode with two electrons and two antineutrinos in the final state (a mode which has been observed in a few cases).

The rather complex computer-assisted calculations lead to decay rates for both modes of the double beta decay for a number of nuclei.[3] The calculated decay rates for the two-neutrino mode are faster than the observed ones. At the present time the discrepancy, noted also by other theorists, is not fully understood although an important mechanism which suppresses the nuclear matrix elements aand therefore prolongs the calculated lifetime has been found.[3] In this work we attempt to relate the double beta decay to other processes which could be observed in a laboratory and which could give us a clue as to how to proceed further. At the same time the calculation has been extended to more nuclei, many of which are being studied experimentally now.

Despite the noted discrepancy, the calculations allow us to put rather stringent upper limits on the mass of neutrinos, if they are indeed Majorana particles. That limit is substantially lower (approximately one tenth) than the mass value implied by the Soviet experiment. Thus, we have to conclude that either the experiment is incorrect or that the neutrino is not a Majorana particle. (Most theories which suggest that neutrinos are massive would prefer them to be Majorana particles.)

Petr Vogel, California Institute of Technology

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OPTICS

Experimental Observations of Laser Cooling and Trapping of Atoms

Since 1970 there has been great interest in the study of the forces exerted by laser light on atoms. Considerable attention has been devoted to methods of using these forces to construct "optical traps" in which atoms could be confined for long periods of time. During 1986, a group of scientists at AT&T Bell Laboratories in Holmdel, New Jersey, demonstrated the optical trapping of atoms for the first time.[1]

Optical potential wells for atoms are very shallow and only extremely "cold" atoms can be confined in them. Before an optical atom trap could be demonstrated it was necessary to learn how to create the collection of ultra-cold atoms needed to load it. In early 1985 the Bell Labs group demonstrated a technique for doing this using three sets of mutually orthogonal laser beams tuned half a linewidth below a resonance transition of the atom.[2] In this configuration the laser beams exert strong viscous damping forces on the atoms and the atomic motion is cooled down to a temperature which is proportional to the natural linewidth of the transition. In the region where the laser beams intersect, the ultra-cold atoms execute a random-walk motion that resembles the Brownian motion of a particle in a highly viscous fluid. For this reason, the viscous "medium" of photons is called "optical molasses." Approximately 10^6 sodium atoms were cooled to 240 μK (approximately the theoretical limit for the transition used) and confined in a region of about 0.5 cm^3 for a period of about 0.5 s.

The optical trap demonstrated in early 1986 is comprised of a single, strongly-focused Gaussian laser beam tuned

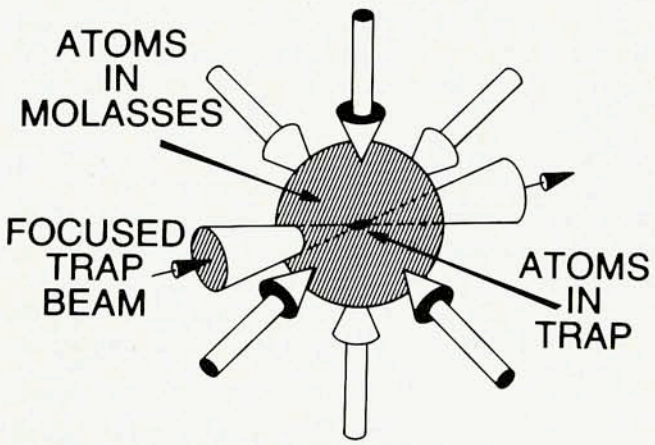

FIG. 1. Schematic diagram of the interaction region inside the vacuum chamber used for trapping atoms. The broad arrows represent the collimated laser beams (about 1 cm in diameter) which intersect to form "optical molasses." The shaded sphere represents the fluorescence emitted by the collection of ultra-cold atoms contained and executing random-walk motion within the optical molasses. The optical trap is formed just beyond the focus of the trap laser beam, which is also shown. The black dot represents the intense fluorescence emitted by the dense collection of atoms confined within the optical trap.

about 10^4 natural linewidths below the atomic resonance.[1] The trap relies on the "dipole force" of resonance radiation pressure, which is proportional to the gradient of the light intensity. For tuning below the resonance transition, the force is such that atoms seek out regions of greatest light intensity. This "single-beam, gradient-force trap" was first proposed by Ashkin in 1978.[3]

In the experiment, the trap laser beam was focused into a collection of atoms confined and cooled by optical molasses. The trapped atoms were observed as an intense, small spot of fluorescence within the much more diffuse light scattered from atoms in the molasses. The use of optical molasses was crucial to the success of the trapping experiment. First, ultra-cold atoms are needed to load the trap, which is only 5 mK deep. Second, the random walk motion and long storage time of atoms in optical molasses allow the atoms to continuously diffuse to the trap surface and be captured (see Fig. 1). Thus, considerably more atoms can be trapped than the number given by the molasses density times the trap volume. Finally, optical molasses was also used to provide cooling for trapped atoms. In the absence of this additional cooling mechanism, trapped atoms heat up and boil out of the trap in times on the order of 5 ms.

Using 200 mW of trap laser power, about 500 atoms were trapped in a volume of about 10^{-9} cm^3 for periods of several seconds. The atomic density in the trap was approximately 5×10^{11} cm^{-3}, about 10^6 times the molasses density. The trap lifetime appears presently to be limited by the 2×10^{-9} torr background pressure within the vacuum chamber; the innate trap lifetime was calculated to be about 10^4 s. The temperature of the trapped atoms was inferred to be about 350 μK, only slightly hotter than atoms in optical molasses. The trapped atoms are confined transversely within 2 μm and the loaded trap can be rapidly moved without a significant loss of trapped atoms by simply redirecting the laser beam. The trap serves as "optical tweezers", giving one the ability to localize and manipulate ultra-cold atoms in a precise way.

The collection of trapped atoms comprise an interesting gas. The high density and ultra-low temperature represents a previously inaccessible regime for gaseous matter. Much higher densities and lower temperatures seem readily attainable. It appears that these dense, ultra-cold gas samples will be ideal candidates for a variety of experiments in which fundamental atom-atom and atom-trap interactions are investigated.

J. E. Bjorkholm, AT&T Bell Laboratories

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Scattering of Free Electrons by Light

Since the invention of the laser, a major focus of optical research has been the study of the interaction of light with single elementary particles. The effect of isolated particles on light in the form of scattering was observed in early experiments, but the complementary observation of the effect of the light on single particles has been very difficult to achieve and often ambiguous in interpretation. Recently researchers from AT&T Bell Laboratories and the University of Maryland have demonstrated large angle scattering of free electrons from a focused laser beam.[1]

The experiment involves the production of low energy (0.5–10 eV) electrons by multiphoton ionization of xenon gas. The electrons were produced by high order processes (absorption of 11 or more photons) at very low densities so that there were no effects from collisions or space charge. Observations of angular distributions of the photoelectrons at low intensities established that the electrons had initial velocities which were highly collimated along the direction of the laser's polarization vector. As the intensity of the light was increased, large angle electron scattering resulted. The initial beam collimation (less than 15°) was destroyed and the distribution became nearly isotropic.

Classically, the scattering is that of a charged particle off the electric and magnetic fields of the light, a phenomenon theoretically described by quantum electrodynamics in terms of stimulated Compton scattering. The first suggestion for experiments of this sort was made by Kapitza and Dirac in 1933[2] and a clear theoretical basis for an understanding of the Bell experiments was provided by Kibble in 1966.[3]

Kibble showed that the behavior of a free electron in a radiation field can be described relativistically in terms of the motion of a particle with constant energy that depends on the local light intensity. The change in rest mass energy is exactly given by the classical "ponderomotive" potential. This potential energy is the result of the oscillatory "quiver" energy of a free electron in the light field. For 1064 nm light focused to an intensity of 10^{13} W cm^{-2}, this amounts to a 1 eV potential. The electron moves under a force given by the gradient of the potential.

The Bell-Maryland researchers studied the angular distribution of electrons at fixed energies as a function of light intensity. The ponderomotive potential at the focus was varied from 0.5 to 5 eV and noncylindrical potentials were produced using elliptical beams. The final trajectories depended on the distribution of the light intensity producing the conservative force field as well as the initial momentum of the electrons, so that the angular distribution was a function of both the electron energy and the light intensity. A computer model of the ponderomotive force field was used to calculate the trajectories of the electrons as they left the region of focus and the model provided excellent predictions of the intensity

and energy behavior of the distributions as well as the dependence on the shape of the focused spot.

With the production of plasmas using intense laser beams in order to produce coherent and noncoherent x-ray sources, the interaction of free electrons with light has become of interest beyond the theoretical regime. On a wider scale, the development of free electron lasers focuses attention on this interaction, which is at the heart of their operation, while optical accelerators are viewed by some as the only hope to reach the next domain of energy for elementary particle physics. These experiments on electron light scattering, for the first time, provide an easy and sensitive tool for studying the fundamental nature of this process with spatially complex, time varying radiation.

R. R. Freeman, P. H. Bucksbaum, and M. Bashkansky,
AT&T Bell Laboratories and
T. J. McIlrath, University of Maryland

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Binary Optics: An Emerging Diffractive Optics Technology

Sheet optics by the square meter, high-quality throw-away optical sensors and arrays of hundreds of small modular lasers coherently added to form powerful laser beams—these are some of the promises of an emerging binary optics technology.

What's so binary about this optics? Binary optics refers to the two-level (high-low) nature of the phase relief patterns used to control the phase, the amplitude, and the polarization of an optical wavefront. The benefit of two-level relief structures is access to the entire integrated circuit (VLSI/VHISIC) technology effort of the electronics industry. All lithographic and dry-etching technologies developed by that industry apply directly to the fabrication of binary optical components. As in integrated circuit fabrication, with binary optics it is possible to produce many optical elements from a single mask. These optical elements can be planar, low-cost, light-weight replacements of conventional optical elements such as lenses and scanners, or they can correspond to unique optical functions not feasible with conventional optics.

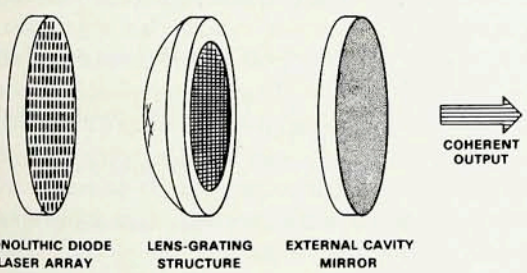

FIG. 2. A laser diode array with micro-turning mirrors etched in the surface produces a mesh of beams. A lens-binary-holographic-grating combination placed in an external cavity provides optical feedback and locks the laser sources in to appropriate phase states. The output is a coherent sum of the modular laser beams.

The simple, elegant properties of binary optics complement conventional optics. Among these properties are the easy formation of multiplexers and phased-array structures and the simplicity of implementing spatial phase distributions in the form of lithographically etched relief patterns under computer control.

Fundamental optical principles stay the same, but a shift from refractive to diffractive elements and the improved accuracy in the fabrication of planar phase relief structures resulting from the blending of high-resolution lithography and reactive ion-beam etching technologies have made it feasible to generate two-dimensional optical transfer functions accurately and efficiently. Present high-voltage electron beams can write lithographic patterns with better than 300 Å accuracy and resolution. High materials cost of conventional infrared optics and ease of binary mask fabrication make infrared optical elements particularly suited for replacement by binary optics. Infrared optical transfer functions such as beam shaping, beam multiplexing, beam steering, focusing, filtering, and scanning can now be accurately implemented on thin transmissive or reflective substrates and can exhibit very high (greater than 95%) diffraction efficiency.

Researchers at the MIT/Lincoln Laboratory have used binary lenses in a CO_2 laser radar telescope to image objects at ranges of a few kilometers. For monochromatic laser operation, far off-axis lenses are appropriate.[1] The advantage of binary optics, however, is in infrared thermal imaging applications where on-axis lens operation is essential. In these applications multi-level lens structures can maintain the high diffraction efficiency. For non-imaging applications, very large apertures can be assembled from planar-etched metal or kapton-embossed components. Present-day diffractive optics technology makes one-meter-diameter planar sub-apertures feasible. At the small end of the scale, arrays of micro-lenses, deep diffractive structures for agile beam steering and very high-speed non-contiguous scanners on spinning thin substrates are recognized applications.

One application exploiting binary optics' unique diffractive properties is in multi-branched laser cavities that coherently add one- and two-dimensional arrays of lasers. Researchers in the DARPA (Defense Advanced Research Projects Agency) sponsored binary optics program tested several techniques with GaAs, CO_2 and HeNe laser arrays.[2] They believe it is feasible to add coherently a few hundred modular lasers. The modular laser array technology permits high laser power from small sources at low cost and avoids catastrophic failures.

Aperture filling with arrays of lasers already phase-locked by evanescent coupling is a related technique developed at Lincoln (see Fig. 2). Here binary optical elements convert an array of laser sources (with associated strong far-field sidelobes) into a uniformly illuminated output aperture with near-perfect efficiency.

Other novel applications of binary optics at Lincoln are broadband anti-reflection coatings and the mixing of refractive or reflective elements with diffractive components for more design flexibility in electro-optical sensors.

Wilfrid Veldkamp, MIT/Lincoln Laboratory

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Tunneling and Photoconductivity

Photoconductivity is a widespread phenomenon in semiconductors and has been known and understood for several decades.[1] If the lifetime of the photogenerated carriers exceeds the transit time of the majority carrier between the two ohmic contacts, photoconductivity is accompanied by current gain. The latter is given by the ratio of the electron-hole pair lifetime to the transit time. The response time of the photoconductor is primarily controlled by the lifetime, while the gain-bandwidth product is simply given by the reciprocal of the transit time. The performance of a "classical" photoconductive detector is therefore determined by bulk properties such as mobilities and lifetimes.

Recently a striking new type of photoconductivity based on quantum mechanical tunneling in superlattices has been discovered at AT&T Bell Laboratories.[2] The underlying physical cause of this phenomenon is "effective mass filtering." Since the tunneling probability of carriers through the barrier layers of a superlattice increases exponentially with decreasing effective mass, electrons are transported through a superlattice much more easily than the heavy holes. When light is shined on the superlattice, the photogenerated holes essentially remain localized in the wells, while electrons can tunnel through the barriers. Thus the superlattice acts as a filter for effective masses. This gives rise to a new photoconductive gain mechanism controlled by tunneling.[2,3]

Since the electron mobility perpendicular to the layers depends exponentially on the superlattice barrier thickness, it follows that the electron transit time, the photoconductive gain and the gain-bandwidth product can be artificially varied over a wide range. This offers great versatility in device design not available in standard photoconductors. High performance infrared photoconductors utilizing effective mass filtering have recently been demonstrated at AT&T Bell Laboratories.[3] The devices grown by molecular beam epitaxy consisted of 100 periods of AlInAs (35 Å)/GaInAs (35 Å) between two contact layers and responded to wavelengths in the 1.6–1.0 μm region. These detectors exhibit high current gain (up to 2×10^4) at very low voltage (less than 1 V) and response times in the 10^{-4} s range. The low bias operation cuts down on the device noise, which was only about 8×10^{-14} W/Hz$^{-1/2}$. These are the highest gain and lowest noise photoconductors operating at such low voltage.

Another important advance by the Bell Labs group is the first observation of sequential resonant tunneling through a superlattice.[4] If the quantum wells are weakly coupled (relatively thick barriers) the states of a superlattice are well described by the quantum-mechanical quasi-eigenstates of the individual wells. Suppose now that a uniform electric field is applied to the superlattice. As the bias is increased, at some point the energy potential drop across the superlattice period equals the energy difference between the first two levels of the quantum well. At this point, resonant tunneling occurs between the ground state of the nth well and the first excited state of the $(n+1)$th well followed by intra-well energy relaxation by phonons. This process is repeated sequentially through the superlattice.

The Bell Labs workers observed two pronounced peaks in the photocurrent of a reverse-biased MBE grown $p^+ i n^+$ diode. The low doped i region had 35 periods of AlInAs (135 Å)/GaInAs (135 Å). The voltage position of the two peaks divided by the numbers of periods (35) gave exactly the calculated energy differences between the first two excited states and the ground states of the quantum wells. This provides direct evidence of sequential resonant tunneling through the superlattice.

There are some potentially very important device applications of this effect. By appropriate realization of a population inversion between the first two excited states of the quantum wells, electrons, upon tunneling into the third energy level of a well, can be made to emit a laser photon, rather than relaxing the energy via phonons. Such a semiconductor laser, first proposed by Kazarinov and Suris,[5] will emit in the infrared region of the spectrum between 5 to 10 μm (depending on the well thickness).

Federico Capasso, AT&T Bell Laboratories

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Photon Localization

It has been appreciated for some time that the transport of electrons in a strongly disordered material will be governed by multiple scattering of the electron wave function. Ultimately, if the scattering is sufficiently strong that the elastic mean free path is

comparable to the de Broglie wavelength (equal to Planck's constant divided by the electron's momentum), conduction will cease at a temperature of absolute zero.[1] Before this strong localization, or "Anderson localization," takes place, multiple scattering is thought to lead to "weak localization". Weak localization[2] manifests itself by resistive corrections to the conductivity at low temperatures and is caused by "coherent backscattering" of the electron wave. Photon propagation in disordered dielectrics and electron localization in disordered conductors have both been shown to be governed by coherent backscattering. This enhanced scattering in the precise backward direction arises from the fact that the time-reversed scattering paths for the wave are in phase in this direction, and this results in a doubling of the scattering in a narrow range of angles about the backscattering direction.

Researchers who have focused on electromagnetic wave propagation in disordered media have appreciated for some time that the cross section for multiple scattering of electromagnetic waves is enhanced in the precise backscattering direction. Ishimaru and collaborators at the University of Washington, who research photon propagation in disordered media, early reported the presence of coherent backscattering in media dominated by multiple scattering.[3,4] But it was only recently that physicists in tune with the problems of electron localization, discovered the rather strict analogies between electron and photon coherent backscattering. Two groups of researchers, van Albada and Lagendijk[5] at the University of Amsterdam, and Wolf and Maynard[6] at Grenoble, independently reported experiments that revealed coherent backscattering peaks from dielectric spheres suspended in a fluid medium and pointed to the close analogy with electron weak localization.

The most recent developments in electron localization have focused on so called universal fluctuations of the resistance of small devices.[7] Here it was pointed out that owing to the build-up of correlation through multiple scattering, the conductance of a microscopic sample will fluctuate in a universal fashion, that is, in a way which is independent of size and degree of disorder. Etemad and his co-workers at Bell Communications Research showed that photon "coherent backscattering" in rigid media is dominated by fluctuations as well.[8] The backscattering peak was completely swamped by fluctuations in the scattered intensity, but they were able to recover the backscattering peak after ensemble averaging.

There remains one glaring omission in the experimental studies of photon localization, especially as they mirror the properties of electrons. No one has reported a disordered media, without loss, in which scattering is sufficient enough that the mean free path for photons becomes comparable to the wavelength. Such a medium is required for the strong localization of photons. Nonetheless, the observation of the photon backscattering peak, the appreciation of the critical role of ensemble averaging, and the rigorous analogy with electron transport in disordered conductors has both broadened and unified our view of wave phenomena in disordered materials.

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PHYSICS APPLIED TO INDUSTRY

For the past several years *Physics News* has had a chapter on physics in industry, thus highlighting the fact that a substantial number of physicists are employed in industry and that their research is motivated at least in part by potential applications in the area of new devices, new materials, or new diagnostic techniques. Physicists in industry do research in a broad range of physics subdivisions (such as condensed matter physics, optics, polymer physics, and vacuum physics), and these overlap the conventional discipline-oriented subdivisions which make up most of the other chapters in *Physics News*. Thus, some "industrial research" is reported in those categories.

In the present chapter we call attention to those developments for which there is a clear industrial application or in which the major share of current research is being carried out in industrial laboratories.

John R. Reitz, Ford Motor Company

Research in Scanning Tunneling Microscopy

Scanning Tunneling Microscopy (STM) is a rapidly growing field, with research groups at both universities and industrial research labs. STM is based on the pioneering efforts of Binnig, Rohrer, Gerber, and Weibel of the IMB Zurich Research Laboratories.[1,2] The STM instrument is based on electron tunneling (a quantum phenomenon) across an adjustable vacuum gap maintained between a conducting tunnel tip and a conducting surface. The atomic structure of the surface may be mapped by moving the tip over the surface using precision actuators. Atomic resolution imaging is possible with STM since the electron tunneling phenomena, depending on overlap of tip and sample wave functions, probes a region of atomic dimensions. STM has already been applied to a variety of different important systems.

STM is expected to be an important contributor to industrial research. In particular, the development of semiconductor devices should be influenced by the capabilities of STM for investigation of device materials and structures. Considerable progress has been made in STM during 1986 by industrial investigators. Major advances have been made in the understanding of metal and semiconductor surfaces using STM imaging methods. Also, new STM devices with improved capabilities have been developed by several laboratories.

Recently, at several industrial labs (IBM, AT&T, and Ford), STM spectroscopy techniques have been developed for the study of surface electronic structure.[3–6] In these methods, a spectrum of tunnel current signal as a function of tunnel voltage is measured. The current-voltage spectrum reveals image potential states in the vacuum region at the surface[3,4] and also intrinsic surface states.[5,6] The surface electronic structure imaging methods developed by Binnig[7] have been extended to detailed investigations of several semiconductor surfaces.[8,9] These methods reveal the distribution of surface states at the Si (111) and Si (100) surface for both vacuum-annealed crystals[8] and cleaved samples.[9] This new capability in STM allows, for the first time, the study of the contribution made by individual surface atoms, adsorbates, and defects to surface electronic structure.

The first high-resolution STM images of the Au (111) surface were obtained in 1986.[10] This is a classic surface which has been studied for many years using standard surface physics techniques, including electron and ion scattering methods. The STM images reveal the presence of an ordered step reconstruction extending over a large (500 Å by 1500 Å) area. Arrays of large amplitude steps (7 atom layers) are also seen. The observation of large amplitude steps has important implications for the mechanism of material transport at surfaces and for the epitaxy of materials.

A collaboration of industrial and university researchers resulted in the development of a novel microscope based on STM. This new device, the Atomic Force Microscope (AFM), employs an STM apparatus for detection of very weak forces.[11] This implementation of the STM is the most sensitive force detector available. The first version of the AFM measures forces between a sharp stylus and the surface under investigation. An image of an insulating Al_2O_3 surface has been obtained with the AFM by mapping contours of constant force between a diamond stylus and the surface. The first ATM has a force sensitivity in the range of interatomic forces. Also, the spatial resolution obtained in the prototype AFM images is comparable to STM images. AFM imaging is expected to reveal entirely new physical properties of surfaces relating to direct measurement of forces between surface and tip atoms.

Progress in 1986 in STM and AFM imaging has a direct impact on industrial physics problems in the areas of surface technology and microelectronics. Since the engineering of catalysts and load-bearing surfaces relies on surface analytical tools, new STM electronic structure imaging methods should directly influence these important areas. In addition, many problems in industrial physics require the investigation of insulating films for microelectronic and other applications. The development of the AFM provides a means for high-resolution studies of these important insulators. The rapidly growing capabilities of STM technology are expected to provide novel methods for investigating a variety of industrial physics problems.

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Direct Observation of Ballistic Electron Transport in GaAs

Ballistic, or collisionless, transport of electrons has been a feature of technology for a long time. It occurs in TV picture tubes, for example, where the residual gas pressure is too low for the few remaining gas molecules to scatter many electrons: the electron beam is ballistic from the time it leaves the cathode until it impinges on the picture surface. In a solid, however, the motion of electrons is generally characterized by frequent scattering in all directions from, for example, thermal vibrations of the lattice (phonons), impurities and defects. Thus the electron drift velocity in a solid is significantly lower than the maximum value that would be achievable in the absence of scattering. Recently scientists at IBM made the first definitive observation of ballistic electron transport in semiconductors.

The average distance travelled between collisions, or mean free path, is a characteristic of every solid and ranges widely. In pure metallic gallium, for example, the mean free path was found to be greater than 1000 μm at temperatures below 2 K;[1] on the other hand, in silicon it is estimated to be only about 100 Å,[2] smaller by a factor of 100 000. This large

difference results mainly from the different energy-band structures of the materials. If the size of material along the path of electron travel can be made comparable to the mean free path, then ballistic transport would be expected to occur. However, in semiconductors, ballistic transport had been only inferred from the results of several experiments on small samples.[3,4]

Recently, modern fabrication techniques (such as molecular-beam epitaxy, which allows the growth of high-purity, single-crystal semiconductors) and electron energy spectroscopy techniques[5,6] (which allow the electron energy to be measured) have been combined to fabricate spectrometer devices which can measure the transport of electron in GaAs in detail. In experiments that employ these devices (also called hot-electron transistors),[7] hot electrons of known energies are injected into one side of a semiconductor layer. They are collected after emerging from the other side of the layer if they have enough energy to surmount the top of a potential barrier. By adjustment of this barrier height with an external bias voltage, the energies of the collected electrons can be determined and compared to the injected values.

Using such spectrometer devices, Yokoyama[8] and Levi[9] observed quasiballistic transport (electrons that suffered a few scattering events) for some of the electrons injected into n-type doped GaAs layers between 650 and 1000 Å thick. By developing a more refined injector and spectrometer, the IBM researchers observed true ballistic transport in 300-Å-thick GaAs layers for up to 75% of the injected hot electrons moving at the limiting velocity of 10^8 cm/s.[10,11] Narrow electron distributions, some 60 MeV wide, with peak energies equal to the injection energies, have been measured. From this, and other measurements, we learn that scattering events remove the other 25% of the electrons completely from the ballistic distribution by causing large energy loss or momentum changes.

Ballistic electrons in high-resolution spectrometer devices are a powerful tool for studying electron transport. In addition to the direct determination of the electron energies, these structures allow the study of many relevant parameters that influence electron transport.[11,12] Since ballistic electrons in GaAs can travel as fast as 10^8 cm/s, about five times faster than in present GaAs devices, such studies might lead to improved high-speed devices.

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Nuclear Magnetic Resonance Spin-Offs

That such a weak quantum-mechanical phenomenon as nuclear magnetic resonance (NMR) can have such profound impact on chemistry, physics, industry, and medicine bears testimony to the long-term practical value of fundamental research. Now NMR imaging technology, whose development was spearheaded by the desire for improved medical diagnostic images, is finding new applications in such diverse disciplines as geology, agronomy, botany, materials science, and microscopy. The versatility of the technique derives from the sensitivity of the NMR signal to a large variety of molecular-level parameters associated with the chemical and motional environments of nuclear spins.

Hydrogen (^{1}H) is ubiquitous and the obvious choice for NMR imaging of water and oil in porous rocks and oil core samples.[1] Figure 1(a), for example, is a hydrogen image showing water distribution in a limestone core, revealing bedding planes and variations in porosity. Such images can be of use in evaluating effective oil extraction procedures which can be tailored to the local environment at the drill site. Since pressurized, doped brine and hydrocarbons move relatively slowly through rock, flow is measured by repeat imaging of cores. The study of water or fluid diffusion into polymers[2] and other nonmagnetic solids[3] is a similar application of NMR imaging, but to materials science. The fluid-absorption properties of solids are key considerations in the design and application of many man-made materials.

Conversely, the ability to render the water in rocks and soil invisible makes hydrogen NMR imaging an ideal and currently unique tool for studying plant root systems undisturbed in the soil medium in which they grow.[4] Apparently, the water in roots is more mobile and has a longer NMR spin-spin relaxation time than water bound to soil particles, so that use of a spin-echo imaging sequence can discriminate against the soil water which often constitutes the dominant component. Figure 1(b) is an NMR image of a bean plant in natural soil. Plant root imaging can be used for studying water transportation and response to light, water stress and disease, and ultimately may prove useful for evaluating the

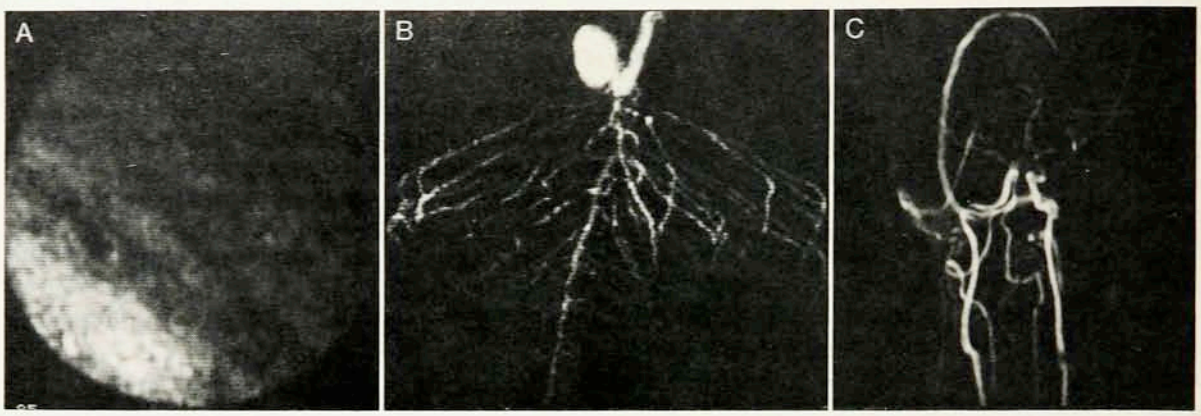

FIG. 1. Nuclear magnetic resonance images of (a) water distribution in a limestone core, (b) a bean plant in natural soil, (c) blood vessels in a human head.

effects of different CO_2 levels, pollutants, chemicals and herbicides, as well as optimizing growth conditions in seed beds.

All this does not mean that progress in medical NMR imaging is at a standstill. Major advances in the past year have been (1) the development of rapid imaging pulse sequences that reduce scan times to several seconds for high quality images,[5] (2) the development of NMR angiography techniques that provide images of only the flowing blood in vessels,[6,7] and (3) NMR microscopy at about 10 μm $\times$ 10 μm resolution, enabling discrimination of structures within larger cells.[8] Rapid imaging is based on the use of many NMR excitation pulses spaced much shorter than the spin-lattice relaxation time. Such sequences bear some resemblance to traditional driven equilibrium NMR pulse techniques.[9] NMR angiography utilizes the fact that spins that move through a gradient change their phase relative to stationary spins. This phase contrast can be used to select only the moving spins, or, in a living person, image the blood vessels. An example in the head is shown in Fig. 1(c).

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Electronic Conduction in Silicon Dioxide

Despite its importance in silicon technology, thermally grown silicon dioxide remains a poorly known material. Thus, the recent experimental[1] and theoretical[2] work performed at IBM on electronic conduction in SiO_2 represents significant progress for both the microelectronics and the physics communities. The knowledge of the physical mechanisms of electron transport in SiO_2 may help us understand the mechanisms of degradation and breakdown of the thin insulators used in the sub-micron technology. In addition, the high fields and high rates of energy loss experienced by the electrons in insulators challenge our basic understanding of the physics of electron transport in solids.

Previous to the IBM work, our understanding of electron transport in insulators still relied on the pioneering work of Fröhlich.[3] In ionic materials, such as the alkali halides, an efficient mechanism by which electrons—accelerated by an external field—lose energy to the lattice is provided by the polar electron–phonon interaction. For slow electrons, the coupling to the dipole field of the polar lattice is strong, since the lattice can easily follow the motion of the electrons and absorb their energy. But when the external field exceeds a critical value (historically called the "breakdown field"), the electrons acquire such a large velocity between successive collisions that the lattice polarization cannot respond. The rate of energy loss decreases, the electrons reach even higher velocities, the rate decreases even more, and so on. In this regime (normally called velocity runaway) nothing can now prevent the charge carriers from reaching the impact ionization threshold. Eventually, avalanche multiplication and the associated Joule-heating will lead to the breakdown of the dielectric.

The extrapolation of these ideas to the less polar SiO_2 seemed so obvious, that for many years the problem of the dielectric breakdown of SiO_2 was considered almost settled.[4] But there was little experimental confirmation of the theory. For this reason, in 1982 the IBM group started a

series of experiments on the energy distribution of the electrons in SiO_2.[1] The first results came as a surprise and successively refined experimental techniques confirmed that not all was going according to the extrapolated Fröhlich picture: the electrons were indeed *running away* from the polar interaction. But this was occurring at fields almost ten times smaller than the threshold field of 10^7 V/cm anticipated at that time.[4,5]

Already in 1975 Ridley had suggested that *nonpolar* electron–phonon scattering could play a major role in the high-field behavior of insulators.[6] Later, similar ideas were successfully applied to the alkali halides.[7] Therefore, it seemed reasonable to identify the "missing" stabilization mechanism with the nonpolar electron–phonon scattering. This is negligible at low energy, but its effect grows larger above 2 eV or so, as the electrons will be scattered more effectively by short-wavelength phonons. Monte Carlo simulations confirmed the correctness of these ideas. Below 1.5×10^6 V/cm the polar scattering behaves as expected and keeps the electrons in steady state at a low average energy. Above this threshold field the electrons try to escape to higher energies, but they are soon affected by large-angle, quasi-elastic nonpolar collisons.[8] Thus the nonpolar scattering behaves as a catalyst, the more frequent nonpolar collisions resulting in higher energy losses via polar processes. This allows steady state transport to occur even at the largest pre-breakdown fields, about 1.6×10^7 V/cm.

These results are encouraging for the device engineer, because the ultimate dielectric strength of SiO_2 does not seem to be limited by intrinsic electronic runaway processes but, rather, by technological limitations which we can hope to overcome: it is enough to recall that the highest breakdown fields have increased from 7×10^6 V/cm in the early 1970s to almost 2×10^7 V/cm. But also for the theoretical physicist, SiO_2 becomes a unique prototype material. Despite the amorphous structure of thermally grown layers, short-range order renders them electronically similar to their crystalline counterpart, alpha-quartz, with the advantage of a higher purity. No other insulator can claim mobilities in excess of 20 $cm^2/V\,s$.[9] The enormous fields sustained by these layers and the evidence of steady-state transport at these fields requires scattering and energy-loss rates which render the familiar Boltzmann transport equation highly suspect. This has stimulated further research in the high-energy "quantum" direction which complements the effort made in the low-energy area of heterostructures and quantum wells.[10,11] Finally the growth of the high-quality films as thin as 5 or 6 monolayers has recently allowed the experimental observation of ballistic electrons, of phonon replicas, and the study of current and energy oscillation owing to quantum reflections at the SiO_2-electrode interface.[12]

Silicon dioxide has given us the chance to analyze directly the mechanism of electron transport at high fields. For the first time, we begin to grasp the principles of charge transport in wide-bandgap materials with the blessing of experimental confirmation. Perhaps further work on ultra-thin films will let us look directly at the physics of electron transport on the microscopic and quantum levels.

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PHYSICS EDUCATION

In 1986 public attention, which for the last few years had focused on high school physics teaching, shifted to the problems of undergraduate physics education. This was accomplished without a corresponding decrease in attention to the high school situation. Publication of the Proceedings of the Physics Department Chair Conference on the Education for Professional Work in Physics, the testimony of A.P. French and R.R. Wilson to the National Science Board Task Committee on Undergraduate Programs, and the Report of that Committee set the tone for the debate. The June 1986 issue of *Physics Today* was devoted to a detailed look at some of these issues. As of this time, it appears that the NSF appropriation for the coming fiscal year will include a substantial sum for support of undergraduate programs. These programs are likely to be administered by the research directorates, which have not been known in the past for their sensitivity to educational issues. The increase in support to the undergraduate science, mathematics, and engineering programs will nevertheless be welcomed in the college and university community.

Pre-college physics education has not suffered from lack of attention in 1986. The Physics Teaching Resource Agents (PTRA) program, sponsored by the NSF and the American Association of Physics Teachers (AAPT), entered its second year with over 200 outstanding high school teachers trained to work with other teachers in their regions. By mid-1986, the PTRA had offered over 400 regional workshops with over 8000 participants. Among the workshop topics were: the microcomputer as a laboratory instrument, lecture demonstrations, a resource kit for new physics teachers, topics in modern physics, astronomy in the high school curriculum, developing student confidence in physics, and many others. In addition to building teachers' competencies, the workshops help to generate an enthusiasm for physics teaching that has attracted some new teachers and encouraged others to remain in teaching.

Other national and regional workshops and programs have contributed to the overall improved situation in the high schools. Examples of these projects include: The Woodrow Wilson Workshops, the VMI workshops on lecture demonstrations, the Mechanical Universe Project (Cal. Tech.), the Harvard Smithsonian Project STAR (Science Teaching from its Astronomical Roots), the Department of Energy's program of work at the National Laboratories, the Fermilab Conference on the Teaching of Modern Physics, the APS/AAPT College High School Interaction Committee, the AIP/AAPT survey of high school physics teachers, the AIP physics poster distribution, the first participation by the U.S. in the International Physics Olympiad, and many local workshops for teachers.

In spite of our best efforts, severe problems continue to face high school physics teaching. Low salaries, lack of professional recognition, reductions in force to match declining enrollments, use of unqualified teachers, lack of enrollment in physics courses, lack of course offerings, lack of teachers, inadequate teacher preparation programs, poorly designed curricula, and poor working conditions remain problems, but progress has been made on each of these fronts. The relentless decay of the 1970s has been replaced by a moderate improvement in the 1980s, but we still have a long way to go.

Participation in two international activities this year illustrated just how inadequate our efforts are in comparison to the rest of the world. The U.S. team at the Physics Olympiad did quite well in spite of the great disparity between their exposure to physics and that of the students from other countries. In many ways the United States could be characterized as an "underdeveloped" country when it comes to physics education. The National Science Foundation (through AAPT) also sponsored a delegation of 14 high school teachers to the International Commission on Physics Education meeting in Tokyo in August of 1986. Each member of the delegation was to research some aspect of physics education, comparing the situation in the U.S. to that in other countries. Preliminary reports indicate that the teachers discovered significant differences in the quality and quantity of programs, teachers, and students.

Computers in physics education and research in how students learn physics continue to be two of the hottest issues in physics education. Both issues were heavily explored in the two AAPT meetings and in the ICPE meeting in Tokyo. Computers in the laboratory, courseware evaluation, interactive videodisk production and use, the teaching of chaos and other "new" topics on the computer, misconceptions, and artificial intelligence seemed to be among those topics raising the most interest. The spiraling numbers of computers in the schools, the homes, the universities, and the work place will continue to make this an area of prime interest in the coming years. AIP is responding to that need by developing a new journal on computers in physics.

Jack M. Wilson, AAPT

The International Physics Olympiad

The 17th International Physics Olympiad was held in July 1986 at Harrow School in London, England.[1,2] The IPO has now truly become international. In 1985 Canada participated for the first time, and China and the United States joined this year. Altogether 21 countries and 103 students participated.

The U.S. team was organized by Jack Wilson (AAPT and the University of Maryland) while Arthur Eisenkraft (Fox Lane H.S., New York) and Ronald Edge (University of South Carolina) served as Academic Directors. Sponsors

for this year's U.S. Olympiad team included: the American Association of Physics Teachers, The American Physical Society, the American Institute of Physics, the American Astronomical Society, the Optical Society of America, the American Association of Physicists in Medicine, the University of Maryland, Duracell, Ford Motor Company, International Business Machines, Exxon Corporation, John Wiley and Sons, Inc., Worth Publishers, Inc., and the Bond Manufacturing Company.

The selection of the team was a four-step process involving nominations from each region, two qualifying exams, and final selection of the five team representatives from a team of twenty of the nation's best high school physics students who were invited to attend a training camp for the International Physics Olympiad at the University of Maryland from June 30 to July 11, 1986.

The Olympiad itself was made up of two days of examination during a five day period. The first examination day was devoted to a typical paper and pencil theoretical exam consisting of three problems. A practical exam in laboratory and computer work, was given on the second exam day.

The five finalists making up the team were Howard Fukuda, Hawaii; Paul Graham, Colorado; Philip Mauskopf, North Carolina; Srinivasan Seshan, Virginia; and Joshua Zucker, California. Graham, Mauskopf, and Zucker came away with bronze medals in the competition. The USSR won three of the four gold medals with Romania taking the fourth.

The International Physics Olympiad is designed to offer encouragement for the study of physics by publicizing the efforts of team members while involving thousands of students in the preliminary portions of the selection process. The first year was an encouraging start.

Arthur Eisenkraft, Fox Lane High School, New York
and Ronald Edge, University of South Carolina

1. Phys. Today **39**, 51 (September 1986).
2. *Ibid.*, 120 (September 1986).

Conference on the Teaching of Modern Physics

A Conference on the Teaching of Modern Physics was held at Fermilab in Batavia, Illinois, in April 1986. The aim was to promote the use of results of current research in high school physics and introductory level undergraduate courses. This conference had its roots in a similar meeting held at the CERN laboratory in Geneva, Switzerland in September 1984.

Leon M. Lederman, the Director of Fermilab, who has involved Fermilab heavily in science education, and Jack Wilson of AAPT approached the National Science Foundation, which provided support for fifty high school teachers to attend the conference. Drasko Jovanovic, Director of Program Planning at Fermilab, and Gordon Aubrecht, Visiting Fellow at AAPT, were designated as conference coordinators/directors on behalf of the respective organizations.

The specific purpose of the Fermilab Conference on the Teaching of Modern Physics was to promote the use of current topics in physics research, especially particle physics and cosmology, in introductory level physics courses. It was decided to focus especially on particle physics and cosmology, partly because of the location (Fermilab) and partly because a short meeting would not allow a full exploration of all of the areas of modern physics. The steering committee agreed that the introduction of aspects of modern physics into physics courses could serve to enliven physics teaching and would allow the teacher to maintain or even enhance the interest in science that students bring with them to school. This interest in many cases is lost by reliance on conventional texts and lesson plans. As a result many students do not acquire even the minimum skills needed to attend college or university.

Among the speakers were: Howard Georgi, one of the originators of grand unified theories, speaking on GUTs and elementary particles; Christopher Hill on symmetry and group theory; Chris Quigg, author of a recent book on gauge theories and coauthor of an important recent paper on the theoretical basis of the proposed Superconducting Supercollider, on discoveries, tools, and insights from particle physics; David Schramm on the Big Bang and the creation of the universe; Victor Weisskopf on the place of qualitative estimates in physics education; and Clifford Will describing observational tests of general relativity.

The participants were assigned to interest groups on the basis of their responses to the acceptance letter. This approach represented an attempt to assist the production of varied classroom materials on the five topics represented at the conference. The interest groups were further subdivided into six subgroups during the first discussion session: lecture presentations; demonstrations; software and audiovisuals; evaluation instruments; experiment and laboratory activities; and homework problems. The subgroups discussed the choice of topics as well as effective strategies for bringing the materials into high school and beginning undergraduate courses.

The final summary of the written reports from the subgroups was published and distributed to the participants before they left Fermilab. We expect that the ideas in this report will serve as the basis of a concerted effort by the conference participants to develop materials for use in the classroom. Production and testing of teacher-generated materials is taking place between the April meeting at Fermilab and a follow-up meeting to be held at the AAPT/APS joint meeting in San Francisco in January 1987. This follow-up will focus on coordination of the materials produced and should stimulate further work.

The plenary lectures at the Fermilab conference will be published in early 1987 and, along with videotapes of the entire conference, will be available from AAPT.

The Latin American physicists at the Fermilab Conference made great progress in planning the next conference in the series, which will probably be held in Latin America (possibly in Brazil) in 1988. There was also a discussion of the possibility of holding such a conference in Mexico in the near future. The topics for these conferences on teaching modern physics will most likely be condensed matter physics. The International Commission on Physics Education has scheduled a follow-up meeting on condensed matter physics in Munich in the Fall of 1988.

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Support for Undergraduate Physics Programs

The problems in undergraduate physics education resulting from the withdrawal of federal support for undergraduate programs during the early 1980s have received much attention lately (see *Physics News in 1985*, pp. 26–28). Several reports, including "Education for Professional Work in Physics,"[1] which arose from a joint AAPT/APS conference held in 1985, and "The Impact of Undergraduate Physics Programs on the Quality and Quantity of Physics Majors,"[2] a survey organized by the APS Committee on Education, have formed the basis for AAPT and APS public positions on the state of undergraduate science and on defining those areas most in need of support. They have been used in a briefing to the acting White House Science Advisor on the views of the physics community about the health of undergraduate and graduate physics programs and students, and they were undoubtedly a factor in helping to prompt the National Science Board to form a special task committee to look at the state of undergraduate science and engineering education.

On November 20, 1985, A.P. French, President of AAPT, and Robert R. Wilson, President of APS, appeared jointly before the Task Committee. They made a strong case for a renewed NSF undergraduate program.[3] They presented data from the Topical Conference of Physics Department Chairs and from the Survey of Quality and Quantity of Undergraduate Majors and Programs. They pointed out that the United States relies upon the undergraduate science programs to make up for the paucity of science taught at the precollege level. French noted that "our undergraduate programs must carry the burden of trying to bring our students, in the short space of four years, up to the level of the graduates from universities in other technologically advanced countries." Wilson emphasized the "intimate and vital relationship between research and teaching which insures the vigor of science." In addition to their personal remarks, French and Wilson presented a detailed series of recommendations that had been prepared by H. Lustig (APS) and J.M. Wilson (AAPT). The recommendations were based on the two AAPT/APS conferences[2,4] and the APS survey referred to earlier.

The Task Committee submitted its report in March, 1986.[5] It begins: "The nation's undergraduate programs in science, mathematics, and technology have declined in quality and scope to such an extent that they are no longer meeting national needs. A unique American resource has been eroded." The report highlighted the historical situation in which support for science education programs has declined from a high of 46.1% of the NSF budget in 1960 to 5.6% today. Most of the existing support is being funneled into the pre-college areas. The once healthy NSF program in undergraduate science education has dwindled to nearly nothing. As Robert R. Wilson observed: "I believe that the time has come for the resumption of programs and for new initiatives in undergraduate science education." Sidney Drell, current President of APS, wrote strong letters to Erich Bloch (NSF Director) and Roland Schmitt (Chairman of the National Science Board) commending the report and encouraging direct action by the NSF.

On 21 March, the full National Science Board accepted the report and passed the following resolution: "The National Science Board requests that the Director, in close consultation with the NSB Committee on Education and Human Resources, prepare a plan of action to respond to the report focusing on new and innovative program approaches that will elicit creative proposals from universities and colleges, and submit such plan to the Board as part of the National Science Foundation FY 1988 budget process."

The report called for expenditures of 100 million dollars by fiscal year 1989, alloted to laboratory development ($20M), instructional equipment ($30M), faculty development ($13M), curriculum development ($13M), comprehensive improvement projects ($10M), undergraduate research participation ($8M), minority institutions programs ($5M), and long-range planning ($1M). The report estimated the total need for laboratory instrumentation alone to be $2–4 billion, and recognizes that the NSF role must be one of providing seed money and stimulating improvements. Roland W. Schmitt, Chairman of the NSB, Senior Vice President for Corporate Research and Development at General Electric, and former AIP Governing Board member, commented that "We cannot afford to allow the deterioration of our undergraduate science and engineering education system to go unchecked."

A.P. French, Massachusetts Institute of Technology, and Jack M. Wilson, University of Maryland

1. "Education for Professional Work in Physics," AAPT (1986).
2. Phys. Today **39**, special issue on physics education (June 1986).
3. Bull. Am. Phys. Soc. **31**, (February 1986).
4. Proceedings of the Physics Department Chairs Conference on the Education of the Physicist, AAPT (1984).
5. Undergraduate Science, Mathematics, and Engineering Education, a report of National Science Board Task Committee, National Science Foundation, March 1986.

PLASMA AND FUSION PHYSICS

Progress Towards Breakeven on the Tokamak Fusion Test Reactor

Much of the experimental program during the last year on the Tokamak Fusion Test Reactor (TFTR) at Princeton University has been focused on searching for enhanced energy confinement regimes to improve the prospects for obtaining approximate energy breakeven in TFTR and thermonuclear ignition in a future Compact Ignition Tokamak. A number of smaller tokamaks have demonstrated techniques for improving energy confinement, but none of these had yet been successfully applied to the current generation of large tokamaks: TFTR, the Joint European Torus (JET), and the Japanese JT-60. During 1986 two different approaches achieved success in different plasma regimes in TFTR.

In the first approach, a high-speed pellet injector developed at the Oak Ridge National Laboratory (ORNL) was used on TFTR to produce very high density plasmas with strongly peaked density profiles. Multiple 3–4 mm pellets of frozen deuterium were injected at speeds of 1250 m/s. These pellets penetrate ohmically heated TFTR plasmas deeply, depositing their deuterium fuel near the center of the discharge, effectively diminishing the effect of particle recycling at the plasma edge. At central ion and electron temperatures of 1.3 keV, record $n\tau$ (central density times global energy confinement time) products of 1.5×10^{20} s/m^3 were obtained,[1] nearly doubly the previous best result obtained in the Alcator C tokamak at MIT.

The second successful approach employed on TFTR also involved the reduction of edge particle recycling, but used a different set of techniques. The first material surface a tokamak plasma encounters is usually a system of graphite tiles, constructed to handle the high power densities in the plasma scrape-off without damage, and without the introduction of deleterious amounts of impurity ions into the plasma. The surface of this graphite "limiter" typically becomes filled with deuterium, and recycles lost particles back to the plasma with nearly 100% efficiency. The TFTR team pursued experiments in which long-pulse helium and low density deuterium discharges were used to deplete the limiters of trapped gas. When neutral beam injection was employed to heat plasmas with outgassed limiters, very favorable results were obtained. The 95-keV neutral deuterium atoms injected in these experiments penetrated to the core of initially low density TFTR plasmas, resulting in very peaked density profiles, and excellent confinement properties.

In the best discharges, at a plasma current of about 1 MA, the total stored energy exceeded the prediction made using previous scaling laws by a factor of up to 3. The *d-d* neutron production rate reached a peak of 9×10^{15}/s, with a total injected power of 17 MW. Since the thermal electron component in tokamak plasmas usually has the poorest thermal insulation, it is very satisfactory that these discharges also showed an improvement by up to a factor of 2 over scaling-law prediction in regard to electron stored energy. The most spectacular feature of these plasmas is the central ion temperature, which reached 20 keV. The $n\tau$ product was slightly over 10^{19} s/m^3. For comparison, the record ion temperature achieved[2] in the PLT tokamak at Princeton in 1980 was 7 keV, with an $n\tau$ of 10^{18} s/m^3.

These results imply favorable prospects for future progress on TFTR towards the goal of approximate energy breakeven. One of the original goals of TFTR, to achieve $n\tau = 10^{19}$ s/m^3 at an ion temperature of 10 keV, has already been exceeded. An ORNL pellet injector with increased capability was recently installed, and is being commissioned. This injector will allow investigation of pellet injection into higher-power TFTR discharges. The use of rf power in the ion cyclotron range of frequencies is planned to supplement neutral beam injection, to heat the center of the very high density discharges obtained with pellet injection. An intriguing feature of the high-ion-temperature discharges is that the ion temperature, neutron emission, and total stored energy are all still rising at the end of the half second beam pulse currently available. The Lawrence Berkeley Laboratory, which built the original neutral beam system, is providing TFTR with a set of long-pulse ion sources which will produce 2-s, 27-MW pulses at 120 keV. Furthermore, experiments in which the plasma current was ramped at 1 MA/s have shown that global confinement improved with plasma current above the levels which could be obtained at 1 MA. The ultimate current capability of TFTR (3MA), may thus be accessible in this regime through the use of the long-pulse beams, with an associated further improvement in confinement.

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Recent Experiments in Inertial Confinement Fusion

The inertial confinement approach to fusion relies on compressing and heating a mixture of deuterium and tritium (DT) contained in a small capsule to ignition conditions. The driving energy can be provided by focused laser or particle beams, but most present experiments are being conducted with short-wavelength high-power lasers.

The full realization of the potential benefits of inertial confinement fusion (ICF) requires the attainment of high gain, which means obtaining a yield of 500–1000 MJ using a multi-megajoule driver. The attainment of ignition and breakeven will be an important scientific achievement, but

high gain is required to provide the large fluxes, x rays, and neutrons that can have many military and civilian applications as well as to experimentally establish the scientific feasibility of economic ICF power generation.

To achieve high gain with 5 to 10 MJ of driver energy, the requirements on the capsule implosion are stringent. Several milligrams of DT fuel must be compressed to a density of about 200 g/cm^3 and a density-radius product (a parameter analogous to the confinement parameter $n\tau$ used in magnetically confined fusion) of about 3 g/cm^2. The thermonuclear burn must be initiated in a high temperature (3–5 keV) central hot spot (constituting a few percent of the fuel mass); the alpha particles generated there will deposit their energy locally and initiate burn in the cold, surrounding dense main part of the fuel. The implosion velocity of the spherical capsule must be uniform to within about 1% to provide symmetrical compression and to minimize contributions to fluid instability break-up of the ablator. To allow the lowest driver energy, the driver-target coupling should be very efficient and the fuel preheat low. Preheat from early shocks, x rays, and hot electrons must be minimized to keep the fuel cold during compression. A combination of fluid instability and pre-heat issues makes it necessary to gradually shape the driver pulse temporally.

There are two basic approaches to imploding ICF pellets; direct and indirect drive. In the direct drive approach, the driver energy is focused directly onto the fuel pellet to heat and ablate the outer regions and drive the implosion. In the indirect drive approach, the driver energy is converted to a flux of soft x rays which in turn drives the fuel capsule.

One thrust of worldwide ICF research is in the area of laser-plasma interaction physics: absorption, energy transport and partitioning, and the conversion of driver energy to x rays. In particular, there has been progress in understanding the scaling of these processes to plasma sizes relevant to high-gain ICF targets. The requirements and techniques needed to provide symmetrical implosions that are not fatally degraded by the growth of fluid-dynamic instabilities is also a major area of study. Diagnostic techniques for accurately measuring the density and temperature achieved in compressed fuel are being developed.

The 100-kJ, 100-TW class Nova neodymium-glass laser facility at the Lawrence Livermore National Laboratory has been brought into full operation for experiments in two target chambers with frequency-converted 0.53 and 0.35 μm wavelength light. It has allowed the extension of short-wavelength laser-target interaction and implosion experiments to scales more relevant to ultimate high gain targets. Recent basic laser-target interaction results include quantification of x-ray conversion efficiency as a function of laser intensity.

Nova has produced a record ICF fusion yield of 10^{13} neutrons (corresponding to a fusion gain of 0.18%) with simple, directly driven DT filled glass microshells. These targets are intended as sources of 14-MeV neutrons for advanced neutron diagnostic development.

Results of the first indirectly (x-ray) driven implosions conducted on Nova are consistent with a calculated confinement density-time in the range of $1.5–3\times10^{14}$ s/cm^3 at a measured fuel ion temperature of 1.5–1.7 keV. This was achieved with 18 kJ of 0.35 μm light. The results of both of these experiments are in close agreement with pre-experiment computer simulations. Substantial improvement in target performance is expected in the future using the full (50–80 kJ, 0.35 μm, 1.5–3 ns pulses) capability of Nova and optimized targets.

A major comprehensive review of the U.S. ICF program was completed by a technical review committee convened under the auspices of the National Academy of Sciences.[1] The previous review committee (1979) had cited several research goals as being important for progress in ICF: (1) the need to go to shorter wavelength lasers; (2) a vigorous laboratory program to understand issues of coupling of laser energy to capsules; (3) vigorous prosecution of a program to investigate design characteristics of efficient ICF targets, and more attention to target fabrication; and (4) research into ion drivers. In its review, the (current) Committee found that the ICF program has made substantial progress in response to all these recommendations.

The following are a few of the excerpts of the executive summary of the March 1986 Final Report. " Since the 1979 Review, it has become clear that the large numbers of hot electrons generated by long-wavelength 10-μm CO_2 laser radiation preheat the targets too much to permit high gain implosions. The CO_2 laser work at Los Alamos National Laboratory (LANL) has therefore been terminated.

Hopes that target coupling would be improved at shorter laser wavelengths have been confirmed by experiments at the University of Rochester (UR) and Lawrence Livermore National Laboratory (LLNL) with doubled (0.53 μm), tripled (0.35 μm), and quadrupled (0.25 μm) Nd:glass laser radiation. The plasma physics of the improved absorption is now understood quantitatively, as shown by the agreement between predictions and observations.

The Nova laser has been completed and is able to deliver 60 kJ of 1.0 μm radiation, and 25 kJ of 0.35 μm radiation. A KrF laser that produces 10 kJ of 0.25 μm radiation directly has been constructed at Los Alamos. Techniques must be developed to shorten the natural 500 ns pulse length of KrF to the few ns needed for driving a target.

A promising new method to reduce plasma instabilities and improve symmetry, induced spatial incoherence (ISI), applicable with broadband lasers, has been demonstrated at the Naval Research Laboratory (NRL). The 24-beam Omega laser has been completed at UR and will serve United States' main direct drive facility in the immediate future. Fusion, Inc., the only private company in the ICF program, has made and continues to make important contributions to target fabrication and to methods for investigating target plasma physics.

The PBFA II light ion accelerator at Sandia National Laboratories (SNL) is potentially capable of depositing 1 to 2 MJ on target in 10 ns. The major construction of this facility is complete and initial testing of the electrical system is under way. To focus an ion beam on target with suitable pulse shaping will require a considerable amount of additional work."

Although the NAS Committee did not address heavy-ion accelerators for ICF, recent experiments and analysis indicate that greater beam currents can probably be transported and focused than previously thought. This has significantly increased the possibility that a heavy ion driver in the 5 to 10 MJ range can be built for a cost significantly less than previously believed.[2]

The prospects for the eventual success of ICF have never been brighter.

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Recent Free Electron Laser Experiments

There are several areas within the field of plasma physics that can benefit from a high-power, efficient source of tunable radiation. Magnetic mirror machines, for example, require high power sources of microwaves to create thermal barriers and end plugs which limit axial ion loss. Recently, there have been suggestions that electron cyclotron resonance heating of tokamaks could have a number of advantages as a heating technique, and may also be able to produce a current drive enabling steady-state tokamak operation. In both of these applications, tunability of the microwave source would be an asset.

At much shorter wavelengths (250–1000 nm), laser-driven inertial confinement fusion also requires a high power source of coherent radiation. All of these sources share two requirements: they must be efficient and they must be inexpensive. Recent experiments hold out promise that the free electron laser (FEL) can meet these diverse and demanding needs.[1]

The FEL directly converts the kinetic energy of a relativistic electron beam into coherent radiation. This conversion is accomplished by passing the electron beam through a spatially periodically reversing magnetic field (called an undulator) which allows energy transfer between the electron beam and a co-propagating radiation field. The successful operation of an FEL requires the maintenance of a very precise relationship between the phase of the radiation field and the position of the electron relative to the periodic magnetic field of the wiggler.

The wavelength of peak optical/microwave gain is determined by the electron beam's energy, the strength of the magnetic field, and the period over which the magnetic field reverses. These parameters are design variables, so that in principle any operating wavelength may be chosen, hence the FEL has a broad range of applications. High efficiency is possible because the thermal loss channels of conventional lasers not present in the FEL.

It was demonstrated long ago that the basic FEL principle was valid, but it was only within the past year that very high conversion efficiencies at microwave frequencies were demonstrated at Lawrence Livermore National Laboratory. The LLNL experiment, called ELF, was configured as an amplifier: the output of a conventional 20 kW (peak), 34.6 GHz magnetron was directed through a 3-meter-long undulator along with an 800 A, 3.5 MeV electron beam produced by the Experimental Test Accelerator to yield an amplified microwave signal.[2] Initial experiments produced 40 dB of gain and a peak output power of 180 MW for a net 6% extraction efficiency. This performance was achieved with only 1.4 m of undulator. Long amplifiers did not increase the output power because the 6% energy extraction was enough to destroy the necessary phase relationships between the electrons and the microwave field.

The ELF undulator can, however, be tapered; that is, the undulator's magnetic field can be reduced so that, in principle, phase synchronism can be preserved even when substantial amounts of the electron beam's kinetic energy is extracted. When the Livermore undulator was tapered, the output power increased from 180 MW to over 1 GW with a net conversion efficiency of over 35%.

Experiments at Los Alamos National Laboratory[3] (10.6 μm wavelength), the University of California at Santa Barbara[4] (400 μm), Stanford University[5] (2.6 μm), TRW/Stanford[6] (1.6μm), and Orsay[7] (0.6μm) have demonstrated that FELs can work at optical wavelengths, albeit thus far at considerably reduced efficiencies. All of these experiments were configured as oscillators. The LANL experiment was able to demonstrate a considerable tuning range, demonstrating the versatility of the FEL.

The success of all of these experiments is very encouraging, but there are many areas of both FEL physics (in terms of wavelength and power scaling) and accelerator physics which must be pursued over the next few years in order to demonstrate that the FEL is truly an inexpensive, efficient, and reliable source of coherent radiation.

D. Prosnitz, Lawrence Livermore National Laboratory

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Relativistic Plasma Waves and Particle Acceleration

In the continuing search for the fundamental building blocks of matter, particle accelerators have become indispensable to physicists since the invention of the cyclotron in the 1930s. In contrast to their earliest table-top ancestor, today's synchrotrons are some of the largest machines ever built, with circumferences measured in kilometers rather than in meters. It is natural to ask, therefore, if it is possible to achieve far higher accelerating gradients than the current typical gradient of 20 MeV/m, thereby permitting machines of ever-increasing energies, but reasonable size and cost, to be built.

In any particle accelerator scheme, the basic requirement for obtaining particles with ultrahigh energies is an intense longitudinal electric field that interacts with particles for a long time. Since highly relativistic particles move at nearly the speed of light (c), the energy gained by the particles is maximum if the accelerating field is made to propagate with the particles. Extremely large electric fields propagating with phase velocities close to c can be produced by space charge waves in a plasma. The maximum electric field of such a so-called relativistic plasma wave is approximately equal to the square root of the plasma electron density per cm^3. For instance, the longitudinal electric field of a relativistic plasma wave with a background density of $10^{16}/cm^3$ can be as high as 10^{10} V/m. Such waves can be either laser-driven, as in the Plasma Beat Wave Accelerator,[1] or excited by a short bunch of relativistic electrons, as in the Plasma Wake Field Accelerator.[2] In both cases the plasma acts as a single-mode, slow-wave cavity, in which the wavelength of the accelerating wave is typically several hundred μm, as compared to 10 cm in linacs. This hitherto unexplored regime of parameter space may hold the key to the possible miniaturization of particle accelerators.

In the Plasma Beat Wave Accelerator, two laser beams of slightly different frequencies resonantly beat in a plasma, in such a way that their frequency and wavenumber differences correspond to the plasma wave frequency and wavenumber. The amplitude modulated beat wave exerts a periodic ponderomotive force on the plasma electrons, causing them to bunch.

The resulting space charge wave has a phase velocity that is equal to the group velocity of the beating waves. If the laser frequencies are much higher than the plasma frequency, the group velocity is nearly c. If an electron is now injected with a velocity close to this, it can be trapped and accelerated by the plasma wave much in the same way as a surfer riding an ocean wave.

In the plasma wake field accelerator, a high-current but low-voltage electron bunch is used to excite the plasma wave. The phase velocity of this plasma wave (like the wake of a boat) is tied to the velocity of the driving bunch, which is close to c. This wave then accelerates a trailing low-density bunch to high voltage or energy. The plasma thus acts as a transformer, increasing the voltage at the expense of current. The key to obtaining a high transformer ratio is to use a slowly ramped but sharply truncated driving bunch.

In both the beat wave and the wake field cases, the trick to inhibiting most of the usual laser or beam plasma instabilities is to use a driver pulse that is only a few picoseconds long. To simulate the plasma wave excitation by a finite cross-section driver pulse and to optimize the energy extraction by the accelerating beam, extensive two-dimensional particle simulations have been carried out.[3,4] Theory predicts, and the simulations confirm, that the maximum energy that the particles get is limited by either the particles. Eventually outrunning the wave (dephasing) or by the pump depletion of the driver.

Experiments are underway at UCLA, Rutherford Laboratory (U.K.), ILE (Japan), INRS (Canada) and elsewhere to demonstrate the excitation of the relativistic plasma wave by the laser beat wave in a reproducible fashion and to demonstrate controlled acceleration of injected test particles. In a recent UCLA experiment, the relativistic plasma wave was excited by beating the 9.6 μm and 10.6 μm lines of a CO_2 laser, with a modest intensity of 2×10^{13} W/cm^2 in a $10^{17}/cm^3$ density plasma.[5] The plasma wave electric field was inferred from Thomson scattering of a probe laser beam to be 10^3 MeV/m, a substantial improvement over the current benchmark gradient for accelerators. A new mechanism which saturates the beat-excited plasma wave in this parameter regime was discovered.[6] The relativistic plasma wave saturates, on the time scale of a few picoseconds, by coupling to other plasma modes which have a much lower phase velocity, via an ion ripple due to stimulated Brillouin scattering of the laser beams. A scaled-up experiment which will demonstrate controlled acceleration of injected electrons is currently underway at UCLA. Experiments on the wake field concept are planned at UCLA and at Wisconsin.

Finally, it is worth mentioning some of the other applications of this new research area in plasma physics. The beat-excited plasma wave may be used as an intense submillimeter wave undulator for generating tunable, short-wavelength radiation using only a modest energy electron beam. Radial electric fields of a relativistic plasma wave with a transverse dimension on the order of a wavelength can be very intense and may be useful for focusing high-energy particles in a linear collider. A beat-excited plasma may also prove to be an ideal system for studying plasma evolution from a deterministic state into turbulence.

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Transport Near The Onset of Chaos

Recent research has shown that systems with only a few dynamical variables can behave in surprisingly complicated ways.[1] A set of three coupled first-order differential equations, such as would describe a frictional pendulum with time-periodic forcing, is sufficient to give motion which is essentially as unpredictable as the proverbial toss coin. Similarly, an energy-conserving, or Hamiltonian, system with dynamical variables (two degrees of freedom) is typically chaotic.[2] Hamiltonian systems with completely regular or integrable motion can be devised, but virtually any perturbation of such a system gives a complicated mixture of regular and chaotic trajectories.

The understanding of these systems is fundamental to designing fusion devices such as tokamaks and stellerators, building efficient accelerator storage rings, determining the stability of the solar system, estimating chemical reaction rates, and many other problems.[2]

An important example is the confinement of charged particles by a magnetic field. When the field is strong, the particle dynamics reduce to two degrees-of-freedom: gyration about the field line can be averaged out and, basically, particles follow field lines.

Since field lines never end, the confinement of particles require a toroidal configuration; if the torus is perfectly axisymmetric there is a constant of motion, associated with the symmetry, which restricts the lines to two-dimensional toroidal surfaces. Such configurations are never realizable, partly because it is impossible to build perfectly axisymmetric field coils, but more generally because of symmetry-breaking collective motions of the plasma. These imperfections cause some of the field lines to wander through three-dimensional regions of space in an extremely complicated, irregular or stochastic way. If these regions extend to the walls of the confinement device, particles will be rapidly lost.

If the chaotic regions filled the entire confinement vessel, a diffusion coefficient could be obtained from a reasonable statistical hypothesis.[3] However, the imperfections may be small enough that many field lines remain confined; on the other hand, a significant fraction of the orbits are often chaotic.

In this transition stage the notion of smoothly diffusive motion must be abandoned; chaotic trajectories linger for long periods in the neighborhood of invariant tori, and are impeded by the remnants of barely destroyed tori.[4] These remnants are called "cantori" because they are invariant Cantor sets (a torus minus an infinitely long ribbon which winds around with irrational rotation number). The flux of trajectories through a cantorus is a well defined quantity and can often be very small even though the cantorus itself occupies zero area.[5]

Between the cantori, there are periodic orbits which result from resonances between frequencies of each degree-of-freedom. These come in stable-unstable pairs. Near stable orbits there are encircling invariant surfaces which ensure local stability. By contrast, the unstable orbits have two-dimensional stable and unstable manifolds which form a "separatrix." The separatrix encloses the stable orbit, and the whole structure is called a "resonance." The volume of the resonance and the flux of trajectories entering and leaving it through the separatrices are well defined quantities.[5]

Numerical evidence indicates that resonances fill all of phase space, except that portion filled with invariant tori.[5] This implies that phase space is divided into states, which are the resonances, separated by "fences," the separatrices and cantori, with gates or "turnstiles" with sizes determined by the flux. Transitions from state to state can be treated statistically because a chaotic orbit diverges from its neighbors exponentially in time: initially close trajectories have wildly different futures. The divergence rate is much faster than the transition rates between resonances; thus successive transitions are nearly statistically independent.

Transition times from states near an invariant torus are arbitrarily long. This leads to the prediction that correlation functions decay algebraically with time.[6,7]

This theory of transport successfully predicts the escape times near onset of chaos in perturbed tokamaks. It also has been applied to the calculation of unimolecular chemical reaction rates and other situations. Numerical experiments to confirm the algebraic decay of correlations are difficult and time consuming, but so far confirm the theory.

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POLYMER PHYSICS

Polymer physics now encompasses research in condensed matter physics, physical chemistry, and materials science on substances composed of very large molecules. While synthesis of new polymeric materials falls outside of what is traditionally termed polymer physics, progress in polymer physics research has depended crucially, in many instances, on the availability or synthesis of macromolecules of specially-tailored molecular weight, topology, stereoregularity or some other structural characteristic. The following articles discuss recent developments giving examples where this is the case: emission spectroscopy, theoretical polymer physics, and polymer surface forces. The choice is illustrative, not comprehensive.

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Polymer Photophysics

Emission spectroscopy of polymers—the observation of fluorescence or phosphorescence after excitation of electronic transitions by visible or uv light—has received much attention recently. Polymer photophysics has been the subject of two books[1,2] and several major symposia. This apparent surge in interest is well-founded, since this technique may have a major impact on the understanding of the static and dynamic properties of polymer systems. This is possible because of the wide applicability of the technique which requires only that some chromophore (an entity capable of absorbing and emitting ultraviolet or visible light) be present in the system. This may be a naturally occurring chromophore, as with the phenyl unit in polystyrene, or it may be a label attached to a polymer lacking chromophores. Analysis may involve one or more types of measurement: monomer or excimer fluorescence, fluorescence depolarization, fluorescence recovery after photobleaching, energy transfer or migration, phosphorescence, luminescence quenching, and transient luminescence measurements.

Emission spectroscopy has proven particularly useful in studying phase separation in multicomponent polymer systems. Morawetz pioneered the use of energy transfer and excimer emission to study phase separation.[3] Recently, Monnerie's group has shown that reduction (quenching) of fluorescence of anthracene-labeled polystyrene (PS) by poly(vinylmethylether) [PVME] is at least as sensitive as excimer fluorescence to phase separation.[4] They have also shown that fluorescence emission is as well-suited as small-angle neutron scattering (SANS) in detecting the earliest stages and kinetics of phase separation. Furthermore, fluorescence emission has an advantage over SANS when isotope effects are present. Emission spectroscopy is also being used to study phase behavior in more complex systems, including colloidal polymer particles[5] and block copolymers and block copolymer/homopolymer blends.[6]

Solution structure and interpenetration of polymer coils has been studied by Morawetz[3] and more recently by Torkelson.[7] Measurements of diffusional processes are possible with emission spectroscopy. Fluorescence recovery after photobleaching an area can be used to measure self-diffusion of polymers in solutions and melts; results obtained in entangled polymer systems are in good agreement with predictions of scaling concepts.[8] Horie and Mita,[9] and Torkelson *et al.*[7] have used phosphorescence quenching in measuring interactions in polymer solutions which may be diffusion-limited. The technique is particularly well-suited for simulating (and isolating) interactions occurring in polymerization processes when polymer entanglement is important.

Mobility and dynamics of polymer solutions and melts have also received considerable attention. By employing excimer fluorescence[10] Winnik and co-workers have done an extensive study of the rate at which the ends of a long chain come into contact with one another (cyclization) for polymers in dilute solution. Fluorescence anisotropy decay has been employed in Monnerie's group[11] to determine orientation dynamics in polymer melts. For anthracene-labeled polybutadiene, the temperature evolution of the orientation of the chain backbone is the same as for the mechanical properties, providing evidence for the connection between the glass transition and local molecular processes.

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Polymer Theory: Crossover and Criticality

Most observed polymer solution properties actually are observed in regimes short of the infinite chain limit, since the chains in practice are of finite length. The description of such crossover regimes presents a challenge in theoretical polymer

physics. In addition, the critical properties of phase separation of polymer-solvent systems and blends have so far been interpreted only within the mean field formalism of Flory and Huggins. Experimental data on these systems clearly suggest that the polymer density fluctuations play a significant role in their critical behavior.

The simplest problem of long-standing interest in polymer science is the calculation of the mean square end-to-end distance, R^2, of an isolated polymer chain of finite length with excluded volume interaction of arbitrary strength. The archtypical model for this problem is the two-parameter model where the polymer is a random-flight chain with the short-ranged interaction between the segments. The dimensionless interaction parameter of this model, called z, equals w, the strength of the excluded volume effect, times the square root of L, the contour length of the chain.

In the absence of excluded volume effect, R^2 is approximately equal to L. There have been many methods proposed to calculate R^2 for any arbitrary value of z.[1] The results from these schemes differ from each other depending on the severity of the intrinsic approximation of the method employed. Worse yet, because the approximations are uncontrolled, there is no way of estimating the uncertainties. It is therefore desirable to perform an accurate calculation of R^2 in order to (a) learn how to describe a finite chain length in a systematic way, (b) assess the extent of the deviations of the various approximate schemes, and (c) find how close the two-parameter model is to reality. Towards this goal, Muthukumar and Nickel have derived a relatively long perturbation series for R^2 in powers of z by evaluating the leading six coefficients.[2] They have obtained R^2 numerically for the full range of z.[3] In addition, they have performed a systematic error analysis and found that their result is accurate within 0.5%. An entirely different analysis[4] of their sixth-order series is in agreement well within the estimated uncertainty. The various previously known formulas deviate from these results significantly. In order to compare with experimental data, similar lengthy calculations need to be done for several quantities such as virial coefficients, radius of gyration, etc.

Although much progress has been made in the theory of polymer physics, polymer science continues to be a rich mine of diverse and challenging theoretical problems. Experiments designed to test these developments clearly will rely on polymers of very well-defined structure.

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Polymer Surface Forces

Direct measurements of intermolecular forces by the technique of bringing two macroscopic surfaces into close proximity and measuring the force exerted between them have a long history.[1] Rapid progress has been made in the last decade since the development by Israelachvili of a version of the apparatus adaptable to studies of colloid, surface and polymer physics.[2] This tool can provide information on surfaces in a liquid, or other desired ambient state in contrast to ultrahigh vacuum techniques. Smooth, basal, cleavage planes of muscovite mica are the substrate surfaces upon which can be deposited other substances between which one would like to measure surface forces. More than half a dozen groups around the world are now pursuing work with this device.

Introduction of this device to polymer studies was made first by Israelachvili and co-workers,[3] though the first polymer experiments readily amenable to theoretical interpretation were made by Klein.[4] We shall mention here only recent developments in the study of forces between absorbed layers of polymers on mica immersed in solvent. These results are directly applicable to understanding the phenomena of polymer stabilization of colloidal dispersions described in Napper's book;[5] an introduction to some other lines being pursued with this device are described in Israelachvili's book.[1]

Klein and co-workers have explored two systems in some detail: polystyrene (PS) in cyclohexane near the theta point[4,6,7] and polyethylene oxide in good solvents, aqueous[8] and organic.[9] In the PS system it has become clear[6] that the attractive forces observed near the theta point consist of two contributions: interactions of polymer segments in the solvent (osmotic) and individual macromolecules spanning the gap between the surfaces (bridging).

Within the last year, Tirrell and co-workers have published two experimental efforts in part designed to clarify this situation. Using block copolymers of 2-vinyl pyridine, which adsorbs more strongly than PS to mica and styrene, they have been able to affix PS cilia to the mica surface and eliminate bridging.[10] They have shown that there are no attractive forces between these PS layers at or above the theta points. They have also discovered some interesting configurational properties of adsorbed block copolymers. At the other extreme, they have examined PS only on one mica surface brought into contact with a bare mica surface.[11] This enables a direct mechanical estimate of the sticking energy of polymer to mica.

Other important developments in this area have been on the side of theoretical interpretation. Scheutjens and Fleer[12] have published results of their lattice model calculations of the force profiles, while Pincus and co-workers[13] have examined the problem from the point of view of gradient theory. Gast and Leibler have used a self-consistent field calculation to examine polymers in solution between the adsorbed layers.[14] Klein and Luckham have recently taken a closer look at the interpretation of the range of the forces measured in these experiments.[15]

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VACUUM PHYSICS

GaAs on Si: Progress and Opportunities

In the area of semiconductor technology, a relatively new material, gallium arsenide (GaAs), is emerging. Gallium arsenide promises much higher performance than the most common and well established material, silicon (Si). The growth of high-quality GaAs on a Si base (or substrate) by a process known as molecular beam epitaxy (MBE) promises to revolutionize telecommunications and computer chips.

The fusion of these two material systems yields a hybrid which utilizes the advantages of both GaAs and Si. The highly developed Si-based chip technology and the superior quality, thermal conductivity, strength, and size of Si substrates provide an ideal foundation for semiconductor devices. On the other hand, electrical signals travel through GaAs much faster than through Si, and GaAs emits light when stimulated by electrical signals.

This combination of GaAs and Si generates some exciting possibilities. Monolithic integration of GaAs and Si circuits will permit chip-to-chip communication via light signals. The viability of this technology has recently been confirmed with reports of room temperature operation of GaAs lasers on Si.[1,2,3] High current GaAs devices can be used as output/interconnect drivers for low current Si NMOS (*N*-channel metal oxide semiconductor) transistor logic circuits to increase the overall speed of computers. Demonstration of this hybridization[4] has aroused the interest of industry.

The surge of activity in this technology has resulted from recent solutions to two serious problems. The first of these obstacles is that the interatomic spacing of GaAs is 4% larger than that of Si. Because the growth of the thin film of semiconductor (epitaxial layer) mimics the size and structure of the substrate, this mismatch in spacing causes strain which generates imperfections. These structural flaws, called misfit dislocations, degrade the electrical and optical performance of devices such as transistors and lasers. The solution to this problem lies in the proper choice of substrate orientation (the way in which the substrate is cut from the bulk crystal or boule) and the growth of dislocation barriers.[5] Confirmation of the defect control offered by these techniques has come from excellent results obtained from heterojunction bipolar transistors grown on Si.[6] These transistors, which have unique electrical transport characteristics, are very sensitive to defects. The second obstacle is encountered in obtaining a coherent arrangement of atoms of a polar material (in this case GaAs) on a nonpolar substrate (Si). By MBE it is possible to deposit a single layer of As or Ga atoms on the substrate. This crystal growth process utilizes the precision-controlled evaporation of materials onto a substrate in ultra high vacuum. This technique provides an elegant solution to this problem by ensuring proper positions for Ga and As atoms.

The potential for GaAs-on-Si technology is vast. Preliminary results have shown that another material system, mercury cadmium telluride, which has specialized applications as a light detector, can be grown on a GaAs-coated Si substrate. Since the signal processing circuitry could be put on the Si substrate, improved optical detectors would result.[7] Another fascinating possibility is the use of calcium fluoride, to serve as an insulator between layers of GaAs allowing three dimensional circuits to be realized.[8] Utilizing the high speed of GaAs to perform time critical functions while using Si to perform the less demanding ones promises to alleviate bottlenecks which now limit overall data processing and computer system speeds. Indeed GaAs on Si offers the best of both these material systems and promises to surpass them in high speed electronic and opto-electronic applications.

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Surface States in Real Space

Surface scientists have long tried to understand the interplay between surface geometric and surface electronic structure. Traditionally, these two have been studied in separate experiments with the link being provided by theory. In such studies experimental information is averaged over the probe area of the experiment and a quantum mechanical theory is employed to provide an understanding at the atomic level. In a series of experiments on silicon surfaces, Scanning Tunneling Microscopy (STM) has been used for the first time to bridge the gap between geometric and electronic structure with atomic resolution.

STM images obtained with different voltages between the tip and the sample are generally different because only the wave functions with energies between the Fermilevels of the tip and the sample contribute to the tunneling process. As the voltage difference increases, the tunneling conductance will experience a stepwise increase each time a new quantum state starts to contribute to the tunneling process (provided that the sample-tip distance is held constant). Thus, the energies at which surface states occur can be determined by measuring current-versus-voltage (I–V) curves. In order to create 2-D images of surface states we have developed a new method, Current Imaging Tunneling Spectroscopy (CITS), to separate spectroscopic information from other contributions, in particular the surface geometry.[1] This new method circumvents several of the problems encountered by previous workers attempting to image surface electronic structure (see Fig. 1).

The basic problem is to separate the geometric from the electronic contributions to the STM images. For a given model a purely geometric image can easily be calculated by superposition of atomic charge densities in which surface states are not considered. Surfaces of constant charge density at the position of the tip reveal what the STM image should look like in the absence of surface states. Experimentally it was found that under suitable bias conditions the tip very closely follows such purely geometric contours. The CITS technique enables us to measure complete I–V curves in each pixel of an STM image while the tip independently follows the geometric contours. In this way the variations of tunneling current with lateral position directly reveal differences in surface electronic structure. With this technique we have succeeded in obtaining the first spatially- and energy-resolved images of the filled and empty surface states of the

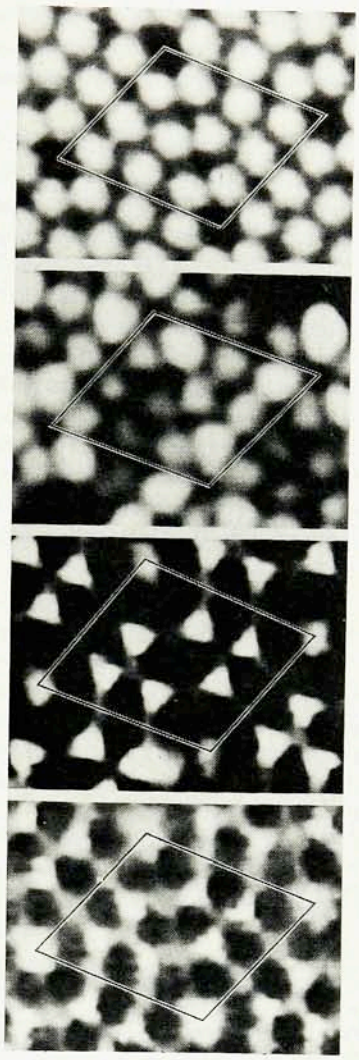

FIG. 1. A scanning tunneling microscopy image of the (a) silicon (111) 7×7 surface, (b) adatom dangling bond state with an energy 0.35 eV below the Fermi energy, (c) restatom dangling bond state at 0.9 eV below the Fermi energy, and (d) backbond state at 1.8 eV below the Fermi energy. One 7×7 unit cell is outlined in each frame.

Si(111)-(7×7) and Si(001)-(2×1) surfaces with atomic resolution.

The observed surface states agree very well with results known from photoemission and inverse photoemission experiments. In addition we were able to directly correlate these surface states with specific atomic features in the surface structure. Thus, we observed a filled surface state close to the Fermilevel associated with the dangling bond orbitals of 12 adatoms (atoms adsorbed on a surface) in the Si(111)-(7×7) unit cell. In addition we found 7 orbitals 0.8 eV below the Fermilevel associated with broken bonds on the threefold coordinated silicon atoms (called restatoms) in the underlying surface layers. The location of these states further correspond with atomic features of the model proposed by Takayanagi *et al.*[2] Recent theoretical work by Northrup on small subunits of the (7×7) cell is in good agreement

with these results.[3] The location of the restatoms states has provided direct, real space evidence for the presence of a stacking fault in the double layer directly underneath the adatoms in one half of the (7×7) unit cell.

The Si(001)-(2×1) surface reconstructs by forming dimer bonds between adjacent surface atoms, thus reducing the number of broken bonds by a factor of 2. We have observed both the bonding state, located on and between the dimer atoms, and the antibonding orbitals, located on the outer ends of the dimers. Some of the dimers are buckled. On these we find that the bonding state is strongly localized on the "up" side of the dimer, whereas the antibonding state is found on the "down" side. This remarkable spatial separation of bonding and antibonding orbitals is strong evidence for charge transfer from the down to the up atom. The possibility of such a charge transfer in conjunction with buckling has been a controversial subject for many years and explains the pronounced surface state bandgap. Our experimental findings are in good agreement with the theoretical work by Ihm *et al.*[4]

In addition to the electronic features associated with the regular surface structure we have also observed a variety of localized electron states introduced by atomic scale structural defects. The study of such defects will be of importance in efforts to improve our understanding of many defect-dominated physical phenomena, such as Schottky barrier formation, surface chemistry (steps, kinks) and oxide dielectric breakdown. Most importantly, surface geometric and electronic structure can now be studied simultaneously at the atomic level.

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Studies of Surface Phonons by Electron Energy Loss Spectroscopy

In both molecular and solid state physics, the study of vibrational modes provides crucial information on the nature of the chemical bonding and subtle aspects of structural geometry. Vibrational spectroscopies employ the absorption and inelastic scattering of photons, or of particle probes such as neutrons.

For the same reasons, one wishes to study vibrational motions of atoms in, or molecules on, crystal surfaces. Conventional spectroscopies function in only limited circumstances because it is very difficult to extract a signal from a monolayer of material against the large background from the crystal upon which the monolayer resides.

Electrons of suitable energy (1–500 eV) are a powerful surface probe, since their mean free path in matter is only three or four interatomic spacings. Electrons backscattered from surfaces thus contain information on only the outermost atomic layers.

As the electron backscatters, it may create a vibrational quantum of frequency ω_v, and lose energy $h\omega_v$ in the process, where h is Planck's constant. Measurement of this small energy loss, which requires the development of highly monoenergetic electron beams, thus provides access to vibrational frequencies. In the last two decades, electron energy loss spectroscopy has evolved into a powerful probe of surface vibrations, notable for its wide spectral range.[1] Recent new experimental and theoretical developments have greatly expanded the information one may obtain from such data.

Traditionally, one measures the energy loss of only those electrons which suffer very small angular deflections in the vibrational excitation process; such events are particularly intense by virtue of the long-ranged coulomb fields generated by surface vibrations. Such electrons emerge very close to the specular direction after reflection off the surface, and these losses are most intense if rather low primary energies—from one to ten electron volts—are employed. Selection rules allow one access to only a subset of the vibrational modes of the surface, in this mode of operation.

A new generation of experiments[2–6] study electrons deflected through large angles in the loss event. They then emerge far from either the specular or Bragg beam directions. The near-specular selection rule breaks down, and one has access to the complete spectrum of vibrational modes, in principle. Electron momentum transfer is a new variable; the dependence of the frequency of a surface vibrational mode (surface phonon) on wavelength may be extracted from the shift of the corresponding loss peak with momentum transfer. The dependence of frequency on wavelength is called the dispersion curve, and we now have access to surface phonon dispersion curves continuously from long wavelengths, out to the shortest allowed, which equals the interatomic spacing. High frequency surface phonons associated with adsorbate layers have now been studied for several systems, along with the influence of adsorbates on the substrate surface phonons. The new spectroscopy is a surface analogue of the inelastic neutron scattering experiments which have proved a powerful probe of bulk matter.

Essential to the success of the new method is use of high beam energies in the 100–300 eV range; it is an experimental tour de force to produce such beams so monoenergetic that the tiny energy losses from vibrational excitating can be detected. In this energy region, it has proved possible[4] to calculate theoretically, in a remarkably quantitative manner, the energy and angle variation of surface phonon excitation cross sections. These have guided the choice of scattering geometry, in a successful search for a surface phonon predicted by theory, but absent in the early data. The systematics of the energy and angle variation of the cross sections are also found to be sensitive to surface geometry, so we have a new means of probing the two closely related topics of surface structure and surface dynamics, simultaneously.

In recent years, highly monoenergetic neutral helium beams have been developed, and employed to study surface phonons by energy loss spectroscopy.[6] We now have two complemen-

tary spectroscopies of surface phonons, and for the first time we have direct access to these modes, which have been studied for many years by theorists.[7]

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XPS and Auger Forward Scattering in Epitaxial Films

In angular-dependent x-ray photoelectron spectroscopy (XPS) and Auger electron spectroscopy (AES) of single crystals, an effect has long been known in which XPS and AES peaks exhibit enhanced intensities along major crystal axes.[1,2] This effect was thought to be due to electrons channeling among planes of atoms in the lattice.[1,3] However, recent studies on the development of these enhanced intensities during layer-by-layer epitaxial growth in metals such as Co, Ni, and Cu on Ni(100) and Cu(100) substrates demonstrate that the enhancements are already present when the metal under study is only two or three atomic layers thick.[2] This is too thin to be the result of channeling, which would require much thicker films.[2]

The actual physical basis of the effect is forward scattering of the outgoing electron by overlying lattice atoms. The initial outgoing electron wave interferes constructively with the scattered wave from an overlying atom to produce an enhanced intensity along the axis connecting the emitting and scattering atom.[4,5] Such an interference was first identified in XPS of molecular CO.[6]

This phenomenon has an interesting classical analogy in that the scattering atom is acting much like a lens, focussing the intensity of the emitting atom along the forward direction.[4] This means the XPS and AES peaks act like "searchlights" pointing out the internuclear axes present in the top several atomic layers.

This effect is a rather short-range one, applying primarily to nearest-neighbor and next-nearest-neighbor scattering atoms, since only the first scattering event tends to be forward focussing with subsequent scattering events (multiple scattering) tending to be defocussing.[4]

As a probe of local or short-range order this effect fills important gaps left by other techniques. In recent work, XPS and AES forward scattering have been found to provide a wealth of new information about such phenomena as the temperature dependence of surface alloying,[2] the effect of surface contamination on epitaxy,[7] misfit dislocations and abrupt junctions in epitaxy,[8] metal-semiconductor interfaces,[9] and surface core-level binding energy shifts.[2]

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PHYSICS NOBEL PRIZE

The 1986 Nobel Prize in physics was awarded for work devoted to the development of microscopes. Ernst Ruska of the Fritz Haber Institute of the Max Planck Gesellschaft in West Berlin received half of the prize money for his invention in 1931 of the electron microscope. The other half of the prize was shared by Gerd Binnig and Heinrich Rohrer, who work at the IBM Zurich Research Laboratory in Switzerland, for their development in the 1980s of the scanning tunneling microscope.

The IBM microscope employs a phenomenon known as quantum tunneling, in which subatomic particles can sometimes pass through "forbidden" regions of space (*see Physics News in 1983*, p. 16). Imagine, for the moment, an experiment in which tennis balls are rolled toward a concrete wall. Imagine also, on the other side of the wall, a detector which lights up every time a ball passes through the solid wall. In the macroscopic world such balls never pass through; the inside of the wall is a forbidden region, and the detector on the other side never lights up. Imagine now a microscopic version of this setup, with balls the size of electrons. Such tiny balls could, according to quantum mechanics, occasionally pass through the wall—the detector would now begin to light up. The likelihood of the quantum mechanical balls negotiating the forbidden passage through the wall is inversely proportional to the thickness of the wall. The thicker the wall, the fewer the number of balls observed on the other side. By working backwards, one could determine the thickness of the wall at any point by observing how frequently balls were able to tunnel through.

In Binnig's and Rohrer's device,[1] electrons are used to probe the surface layer of atoms in a material sample. The forbidden region in this case is a layer of vacuum (only several angstroms thick) separating two electrodes. One electrode, a very sharp needle (whose point is only a few atoms across), is equivalent to the source of tennis balls in the imaginary experiment. The other electrode is the sample whose surface properties are to be studied. By applying a tiny voltage difference between the needle tip and the sample surface, a tiny tunneling current of electrons will flow between them; the size of the current depends on the distance between the tip and the sample surface. By moving the needle (which is poised vertically above the sample) from place to place like a phonograph stylus over a record, a series of readings measuring the tip-sample separation at many points can be compiled. This scanning data can be converted into a three dimensional map of the surface layer of atoms in the sample.[2] The whole setup acts, in effect, as a microscope for imaging the sample surface.

In recent years this "scanning tunneling microscope" has been improved and now possesses a lateral resolution of 1 Å (the size of an atom) and an equivalent vertical resolution of about 0.01 Å.[3] The STM has generally been used to study the surface topography and chemical bonds between atoms in semiconductors and metals but has also been used to image biological subjects such as viruses. The STM has also been used as a device for measuring forces as small as 10^{-18} Newtons.[4] (For further information on scanning tunneling microscopy, refer to the articles in this issue in the chapters on condensed matter physics, vacuum physics, and on physics applied to industry.)

In the electron microscope, developed by Ruska and M. Knoll in Germany in 1931–32, electrons take the place of the light waves used in conventional optical microscopy.[5] In Ruska's device, which would now be called a transmission electron microscope, a beam of electrons strikes a sample. The scattered electrons pass through an aperture and are focused by a magnetic "lens" onto a screen or a photographic plate.

The advantage of using electrons over lightwaves is in their much smaller wavelengths: 0.1 Å for electrons in a typical device compared to thousands of angstroms for visible light. The resolution of the final image is inversely proportional to the wavelength of the illuminating beam. Typical electron microscope resolutions are about 2 Å.[6]

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